The High Luminosity LHC programme: Science case, challenges and R&D

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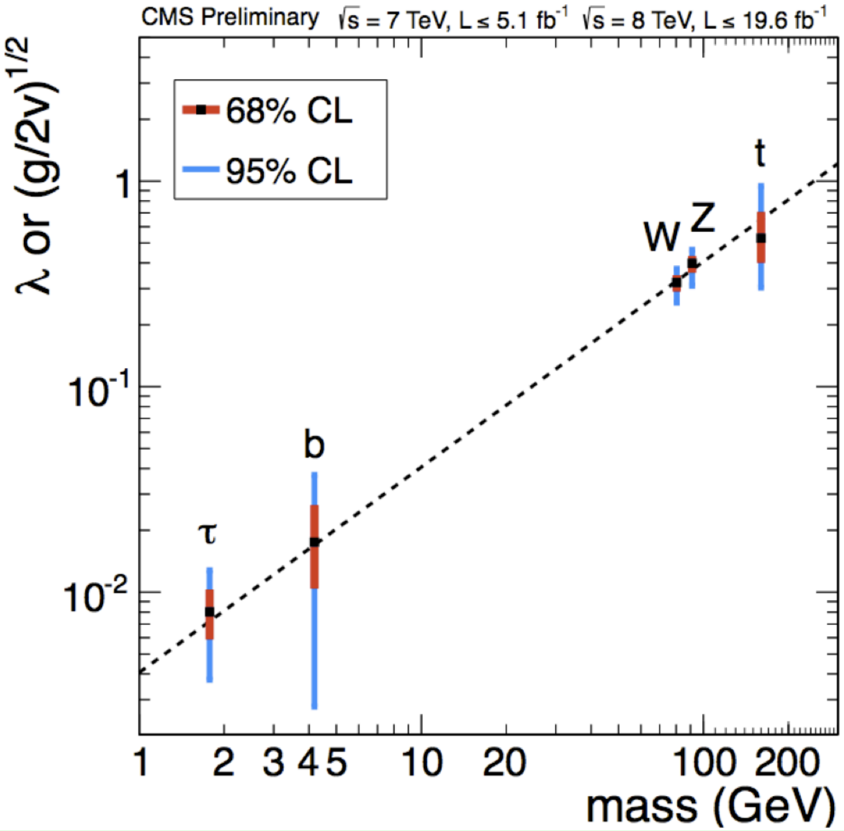
HEP Seminar, UCL, 21/02/2014

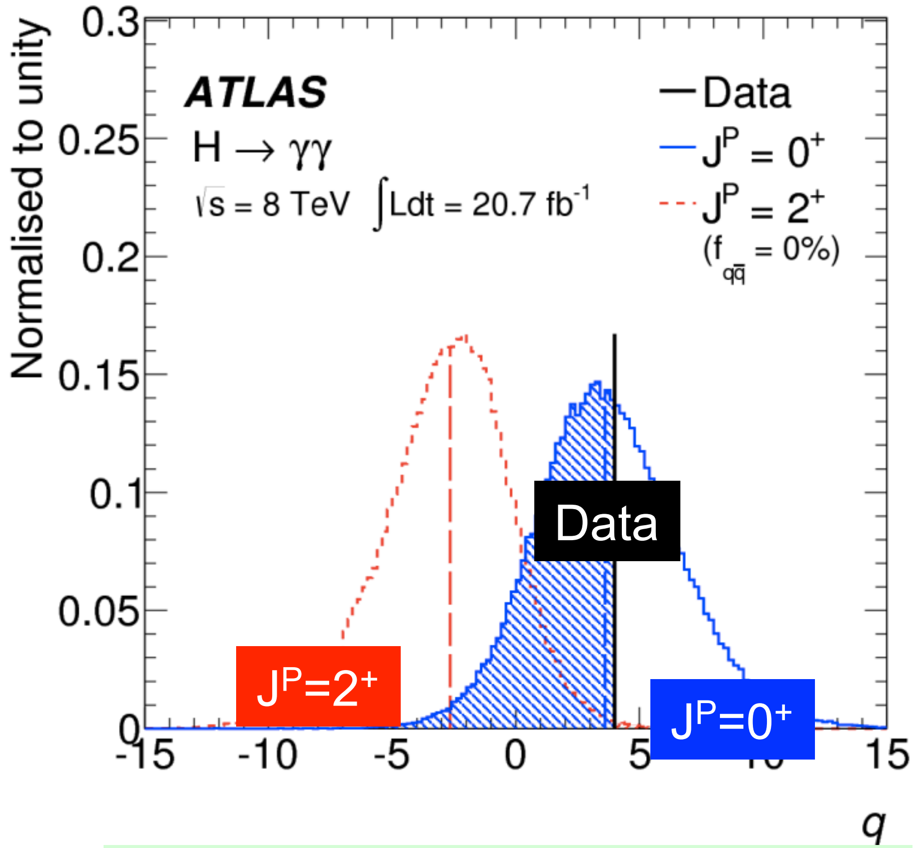
Outline

- What has LHC achieved so far?
- The LHC 20(+)-year plan – timelines and targets
- Science case for 3000fb^{-1} with HL-LHC
- LHC upgrades – how to deliver 3000fb^{-1}
- Detector upgrades for collecting efficiently 3000fb^{-1}
- Summary & Outlook

LHC result 1: the 125GeV Higgs

Arguably, the greatest discovery in fundamental science for half a century!





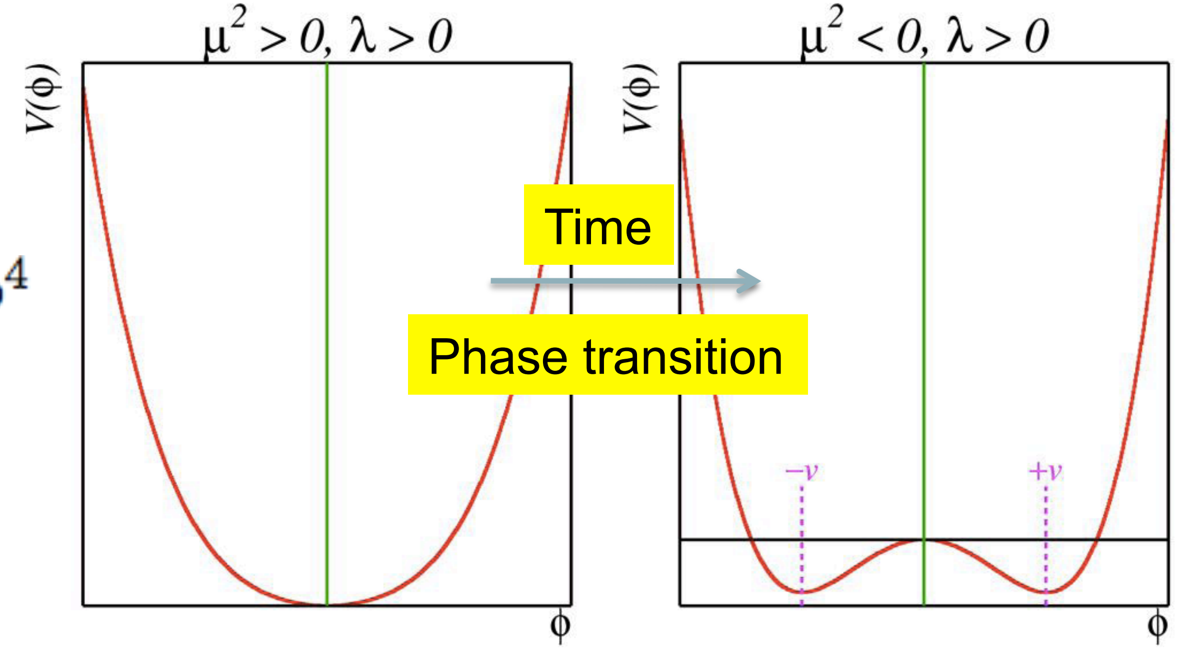
Showed that it couples to particles as the SM predicts (within current experimental accuracy)

Proved that its spin-parity is $J^P=0^+$. Other values excluded at 97-99.XX% C.L.

The 125GeV Higgs revolution

- The first-ever fundamental scalar particle observed in nature
- The Higgs field played vital role in the evolution of the universe
  - Phase transition ~10^{-11} sec after the Big Bang changed our universe:
    - From all massless particles => mostly massive particles

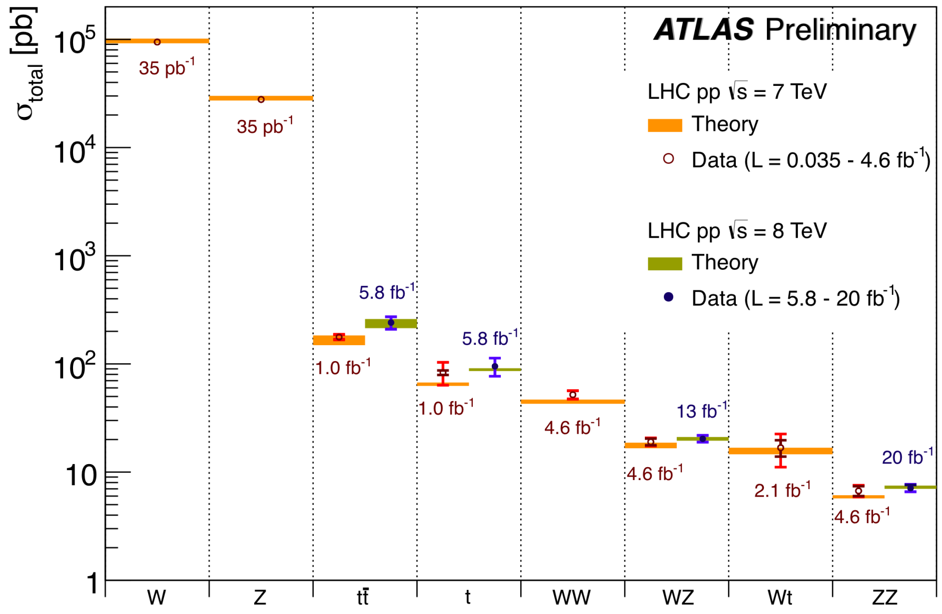
$$V(\phi^\dagger\phi) = \mu^2\phi^2 + \lambda\phi^4$$



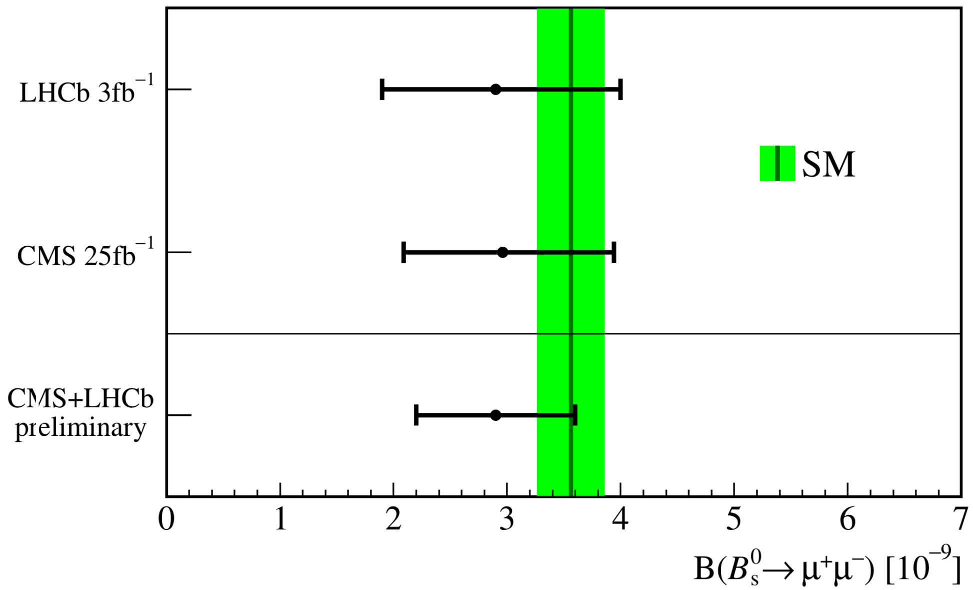
- How is this linked to the inflation theory?
  - According to cosmology, inflation was triggered by a scalar field
    - (E.g. see talk by Mikhail Shaposhnikov at EPS 2013 in Stockholm)

LHC result 2: the triumph of the SM

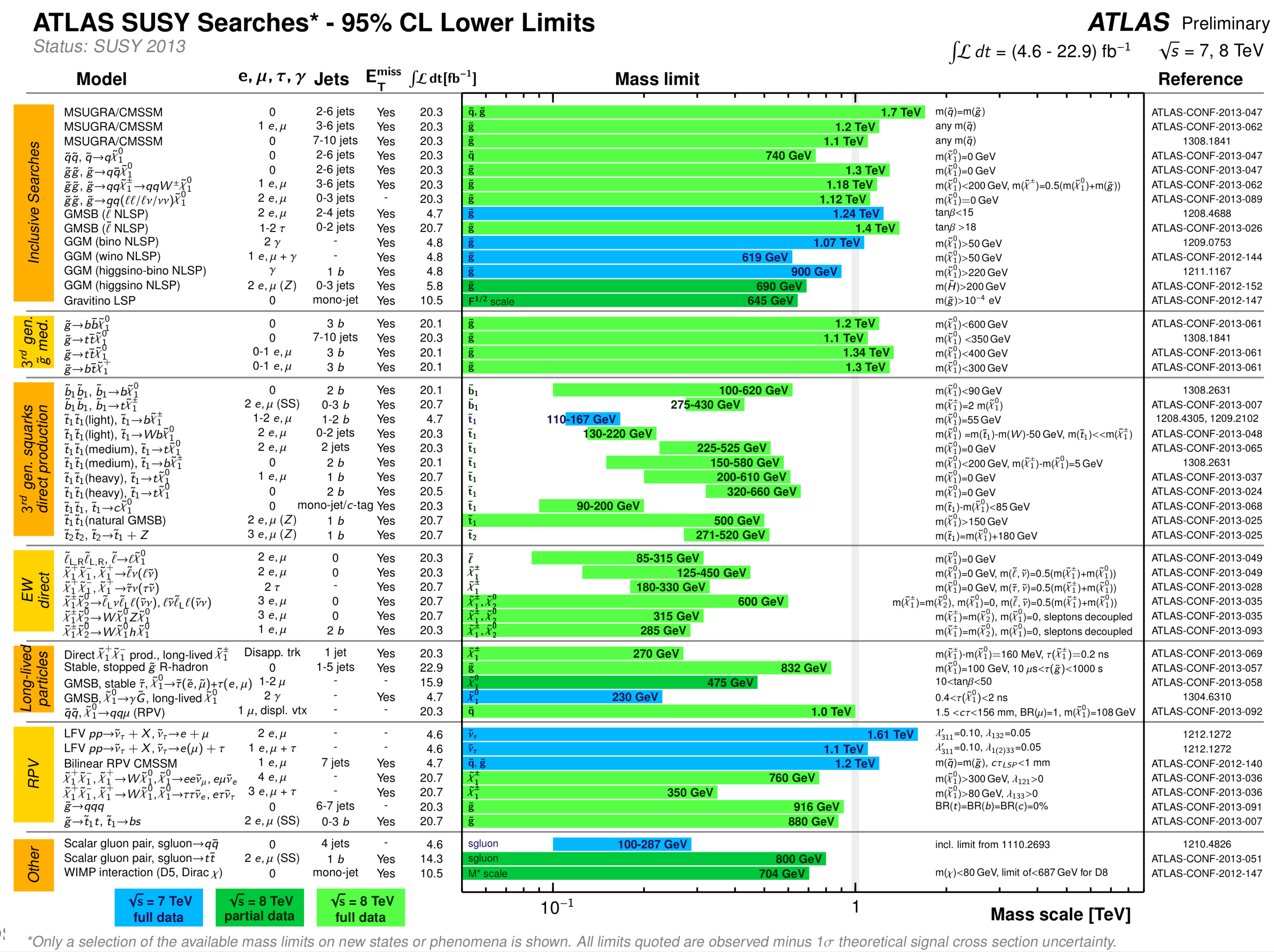
- A wealth of measurements at 7-8 TeV, all in good agreement with the Standard Model predictions



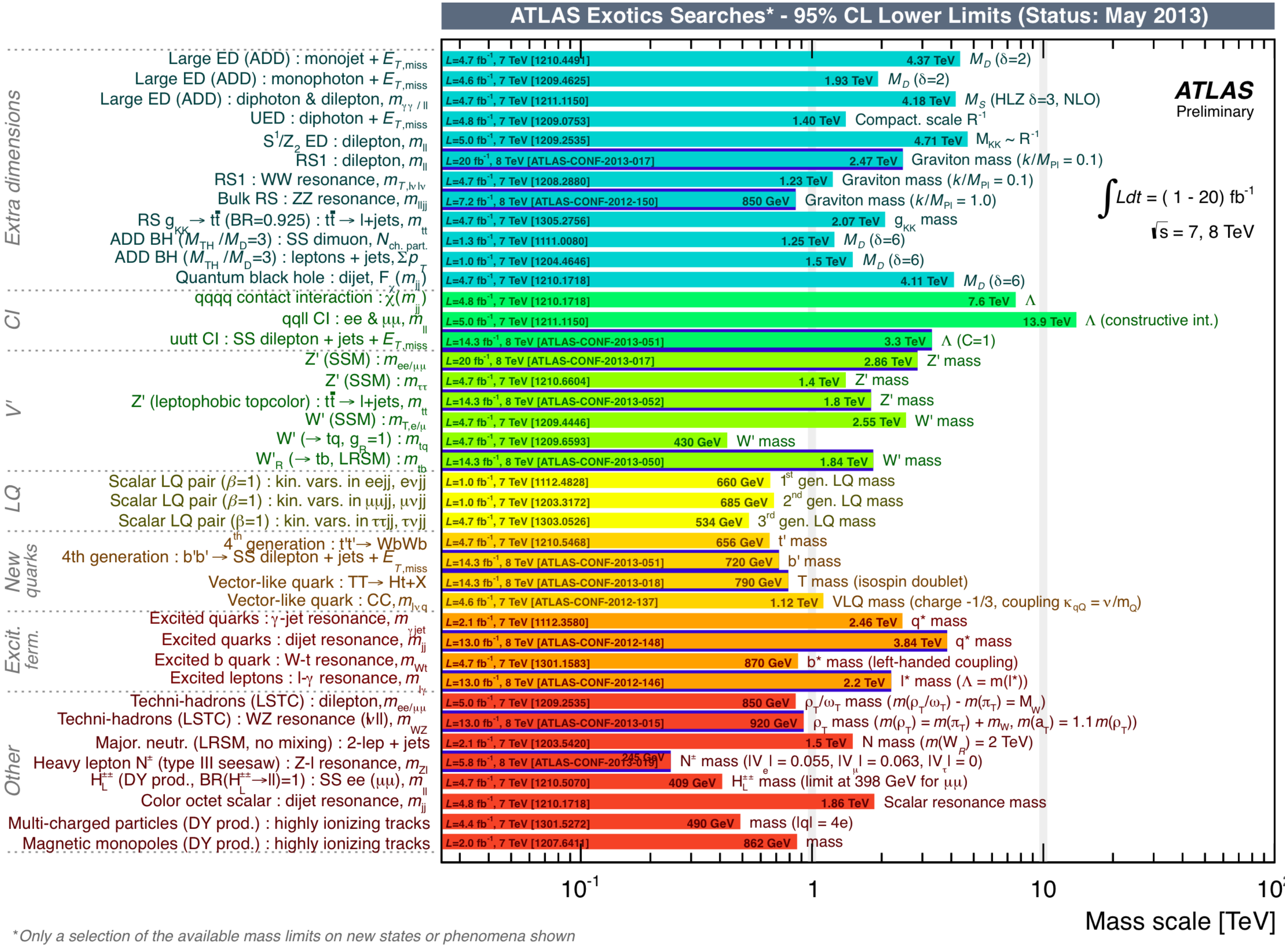
- Rare processes observed for the first time (notably $B_s \rightarrow \mu\mu$ with BR~$3x10^{-9}$) and their rate agree well with the Standard Model expectations



LHC result 3: No new physics!



LHC result 3: No new physics!



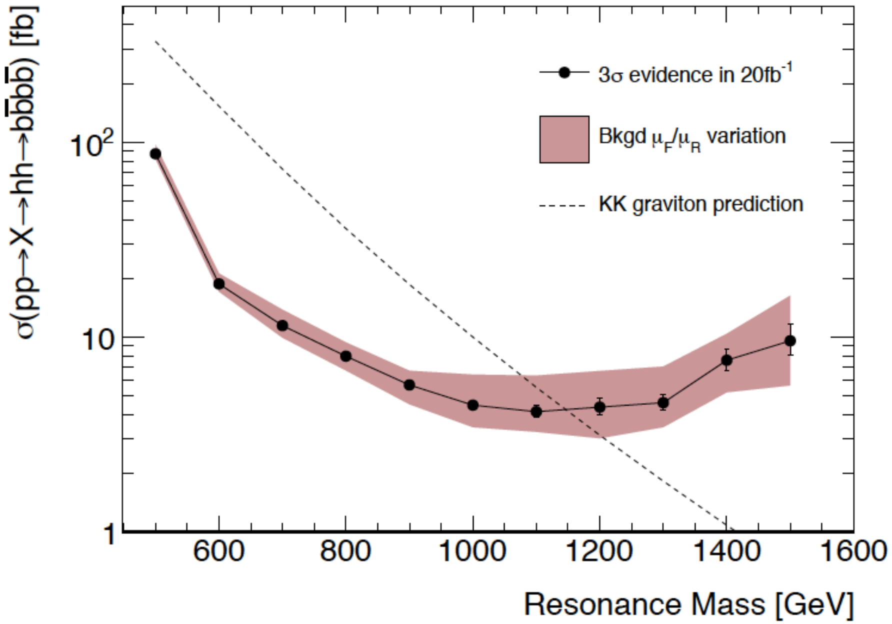
No new physics *yet* !…

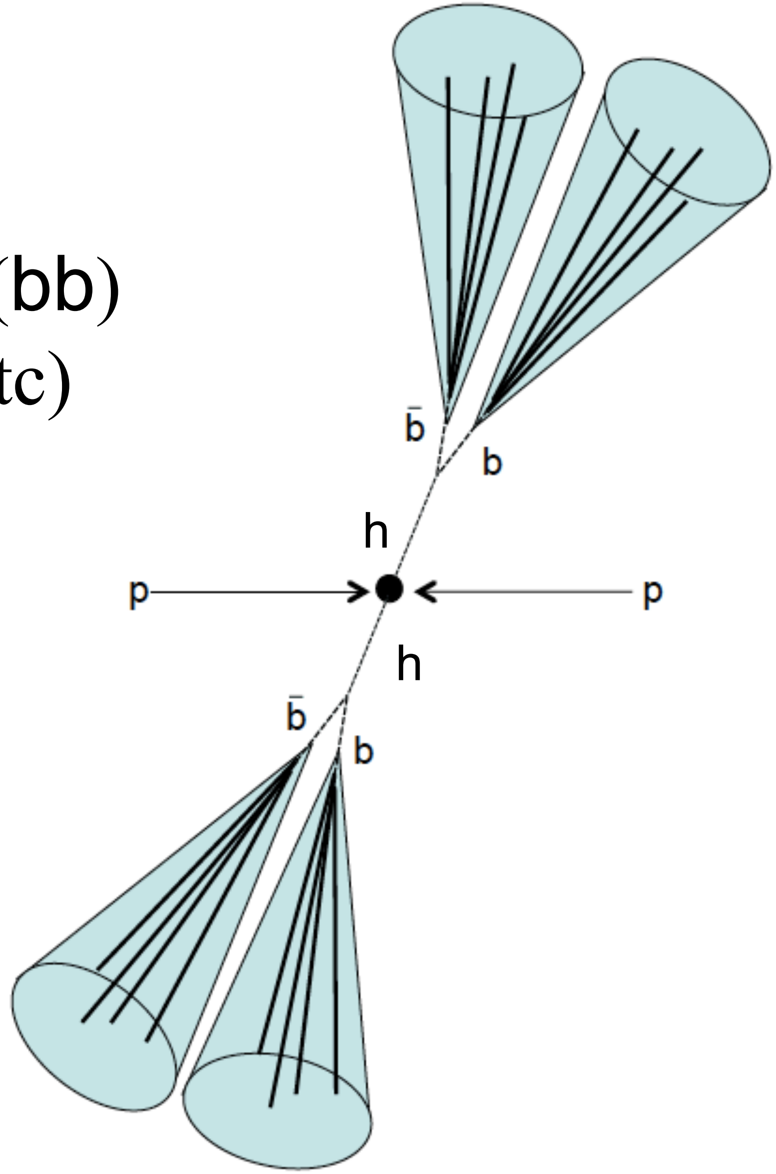
We have just started the exploration of the TeV scale!!!

Example: TeV-scale X→hh→(bb)(bb)

(X could be heavy Higgs, Graviton etc)

Sensitivity to x-sections of a few fb!





Phys. Rev. D 88, 114005 (2013) (Cooper, Konstantinidis, Lambourne, Wardrope)

LHC Run 1 summary & what next?

- The Standard Model has come out triumphant at 7-8TeV!

- No sign of BSM physics => New Physics is heavy or less abundantly produced than what we could detect so far

- Despite the Higgs discovery, fundamental questions remain
  - How come the Higgs is so light ("naturalness" or "hierarchy" problem)?
  - What is Dark Matter and Dark Energy (the ~96% of our universe!)?
  - Why is Gravity so weak? Extra dimensions?
  - What's the reason for the matter-antimatter asymmetry in our universe?

Top priorities for energy frontier research

- Investigate thoroughly the mass generation mechanism
  - Measure the Higgs properties as accurately as possible
  - Are there heavier partners of the 125GeV Higgs boson?
  - Does Higgs moderate the vector boson scattering cross section @~1TeV?

- Explore the multi-TeV (and sub-TeV!) region as thoroughly as possible
  - Go to as high masses and as low cross sections as possible

- Search for/observe rare processes that would signal deviations from the Standard Model
  - E.g. flavour changing neutral currents in top decays, or rare B decays

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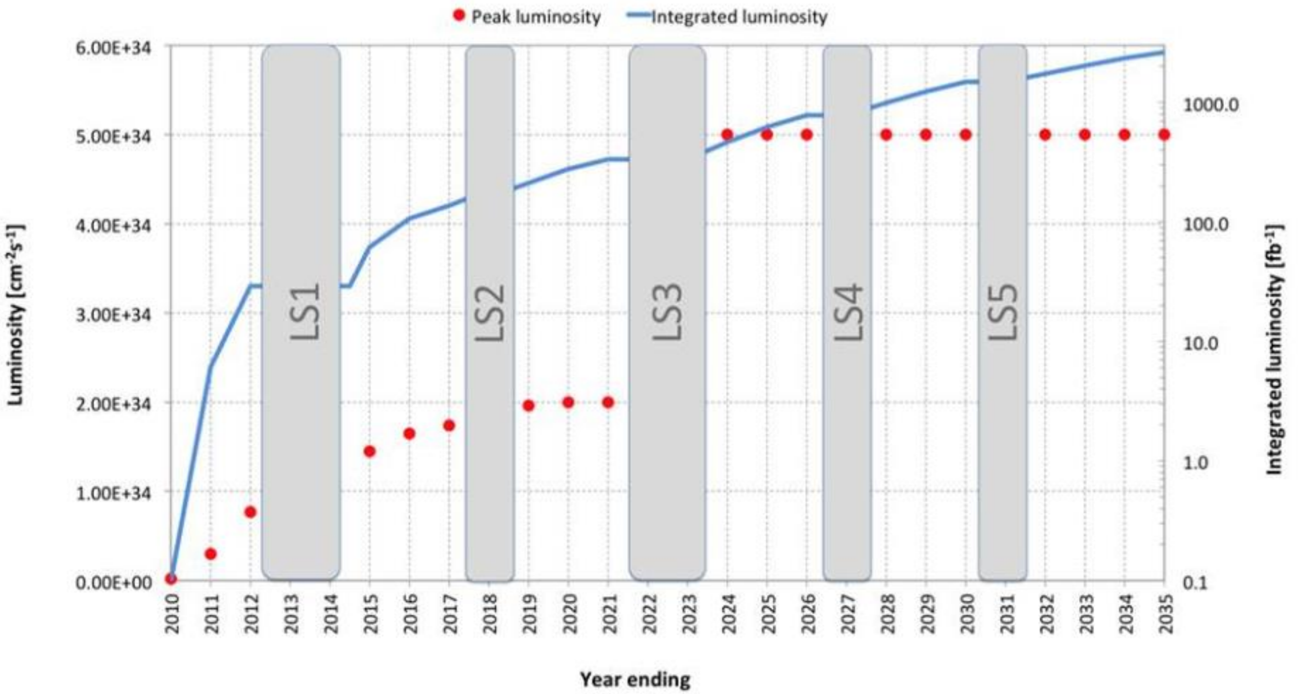
  - [illegible]avour changing neutral currents in top decays, or rare B decays

The High Luminosity LHC is the only programme for the next 20 years that can have a good shot in all these fronts

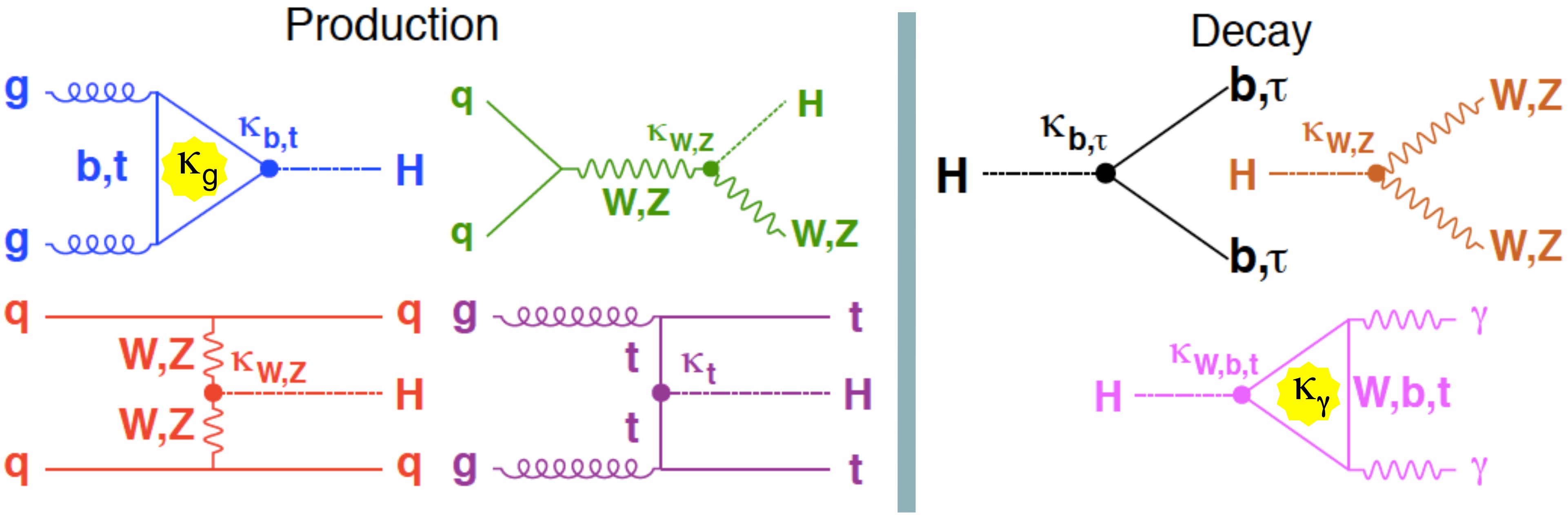
LHC future: The next 20+ years



Next ~10 years:
Peak lumi: ~2e34cm^{-2}s^{-1}
O(30fb^{-1}) → O(300fb^{-1})
Programme approved

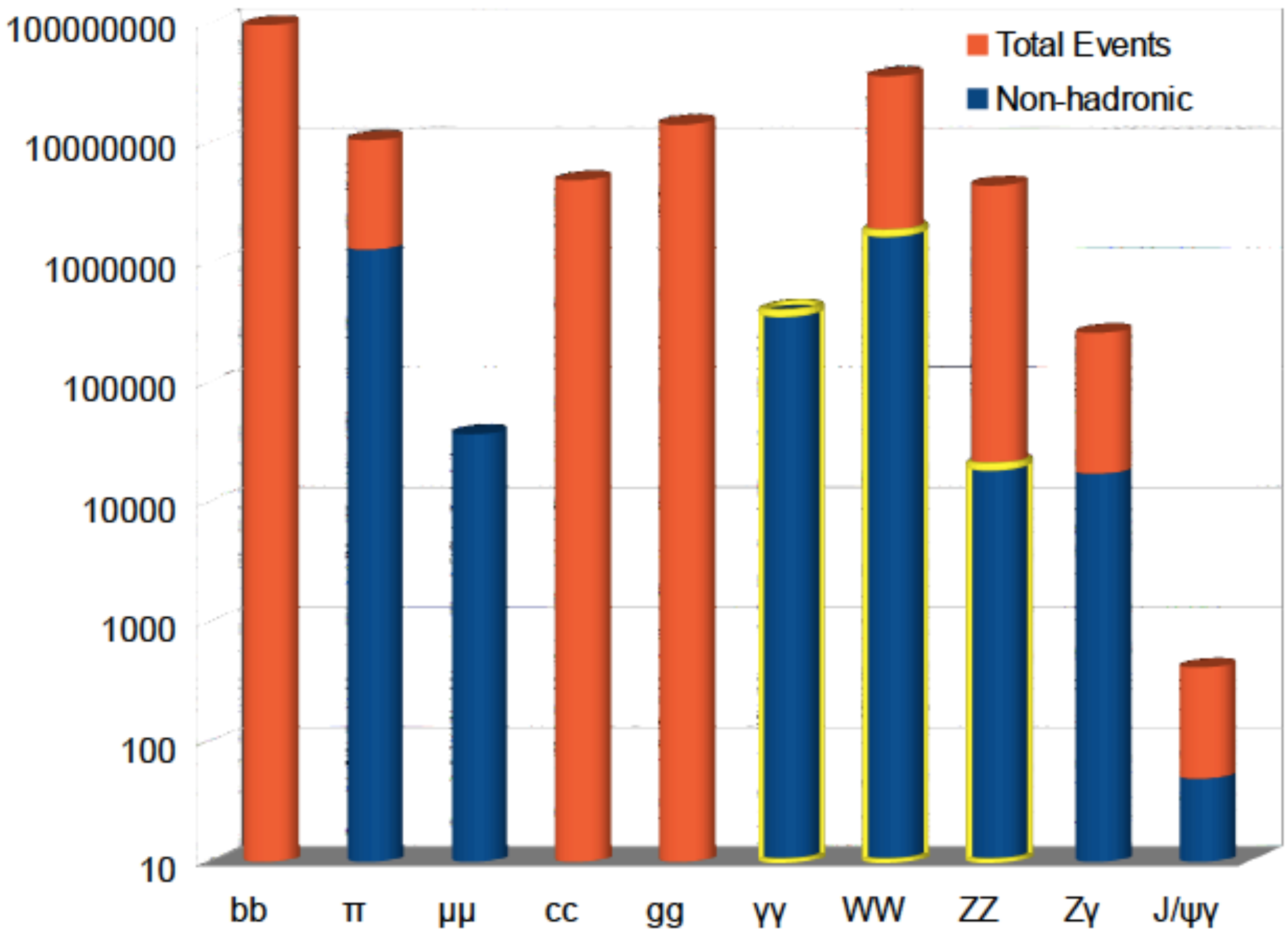
- HL-LHC programme:
  - Start in 2024 after a ~30-month shutdown (LS3)
  - Peak luminosity: ~5e34cm^{-2}s^{-1}
  - ~140 pp collisions bunch crossing
  - Collect ~250-300fb^{-1}/year/expt for a total of ~3000fb^{-1} by the mid-2030s

- At the LHC, only possible to measure σxBR's
  - Expressed as ratio to the SM values: $\mu=(\sigma x BR)/(\sigma x BR)_{SM}$
- Ratios of partial widths can be derived without any model assumptions
- Interpretation in terms of couplings is model dependent
  - Expressed in terms of scale factors, κ, wrt SM values; $\Gamma_X/\Gamma_Y \sim (\kappa_X/\kappa_Y)^2$



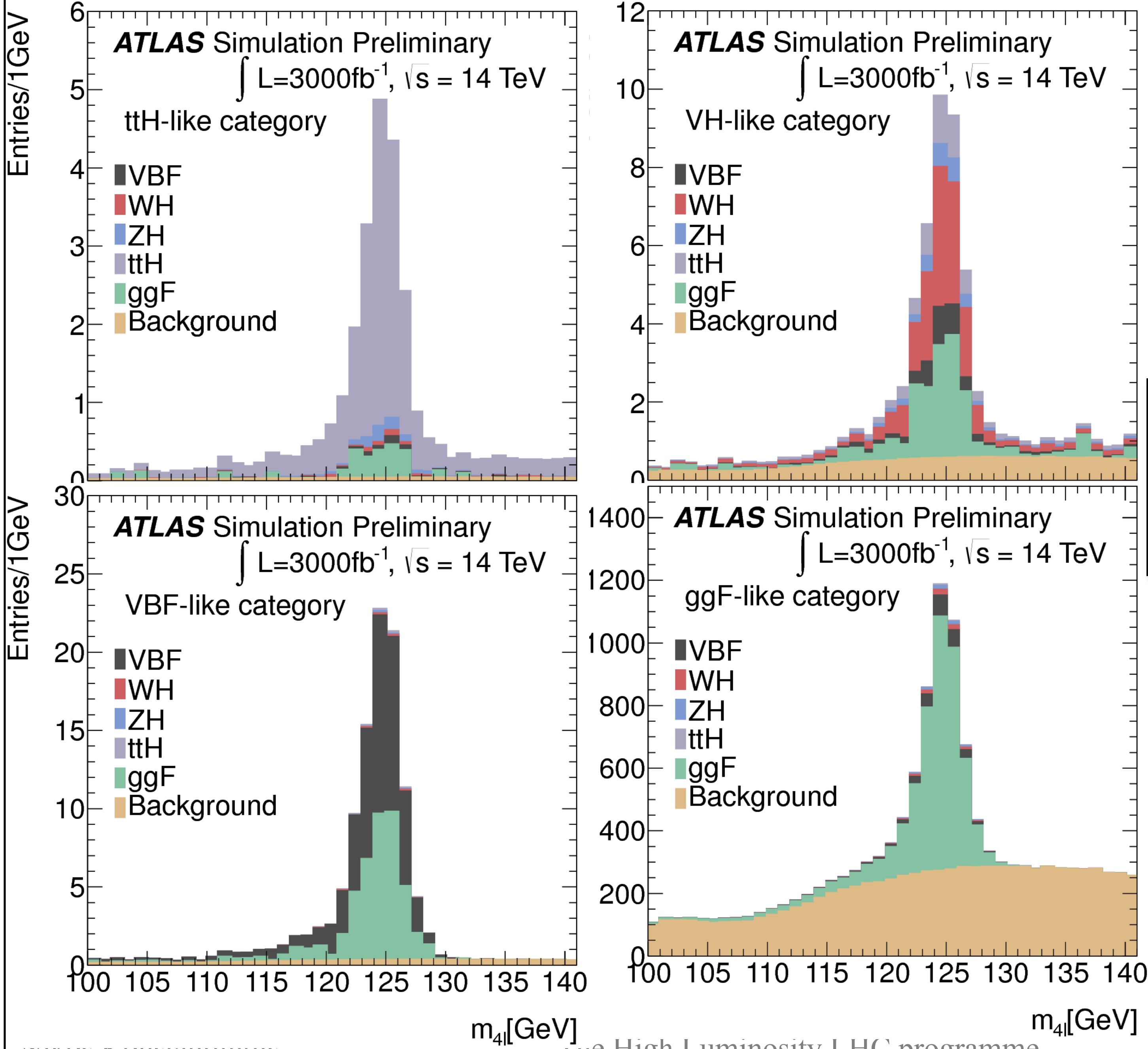
HL-LHC (3000fb^{-1}): the Higgs factory

Will produce more than 100M Higgs bosons!
(including over a million non-hadronic decays)
Current results with ~1500 Higgs events (ATLAS+CMS)



H→ZZ* decomposition

ATL-PHYS-PUB-2013-014

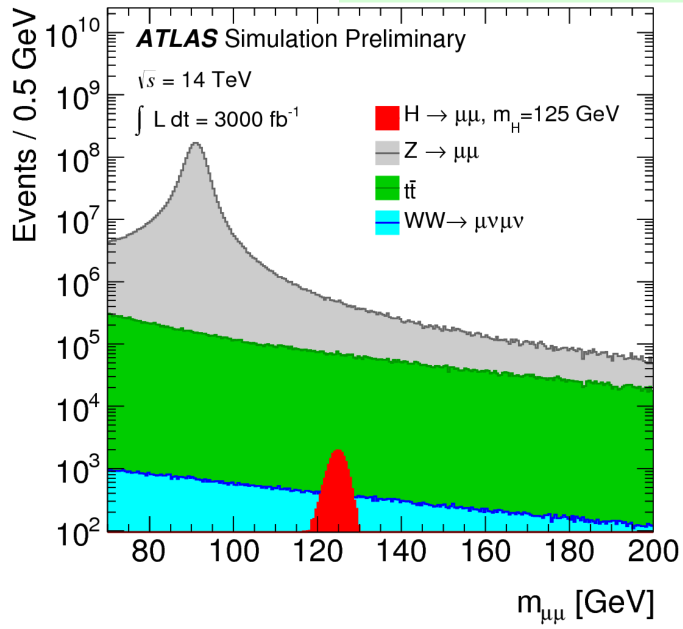


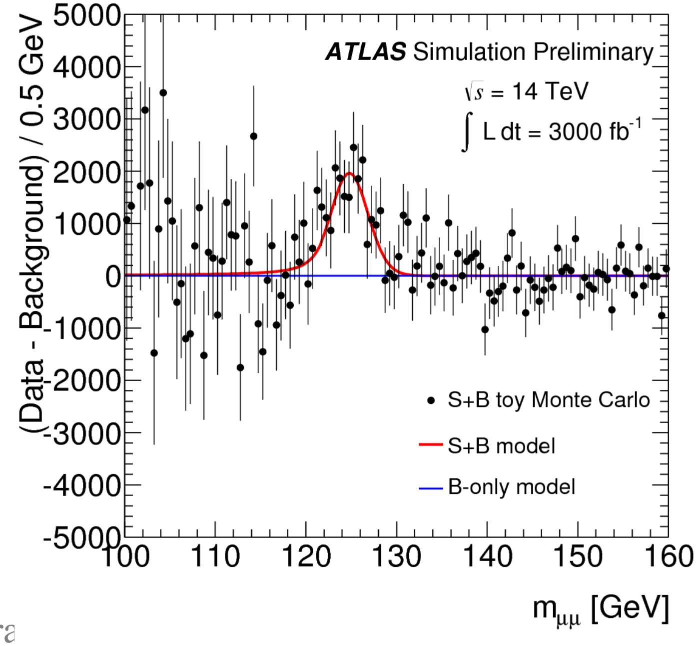
High purity channel: Possible to decompose into all production processes

Rare Higgs decays: H→μμ

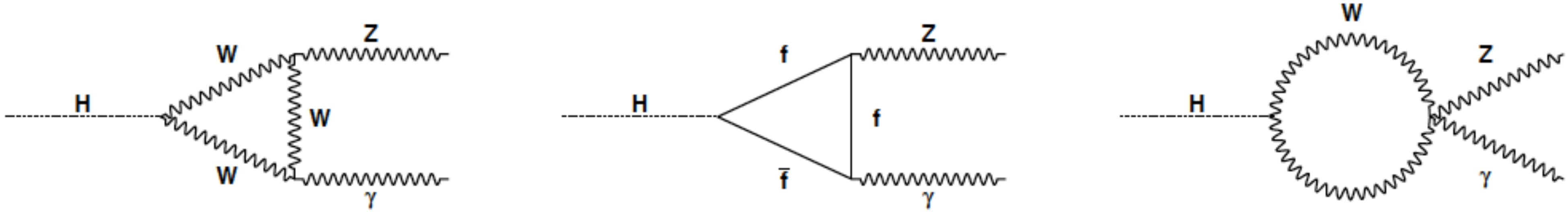
ATL-PHYS-PUB-2013-014

- ~2σ with 300fb^{-1} becomes
  ~6σ with 3000fb^{-1}
- First direct measurement of Higgs coupling to 2nd generation fermions
  - Compare τ to μ couplings
- Possible to observe ttH, H→μμ
  - Involves only fermion couplings
    - Relevant for CP violation studies
  - Only ~30 events in 3000fb^{-1}, but very pure: s/b~1

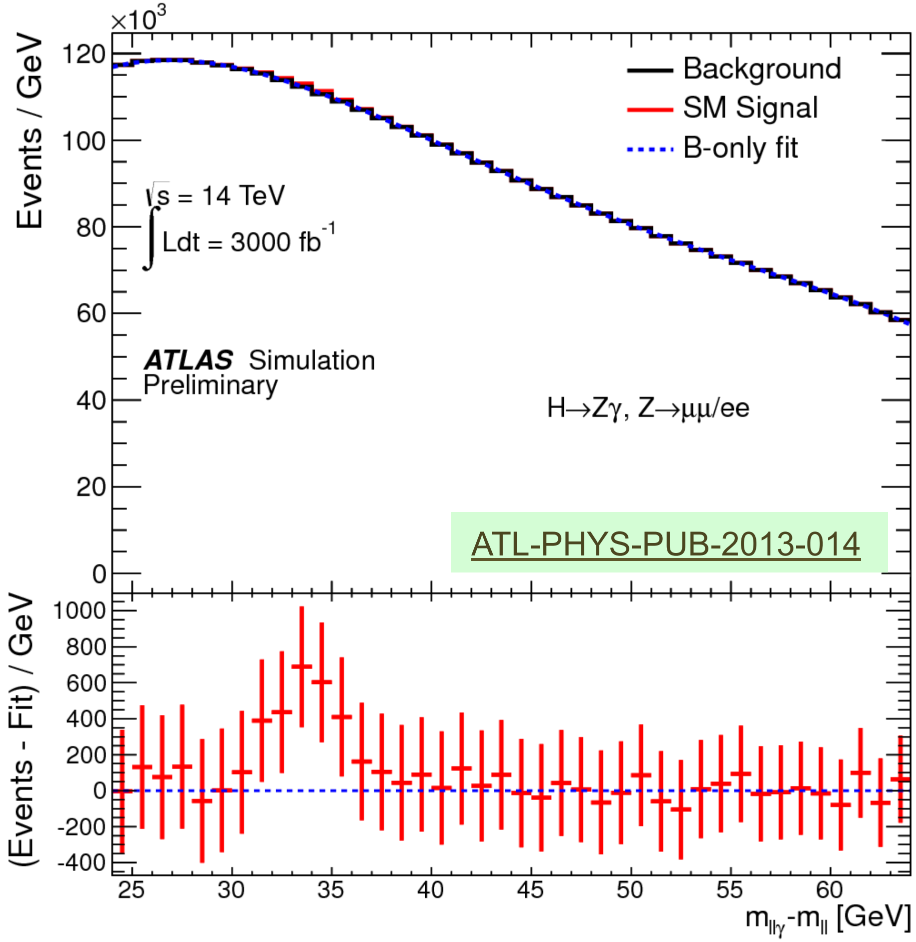




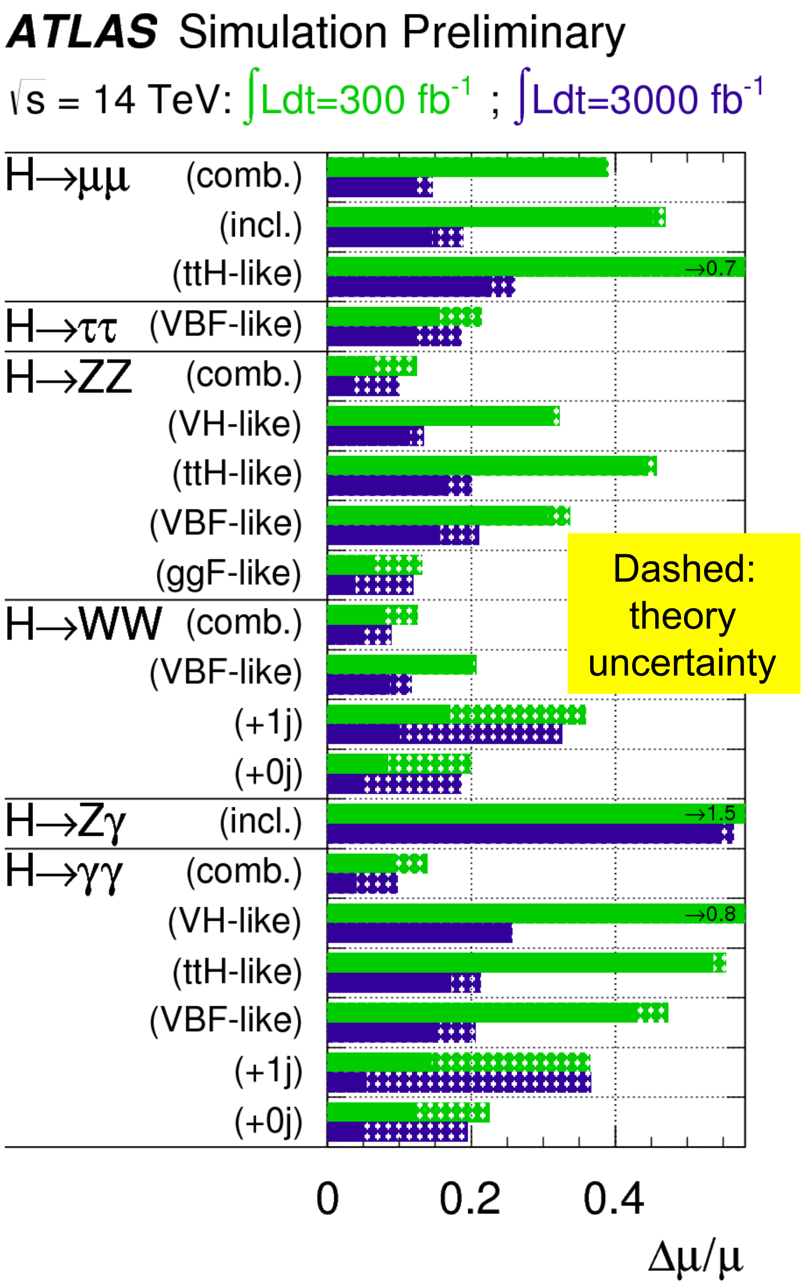
Rare Higgs decays: H→Zγ



- Good test of the loop structure
  - Compare to H→γγ
- Marginal s/b, but measurement possible with 3000fb^{-1} thanks to good mass resolution



Signal strength and couplings



ATL-PHYS-PUB-2013-014

Minimal fit: only two coupling scale factors, κ_F for fermions and κ_V for vector bosons

- No BSM contributions in either loops or in the total Higgs width

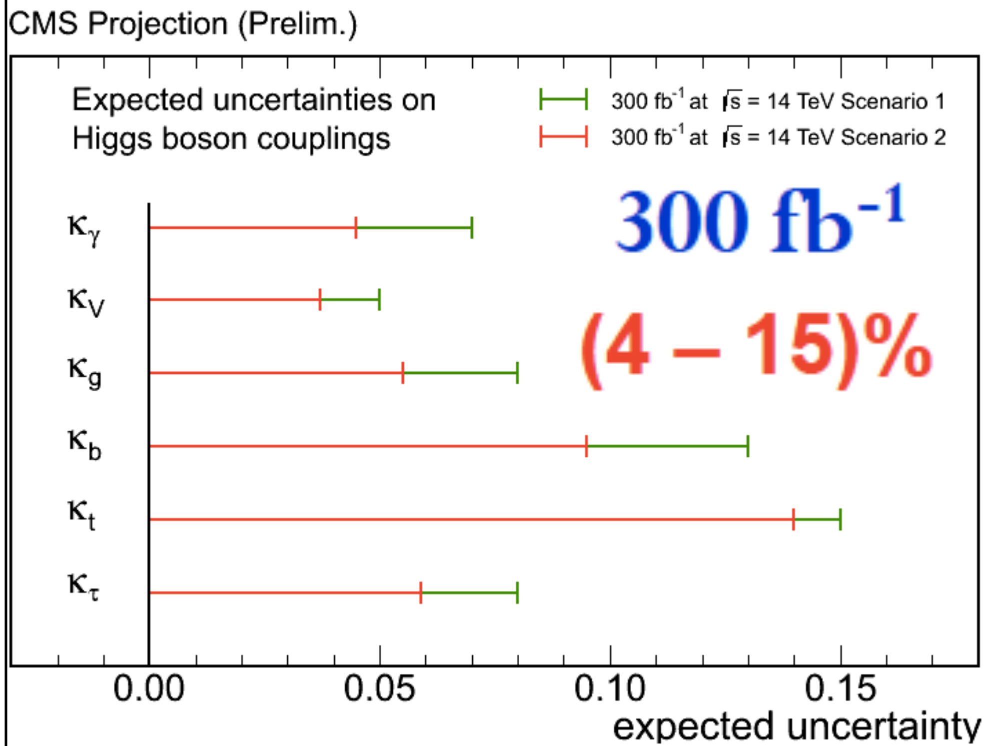
Sensitivity without (with) theory uncertainties:

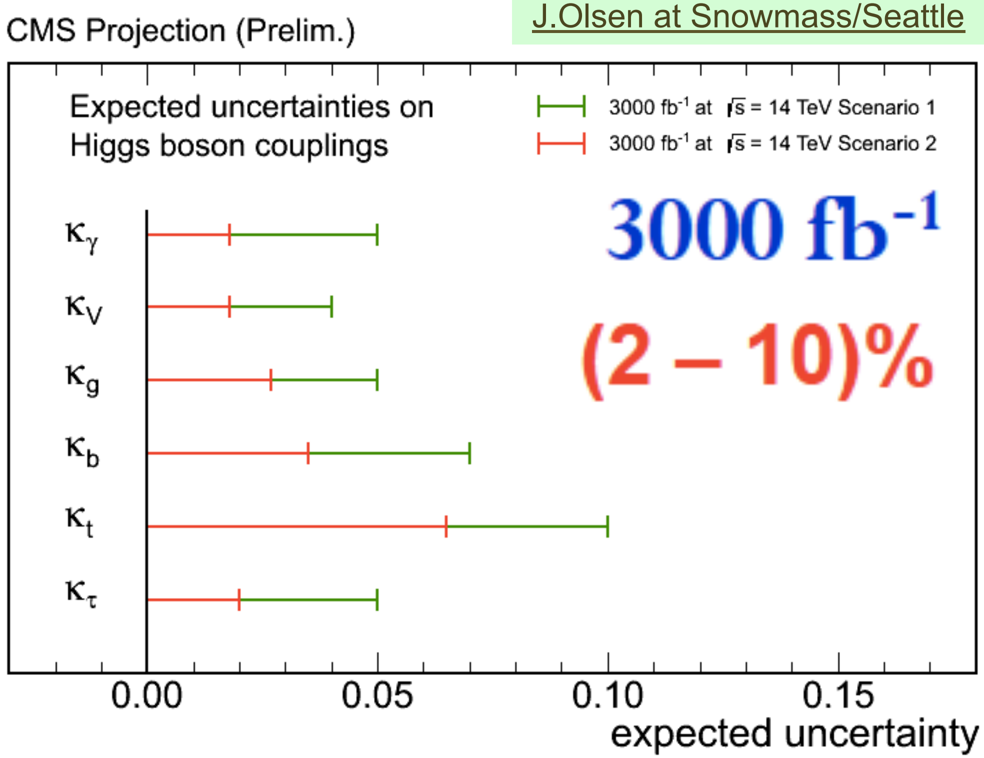
ATLAS	300 fb^{-1}	3000 fb^{-1}
κ_V	3.0 % (5.6 %)	1.9 % (4.5 %)
κ_F	8.9 % (10 %)	3.6 % (5.9 %)

A big improvement, esp. on κ_F, with 3000fb^{-1} provided the theory uncertainties are reduced!

Couplings

J.Olsen at Snowmass/Seattle





Numbers in brackets are % uncertainties on coupling deviations for [scenario 2, scenario 1]

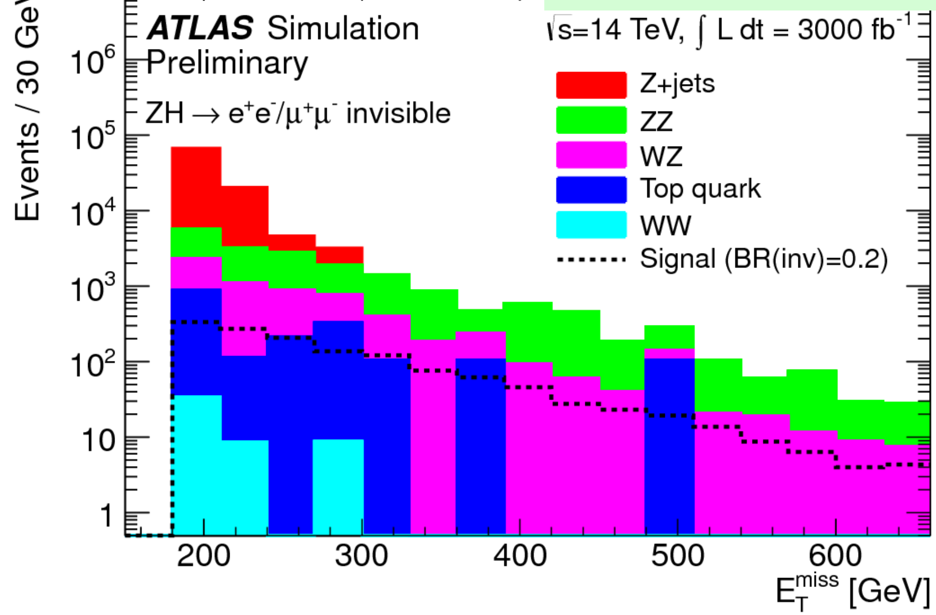
L (fb^{-1})	κ_γ	κ_V	κ_g	κ_b	κ_t	κ_τ
300	[5, 7]	[4, 5]	[6, 8]	[10, 13]	[14, 15]	[6, 8]
3000	[2, 5]	[2, 3]	[3, 5]	[4, 7]	[7, 10]	[2, 5]

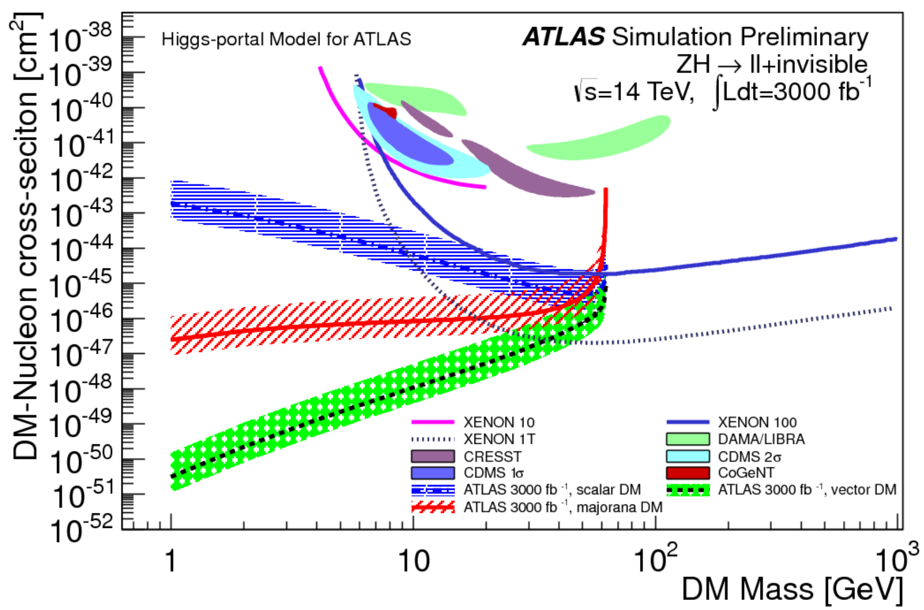
Ultimately, combined ATLAS+CMS precision down to a few %.

Invisible Higgs branching ratio

ATL-PHYS-PUB-2013-014

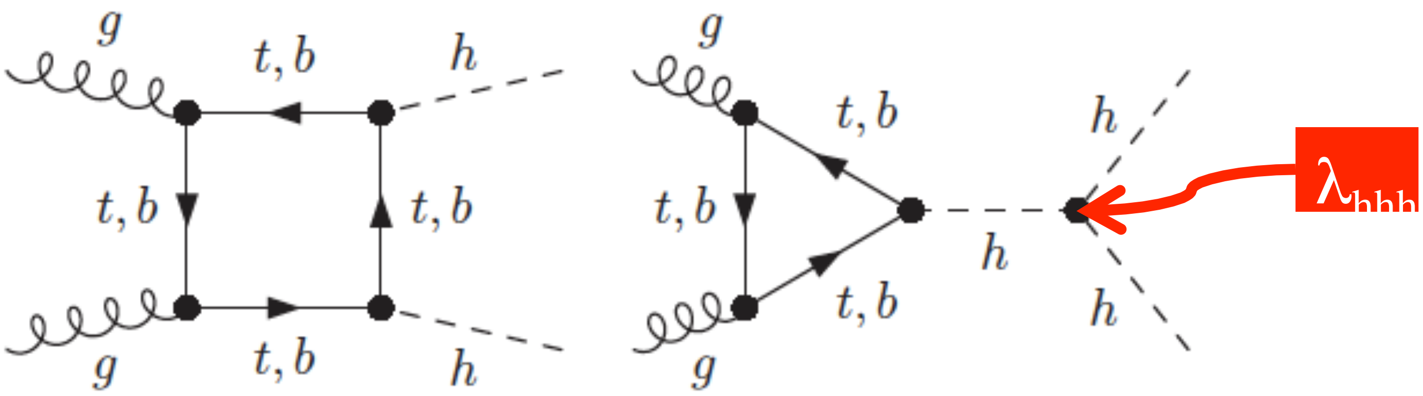
- Search for ZH→ℓℓXX
  - Needs good control of E_T^{mis}
- BR(H→XX) sensitivity
  - 23% with 300fb-1
  - 8% with 3000fb-1
- Other channels can add more sensitivity (e.g. VBF)
- Can be interpreted in terms of Dark Matter searches





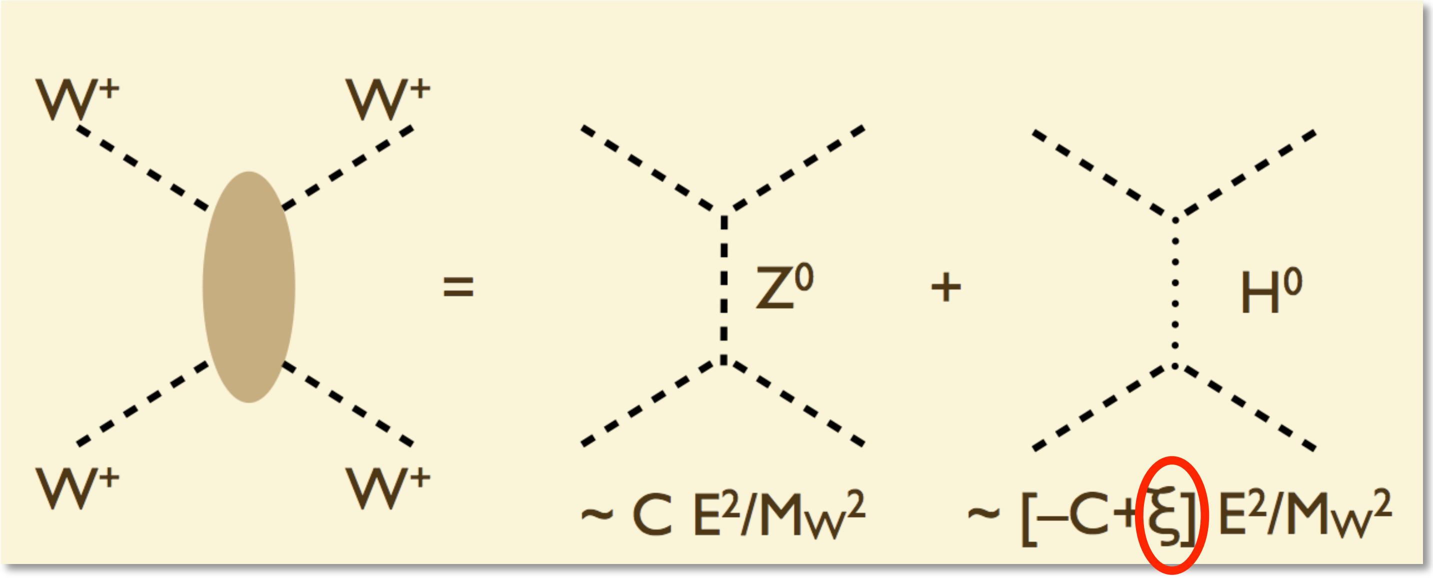
Higgs self-coupling

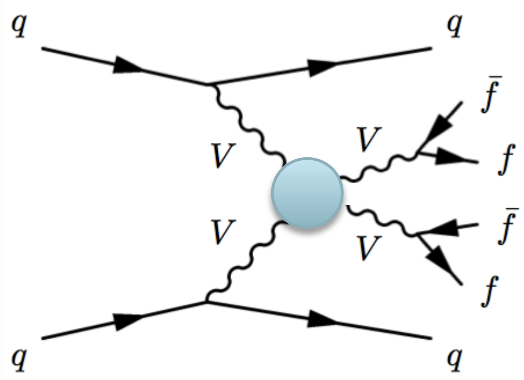
Important consistency check of the EWSB mechanism



- Arguably, the most challenging measurement at the LHC!
  - Destructive interference with diagrams not containing the hhh vertex
  - For $\lambda_{HHH}/\lambda_{HHH}^{SM}$ = 0/1/2, the cross section is 71/34/16fb
- Preliminary ATLAS studies indicate that hh→bbγγ is promising
  - σxBR~0.1fb, backgrounds are largely Xh(h→γγ) and continuum bbγγ
  - Additional signal channels under study, e.g. bb-bb, bbττ
- A ~3σ measurement by ATLAS+CMS with 3000fb^{-1} seems possible

Vector Boson Scattering

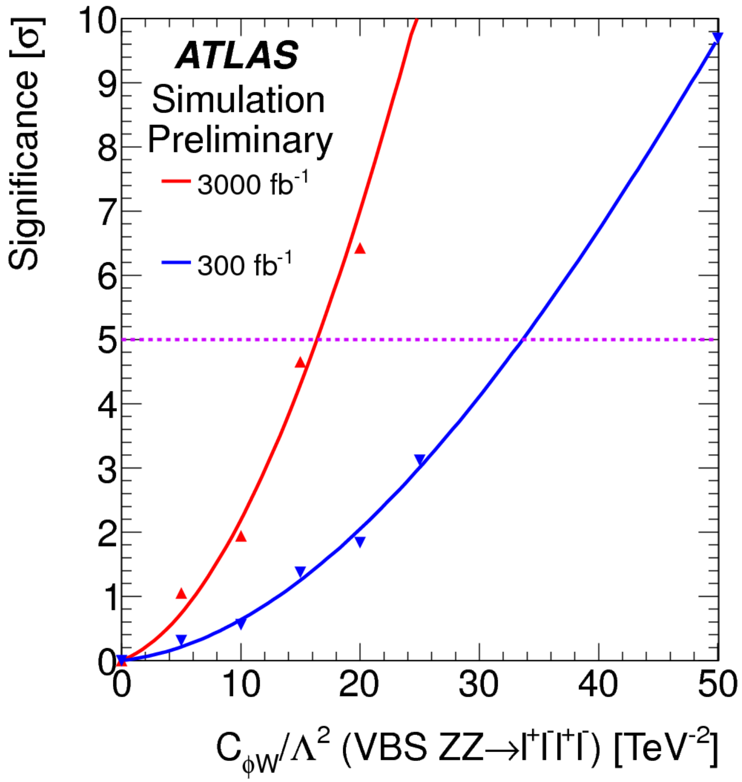


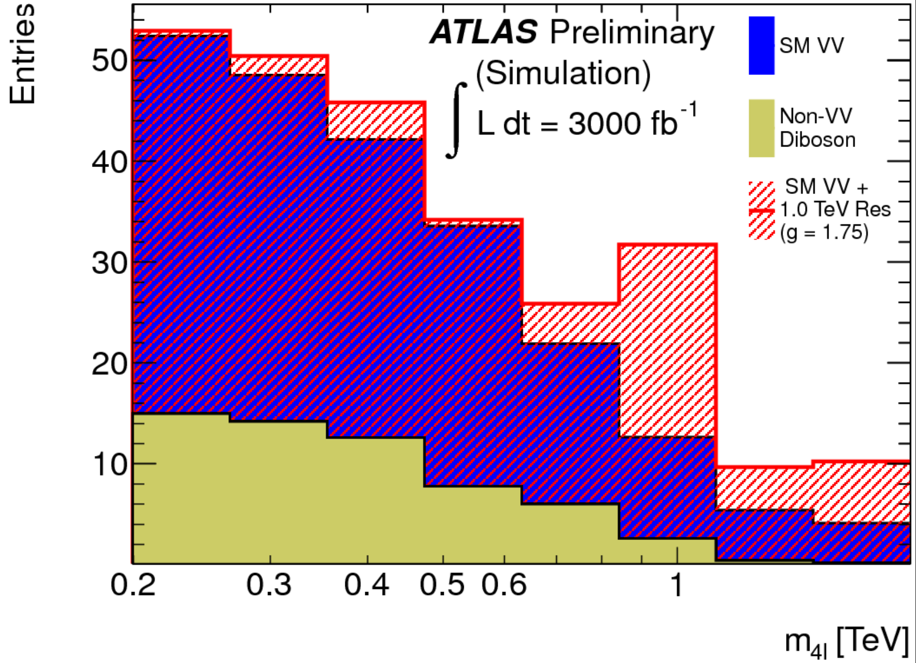


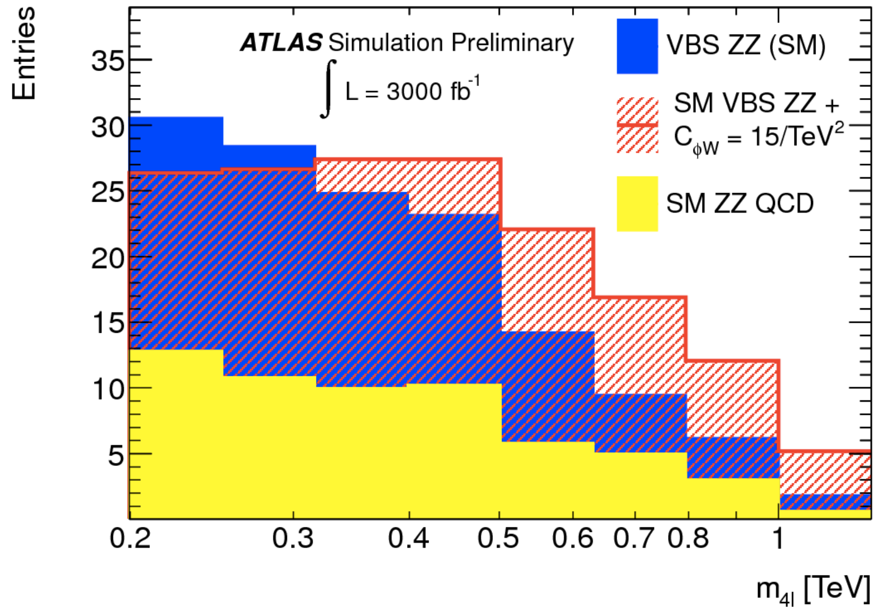
- Provides insight into the dynamics of EW symmetry breaking
  - Important closure test of the Standard Model
  - In SM with Higgs, ξ=0; ξ≠0, would be sign for new (resonant and/or non-resonant) physics
  - If ξ≠0, important to study as many final states as possible (WW/WZ/ZZ) in order to learn the most about the new dynamics

Vector Boson Scattering

- Big gains in sensitivity from 300fb^{-1} to 3000fb^{-1}
  - Factor ~3 improvement in measuring the Standard Model σxBR
  - Factor ~2 better sensitivity to models predicting TeV-scale resonances

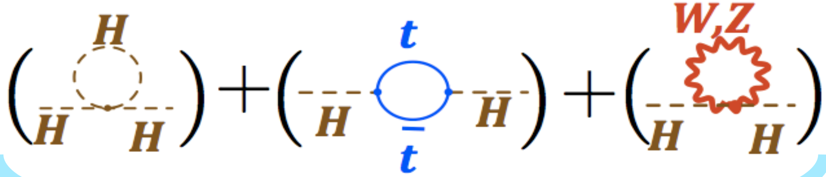






Observed mass (~125GeV)

$$M_H^2 = M_{\text{bare}}^2 +$$



Bare mass to cancel radiative corrections

Radiative corrections, top loop dominates: ~$m_t^2\Lambda^2$

Λ^2: the energy scale at which the SM breaks down

If Λ was the Planc scale (~10^{19}GeV), one would need a cancellation to 33 digits!

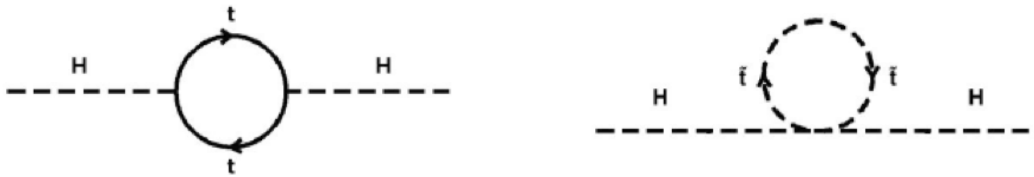
Fine tuning!

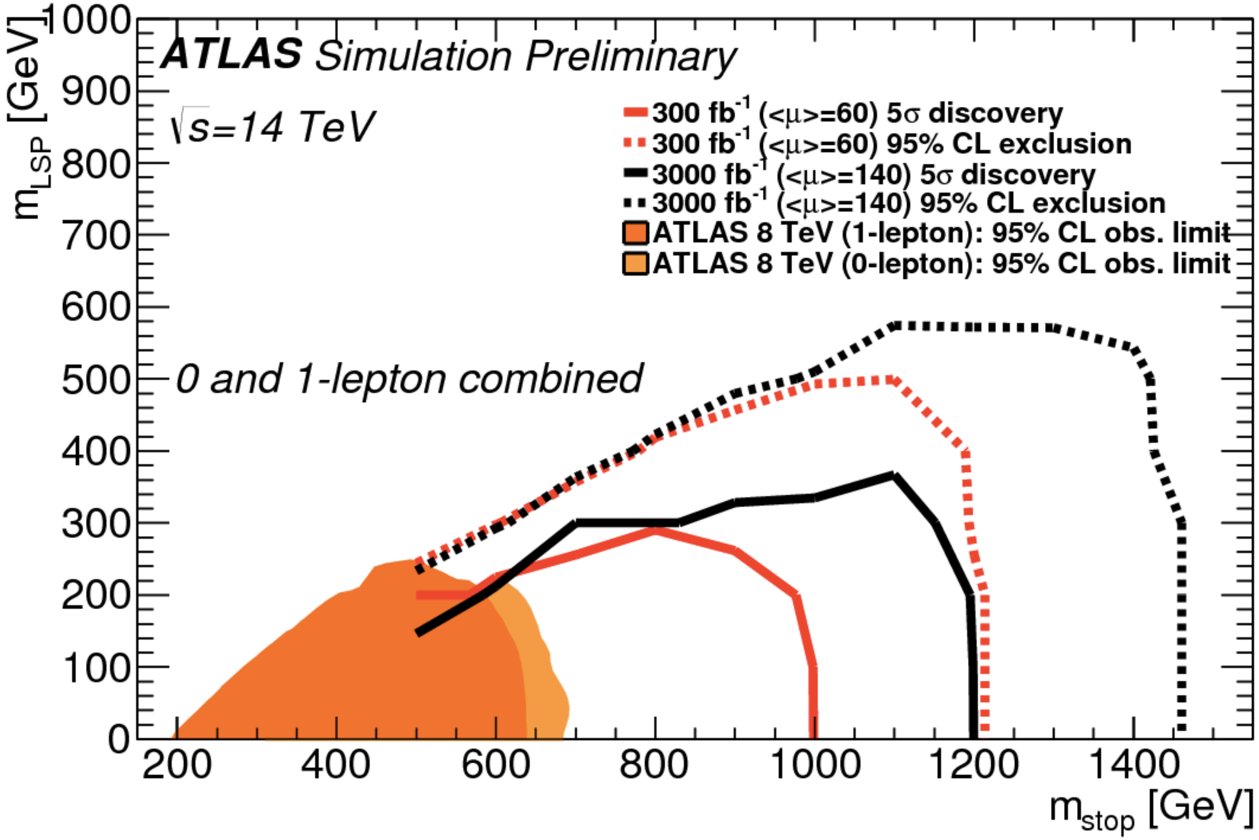
Even for Λ=10TeV the fine tuning is at the per mille level!

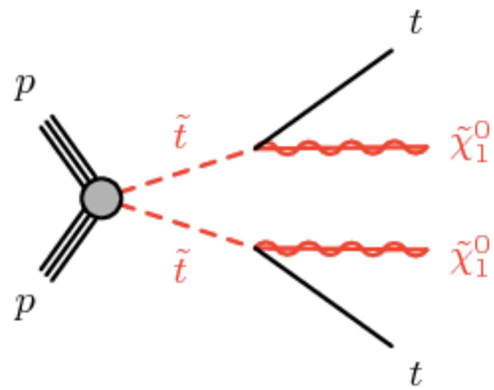
Strongest motivation for new physics at TeV scale

SUSY: one way to avoid fine tuning

In SUSY, the stop loop would cancel the top loop contribution to the Higgs mass.
But cancellation <u>*only works*</u> if stop mass is not much heavier than top mass.
Stop cannot be heavier than O(~1TeV).

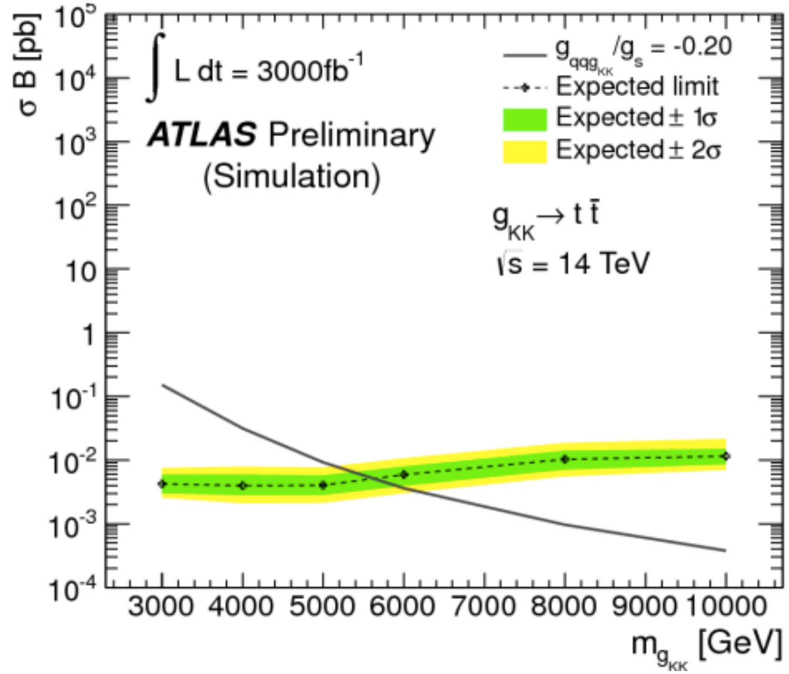






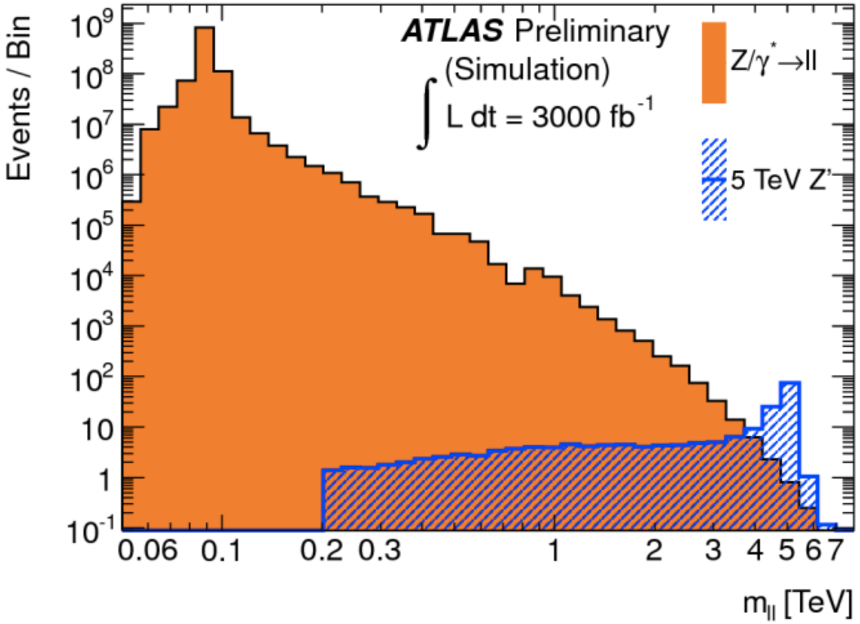
20% increase in reach with 3000fb^{-1} may prove vital

Exploration of the Multi-TeV scale



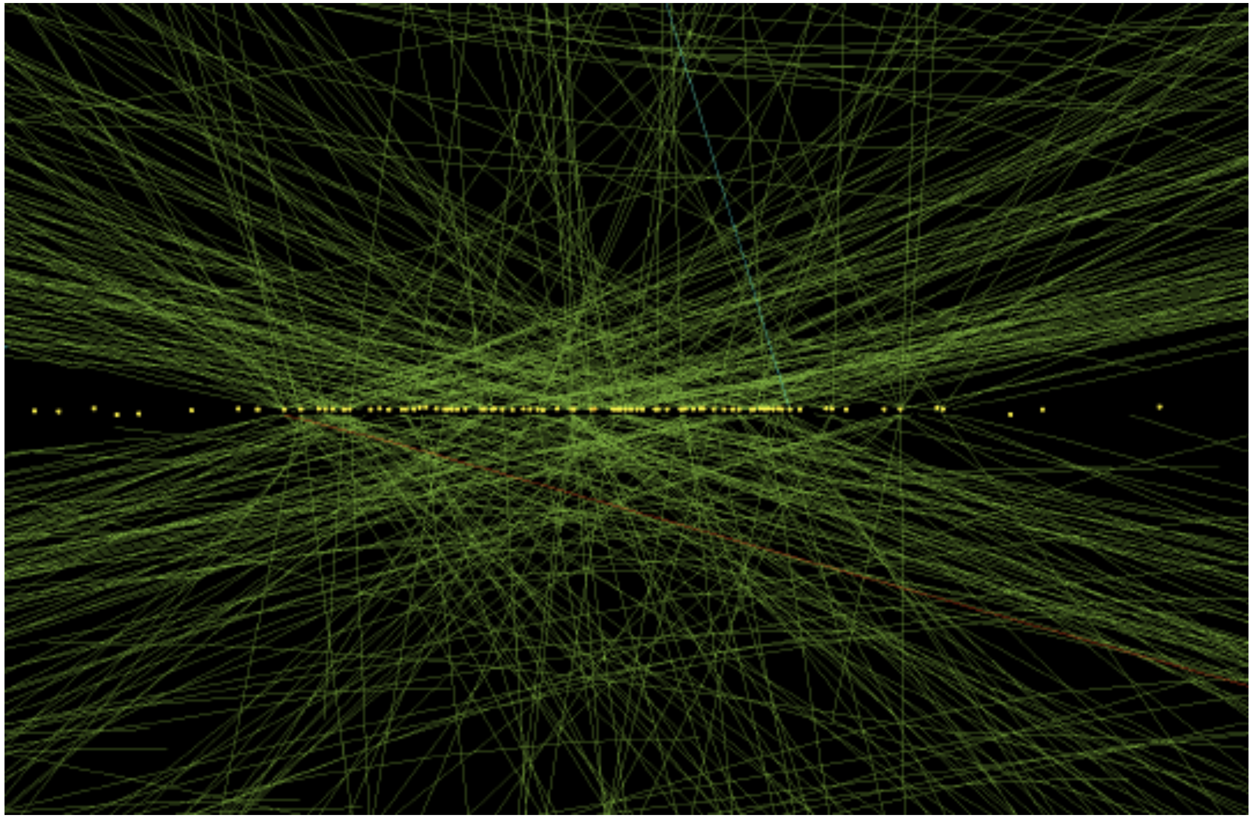
model	$300\ \mathrm{fb}^{-1}$	$1000\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)
Z'_{topcolor}	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)

Sensitivity improvements up to 50% in the multi-TeV scale

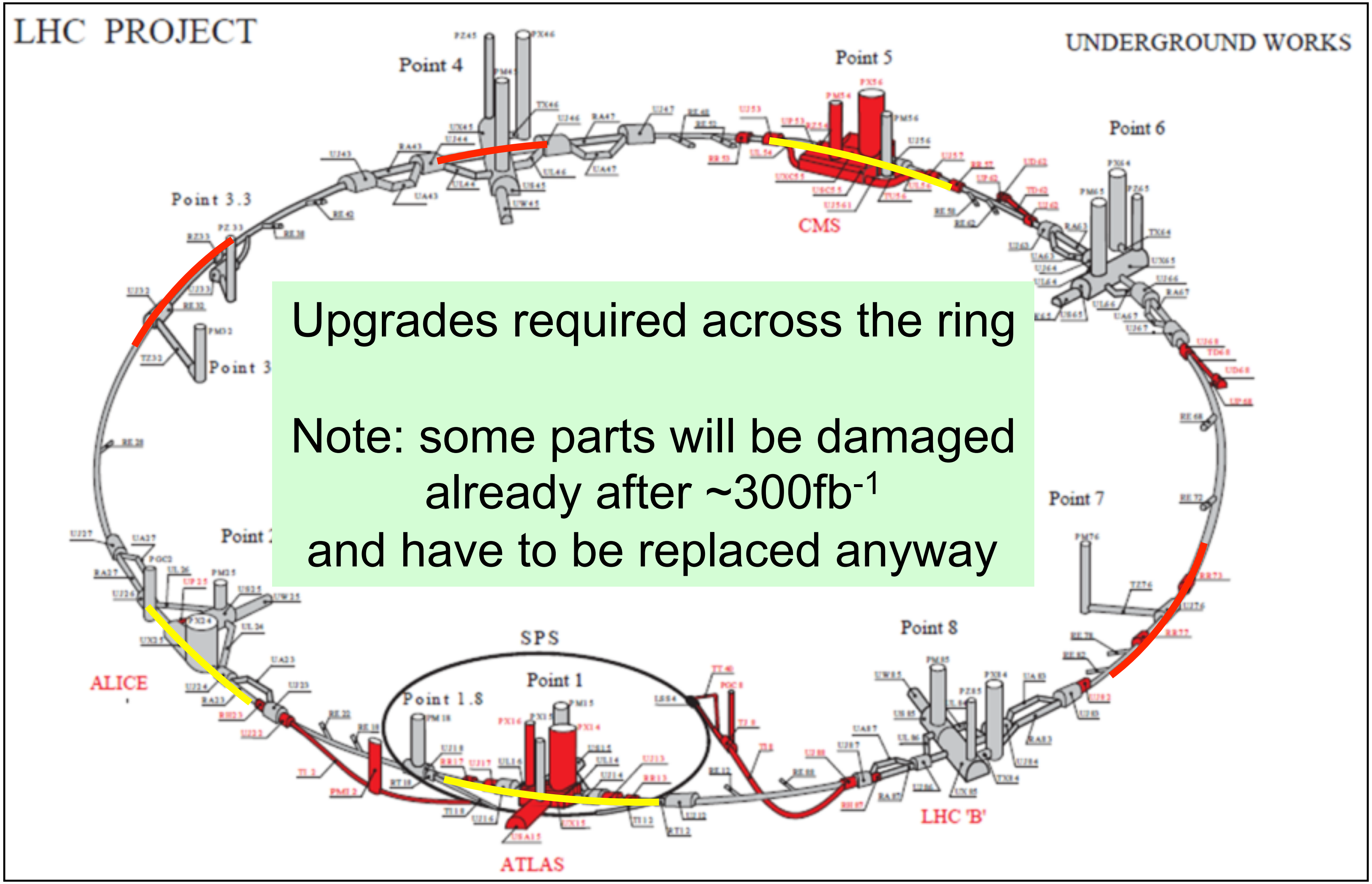


model	$300\ \mathrm{fb}^{-1}$	$1000\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
$Z'_{SSM} \rightarrow ee$	6.5	7.2	7.8
$Z'_{SSM} \rightarrow \mu\mu$	6.4	7.1	7.6

LHC upgrades: How to deliver 3000fb^{-1}



HL-LHC: how to deliver 3000fb^{-1}

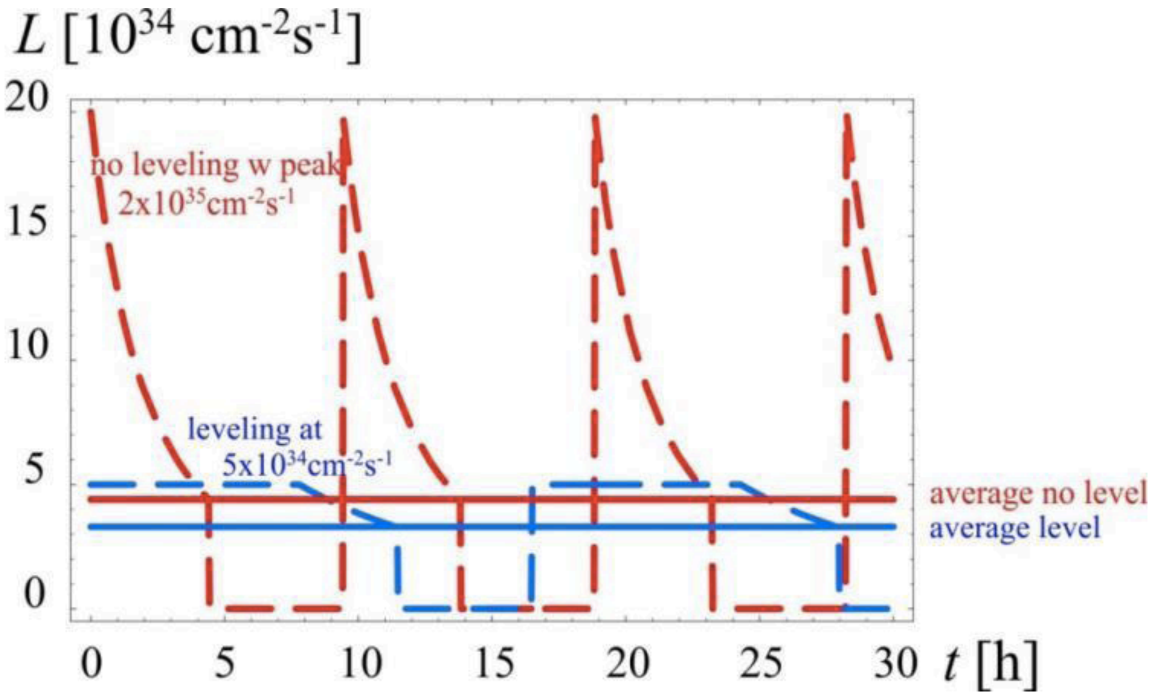


Upgrades required across the ring

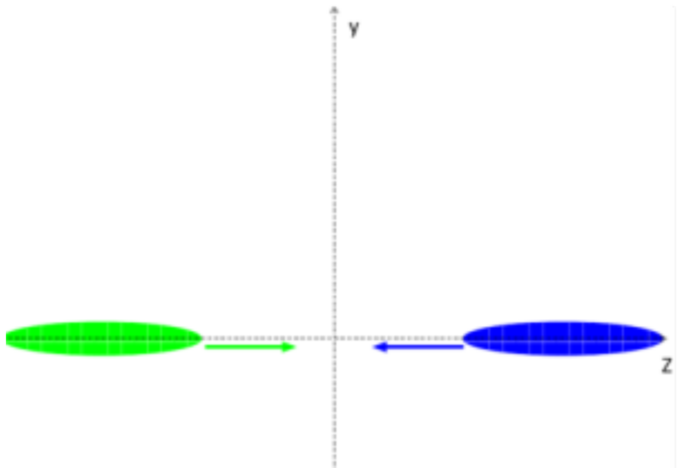
Note: some parts will be damaged already after ~300fb^{-1} and have to be replaced anyway

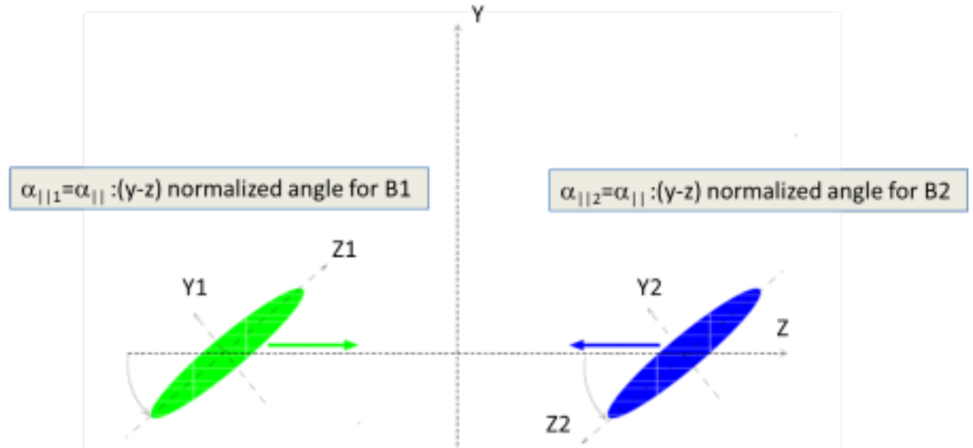
- Replace components damaged by radiation after ~300fb^{-1}
  - Stronger focusing magnets in ATLAS/CMS interaction regions

- Most important: luminosity levelling
  - Deliver max. integrated luminosity with lowest possible pile-up density
  - Main handles: crab cavities and crab kissing



Crab kissing – impact on pile-up density



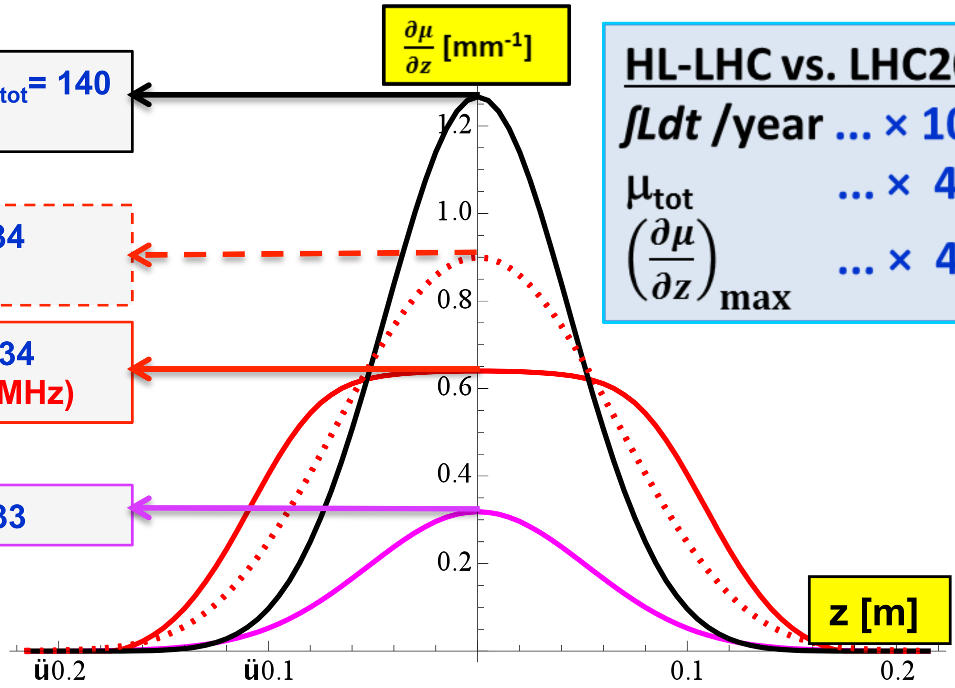


HL-LHC baseline and backup (25 ns): 250 fb^{-1}/y , μ_{tot}= 140 @5E34
(BB wire .or. crab w/o CK scheme)

"HL-LHC+" (25ns): 250 fb^{-1}/y , μ_{tot}= 140 @5E34
(BB wire .and. crabs with CK scheme)

"HL-LHC++" (25ns): 250 fb^{-1}/y , μ_{tot}= 140 @5E34
(BB wire .and. crabs with CK scheme .and. 800 MHz)

LHC2012 (50 ns): 25 fb^{-1}/y, μ_{tot}= 40 @7.5E33



HL-LHC vs. LHC2012:

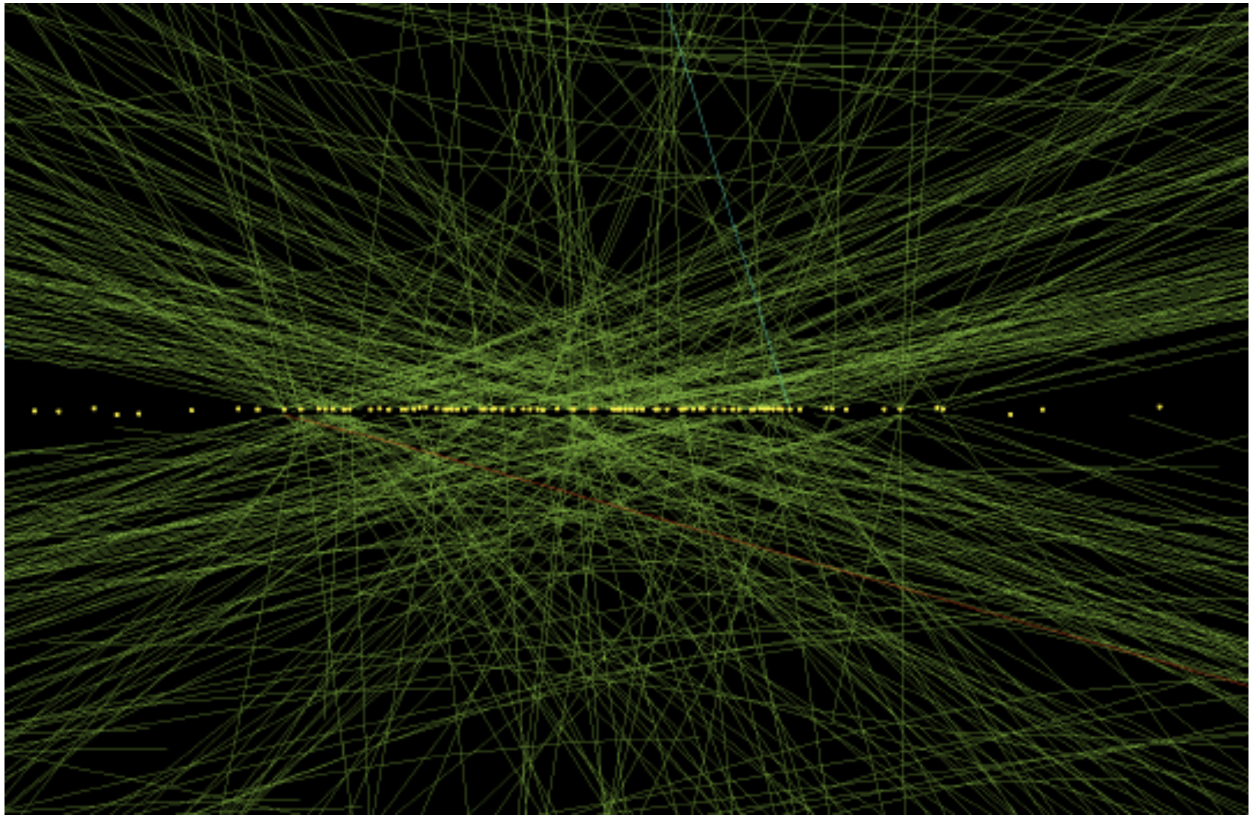
$\int Ldt$ /year ... × 10

μ_{tot} ... × 4

$\left(\frac{\partial\mu}{\partial z}\right)_{max}$ ... × 4 → 2

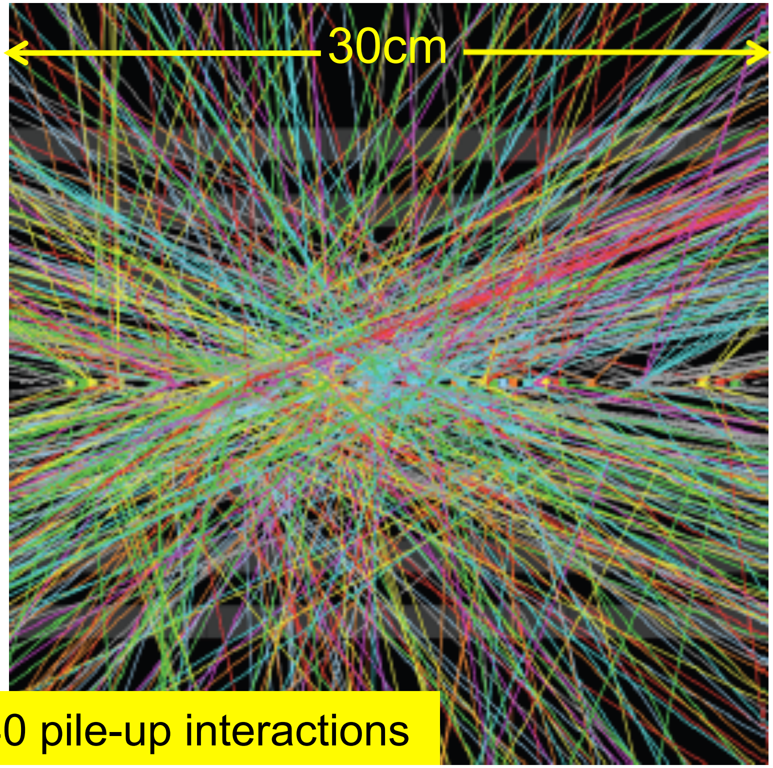
How to collect efficiently 3000fb^{-1}

Upgrading ATLAS and CMS for HL-LHC



Detector Challenges at HL-LHC

- Maintain (if possible, improve) today's performance at 5-10 times higher pile-up and instantaneous luminosity
- Survive 10 years of extreme irradiation!



Top event in ATLAS with 140 pile-up interactions

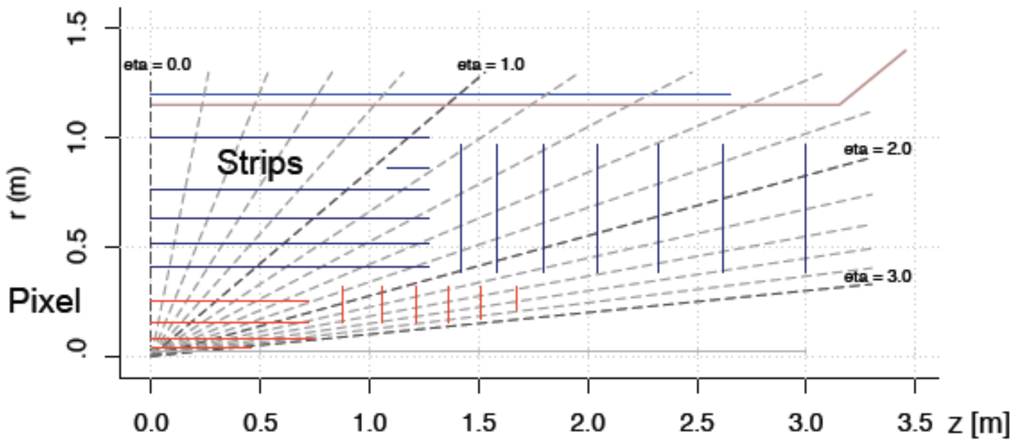
Many systems need upgrading, but most importantly the Tracker and Trigger

Tracker upgrades

- Current trackers must be replaced
  - They cannot withstand radiation beyond ~500fb^{-1}
  - Finer granularity is needed for the pattern recognition at pile-up of ~140
    - The ATLAS TRT (drift tubes) reaches such high level of occupancy that it becomes inoperable
  - Not enough bandwidth to readout the high volume of data
  - Need to provide info for the Level-1 Trigger
    - Current L1 Trigger uses only coarse granularity Calo and Muon information

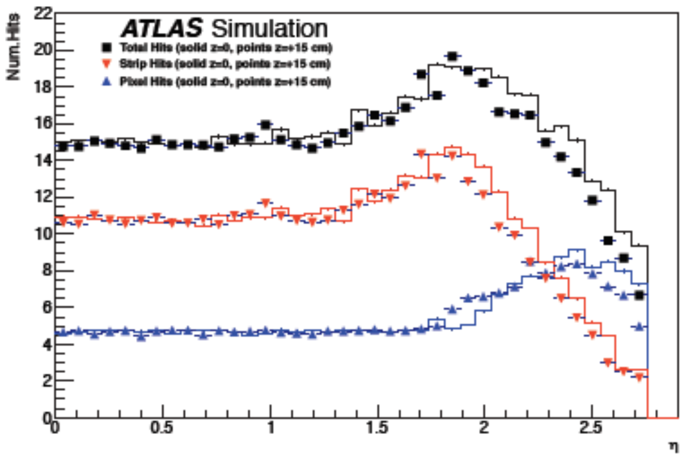
ATLAS Tracker Upgrade

	Silicon Area	Channels [10^6]
Pixel	8.2m^2	638
Strip	193m^2	74

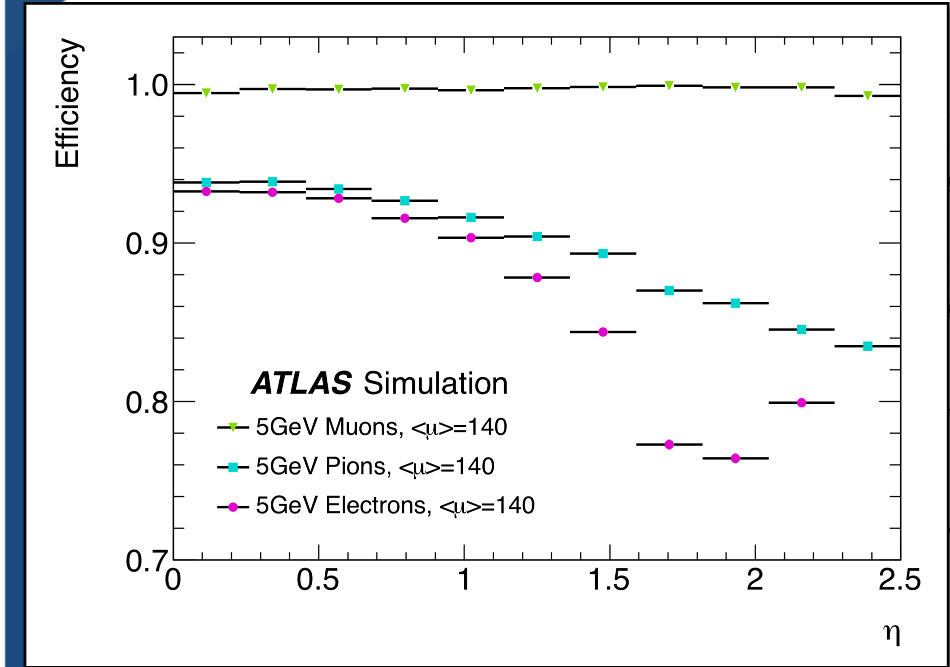


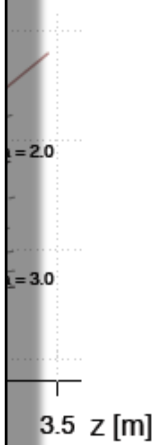
- Baseline layout optimized for tracking performance
  - Full simulation of tracker with LoI layout including service layout
- Biggest changes compared to current tracker:
  - pixels system extends out to larger radii
  - more pixel hits in forward direction to improve tracking
  - smaller pixels and short inner strips to increase granularity
  - outer active radius slightly larger to improve momentum resolution

- Remove Transition Radiation Tracker (TRT) as occupancy is too high during HL-LHC
- Install new all-Silicon tracker with pixels and strips
- Granularity increase by factor >4



ATLAS Tracker Upgrade



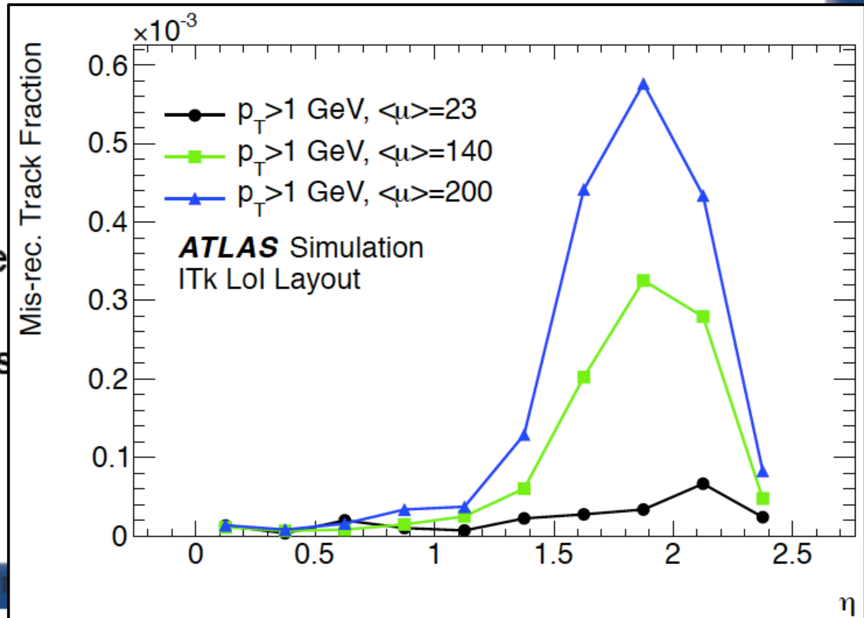


	Silicon Area	Channels [10^6]
Pixel	8.2m^2	638
Strip	193m^2	74

- Remove Transition Radiation Tracker (TRT) as occupancy is too high during HL-LHC
- Install new all-Silicon tracker with pixels and strips
- Granularity increase by factor >4

rmance

- Biggest changes compared to current tracker:
  - pixels system extends out to larger radii
  - more pixel hits in forward direction to improve tracking
  - smaller pixels and short inner strips to increas granularity
  - outer active radius slightly larger to improve momentum resolution



ATLAS-UK tracker upgrade R&D

"Short strips": Lead role in entire programme: hybrid/module/stave design, to powering & readout, to mechanics & integration

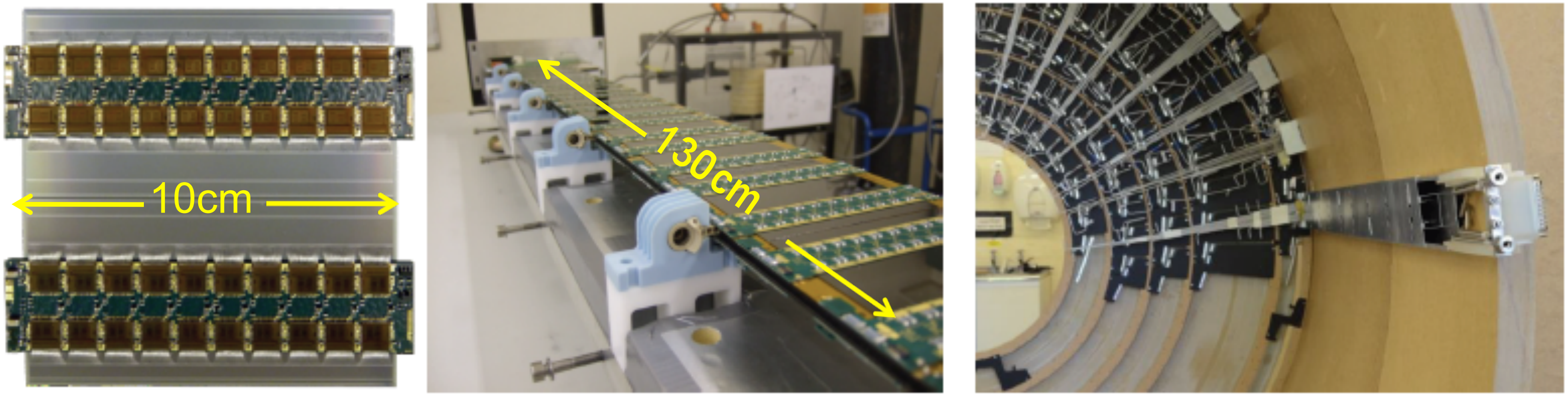
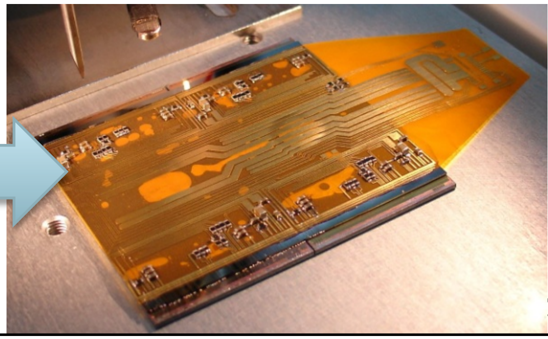
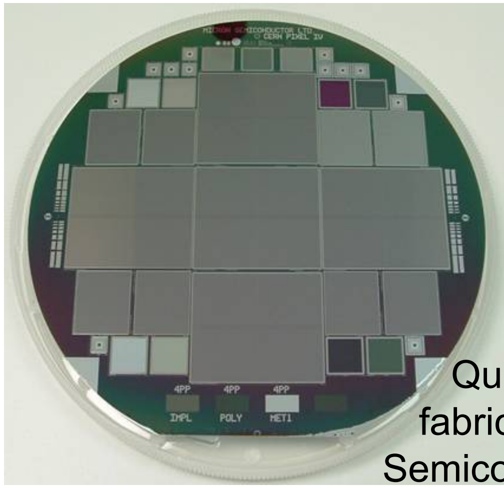


Figure 11: (Left) A strip module with hybrids, (middle) a thermo-mechanical strip stave and (right) the end of the barrel services mock-up

Pixels: Development & construction of forward pixel disks, R&D on sensors

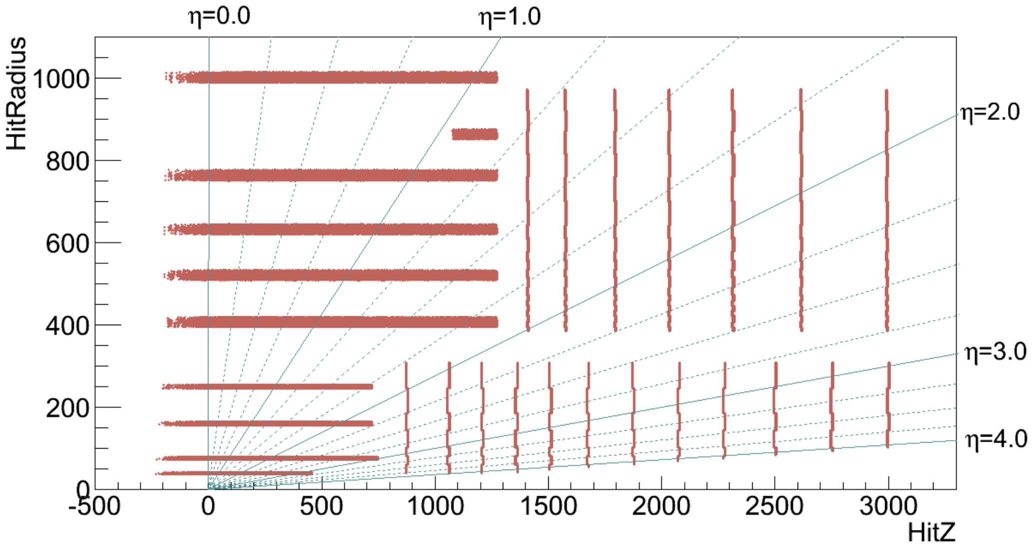
Quad module Prototype ($4x4cm^2$)



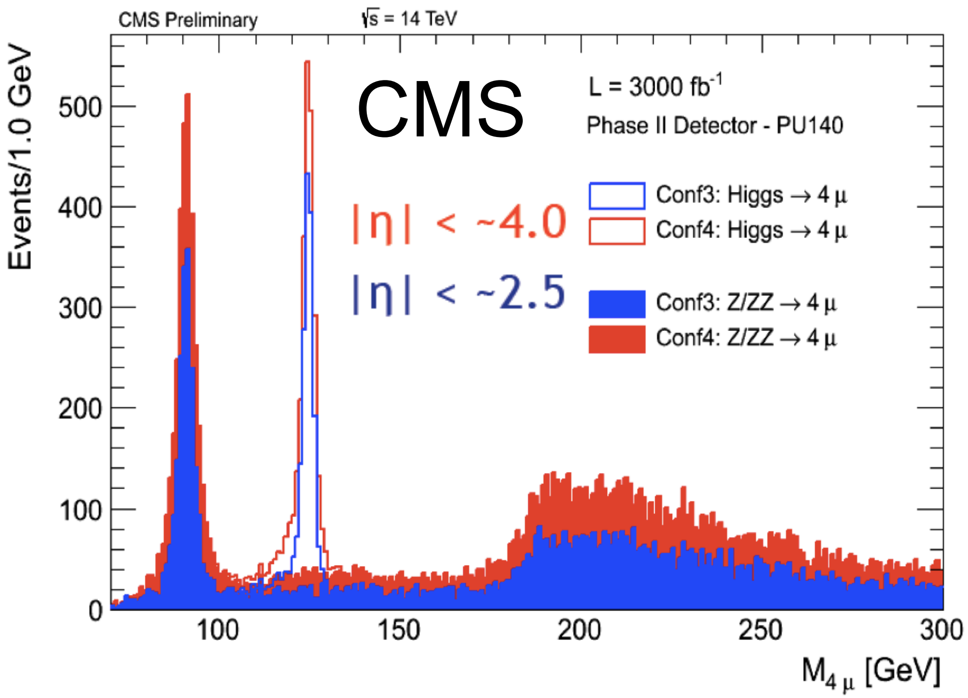


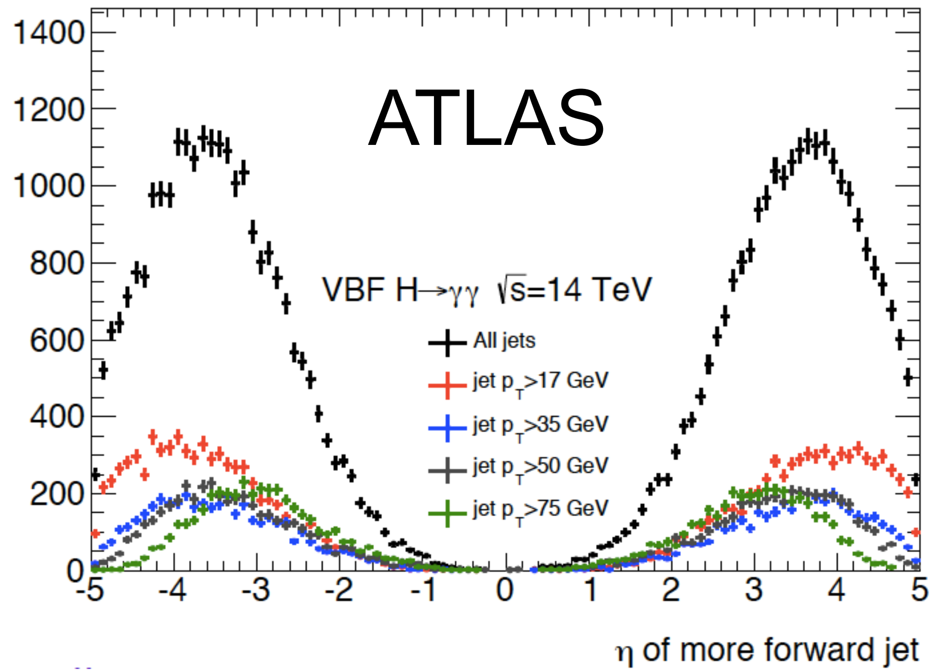
Quad sensor masks fabricated with Micron Semiconductor (UK) Ltd

How forward should tracking go?



Consider benefits from forward tracking: ~2.5>|h|>~4



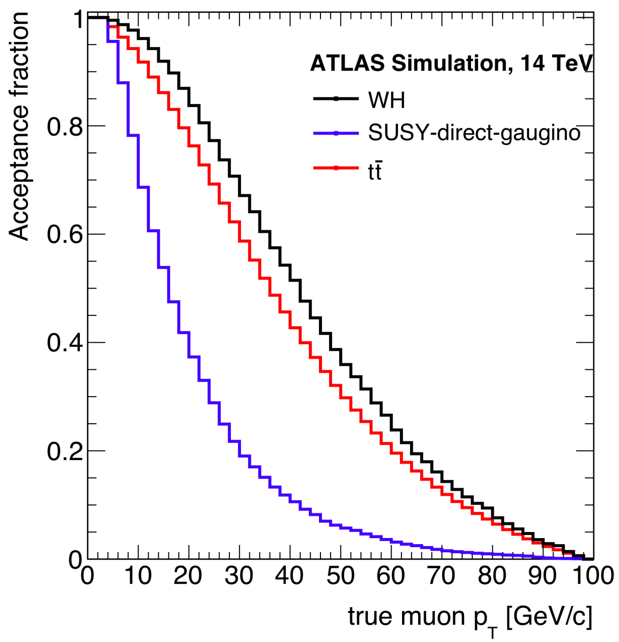


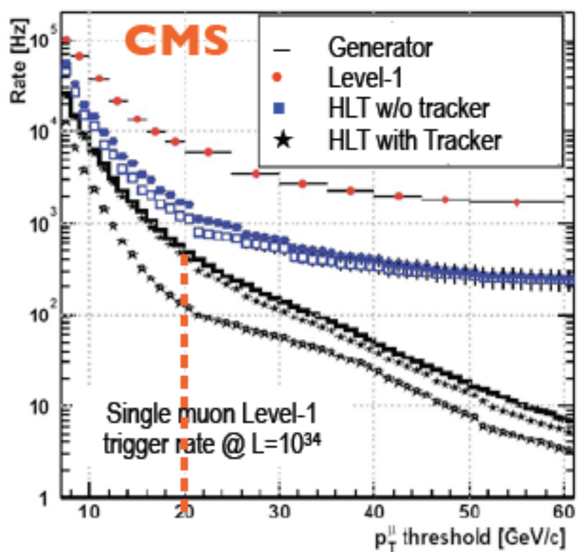
Tracker Upgrade timelines

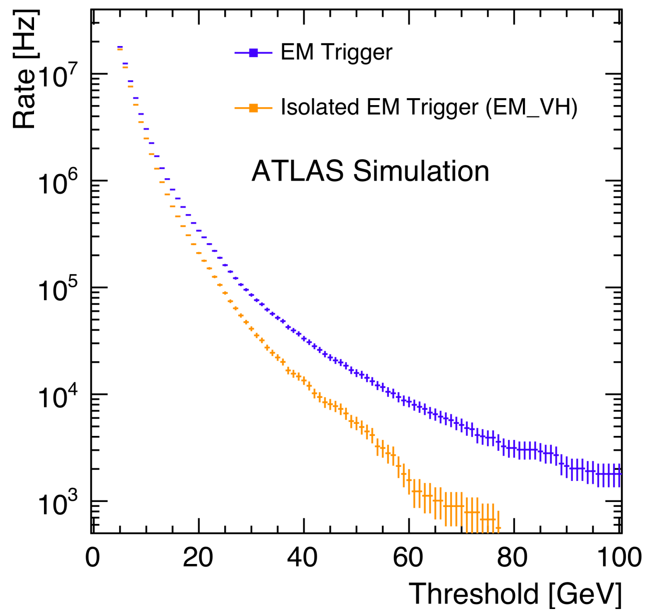
- Thanks to past experience construction can be more efficient
- But a much larger detector to be built!
- For a start-up in 2024, the detector must be ready on the surface by end of 2022, hence construction should start early in 2017
- Hence TDR and MoUs by end 2016
- Already a tight schedule, but feasible!

Trigger Upgrades

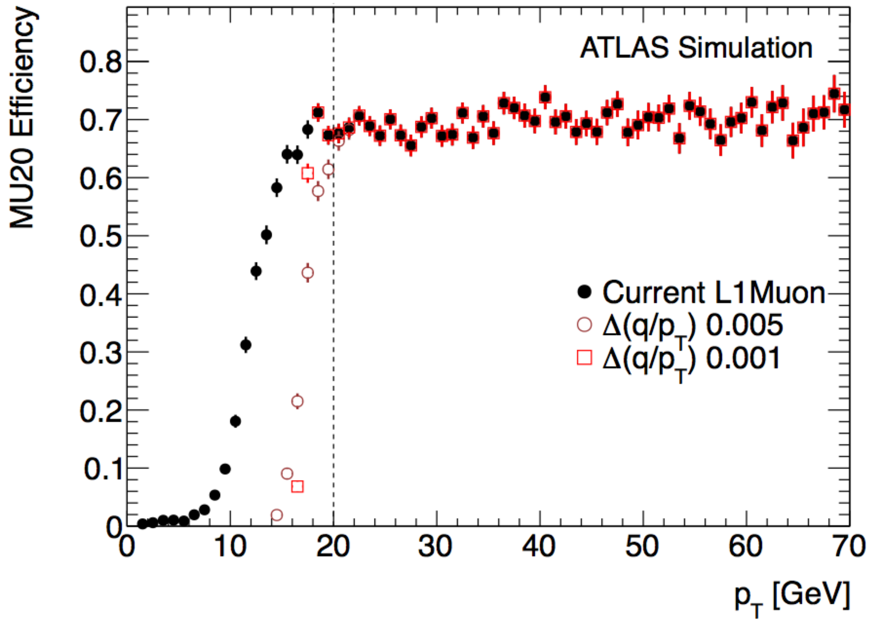
- Physics programme requires p_T thresholds similar to 2012 values in order to get maximum benefit from the 3000 fb^{-1}
- Main challenge is the (hardware) Level-1 trigger
- Improvements in L1 Calo and Muon systems not sufficient for achieving manageable rates with acceptable physics

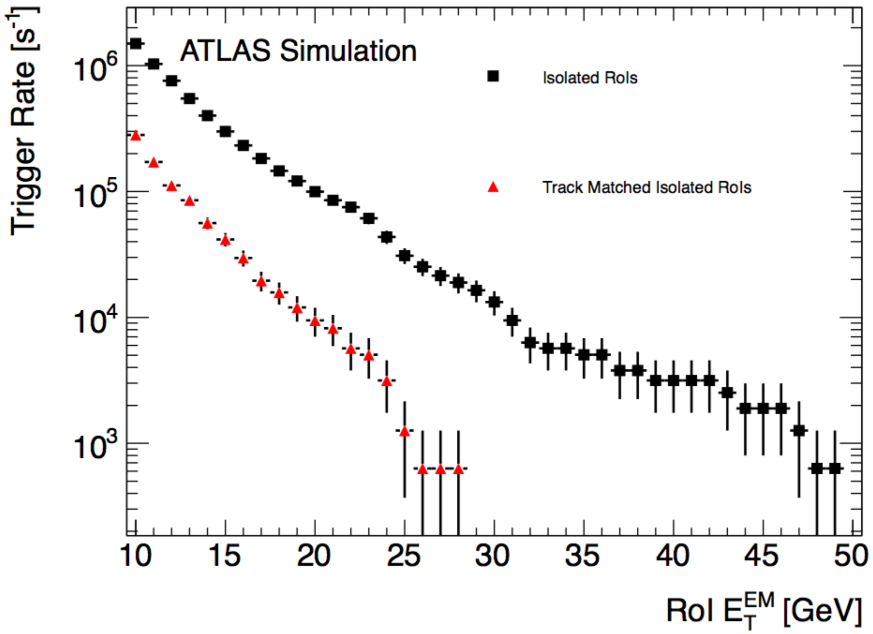


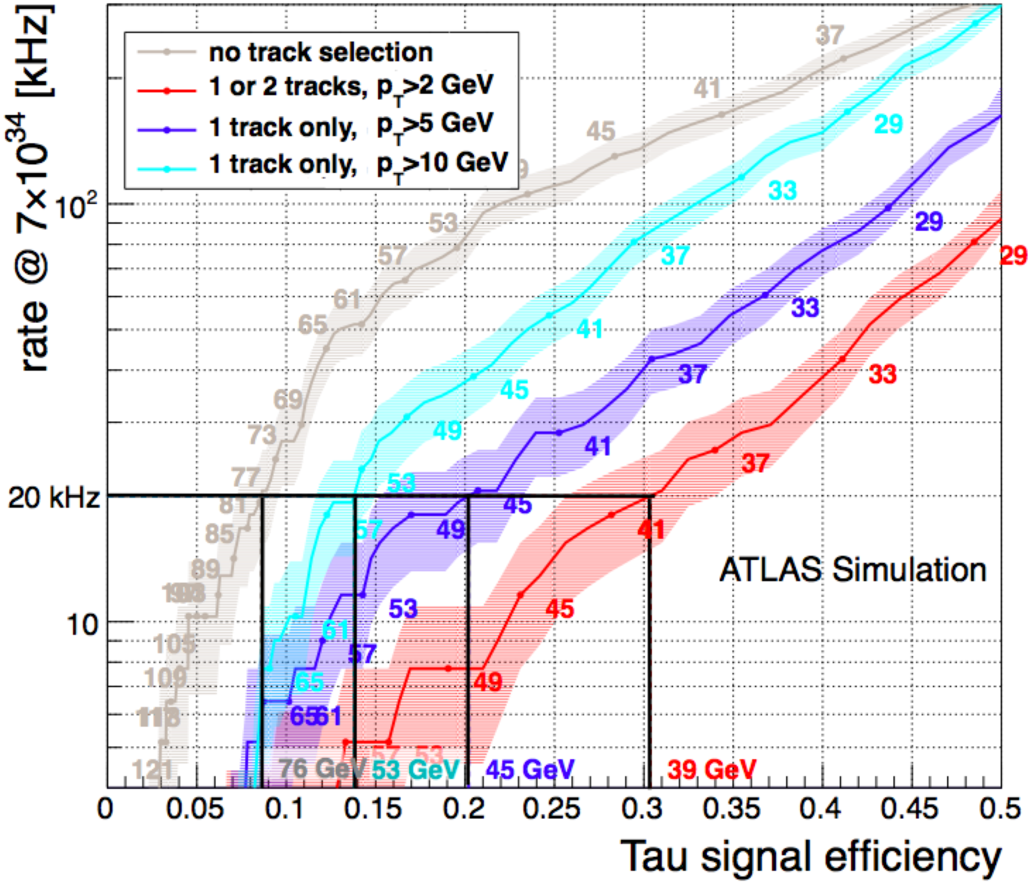




The benefits of tracking info at L1







L1 Track Trigger

- Full tracker readout at 40MHz practically impossible
  - EITHER:

    CMS

    apply some hit filtering at 40MHz and bring off-detector a very small fraction of data, e.g. only hits from high-pT tracks
  - OR:

    ATLAS

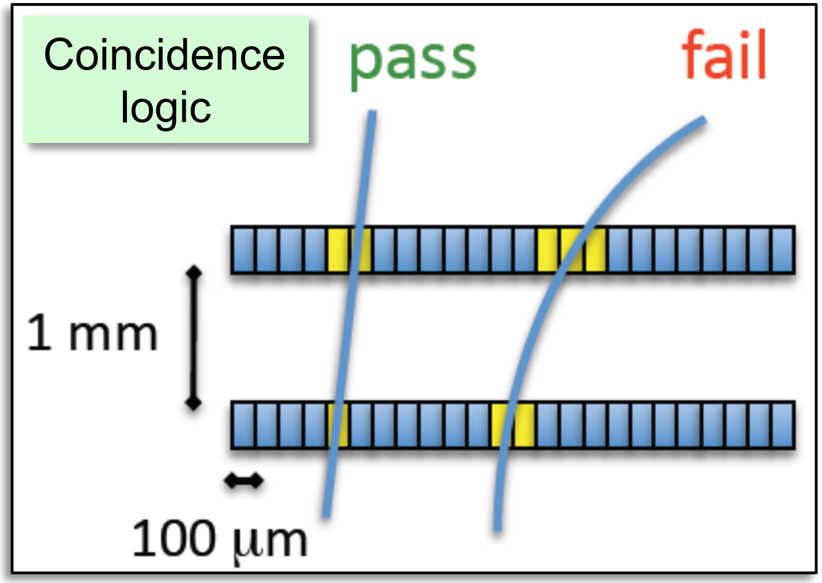
    L1 in two steps:
    - L0: reduce the rate from 40MHz to ~1MHz using Calo/Muon info
    - L1: read out only interesting regions of the tracker at L0 rate for L1 decision

- Optimal choice depends on additional boundary conditions
  - Second option requires increased latency: L0+L1 ~20μs

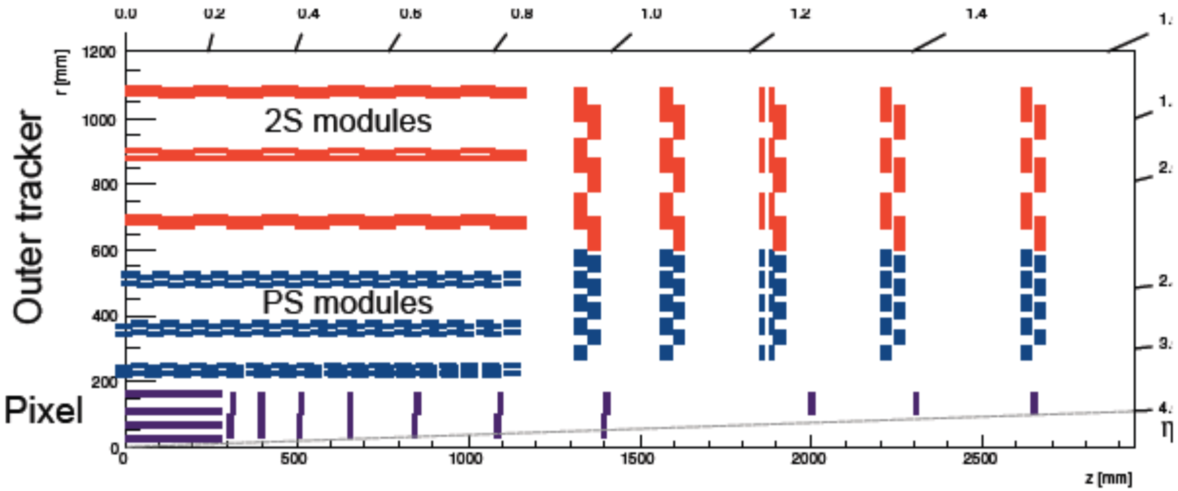
- A lot of R&D – final decisions are yet to be taken

L1 Track Trigger in CMS

- p_T filtering in stacked double layers of silicion wafers
  - Coincidence hits read out at 40MHz and combined off-detector to form track trigger primitives



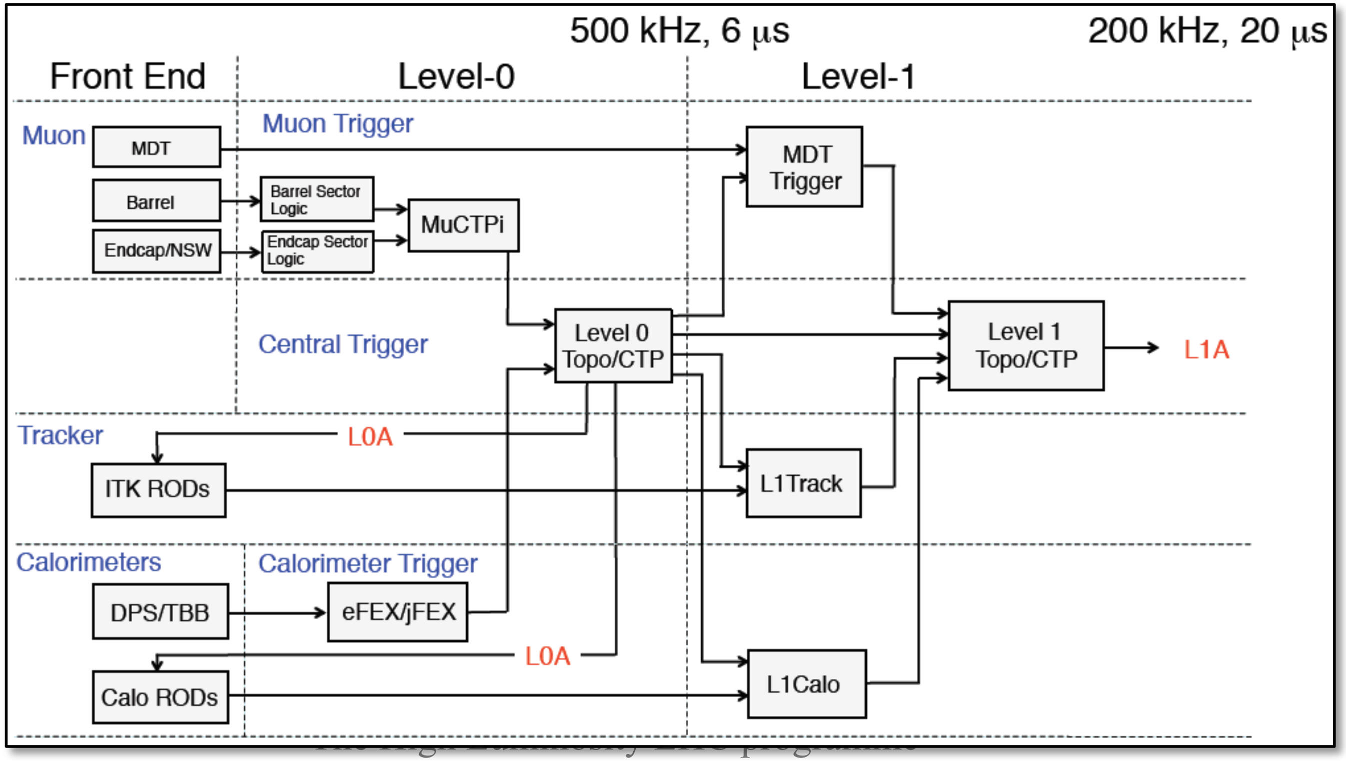
- Major impact on the layout of the tracker



Baseline layout of CMS tracker

L0/L1 design for ATLAS Phase-II

- Phase-I L1 trigger (Calo/Muon) becomes Phase-II L0
  - Latency: ~ 3-5μs; rate: 0.5-1.0MHz, synchronous
- From L0 to L1, bring in tracking and other new information
  - L1Track in Regions of Interest found by L0
    - Read out only ~10% of tracker at L0 rate (takes ~6-7μs)
  - Full granularity Calo and precision Muon chambers
  - Latency ~15-17μs; rate <200kHz, asynchronous



Conclusions

- Top priorities for the energy frontier in the next two decades:
  - Study the 125GeV Higgs and investigate the dynamics of EWSB
  - Explore thoroughly the multi-TeV scale
    - This exploration has only just started!
    - Strong motivations that new physics must appear at the ~TeV scale!
- The HL-LHC(3000) programme is unique in addressing both of these priorities in ~2024-2035
  - As well as studying and characterising any new physics that might be discovered in the 13-14TeV runs before 2024
- Intense R&D ongoing, both for upgrading the LHC so that it can deliver 3000fb-1, and for the detectors so that they can cope with and profit from the delivered luminosity!

Further reading

- ECFA HL-LHC workshop in Aix-Les-Baines
- Review of LHC & Injector Upgrade Plans Workshop (RLIUP)
- RLIUP summary session

Back up slides

Update of the European Strategy for Particle Physics

High-priority large-scale scientific activities

After careful analysis of many possible large-scale scientific activities requiring significant resources, sizeable collaborations and sustained commitment, the following four activities have been identified as carrying the highest priority.

c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle's properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue this programme.
Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade programme will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

CP violation in Higgs sector (ATLAS)

$$A(X \to VV) \sim \left(a_1 M_X^2 g_{\mu\nu} + a_2 (q_1 + q_2)_\mu (q_1 + q_2)_\nu + a_3 \varepsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta\right) \varepsilon_1^{*\mu} \varepsilon_2^{*\nu}$$

- HZZ amplitude can have CP-even & CP-odd terms: CP violation

Significance for various a_3

Integrated Luminosity	Signal (S) and Background (B)	$6+6i$	$6i$	$4+4i$
100 fb^{-1}	$S = 158$; $B = 110$	3.0	2.4	2.2
200 fb^{-1}	$S = 316$; $B = 220$	4.2	3.3	3.1
300 fb^{-1}	$S = 474$; $B = 330$	5.2	4.1	3.8

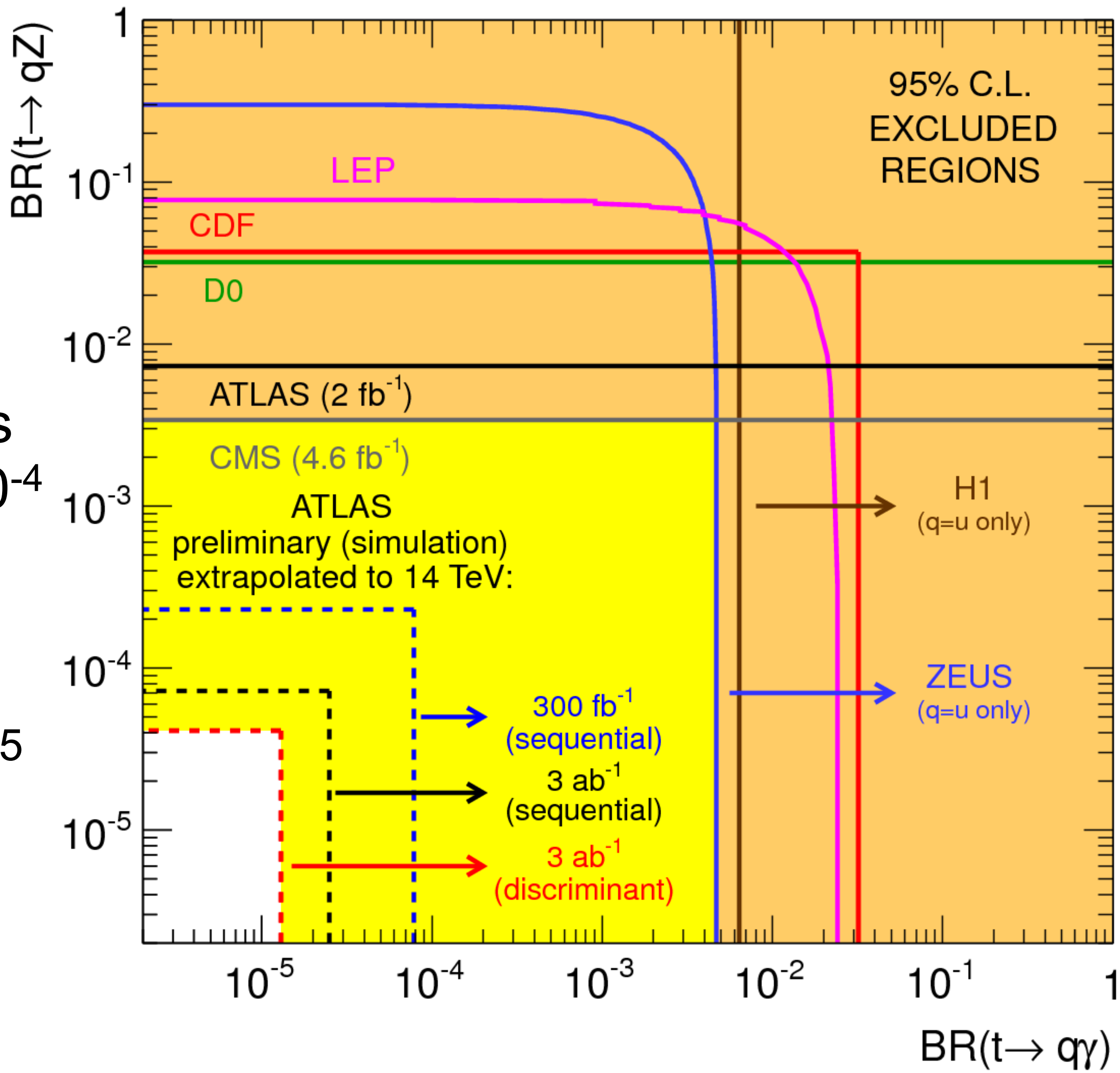
3000fb^{-1} would give sensitivity to much smaller levels of CP violation.

Rare decays: FCNC t→Zq, t→γq

In SM, BR ~10^{-12}

New physics models predict BRs up to ~10^{-4}

with 3000fb^{-1} sensitivity to BR~10^{-5}



How well should the Higgs couplings be measured ?

Brock/Peskin, Snowmass 2013

Facility	LHC	HL-LHC	ILC500	ILC500-up	ILC1000	ILC1000-up	CLIC	TLEP (4 IPs)
$\sqrt{s}$ (GeV)	14,000	14,000	250/500	250/500	250/500/1000	250/500/1000	350/1400/3000	240/350
$\int \mathcal{L}dt$ (fb^{-1})	300/expt	3000/expt	250+500	1150+1600	250+500+1000	1150+1600+2500	500+1500+2000	10,000+2600
κ_γ	$5-7\%$	$2-5\%$	8.3%	4.4%	3.8%	2.3%	$-/5.5/<5.5\%$	1.45%
κ_g	$6-8\%$	$3-5\%$	2.0%	1.1%	1.1%	0.67%	3.6/0.79/0.56%	0.79%
κ_W	$4-6\%$	$2-5\%$	0.39%	0.21%	0.21%	0.13%	1.5/0.15/0.11%	0.10%
κ_Z	$4-6\%$	$2-4\%$	0.49%	0.24%	0.44%	0.22%	0.49/0.33/0.24%	0.05%
κ_ℓ	$6-8\%$	$2-5\%$	1.9%	0.98%	1.3%	0.72%	$3.5/1.4/<1.3\%$	0.51%
κ_d	$10-13\%$	$4-7\%$	0.93%	0.51%	0.51%	0.31%	1.7/0.32/0.19%	0.39%
κ_u	$14-15\%$	$7-10\%$	2.5%	1.3%	1.3%	0.76%	3.1/1.0/0.7%	0.69%

HL-LHC (3000 fb^{-1}): percent level
→ some sensitivity to physics beyond SM

ILC/TLEP: sub-percent level
Note: hard to believe that New Physics will manifest itself through tiny effects on Higgs couplings and nothing else
...unless very heavy (but then how to interpret the observed deviations ?)

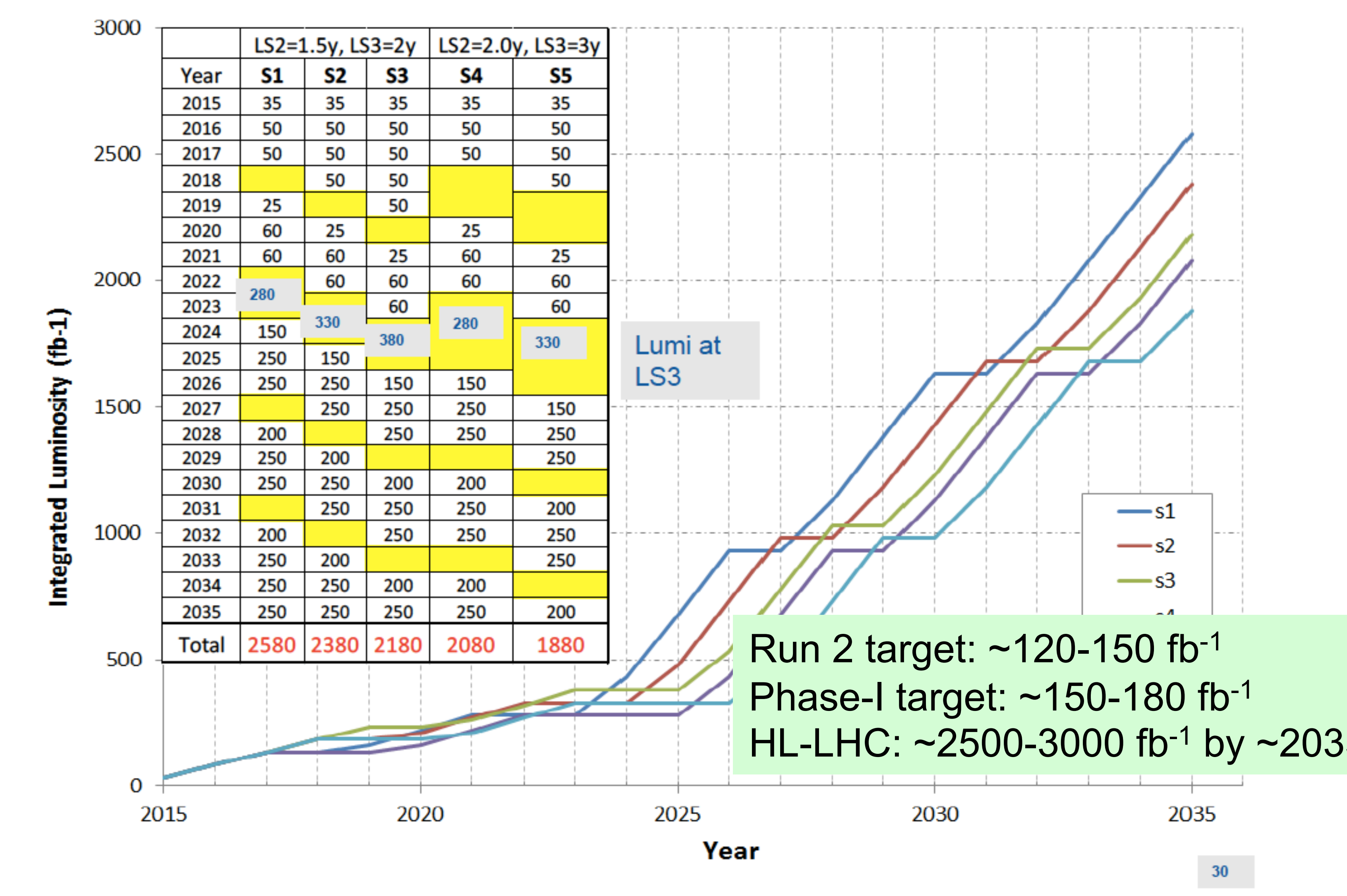
Scenarios with no new particles observable at LHC

	κ_V	κ_b	κ_γ
Singlet Mixing	$\sim 6\%$	$\sim 6\%$	$\sim 6\%$
2HDM	$\sim 1\%$	$\sim 10\%$	$\sim 1\%$
Decoupling MSSM	$\sim -0.0013\%$	$\sim 1.6\%$	$< 1.5\%$
Composite	$\sim -3\%$	$\sim -(3-9)\%$	$\sim -9\%$
Top Partner	$\sim -2\%$	$\sim -2\%$	$\sim -3\%$

LHC schedule beyond LS1

Only EYETS (19 weeks) (no Linac4 connection during Run2)
LS2 starting in 2018 (July) 18 months + 3months BC (Beam Commissioning)
LS3 LHC: starting in 2023 => 30 months + 3 BC
injectors: in 2024 => 13 months + 3 BC

Luminosity targets till ~2035



	LS2=1.5y, LS3=2y			LS2=2.0y, LS3=3y	
Year	S1	S2	S3	S4	S5
2015	35	35	35	35	35
2016	50	50	50	50	50
2017	50	50	50	50	50
2018		50	50		50
2019	25		50		
2020	60	25		25	
2021	60	60	25	60	25
2022		60	60	60	60
2023	280		60		60
2024	150	330	380	280	330
2025	250	150			
2026	250	250	150	150	
2027		250	250	250	150
2028	200		250	250	250
2029	250	200			250
2030	250	250	200	200	
2031		250	250	250	200
2032	200		250	250	250
2033	250	200			250
2034	250	250	200	200	
2035	250	250	250	250	200
Total	2580	2380	2180	2080	1880

Run 2 target: ~120-150 fb^{-1}
Phase-I target: ~150-180 fb^{-1}
HL-LHC: ~2500-3000 fb^{-1} by ~2035

S. Myers 7th November 2013 RLIUP Summary 15

Studies with 3000fb^{-1} at HL-LHC

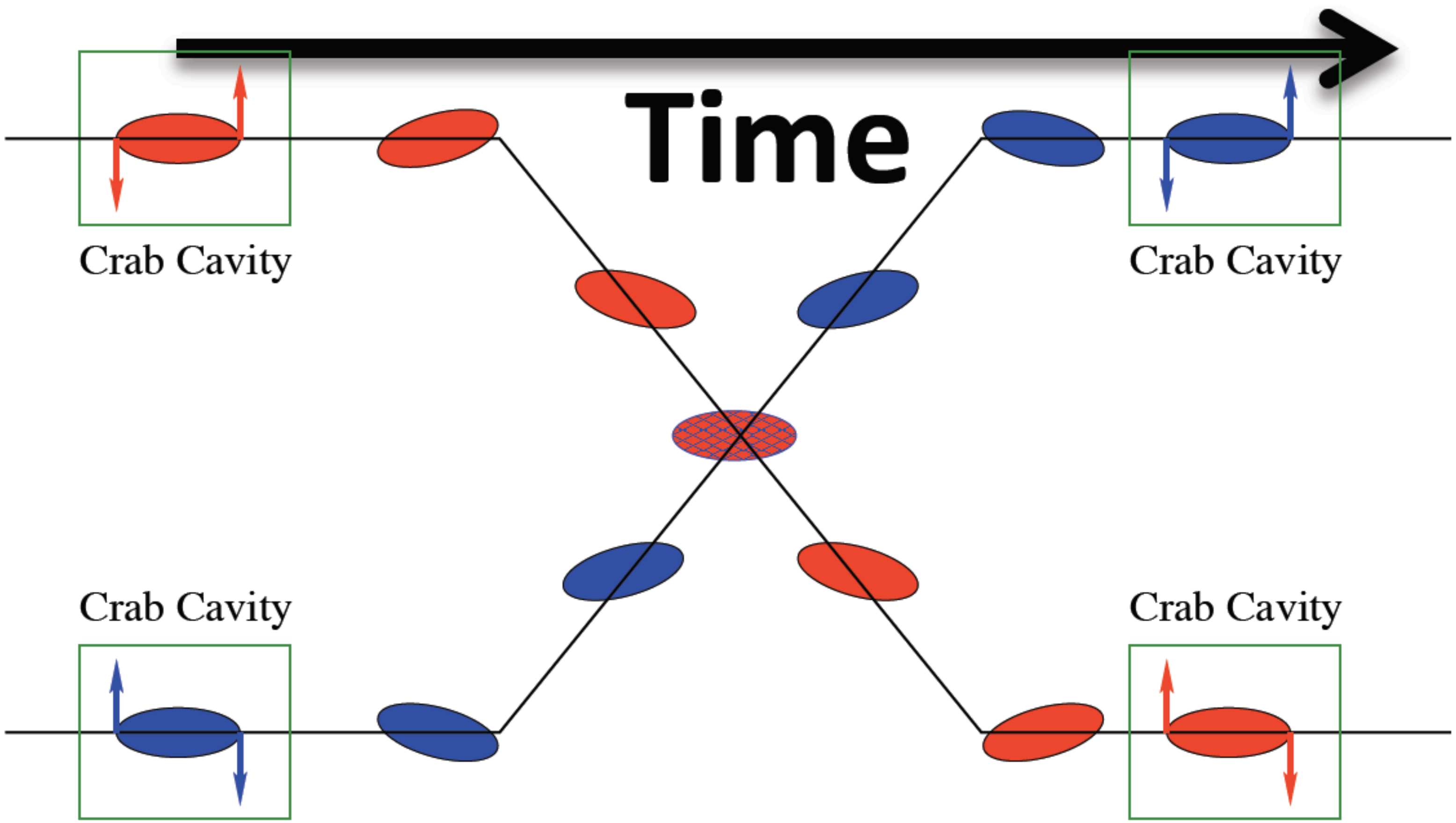
- Studies initiated for the European Strategy process in 2012-13
  - Boosted by the Higgs discovery in summer 2012
  - Accelerated thanks to the LHC shutdown in 2013-14

- Projections use conservative assumptions about detector performance at HL-LHC and the evolution of systematic uncertainties
  - Impressive progress in minimizing the impact of pile-up during 2012
  - In 2012, <μ> up to ~35; extrapolation to <μ>~140 not huge

- ATLAS performed generator-level studies, applying resolution and efficiency parameterisation functions for the HL-LHC conditions
  - With realistic/conservative assumptions for the effects of pile-up
    - E.g. full sim. studies of b-tagging with tracker upgrade now show better performance

- CMS extrapolate current results with two different assumptions
  (1) Pessimistic: experimental and theory systematics as of today
  (2) Optimistic: experimental systematics scale as $1/\sqrt{L}$, theory systematics halved

Crab cavities



First operated successfully at KEKB, but never at a p-p machine