Future of LHC

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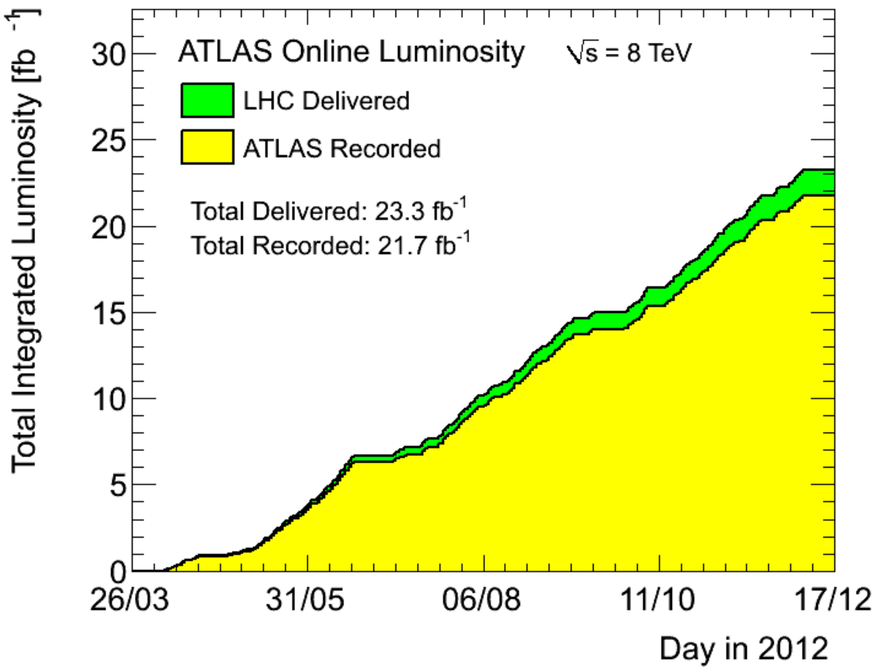
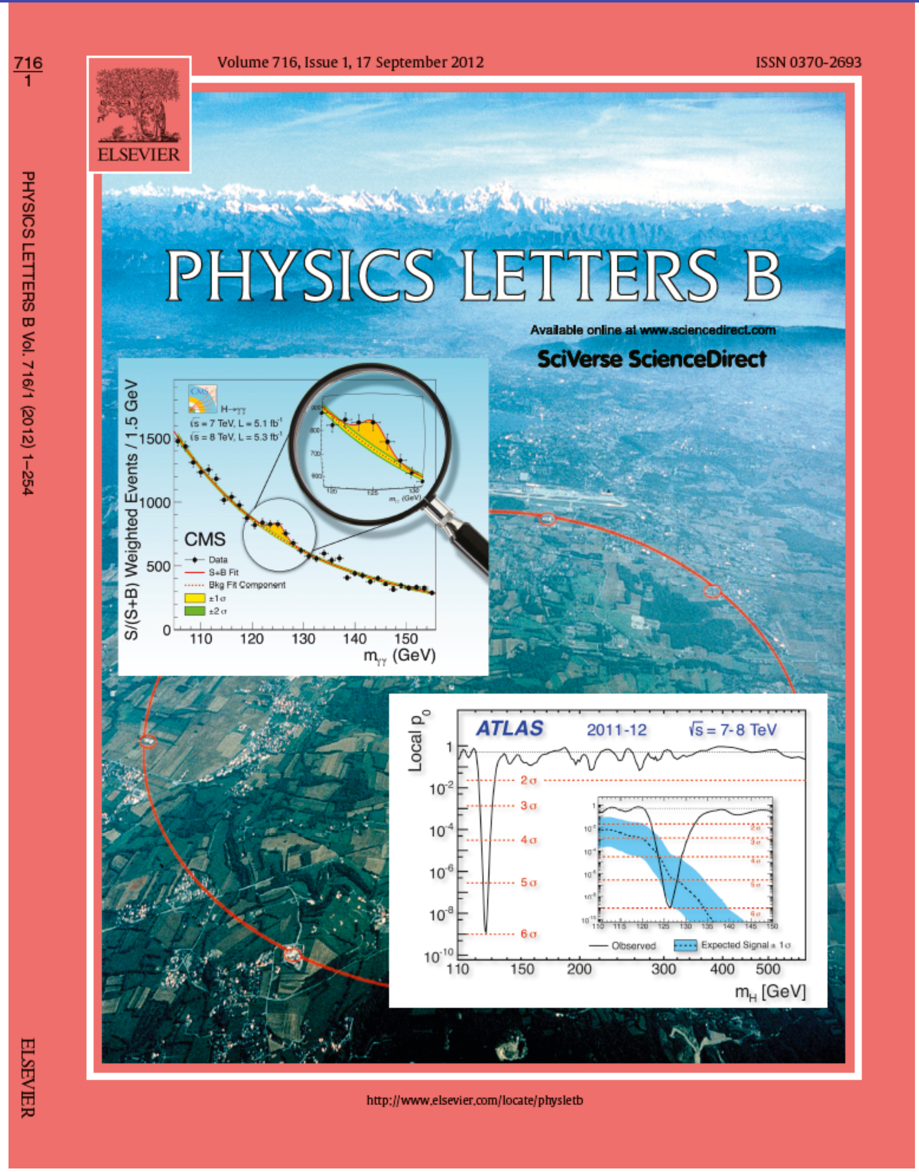
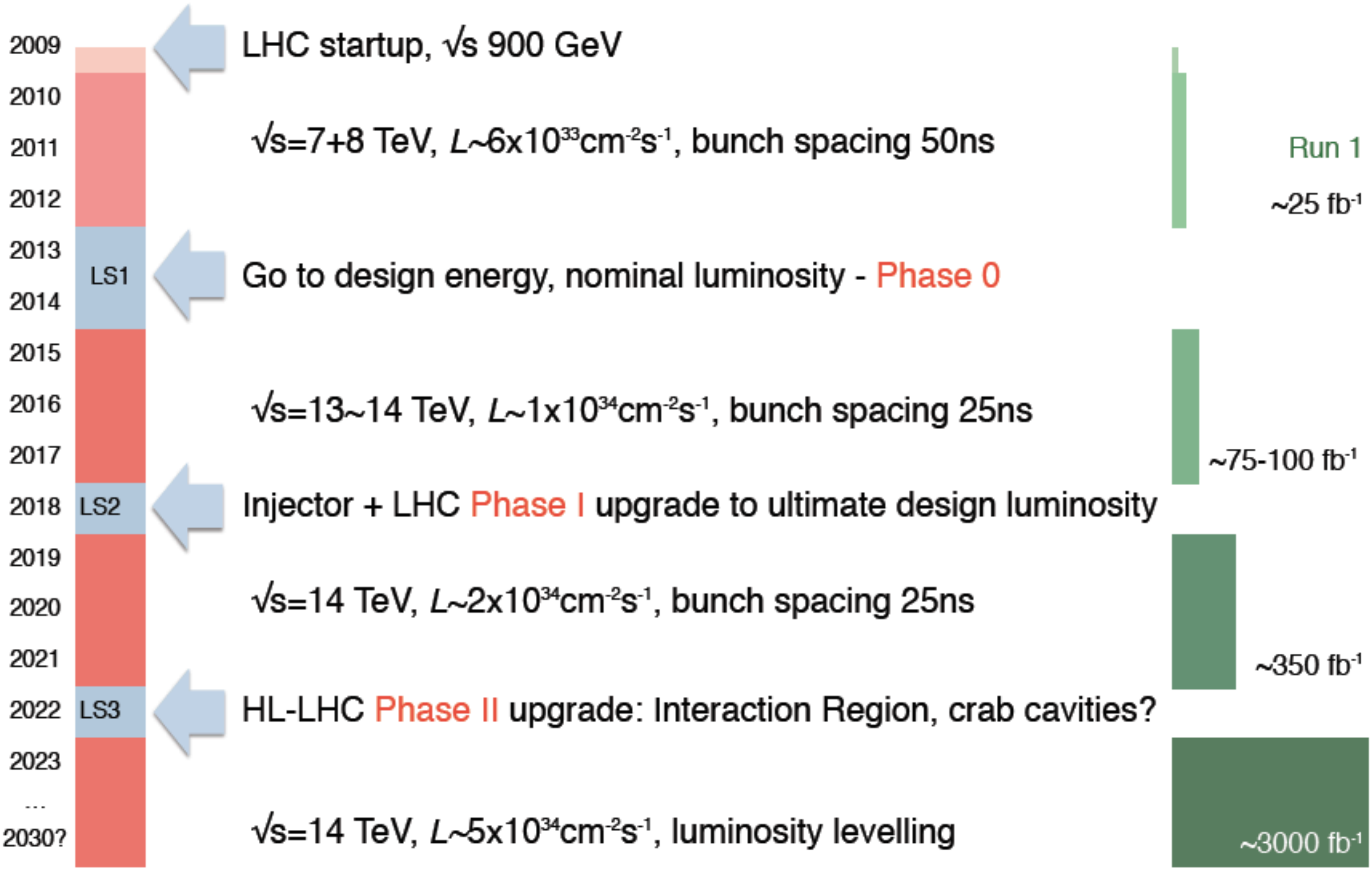
LHC Run 1: 2009-2012





- 25 fb^{-1} of 7+8 TeV pp data
- Higgs boson found!
  - Looks like SM at first glance
- No physics beyond the SM found
- 510 publications from ATLAS & CMS alone (…and counting)

LHC Roadmap


2009
2010
2011
2012
2013
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2015
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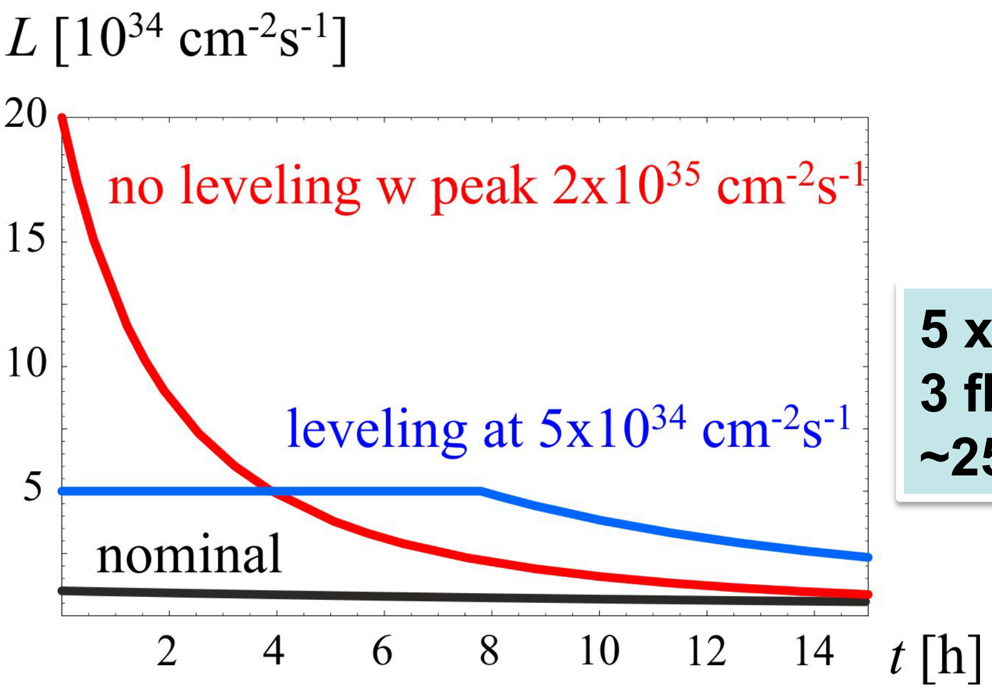
2017
2018
2019
2020
2021
2022
2023
...
2030?
LS1
LS2
LS3
LHC startup, $\sqrt{s}$ 900 GeV
$\sqrt{s}$=7+8 TeV, L~6x10^{33}cm^{-2}s^{-1}, bunch spacing 50ns
Go to design energy, nominal luminosity - Phase 0
$\sqrt{s}$=13~14 TeV, L~1x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns
Injector + LHC Phase I upgrade to ultimate design luminosity
$\sqrt{s}$=14 TeV, L~2x10^{34}cm^{-2}s^{-1}, bunch spacing 25ns
HL-LHC Phase II upgrade: Interaction Region, crab cavities?
$\sqrt{s}$=14 TeV, L~5x10^{34}cm^{-2}s^{-1}, luminosity levelling
Run 1
~25 fb^{-1}
~75-100 fb^{-1}
~350 fb^{-1}
~3000 fb^{-1}

HL-LHC

- 3000 fb^{-1} delivered in the order of 10 years
- High "virtual" luminosity with levelling anticipated
- Challenging demands on the injector complex
  - major upgrades foreseen (Linac 4, Booster 2GeV, PS and SPS)



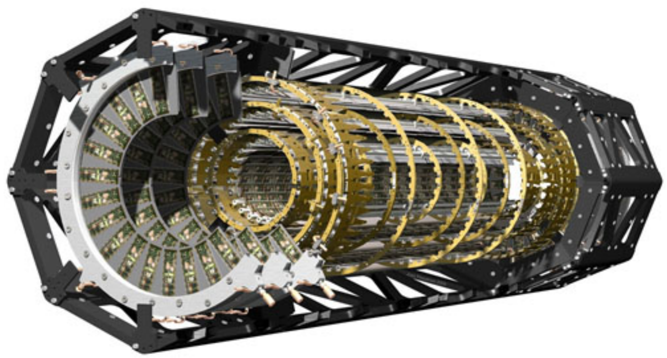
5 x 10^{34} $cm^{-2}s^{-1}$ levelled luminosity
3 fb^{-1} per day
~250 fb^{-1} /year

Detector Upgrades

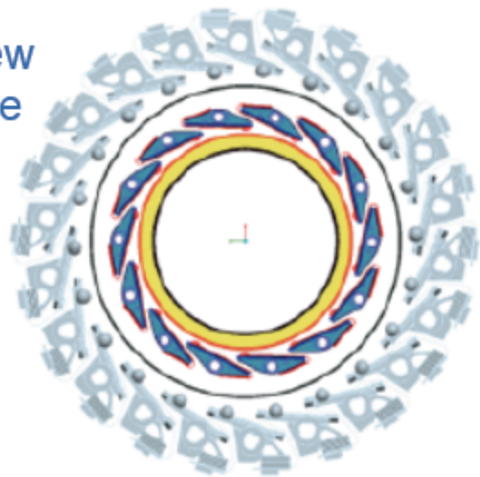
- Detectors need to be upgraded to be able to cope with higher luminosity, e.g.
  - Improve trigger capabilities to better discriminate the desired events from background as early as possible (at Level-1)
  - Upgrade and/or replace inner tracking detectors as they e.g.
    - Cannot handle higher rate due to bandwidth limitations
    - Suffer from radiation damage making them less efficient
    - Have not trigger capabilities but these will likely be needed at phase-2

Phase-0 upgrade in ATLAS: a new pixel layer

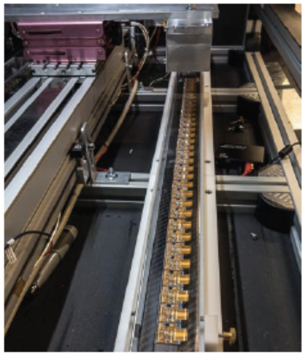
- ATLAS Pixel detector currently has three barrel layers
- 4th layer (called "IBL"=insertable B-layer) added in current shutdown
- Will improve tracking, vertexing and b-tagging performance
- Install during current shutdown

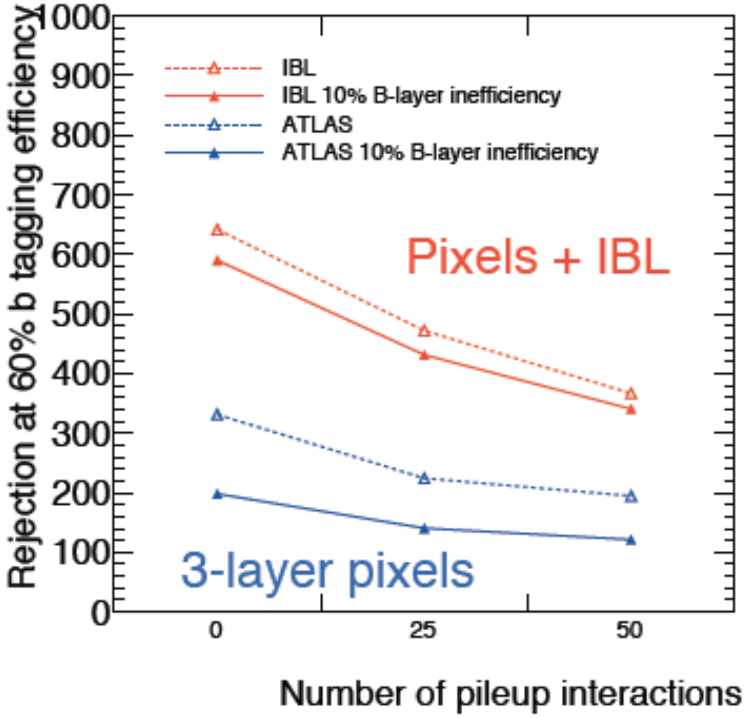


IBL on new beam pipe



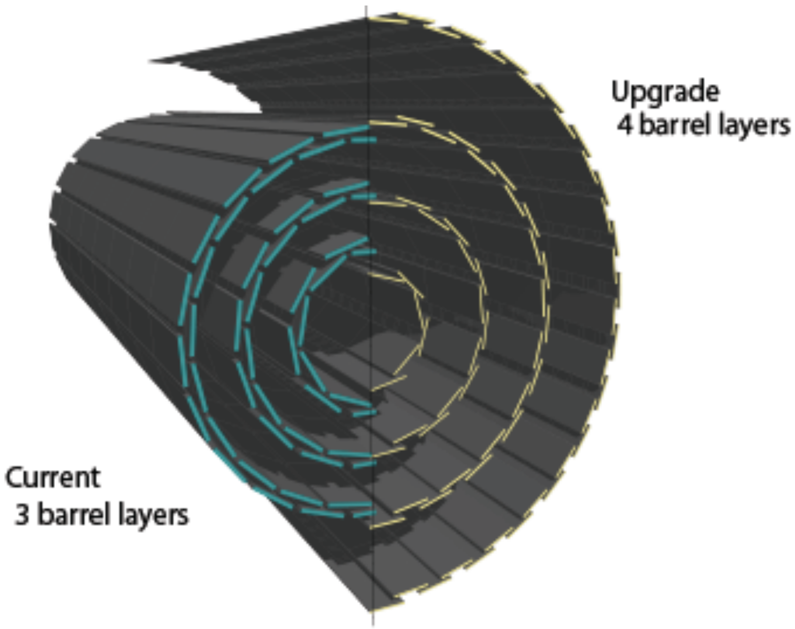
First production stave

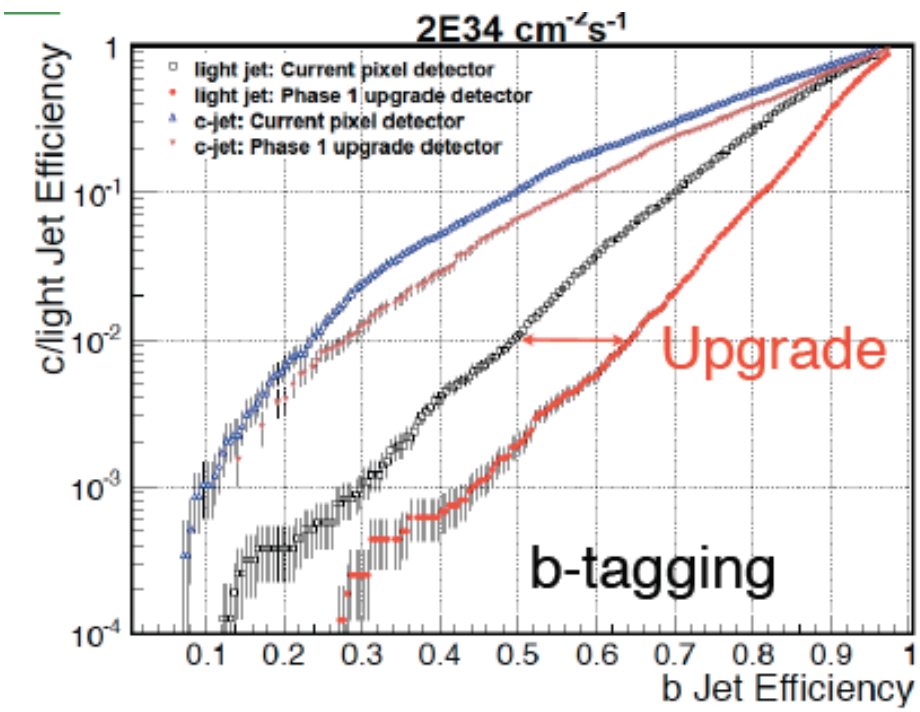




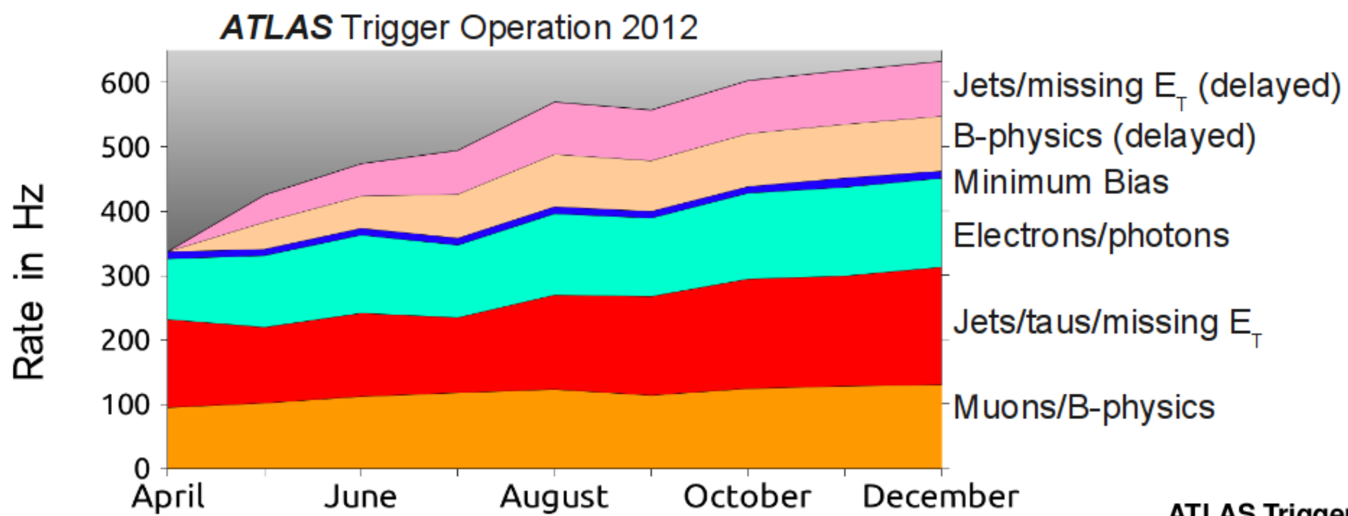
CMS Pixel upgrade

- CMS is building a new Pixel detector
  - with 4 layers
  - less material
  - Improved readout chip to reduce data loss
- To be installed in 2016/2017 shutdown

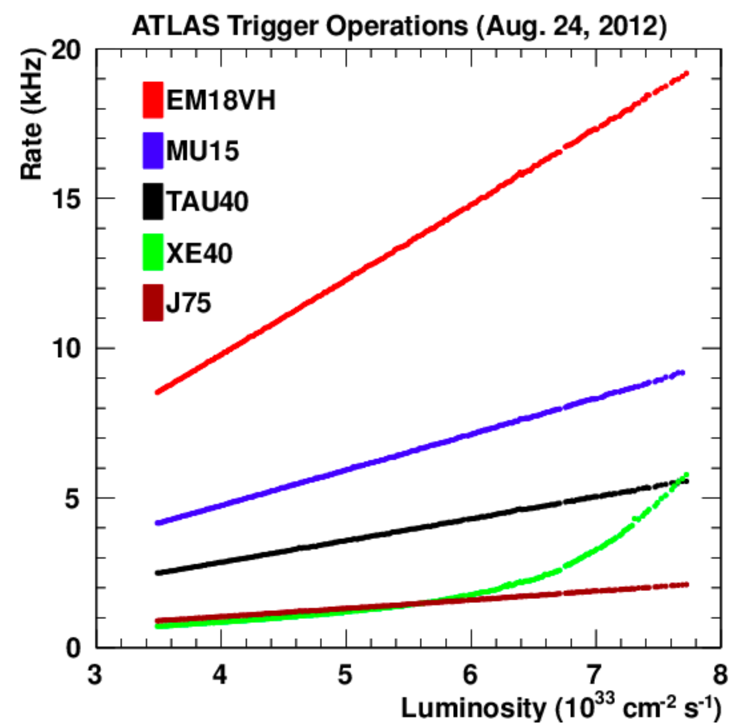




Triggering is Huge Challenge

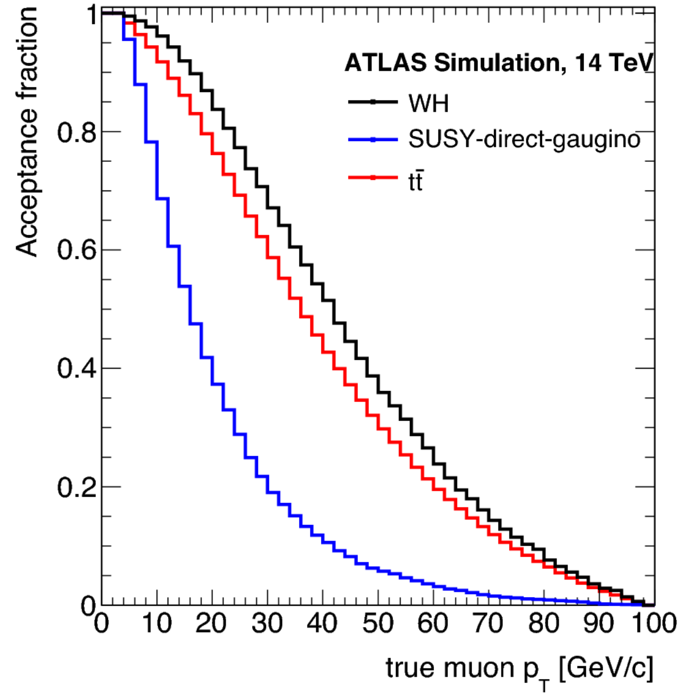


- Trigger reduces 40 MHz collision rate to 1 kHz storage rate
  - 2-3 level trigger system
  - L1 hardware trigger: 100 kHz limit
- Has to become increasingly selective as luminosity increases
  - Cannot afford to waste bandwidth on background



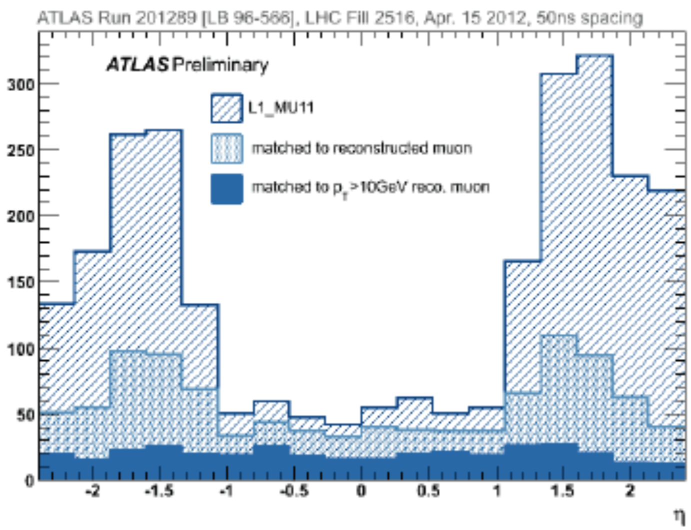
Trigger Upgrades

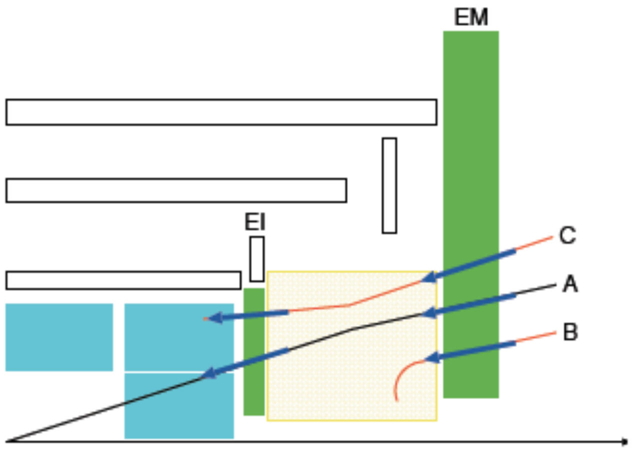
- ATLAS is trying to salvage single-lepton triggers
  - Major working horse for MANY analyses
- At HL-LHC leptonic W's alone have a rate of 1 kHz!
- Upgrades:
  - Track trigger (FTK) at Level 1.5 (~2015)
  - New Muon detector in forward region (2018)
  - Improved segmentation in LAr calorimeter trigger (2018)



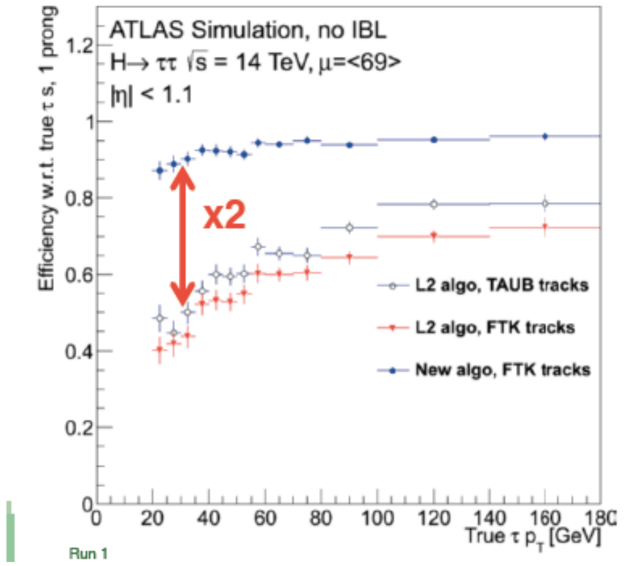
period	W->lv rate
Run-1	80 Hz
Run-2	200 Hz
Run-3	400-600 Hz
HL-LHC	1 kHz

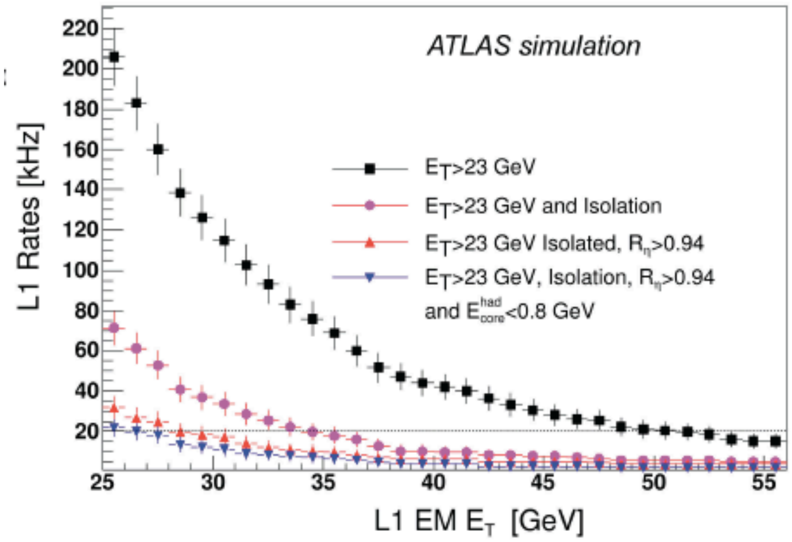
ATLAS Trigger Upgrades



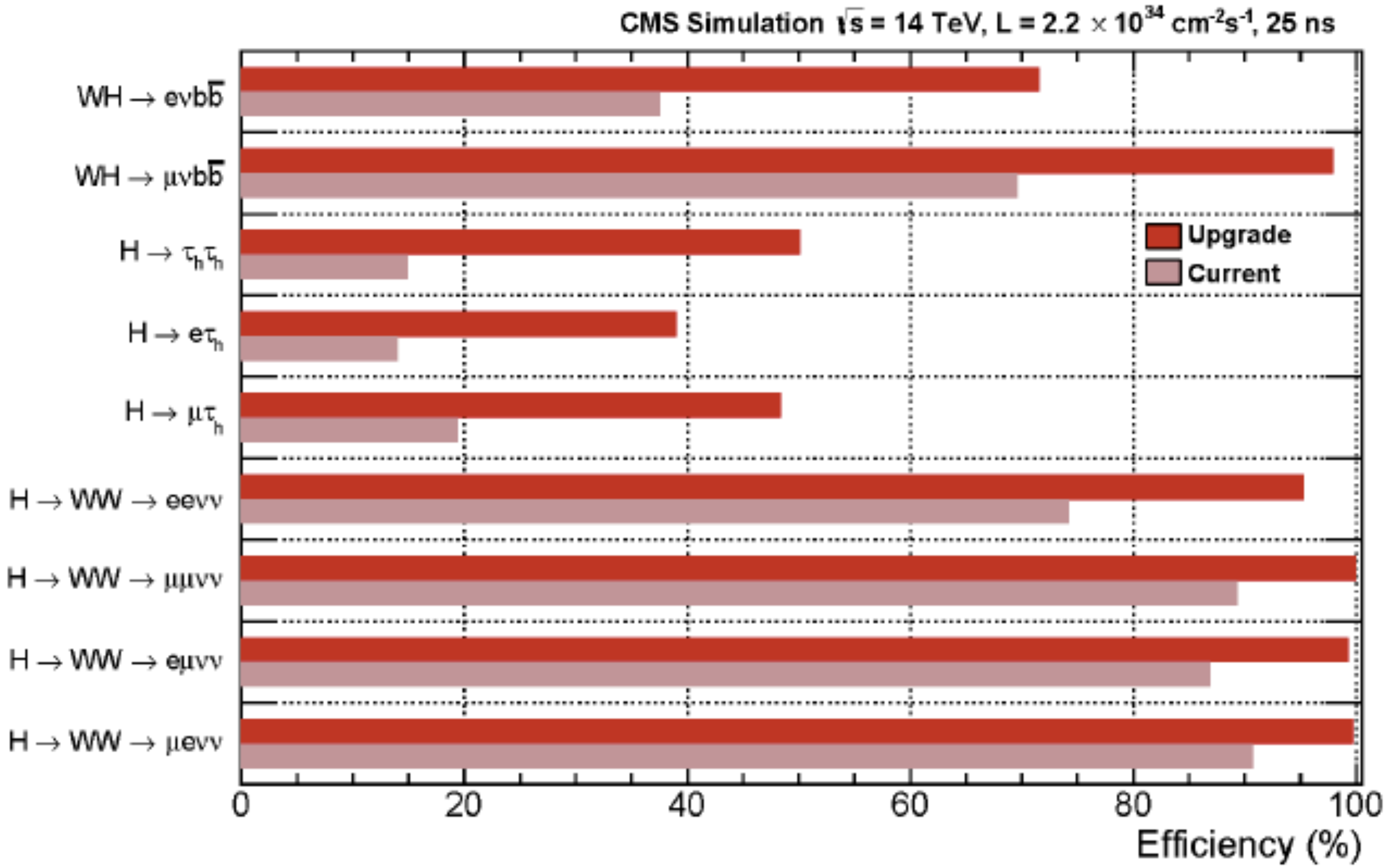


A: good, B+C: fakes.
NSW with micromegas & small-strip thin gap chambers





CMS trigger upgrades

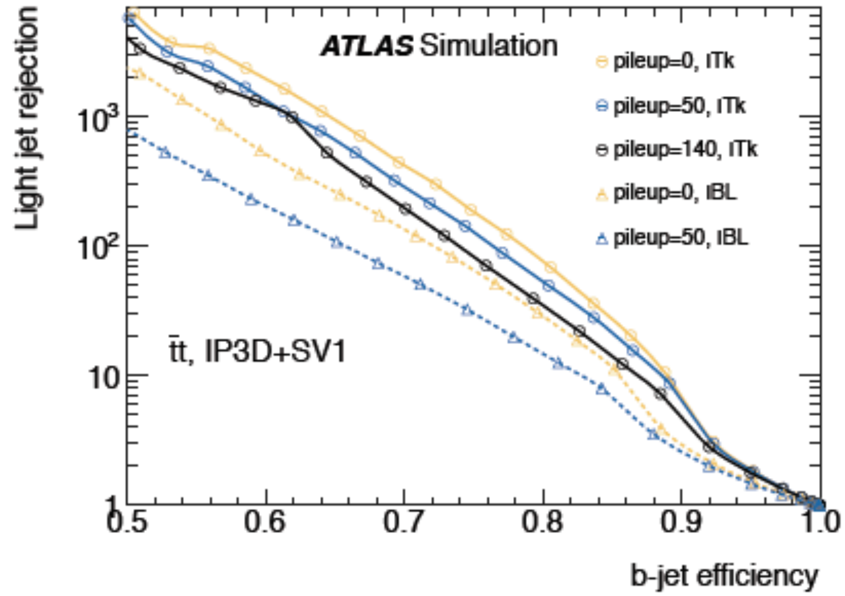


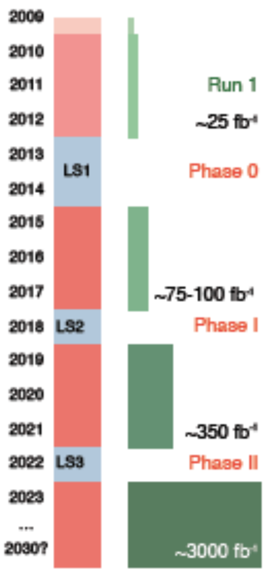
- Upgrades result in significant improvement in triggering on Higgs bosons

ATLAS Phase II

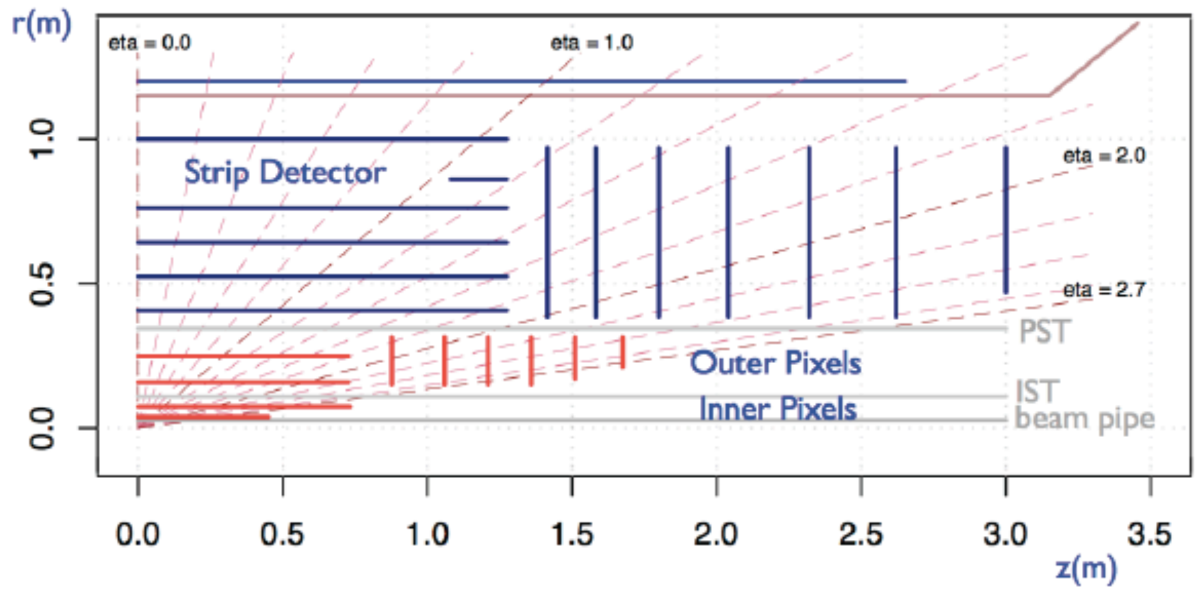
- Radiation damage & occupancy of present tracker → full replacement
- New L0(500kHz)/L1 trigger scheme, with RoI based L1 track trigger
- Phase I calo/muon upgrades are Phase II compatible. Additional readout electronics upgrade.
- Forward calorimeter options
- Computing & software upgrades

b-tagging: ITk with 140 pileup better than ATLAS+IBL with no pileup



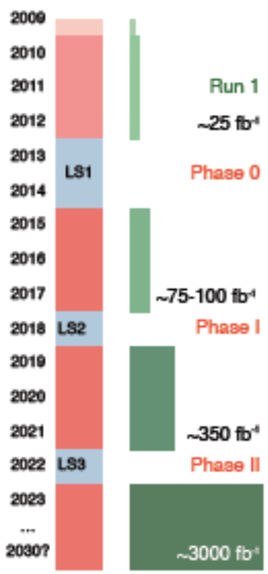


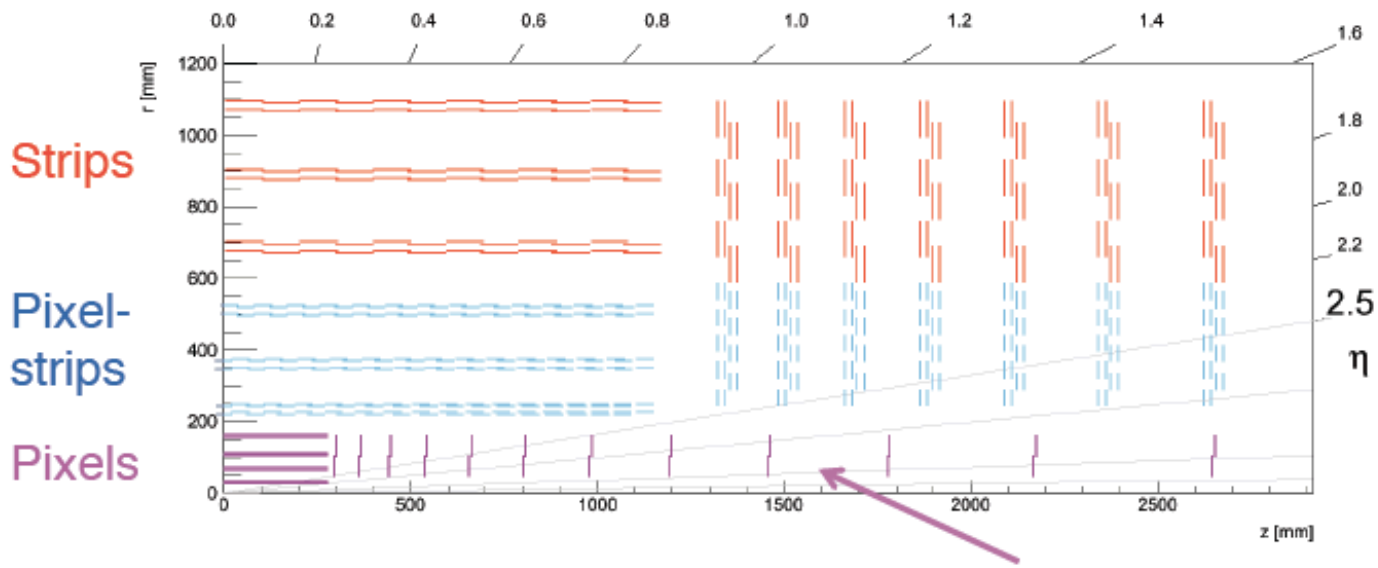
Baseline LoI ITk tracker design: all silicon with reduced granularity



CMS Phase II

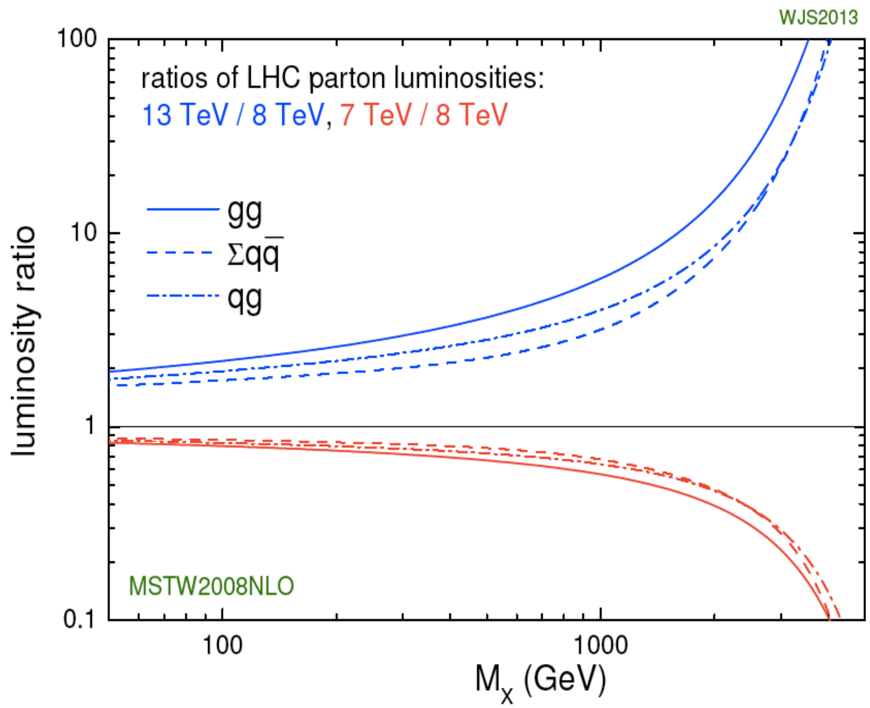
- Scope to be defined in Technical Proposal (2014)
  - New tracker with possible increased coverage to |η|<4, with an L1 track trigger (p_T>2.5 GeV)
  - DAQ and HLT upgrade → 1 MHz L1, 10 kHz event storage
  - Replace endcap and forward calorimeters
  - Possible electromagnetic preshower system to provide photon pointing and pileup discrimination from time-of-flight

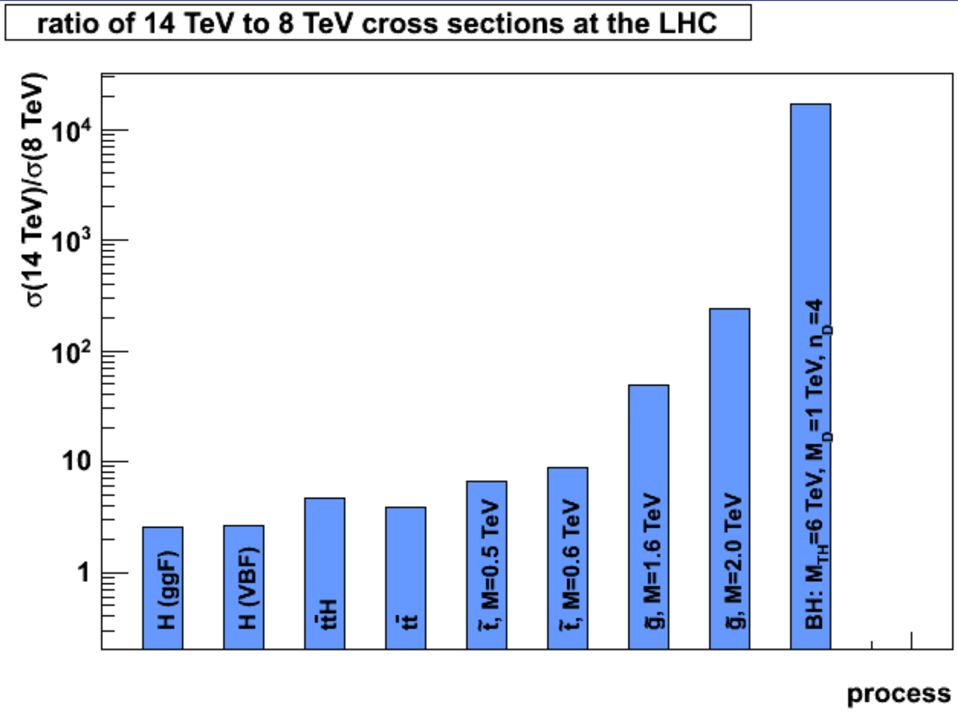




Possible tracker layout with forward pixel disks

Near Future: Run-2



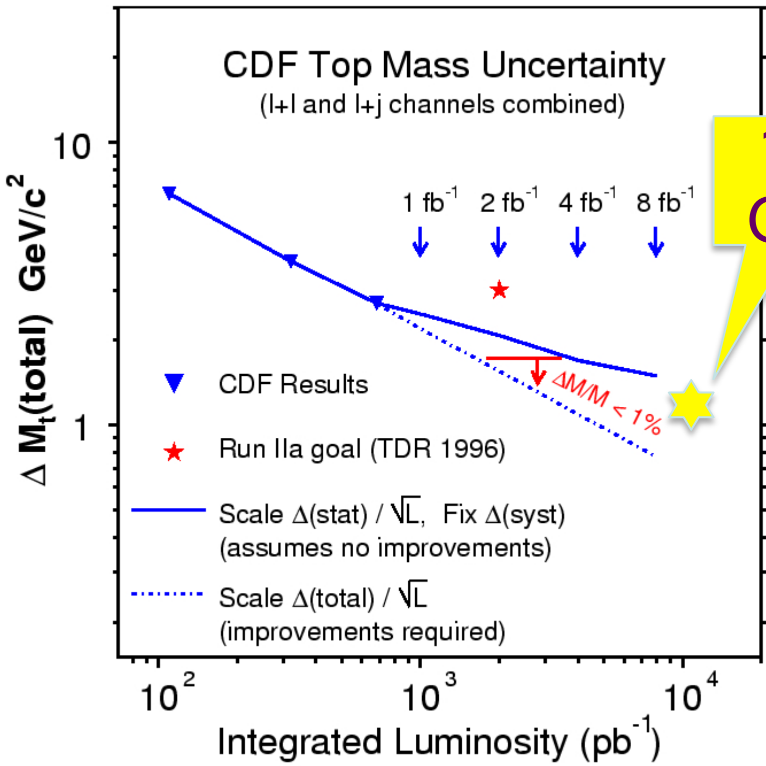


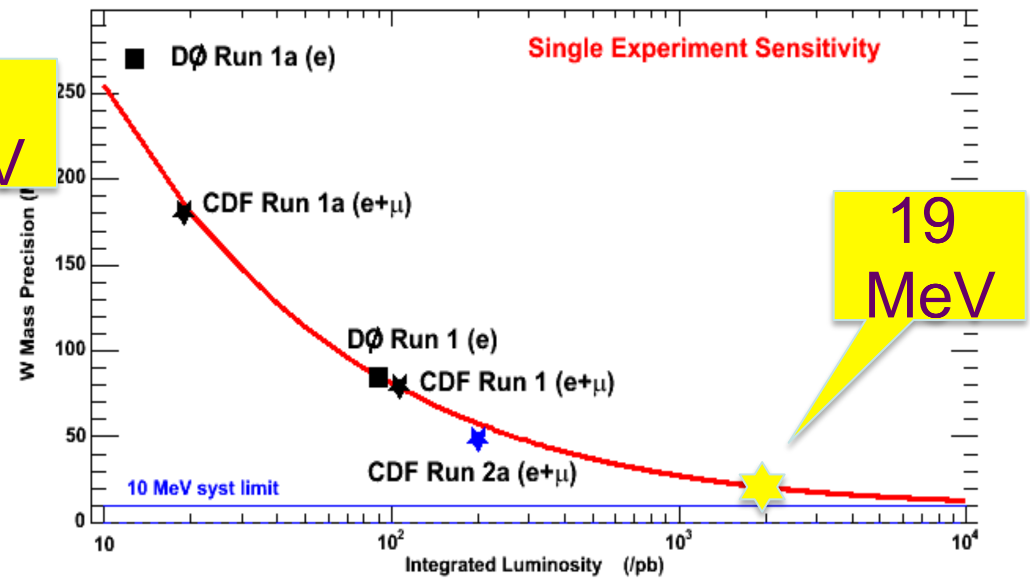
- Increase in cross section by factor ~10 for M~2 TeV
  - Discovery of TeV scale particles possible with a few fb^{-1}
- Higgs measurement program enters new phase
  - 3x larger cross section and 5x more data
  - Statistical precision improved by about a factor 4

Future Physics Prospects (beyond run-2)

- Studies have been done for $\sqrt{s}$=14 TeV for integrated luminosities of 300 fb^{-1} (LHC) and 3000 fb^{-1} (HL-LHC)
- ATLAS
  - Studies based on smearing functions applied to generated MC events based on realistic/pessimistic assumptions for detector performance
  - E.g. b-tagging and missing E_T performance was found to be better in the meantime but studies not yet updated accordingly
- CMS
  - Current analyses are extrapolated to higher $\sqrt{s}$ and luminosity assuming
    - Scenario 1: systematic and theoretical uncertainties stay as they are
    - Scenario 2: systematic uncertainties scale as $\sqrt{L}$ and theoretical errors get cut by factor 2

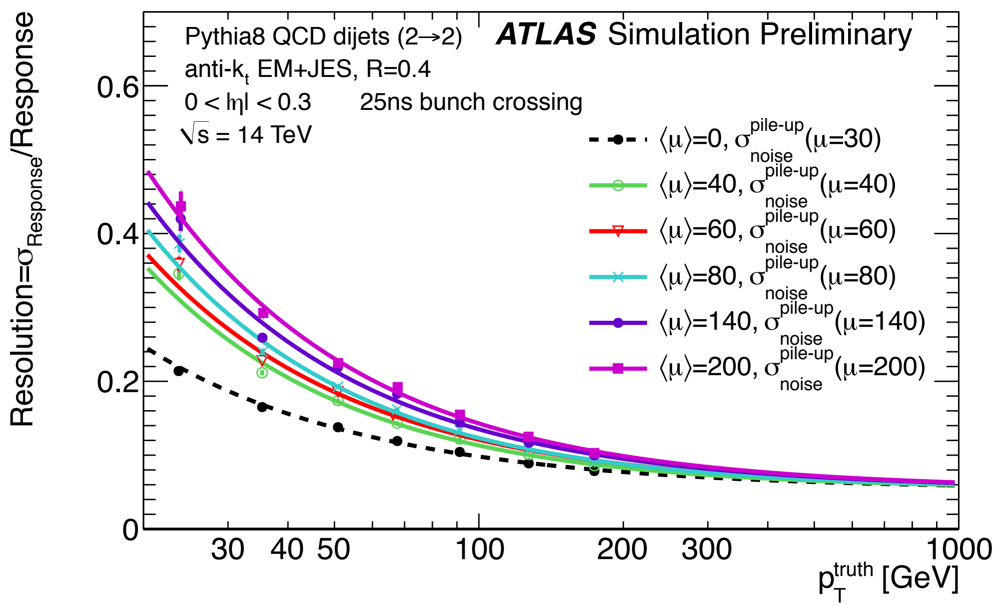
Comment on Hadron Collider Projections

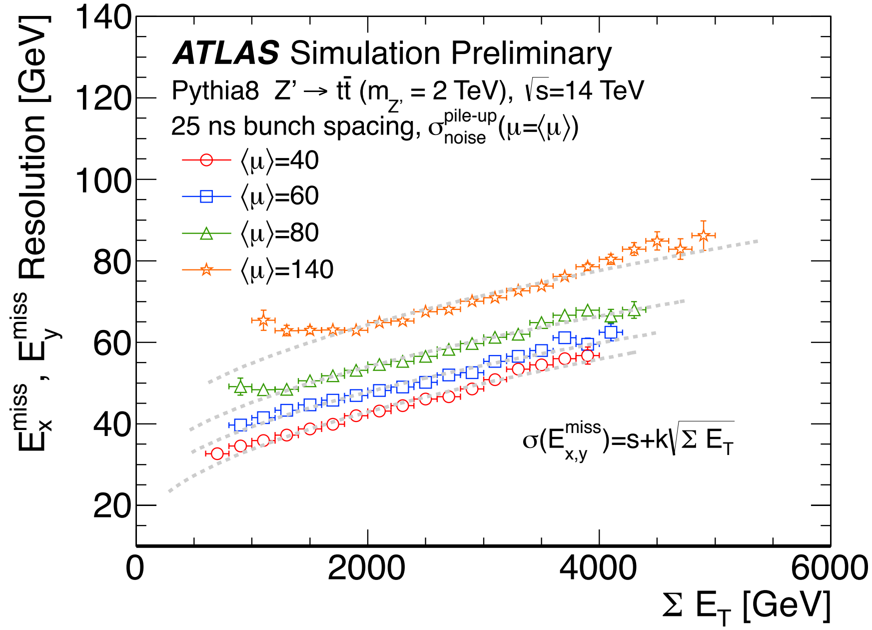




- I personally think that assuming √L scaling of systematic uncertainties is reasonable
  - Having large statistics allows to select the “best events”
  - Data can be used to constrain systematics *in situ*

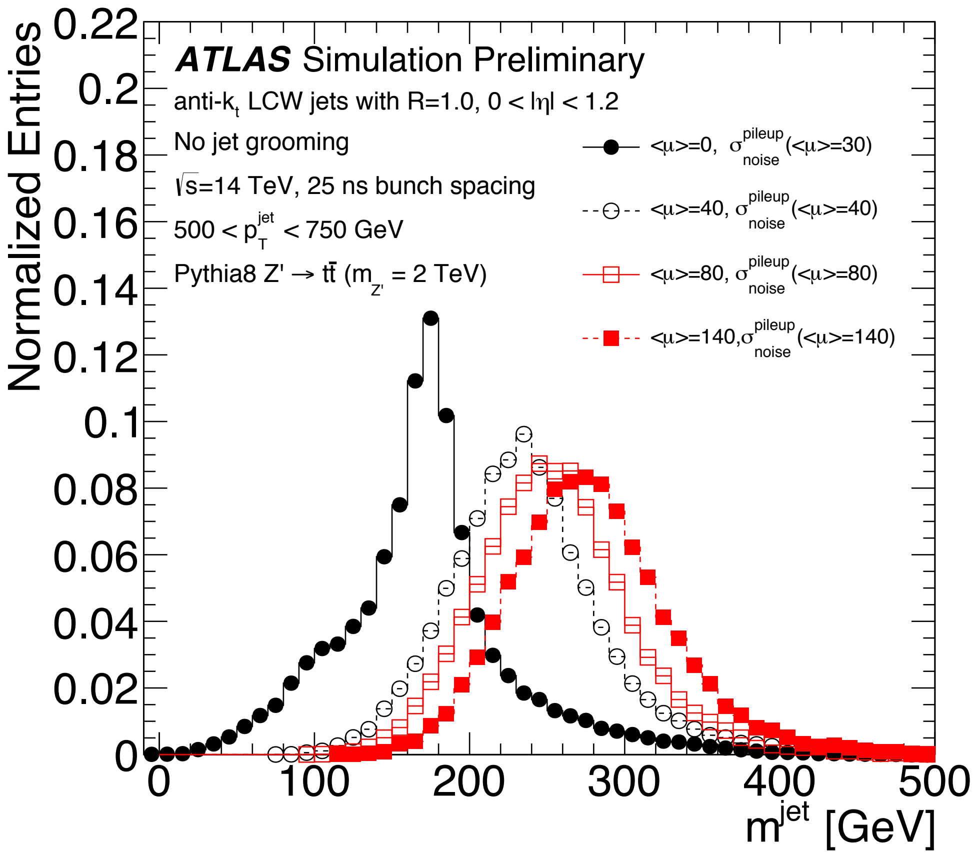
Jet and Etmiss resolution at high pileup

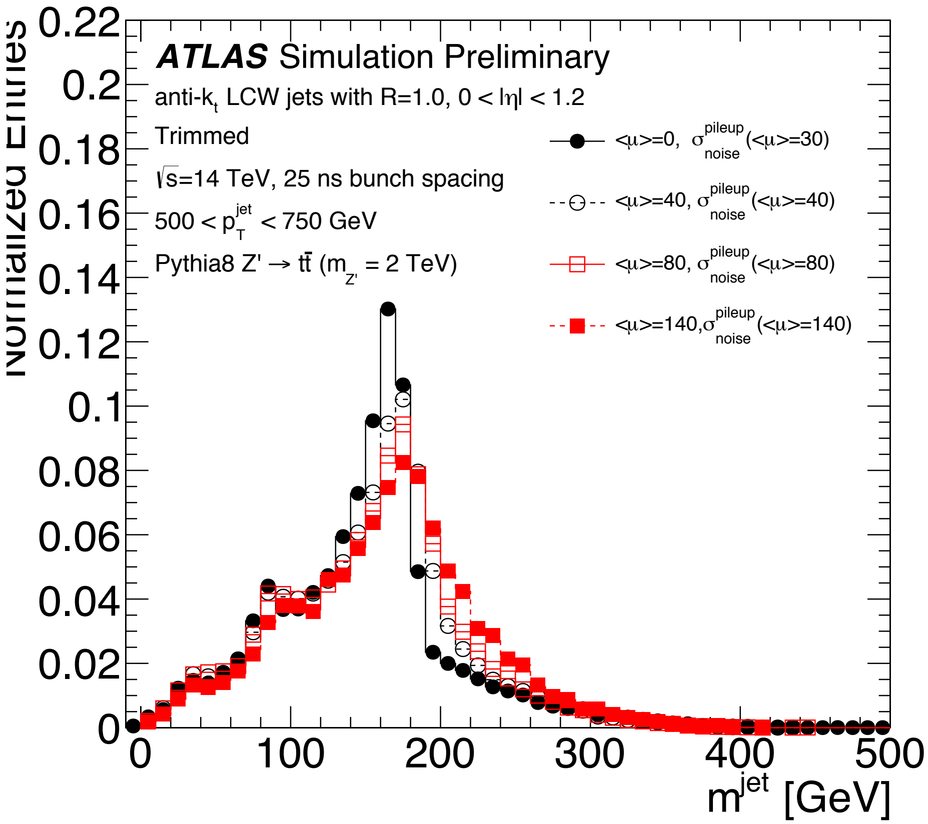




- Jet resolution significantly degraded at low p_T
  - Degrades sensitivity to low mass dijet resonances (e.g. H->bb)
  - For p_T>100 GEV effect rather small
- E_T^{miss} resolution also degrades but ~OK

Jet substructure at high pileup



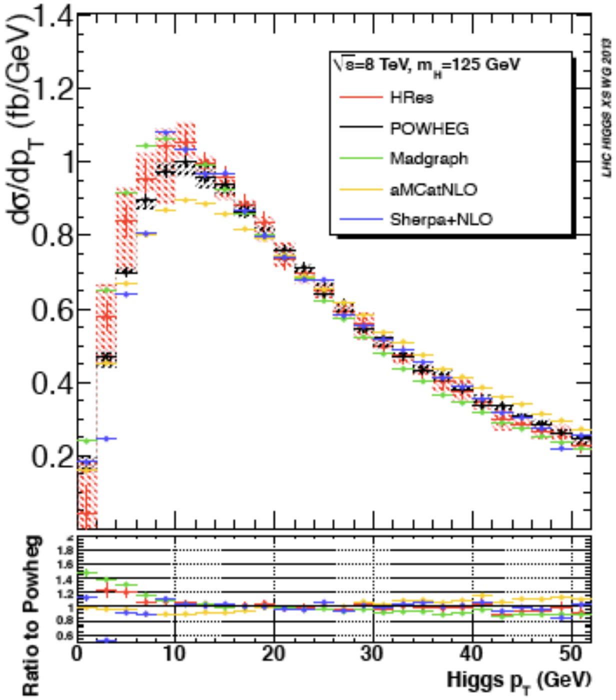


- Substructure techniques still work even at 140 pileup events
  - Thanks to trimming!

Theoretical Uncertainties

- Theoretical predictions for processes are critical for estimating cross sections and acceptances
  - Missing higher order QCD corrections
    - Estimated by varying renormalization and factorization scales
  - Electroweak corrections (up to 20% at high mass)
  - PDF uncertainties
    - Can be reduced with future precision measurements at LHC
- Beware of acceptance!
  - E.g. data are analyzed in N_{jet} bins etc.
  - Need understanding of $p_T(H)$

arXiv:1307.1347



Breakdown of Theoretical Uncertainties

Higgs production at 125 GeV

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

- Model testing requires assessment of theoretical uncertainties
  - uncertainties from scale variation and PDF+strong coupling

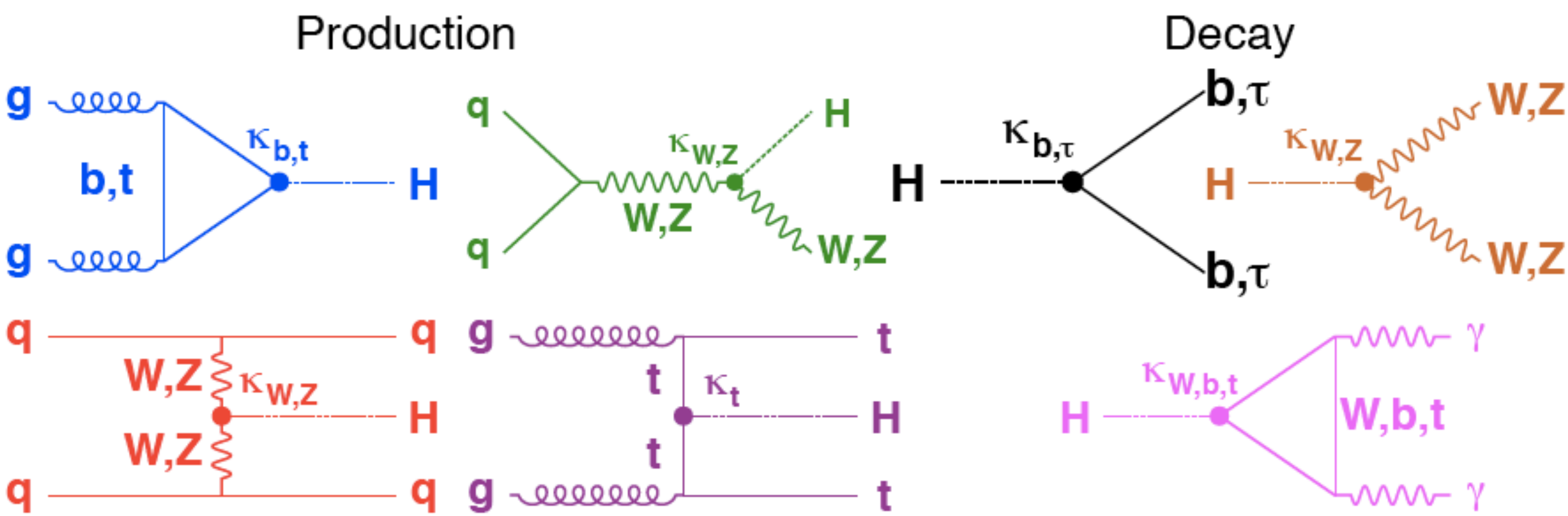
		σ (8 TeV)	uncertainty
NNLL QCD +NLO EW	gg→H	19.5 pb	14.7%
	VBF	1.56 pb	2.9%
NNLO QCD +NLO EW	WH	0.70 pb	3.9%
	ZH	0.39 pb	5.1%
NLO QCD	ttH	0.13 pb	14.4%

Perturbative QCD: Status - John Campbell, Fermilab ICHEP2012 30

Measurements of the Higgs Boson

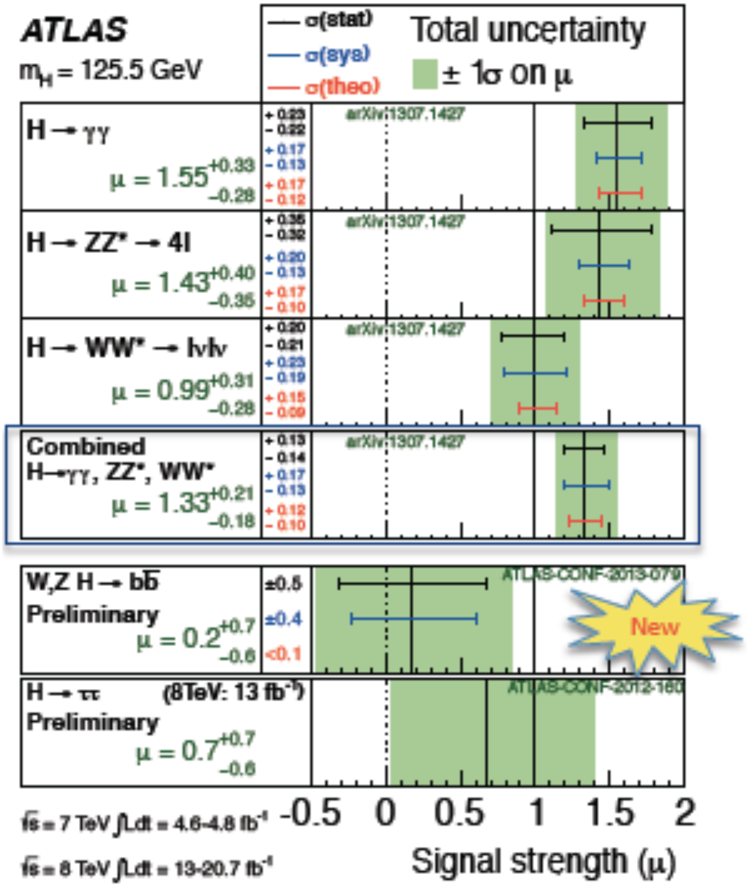
- Mass will already have precision of ~100 MeV after run-2
  - Difficult to improve
- Width expected to be very narrow for Higgs
  - Cannot be measured due to limited detector resolution
- Spin/parity already pretty much established as 0^+
  - Will investigate CP violating contributions
- Couplings to fermions and bosons can be constrained via measurements of σxBR expressed as $\mu=(\sigma x BR)_{data}/(\sigma x BR)SM$
  - Interpretation in terms of couplings requires understanding of correlation between measurements and is model dependent

LHC Higgs Boson Production and Decay



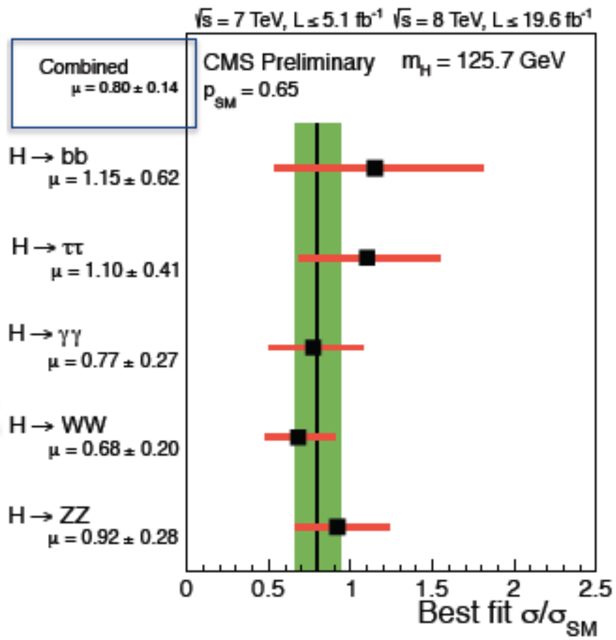
- Couplings quantified by factors κ inserted at all the Higgs vertices
  - Study how they are constrained in global fit with all processed jointly

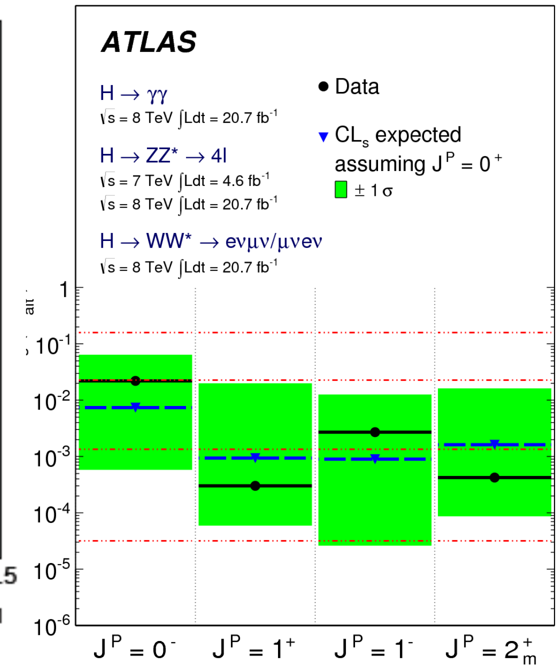
Higgs: Run-1 Data Reminder



ATLAS: $M_H = 125.5 \pm 0.2_{stat} \pm 0.6_{sys}$ GeV

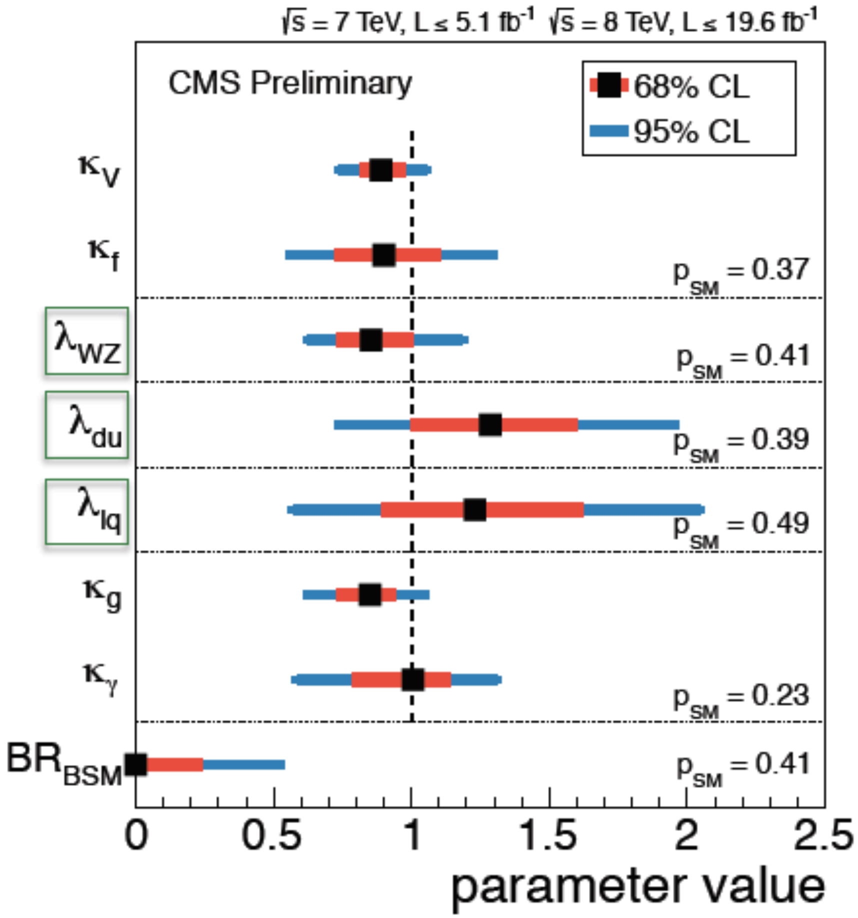
CMS: $M_H = 125.7 \pm 0.3_{stat} \pm 0.3_{sys}$ GeV

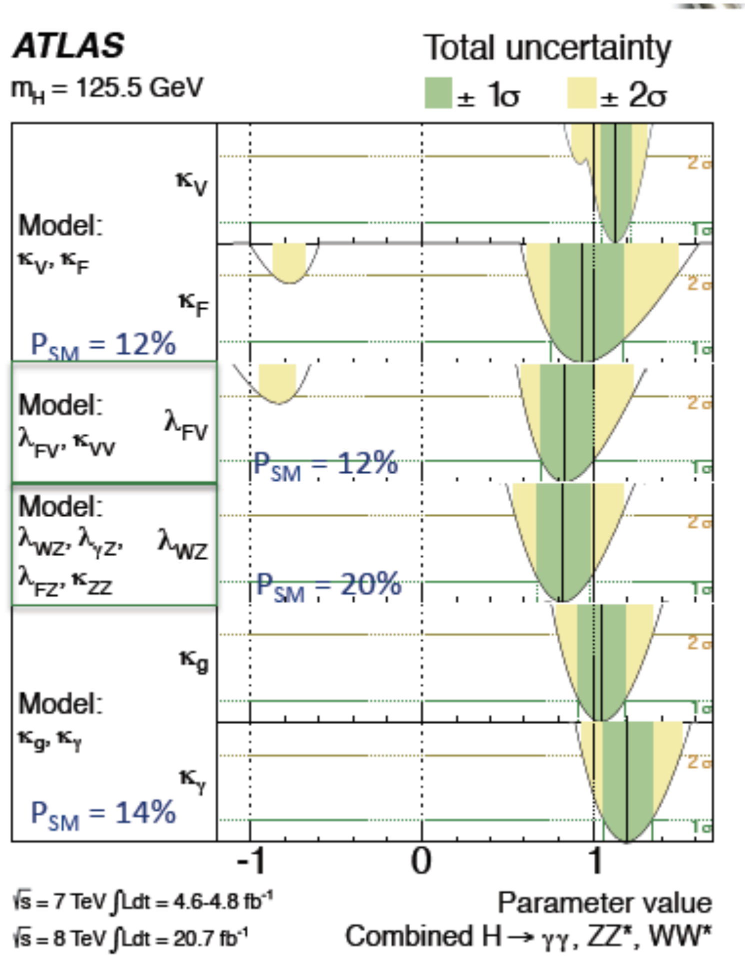




- Signal strength μ consistent with SM
- Mass known to 0.6 GeV already
- Hypotheses $J^P \neq 0^+$ rejected at 95% CL

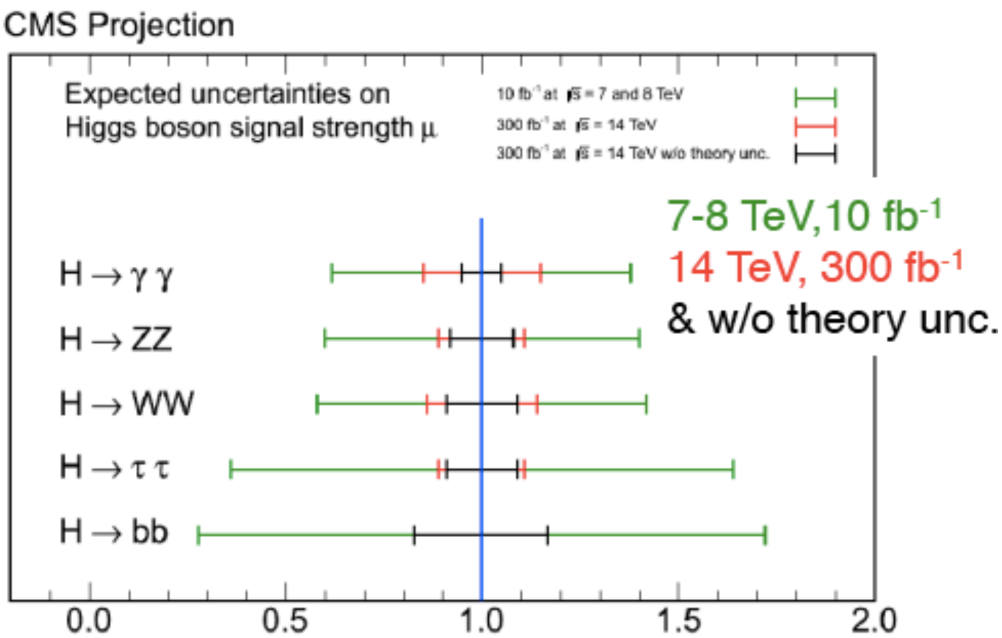
Higgs: Run-1 coupling measurements

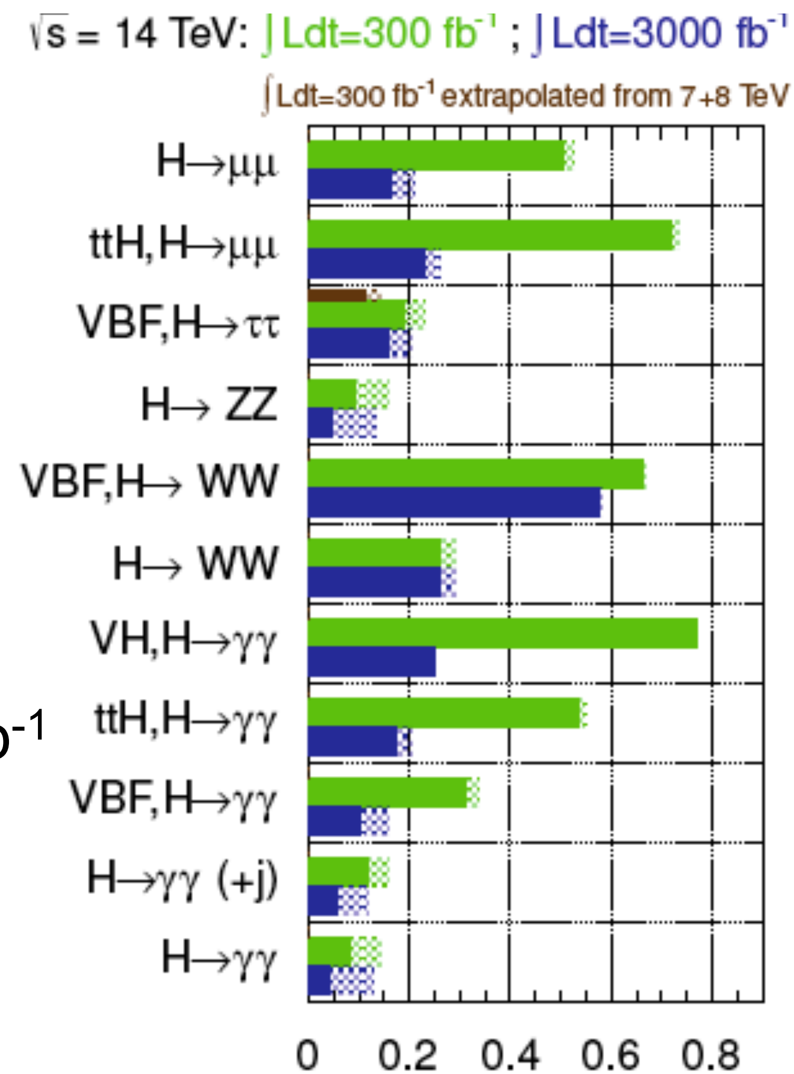




- Higgs boson overall consistent with SM expectation for fermion and boson couplings but uncertainties still large in many cases
  - Down vs up-quark coupling (λ_{du})
  - Quark vs lepton coupling (λ_{lq})

Future Precision on μ

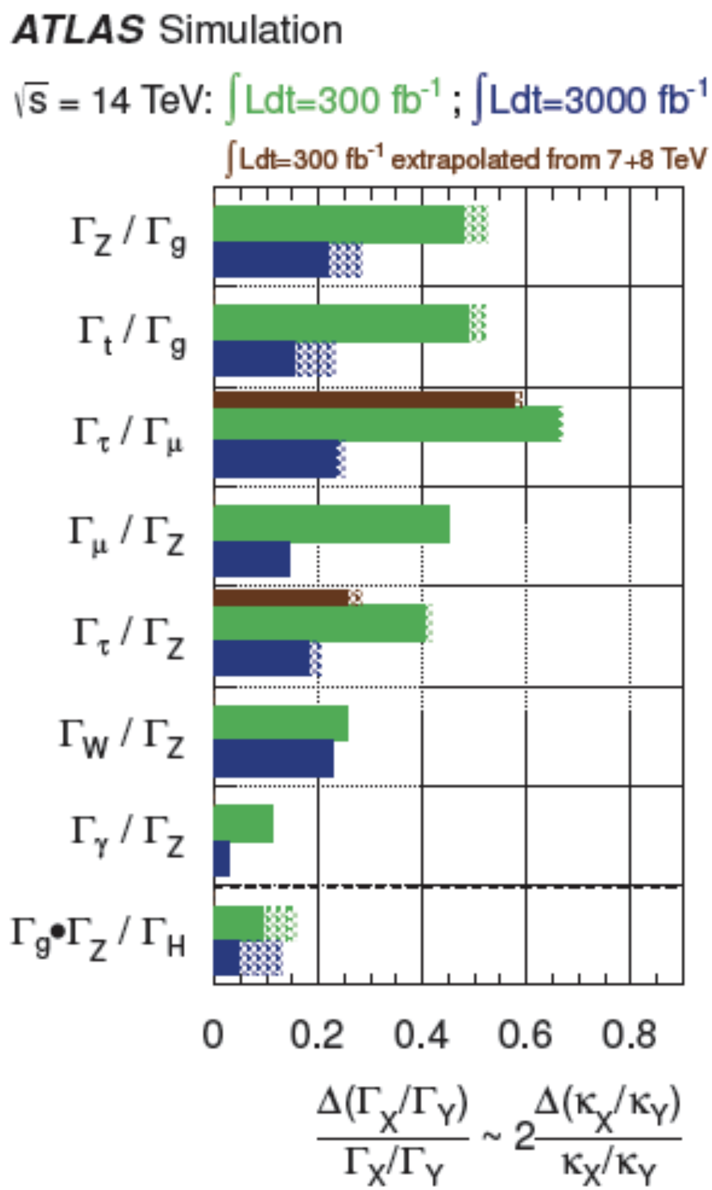




- About 10-15% achieved with 300 fb^{-1} for main decay modes
- HL-LHC (3 ab^{-1}):
  - Most decay modes: precision improved by factor 2-3
  - Depends on assumption on theory and exp. uncertainties

Higgs boson couplings / partial widths

- Some uncertainties cancel in ratio of partial widths
  - Sensitive probe as we expect new physics to affect different couplings differently
- Expected precision ~10-20% for HL-LHC
  - Factor 2-3 better than LHC alone
- Theory uncertainty limiting in several cases

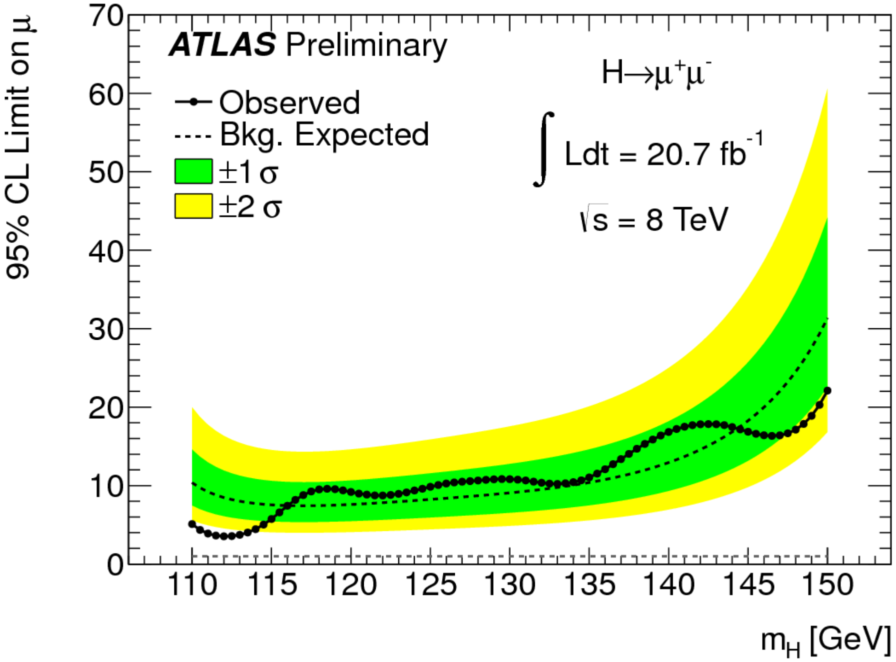


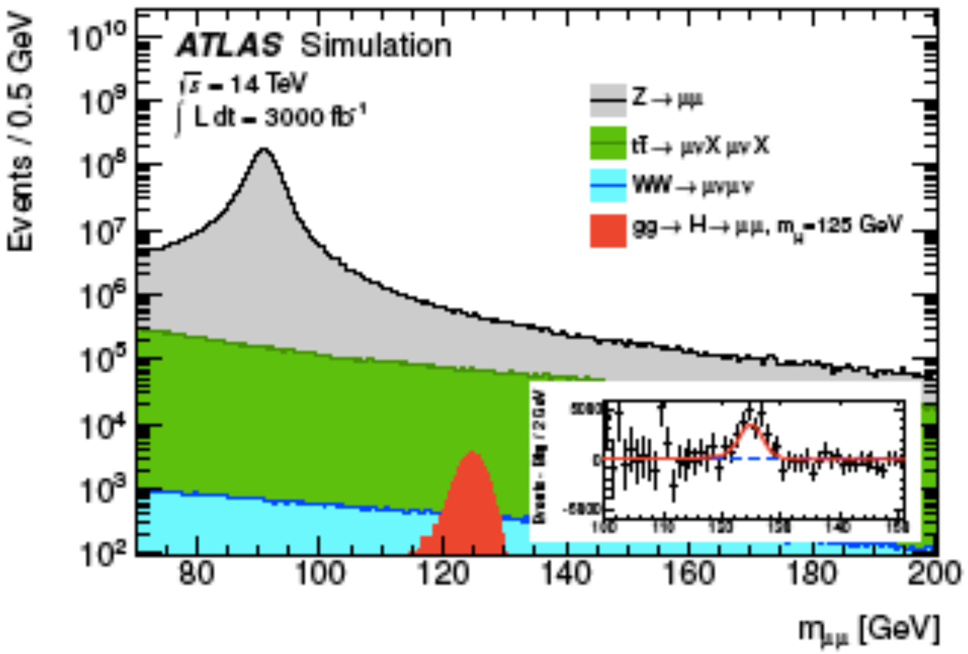
Higgs boson couplings/partial width

- Full fit of analyses done by CMS under the two sets of assumptions:
  - Scenario 1: systematic and theoretical uncertainties stay as they are
  - Scenario 2: systematic uncertainties scale as $\sqrt{L}$ and theoretical errors get cut by factor 2
- Truth is likely between these 2 scenarios
- Relative precision of 2-5% seems achievable on many couplings
  - Depending on whether theory systematics can be reduced by ~2

CMS	Uncertainty (%)			
Coupling	300 fb^{-1}		3000 fb^{-1}	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
κ_γ	6.5	5.1	5.4	1.5
κ_V	5.7	2.7	4.5	1.0
κ_g	11	5.7	7.5	2.7
κ_b	15	6.9	11	2.7
κ_t	14	8.7	8.0	3.9
κ_τ	8.5	5.1	5.4	2.0

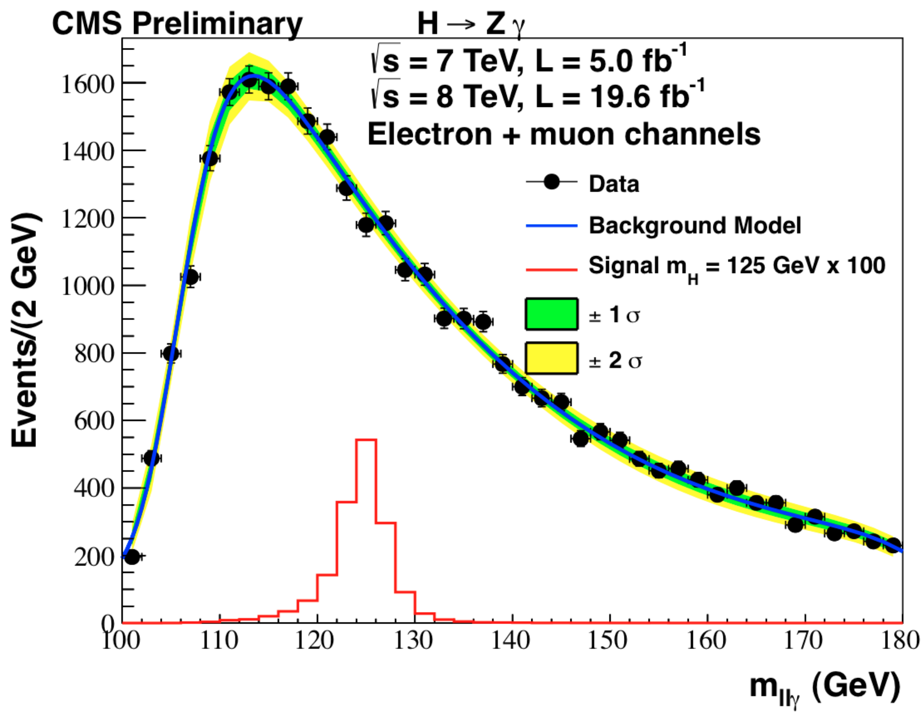
Rare processes: H->μμ

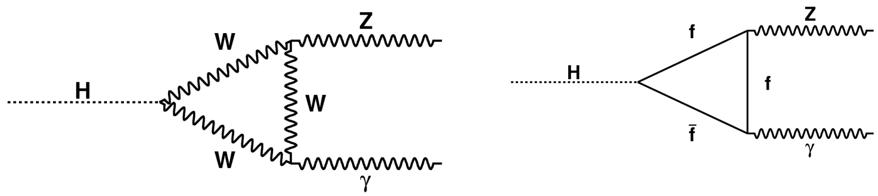


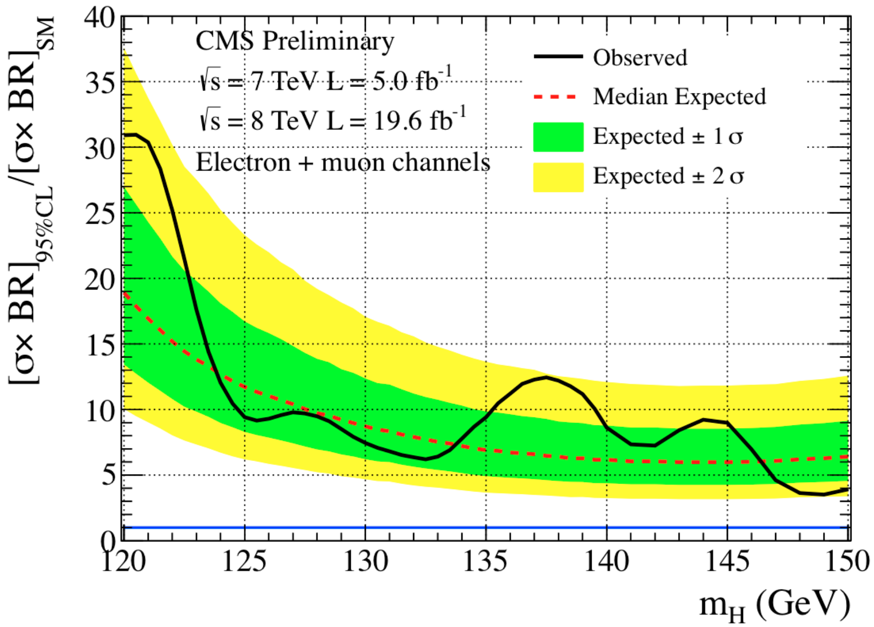


- H->μμ
  - Current upper limit 9.8 x SM expectation at m_H=125 GeV
  - Expect >5σ significance from each of the two experiments with 3 ab^{-1}
  - Precision of coupling to muons ~10-15%

Rare processes: H->Zγ

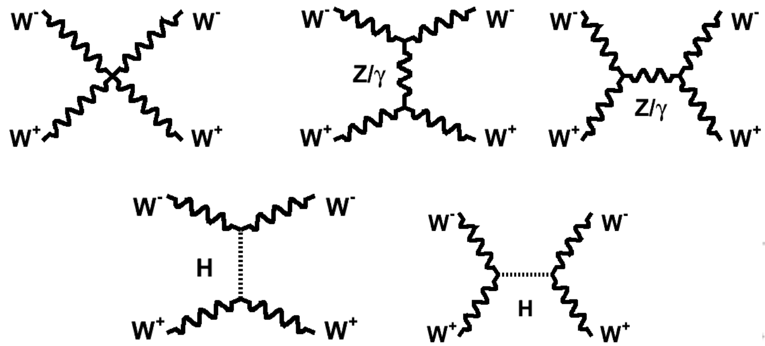






- H->Zγ
  - Current limit about a factor 10 larger than SM expectation
  - No future prospect studies yet from either collaboration
  - Based on run-1 results expect similar sensitivity as H->μμ

Weak Boson Scattering



$$A \approx g^2 \frac{E^2}{M_W^2}$$

$$A \approx -g^2 \frac{E^2}{M_W^2}$$

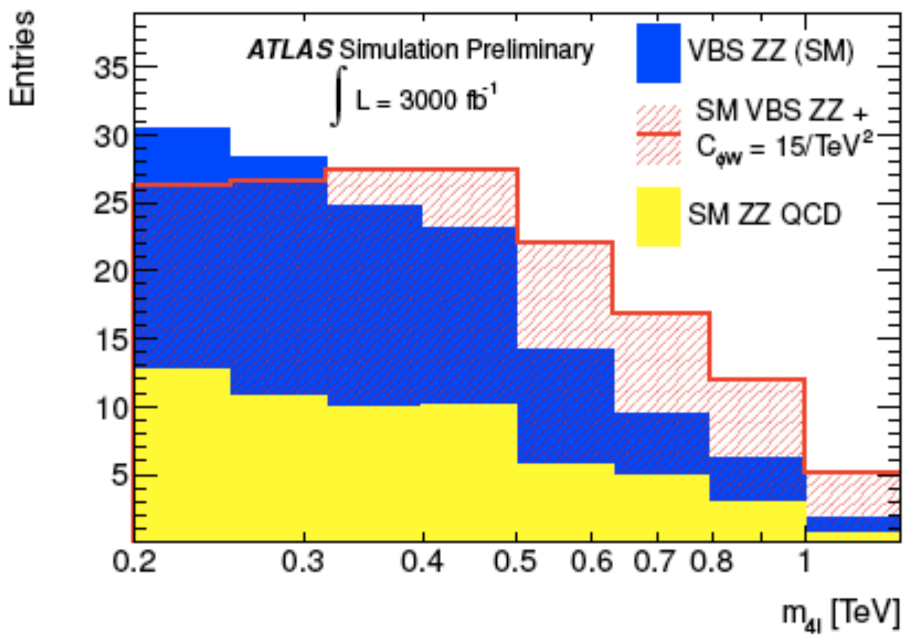
Terms which grow with energy cancel for E >> M_H

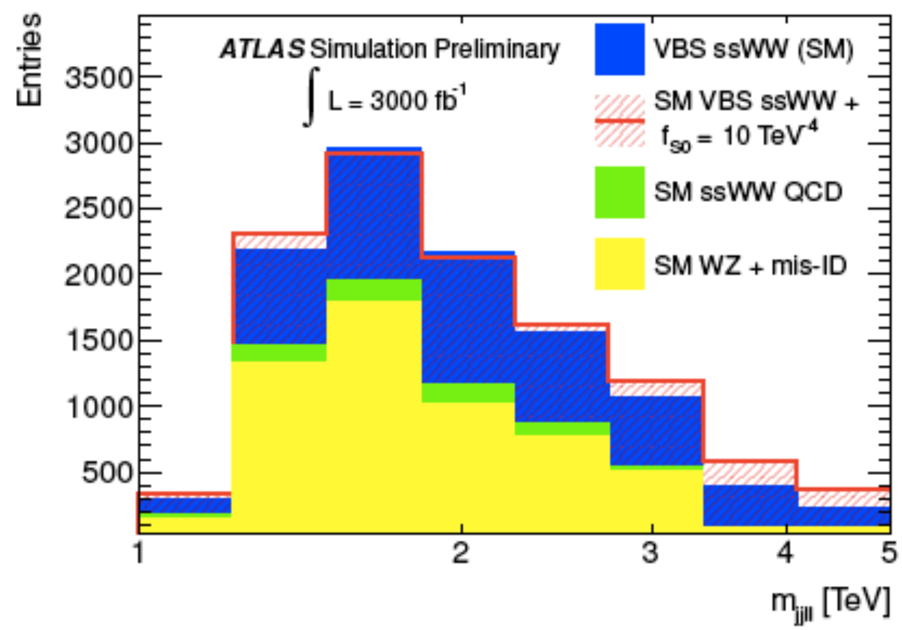
This cancellation requires M_H < 800 GeV

- Higgs boson cancels divergence at high energy in SM
- Test experimentally
  - Does any strong dynamics contribute to vector boson interactions?

Weak Boson Scattering

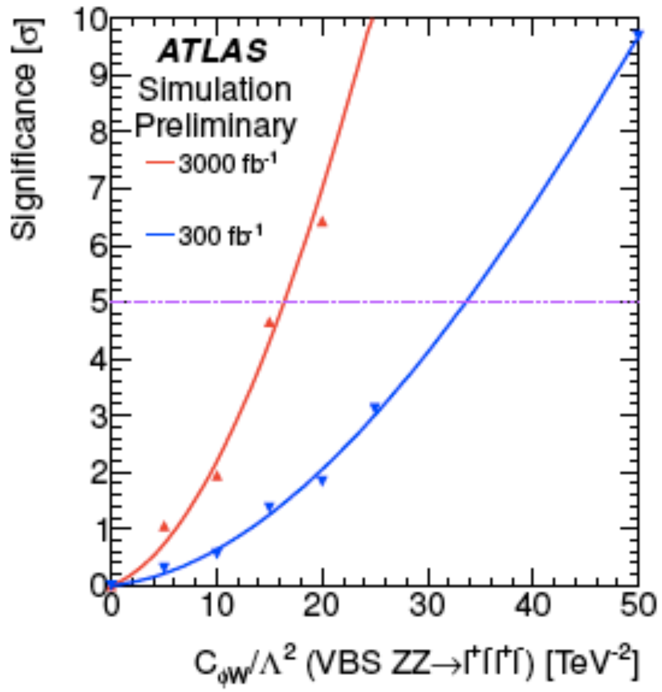
- Signature of anomalous coupling is high mass production of pairs of vector bosons
- ATLAS has studied ZZ, WZ and $W^{\pm}W^{\pm}$

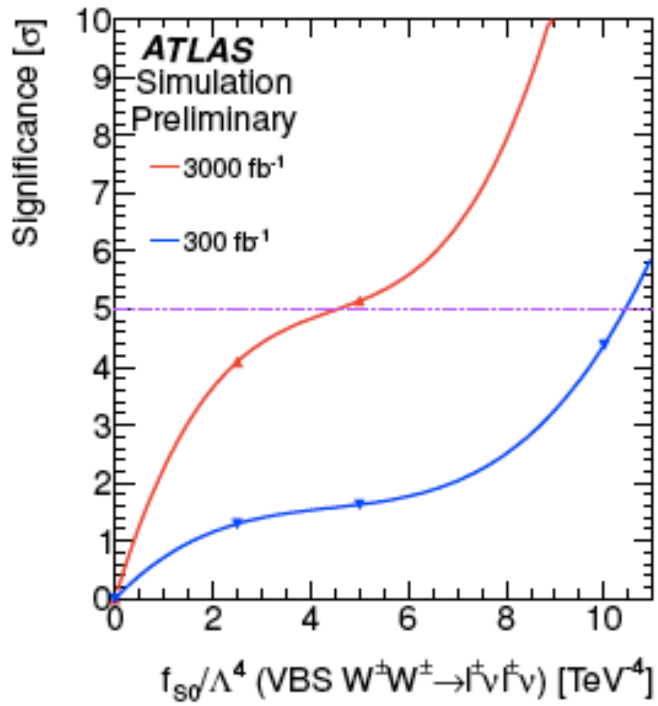




Weak Boson Scattering

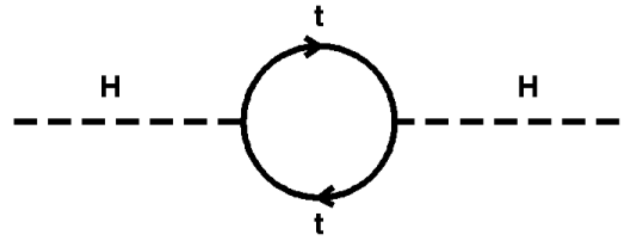
- Use framework of effective operators to parameterize new physics as quartic coupling, e.g
  - ZZ: dimension-6 operator $\mathcal{L}_{\phi W} = \frac{c_{\phi W}}{\Lambda^2} \mathrm{Tr}(W^{\mu\nu} W_{\mu\nu}) \phi^\dagger \phi$
  - WZ: dimension-8 operator $\mathcal{L}_{T,1} = \frac{f_{T1}}{\Lambda^4} \mathrm{Tr}[\hat{W}_{\alpha\nu} \hat{W}^{\mu\beta}] \times \mathrm{Tr}[\hat{W}_{\mu\beta} \hat{W}^{\alpha\nu}]$
  - $W^\pm W^\pm$: dimension-8 operator $\mathcal{L}_{S,0} = \frac{f_{S0}}{\Lambda^4} [(D_\mu \phi)^\dagger D_\nu \phi)] \times [(D^\mu \phi)^\dagger D^\nu \phi)]$

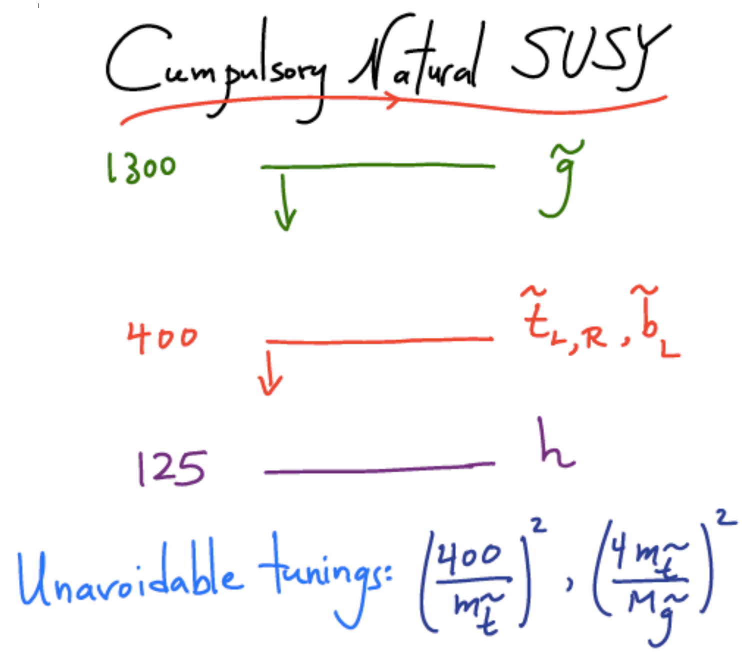




What protects Higgs mass from being higher?

- Known possible answers:
  - SUSY: top squark at m<400 GeV
    - and gluino with m<1.6 TeV
  - vector-like top quarks
    - E.g. Little Higgs theories
  - some other dramatic new physics a mass scale of a few TeV
    - E.g. extra dimensions
  - weak scale is fine-tuned at <1%
- Can directly search for these particles at colliders

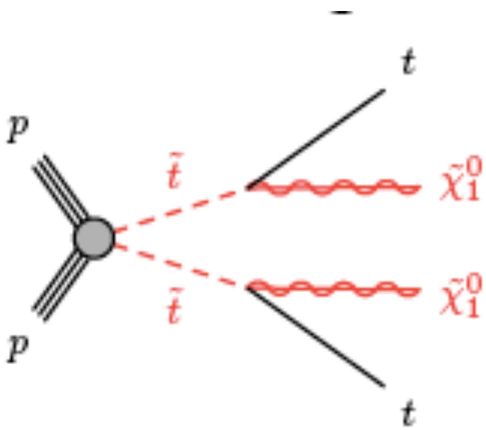


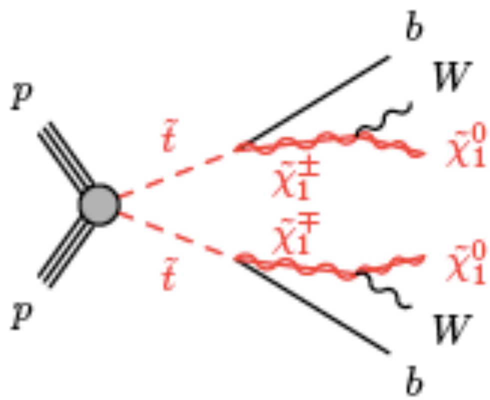


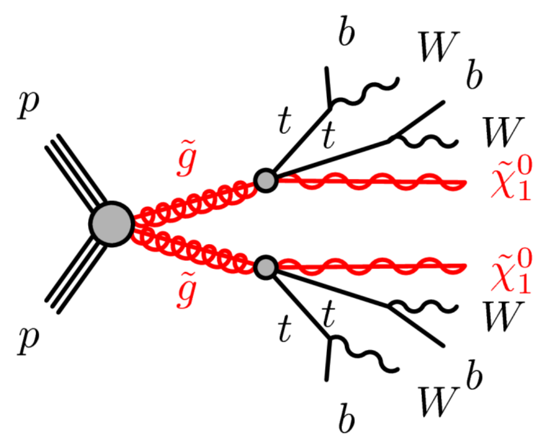
N. Arkani-Hamed

Top squark production

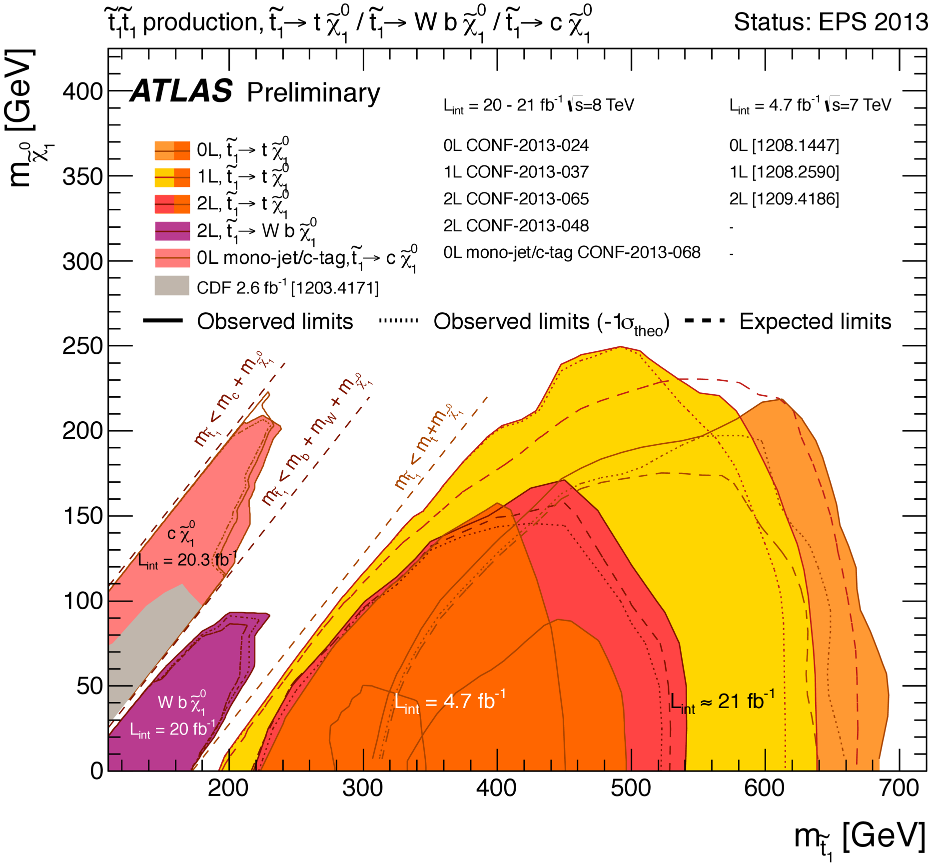
- Top squarks production occurs
  - Directly
  - From gluino decays if gluino mass low enough
- Decay via top quarks or via charginos to final states of W’s and b’s

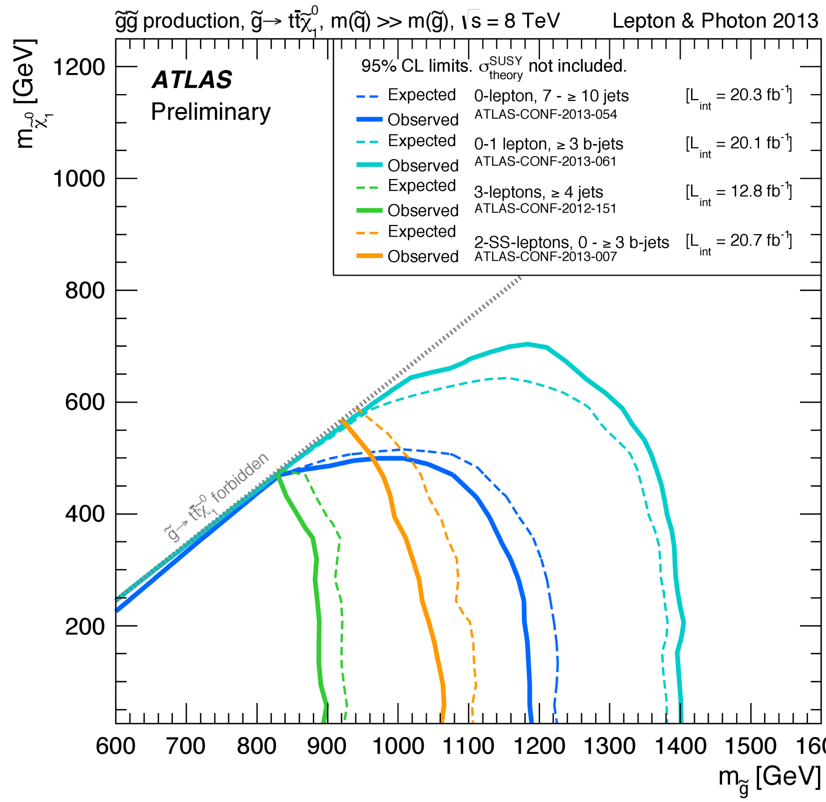






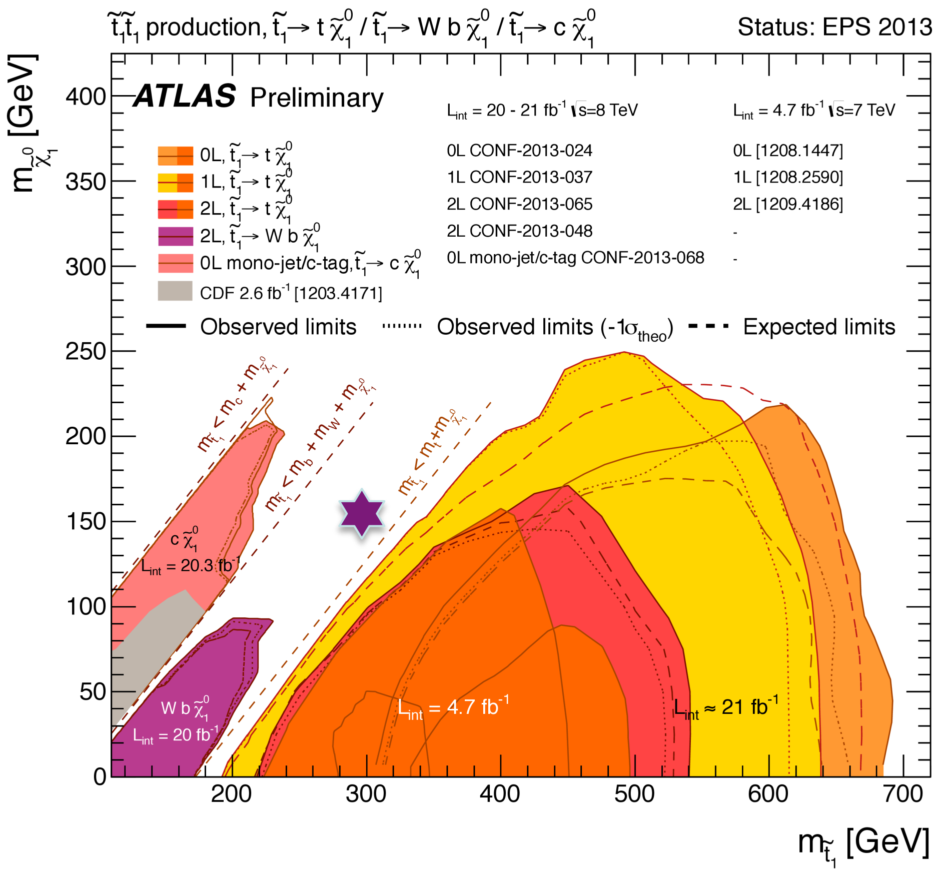
Constraints on top squarks

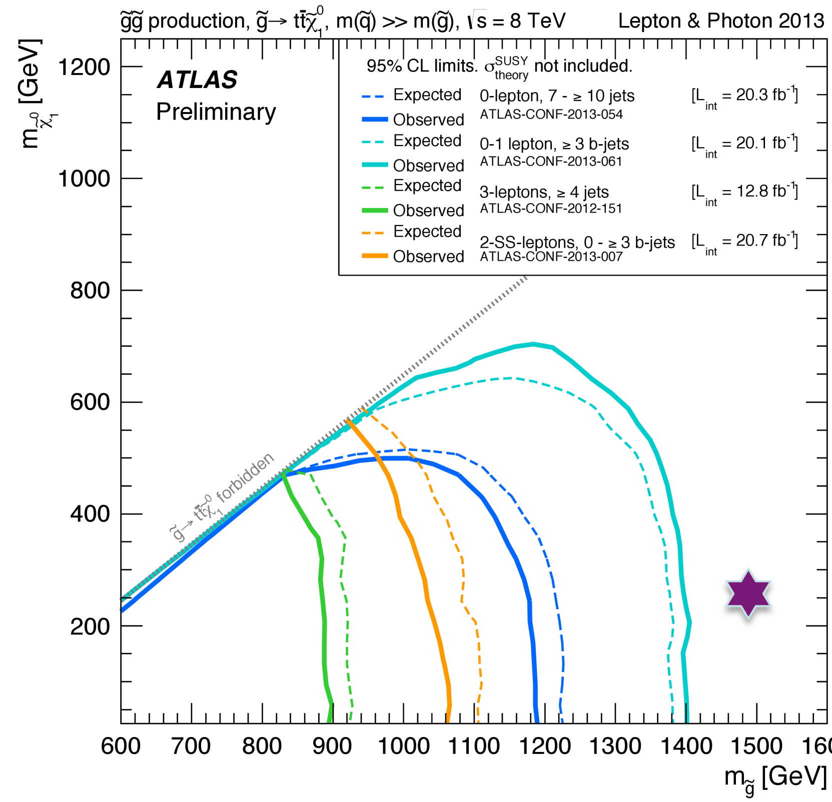




- Constraints ever improving from both ATLAS and CMS

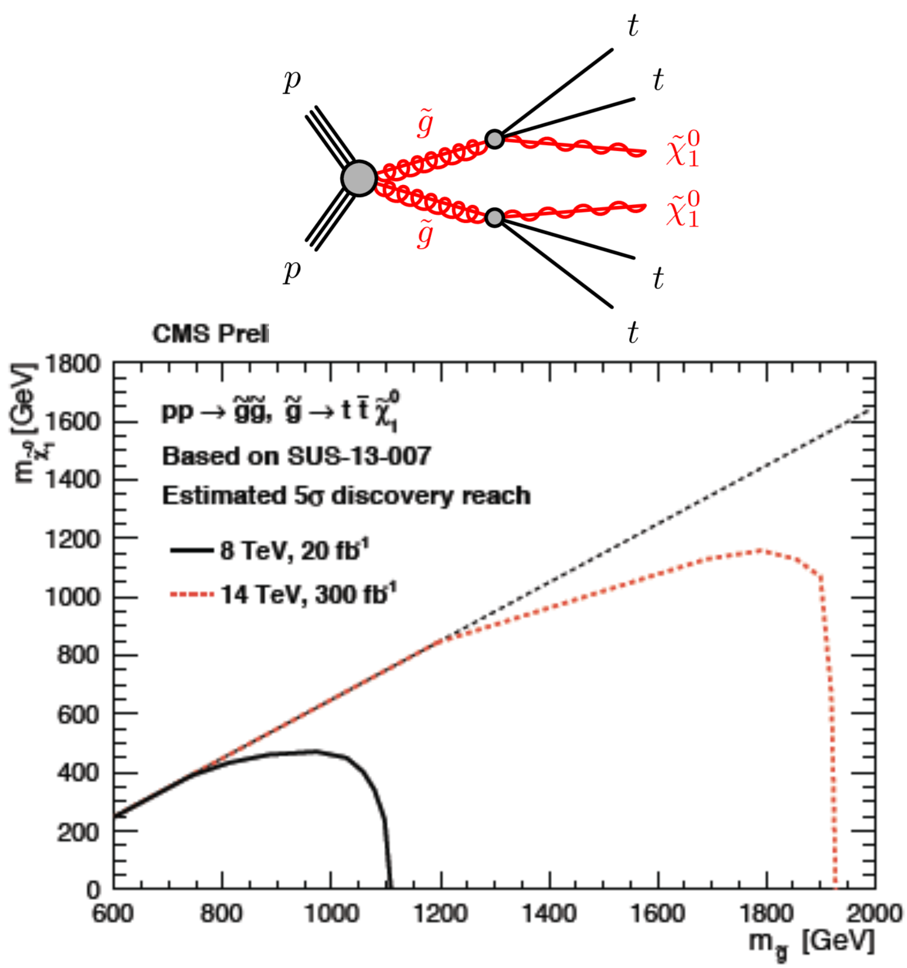
Constraints on top squarks

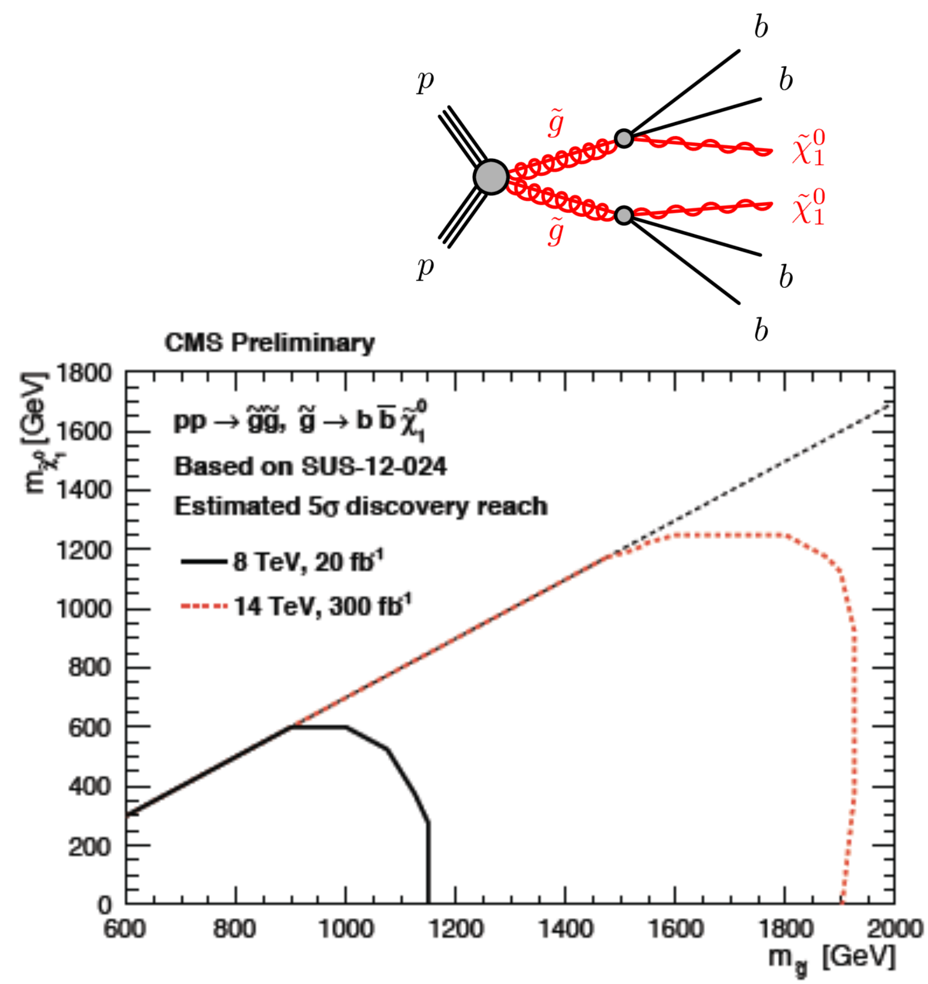




- Constraints ever improving from both ATLAS and CMS
- However, **pretty natural** scenarios still allowed, e.g
  - M(gluino)=1.5 TeV, m(stop)=300 GeV, m(LSP)=150 GeV
- LHC (and HL-LHC) will be able to discover such scenarios

Gluino reach if decay via top/bottom

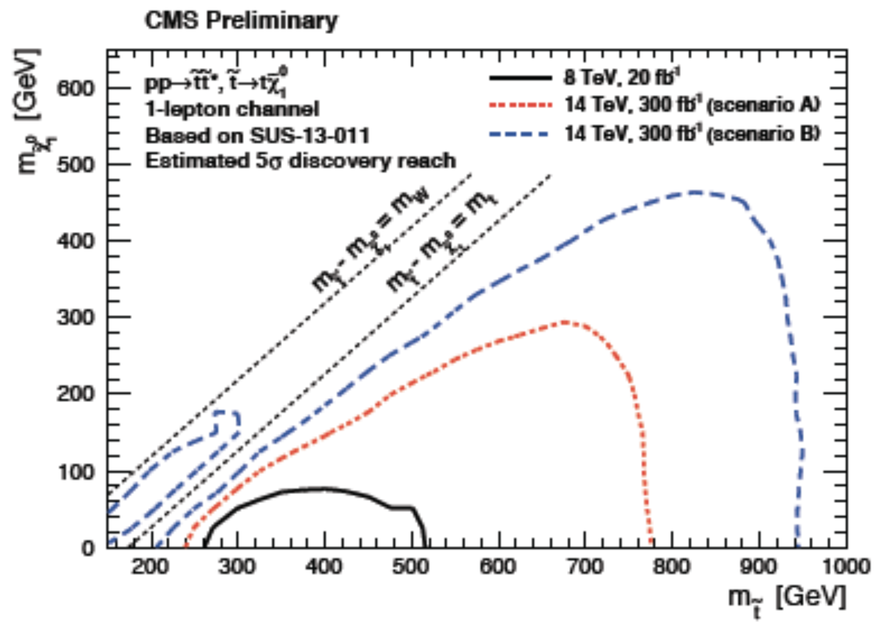


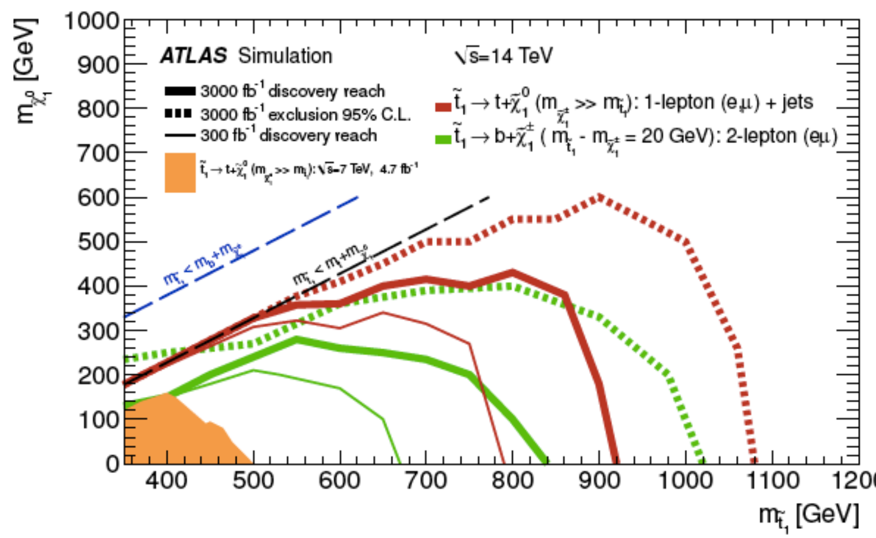


- With 300/fb reach about 2 TeV in gluino mass

Top squark discovery potential

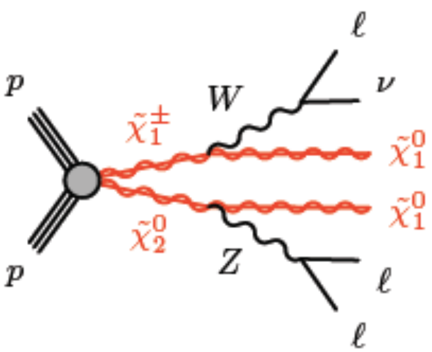
- 300 fb^{-1}:
  - Discovery up to ~800 GeV in direct production
- Using same analysis cuts for 3000 fb^{-1}:
  - Discovery up to ~900 GeV
  - Expect to improve when analysis cuts retuned for higher luminosity
    - Can probably improve further when optimized
  - Exclusion covers 1 TeV

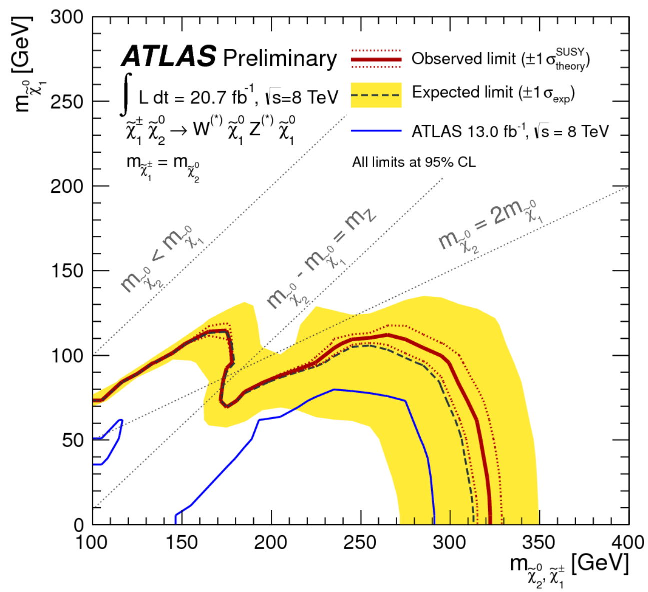


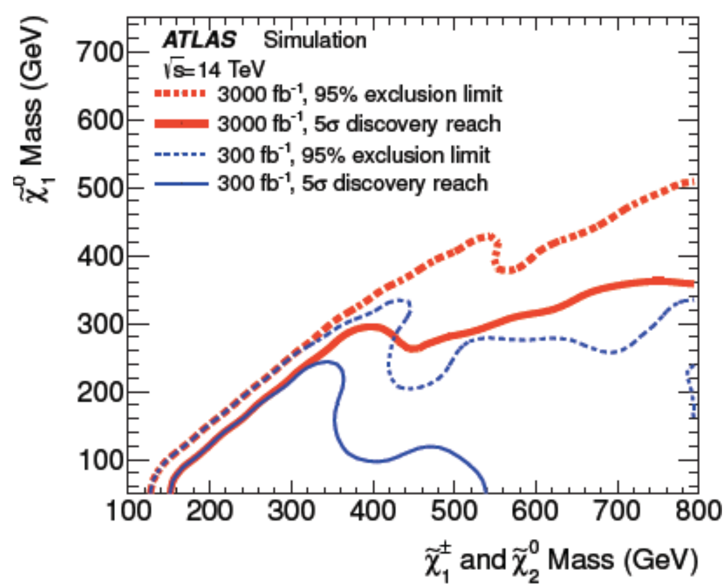


New physics at the weak scale

- Even if Nature is finetuned and stop is heavy we have other reasons for new physics at weak scale
  - Unification of couplings, Dark Matter, …
- E.g. in "split-SUSY" other scalars are all heavy but gauginos are at ~low mass

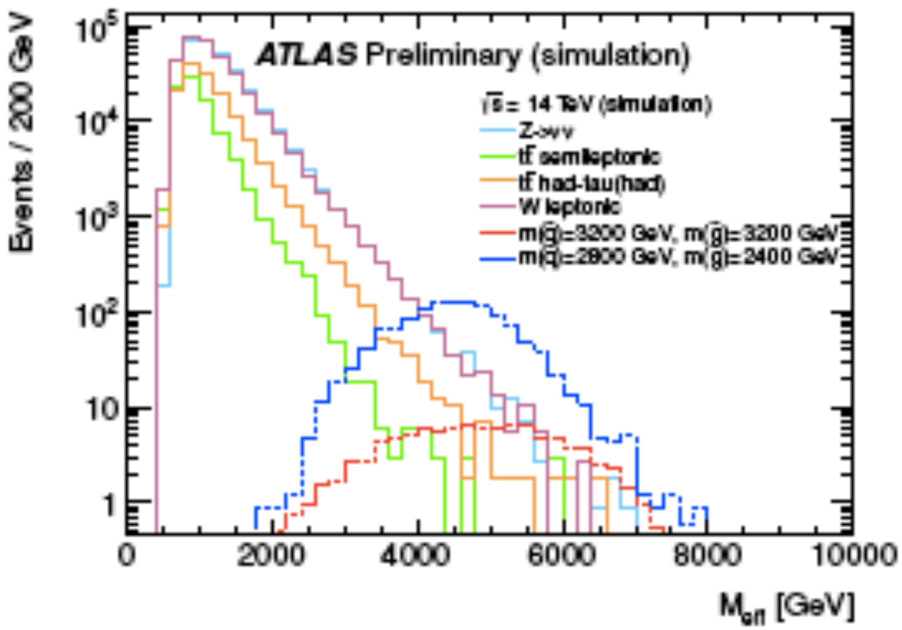


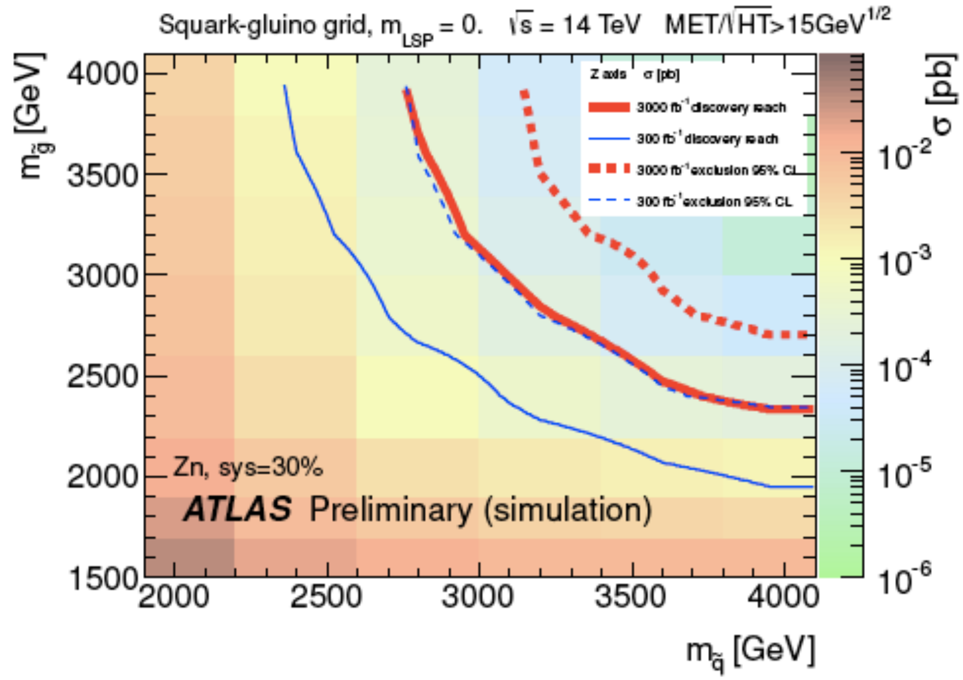




Dramatic improvement in reach by HL-LHC: probing ~1 TeV charginos!

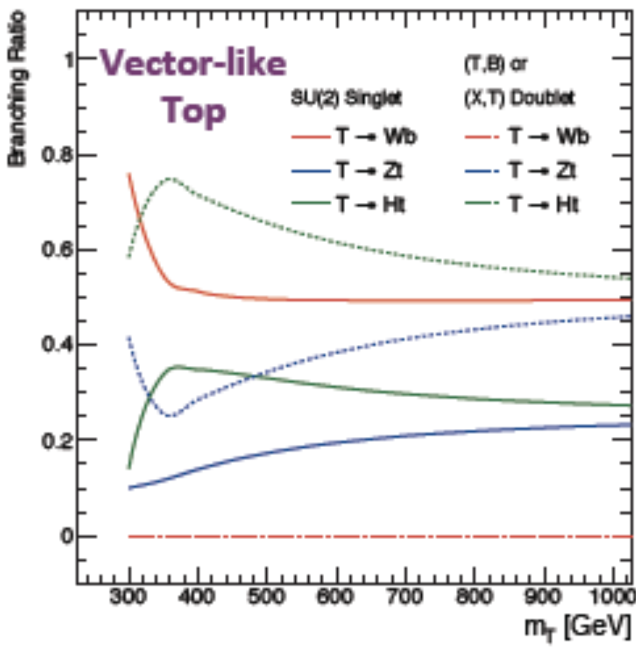
Generic Squarks and Gluinos

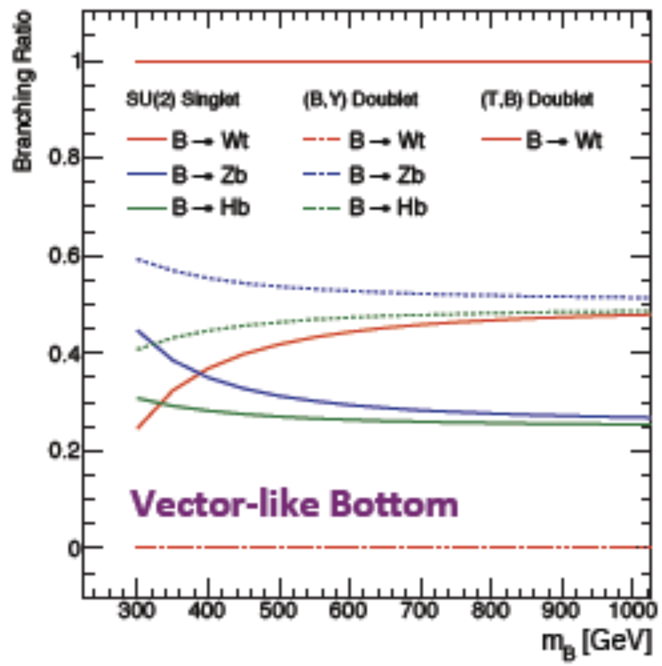


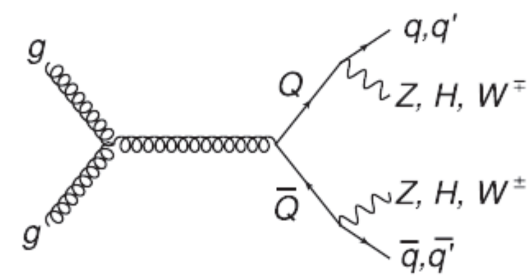


- Search for large E_T^{miss} and large M_{eff}
- Current limit ~1 TeV at 95% CL:
  - Will be extended to 2.3 (2.7) TeV with LHC (HL-LHC) if we don't discover it
- Discovery potential ~2.3 TeV with HL-LHC

Vector-like Quarks

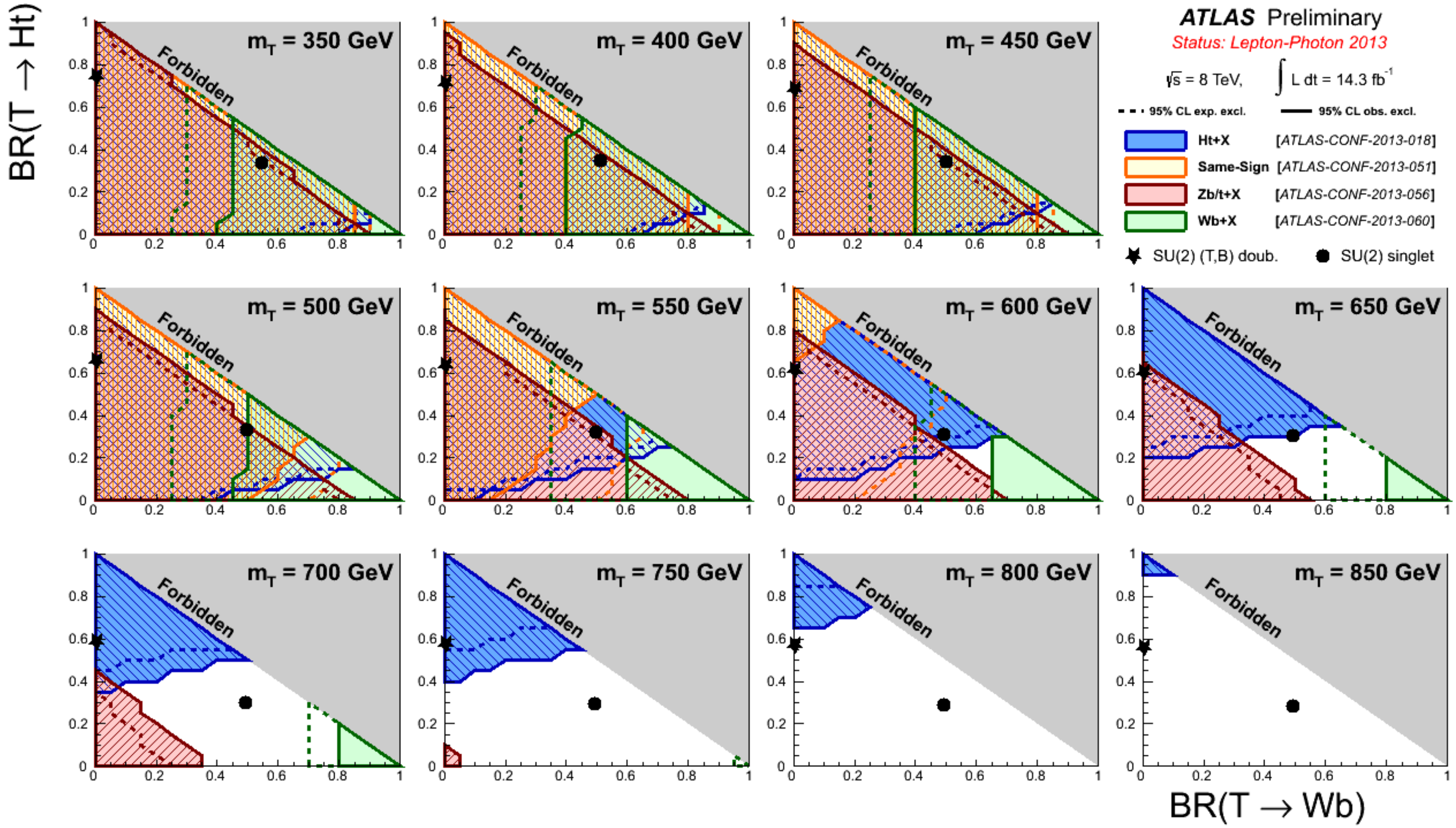






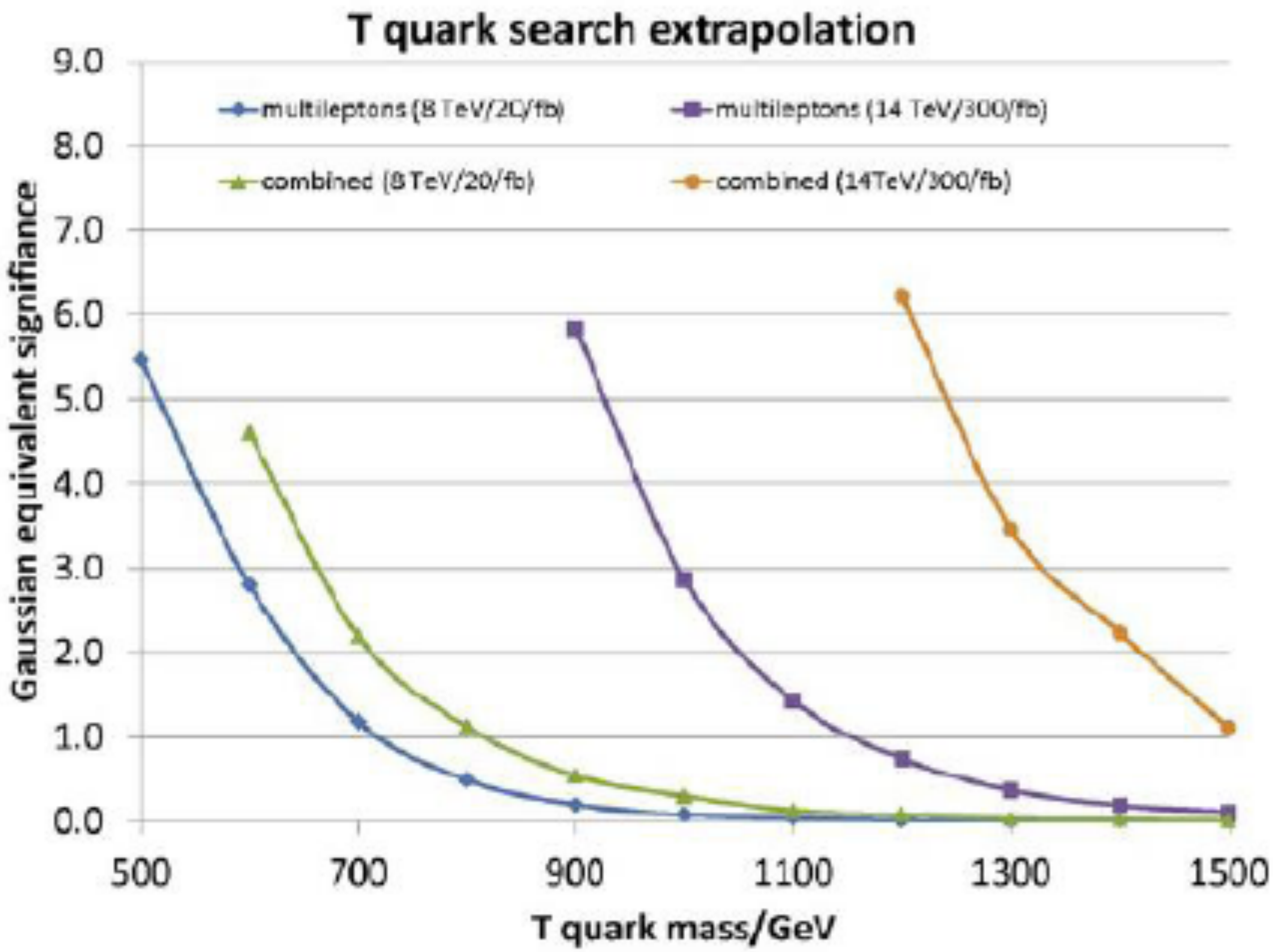
- Vector-like quarks are colored spin-1/2 fermions which transform the same for left- and right-handed under EW gauge group
- Alternative solution to little hierarchy problem
- Appear in many BSM models, e.g.
  - Little Higgs, Extra Dim., …

Vector-like Top: Present



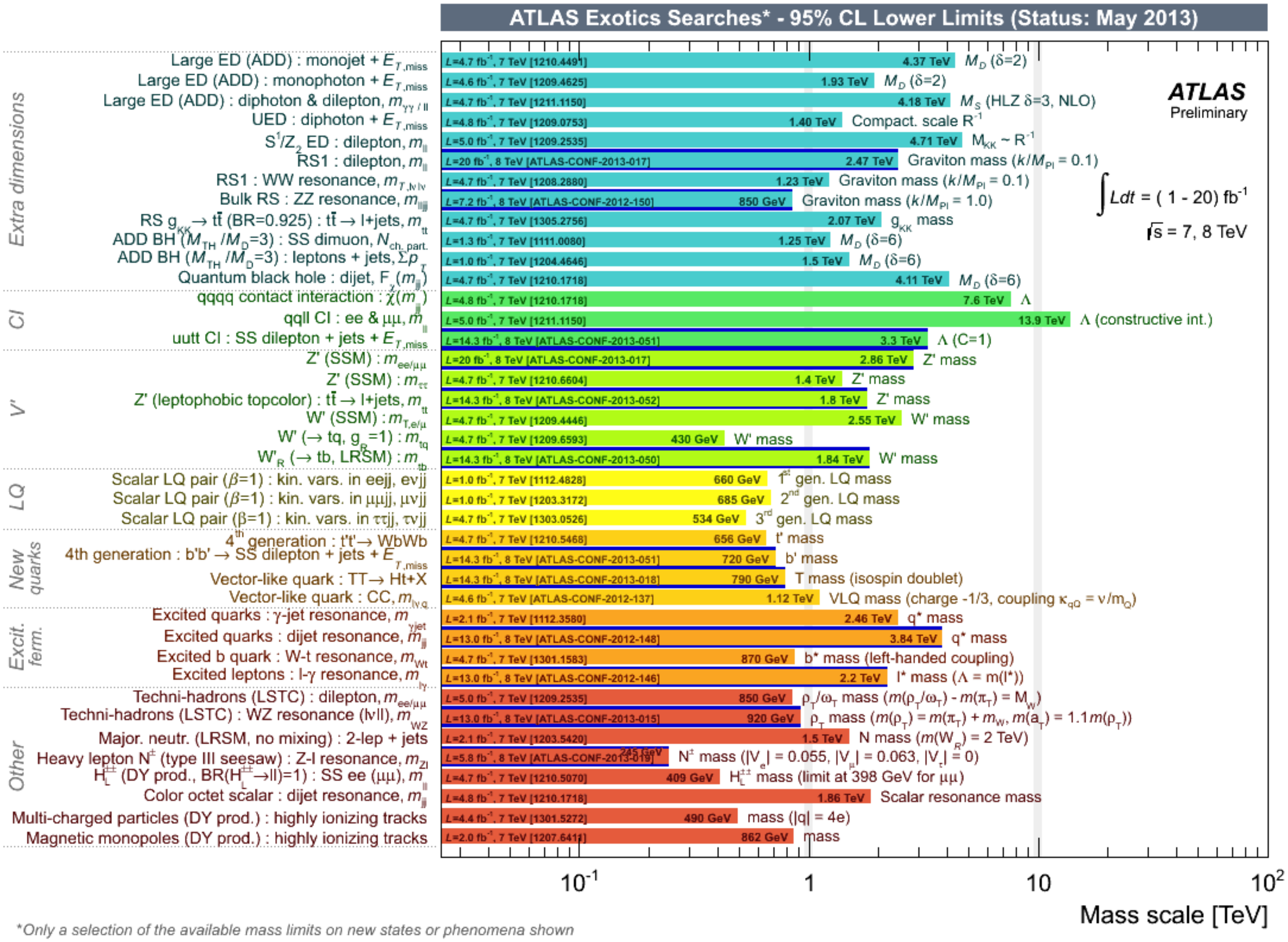
Currently probing up to about 600-800 GeV

Vector-like Quarks: future



- Probe up to 1.5 TeV with 300 fb^{-1}

Other New Particles: Present

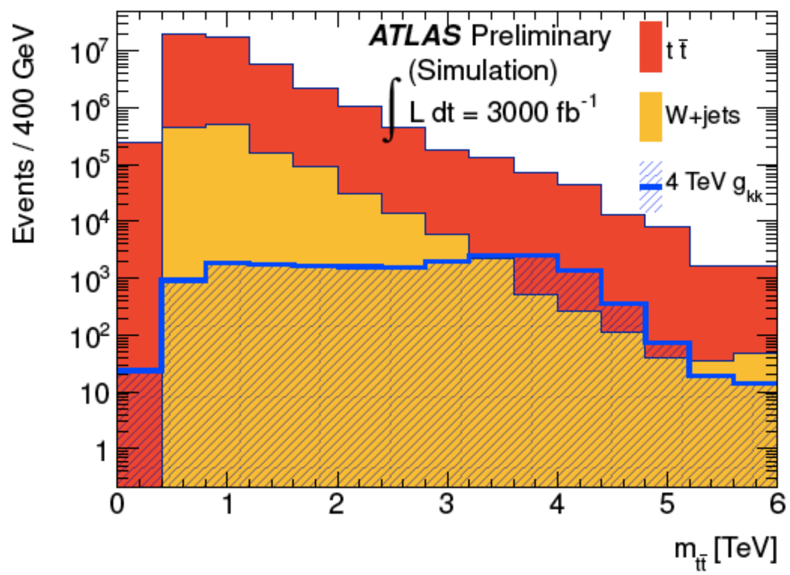


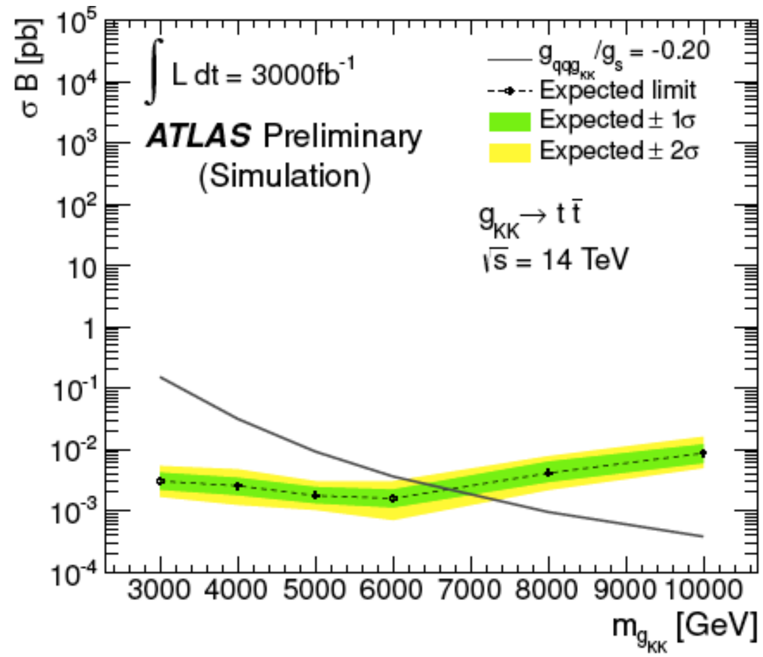
- Reach ranges from a few 100 GeV to a few TeV

ttbar resonances

- Current limits are on σxBR are ~0.1 pb
  - Expect to improve by a factor of ~100 with HL-LHC
  - Probe KK gluons up to masses of ~6.7 TeV

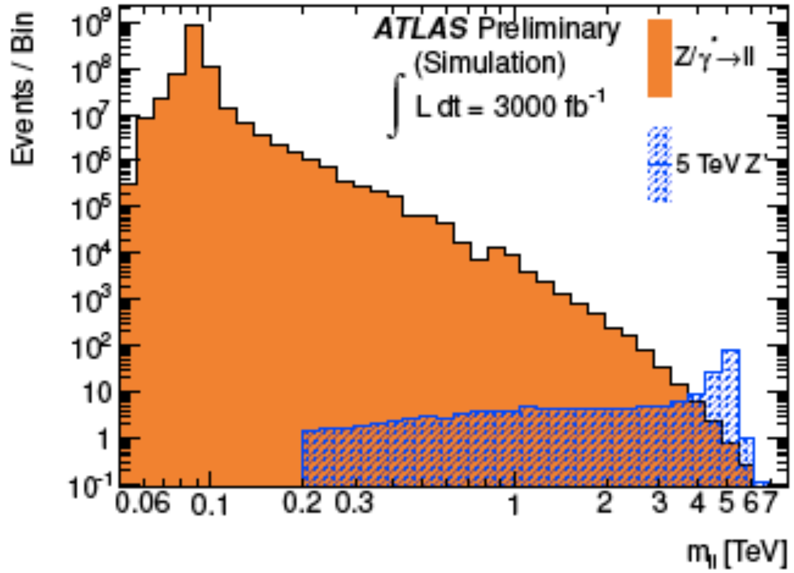
95% CL limits on:		
	Z' (TeV)	g_{KK} (TeV)
Run-1	1.8	2.0
300 fb^{-1}	3.3	4.3
3000 fb^{-1}	5.5	6.7



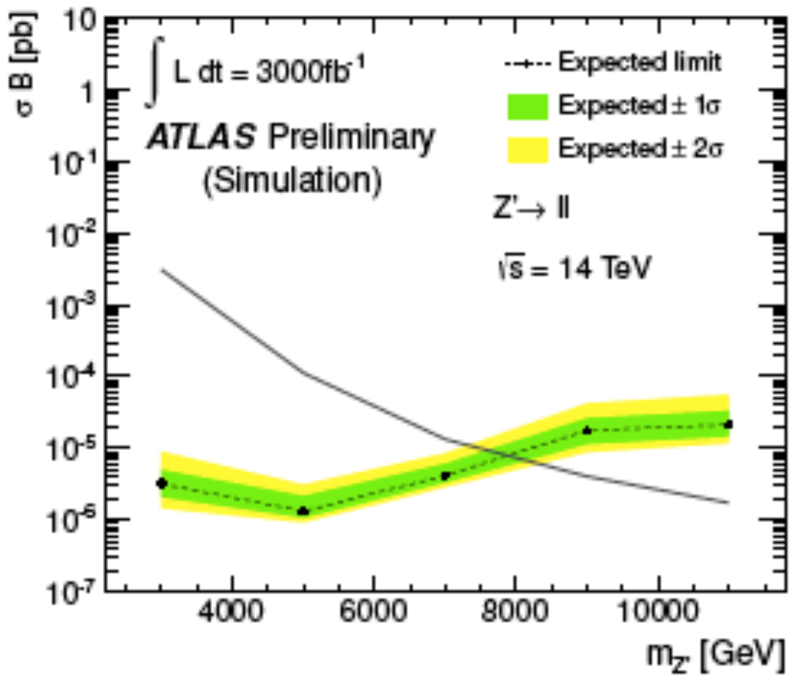


Dilepton resonances

- Current limits are on σxBR are ~0.3 fb
  - Expect to improve by a factor of ~100 with HL-LHC
  - Probe Z'SSM up to masses of 7.8 TeV



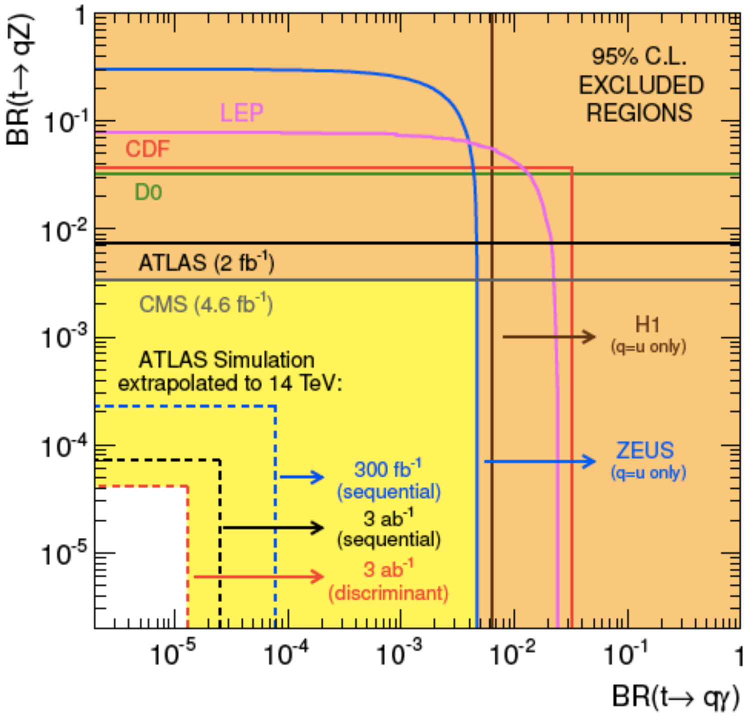
95% CL limits on:		
	Z'-> ee (TeV)	**Z'->μμ (TeV)**
Run-1	2.79	2.48
300 fb^{-1}	6.5	6.4
3000 fb^{-1}	7.8	7.6



Rare Decays of Top quark

Process	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$	TC2	RS
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	—	—	2×10^{-6}	1×10^{-6}	—	$\sim 10^{-11}$
$t \to uZ$	8.0×10^{-17}	1.1×10^{-4}	—	—	2×10^{-6}	3×10^{-5}	—	$\sim 10^{-9}$
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	—	—	8×10^{-5}	2×10^{-4}	—	$\sim 10^{-11}$
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}	$\sim 10^{-6}$	$\sim 10^{-9}$
$t \to cZ$	1.0×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}	$\sim 10^{-4}$	$\sim 10^{-5}$
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8.5×10^{-5}	2×10^{-4}	$\sim 10^{-4}$	$\sim 10^{-9}$

- In SM top quark decays to Wb nearly 100%
  - Observing decays to other modes clear sign of new physics
  - Many models predict enhancements
    - Interesting range starts at ~10^{-4}
- HL-LHC will probe ~3×10^{-5} at least



European Strategy

- In 2012 European Strategy convened to plan the future of particle physics in Europe

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.

European Strategy Update

European Strategy

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European Strategy Update

Snowmass process in US ongoing, followed by P5 panel which will suggest funding priorities

Do we have to know results from 13 TeV run to decide on HL-LHC?

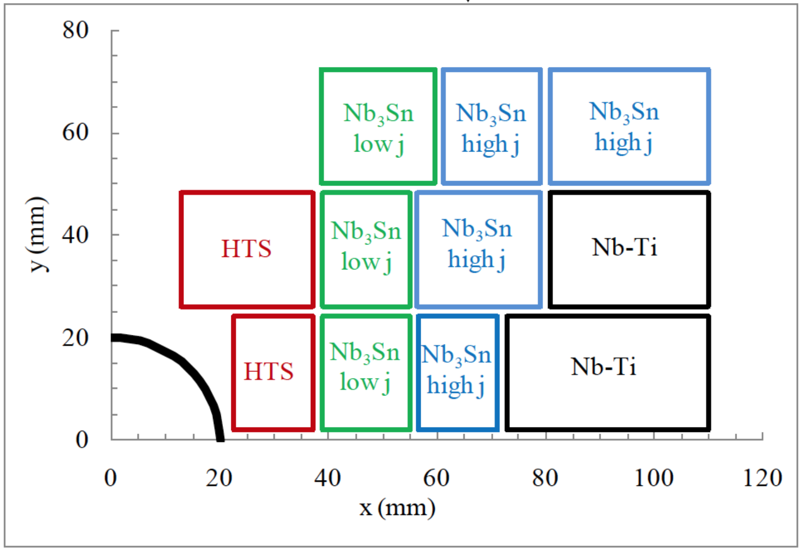
- Compare scenarios depending on what we know by 2017
  - Assume about 50 fb^{-1} by 2017 analyzed

	Observation in 2017	Conclusion
A	Found 5σ excess in data in at least one BSM signature	
B	Found 3σ excess in data in at least one BSM signature	
C	Found no excess in data >2σ but deviation in Higgs by 3σ	
D	Found no excess in data and no deviation in Higgs either	

Far(ish) Future

High Energy LHC: HE-LHC

Re-equip existing LHC tunnel with high field magnets



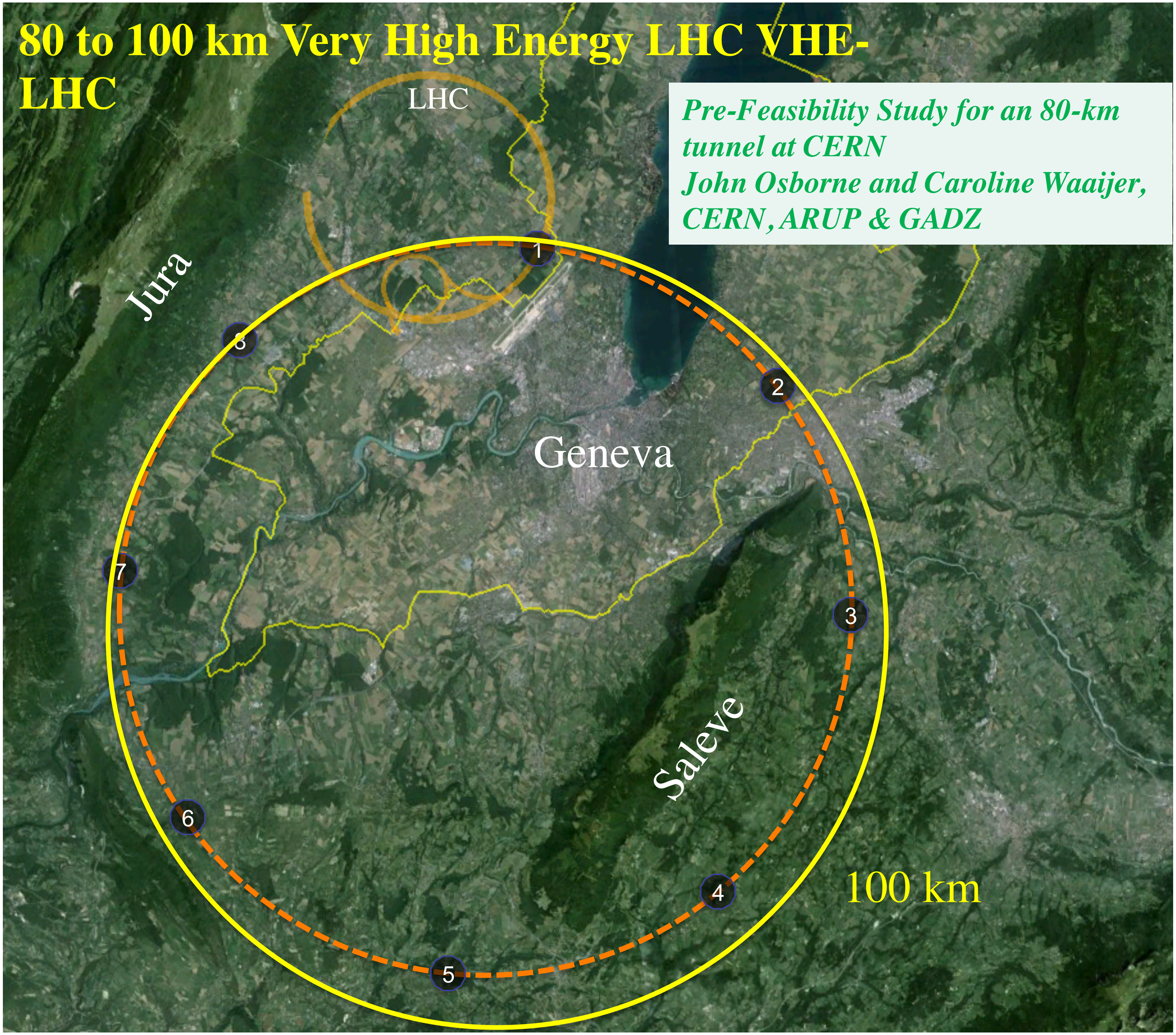
Conceptual layout of 20 T dipole magnet (Nb_3Sn and HTS)

Intense R&D required

L. Rossi and E. Todesco

Circumference	26.7 km
Maximum dipole field	20 T
Injection energy from SC-SPS	1.3 TeV
Maximum c.o.m. energy	33 TeV
Peak luminosity	5 x 10^{34} $cm^{-2}s^{-1}$

80 to 100 km Very High Energy LHC VHE-LHC



Pre-Feasibility Study for an 80-km tunnel at CERN
John Osborne and Caroline Waaijer, CERN, ARUP & GADZ

VHE-LHC

Circumference	80 or 100 km
Maximum dipole field	20 or 16 T
Injection energy	> 3.0 TeV
Maximum c.o.m. energy	100 TeV
Peak luminosity	5×10^{34} $cm^{-2}s^{-1}$
Stored beam energy	~5500 MJ

Among the many challenges:

- Synchrotron radiation heat load 33 W/m
- Collimation!
- IR quadrupoles
- Arc quadrupoles (naïve scaling gives 1593 T/m at 50 TeV beam energy)

Conclusions

- **Run-1 has been a fantastic success**
  - Found a Higgs boson
  - Severe constraints on physics BSM
  - >500 papers published on vast variety of topics
- **Knowledge of TeV scale physics will be improved dramatically by future LHC running**
  - Going to full energy and increase L by factor 100
  - Higgs couplings will be measured with precision of 2-10%
  - Searches for new particles will extend mass reach by ~2-3
- **Theorists play critical role in fully exploiting LHC**
- **HL-LHC significantly improves upon LHC and considered top priority in Europe**
- **Higher energy options being studied (R&D)**