LHC: Upgrades and Future Perspectives

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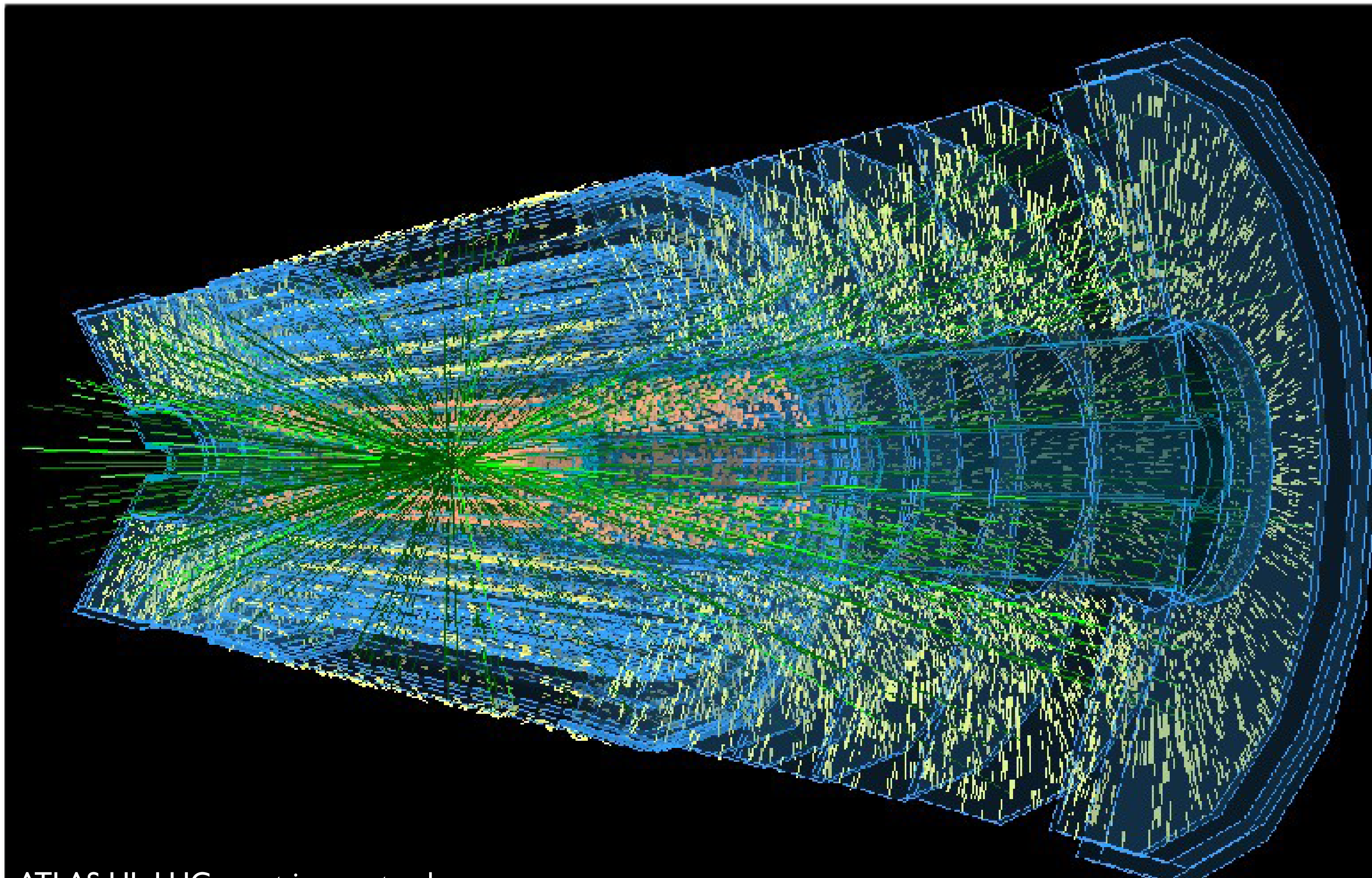
ECFA Linear Collider Workshop, DESY, 27-31.5.2013



ATLAS HL-LHC event in new tracker

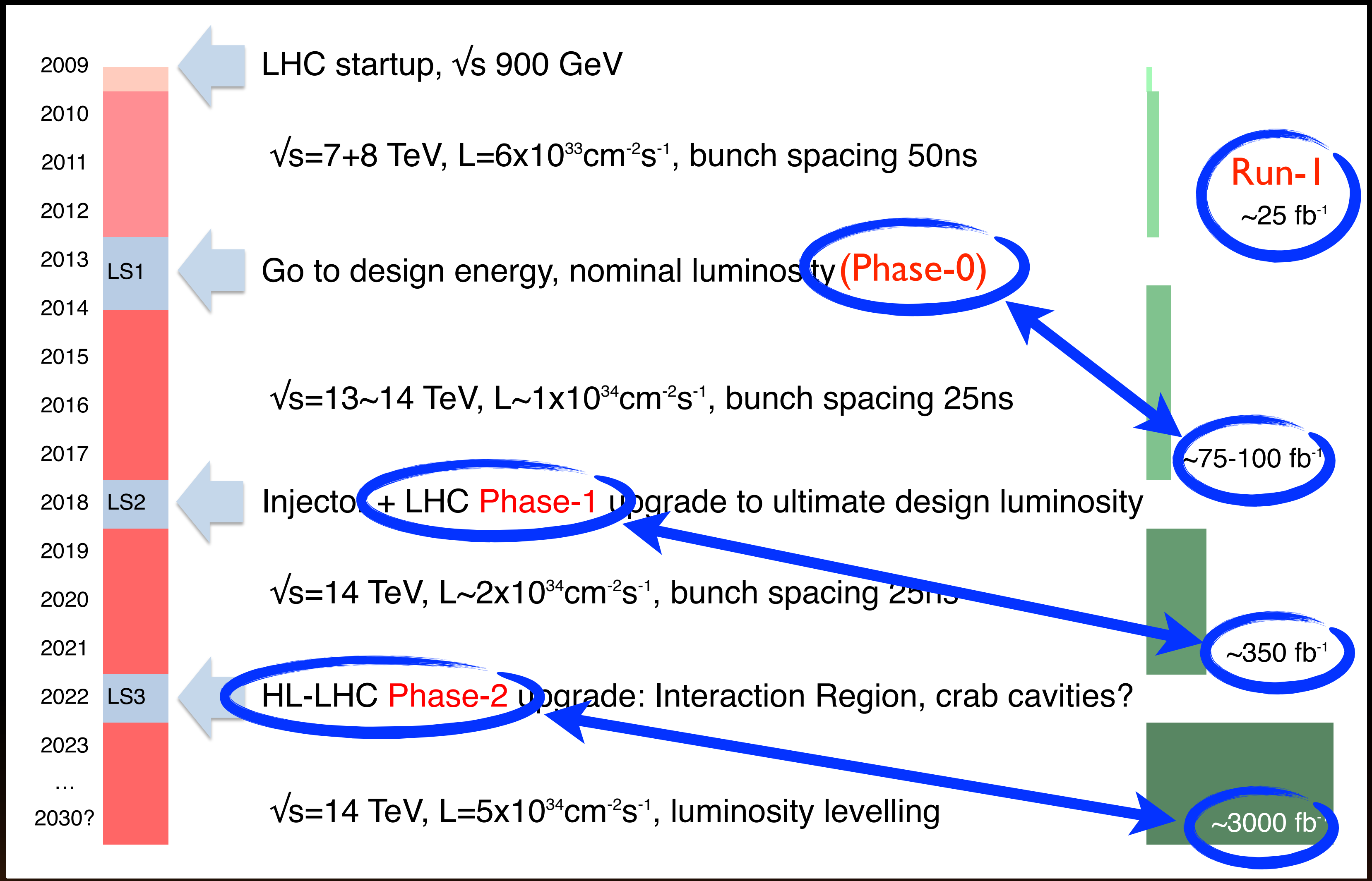
LHC Upgrade Program

- Higgs discovery opens up new era
  - ➡ done at half the nominal energy and 25 fb^{-1} collected so far
    - with pileup at design levels
  - ➡ 2015-2021: running at 13-14 *TeV* for a total of about 350 fb^{-1}
    - double mass reach for BSM searches
  - ➡ recent studies for the future perspectives of the HL-LHC
    - in the context of the European Strategy for Particle Physics
- HL-LHC running in 2023-2030 (not yet approved)
  - ➡ $\mathscr{L} = 5 \cdot 10^{34} cm^{-2} s^{-1}$ with luminosity leveling for a total of 3000 fb^{-1}, expected pileup of ~140
  - ➡ challenge: maintain detector performance in those conditions (for taus, photons, jets, b-tagging, missing $E_{T, \ldots}$)
  - ➡ need to keep sensitivity for moderate p_T objects even at large η (e.g. to study vector boson fusion)
- LHC experiments run a significant upgrade program
  - ➡ upgrade detector components, readout, trigger, DAQ, computing

Physics Prospects of the LHC Upgrade

- main results of LHC Run-1: *(see Günther's talk)*
  - ➡ discovery of a Higgs Boson and first measurement of properties
  - ➡ no signs for *TeV* scale physics beyond the Standard Model yet
- physics goals of the LHC upgrade program:
  - ➡ electroweak symmetry breaking and the Higgs Boson
    - measure its properties (couplings, ...), try to assess its self-coupling
    - verify vector boson scattering cross section behaves as predicted in SM
  - ➡ hierarchy in the *TeV* domain
    - search for new phenomena moderating the hierarchy problem
    - search for dark matter candidates in the (sub-)TeV regime
    - search for the unexpected at the high-energy frontier
    - and eventually study in detail any new physics discovered
  - ➡ flavor and precision tests of the Standard Model
  - ➡ as well: heavy ion program with increased luminosity *(ALICE, not covered here)*

LHC Program and Upgrades

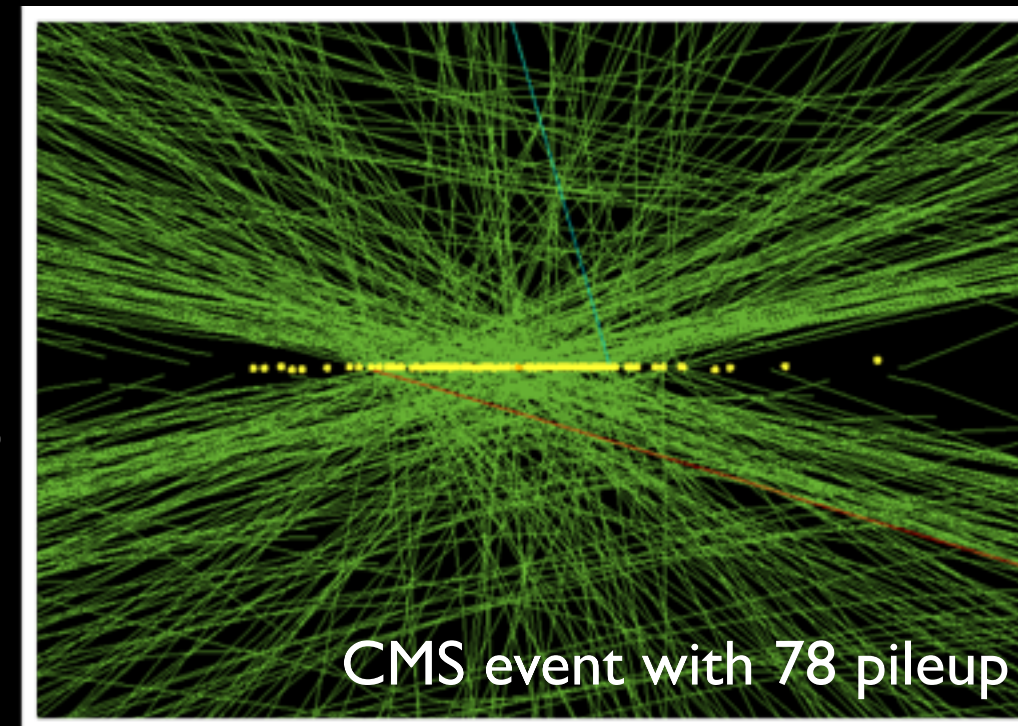


- foreseen schedule
  - ➡ as shown by R.Heuer ('13)

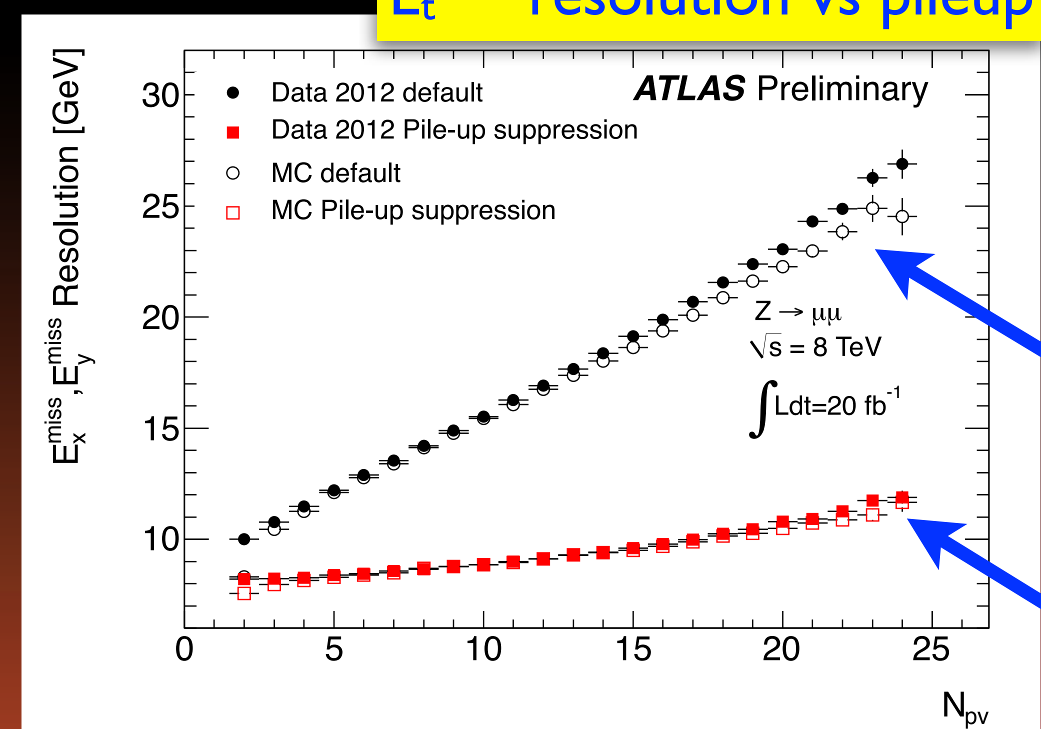
- update of the European Strategy for Particle Physics (adopted)
  - ➡ "Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030"
- ECFA HL-LHC Upgrade workshop planned (1-3 October)
  - ➡ this event should be start of a series of regular workshops

Experience with Pileup during Run-1

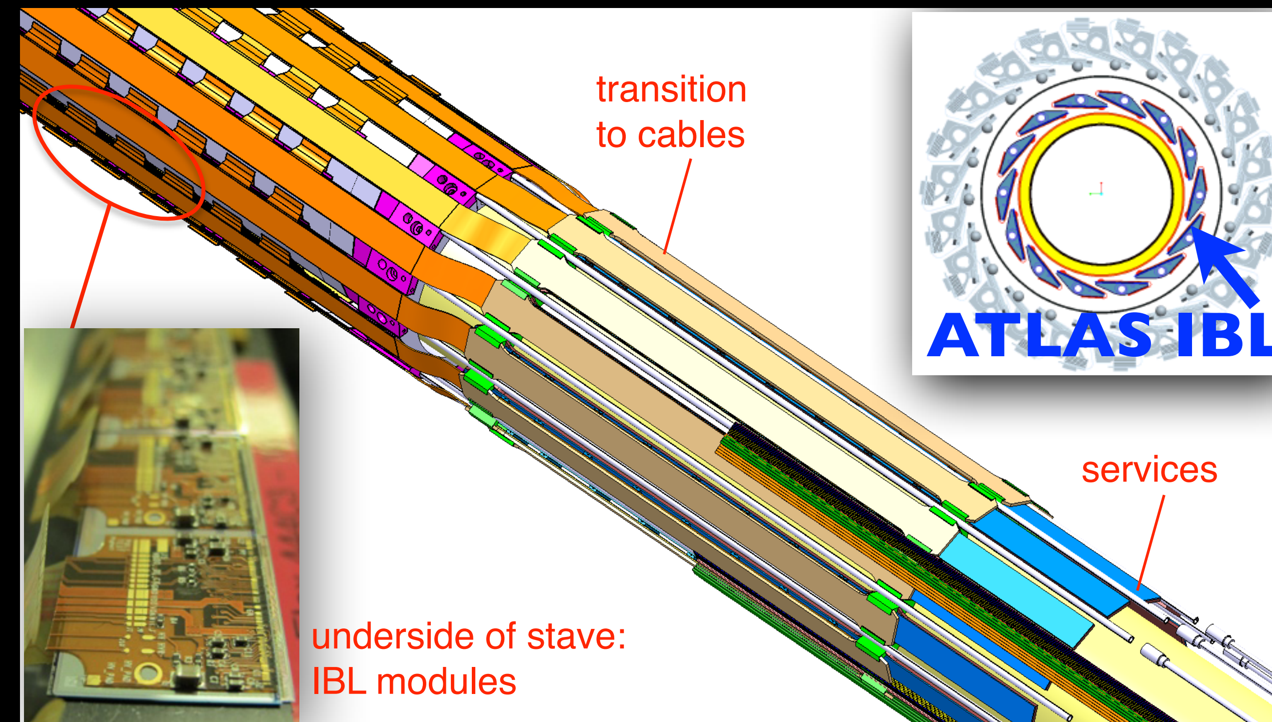
- pileup in 2012 exceeded design
  - ➡ average pileup up to 35 (1.5 × design)
  - ➡ due 50 *nsec* operation
- good stability of detector performance
  - ➡ thanks to several algorithmic improvements
    - for pileup levels seen so far
  - ➡ test with high pileup runs look promising
    - known limitations when going much further
- ATLAS / CMS upgrade goals
  - ➡ restore (and if possible, improve on) performance at increasing levels of pileup
  - ➡ includes major upgrades in view of HL-LHC, especially the need for new tracking detectors



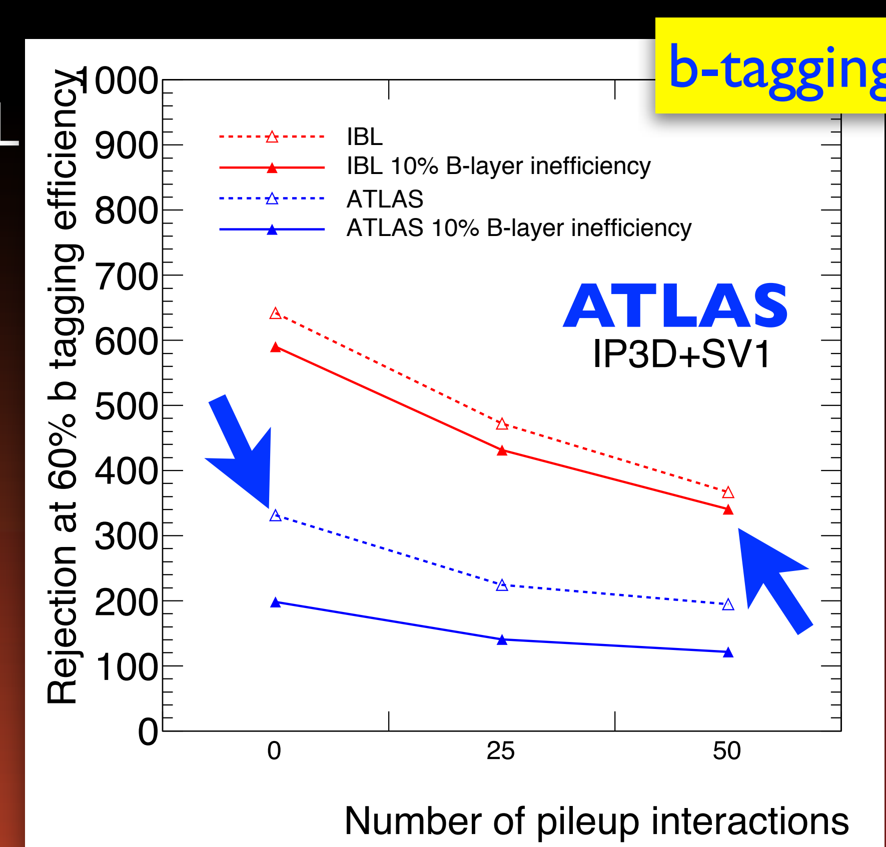
E_t^{miss} resolution vs pileup



Phase-0 Upgrade in current Shutdown (LS1)

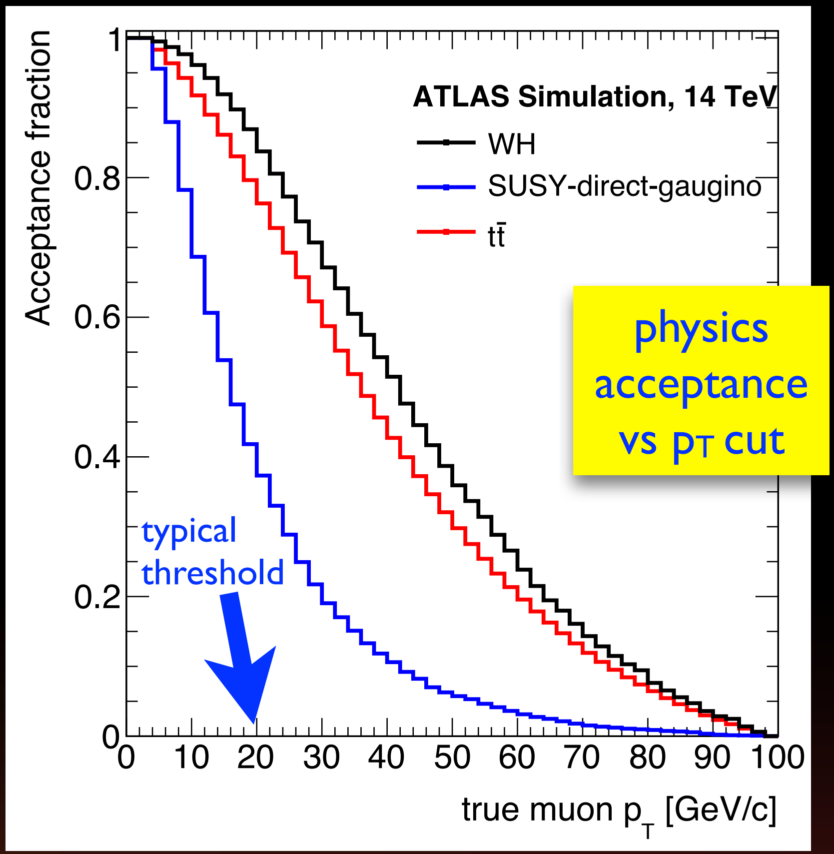


- detector **consolidation**
  - ➡ all across ATLAS and CMS, e.g.
    - new cooling plant for ATLAS Si trackers
    - CMS replaces photo-detectors in HCAL
- detector **upgrade**
  - ➡ completion of muon spectrometers
    - CMS endcap coverage and
    - ATLAS chambers in barrel/endcap transition
  - ➡ CMS replaces photodetectors in Forward and outer HCAL
  - ➡ ATLAS and CMS install smaller beam pipes
    - anticipating Pixel detector upgrades
- ATLAS installs 4th Pixel layer (IBL) in LS1
  - ➡ low mass layer, closer to beam, with smaller pixel size
    - will as well recover from present b-layer defects
    - replace services of current Pixel (increased bandwidth)
  - ➡ improves tracking, vertexing, b-tagging and τ-reconstruction at high pileup



Phase-1 (2018) Upgrades - The Challenge

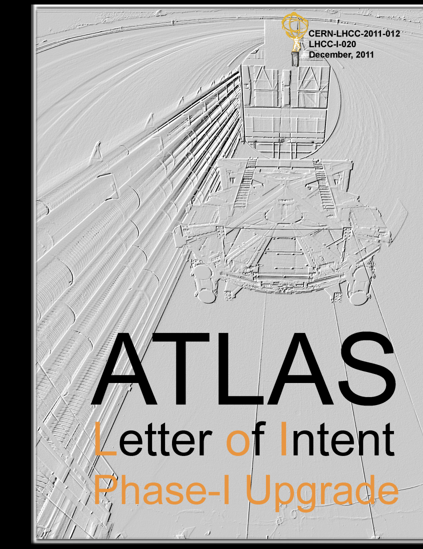
- pileup as high as 55-80 for $\mathscr{L} = 2\text{-}3 \times 10^{34} cm^{-2} s^{-1}$ (@ 25 *nsec*)
  - ➡ need to control pileup effects e.g. on jets and missing E_T
  - ➡ Level-1 trigger rate limits, difficult to:
    - preserve single lepton thresholds around 20-25 *GeV*
    - control forward muon trigger rates and efficiency



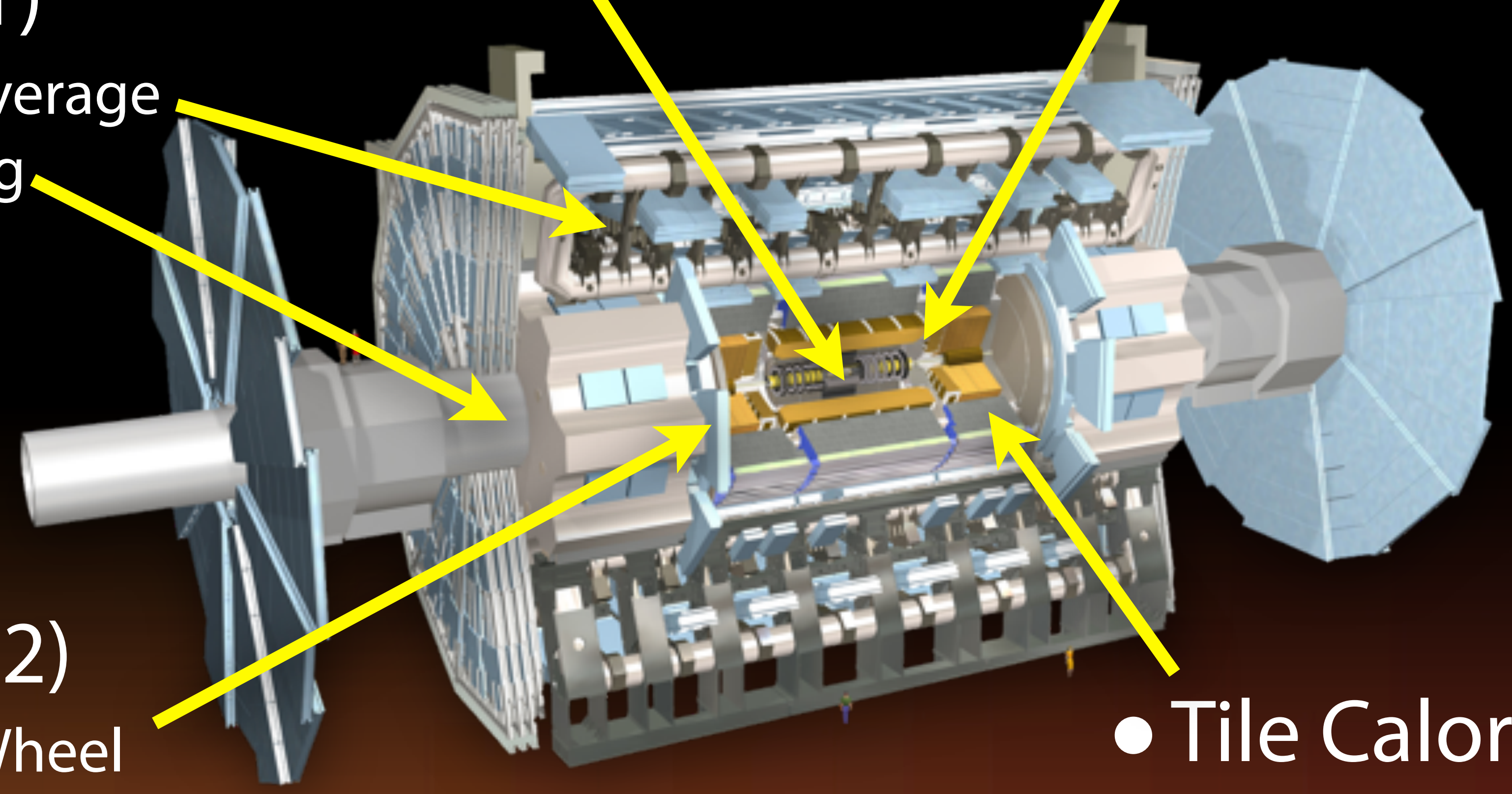
- Phase-1 trigger strategy of CMS and ATLAS
  - ➡ replace readout electronics to increase granularity for Level-1
  - ➡ topological (multi-object) trigger processors for Level-1
    - upgrade high level trigger farms and networks
  - ➡ ATLAS introduces Fast Track Trigger (FTK) at input to Level-2
  - ➡ both experiments upgrade forward muon detectors
  - ➡ CMS adds longitudinal HCAL segmentation (particle flow)

- other upgrades:
  - ➡ CMS replaces its Pixel detector in year-end shutdown 2016
  - ➡ ATLAS introduces forward physics detector AFP

ATLAS Upgrades up to Phase-1



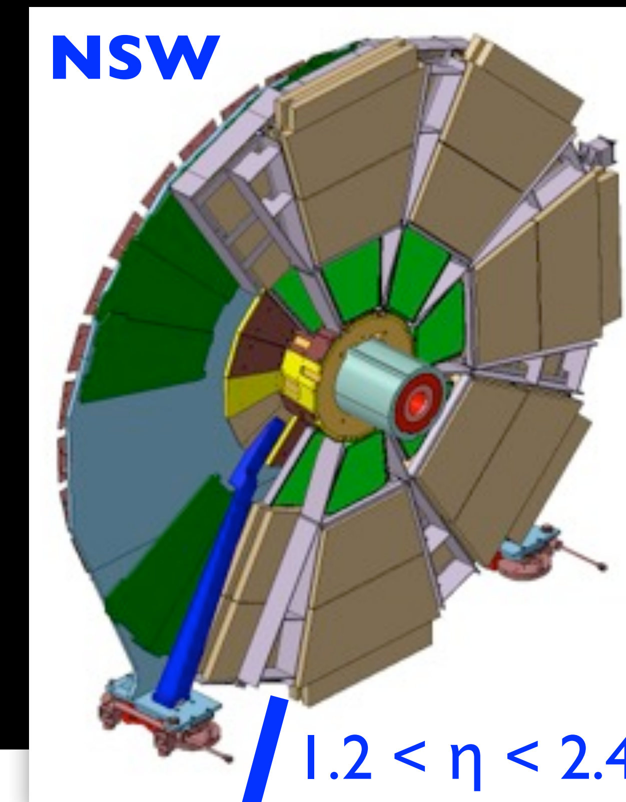
- Insertable B-Layer (LS1)
  - ➡ and new services for Pixels
- LAr Calorimeter (LS2)
  - ➡ fine granularity readout for Level-1
- Muons (LS1)
  - ➡ complete coverage
  - ➡ new shielding
- Level-1 Trigger
  - ➡ new electronics
  - ➡ topological trigger (phased in before LS2)

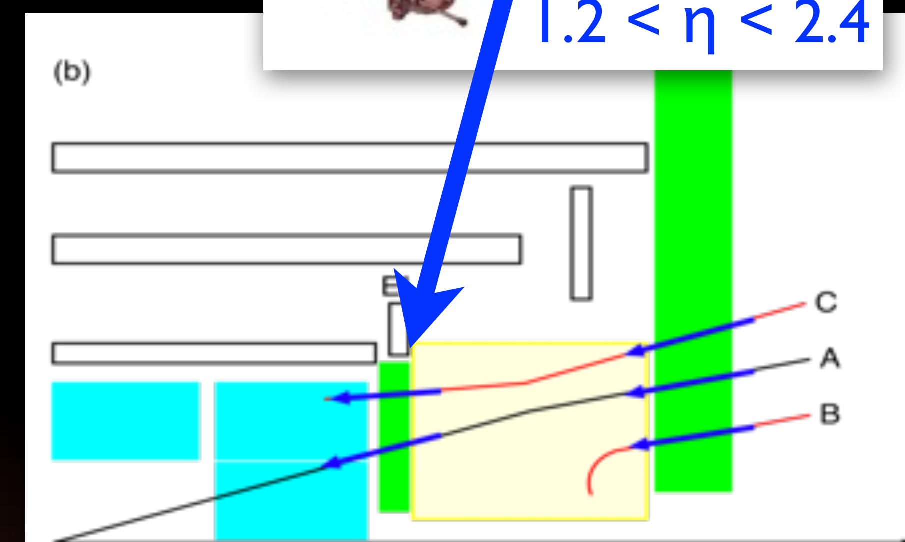


- High Level Trigger farm (phased in before LS2)
- Muons (LS2)
  - ➡ New Small Wheel
- Tile Calorimeter (LS2)
  - ➡ new gap scintillators
  - ➡ new trigger electronics
- ATLAS Forward Physics AFP
  - ➡ 210m downstream from P1 (before LS2)
- Fast Track Trigger FTK (LS2)
  - ➡ HW tracking input to Level-2

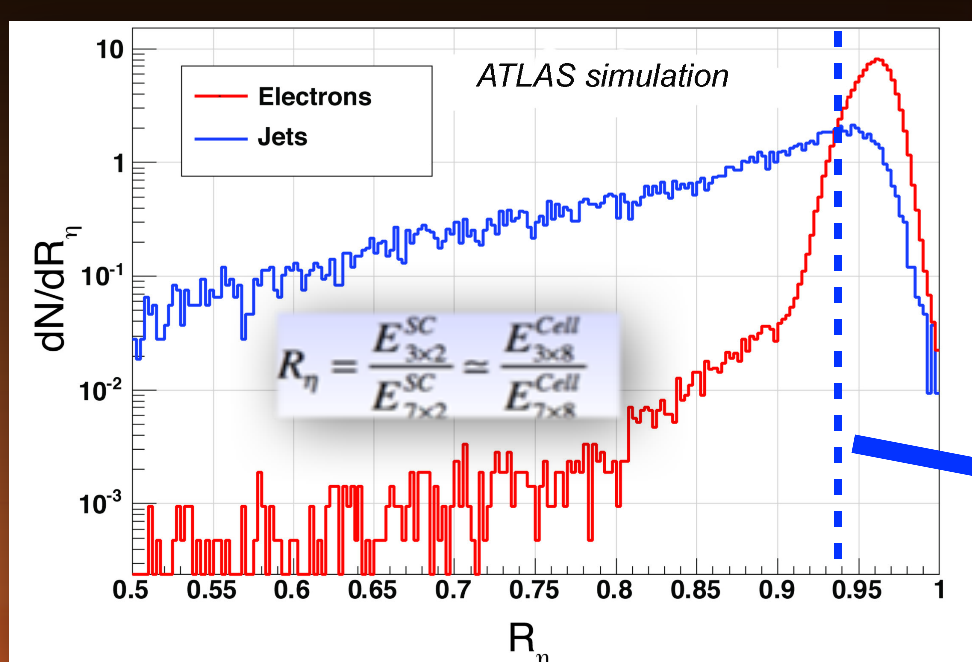
ATLAS - Effects on Lepton Triggers

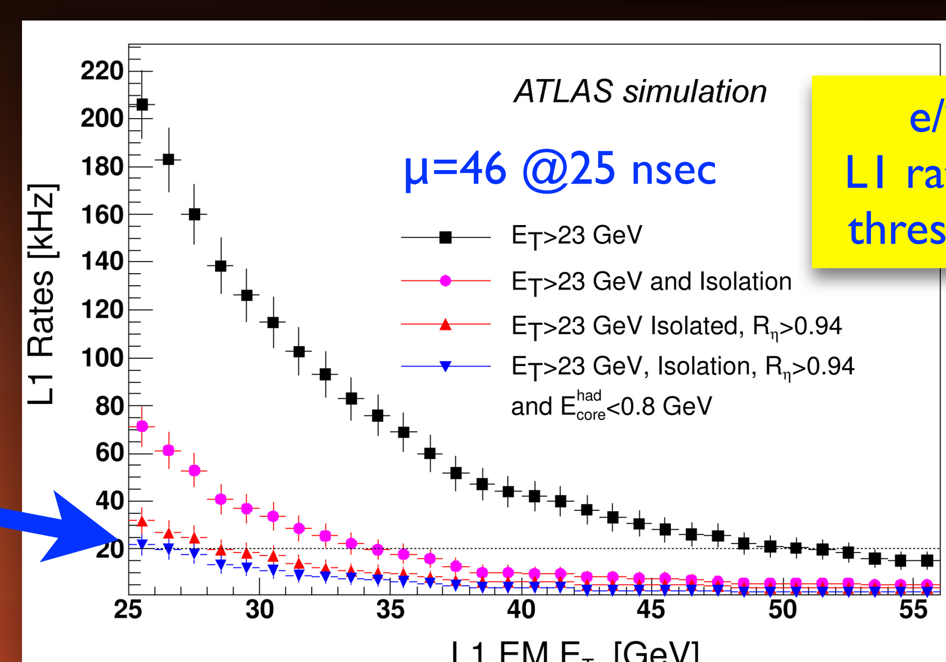
- new Muon Small Wheel (NSW)
  - ➡ 4 layers low resistivity sTGC (Thin Gap Chambers) for trigger, 4 layers of MicroMegas for a total of 2 *M* channels
    - < 1 *mrad* angular resolution on track segments at Level-1
  - ➡ allows for trigger rate reduction by factor 6





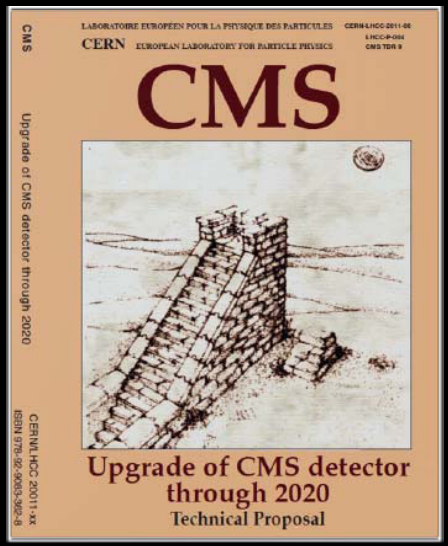
- increased granularity calorimeter trigger
  - ➡ requires new front end digital chain
  - ➡ explore LAr lateral show shapes to improve rejection
    - Level-1 uses ratio of energies of different size clusters
  - ➡ with isolation, un-prescaled threshold at ~25 *GeV*



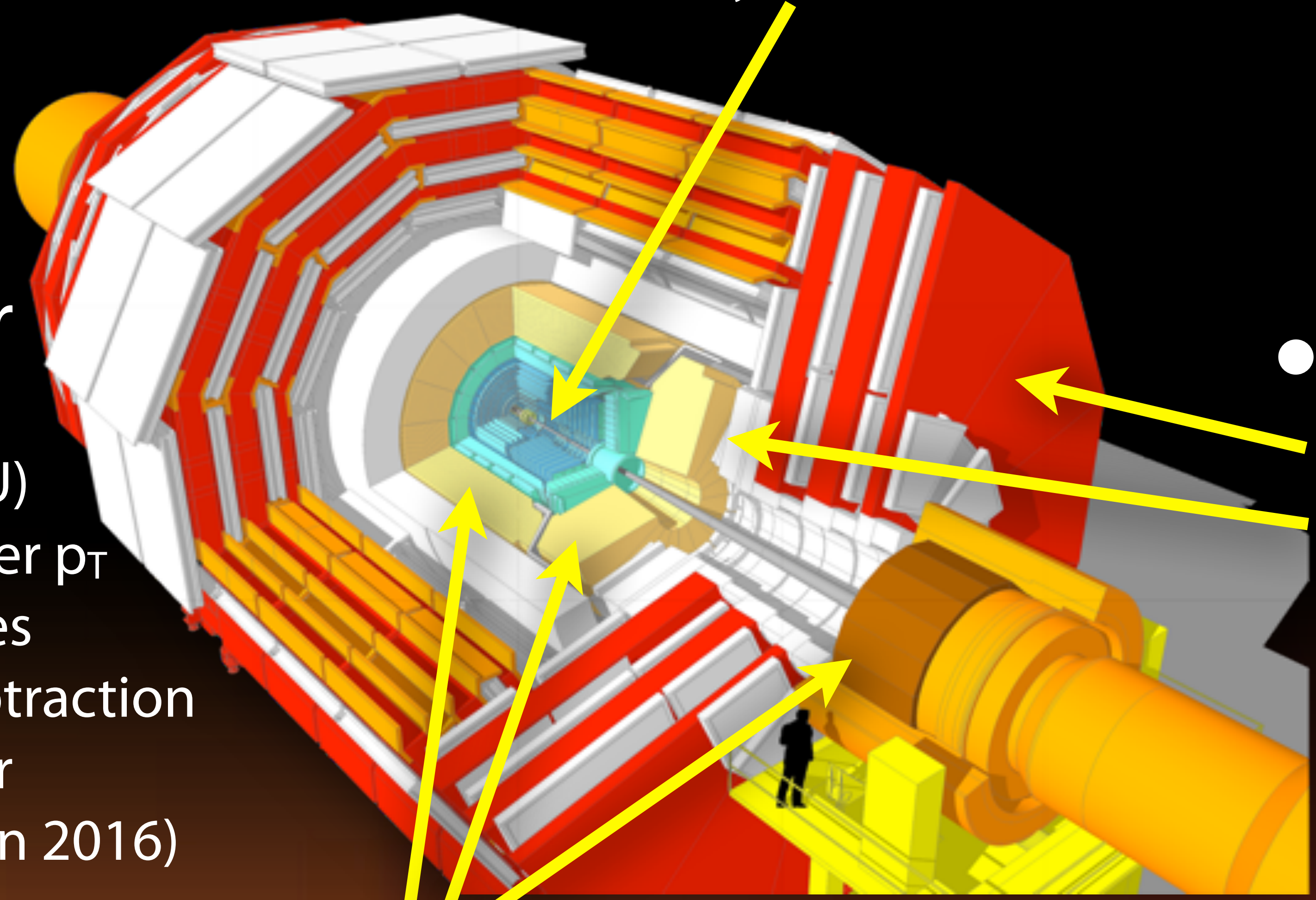


e/γ L1 rate vs threshold

CMS Upgrades up to Phase-1



- new Pixel detector
  - ➡ installation in 2016/17 in end of year shutdown



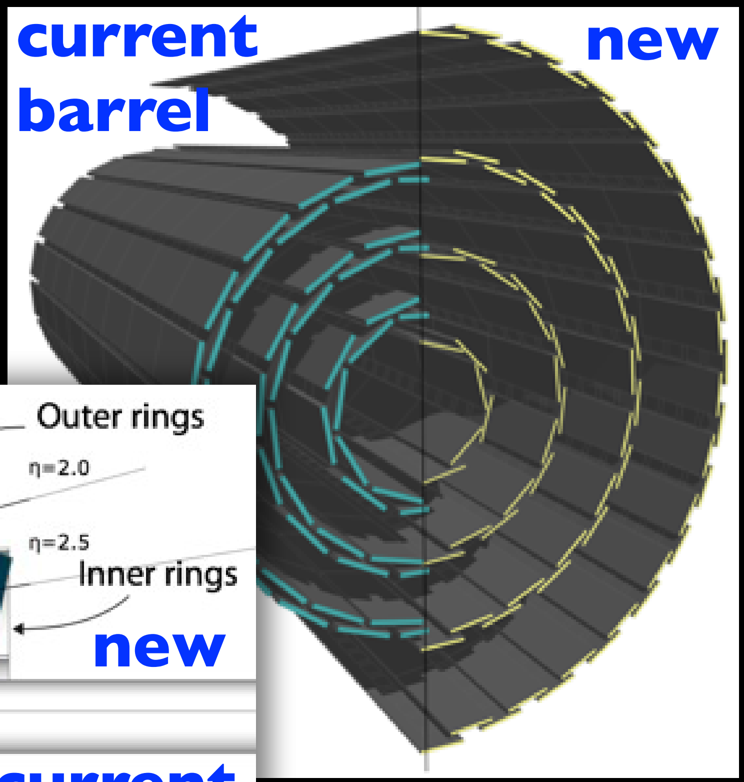
- Level-1 Trigger
  - ➡ new electronics
    - e, γ isolation (PU)
    - μ isolation, better p_T
    - narrower τ-cones
    - jets with PU subtraction
  - ➡ topological trigger

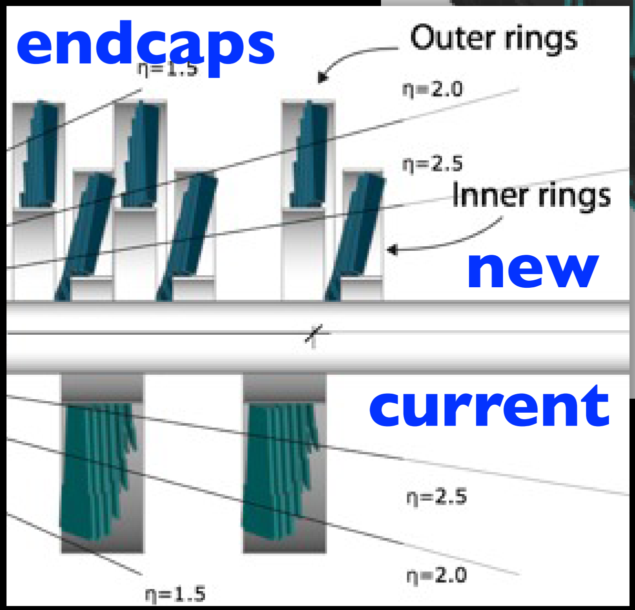
  (ready for operation in 2016)

- Muons (LS1)
  - ➡ complete coverage
  - ➡ increase CSC readout granularity

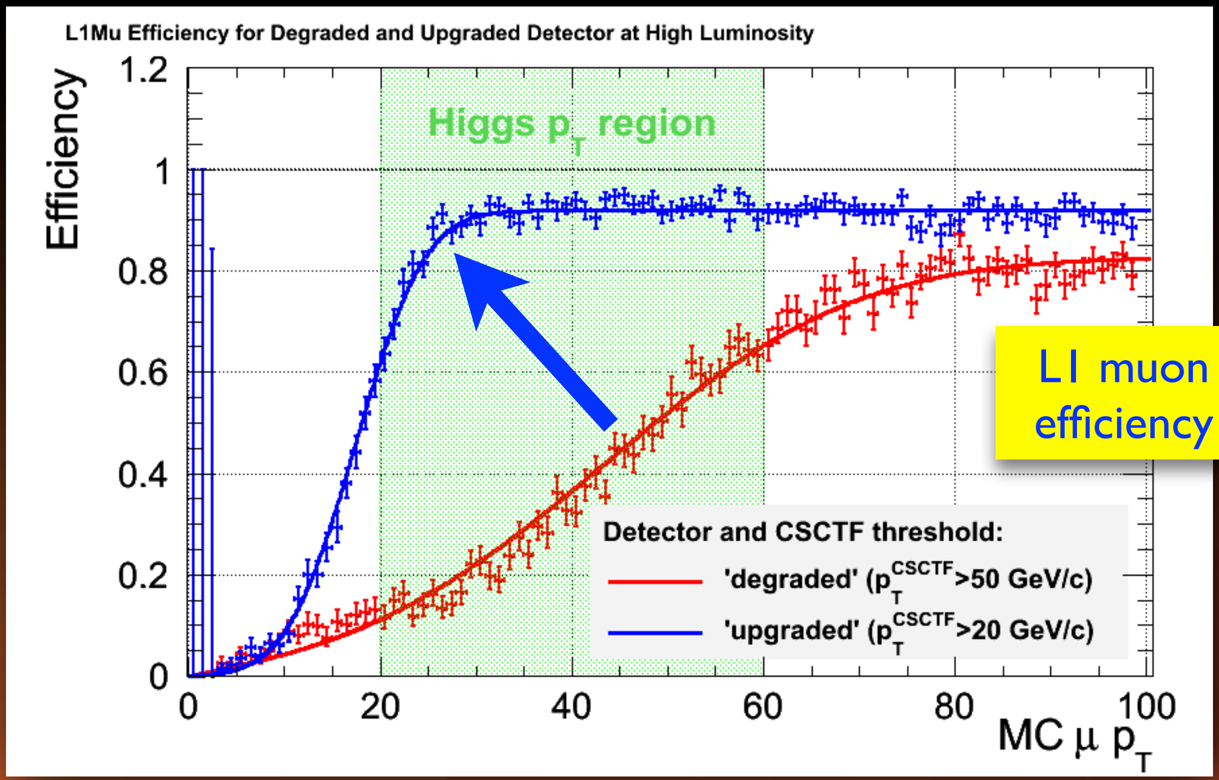
- Hadron Calorimeters (LS2)
  - ➡ new photodetectors, higher Level-1 granularity
    - better background rejection using timing
  - ➡ longitudinal segmentation (5 HB and 3 HE segments)

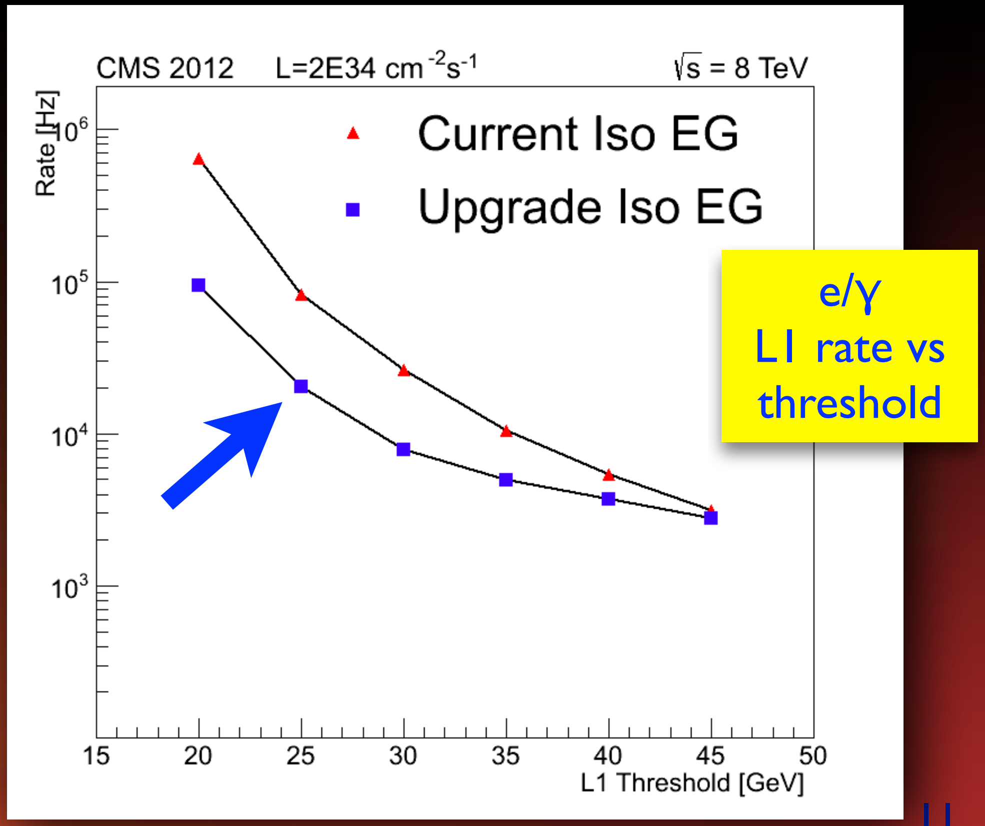
CMS Upgrades up to Phase-1





- new CMS Pixel detector
  - ➡ 4 barrel layers and 3 endcap inner/outer rings
    - smaller radius inner barrel layer, spaced out in *R*
    - same pixel size 100×150 *μm²*
    - less material per layer, new cabling and powering scheme, CO_2 cooling
    - new readout recovers inefficiency at high pileup
  - ➡ installation in long winter shutdown 2016/17
- effect of CMS upgrades on Level-1 trigger performance



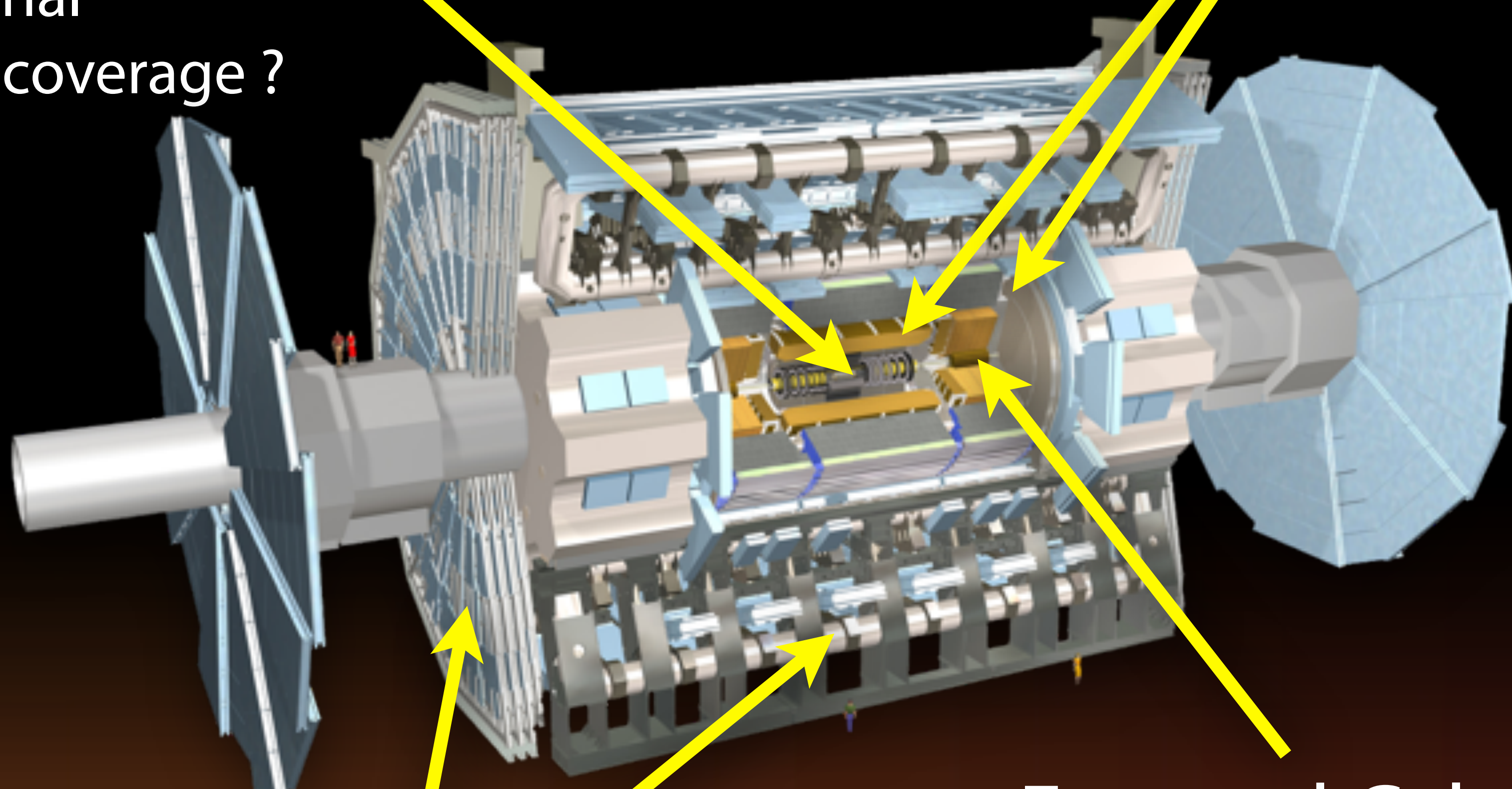


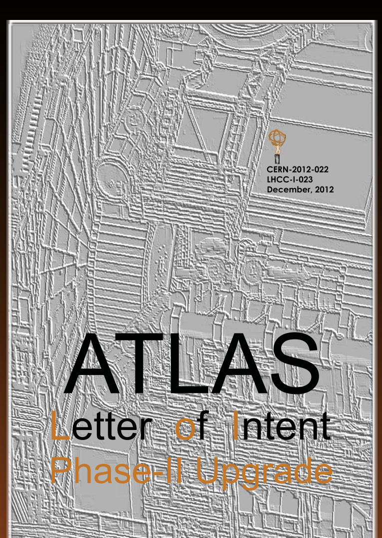
Phase-2 Upgrades - the Challenge

- by end of Phase-1 LHC will have delivered about 350 fb^{-1}
  - ➡ LHC will be made ready for $5{\cdot}10^{34} cm^{-2}s^{-1}$
  - ➡ expecting 140 pileup with luminosity leveling
- ATLAS and CMS Phase-2 upgrade programs taking shape
  - ➡ one main activity will be construction of a new inner trackers
    - current silicon tracker designed to survive up to ~10 *MRad* (≤ 700 fb^{-1})
    - track density and data volumes at HL-LHC beyond capabilities of current detectors
    - already ongoing - major R&D, prototyping and engineering effort
    - both experiments foresee hardware track trigger at Level-1 (ATLAS Level-0 seeded)
  - ➡ upgrade Trigger systems, detector electronics and DAQ
    - much increased HLT output rates will provide challenge to offline computing
  - ➡ Muon Spectrometers will be upgraded to sustain rates
  - ➡ Phase-2 conditions may require to replace/upgrade Forward Calorimeters
- plan is to be ready for installation in 2022/3
  - ➡ will need a 2 year shutdown

ATLAS Phase-2 Upgrades

- new Inner Tracker
  - ➡ radiation hardness
  - ➡ better granularity and faster links
  - ➡ improved precision
  - ➡ less material
  - ➡ extend η coverage ?
- LAr and Tile Calorimeter
  - ➡ new FE and BE electronics
- T/DAQ
  - ➡ Level-0 at 500 *kHz*
  - ➡ Tracks at Level-1
  - ➡ 200 *kHz* input to HLT
  - ➡ output 5 *kHz* ?



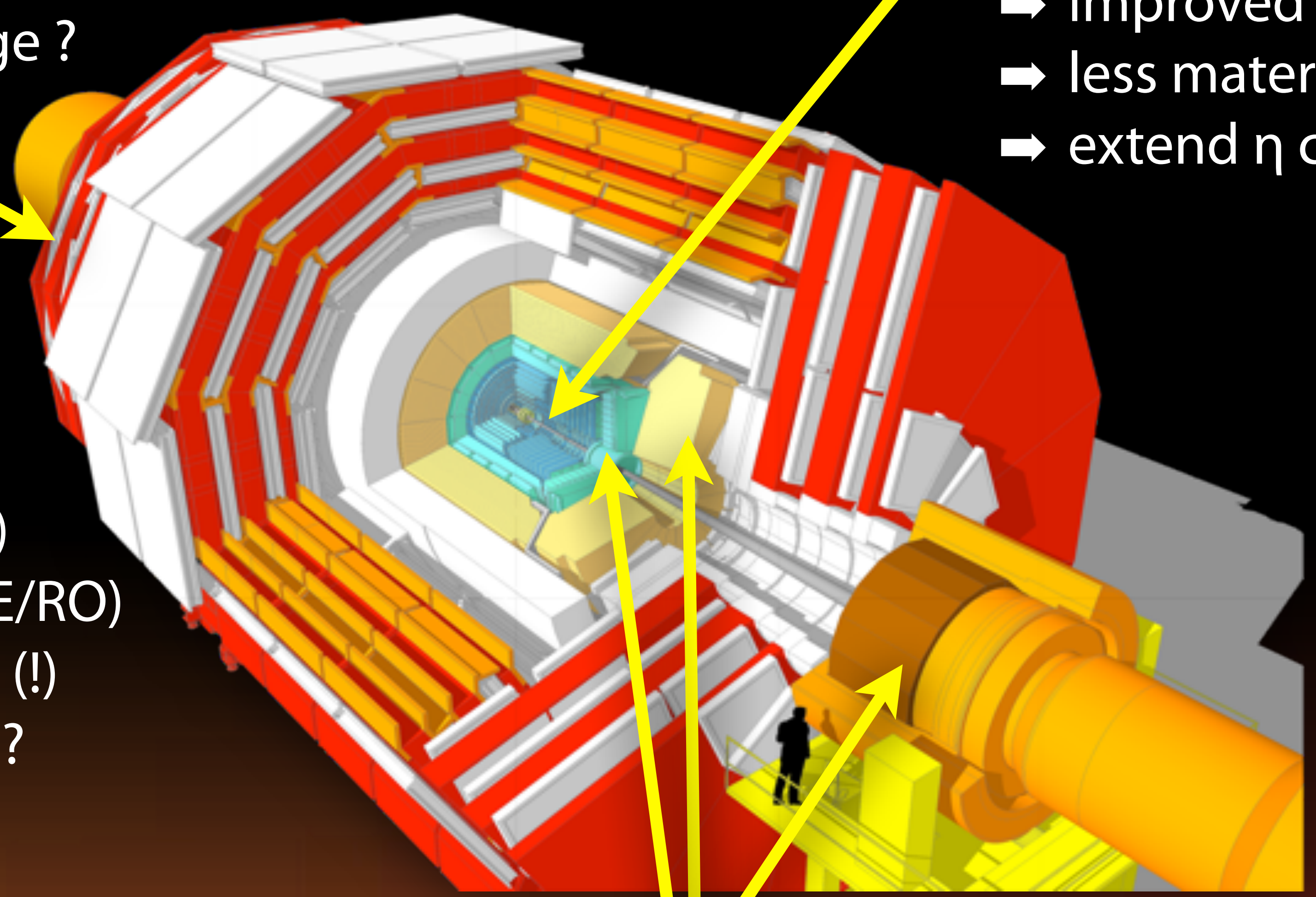


- Forward Calorimeters
  - ➡ replace FCal ?
  - ➡ replace HEC cold electronics ?
- Muons
  - ➡ new FE electronics
  - ➡ improved resolution

CMS Phase-2 Upgrades

- **Muons**
  - ➡ complete RPCs in forward region with new technology, GEM or GRPCs
  - ➡ extend η coverage ?

- **new Inner Tracker**
  - ➡ radiation hardness
  - ➡ better granularity and faster links
  - ➡ improved precision
  - ➡ less material
  - ➡ extend η coverage ?

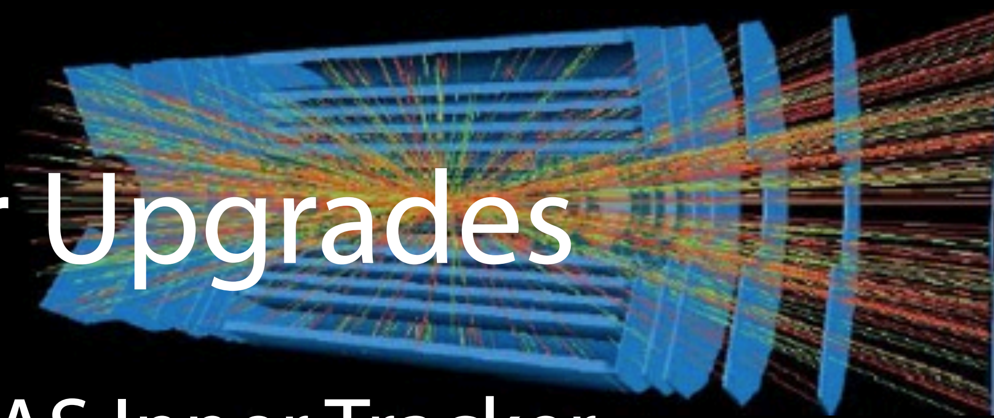


- **T/DAQ**
  - ➡ Level-1 at 1 *MHz* (?) (requires all new FE/RO)
  - ➡ Tracking at Level-1 (!)
  - ➡ HLT output 10 *kHz* ?

Technical Proposal in 2014

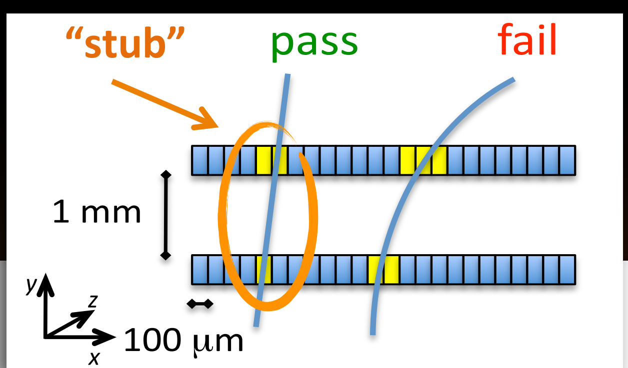
- **upgrade/replace Forward Calorimeters**
  - ➡ extend η coverage ?
  - ➡ mitigate pileup effects with tracking and precise timing

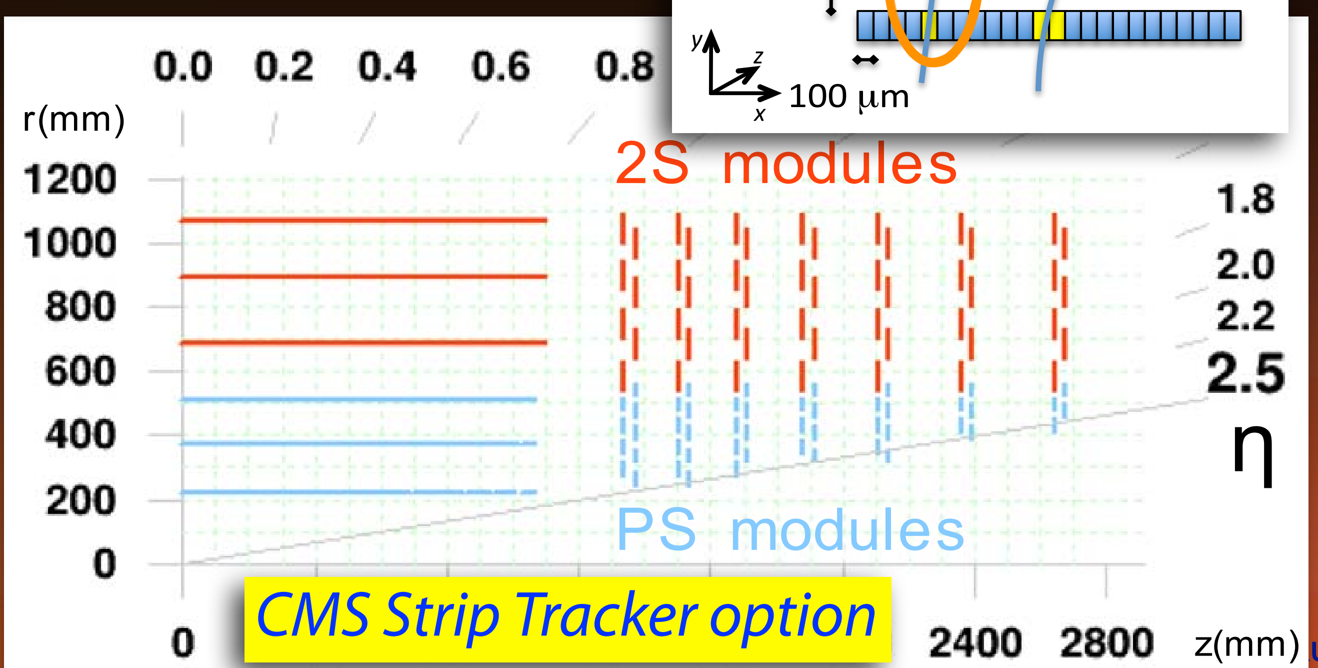
ATLAS and CMS Inner Tracker Upgrades

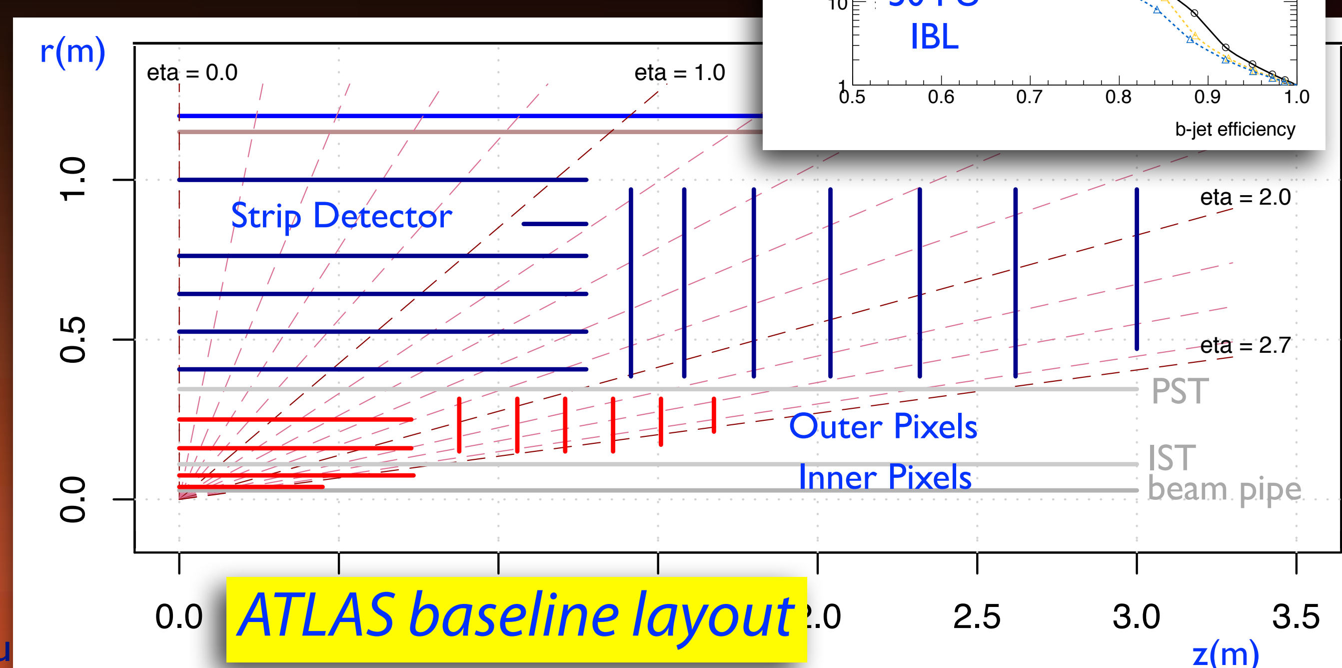


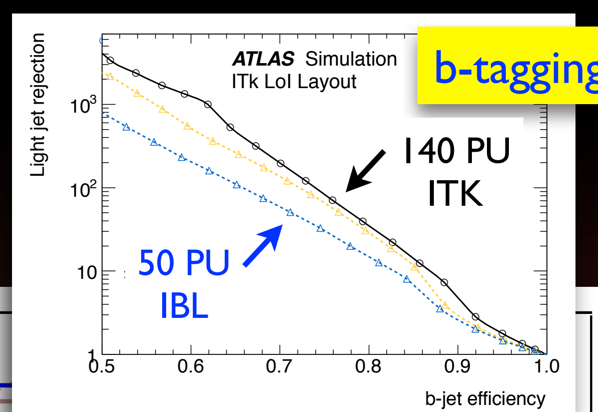
- CMS Inner Tracker
  - ➡ Strip tracker replacement
    - several layouts under consideration
    - short strips in *R*ϕ, macro-pixels in *z*
  - ➡ Level-1 track trigger with high p_T stubs
    - correlate 2 sensors, threshold ~ *2 GeV*
    - pattern in associative memory, FPGA fit
  - ➡ Pixel replacement: extend *η* coverage ?

- ATLAS Inner Tracker
  - ➡ baseline: all silicon tracker, 14 hits
    - robust tracking @140 PU for *η*<2.5
  - ➡ Strip tracker with short strips + stereo
  - ➡ Pixels cover *η*<2.7 (Muons)
    - inner Pixels replaceable, reduced pitch
    - alternative layouts ("Alpine", conical)
  - ➡ Level-1 track trigger seeded by Level-0
    - FTK inspired, reduced latency



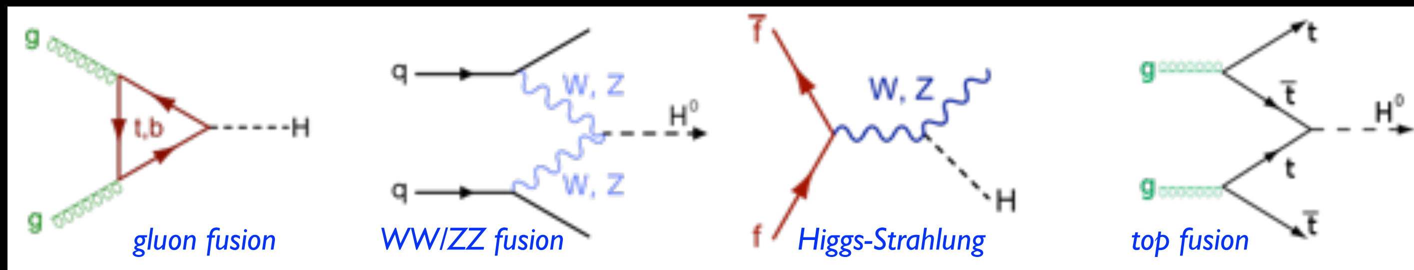






Prospects for Higgs Couplings at the LHC

- relevant Higgs production channels:



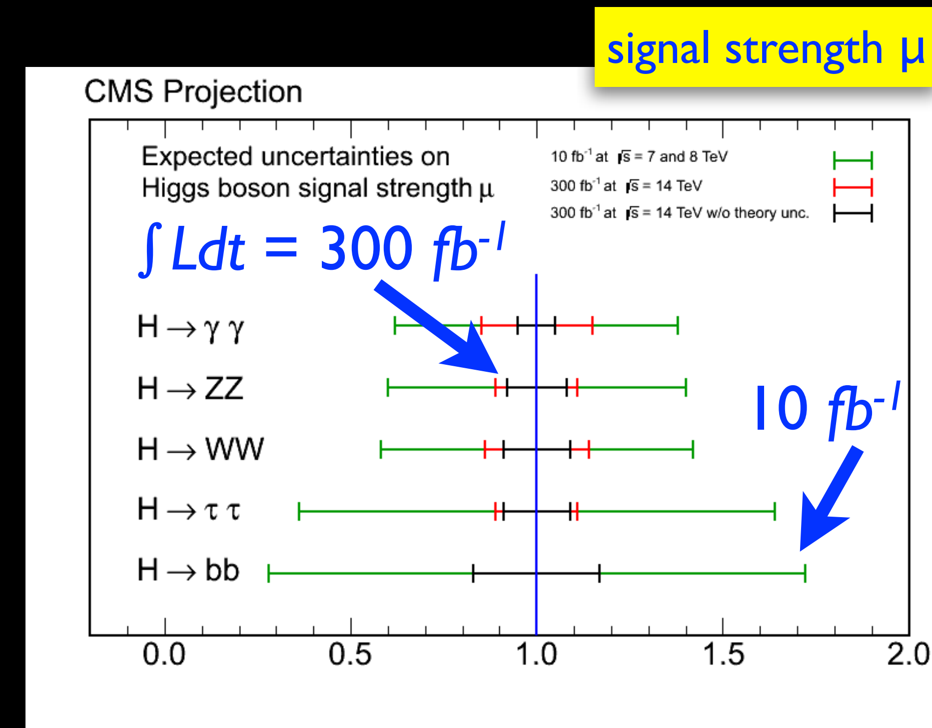
➡ cross-section proportional to $\Gamma_i \Gamma_f / \Gamma_H$, at the LHC
  - Γ_H and absolute couplings requires theory assumptions
  - ratios measure Γ_j / Γ_k with no model dependence

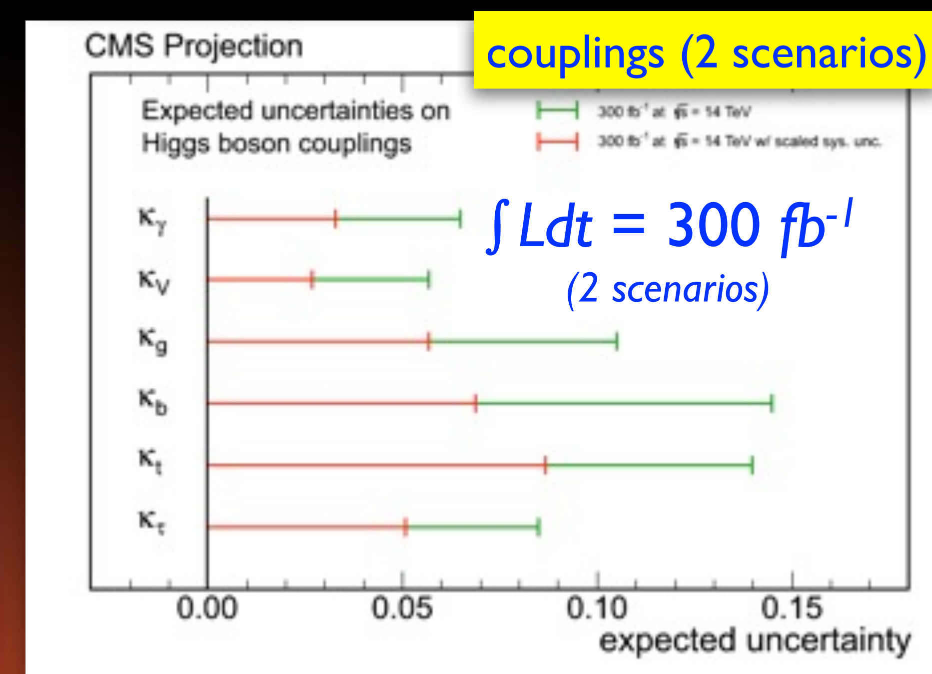
➡ however: seems difficult to invent a model that keeps all cross-sections and ratios at their SM values but deviates in the unmeasurable quantities

- CMS extrapolate their existing analyses

➡ scenarios for going to 300 and 3000 fb^{-1}:
  1. all systematics are unchanged
  2. current theory systematics are halved and experimental systematics scale with $\sqrt{L}$

➡ truth will probably be in between

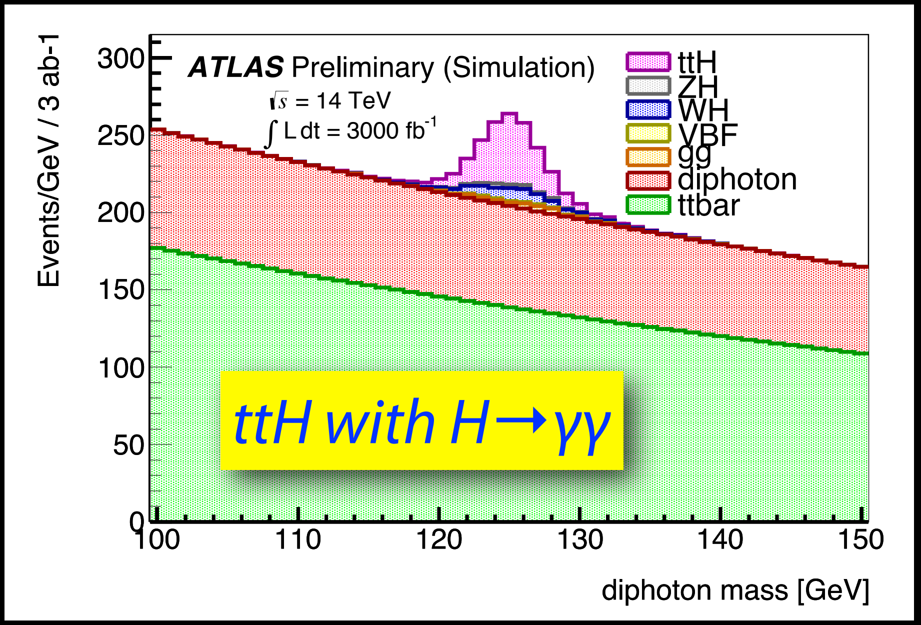


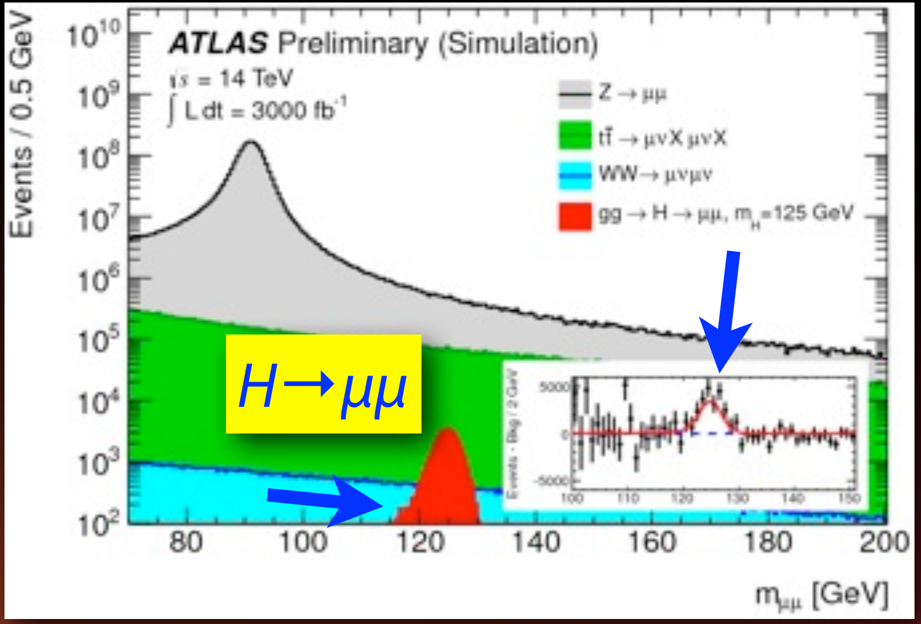


CMS NOTE -2012/006

ATLAS performs Specialized Analyses

- 3000 fb^{-1} studies based on fast simulation
  - ➡ smear physics objects according to expected resolution
- currently restrict to more robust channels
  - ➡ e.g. only *VBF* used for $H\rightarrow\tau\tau$
- new analyses added for HL-LHC
  - ➡ *ttH* with $H\rightarrow\gamma\gamma$ were added
- $H\rightarrow\mu\mu$ becomes accessible at HL-LHC
  - ➡ like $H\rightarrow\gamma\gamma$ today, signal is peak on smooth background
  - ➡ possible precision is <20% per experiment (>6σ)
- more studies to follow
  - ➡ towards results based on full simulation

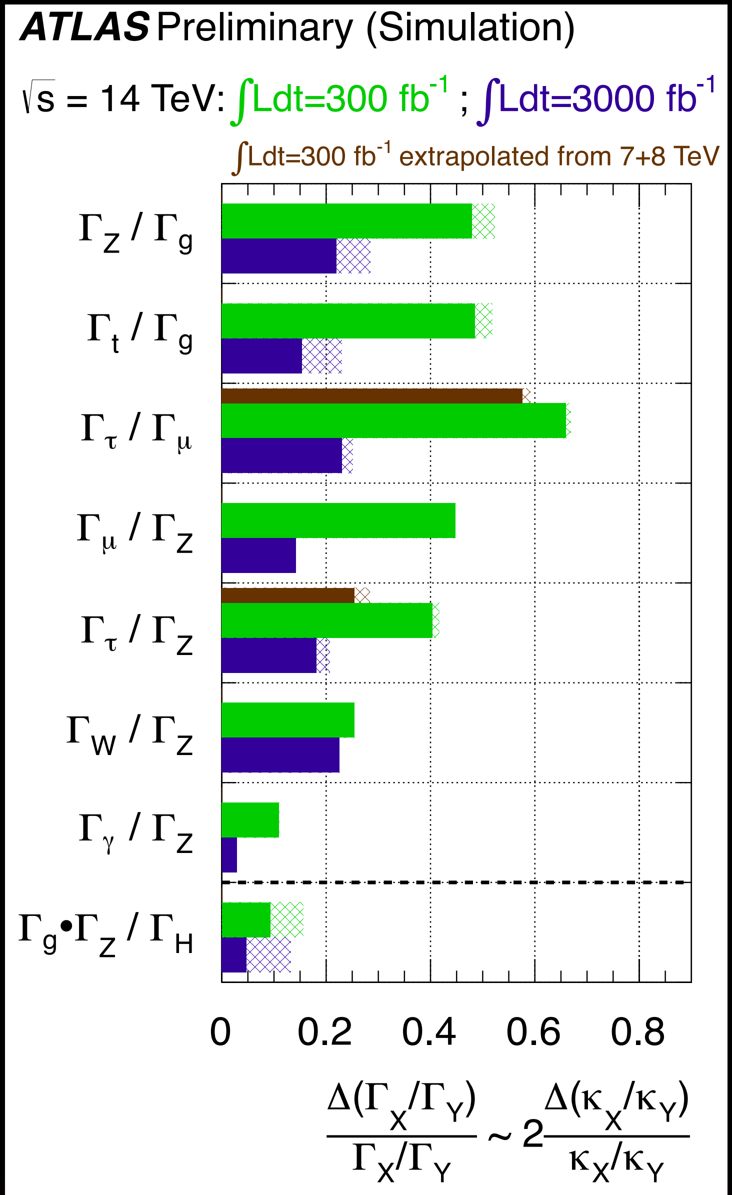




ATLAS-PHYS-PUB-2012-04

Expected Precision on Couplings

- results presented differently
  - ➡ ATLAS model independent ratios of partial widths
  - ➡ CMS coupling scale factors, assumes no unknown decays
- results agree within the uncertain assumptions
  - ➡ measurements of few % precision will be possible
  - ➡ nice complementarity with ILC (*γγ,μμ,tt,ZZ*)



ATLAS-PHYS-PUB-2012-04

Coupling	CMS 300 fb^{-1}		CMS 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%

CMS NOTE-2012/006

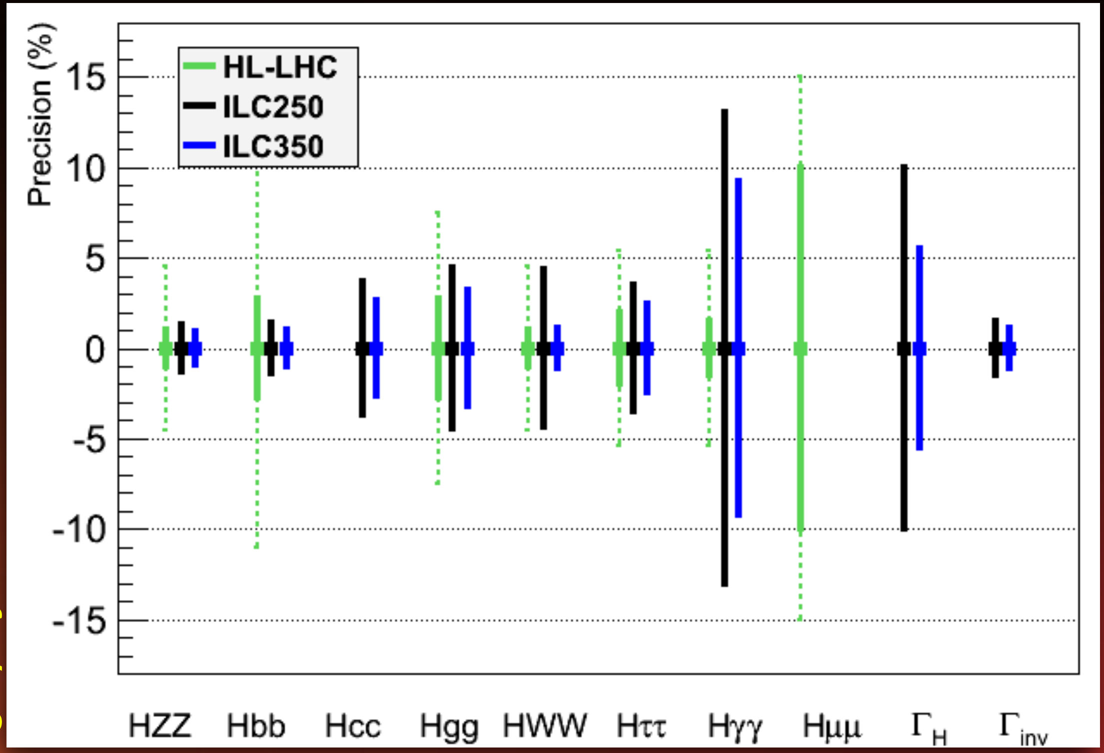
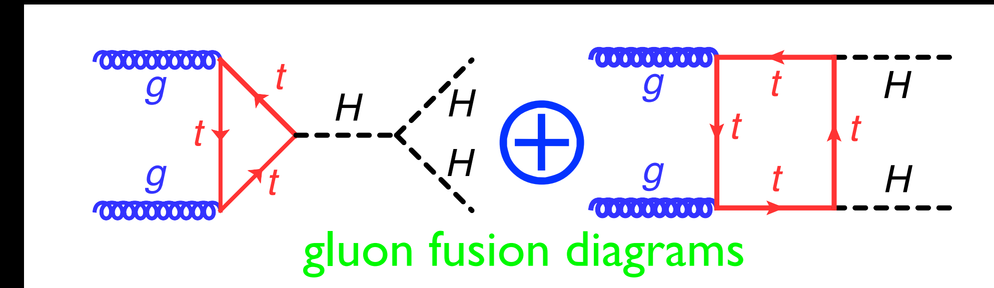
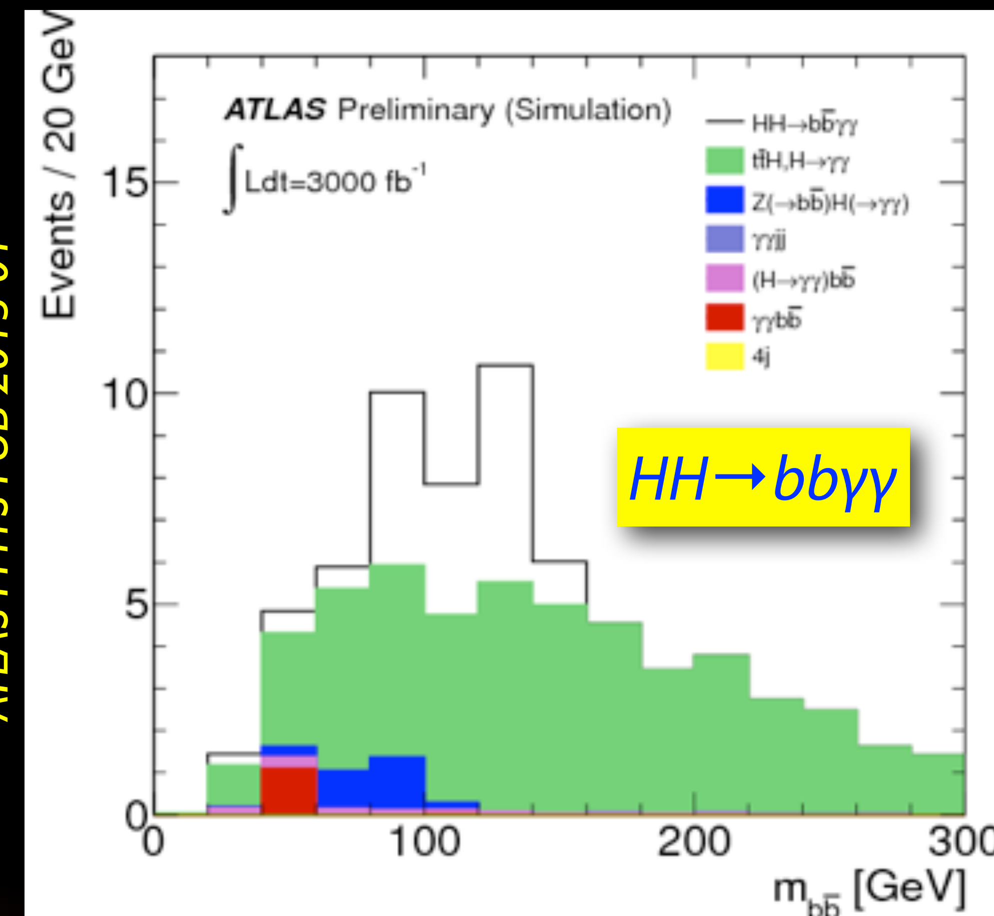


fig. by P.Janot based on arXiv:1302.3318

Higgs Self Couplings

- triple-Higgs coupling can be measured from double Higgs production
  - ➡ (negative) interference with independent two-Higgs production
- ATLAS study of *HH→bbγγ* double Higgs production
  - ➡ can be seen with close to 3*σ*
- 30% accuracy within reach for triple-Higgs coupling
  - ➡ if a 2nd channel with 3*σ* significant is found
  - ➡ two experiments are combined





ATLAS-PHYS-PUB-2013-01

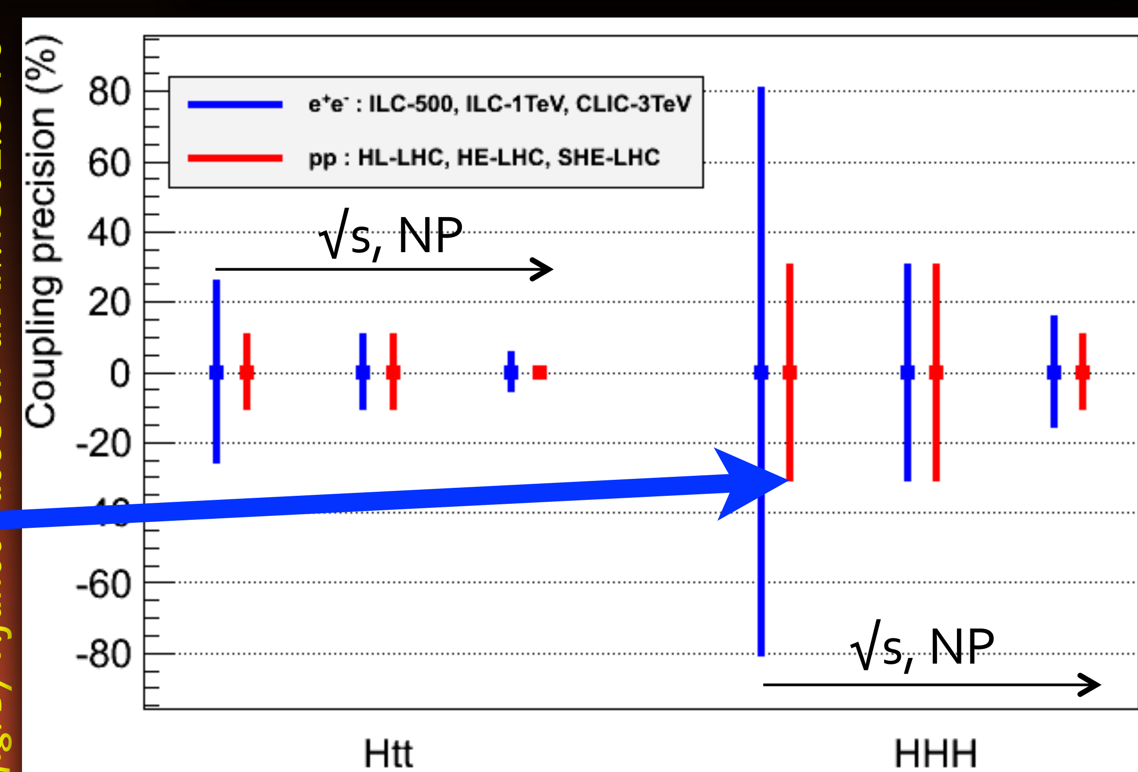
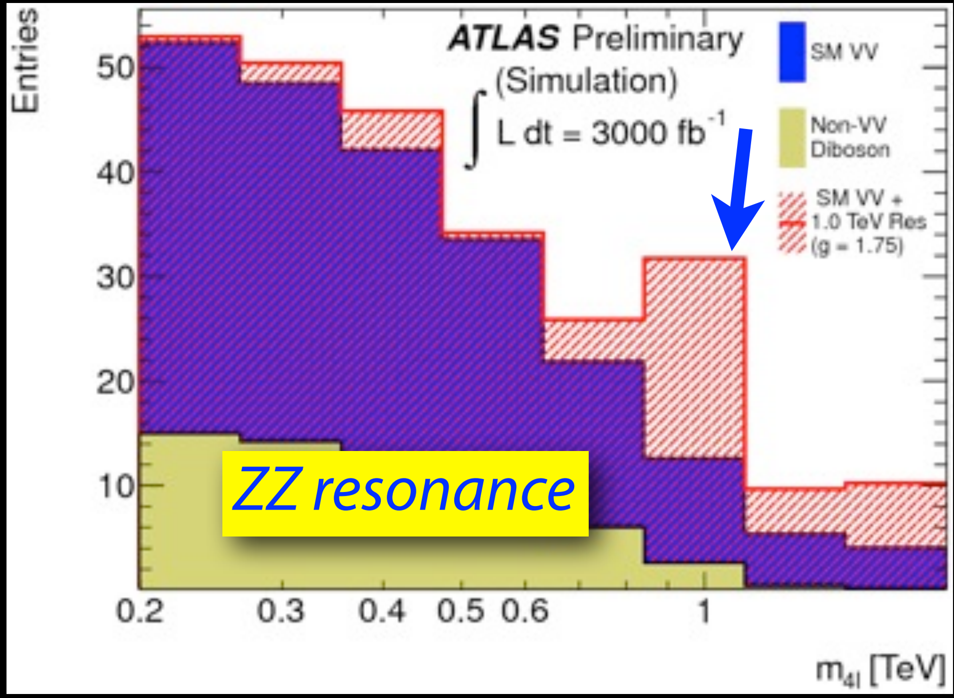


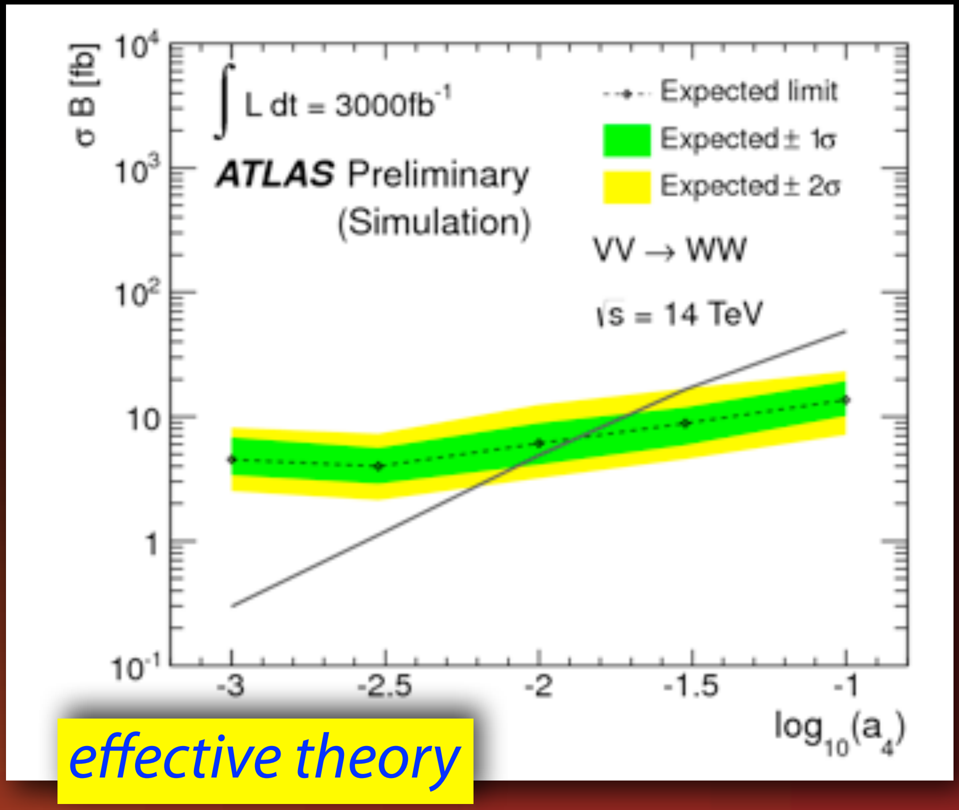
fig. by P.Janot based on arXiv:1302.3318

Studies of Vector Boson Scattering

- new effects in *VV* scattering ?
  - ➡ without a Higgs
    - *VV* scattering violates unitarity around 1 *TeV*
    - unitarity gets restored by the Higgs
  - ➡ if the Higgs is non-standard
    - there can still be new effects (resonances) in *VV* scattering at the *TeV* scale
  - ➡ however: no concrete models exist yet with a non-SM Higgs at 126 *GeV* and new effects in *VV* scattering
    - this makes projections difficult at the moment



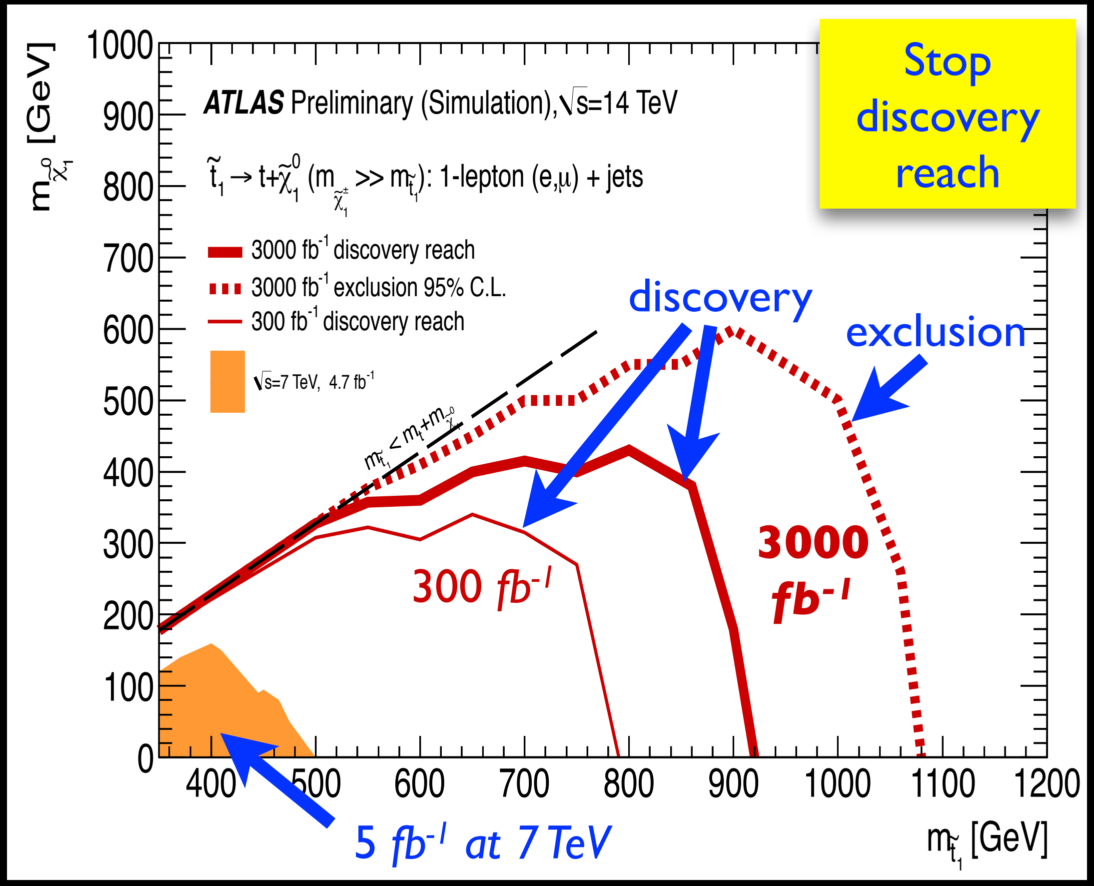
- two ATLAS studies:
  - ➡ search for *ZZ* resonances in *pp*→*ZZjj* in a model including a Higgs
    - no useful limits with 300 fb^{-1}
    - limits in the TeV range for 3000 fb^{-1}
  - ➡ limits on anomalous quadratic coupling term a_4 in an effective Lagrangian for *WW* production (without a Higgs)
    - improvement of a factor 4 (0.066 → 0.016)



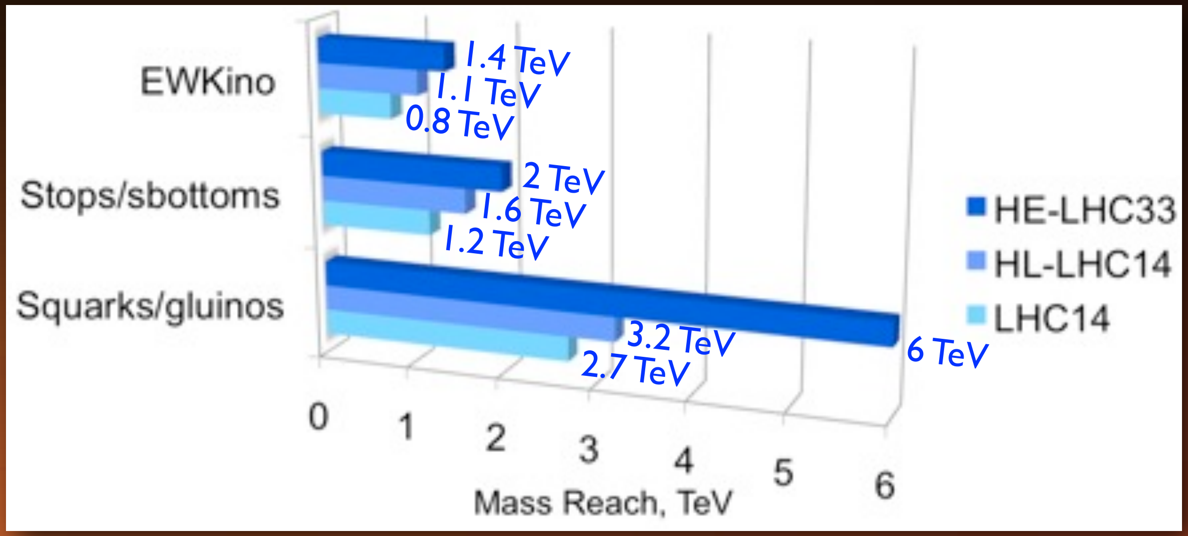
ATLAS-PHYS-PUB-2012-05

Supersymmetry

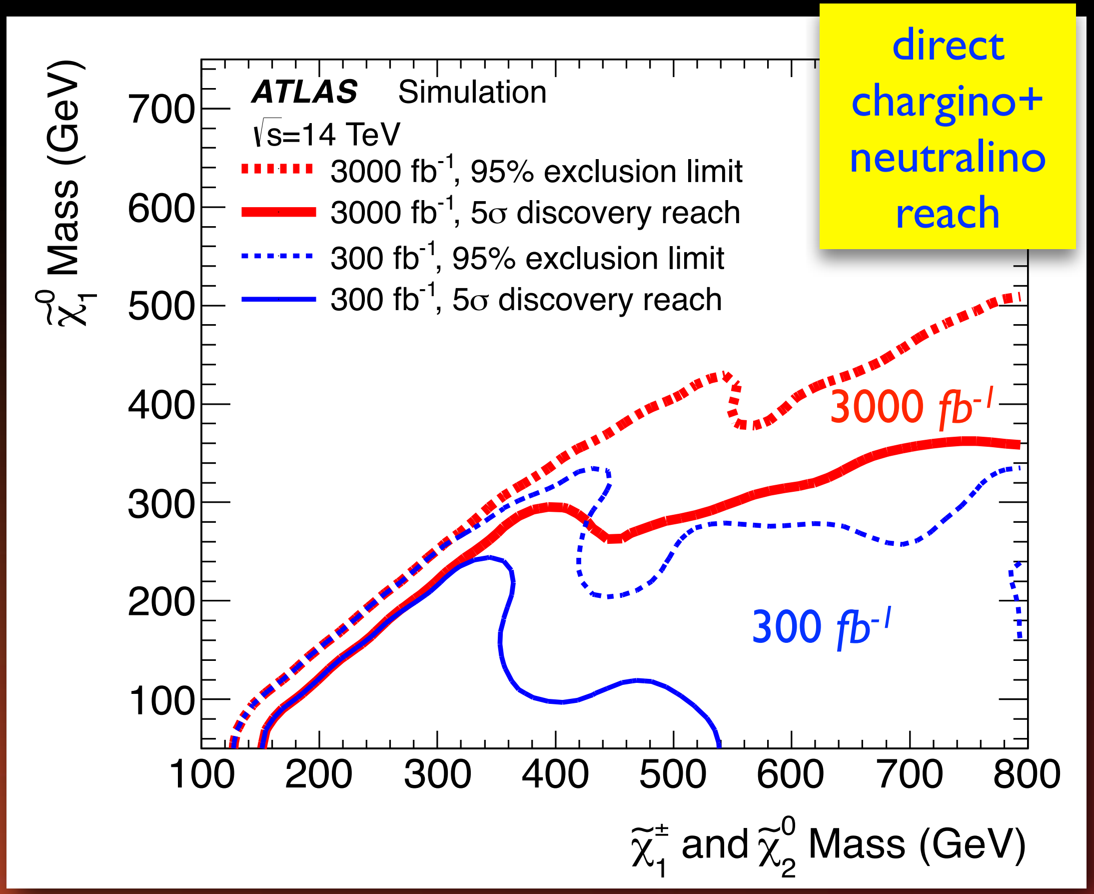
- 3rd generation squarks and gauginos
  - ➡ low cross section, more luminosity helps to improve limit
    - significant gain for stops, large gain for gauginos
    - reach interesting region to justify CLIC
- squark and gluino production
  - ➡ large cross section and PDFs fall quickly at large *x*
  - ➡ only moderate gain from luminosity increase
    - limits around 3 *TeV* can be reached (well above any lepton collider)



ATLAS-PHYS-PUB-2013-02



CMS NOTE -2012/006



LHCC-1-23

Exotic Particle Searches

- several studies of searches for exotics
  - ➡ "easy" searches with low background ($Z'\rightarrow ll$)
    - the gain from HL-LHC is only 20%

ATLAS:

model	11 fb^{-1} (7+8TeV)	300 fb^{-1}	3000 fb^{-1}
$Z'_{SSM}\rightarrow ee$	2.4 TeV	6.5 TeV	7.8 TeV
$Z'_{SSM}\rightarrow \mu\mu$	2.2 TeV	6.4 TeV	7.6 TeV

  - ➡ more complex searches with higher background yield larger gain with luminosity
- searches for $t\bar{t}$-resonances
  - ➡ models with K.K. gluon production or a narrow $Z'_{topcolor}$
    - exploring lepton+jets (as well di-lepton) channel

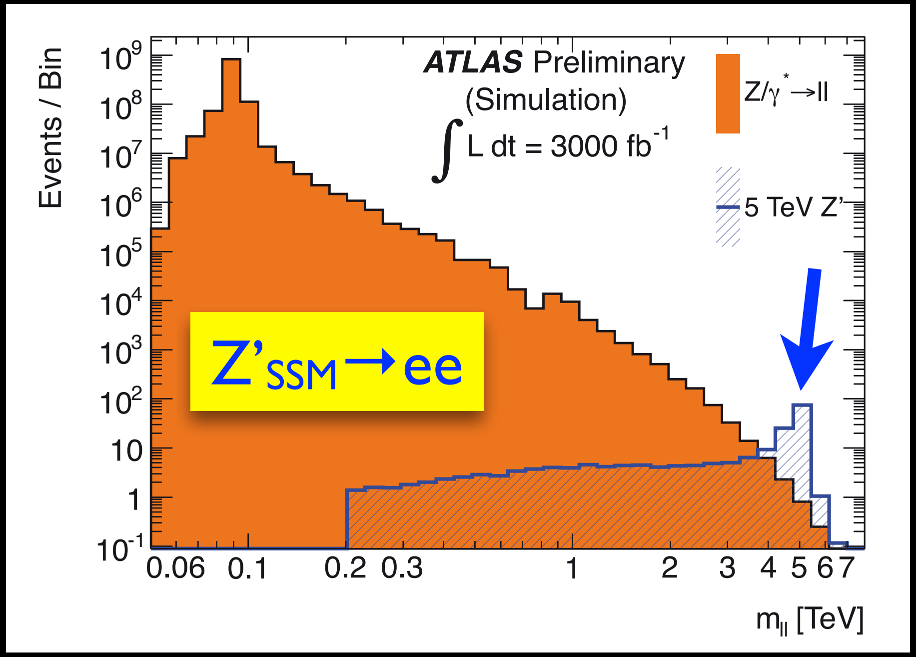
ATLAS:

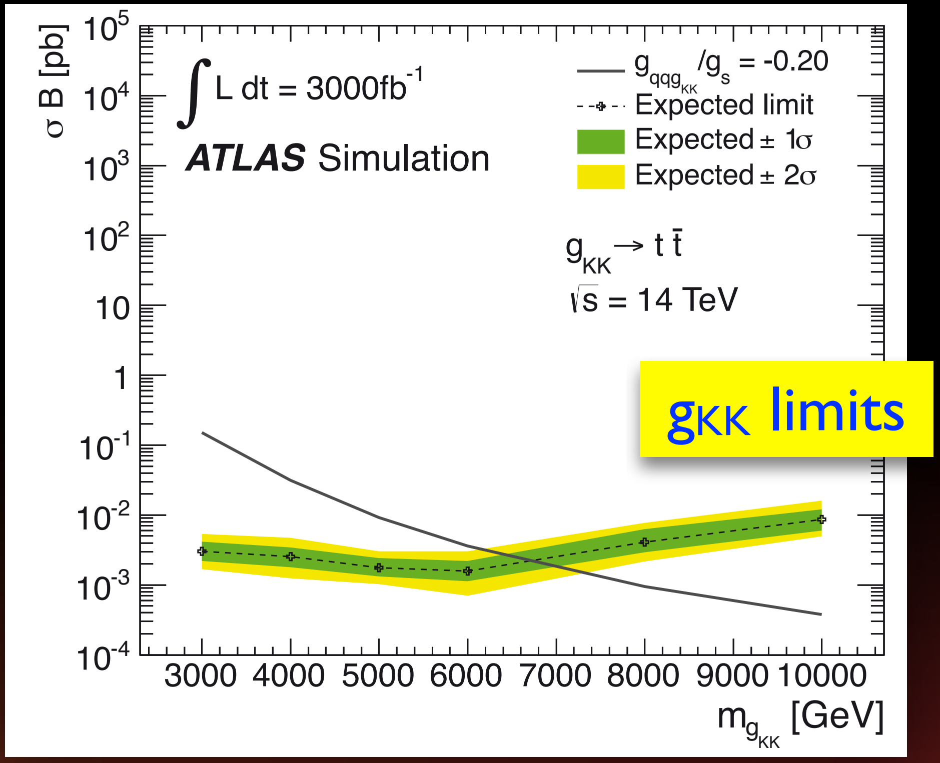
model	5 fb^{-1} (7TeV)	300 fb^{-1}	3000 fb^{-1}
g_{KK}	1.9 TeV	4.3 TeV	6.7 TeV
$Z'_{topcolor}$	1.7 TeV	3.3 TeV	5.5 TeV

- CMS studied reach for leptoquarks
  - ➡ extrapolate *eejj*-analysis, study different working points

model	5 fb^{-1} (7 TeV)	300 fb^{-1}	3000 fb^{-1}
LQ (eejj)	0.83 TeV	1.7 TeV	2.3 TeV

CMS NOTE -2012/006



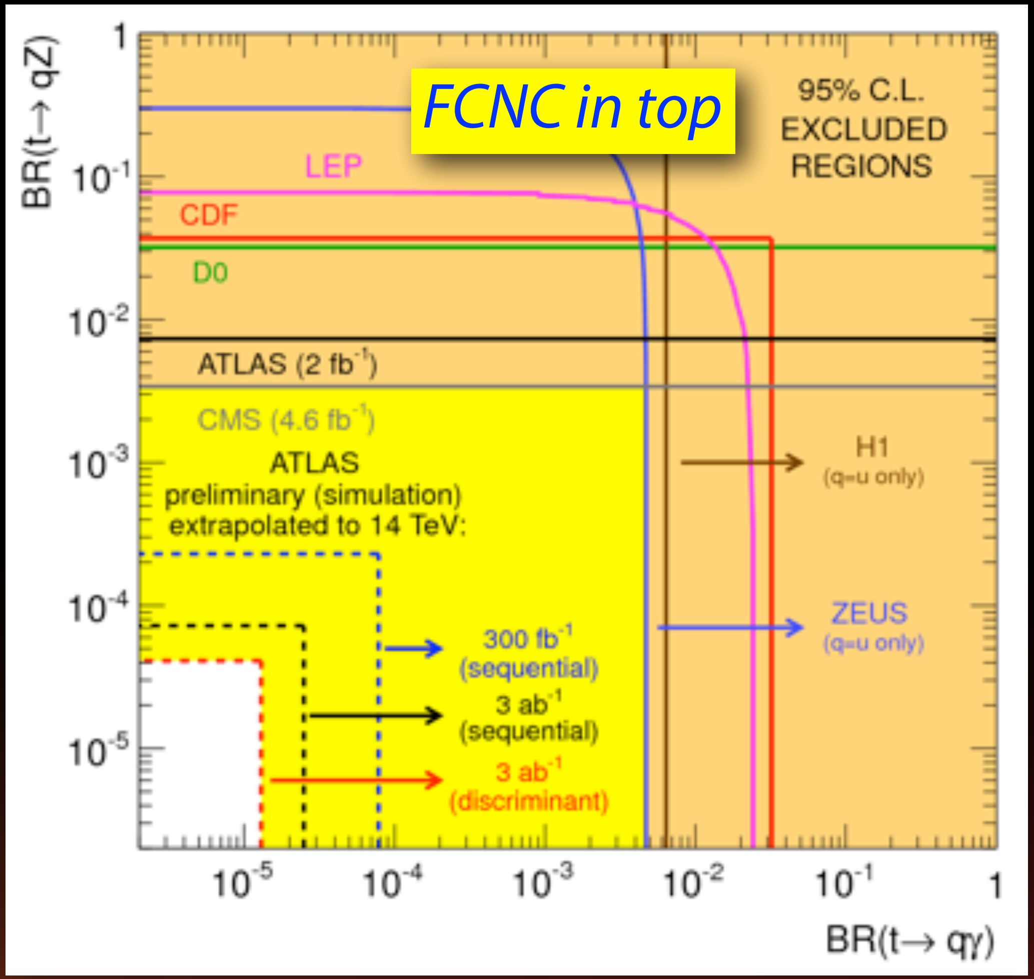


ATLAS-PHYS-PUB-2013-03

FCNC in *top* Decays, Triple Gauge Couplings

- enormous *top* sample with 3000 fb^{-1} (~$3 \cdot 10^{12}$ $t\bar{t}$-pairs)
  - ➡ can be used to measure rare top decays
  - ➡ ATLAS study:
    - search for $t \to q\gamma$ and $t \to qZ$ decays
    - limits $O(10^{-5})$ are possible

ATLAS-PHYS-PUB-2012-01



- CMS extrapolated an older TGC study

(Gianotti, Mangano, Virdee et al., EPJ C39 (2005) 293)

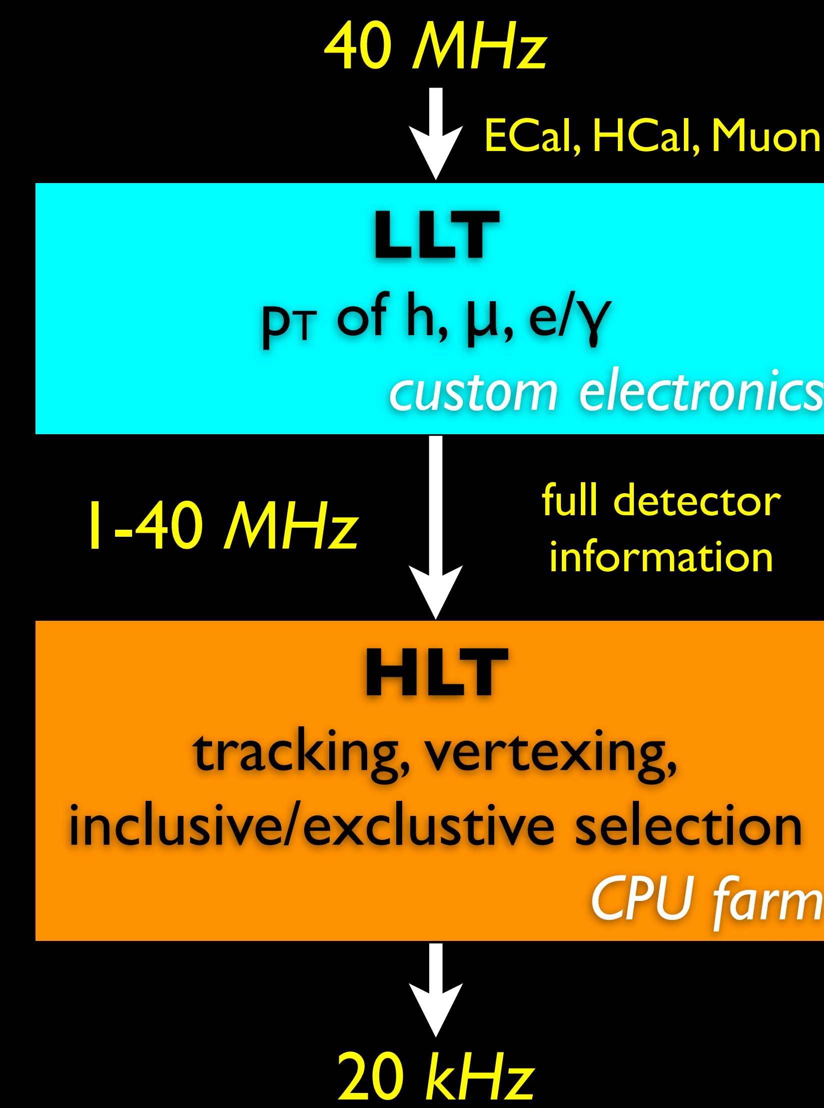
coupling	LHC	HL-LHC	HE-LHC	ILC500
g_1^Z	0.0030	0.0019	0.0013	0.0016
λ_γ	0.0009	0.0004	0.0004	0.0006
λ_Z	0.0023	0.0014	0.0014	0.0007
κ_γ	0.026	0.016	0.019	0.0003
κ_Z	0.037	0.031	0.022	0.0003

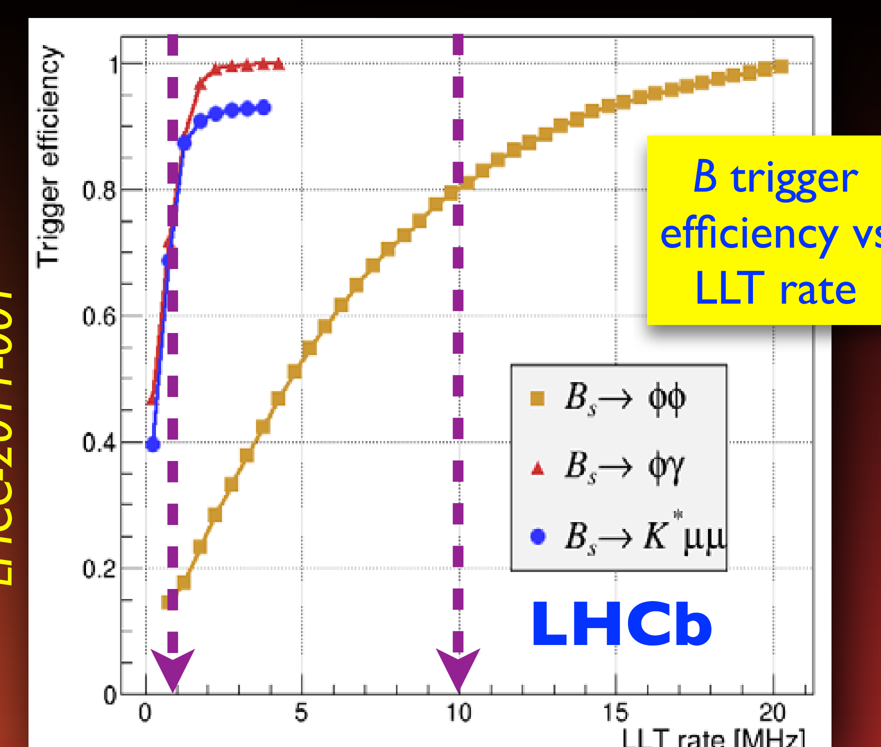
CMS NOTE -2012/006 (ILC RDR)

- ➡ improvements between 20% and a factor 2.2 at HL-LHC
  - large improvement in g_1^Z and λ , where ILC is weaker
  - smaller improvement in κ , where ILC is far better anyway

LHC-b Upgrade Program

- current program until 2018
  - ➡ collected so far 3 fb^{-1} at 2-4×$10^{32} cm^{-2}s^{-1}$
  - ➡ aim is to collect 10 fb^{-1}
- LHCb upgrade in LS2
  - ➡ 10 year program, independent from HL-LHC
    - operate at 3×$10^{33} cm^{-2}s^{-1}$ to collect 50 fb^{-1} (5×)
    - increase hadronic trigger acceptance by 2×
- significantly increases physics reach:
  - ➡ unique for new physics searches in B_s system, very competitive for B_d
  - ➡ unprecedented charm yields
- new "trigger-less" readout scheme
  - ➡ replace L0 with LLT operated at up to 40 *MHz*
    - replace all front-end electronics (except muons)
  - ➡ full reconstruction in HLT farm for trigger selection
- high occupancy and radiation
  - ➡ replace tracking stations, modify other detectors

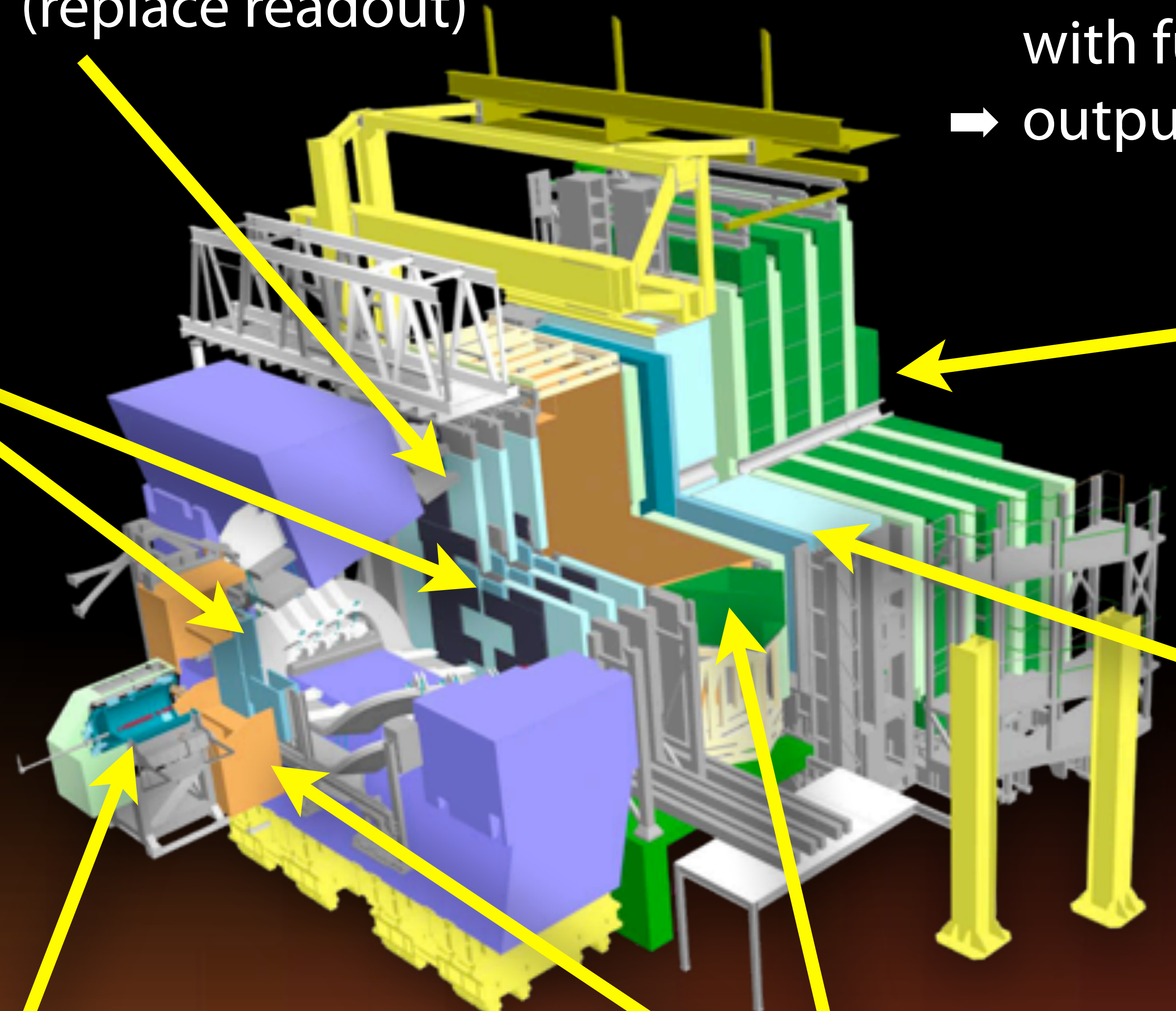


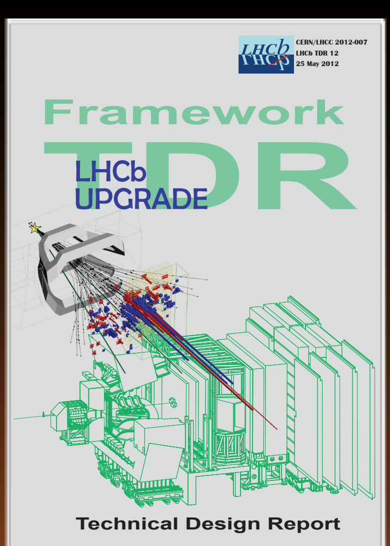


LHCC-2011-001

LHCb Detector Upgrades in LS2

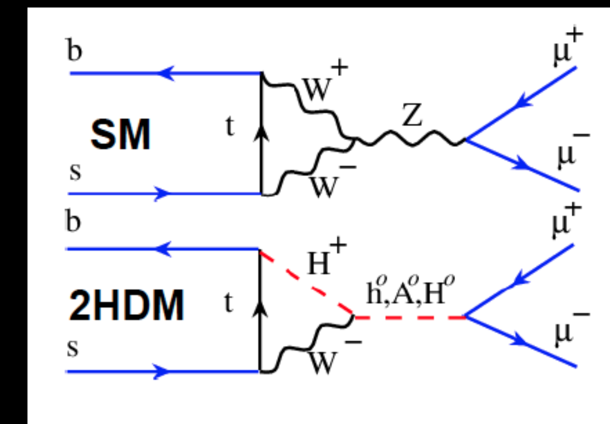
- option:
  - ➡ Fiber Tracker to replace Inner (Si) and Outer Tracker
- Outer Tracker
  - ➡ straw tubes (replace readout)
- LLT Trigger Scheme
  - ➡ up to 40 MHz into HLT with full reconstruction
  - ➡ output 20KHz
- Silicon Trackers
  - ➡ Si strips (replace all)
- Muons
  - ➡ MWPC (almost compatible)
- Calorimeter
  - ➡ PMTs (reduce PMT gain, replace readout)





- VELO
  - ➡ Si strips (replace all)
  - ➡ pixel or strips options
- RICH 1 & 2
  - ➡ HPDs (replace HPDs and readout)

Sensitivity in B_s Channels



- search for new physics in $B_{(s)}\rightarrow\mu\mu$
  - ➡ NP loop effects vs precise SM predictions
  - ➡ $B\rightarrow\mu\mu$ / $B_s\rightarrow\mu\mu$ probes minimal flavor violation
  - ➡ recent evidence for $B_s\rightarrow\mu\mu$

LHCb	current	10 fb^{-1}	50 fb^{-1}	Theory
$B_s\rightarrow\mu\mu$	1.5×10^{-9}	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9} (~7%)
$B\rightarrow\mu\mu$ / $B_s\rightarrow\mu\mu$	-	100%	35%	5%

arXiv:1208.3355v2

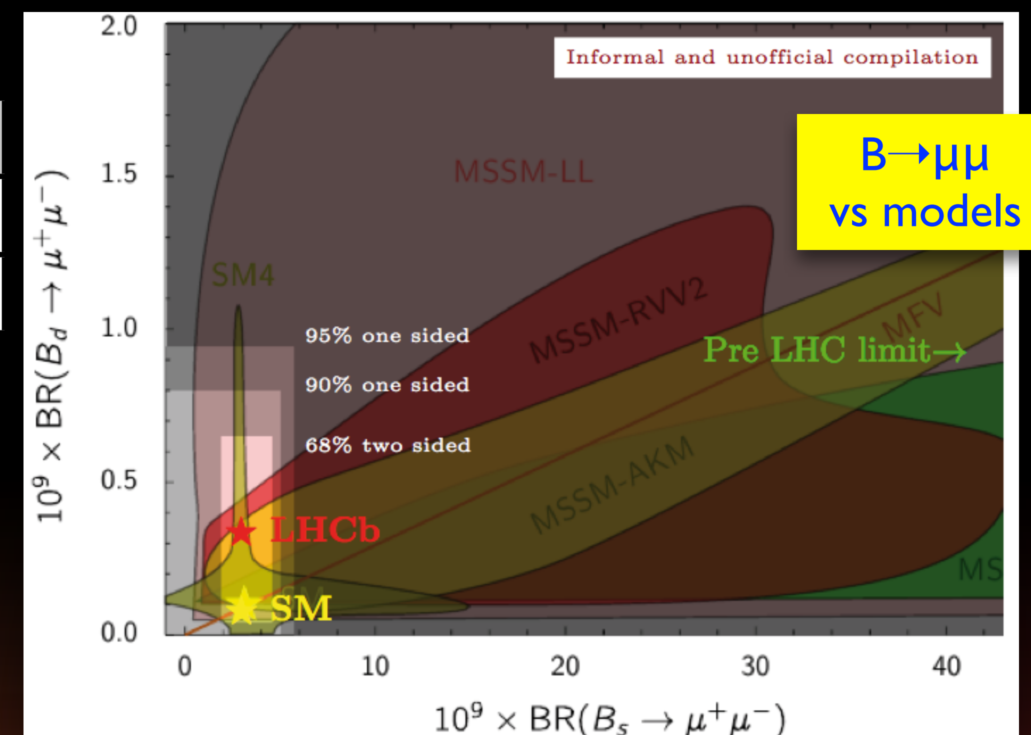


Fig.: M.Martinelli based on D.Straub

- search for CP violation in $B_s\rightarrow\phi\phi$
  - ➡ penguin dominated, particularly sensitive to NP
    - SM: decay and mixing phases cancel ⇒ $\phi_s^{sss} \sim 0$
  - ➡ LHCb: recently first time dependent measurement of ϕ_s^{sss}

LHCb	current	10 fb^{-1}	50 fb^{-1}	Theory
ϕ_s from $B_s\rightarrow\phi\phi$	100%	17%	3%	2%

arXiv:1208.3355v2

- expected precision will approach theory uncertainty

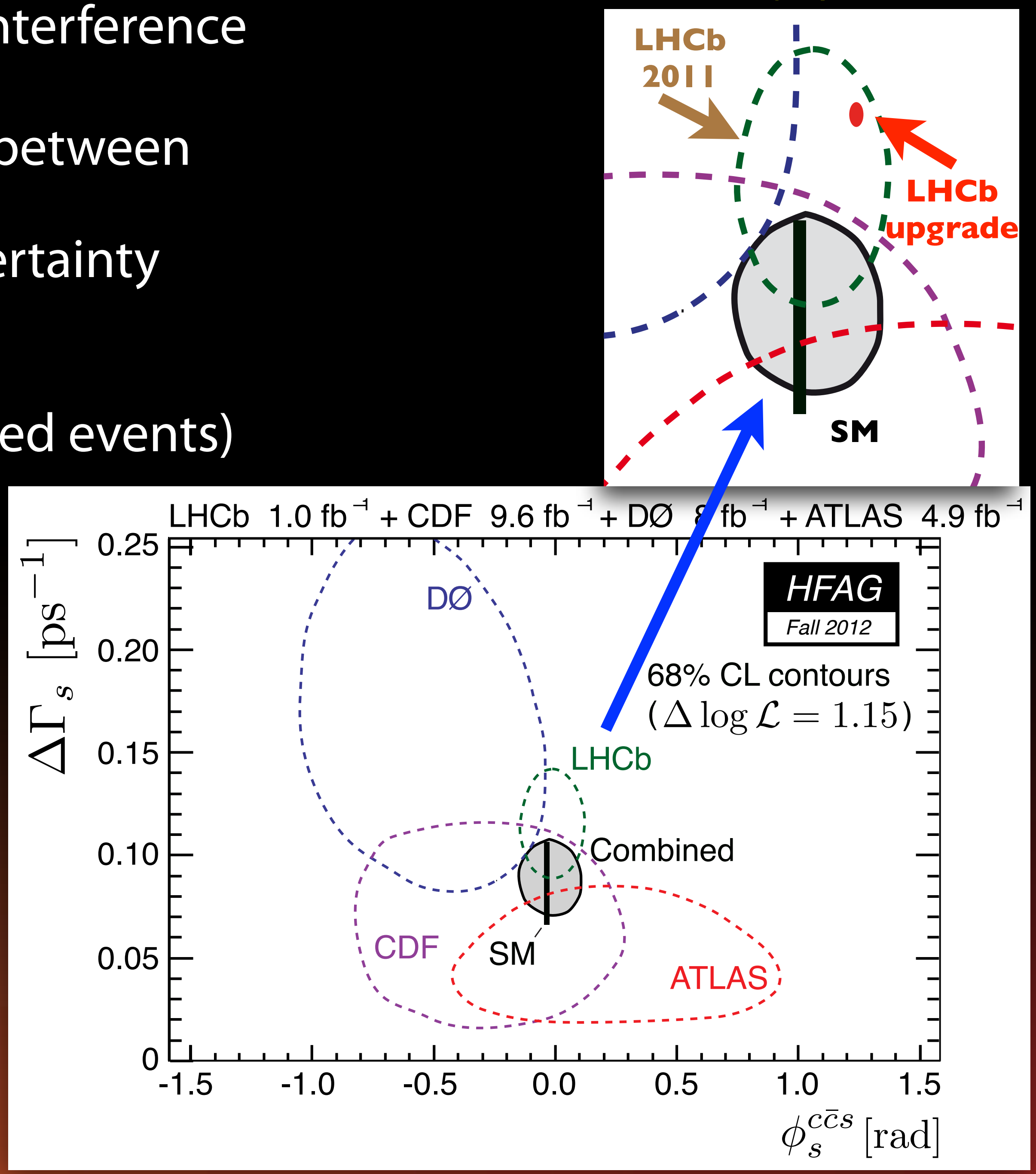
Sensitivity in B_s Channels (II)

- mixing induced CP violation in $B_s \to J/\Psi\phi$
  - ➡ CP violating phase ϕ_s^{ccs} in B_s mixing-decay interference
  - ➡ golden mode:
    - sensitivity to new physics entering mixing between 2nd and 3rd quark generation
    - precise SM prediction, tiny theoretical uncertainty (assume $\phi_s^{ccs} \approx -2\beta_s$)
  - ➡ LHCb does time dependent analysis (of tagged events)
    - recent (untagged) ATLAS measurement
  - ➡ so far consistent with SM prediction
    - remains priority to improve precision

LHCb	current	10 fb^{-1}	50 fb^{-1}	Theory
$2\beta_s$ ($B_s \to J/\Psi\phi$)	0.1	0.025	0.008	0.003

arXiv:1208.3355v2

illustration of precision based on fig. by G.Wilkinson



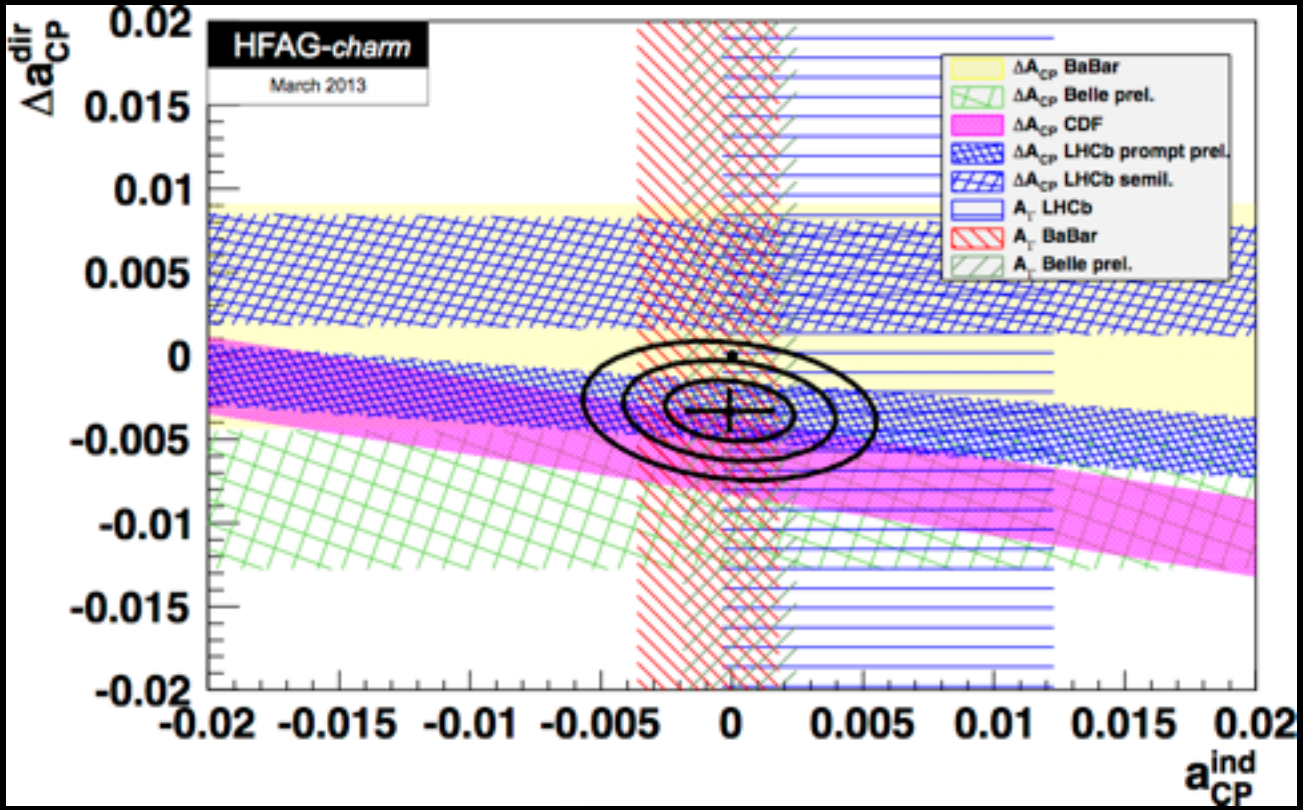
CP Violation in Charm Decays

- SM expectation < 0.1 %

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to hh) - \tau(D^0 \to hh)}{\tau(\overline{D}^0 \to hh) + \tau(D^0 \to hh)}$$

$$\Delta A_{CP} \equiv A_{CP}(KK) - A_{CP}(\pi\pi)$$

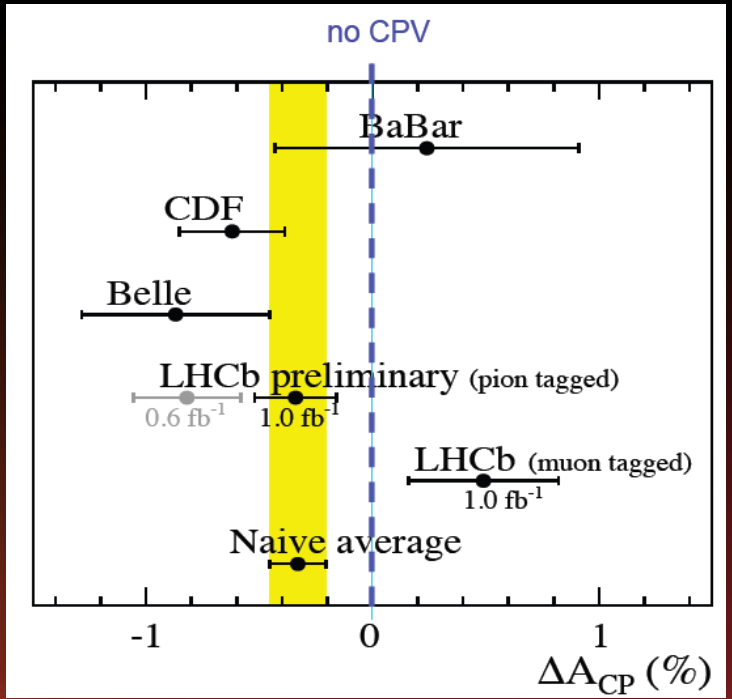
  - A_Γ assumed to be $-a_{CP}^{ind}$
  - ΔA_{CP} mainly Δa_{CP}^{dir}



- recent results on ΔA_{CP}
  - ➡ data consistent with no CP at 2.1% C.L.
    - need to achieve high precision

LHCb	current	10 fb^{-1}	50 fb^{-1}	Theory
A_Γ	2.3×10^{-3}	0.4×10^{-3}	0.07×10^{-3}	-
ΔA_{CP}	2.1×10^{-3}	0.65×10^{-3}	0.12×10^{-3}	-

arXiv:1208.3355v2



Summary

- LHC upgrade program
  - ➡ experiments have plans in hand to fully exploit the physics potential offered by the LHC
- LHCb upgrade after 2018
  - ➡ new trigger scheme will allow to statistics by 5-10 times over 10 years
  - ➡ unique sensitivity for B_s and charm sector, very competitive for B_d with Belle-II
- ATLAS and CMS
  - ➡ upgrades to preserve detector performance with rapid increase in pileup
    - control trigger rates during Phase-1
    - HL-LHC requires new Inner Trackers and new trigger and electronics chain
  - ➡ precise studies of Higgs properties, explore LHC reach for new physics
    - experiments are engaged in updating their projections as part of the Snowmass and ECFA processes
- beyond the HL-LHC
  - ➡ CERN's infrastructure could support a possible high-energy upgrade (HE-LHC)

Acknowledgements

- like to thank for their help and useful discussions:
  P.Allport, D.Contardo, A.Höcker, K. Mönig, T.Ruf, P.Wells, ...

European Strategy and HL-LHC

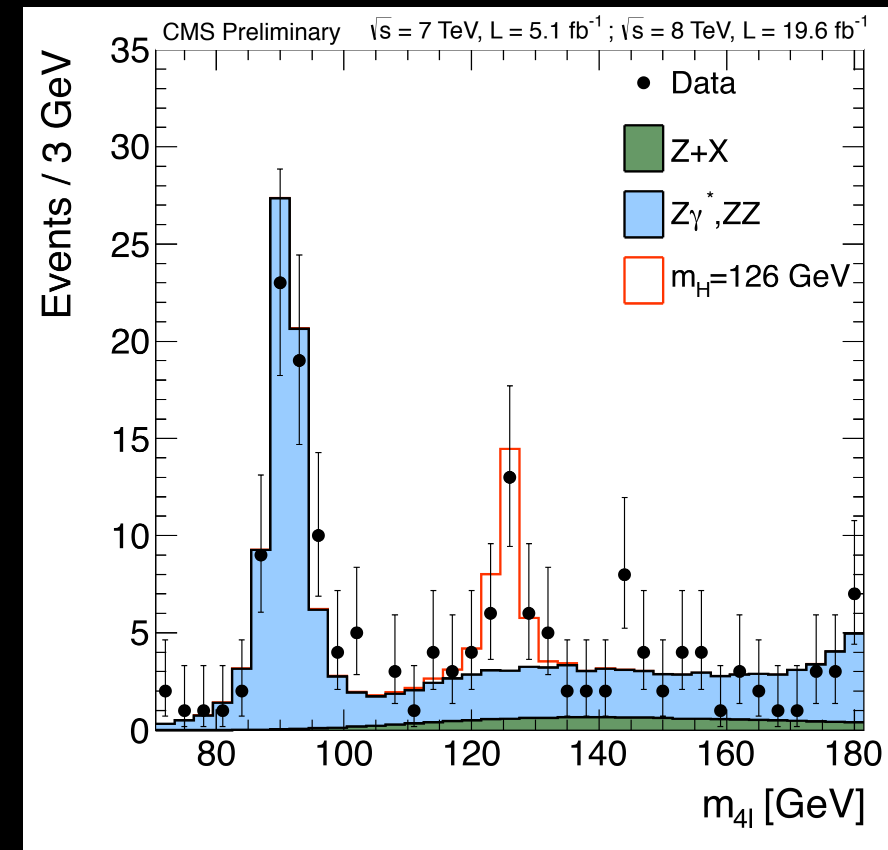
- Erice meeting, January ’13:
  - ➡ document (draft) for the update of the European Strategy for Particle Physics:
    - highest priority for large-scale scientific activities:

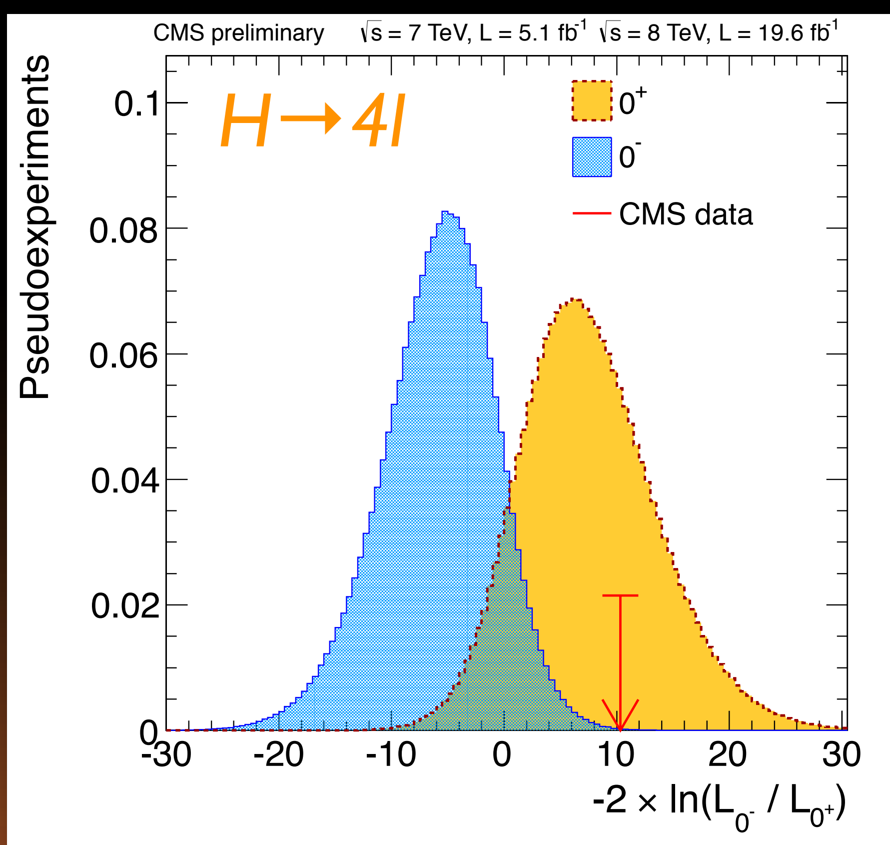
> c) The discovery of the Higgs boson is the start of a major programme of work to measure this particle’s properties with the highest possible precision for testing the validity of the Standard Model and to search for further new physics at the energy frontier. The LHC is in a unique position to pursue 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.*

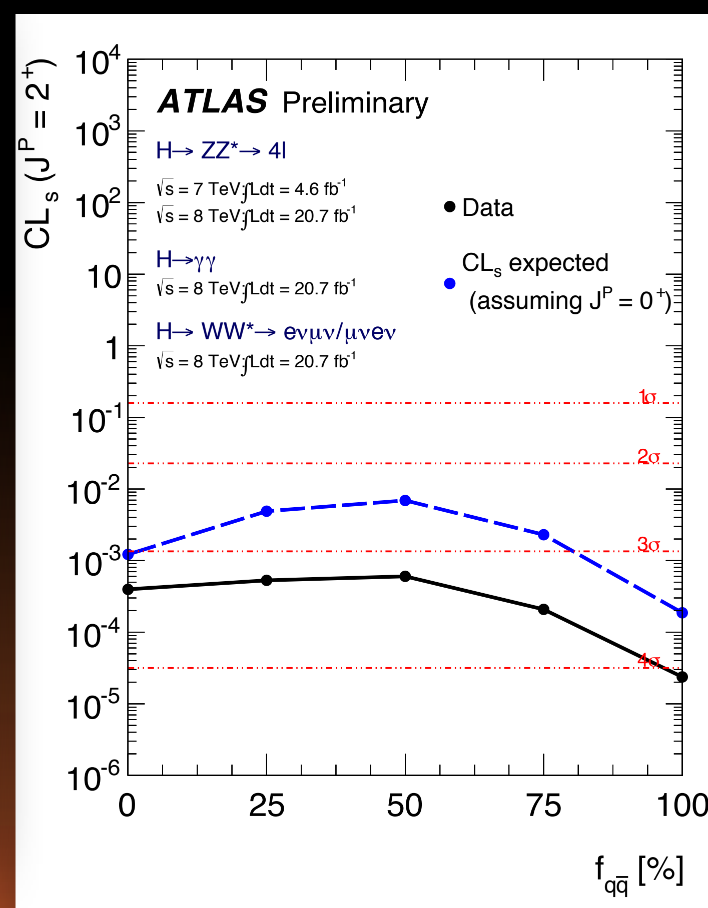
  - ➡ alongside, the document states:
    - the strong scientific case for an electron-positron collider, referring explicitly to a european role in the japanese initiative
    - CERN should undertake design studies for accelerator projects in a global context
    - a substantial European role in future long-baseline neutrino experiments
    - etc. ...

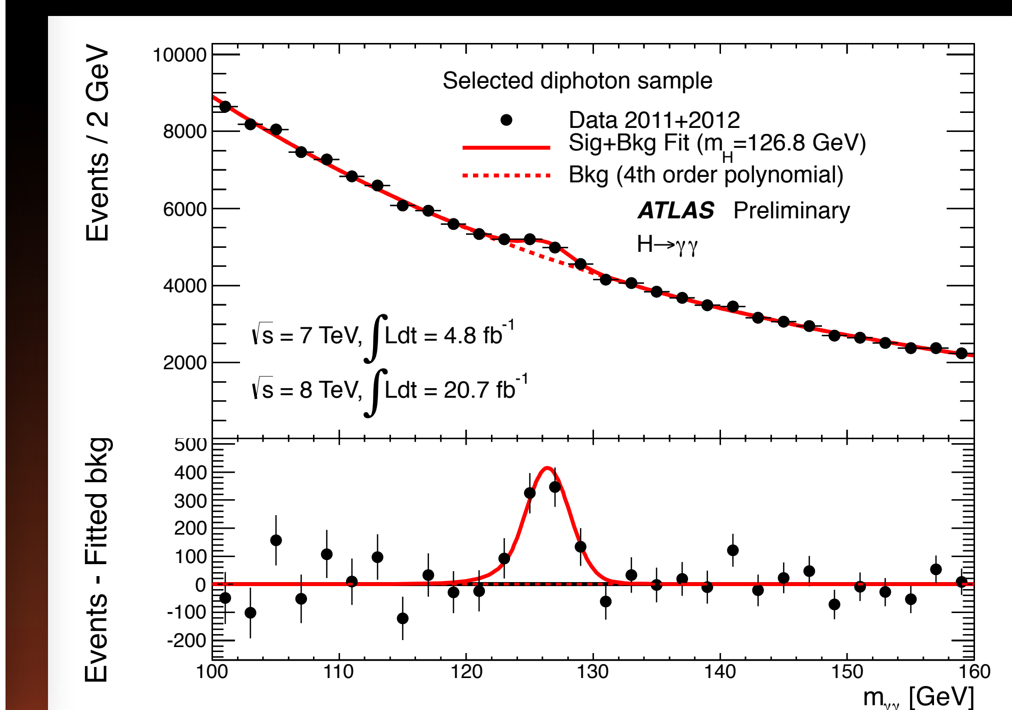
Higgs Physics

- Higgs observation at ~126 *GeV* now firmly established
  - ➡ strong preference for 0+ over 0- and for *S*=0 over *S*=2





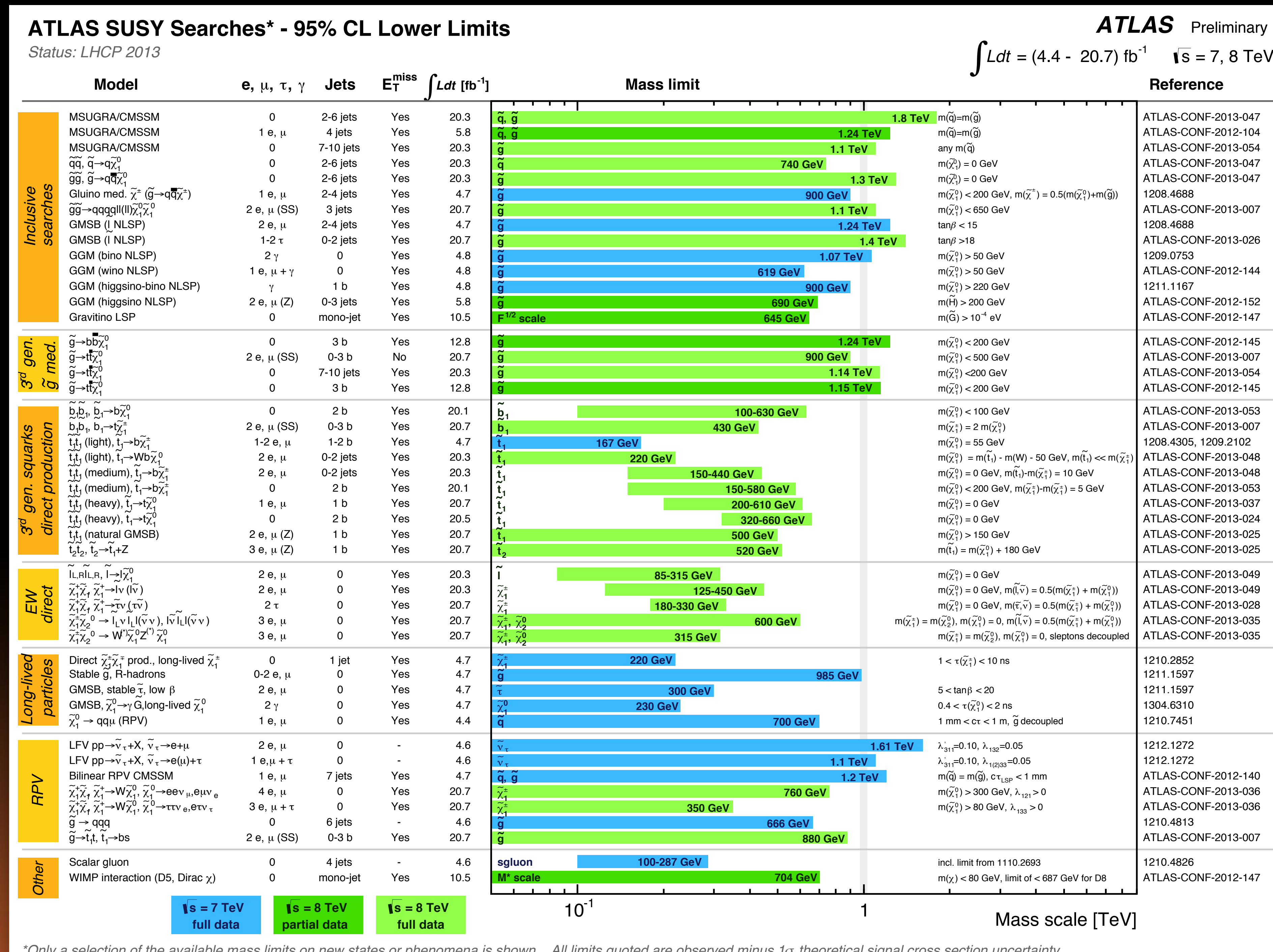




status: Winter '13

Supersymmetry

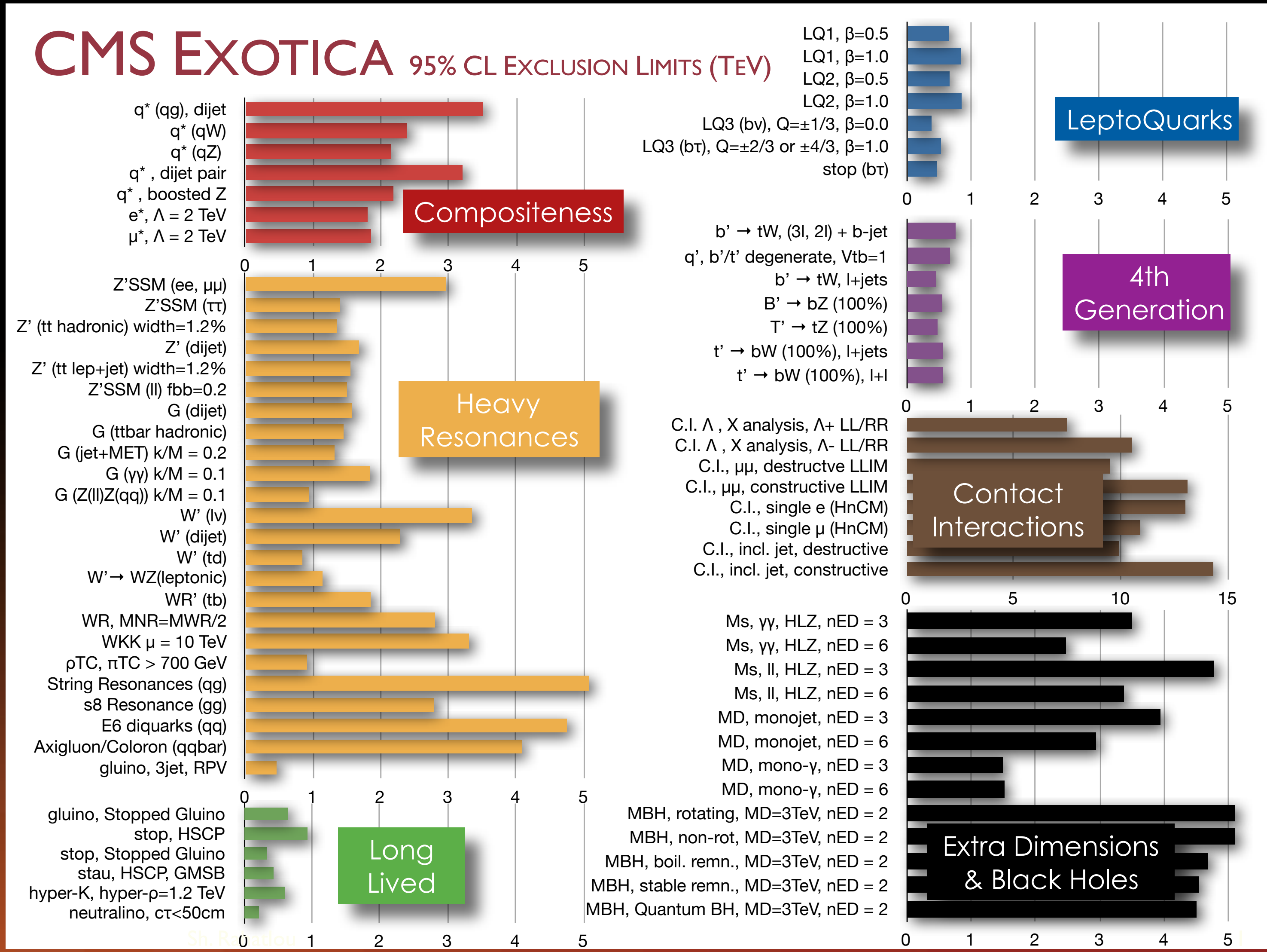
- present limits:
  - ➡ 1 *TeV* for gluinos and squarks
  - ➡ 560 *GeV* for stop
  - ➡ 200-500 *GeV* for gauginos
  - ➡ all limits are within specific assumptions
  - ➡ all limits need relatively large mass difference



status: LHCP '13

Exotic Particle Searches

- typical limits:
  - ➡ singly produced objects with QCD couplings ~ ***3.5 TeV***
  - ➡ singly produced objects with EW couplings ~ ***4 TeV***
  - ➡ pair produced objects with QCD couplings ~ ***600 GeV***
  - ➡ unitarity limited rates ~ ***4 TeV***
  - ➡ compositeness scale ~ ***8 TeV***



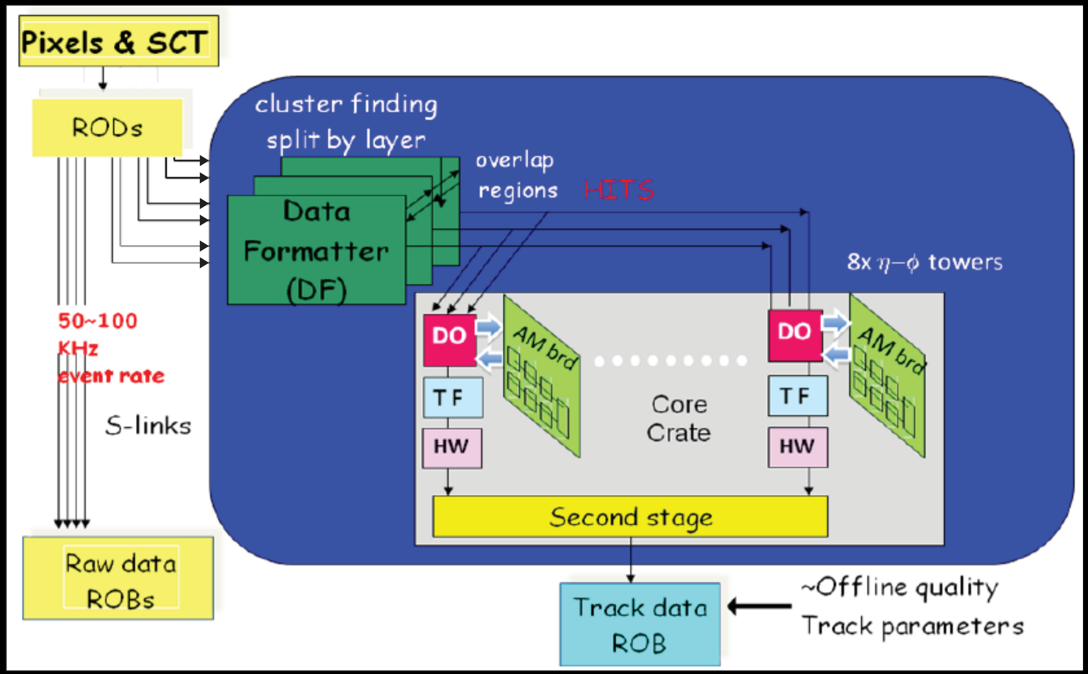
status: Winter '13

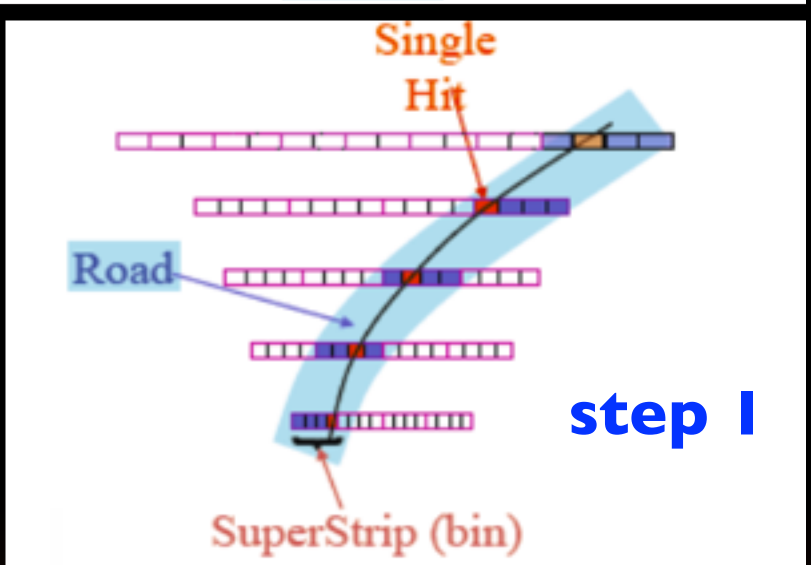
The Fast Tracker (FTK)

- current ATLAS trigger chain
  - ➡ Level-1: hardware based (~50 *kHz*)
  - ➡ Level-2: software based with RoI access to full granularity data (~5 *kHz*) ← tracking enters here
  - ➡ Event Filter: software trigger (~500 *Hz*)

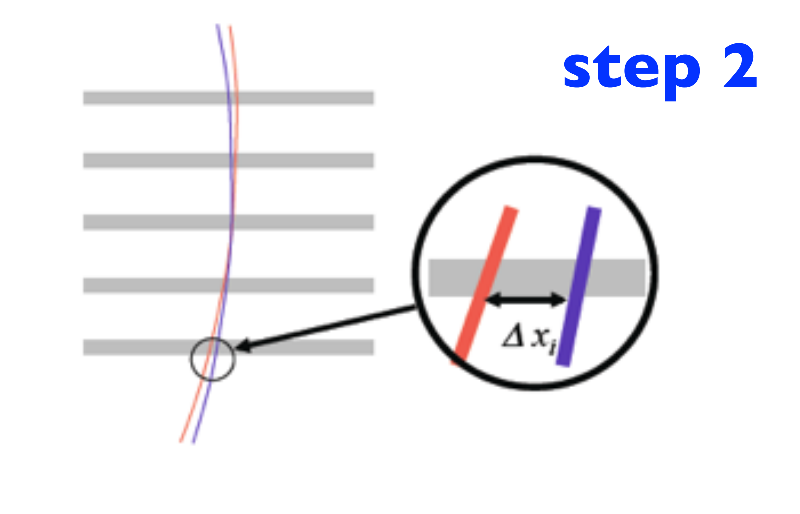
- FTK: hardware based tracking
  - ➡ descendent of the CDF Silicon Vertex Trigger (SVT)
  - ➡ inputs from Pixel and SCT
    - data in parallel to normal read-out
  - ➡ two step reconstruction
    - associative memories for parallel pattern finding
    - linearized track fit implemented in FPGAs
  - ➡ provides track information to Level-2 in ~ 25 μs

- major Level-2 improvement for
  - ➡ b-tagging, τ-reconstruction
  - ➡ lepton isolation
  - ➡ primary and pileup vertex reconstruction





Pattern recognition in coarse resolution (superstrip➔road)



Track fit in full resolution (hits in a road)

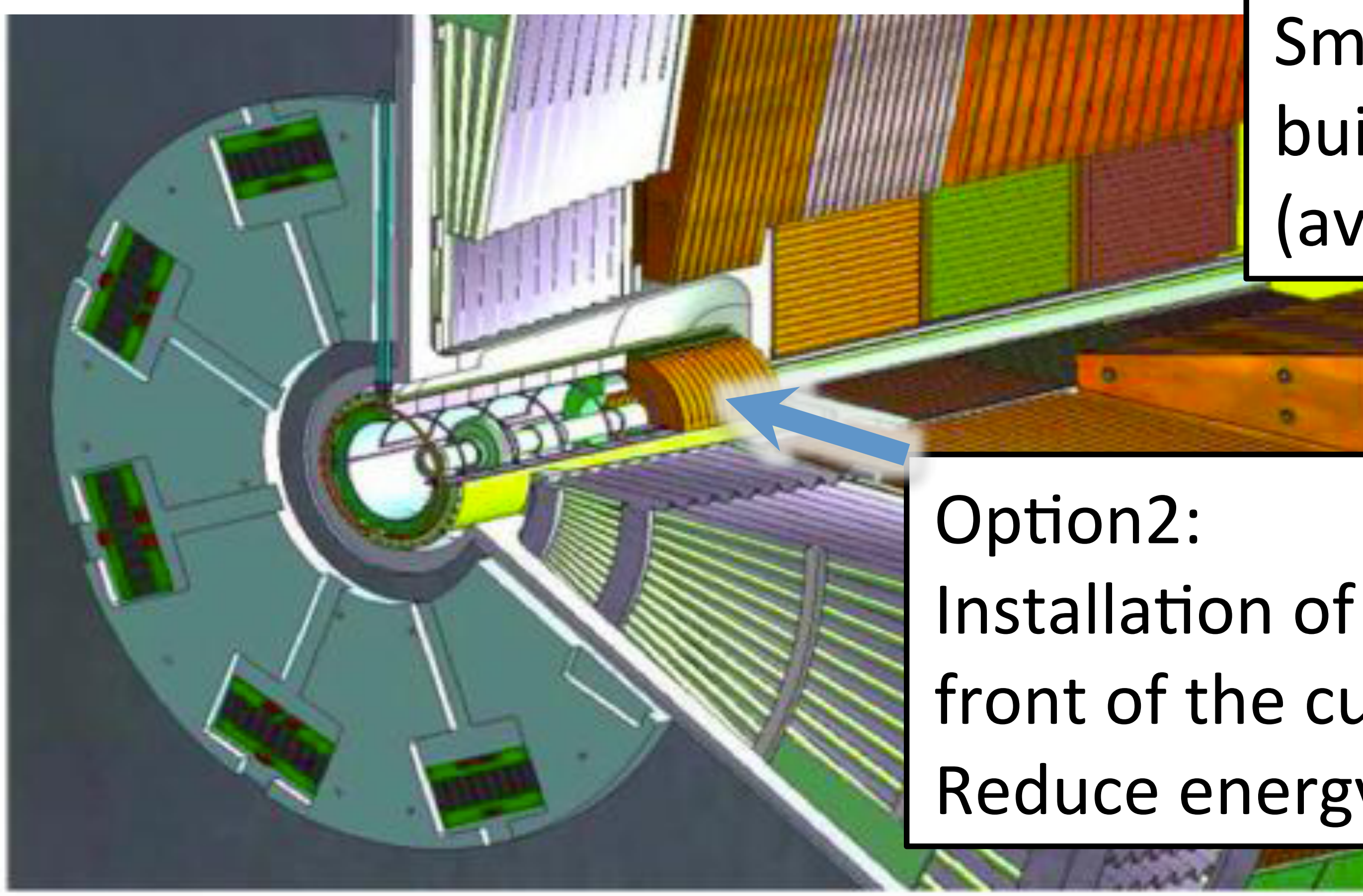
$F(x_1, x_2, x_3, \ldots) \sim a_0 + a_1\Delta x_1 + a_2\Delta x_2 + a_3\Delta x_3 + \ldots = 0$

Phase 2: Calorimeters

Phase 2 Upgrade 2022-23 **Run** 2023-3x => **3000fb^{-1} @ 14 TeV**

- EM LAr Barrel & Tile Calorimeter will work fine: no upgrade.
- Full upgrade of FE and BE electronics (radiation, lifetime, performance …)
  - Both LAr and Tiles
- Hadronic EndCap electronics designed for 1000 fb^{-1} – possible replacement
- Forward Calorimeter @ HL-LHC instantaneous luminosity: overheating / ion build-up / HV drop / signal loss...

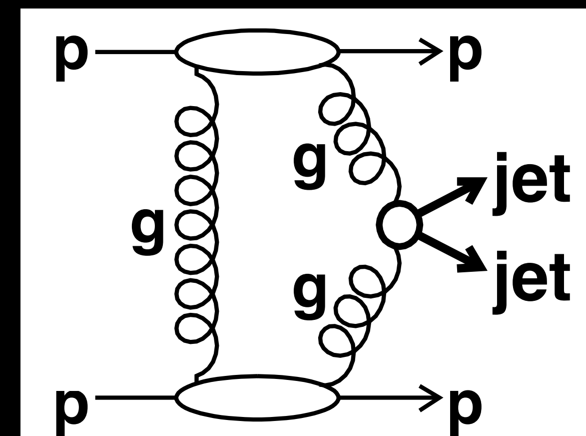
Option1:
Complete replacement of the FCal
Smaller LAr gaps (to reduce ion build-up/HV drop) + better cooling (avoid overheating)

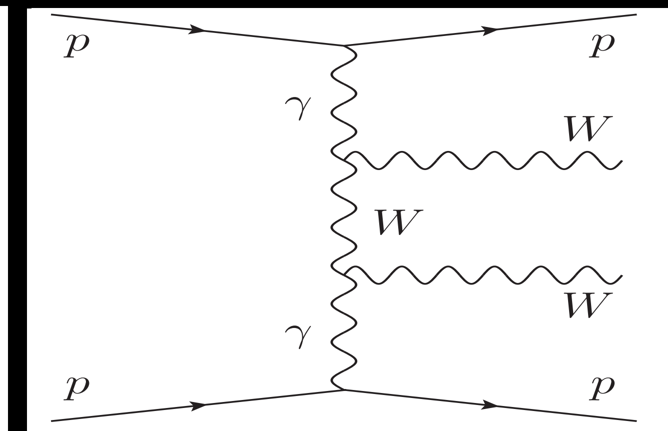


Option2:
Installation of a small calorimeter in front of the current FCal: Mini-FCal => Reduce energy and ionization @ FCal

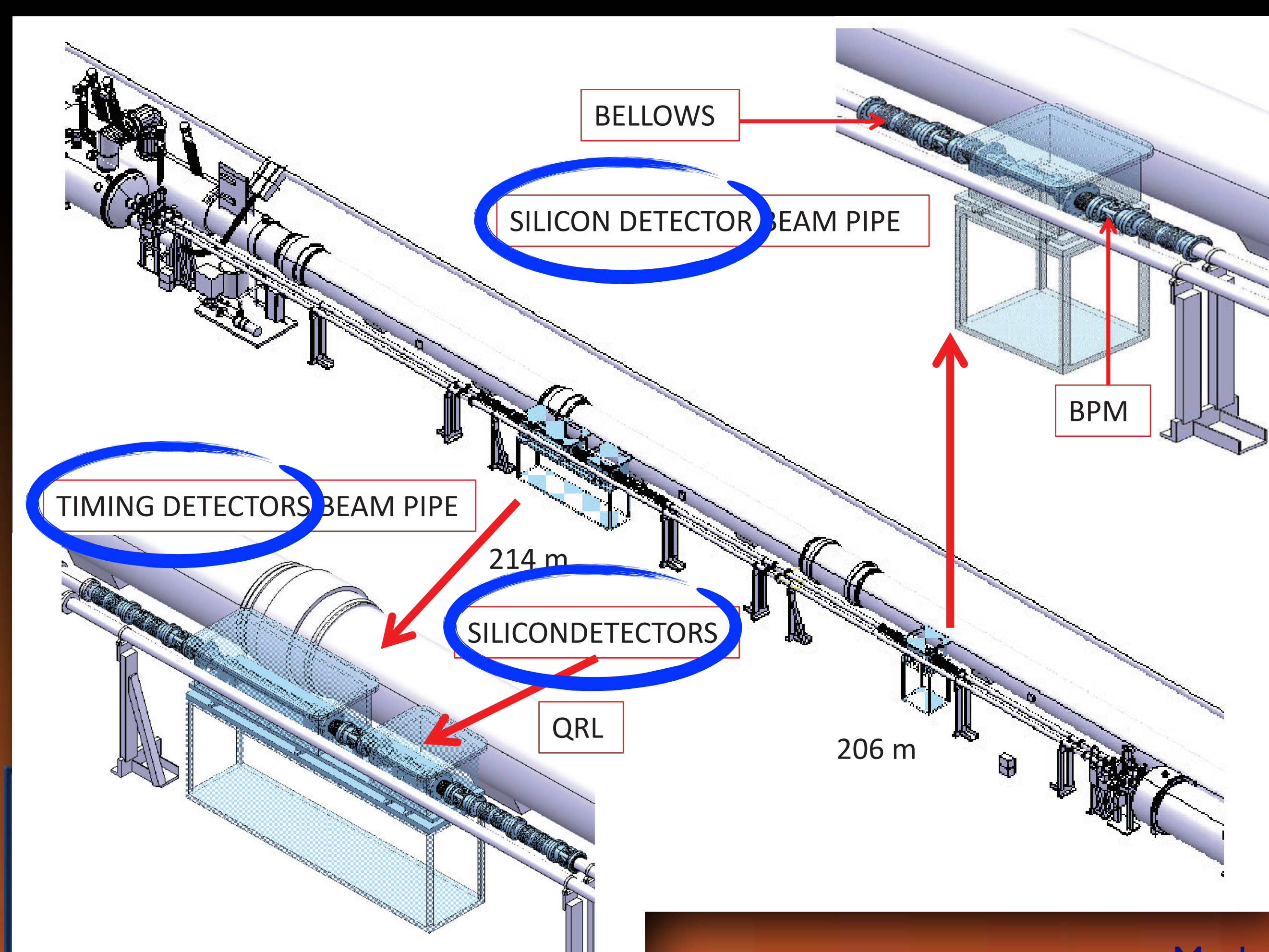
ATLAS Forward Physics (AFP)

- study tagged color singlet or photon exchange processes
  - ➡ p-p tagged high mass central system
  - ➡ anomalous WW couplings, diffractive jet production, new physics ?



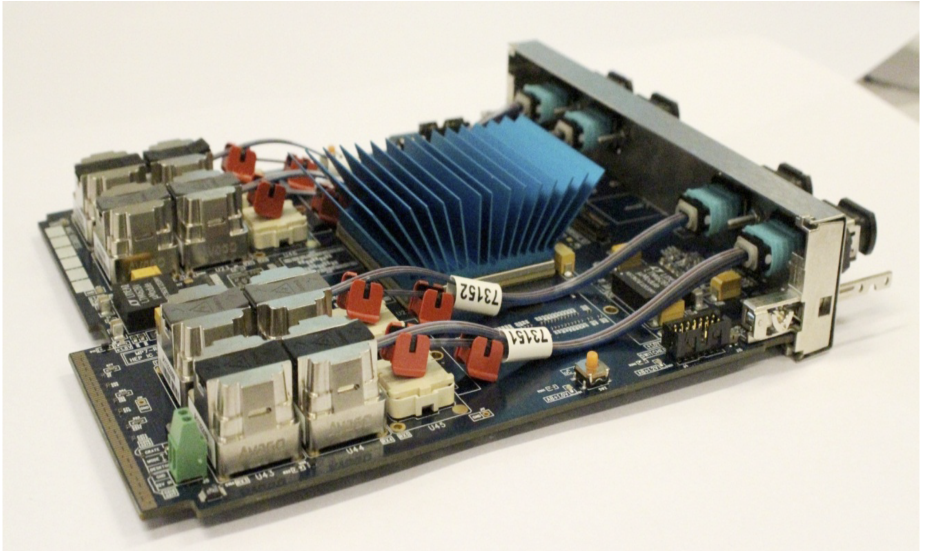


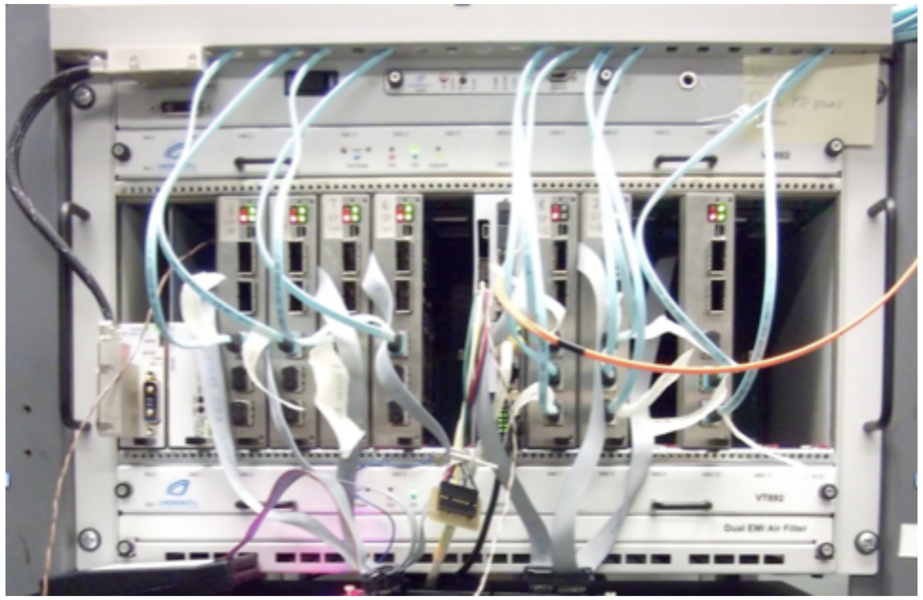
- system of timing and silicon detectors
  - ➡ installed in movable beam pipe to move detectors in while stable beams
  - ➡ at 210 *m* away from P1
  - ➡ 2x6 layer 3D pixel detector (IBL) to measure proton position ~15 *μm*
    - radiation few *mm* from beam
  - ➡ array of 4x8 quartz bars to measure proton timing ~10 *psec* to separate signal and pileup interactions

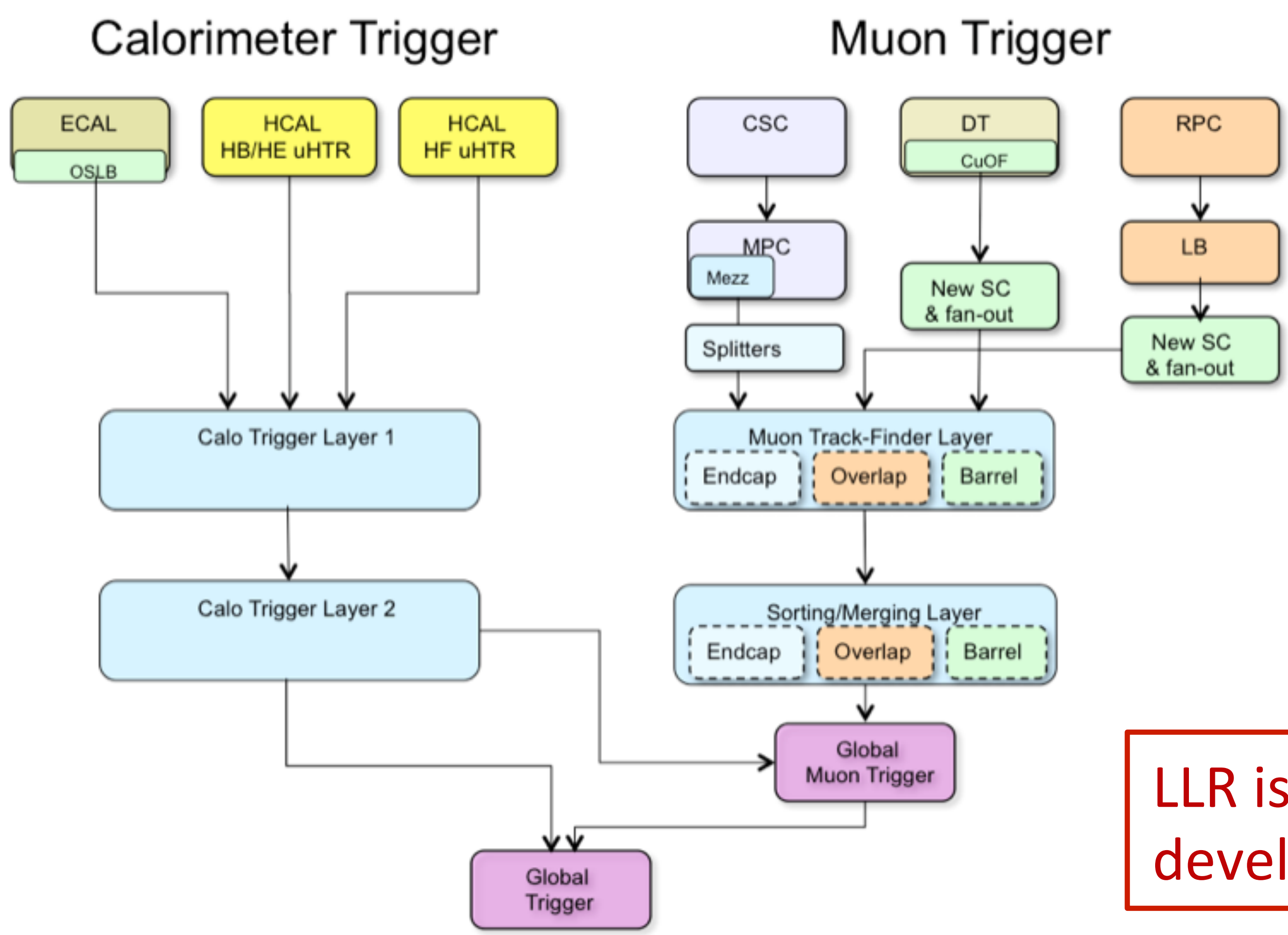


Highlights of the L1-Trigger upgrade (Phase 1)

- **Modern FPGAs and µTCA backplane technology for high bandwidth and processing power**
- **New architecture for calorimeter with a full event in one processor**
  - Higher calorimeter granularity, earlier combination of muon systems and improved algorithms
    - e, γ and µ isolation with PU subtraction
    - Jet finding with PU subtraction
    - Tau finding with much narrower cone
  - Global trigger with more inputs and algorithms correlated quantities (e.g. invariant mass)







LLR is involved in algorithms and firmware developments for the calorimeter trigger

ALICE Upgrades during LS2

- Study Quark Gluon Plasma with Pb-Pb collisions : 6×10^{27} Hz/cm^2 → 10 nb^{-1}
  - Increase DAQ acquisition rate (current 5 kHz) to register all interactions ≥ 50 kHz

Replace Internal Tracking System
→ Improve IP resolution to measure meson and baryon down to P_t ~ 0

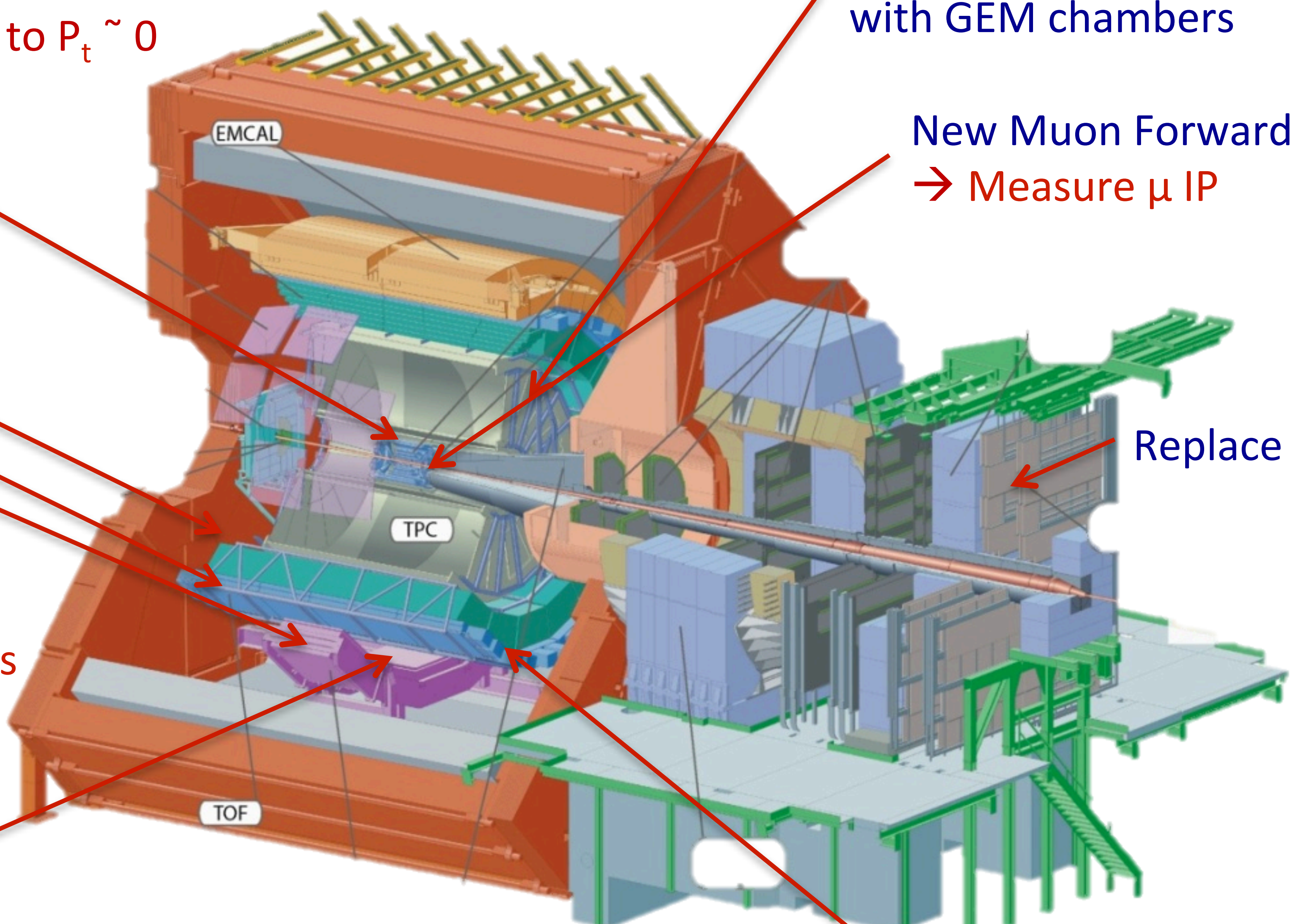
TPC: replace wire chambers with GEM chambers

New Muon Forward Tracker?
→ Measure μ IP

Replace FE and RO of TOF/PHOS/TRD

Replace Muons FE

Very forward EM + Hadron Calorimeter?
→ Access very small x values



VHMPID: Cherenkov + EM
→ PID up to 20 GeV/c

DCAL (during LS1)
→ Complete EMCAL back to back coverage

LoI in 2012 - Detector TDRs in 2013 - Online and Offline in 2014

Table 2.1: Expected performance on the Higgs boson couplings from the LHC and e^+e^- colliders, as compiled from the Higgs Factory 2012 workshop. CLIC numbers from Ref [11-12].

Accelerator → Physical Quantity ↓	**LHC** 300 fb^{-1} /expt	**HL-LHC** 3000 fb^{-1} /expt	**ILC** 250 GeV 250 fb^{-1} 5 yrs	**Full ILC** 250+350+ 1000 GeV 5yrs each	**CLIC** 350 GeV (500 fb^{-1}) 500 GeV (500 fb^{-1}) 1.4 TeV (2 ab^{-1}) 5 yrs each	**LEP3, 4 IP** 240 GeV 2 ab^{-1} (*) 5 yrs	**TLEP, 4 IP** 240 GeV 10 ab^{-1} 5 yrs (*) 350 GeV 1.4 ab^{-1} 3 yrs (*)
N_H	1.7×10^7	1.7×10^8	6×10^4 ZH	10^5 ZH 1.4×10^5 Hνν		4×10^5 ZH	2×10^6 ZH
m_H (MeV)	100	50	35	35	~70	26	7
$\Delta\Gamma_H / \Gamma_H$	--	--	10%	3%	6%	4%	1.3%
$\Delta\Gamma_{inv} / \Gamma_H$	Indirect (30%?)	Indirect (10% ?)	1.5%	1.0%	--	0.35%	0.15%
$\Delta g_{H\gamma\gamma} / g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%	--	5%	N/A	3.4%	1.4%
$\Delta g_{Hgg} / g_{Hgg}$	11 – 5.7%	7.5 – 2.7%	4.5%	2.5%	N/A	2.2%	0.7%
$\Delta g_{Hww} / g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%	4.3%	1%	1%	1.5%	0.25%
$\Delta g_{HZZ} / g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%	1.3%	1.5%	1%	0.65%	0.2%
$\Delta g_{HHH} / g_{HHH}$	--	< 30% (2 expts)	--	~30%	~20%	--	--
$\Delta g_{H\mu\mu} / g_{H\mu\mu}$	< 30%	< 10%	--	--	15%	14%	7%
$\Delta g_{H\tau\tau} / g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%	3.5%	2.5%	3%	1.5%	0.4%
$\Delta g_{Hcc} / g_{Hcc}$	--	--	3.7%	2%	4%	2.0%	0.65%
$\Delta g_{Hbb} / g_{Hbb}$	15 – 6.9%	11 —2.7%	1.4%	1%	2%	0.7%	0.22%
$\Delta g_{Htt} / g_{Htt}$	14 – 8.7%	8.0 – 3.9%	--	15%	3%	--	30%

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[20]

LHCb Flavor Physics Capabilities

Table 16: Statistical sensitivities of the LHCb upgrade to key observables. For each observable the current sensitivity is compared to that which will be achieved by LHCb before the upgrade, and that which will be achieved with $50\,\mathrm{fb}^{-1}$ by the upgraded experiment. Systematic uncertainties are expected to be non-negligible for the most precisely measured quantities. Note that the current sensitivities do not include new results presented at ICHEP 2012 or CKM2012.

Type	Observable	Current precision	LHCb 2018	**Upgrade** ($50\,\mathrm{fb}^{-1}$)	Theory uncertainty
B_s^0 mixing	$2\beta_s$ ($B_s^0 \to J/\psi\ \phi$)	0.10 [137]	0.025	0.008	~ 0.003
	$2\beta_s$ ($B_s^0 \to J/\psi\ f_0(980)$)	0.17 [213]	0.045	0.014	~ 0.01
	a_{sl}^s	6.4×10^{-3} [43]	0.6×10^{-3}	0.2×10^{-3}	0.03×10^{-3}
Gluonic penguins	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\phi)$	–	0.17	0.03	0.02
	$2\beta_s^{\mathrm{eff}}(B_s^0 \to K^{*0}\bar{K}^{*0})$	–	0.13	0.02	< 0.02
	$2\beta^{\mathrm{eff}}(B^0 \to \phi K_S^0)$	0.17 [43]	0.30	0.05	0.02
Right-handed currents	$2\beta_s^{\mathrm{eff}}(B_s^0 \to \phi\gamma)$	–	0.09	0.02	< 0.01
	$\tau^{\mathrm{eff}}(B_s^0 \to \phi\gamma)/\tau_{B_s^0}$	–	5 %	1 %	0.2 %
Electroweak penguins	$S_3(B^0 \to K^{*0}\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.08 [67]	0.025	0.008	0.02
	$s_0\ A_{\mathrm{FB}}(B^0 \to K^{*0}\mu^+\mu^-)$	25 % [67]	6 %	2 %	7 %
	$A_{\mathrm{I}}(K\mu^+\mu^-; 1 < q^2 < 6\,\mathrm{GeV}^2/c^4)$	0.25 [76]	0.08	0.025	~ 0.02
	$\mathcal{B}(B^+ \to \pi^+\mu^+\mu^-)/\mathcal{B}(B^+ \to K^+\mu^+\mu^-)$	25 % [85]	8 %	2.5 %	~ 10 %
Higgs penguins	$\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	1.5×10^{-9} [13]	0.5×10^{-9}	0.15×10^{-9}	0.3×10^{-9}
	$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	–	~ 100 %	~ 35 %	~ 5 %
Unitarity triangle angles	γ ($B \to D^{(*)}K^{(*)}$)	~ 10–12° [243, 257]	4°	0.9°	negligible
	γ ($B_s^0 \to D_s K$)	–	11°	2.0°	negligible
	β ($B^0 \to J/\psi\ K_S^0$)	0.8° [43]	0.6°	0.2°	negligible
Charm *CP* violation	A_Γ	2.3×10^{-3} [43]	0.40×10^{-3}	0.07×10^{-3}	–
	$\Delta\mathcal{A}_{CP}$	2.1×10^{-3} [18]	0.65×10^{-3}	0.12×10^{-3}	–

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