ATLAS and CMS Prospects for Higgs Physics at the HL-LHC

SUSY'15

27th August 2015

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on behalf of ATLAS and CMS Collaborations


or
how far is the future
from us

overview

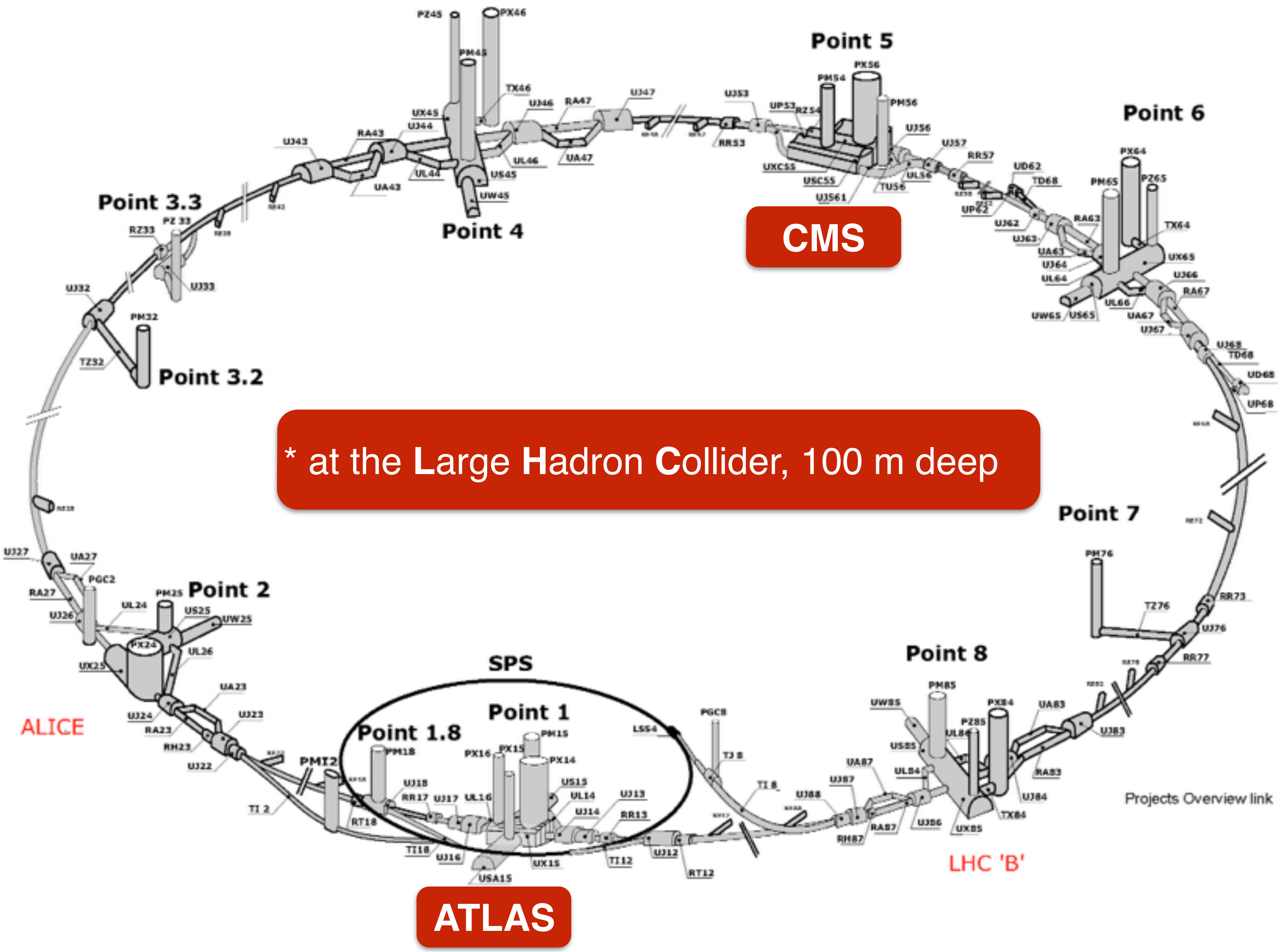
* the road to High Luminosity LHC (el Dorado)

* ATLAS and CMS upgrade to cope with the HL LHC challenges

* Higgs Physics priorities at HL LHC
— couplings projections
— rare decays
— pair production

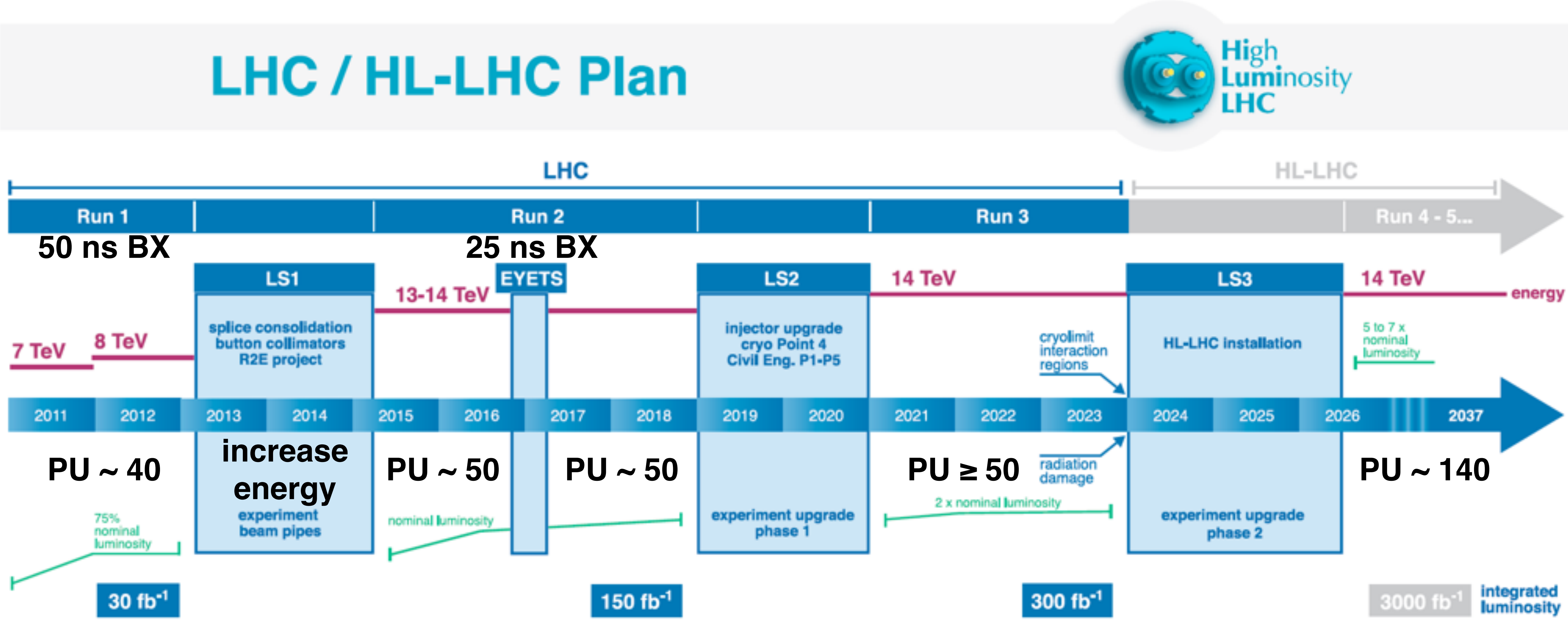
* what could still be in the “visible” range
— VV scattering

where it all (really) happens



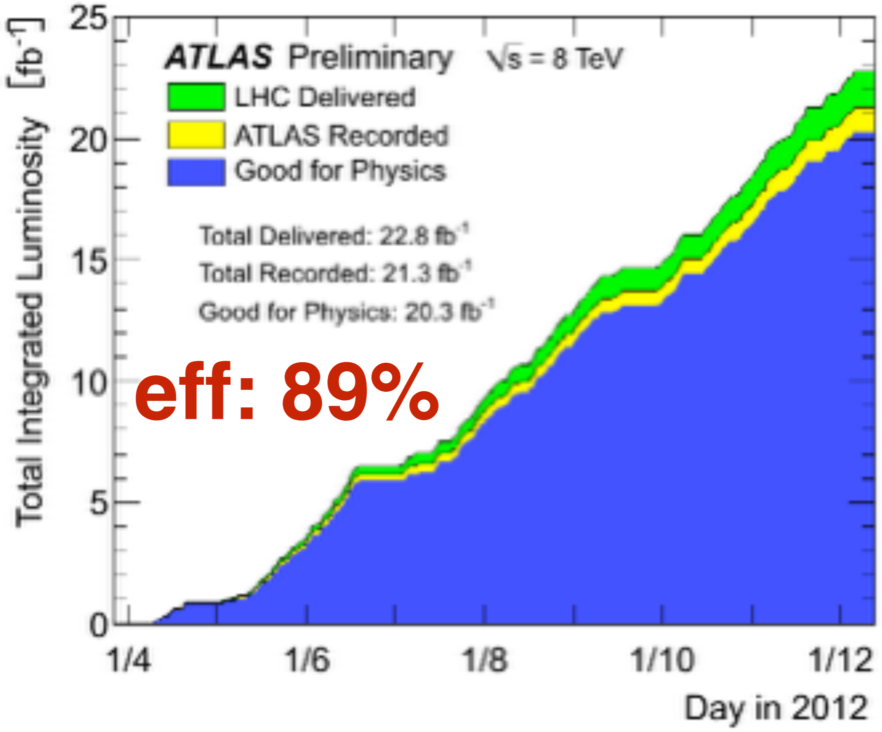
* at the **L**arge **H**adron **C**ollider, 100 m deep

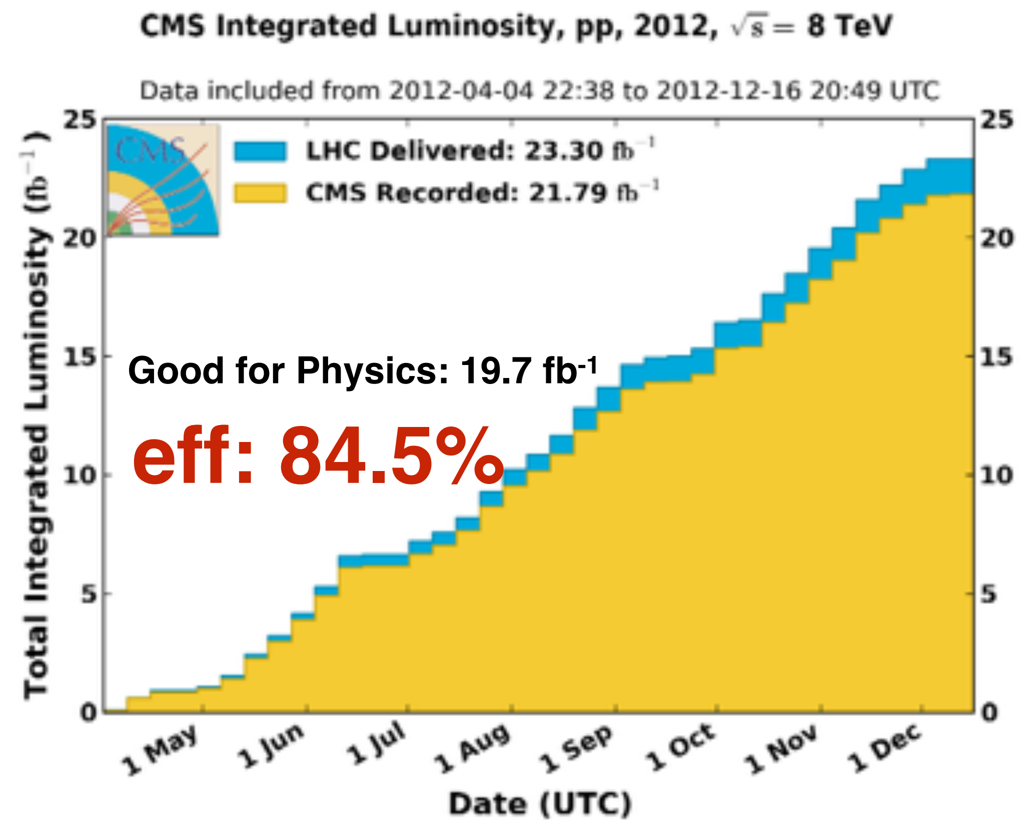
High Lumi LHC: time scale

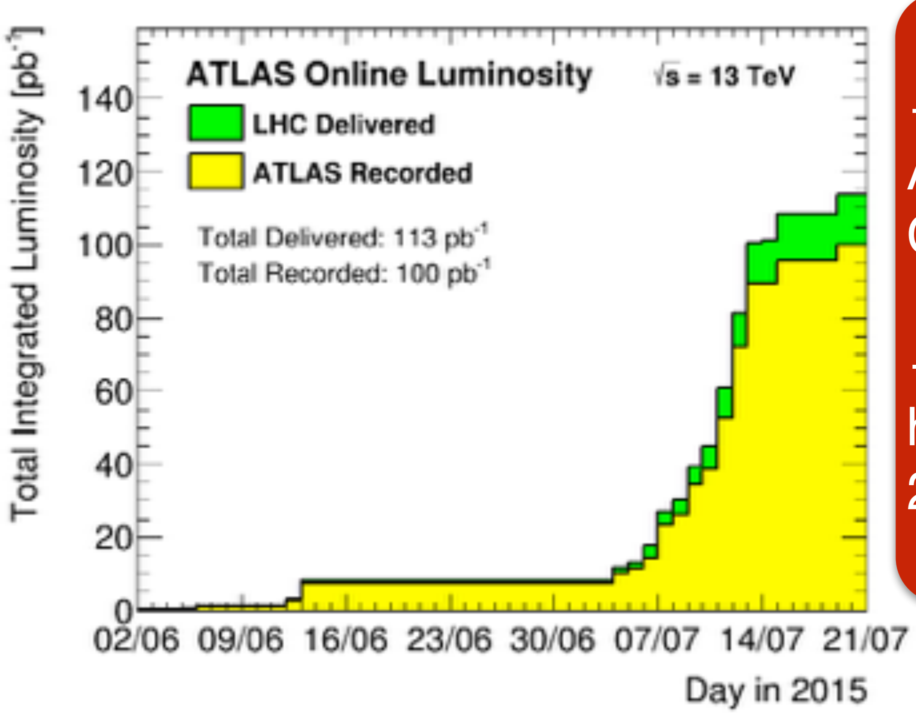


* experiments survived Run I and LS 1 without being damaged by their own constructors
* new data at 13 TeV start accumulating (slowly, but steadily)
* experiments and LHC will have a major upgrade during LS3
* from **mid 2026** (probably 2027) we can talk about HL-LHC data
* goal: deliver 200 to 300 fb^{-1} a year
* many results that your will see in the next slides are quoting 3000 fb^{-1}, nice dream :)

Integrated Luminosity at 8 TeV and 13 TeV

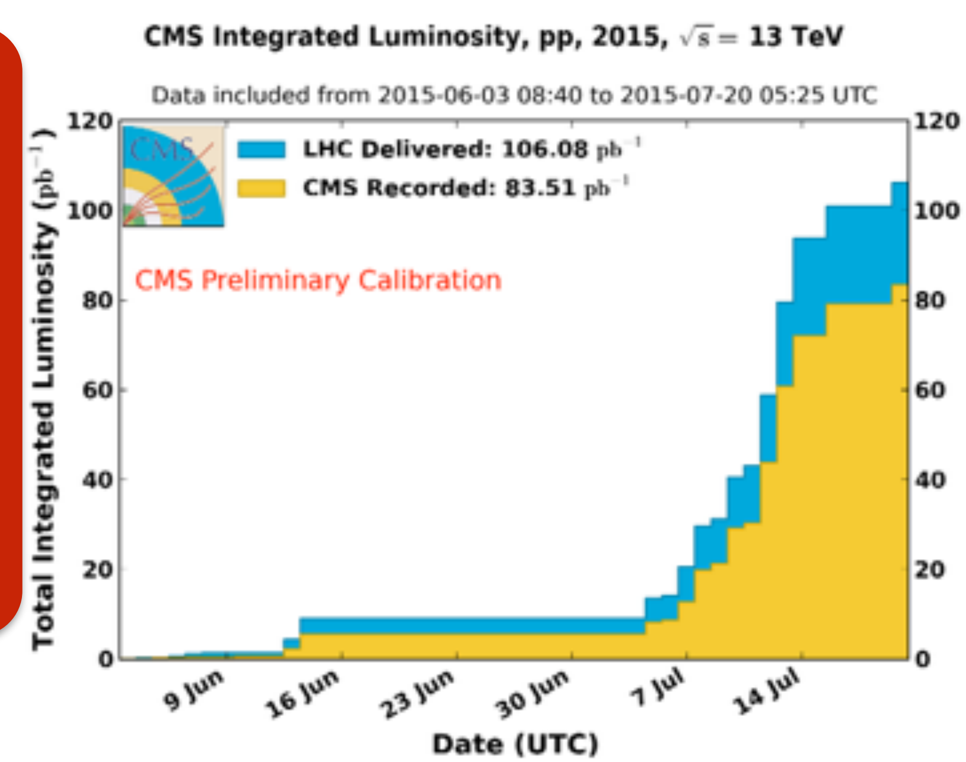




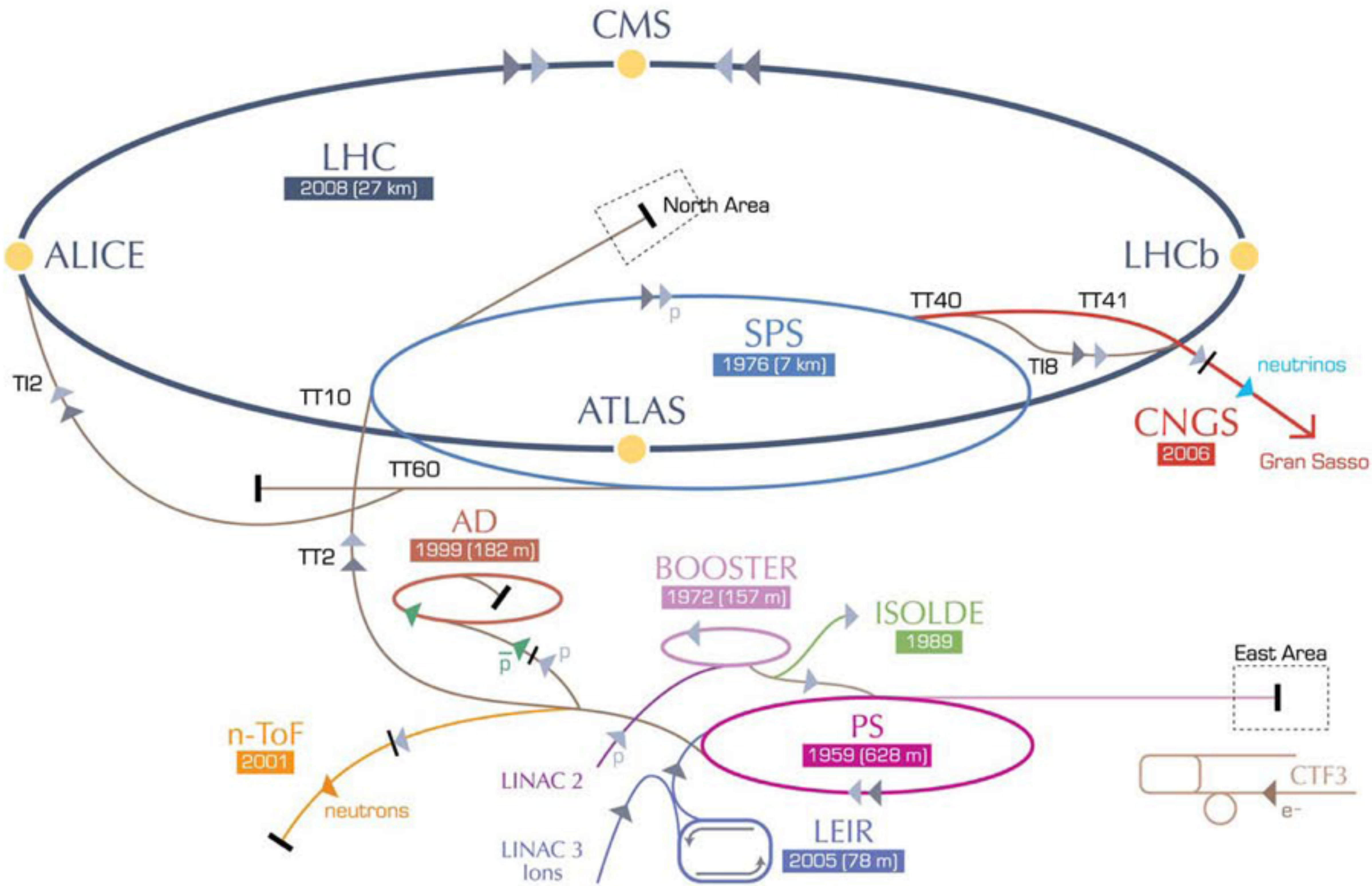


* in more realistic numbers:
— you would need to scale down ATLAS results to 2670 fb^{-1}
CMS results to 2535 fb^{-1}

— or as alternative: we “only” have to keep HL-LHC running for 2 more years to really reach 3000 fb^{-1}

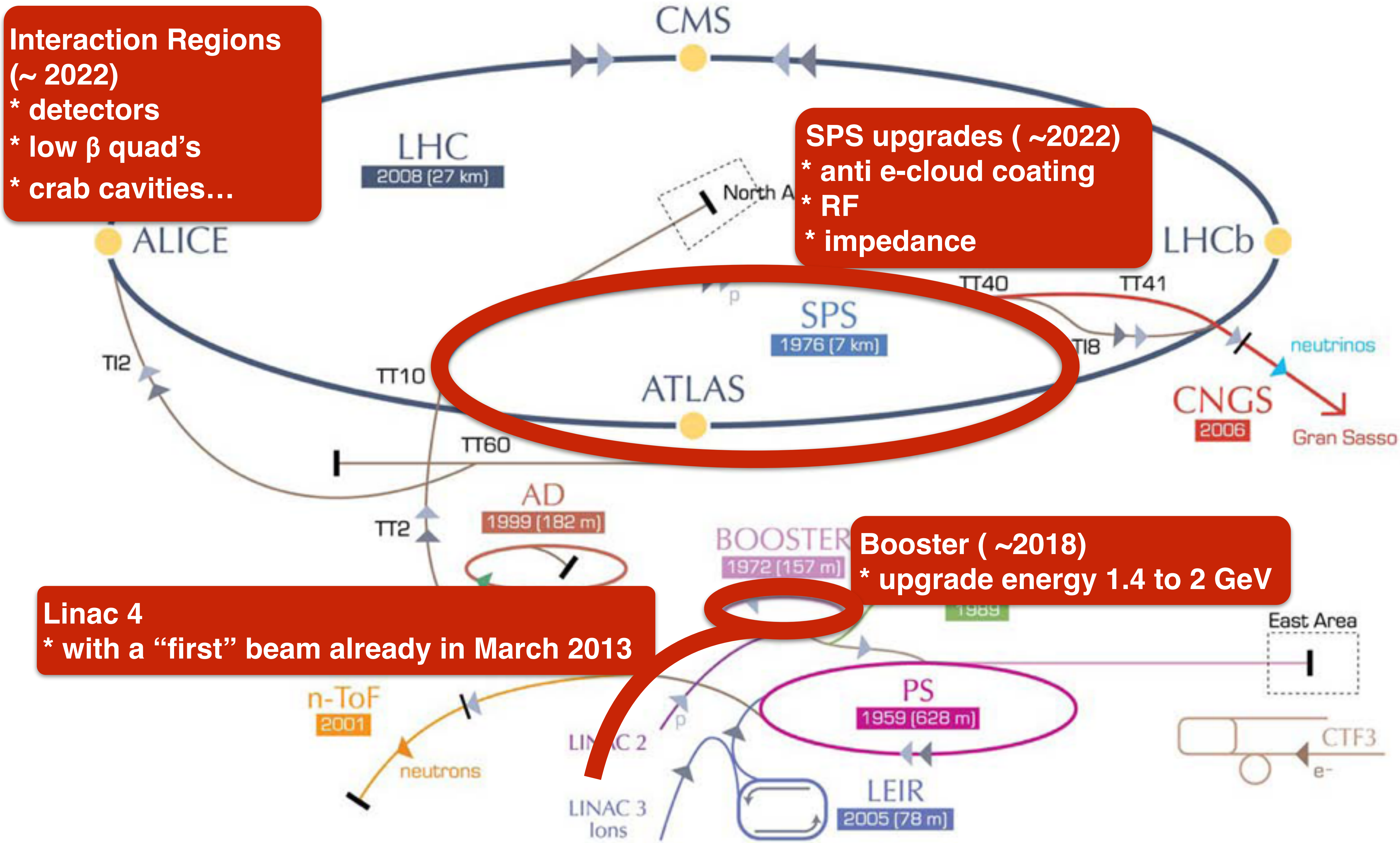


from LHC



CMS
LHC
2008 (27 km)
North Area
ALICE
LHCb
TT40
TT41
p
SPS
1976 (7 km)
TI8
neutrinos
TI2
TT10
ATLAS
CNGS
2006
Gran Sasso
TT60
AD
1999 (182 m)
TT2
BOOSTER
1972 (157 m)
ISOLDE
1989
East Area
p̄
p
n-ToF
2001
PS
1959 (628 m)
p
LINAC 2
CTF3
e–
neutrons
LINAC 3
Ions
LEIR
2005 (78 m)

to HL LHC



Interaction Regions (~ 2022)
* detectors
* low β quad's
* crab cavities…

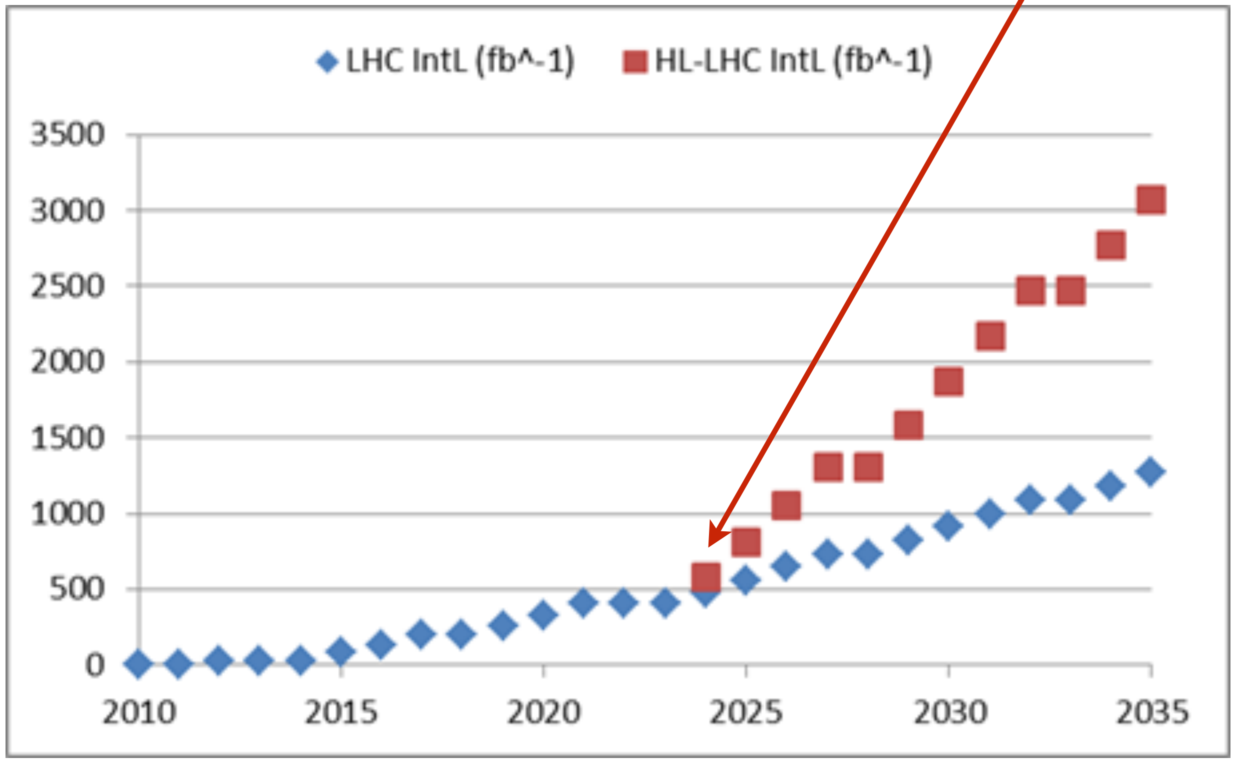
SPS upgrades (~2022)
* anti e-cloud coating
* RF
* impedance

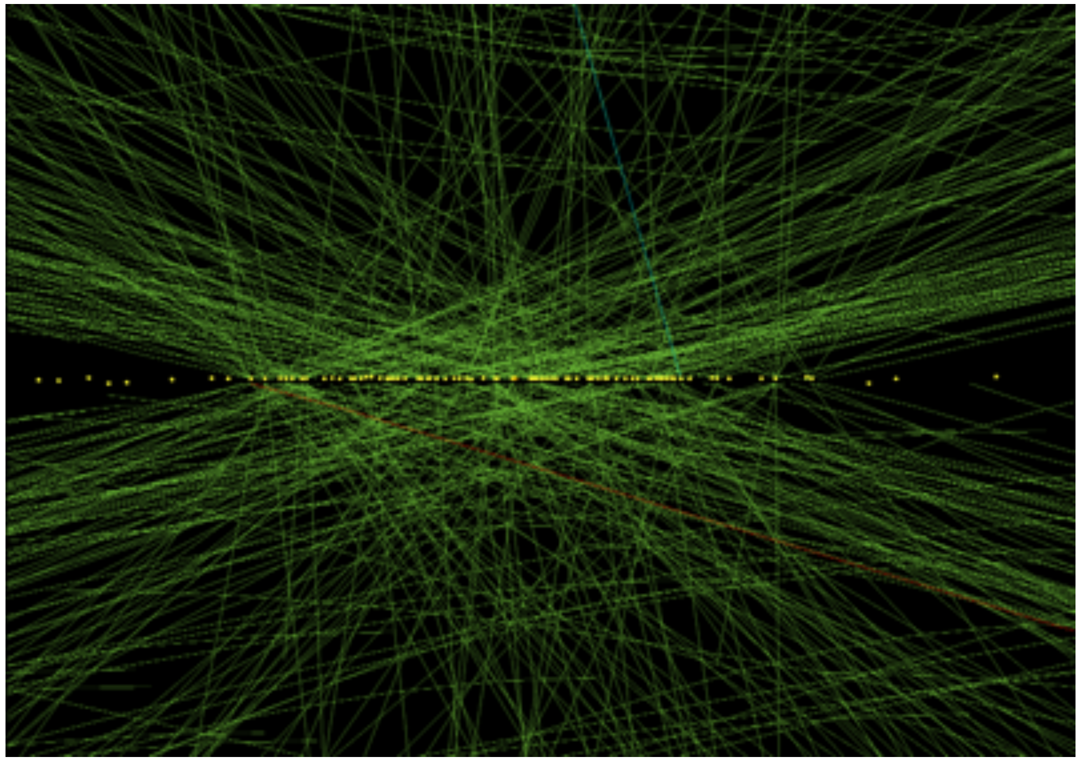
Booster (~2018)
* upgrade energy 1.4 to 2 GeV

Linac 4
* with a "first" beam already in March 2013

and the detectors…

will have to face an expected average number of ~140 PU





* here is “only” a 78 PV example in an event from high-pileup run at 8 TeV in CMS

… will have a different DNA than before

ATLAS

LS 2

* Forward Muon Spectrometer:
— new small wheel (nSW)
* L1-trigger: high precision calorimeter
* L2-trigger: fast tracking (FTK)
* new forward diffractive physics detectors (AFP)

LS 3

* new Tracker (Silicon)
* Calorimeter electronics upgrade
* Muon System upgrade
* L0/L1 trigger architecture with L1-Track Trigger
* Forward Calorimeter upgrade

they will almost look like twins

CMS

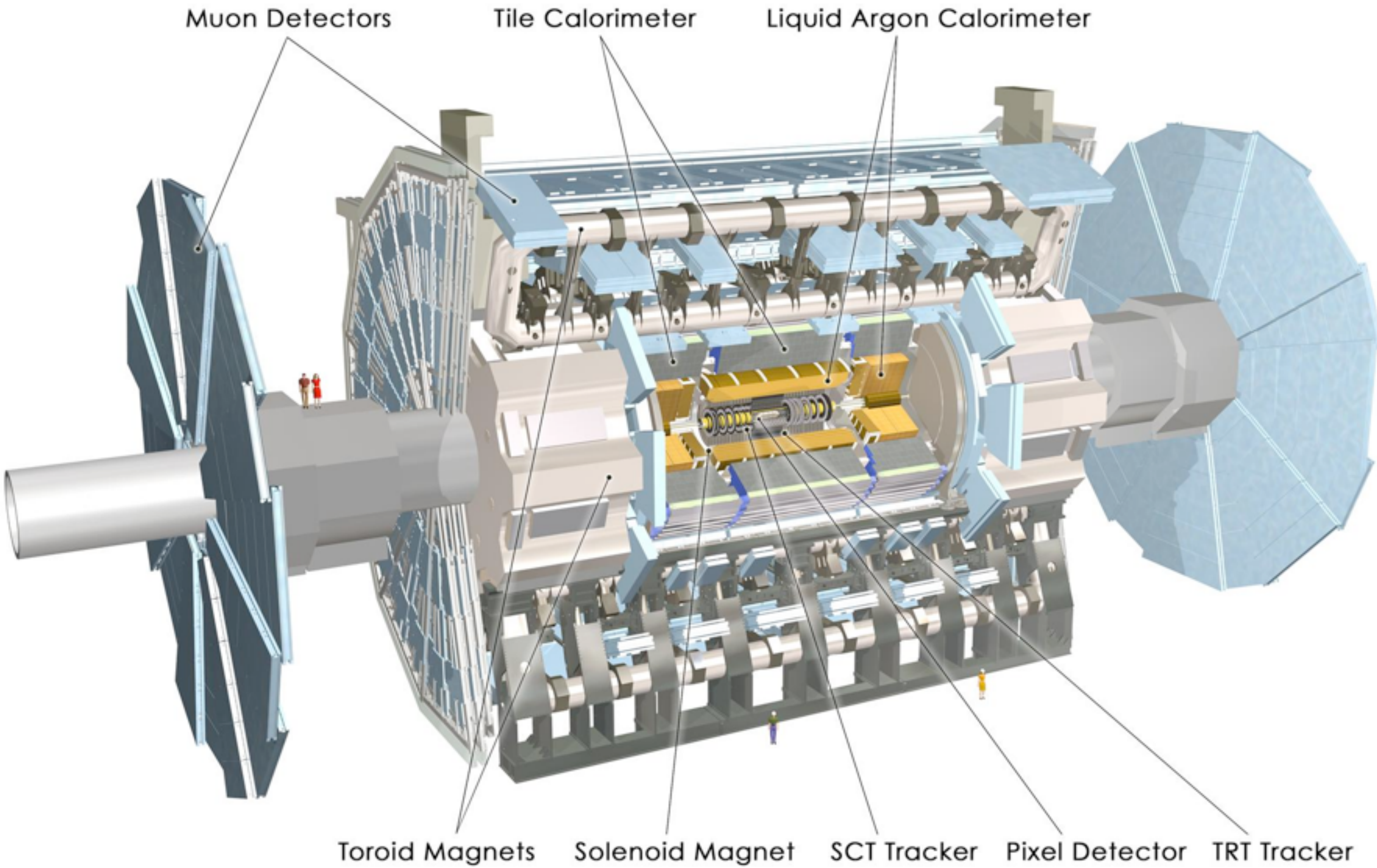
LS 2

* Pixel detector: add Layer 4 and squeeze Layer 1 radius
* HCAL electronics
* L1 trigger upgrade
* GEM: forward muon

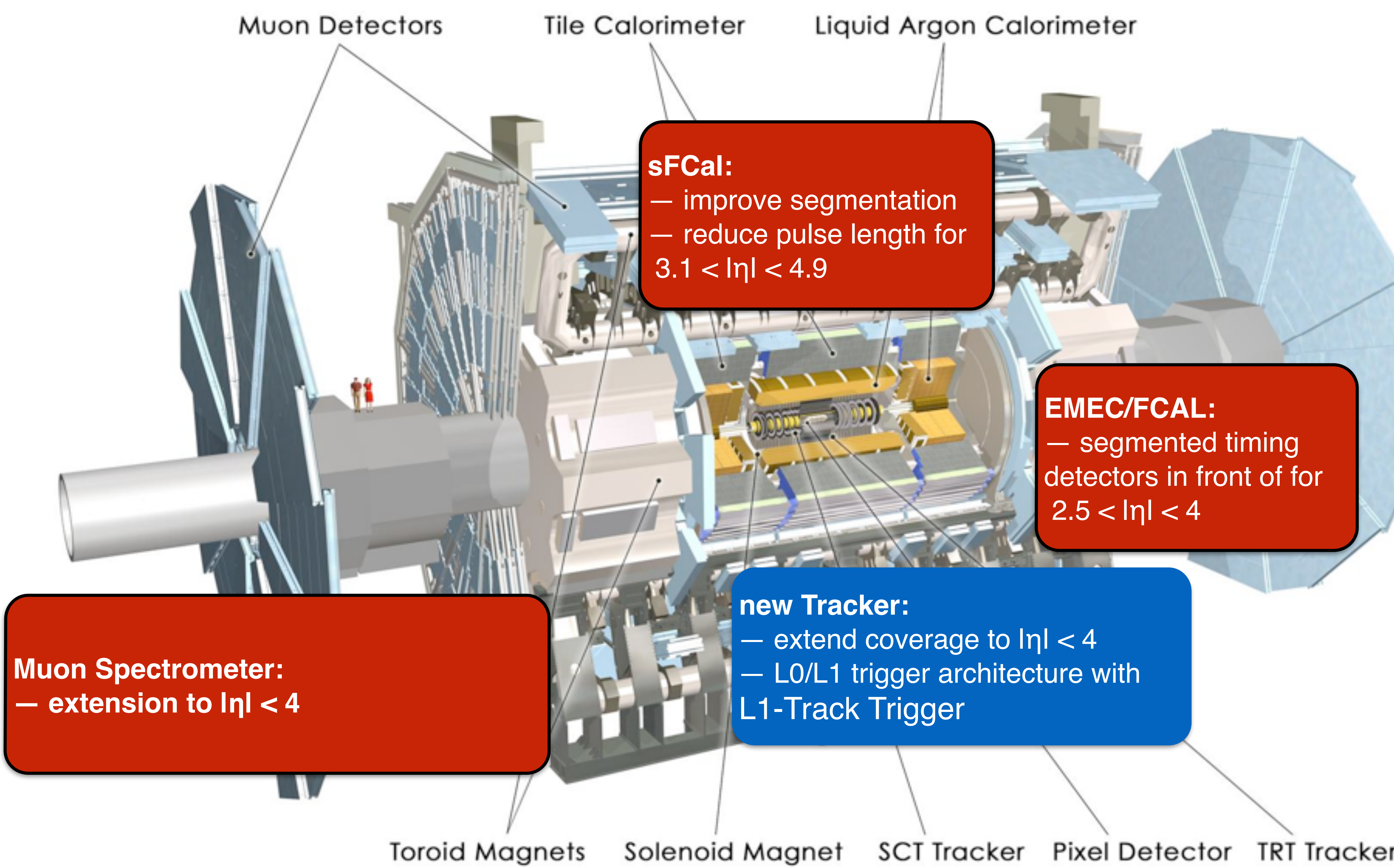
LS 3

* complete Tracker replacement
* L1-Track Trigger
* forward regions: improve tracking, calorimetry, muon ID
* High precision timing for PU mitigation
* Trigger upgrade
* DAQ upgrade

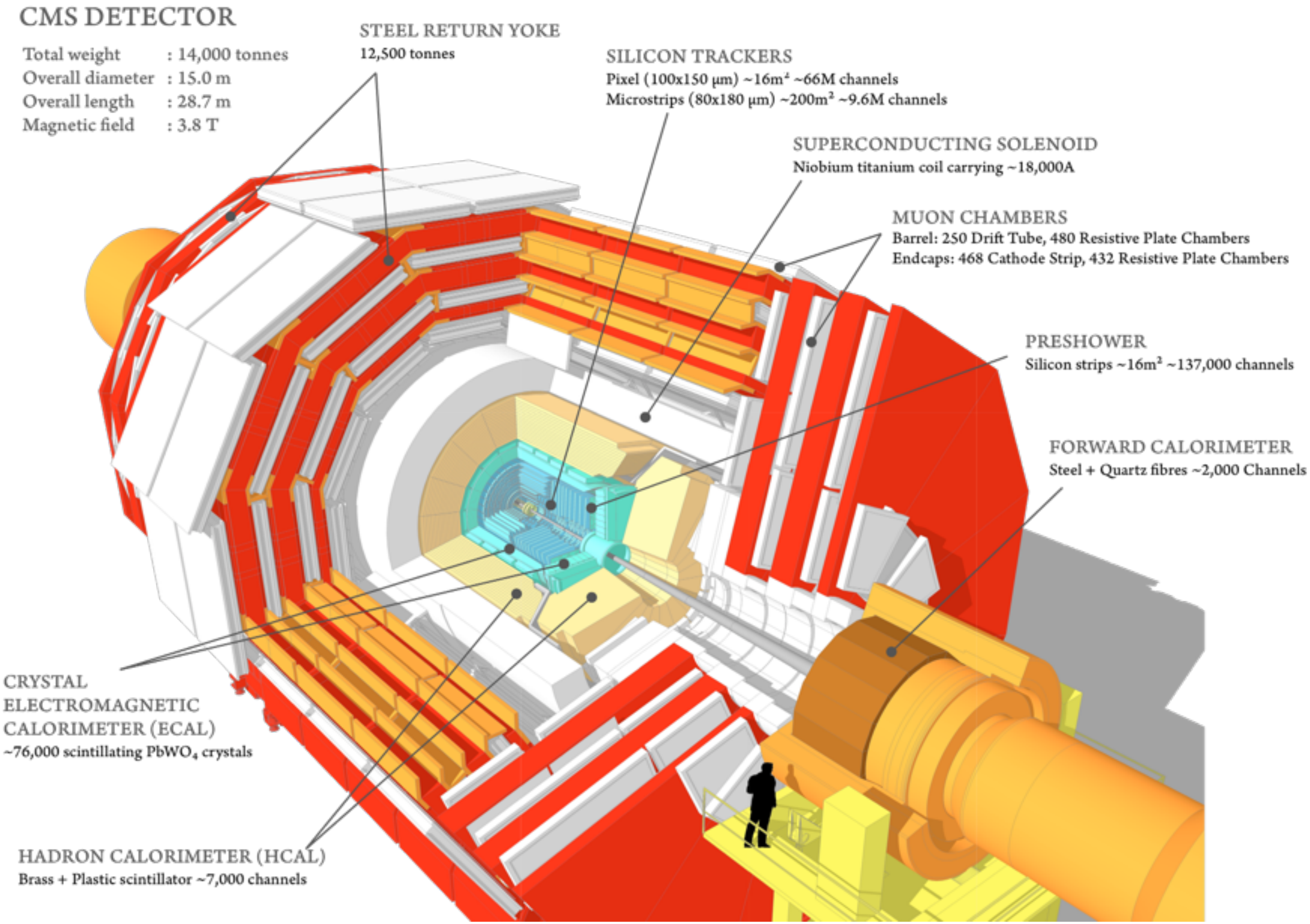
ATLAS


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

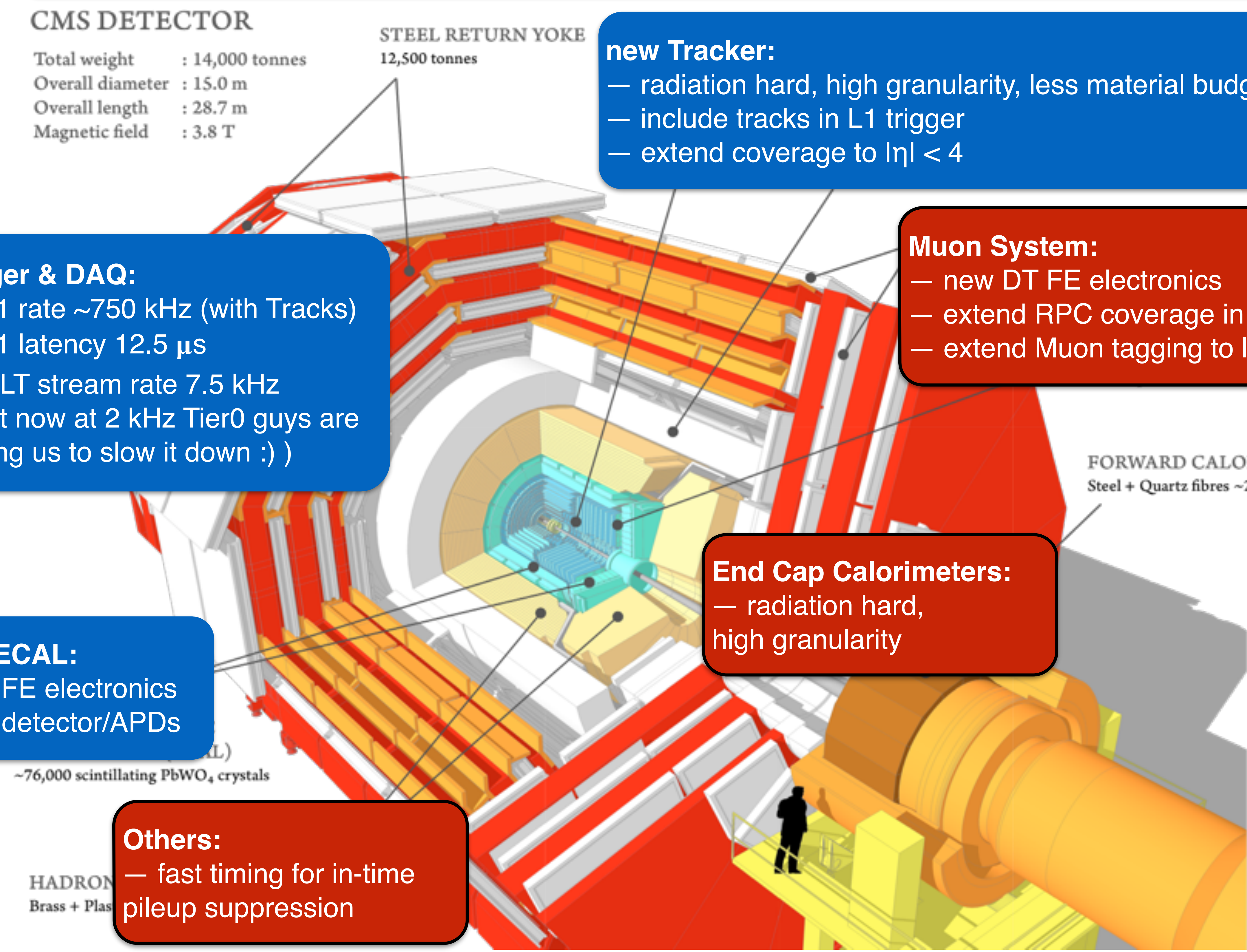
and now forget the old ATLAS



CMS


CMS DETECTOR
Total weight : 14,000 tonnes
Overall diameter : 15.0 m
Overall length : 28.7 m
Magnetic field : 3.8 T
STEEL RETURN YOKE
12,500 tonnes
SILICON TRACKERS
Pixel (100x150 μm) ~16m² ~66M channels
Microstrips (80x180 μm) ~200m² ~9.6M channels
SUPERCONDUCTING SOLENOID
Niobium titanium coil carrying ~18,000A
MUON CHAMBERS
Barrel: 250 Drift Tube, 480 Resistive Plate Chambers
Endcaps: 468 Cathode Strip, 432 Resistive Plate Chambers
PRESHOWER
Silicon strips ~16m² ~137,000 channels
FORWARD CALORIMETER
Steel + Quartz fibres ~2,000 Channels
CRYSTAL ELECTROMAGNETIC CALORIMETER (ECAL)
~76,000 scintillating PbWO4 crystals
HADRON CALORIMETER (HCAL)
Brass + Plastic scintillator ~7,000 channels

and now forget the old CMS



new Tracker:
— radiation hard, high granularity, less material budget
— include tracks in L1 trigger
— extend coverage to $|\eta| < 4$

Muon System:
— new DT FE electronics
— extend RPC coverage in forward region
— extend Muon tagging to $|\eta| < 3$

Tigger & DAQ:
— L1 rate ~750 kHz (with Tracks)
— L1 latency 12.5 µs
— HLT stream rate 7.5 kHz
(right now at 2 kHz Tier0 guys are calling us to slow it down :))

End Cap Calorimeters:
— radiation hard,
high granularity

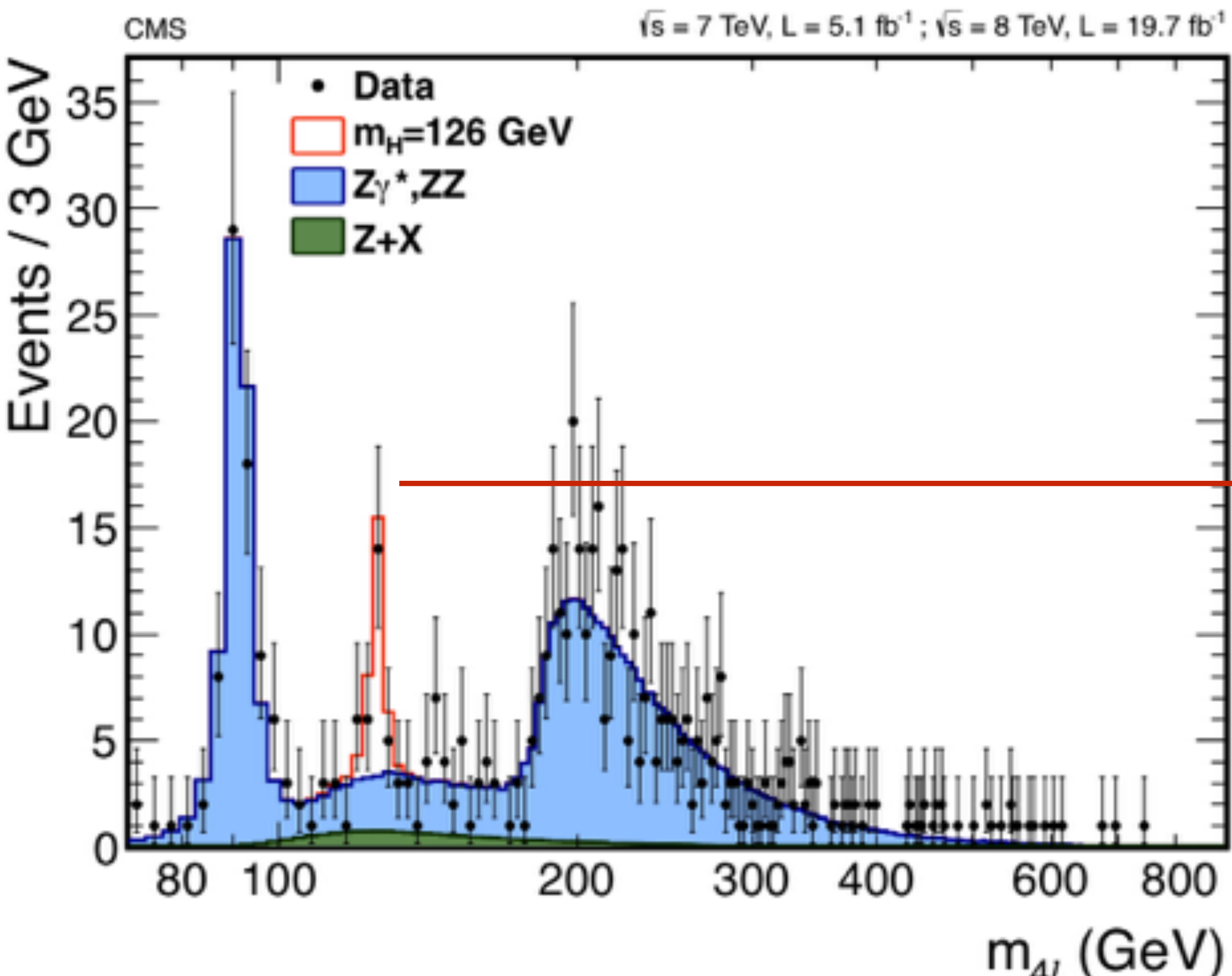
barrel ECAL:
— new FE electronics
— cool detector/APDs

Others:
— fast timing for in-time pileup suppression

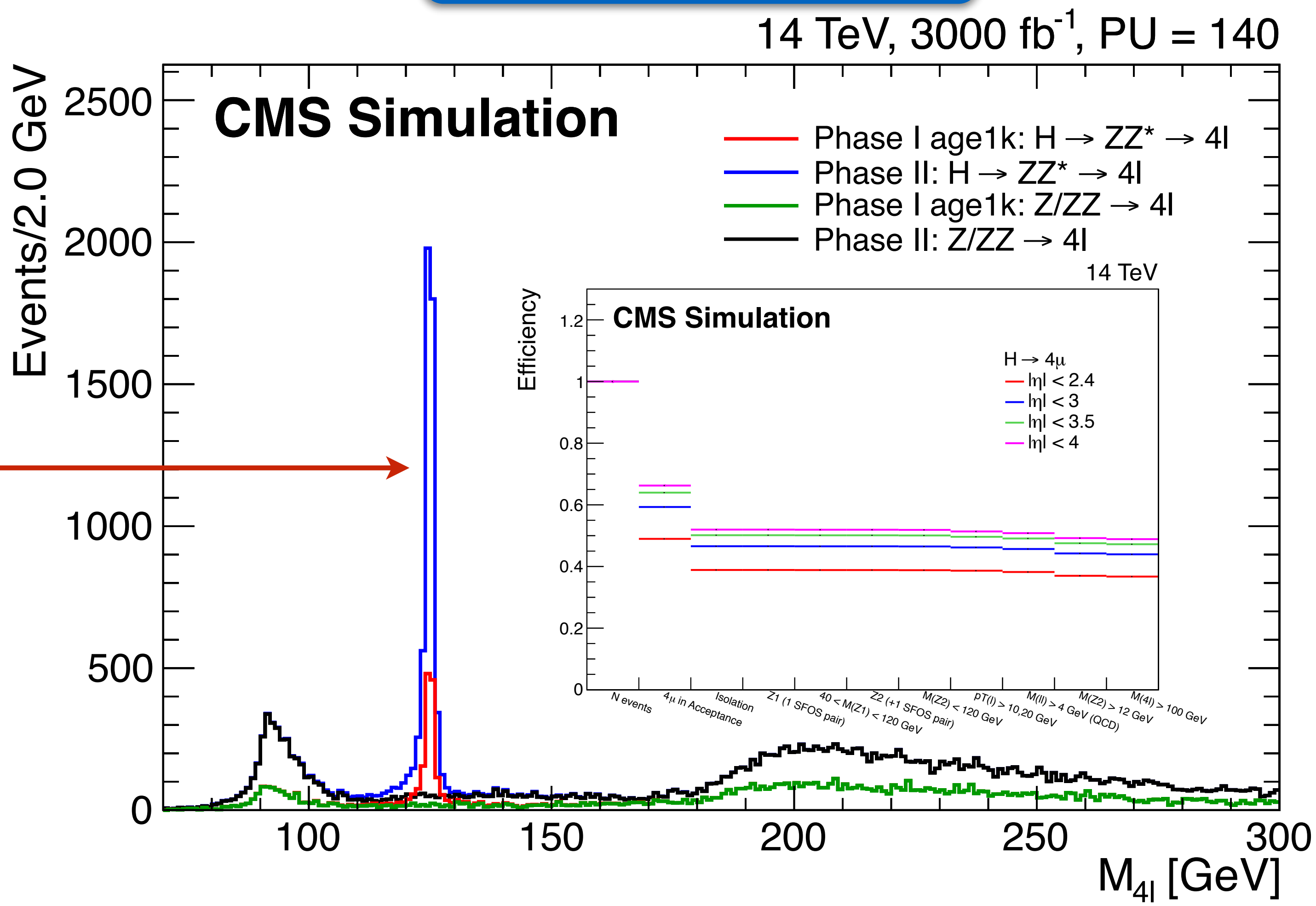
what can we improve with all these…

one example from CMS

LHC Run I



after HL LHC



*** alone, an extension to |η| < 3 gives 20% more acceptance**

*** after all, the Higgs signal becomes dominant and Higgs to ZZ can be used as reference for additional studies**

… and more…

Performance/ Physics	Higgs VBF H→$\tau\tau$	Higgs H→μμ	Higgs H→ZZ→4l	Higgs HH→bbγγ	Higgs HH→bb$\tau\tau$	SMP VBS	SUSY VH(bb) +MET	EXO A_{fb} (Z')	EXO Dark Matter	BPH $B_{s,d}$→μμ
Tracker										
Performance		*mass resolution*	mass resolution	*b-tagging*	*b-tagging*					*mass resolution*
Extensions	*forward jets / MET*		*acceptance*		*MET resolution*	*forward jets*	*MET resolution*	*acceptance*	*acceptance*	
Trigger										
Bandwidth	*acceptance*				*acceptance*					
Track Trigger	*background rejection*				*background rejection*					*background rejection*
Calorimeter										
ECAL	*forward jets / MET*		*acceptance*	*acceptance*	*MET resolution*	*forward jets*	*MET resolution*	*acceptance*	*acceptance*	
HCAL	*forward jets / MET*				*MET resolution*	*forward jets*	*MET resolution*			
Muons										
Extension			*acceptance*					*acceptance*	*acceptance*	

today I will cover the Higgs part

Higgs Physics priorities at HL LHC

* high precision measurements of:
— production cross-sections, couplings, J^{PC}, width

* measure and search for anomalies in rare and very rare decays

* measure self-coupling

* study VV scattering

* if any new Physics — can it be integrated with the SM-like Higgs boson?

where do we stand now?
- this is what we know so far from **CMS** -

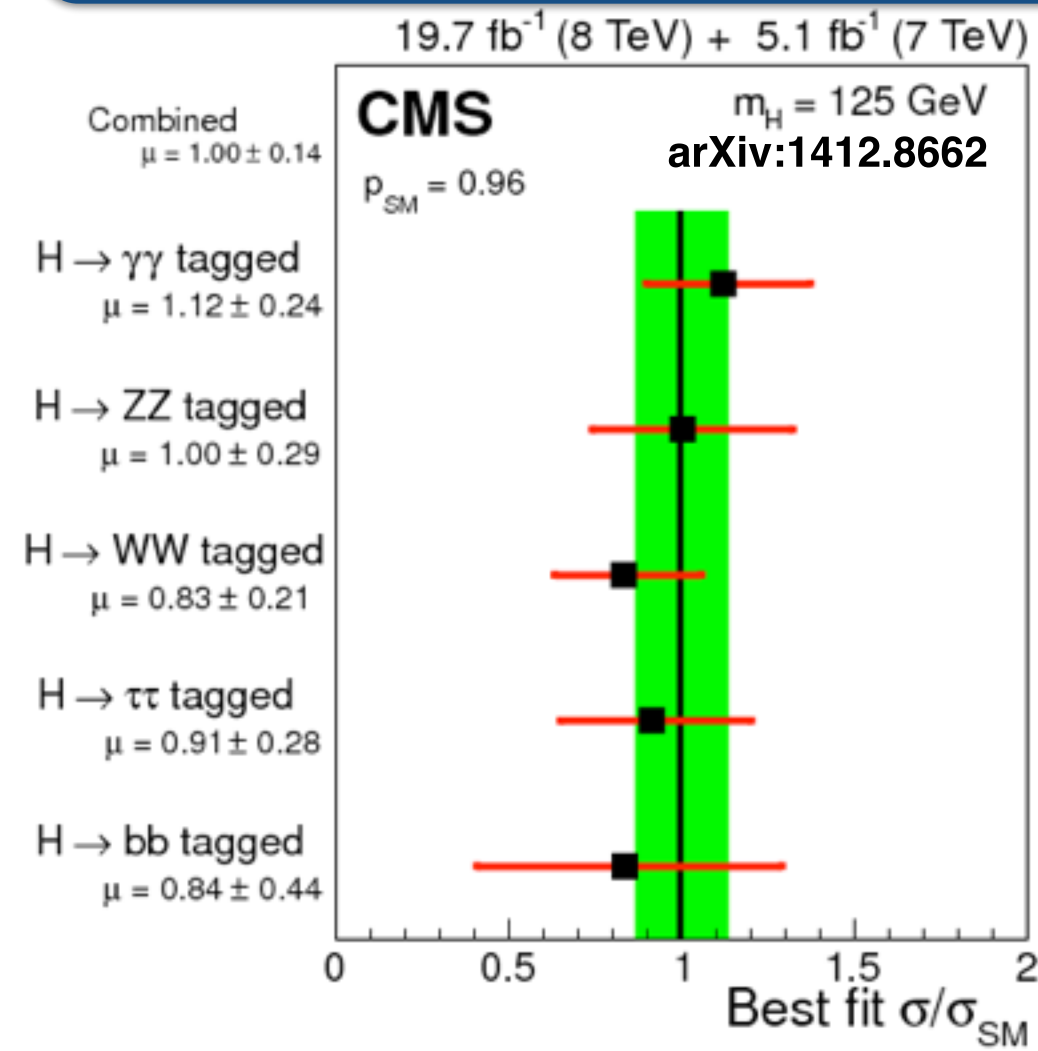
mass of the new boson:

$125.02\ ^{+0.26}_{-0.27}\,(\text{stat.})\ ^{+0.14}_{-0.15}\,(\text{syst.})$ **GeV**

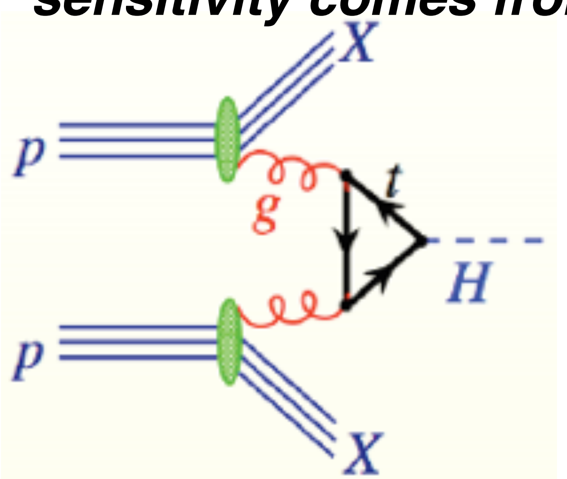
- Significance (m_H = 125.0 GeV)

Combination	Expected (post-fit)	Observed
H→ZZ tagged	6.3 σ	6.5 σ
H→γγ tagged	5.3 σ	5.6 σ
H→WW tagged	5.4 σ	4.7 σ
H→ττ tagged	3.9 σ	3.8 σ
H→bb tagged	2.6 σ	2.0 σ
H→μμ tagged	<0.1 σ	0.4 σ

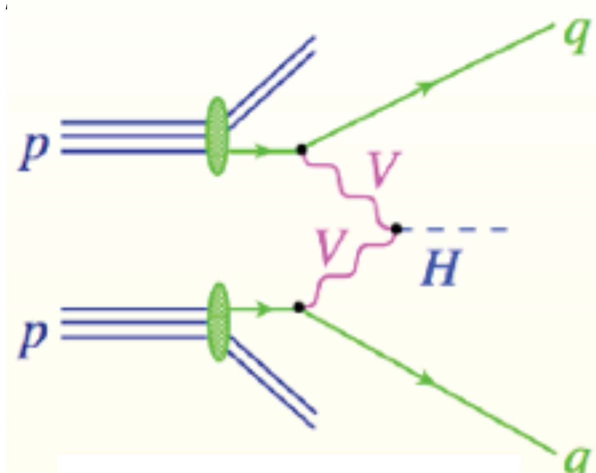
- combined signal strength: **μ = 1.00 ± 0.14**



sensitivity comes from:



gluon-gluon fusion



Vector Boson fusion

*** there is a new boson**

*** with properties consistent with the SM Higgs, within current uncertainties**

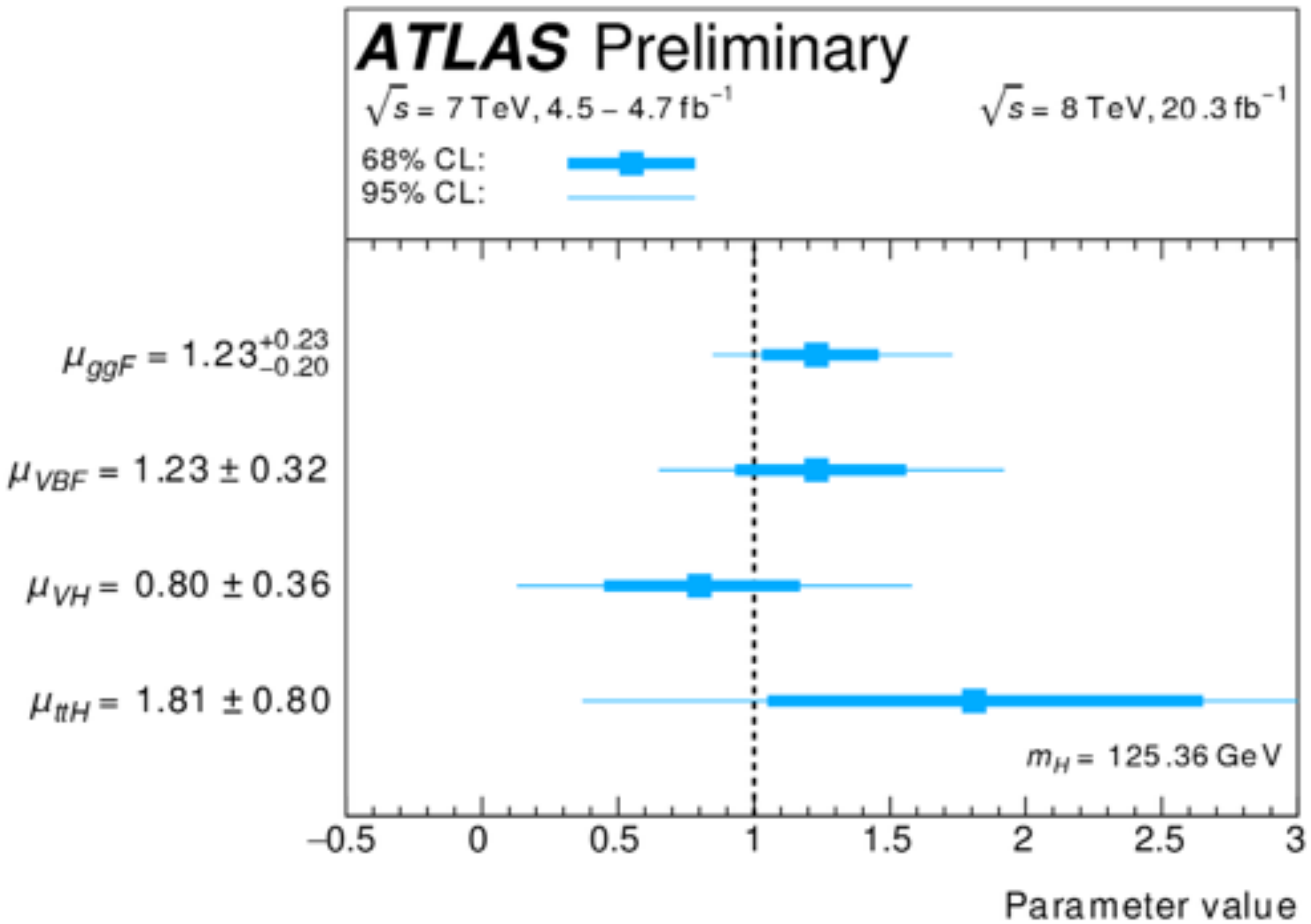
where do we stand now?

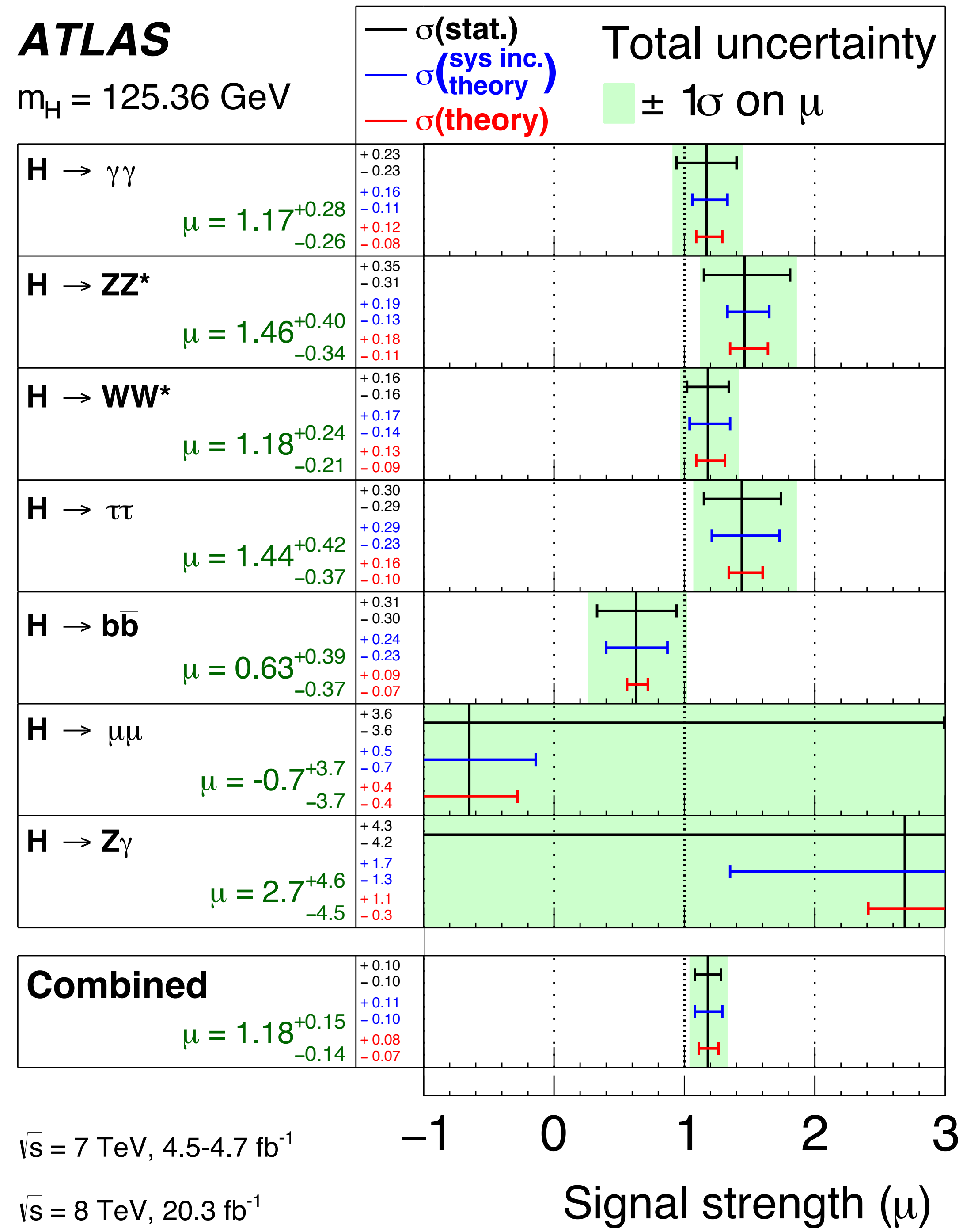
- this is what we know so far from **ATLAS** -

- combined signal strength: **$\mu = 1.18\ ^{+15}_{-14}$**

mass of the new boson:

$$m_H = 125.36 \pm 0.37\,(\mathrm{stat}) \pm 0.18\,(\mathrm{syst})\ \mathrm{GeV}$$





a historical combination
ATLAS + CMS: Higgs mass after Run I

* Higgs boson cross section and branching fractions uncertainties
* normalisation of SM background processes

* statistic uncertainty

$$m_H = 125.09 \pm 0.21(\text{stat.}) \pm 0.11(\text{scale}) \pm 0.02(\text{other}) \pm 0.01(\text{theory})\ \text{GeV}$$

* energy scale and resolution

all in one

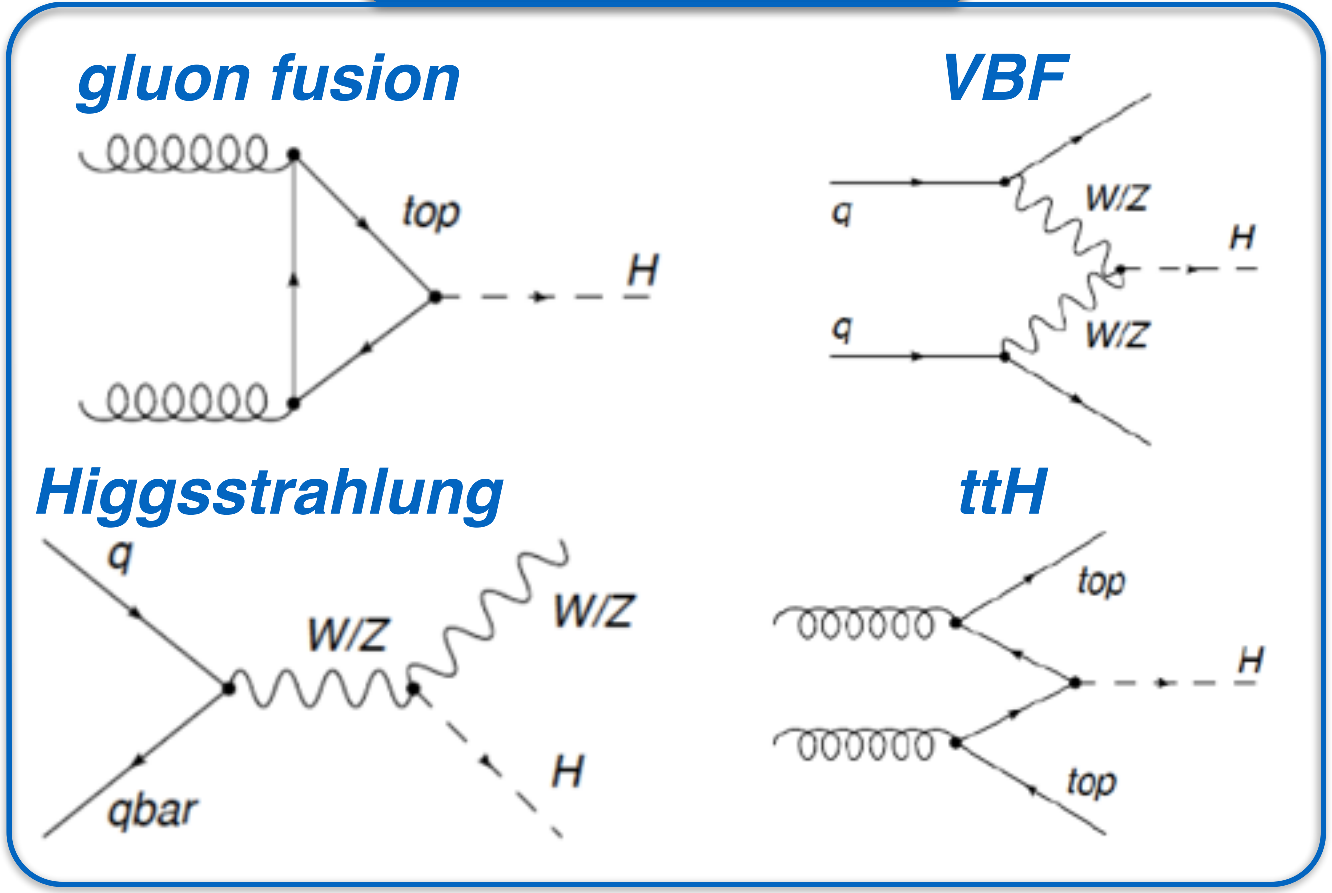
$$m_H = 125.09 \pm 0.24\ \text{GeV}$$

* overall: 0.19% precision

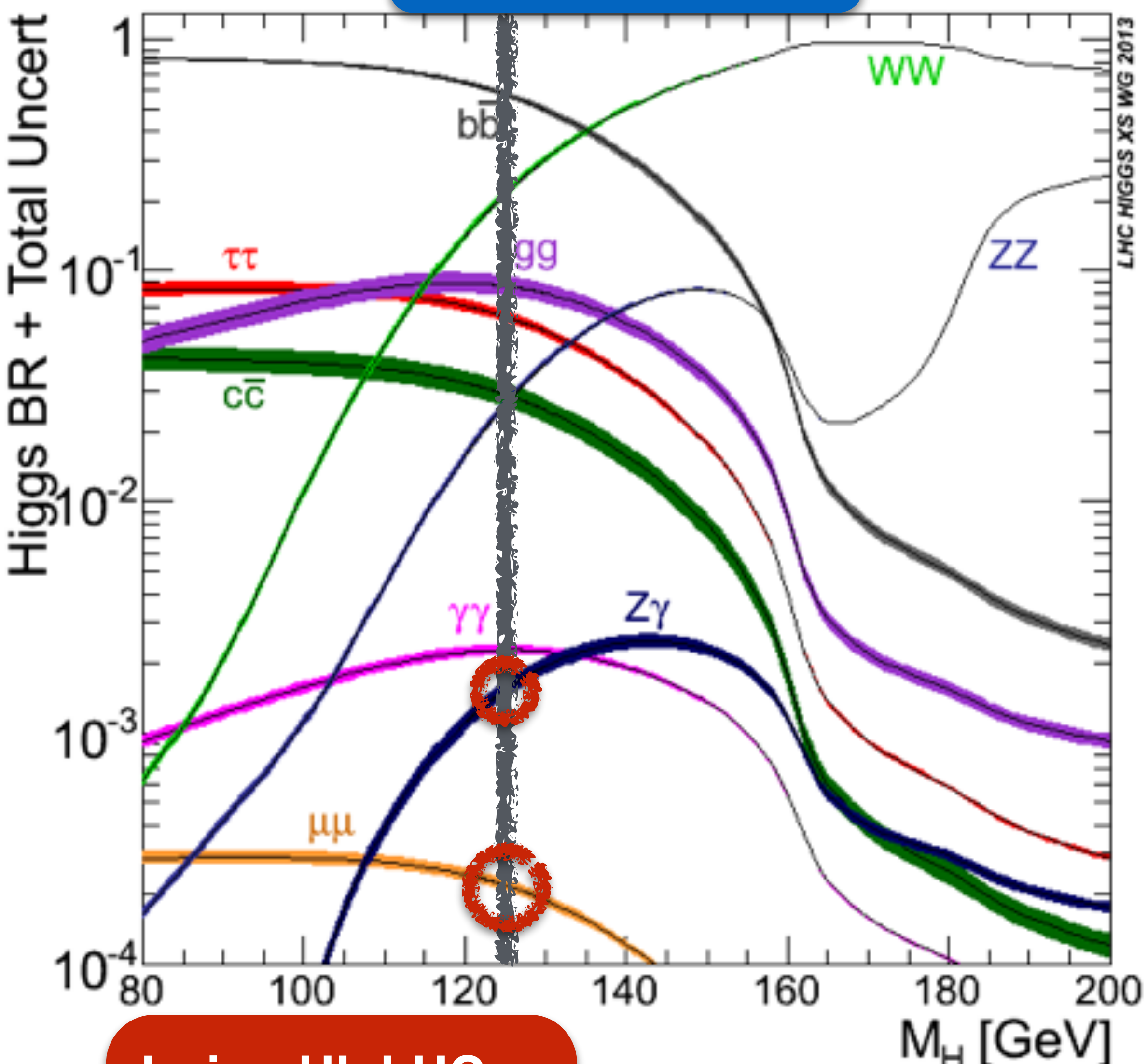
and where do we want to go…

Higgs production & decays

production



decays



* before HL LHC we should already have a first measurement on:
— VBF, VH, and ttH

during HL LHC
* rare decays:
— μμ
— Zγ

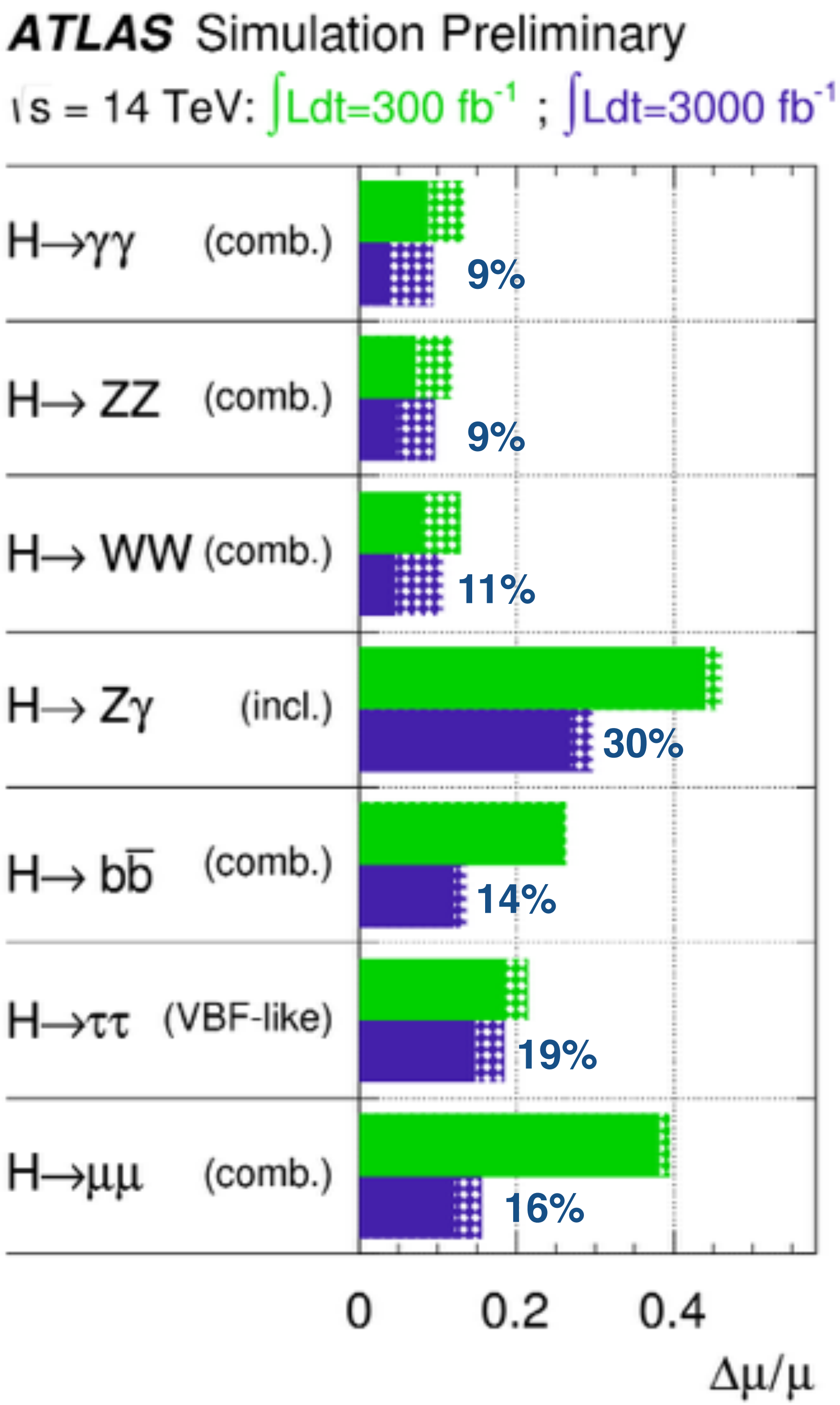
during HL LHC
* BSM decays:
— LFV: μτ, eτ, eμ

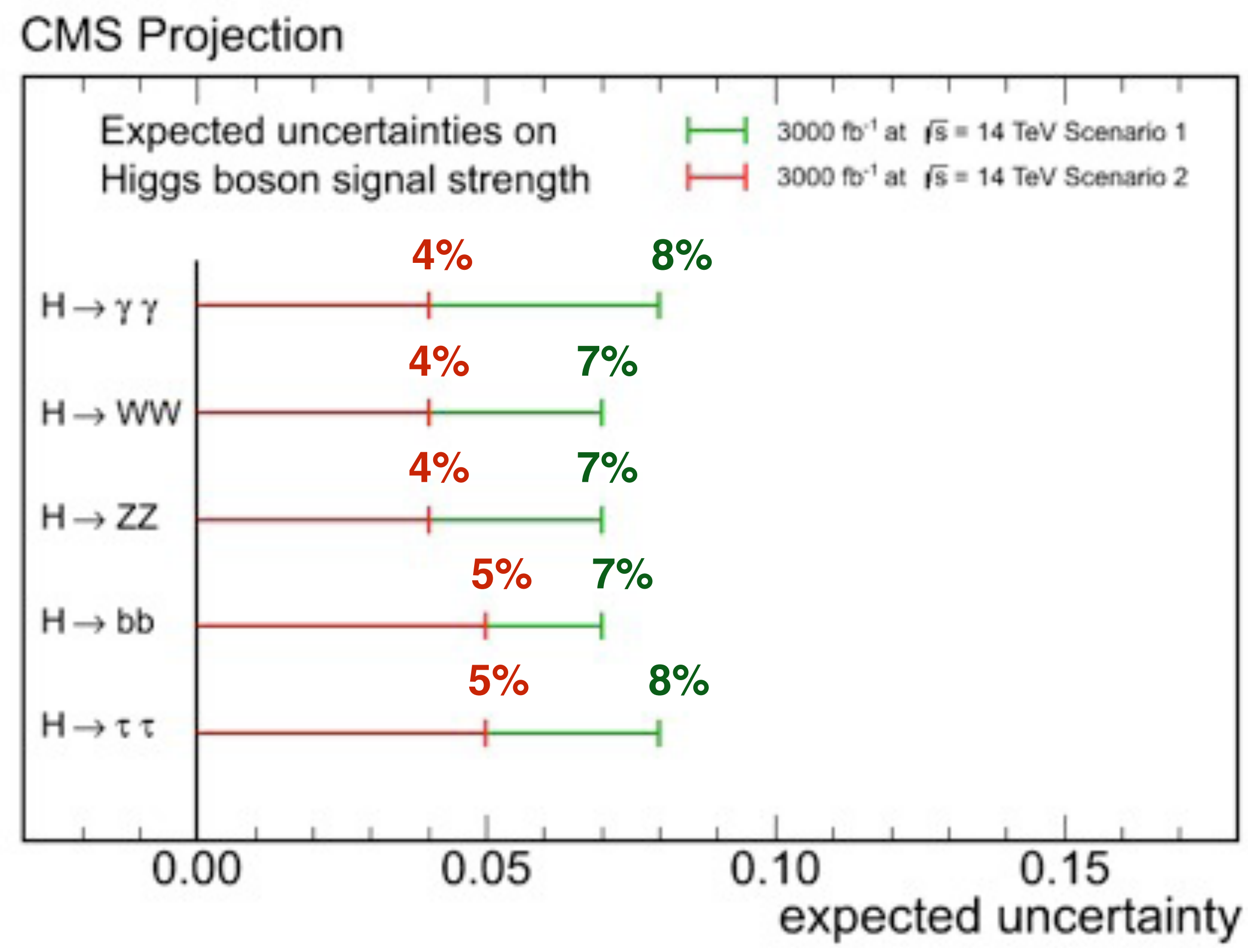
our expectations in Higgs numbers

HL LHC 3000 fb^{-1}	at 14 TeV (before cuts)
all	170 M
VBF	13 M
ttH	1.8 M
$Z\gamma$ decay	230 k
$\mu\mu$ decay	37 k
HH	121 k

from how many millions can one call an accelerator a factory? do they have to start paying taxes :)

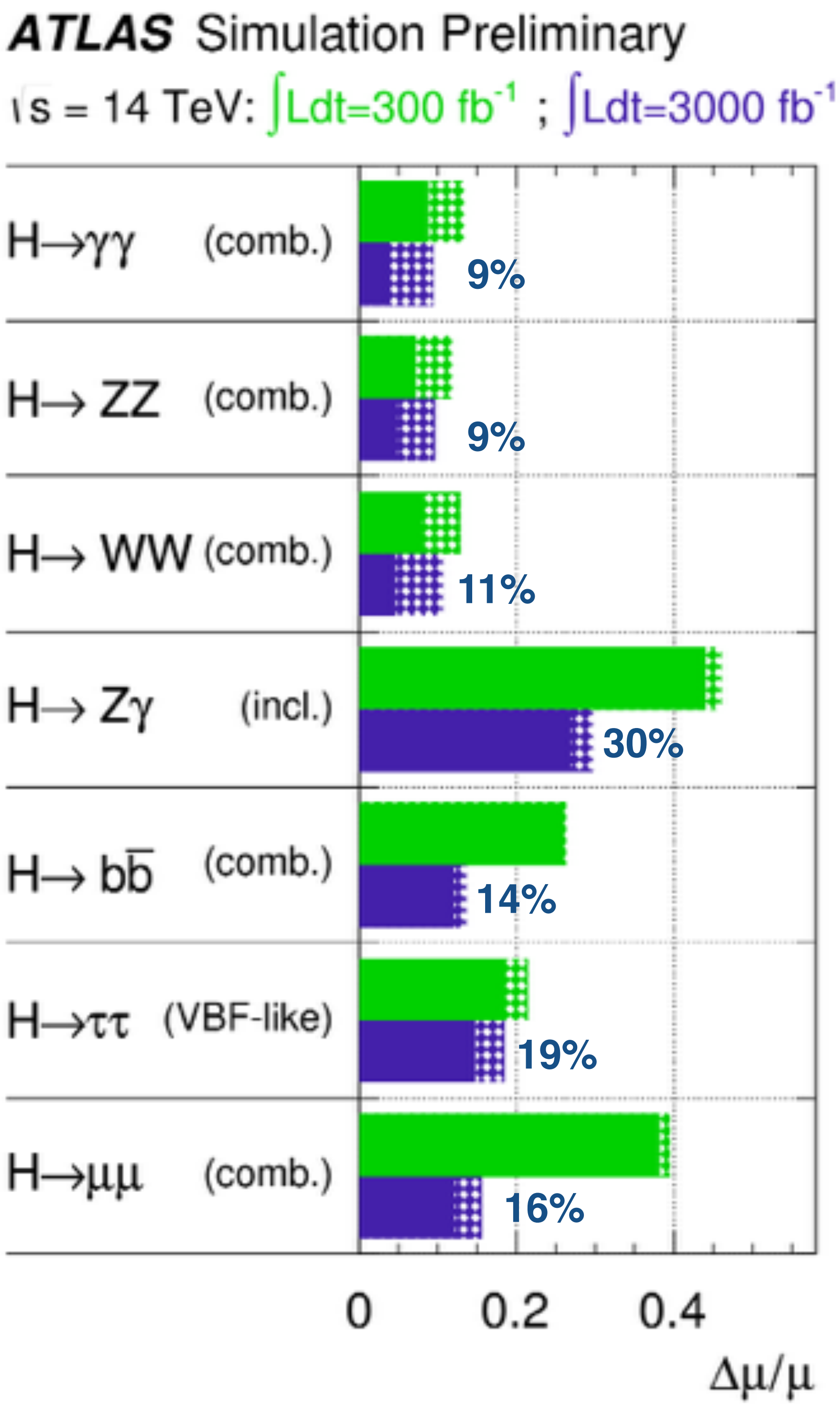
Higgs (decay) signal strengths

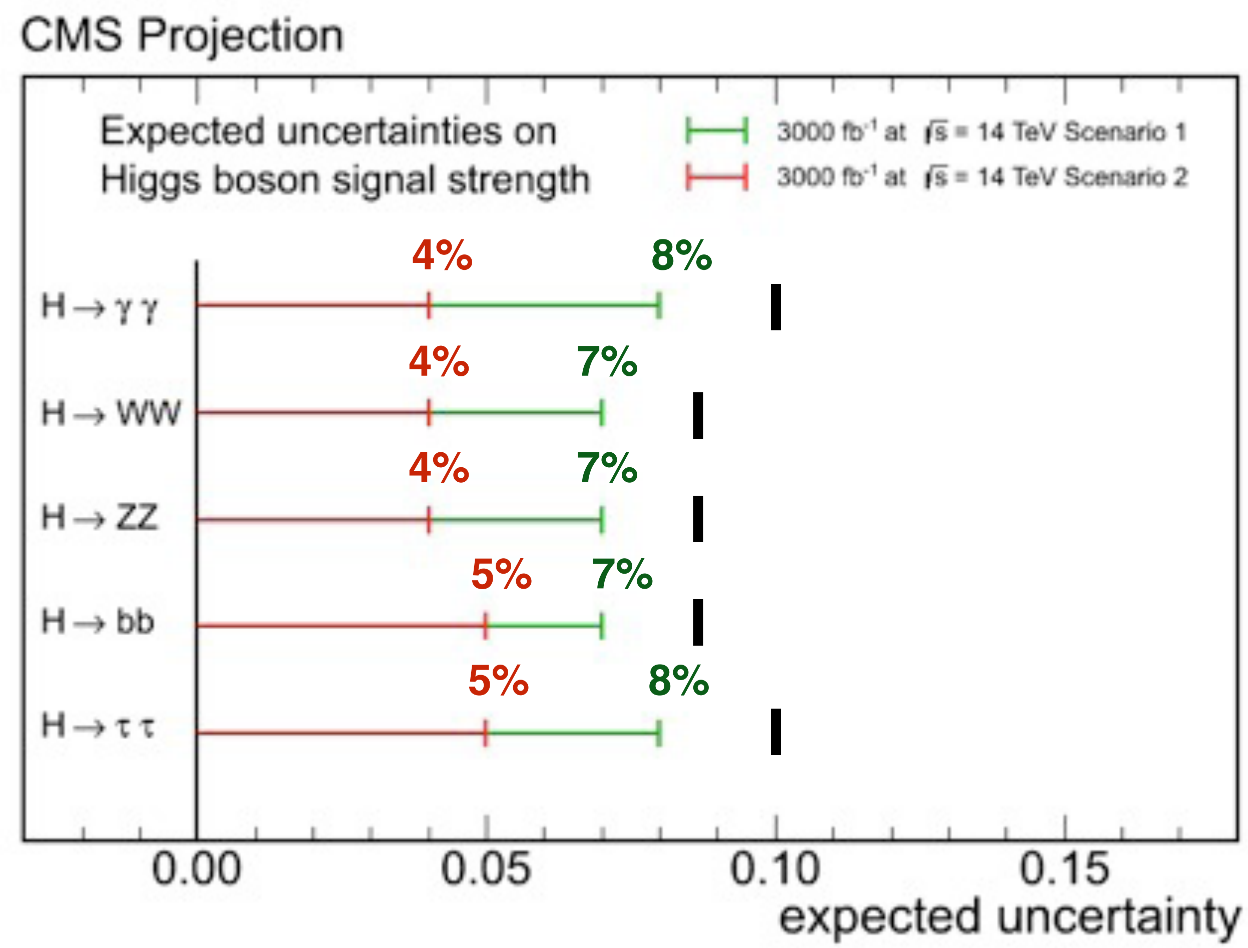




*** Scenario 1: assumes same systematics as in Run I**
*** Scenario 2: assumes systematics from theory scaled by a factor 1/2 and the rest of systematics scaled by 1/√L**
— hashed areas are theory systematics

Higgs (decay) signal strengths





* Scenario 1: assumes same systematics as in Run I
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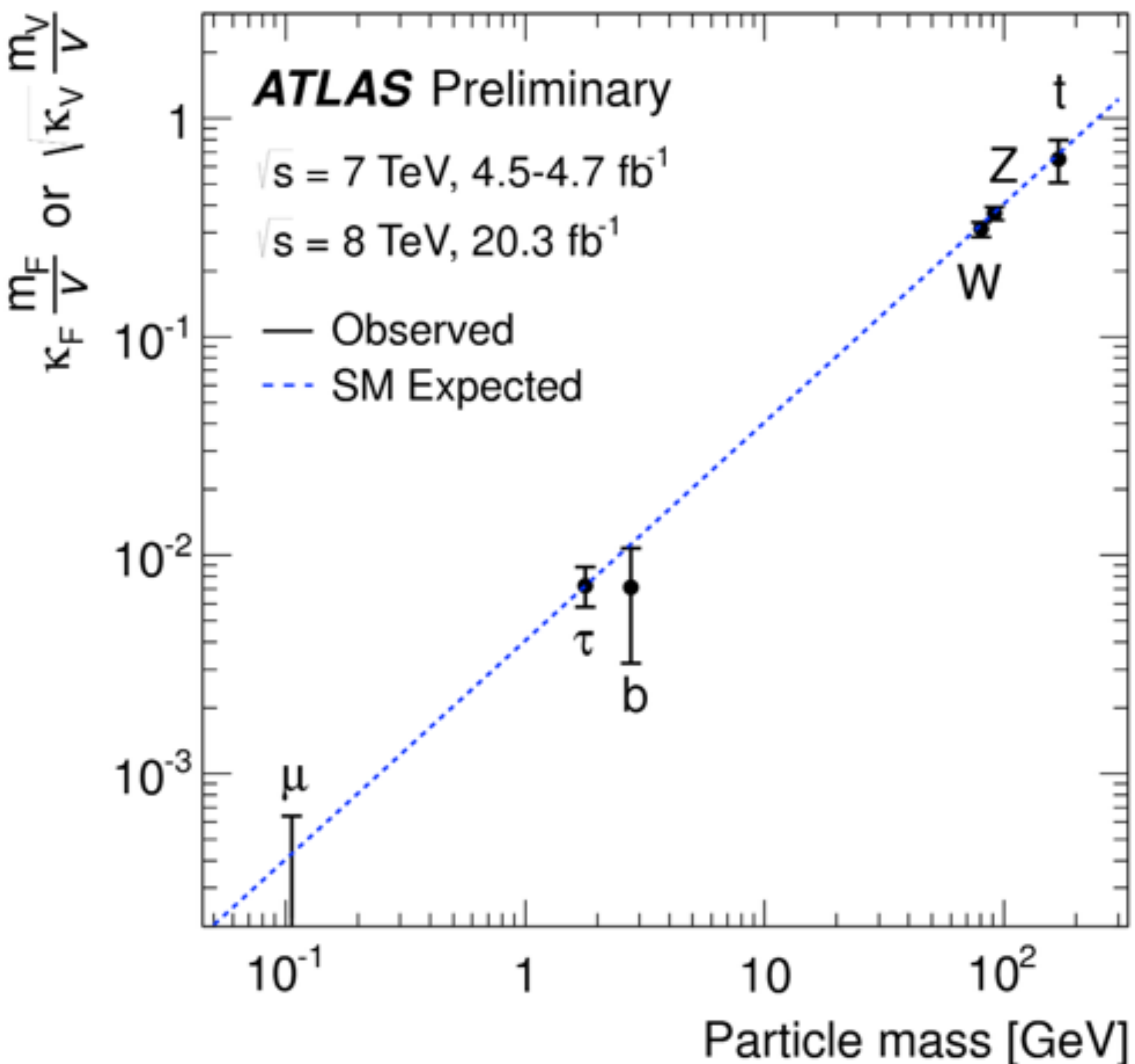
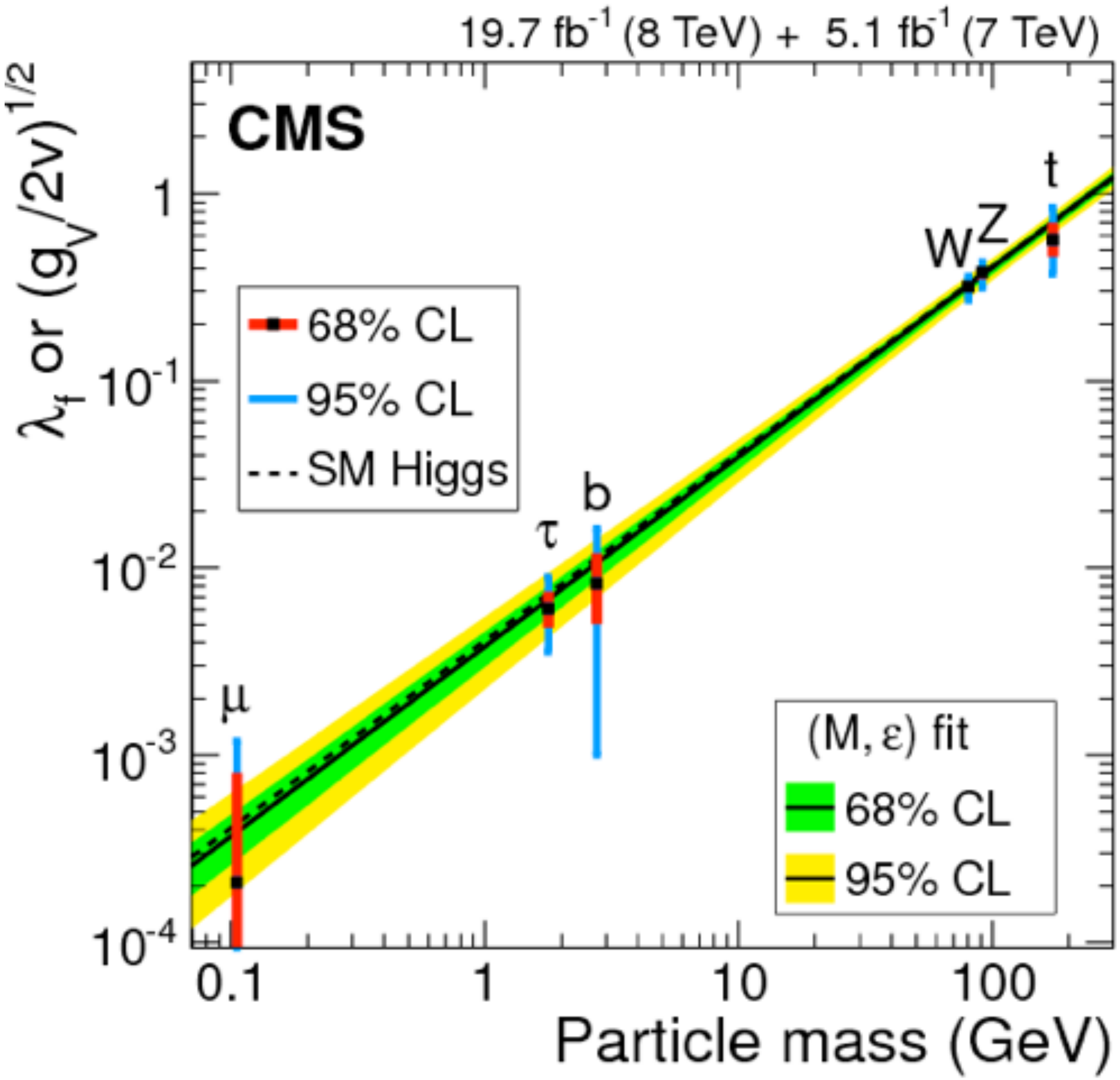
— hashed areas are theory systematics

Higgs couplings
— what we can see so far —

reduced coupling parameters

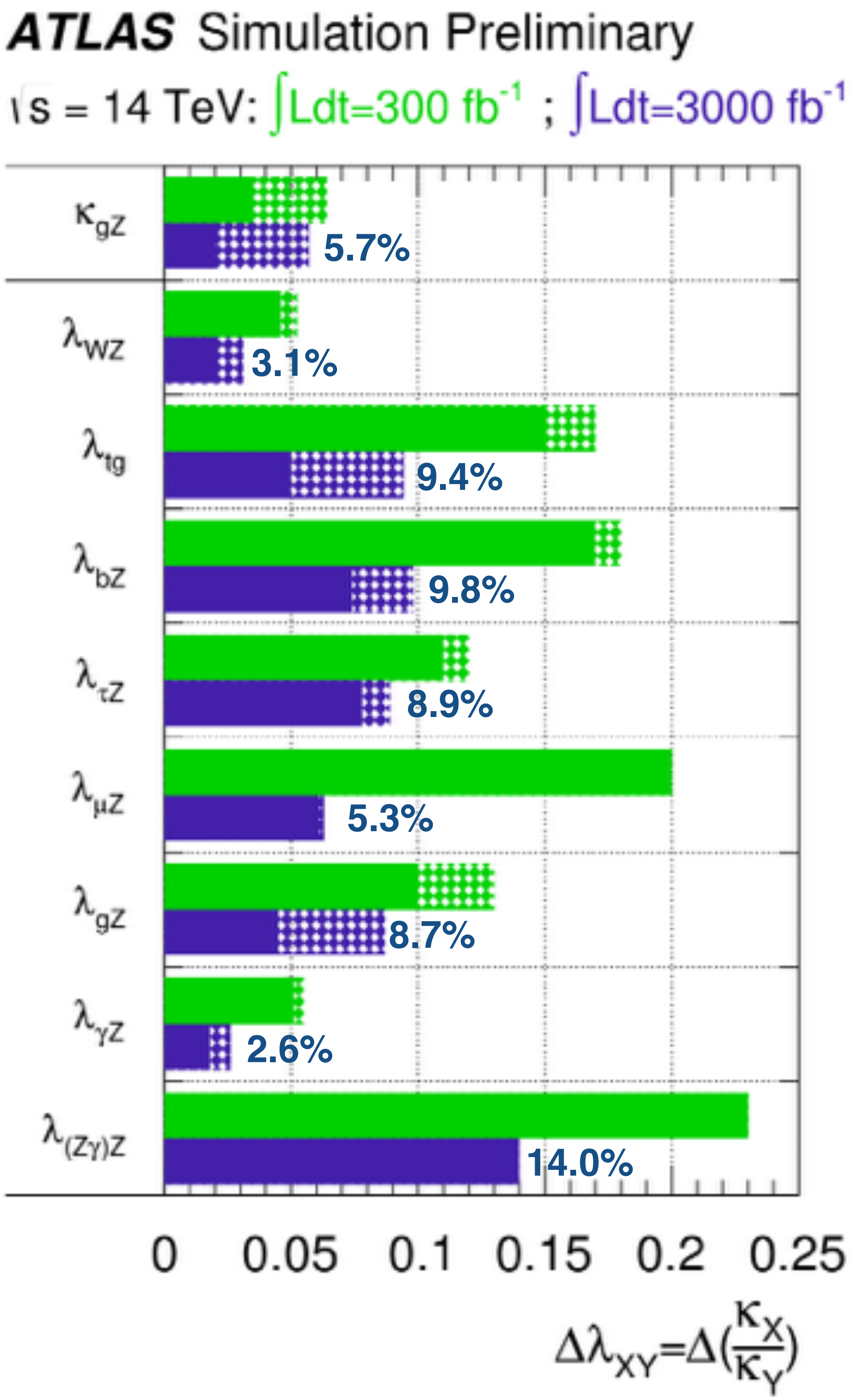


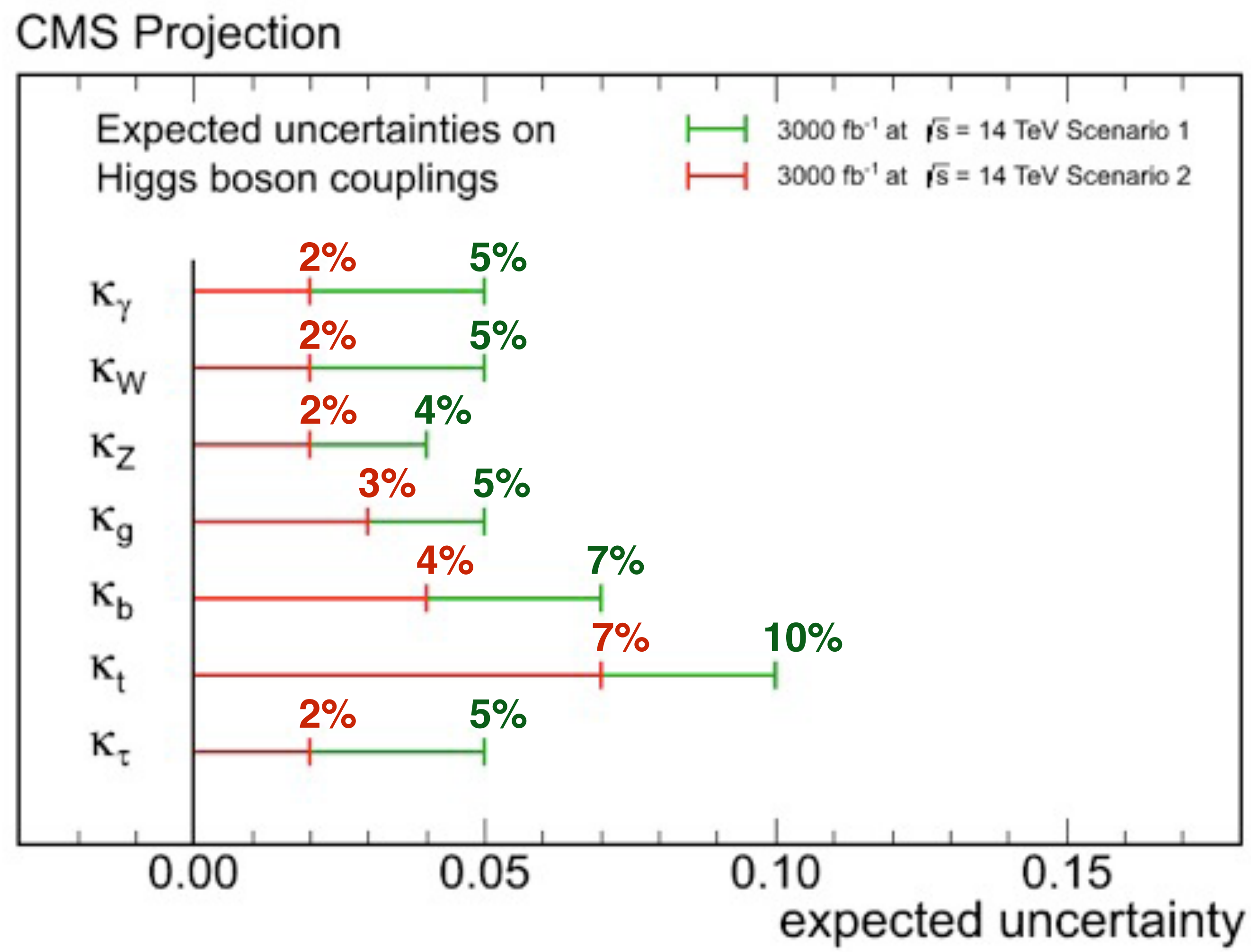


poor muon coupling, maybe in HL LHC era will receive more space on the plots

Higgs couplings

— what we could expect with "3000" fb^{-1} —

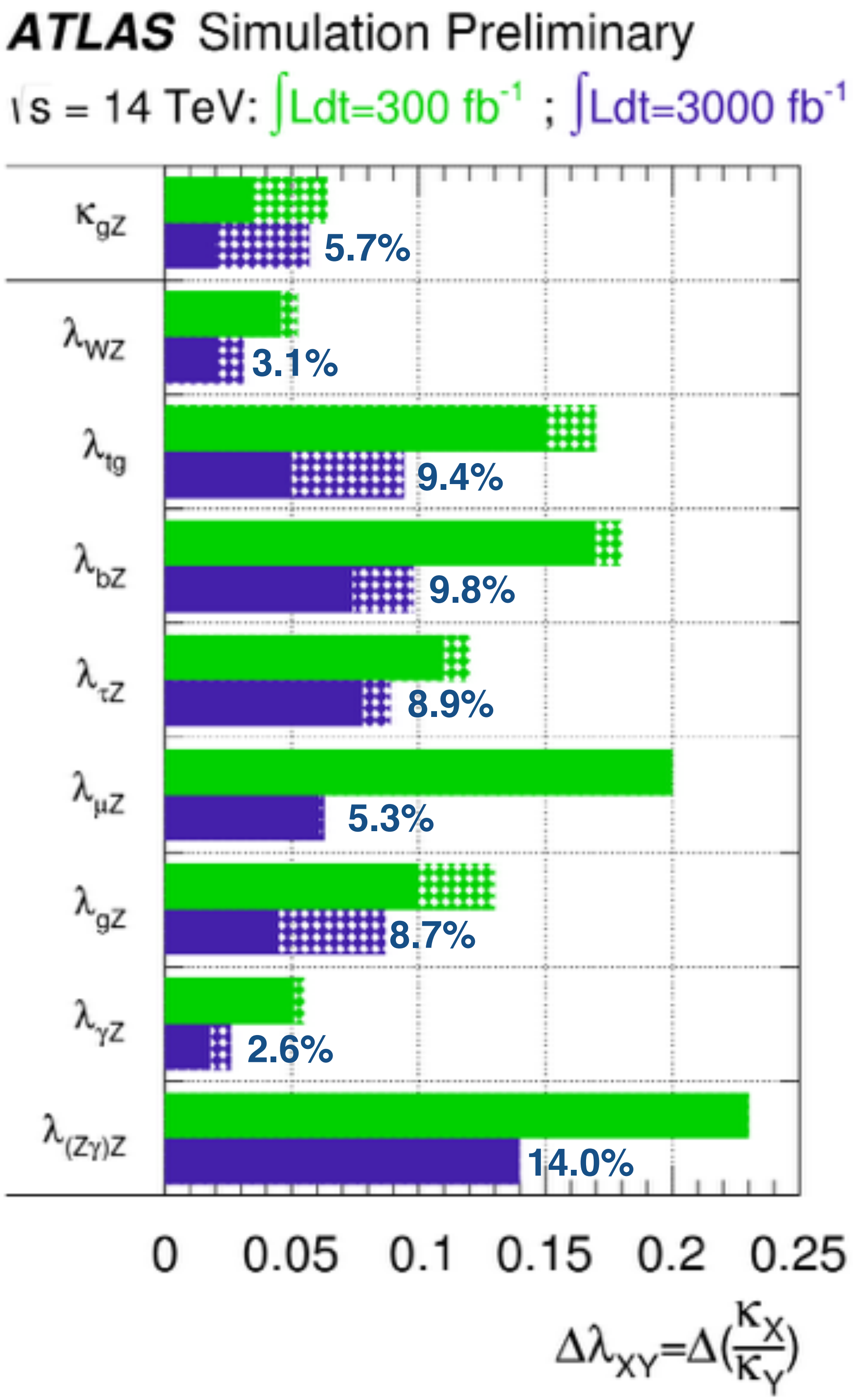


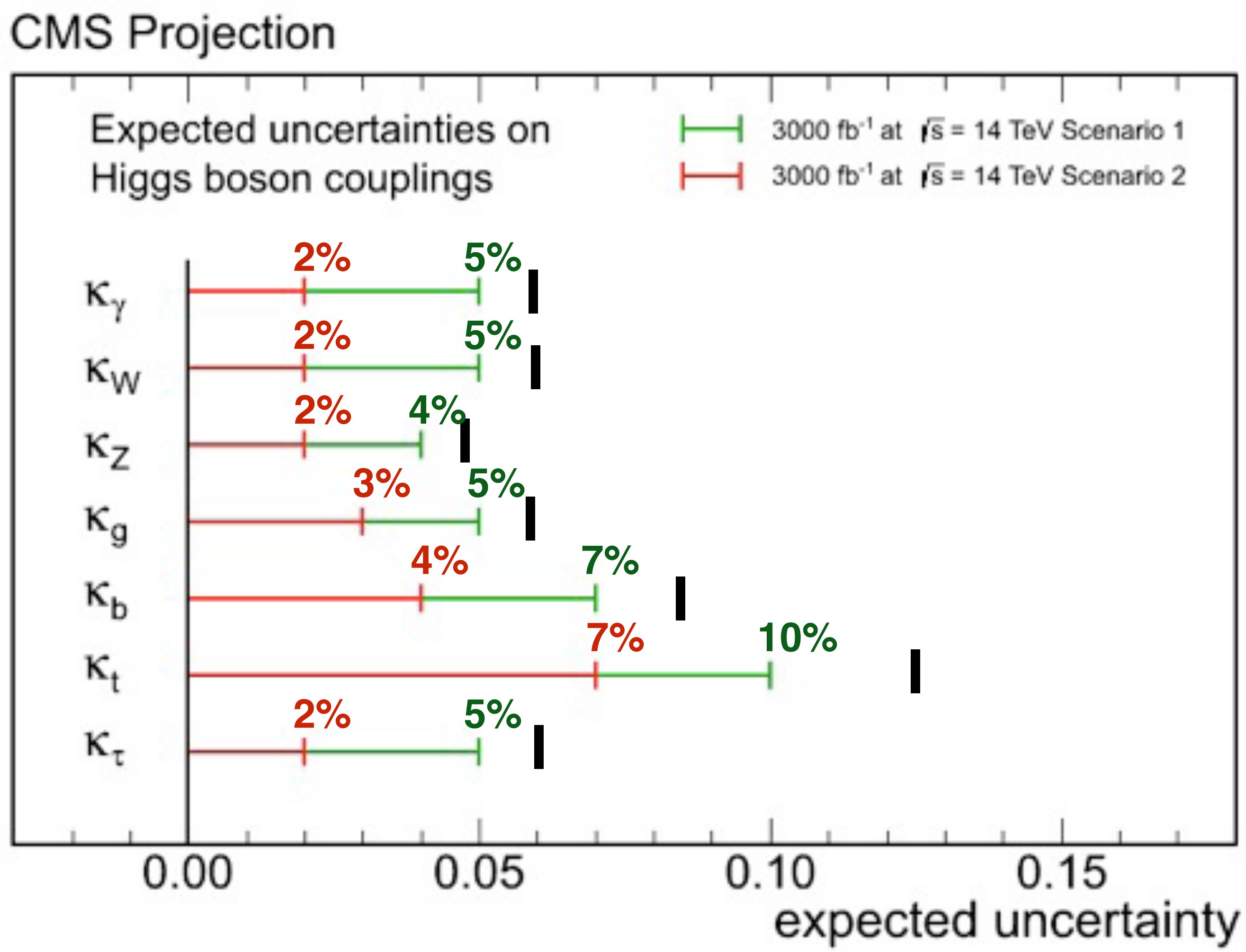


* only coupling scale factors ratios at LHC
* use are reference H (ZZ)
— hashed areas are theory systematics

Higgs couplings

— what we could expect with “3000” fb^{-1} —

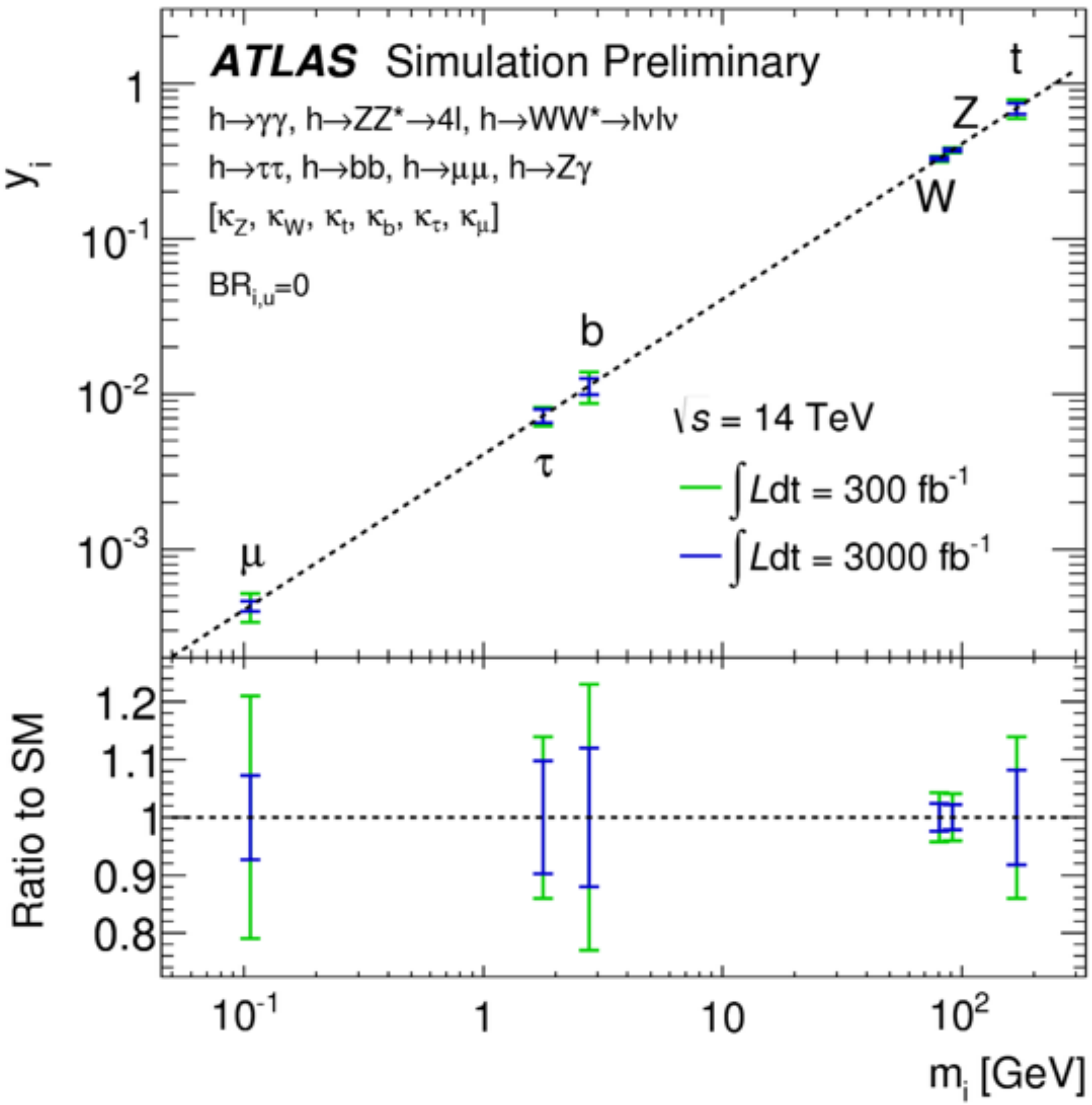




- * only coupling scale factors ratios at LHC
- * use are reference H (ZZ)
- — hashed areas are theory systematics

Higgs couplings at 3000 fb^{-1}

— to take home with you —



we'll remain biased by the SM expectation for some while

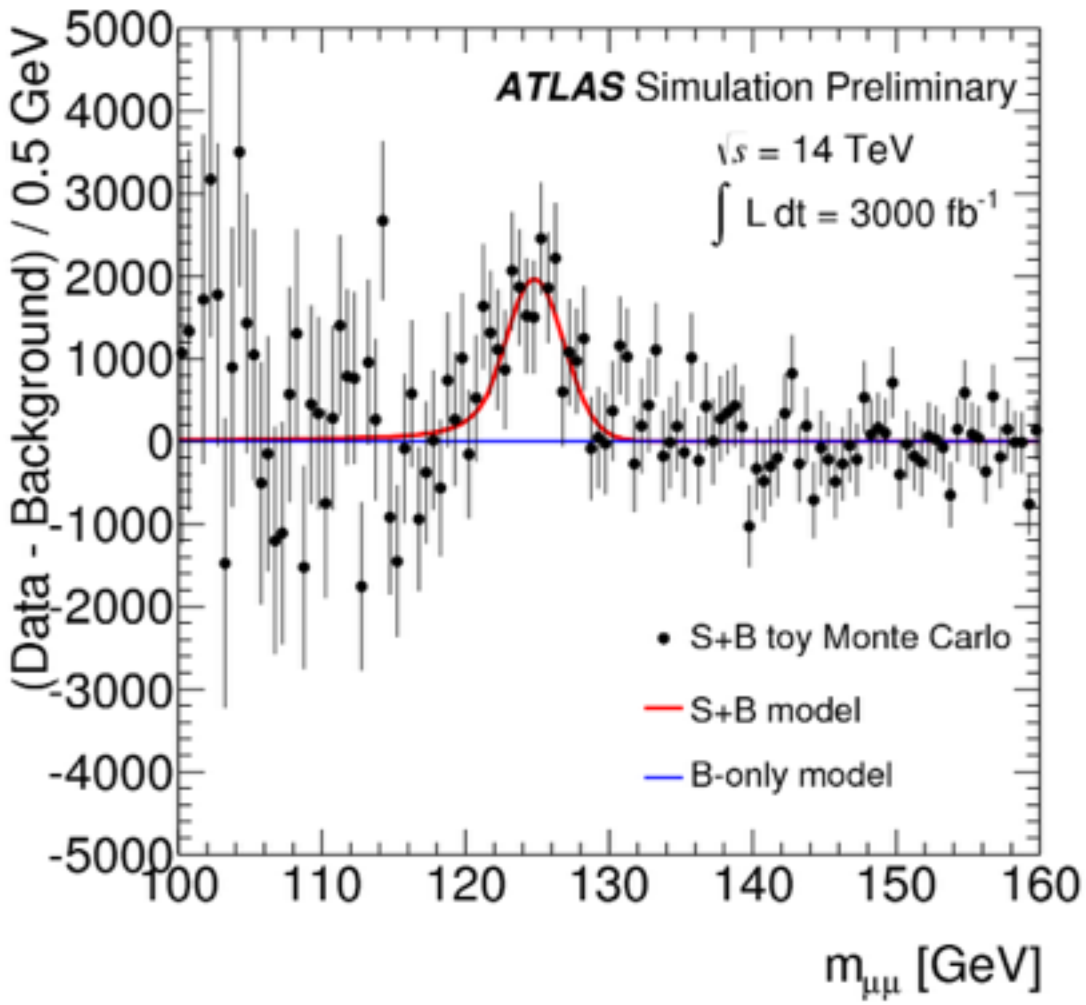
uncertainty on	ATLAS	CMS (Scenario 1)
κ_{gZ}	5.7%	5%
λ_{WZ}	3.1%	3%
λ_{tg}	9.4%	8%
λ_{bZ}	9.8%	5%
$\lambda_{\tau Z}$	8.9%	4%
$\lambda_{\mu Z}$	5.3%	8%
λ_{gZ}	8.7%	5%
$\lambda_{\gamma Z}$	2.6%	5%
$\lambda_{(Z\gamma)Z}$	14%	12%

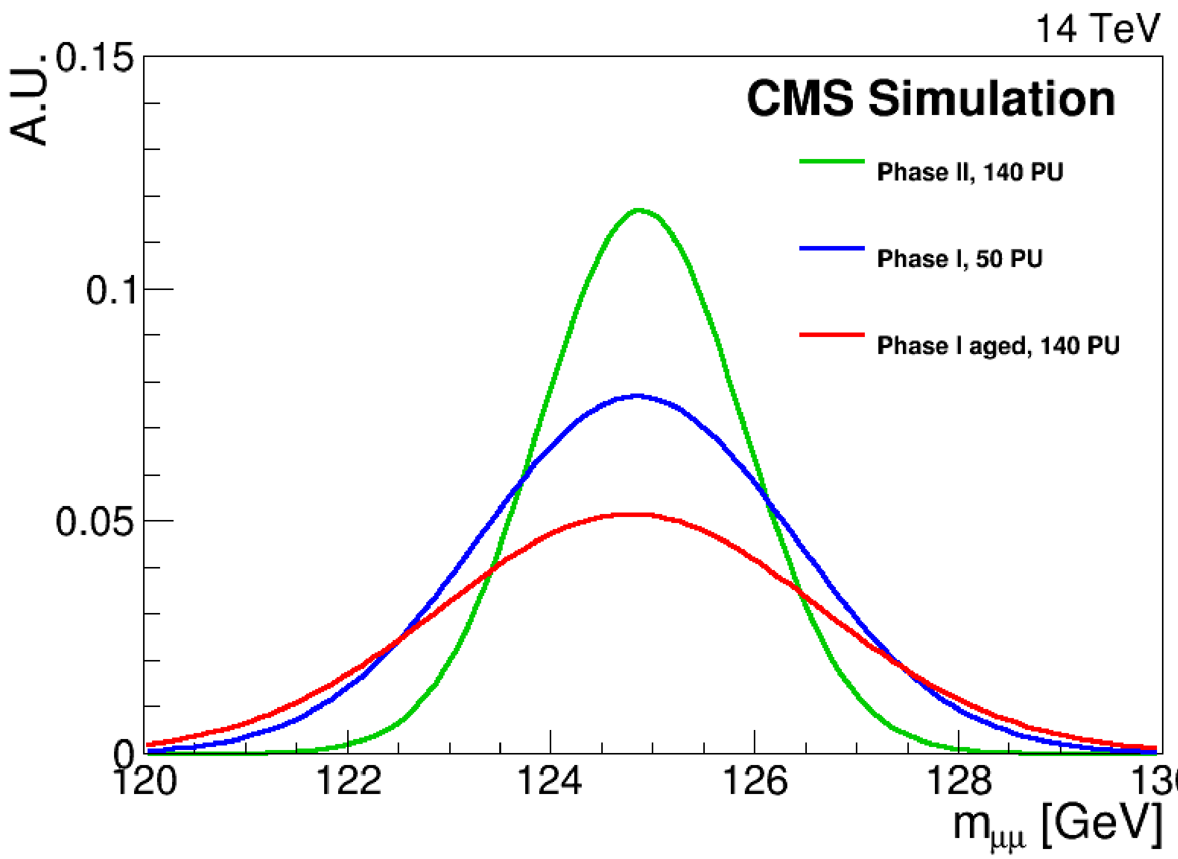
Higgs relative couplings could be known with a precision of up to few %

Higgs rare decays

— dimuon decay —

*** dimuon channel will give us access to the 2nd lepton generation**
*** allows ratio of 2nd and 3rd generation lepton couplings:**
— are we talking about the same mass generation mechanism for the 2nd and 3rd generation lepton?
— what about the 2nd and 3rd generation quarks?

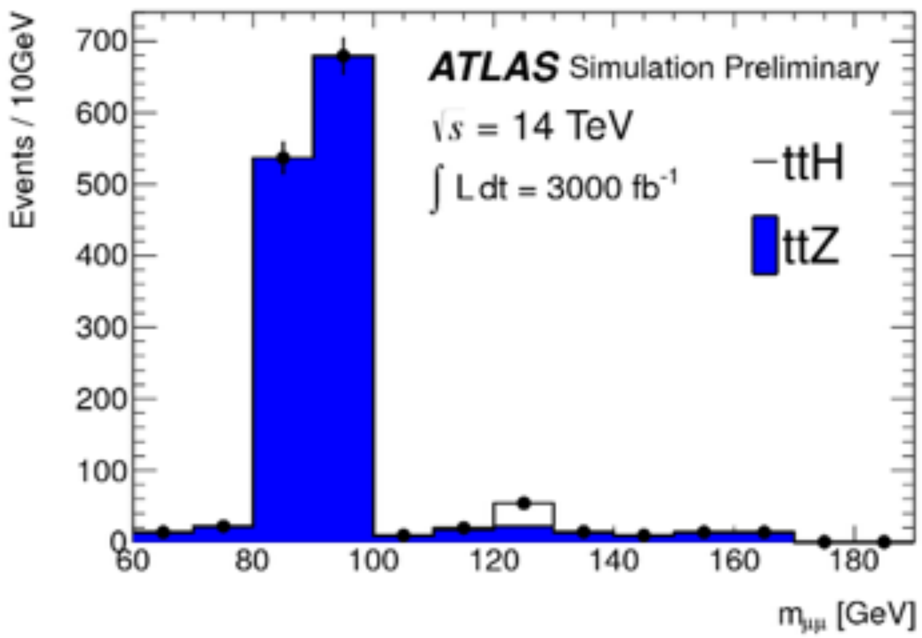




*** new detectors design will make possible to improve dimuon mass resolution considerably**

Higgs rare decays

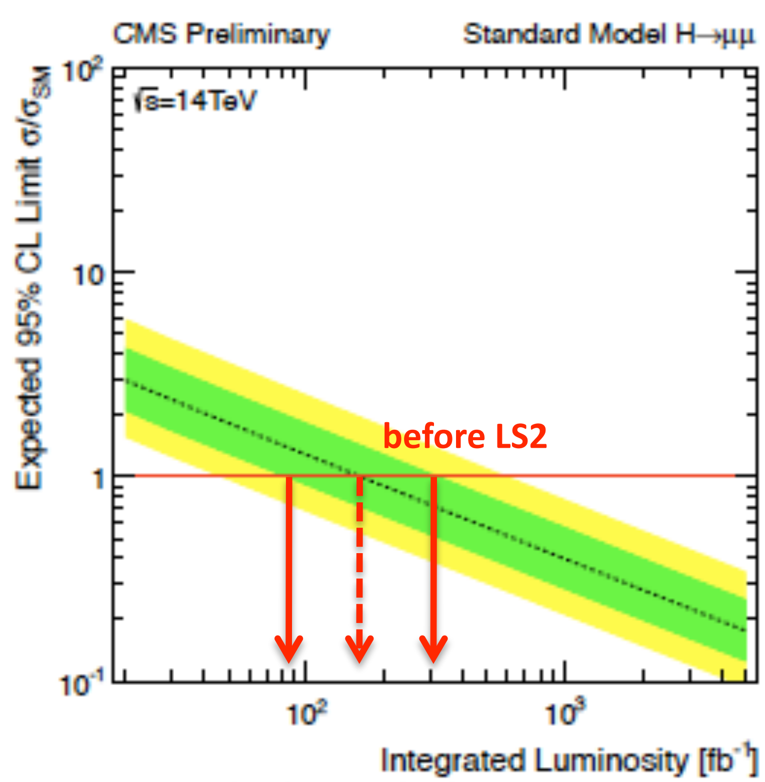
— dimuon decay —

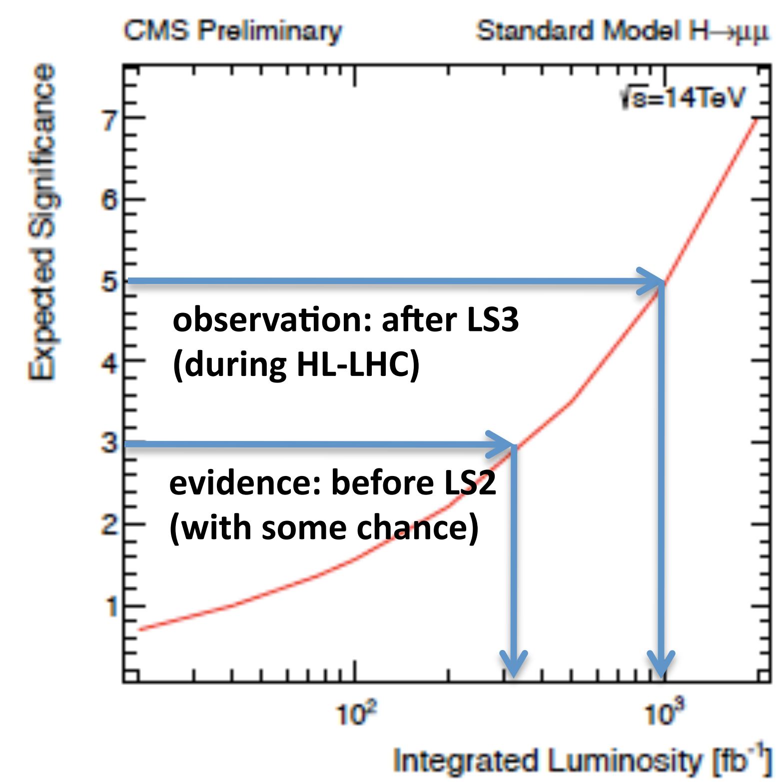


* one more channel will become interesting: ttH with S/B better than 1 and $\Delta\mu/\mu \sim 25\%$.

* SM sensitivity will be reached before LS2

* observation (> 5σ) expected during HL-LHC





hopefully some of us will still try to answer the questions mentioned before

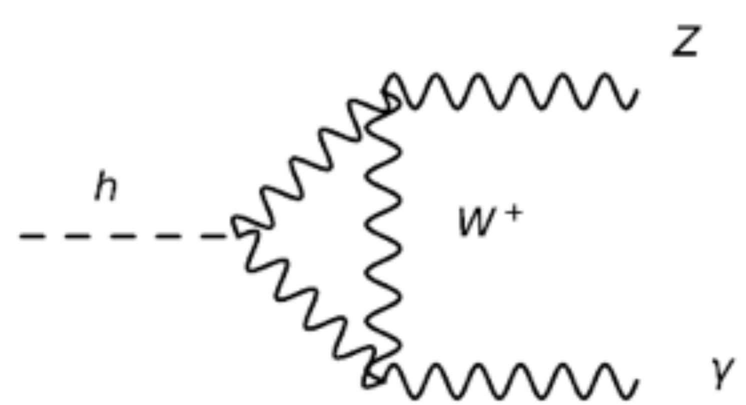
Higgs rare decays

— Z plus γ —

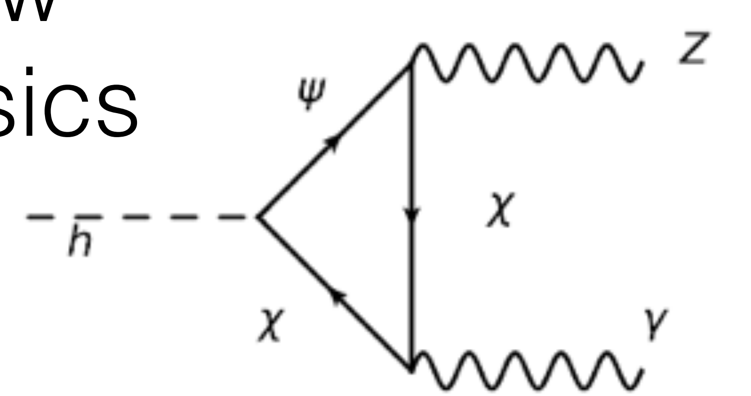
* Z γ is loop induced similar to γ γ and gg

* could be sensitive to additional effects
— expected to be dominant in composite Higgs

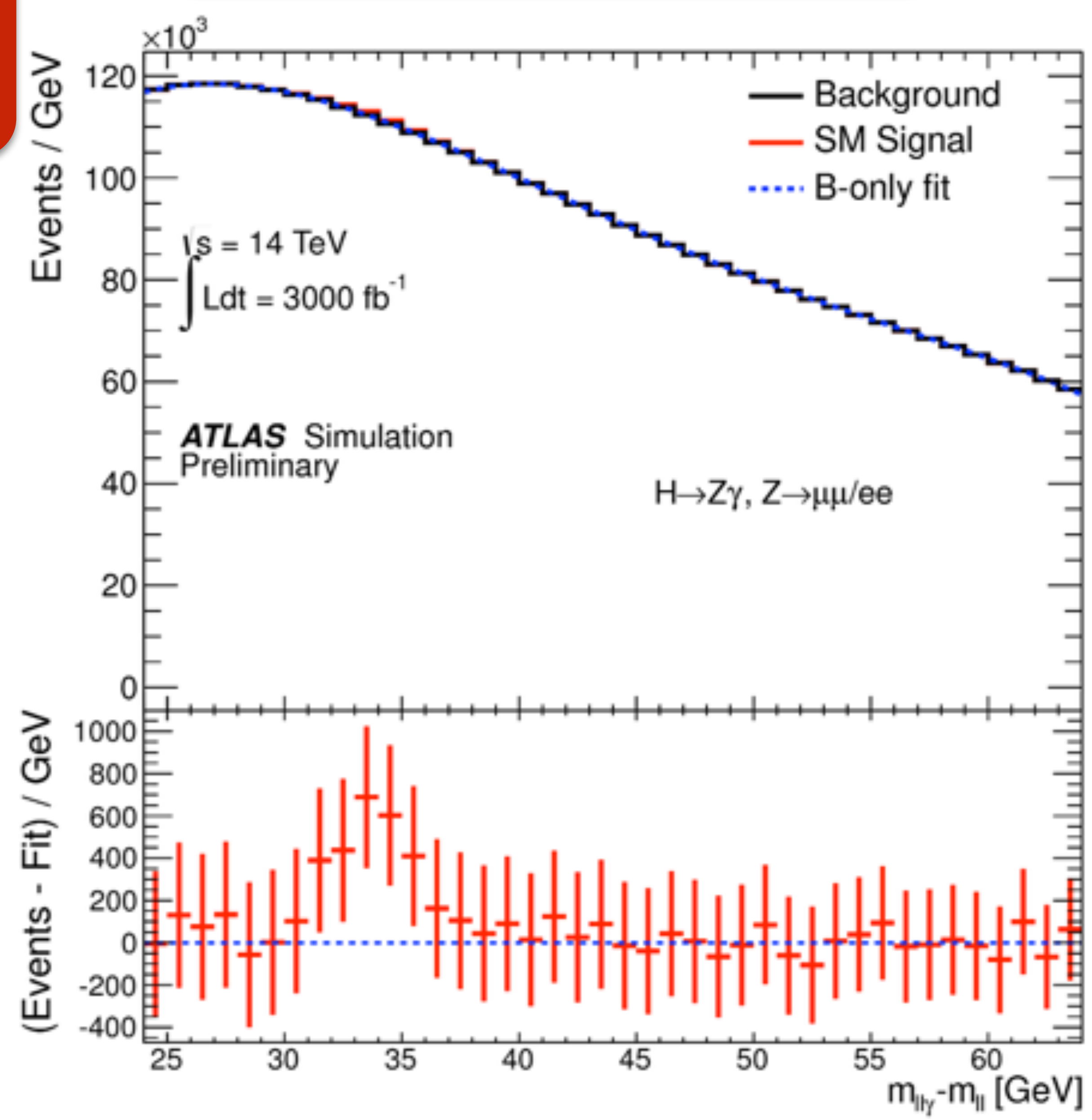
SM



new physics



* small signal on top of a large background from radiative Z

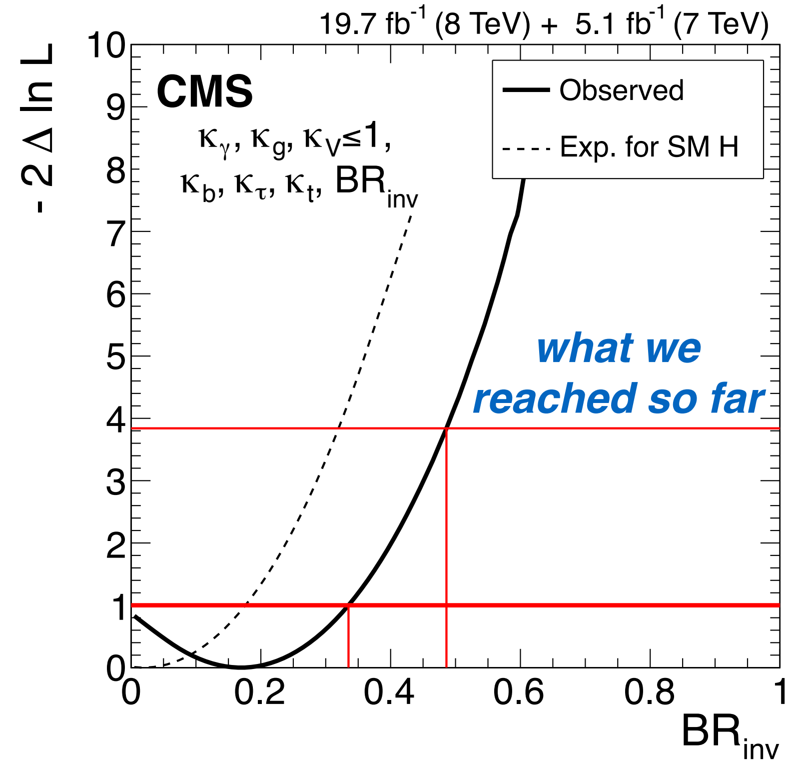


Higgs rare decays

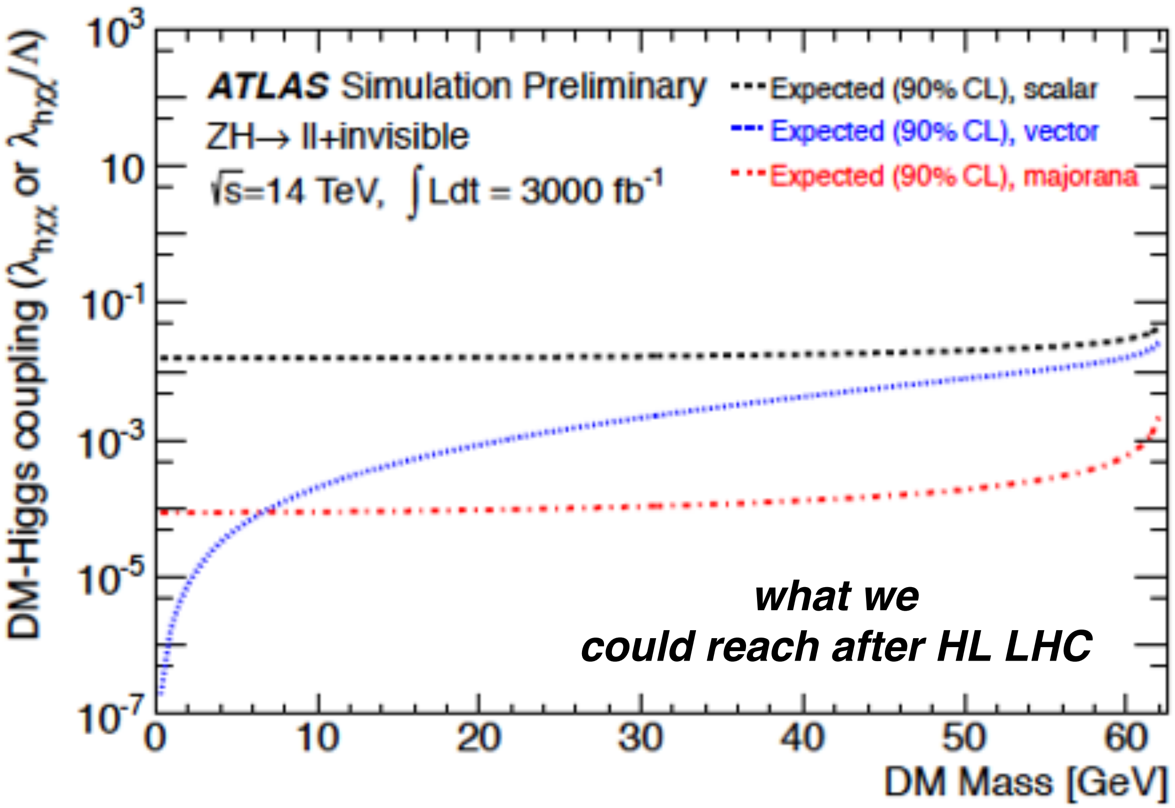
— invisible —

* direct access: VBF and ZH production

* indirect access: combined coupling fit



at CMS after $3000\ fb^{-1}$	Z H (inv.) 95% CL upper limit
Scenario 1	17%
Scenario 2	6.4%

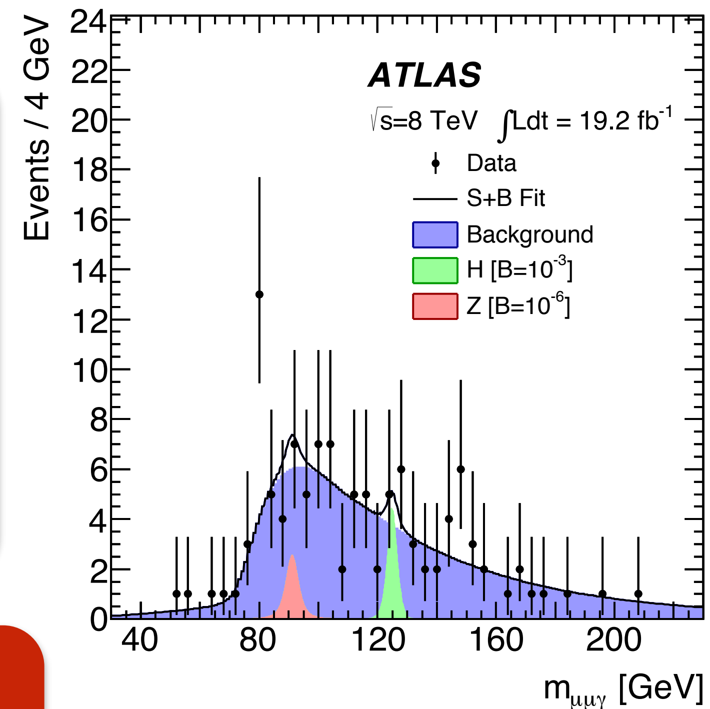


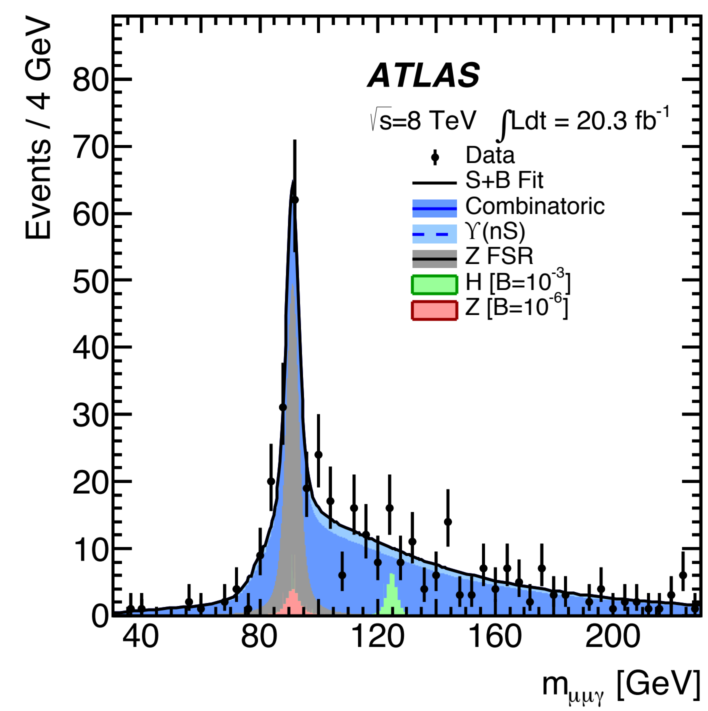
Higgs rare decays

— to be added on the prediction list: J/ψ and Υ(nS) plus γ —

*** rather simple final state:**
— J/ψ and Υ(nS) reconstructed via dimuon and dielectron channels

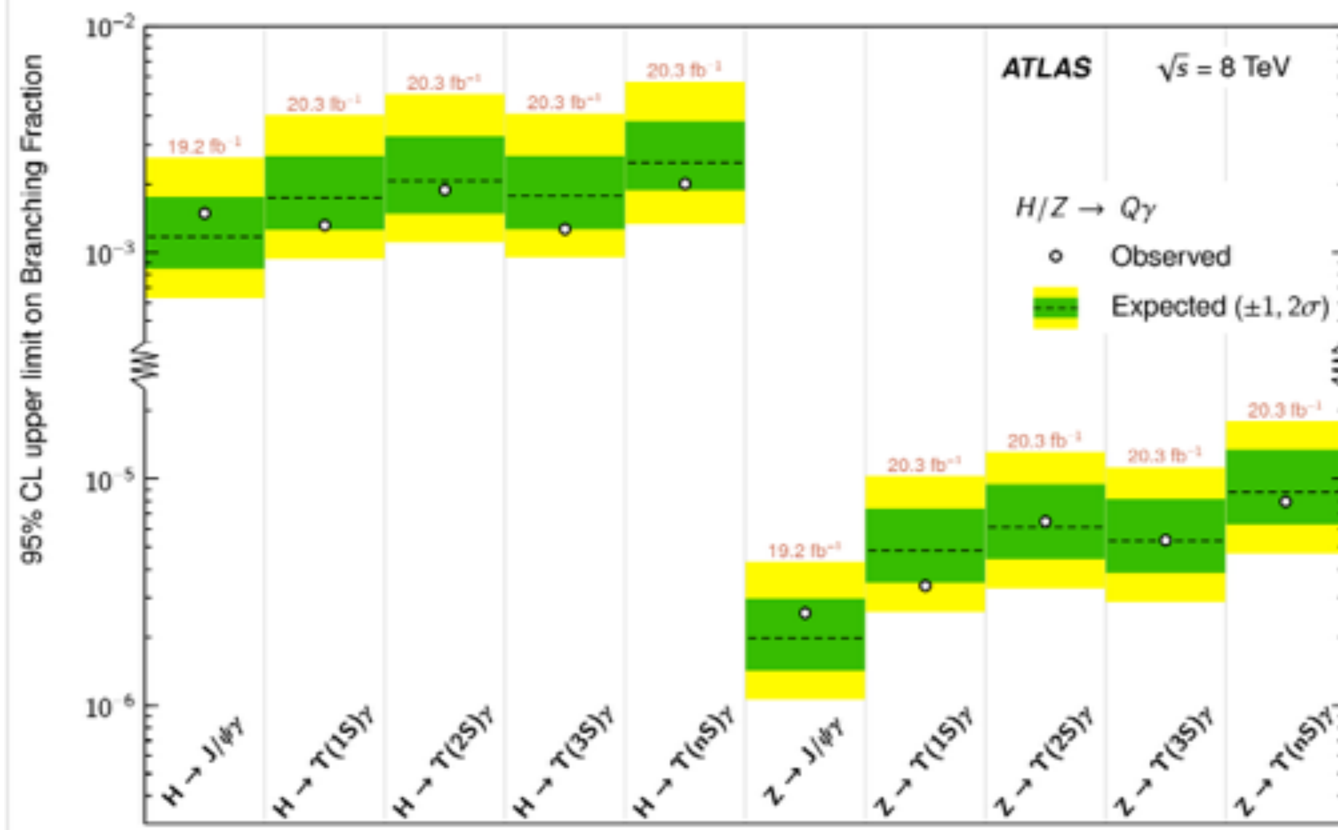
— plus a γ with $p_T > 36$ GeV while $|\eta| < 1.37$ for barrel and $1.52 < |\eta| < 2.37$ for end cap





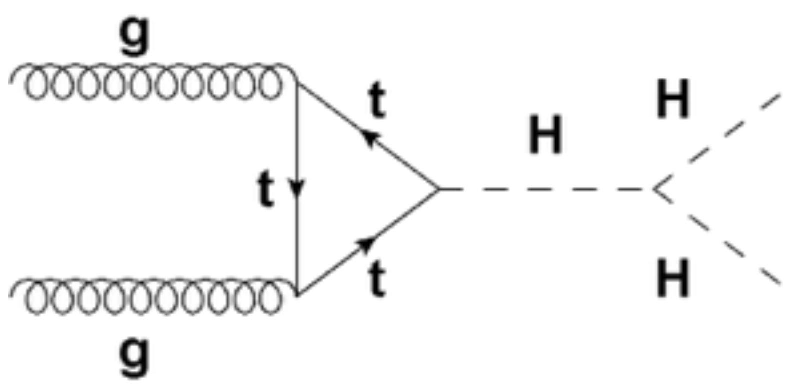
*** so far only 8 TeV results:**

	95% CL Upper Limits				
	J/ψ	$\Upsilon(1S)$	$\Upsilon(2S)$	$\Upsilon(3S)$	$\sum_n \Upsilon(nS)$
	$\mathcal{B}\,(H \to \mathcal{Q}\,\gamma)$ [10^{-3}]				
Expected	$1.2^{+0.6}_{-0.3}$	$1.8^{+0.9}_{-0.5}$	$2.1^{+1.1}_{-0.6}$	$1.8^{+0.9}_{-0.5}$	$2.5^{+1.3}_{-0.7}$
Observed	1.5	1.3	1.9	1.3	2.0
	$\sigma\,(pp \to H) \times \mathcal{B}\,(H \to \mathcal{Q}\,\gamma)$ [fb]				
Expected	26^{+12}_{-7}	38^{+19}_{-11}	45^{+24}_{-13}	38^{+19}_{-11}	54^{+27}_{-15}
Observed	33	29	41	28	44

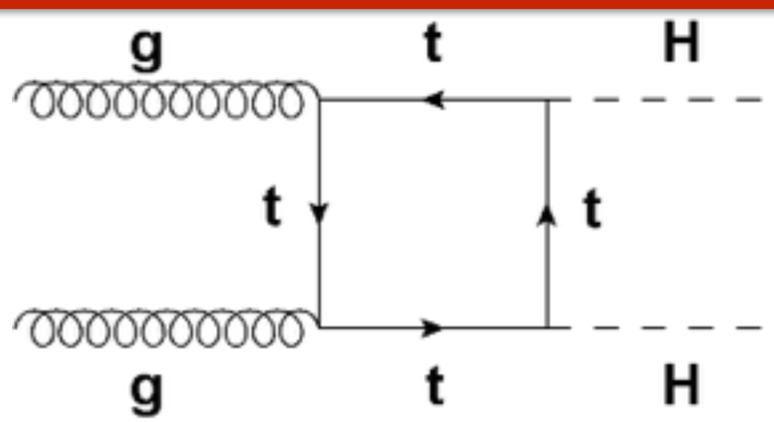


*** will give us access to the 2nd quarks generation**

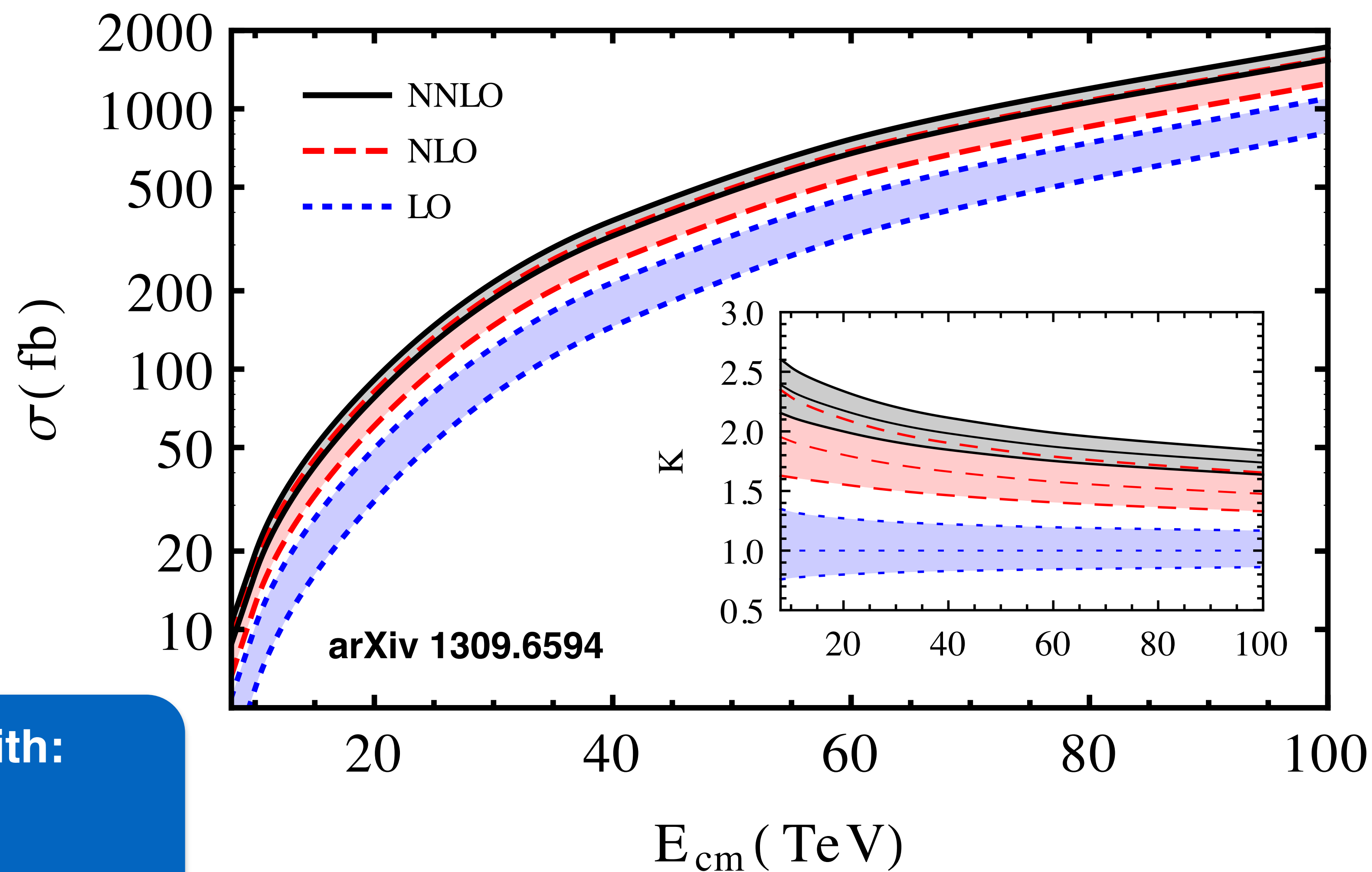
Higgs pair production



* in destructive interference with:



* NNLO expectation:
  40.2 $^{+3.2}_{-3.5}$ fb for 125 GeV Higgs mass



* channels that we can start something with:
— bb WW after HL LHC: ~30 k events
— bb $\tau\tau$ after HL LHC: ~8.9 k events
— bb γ γ after HL LHC: ~0.3 k events, but clean

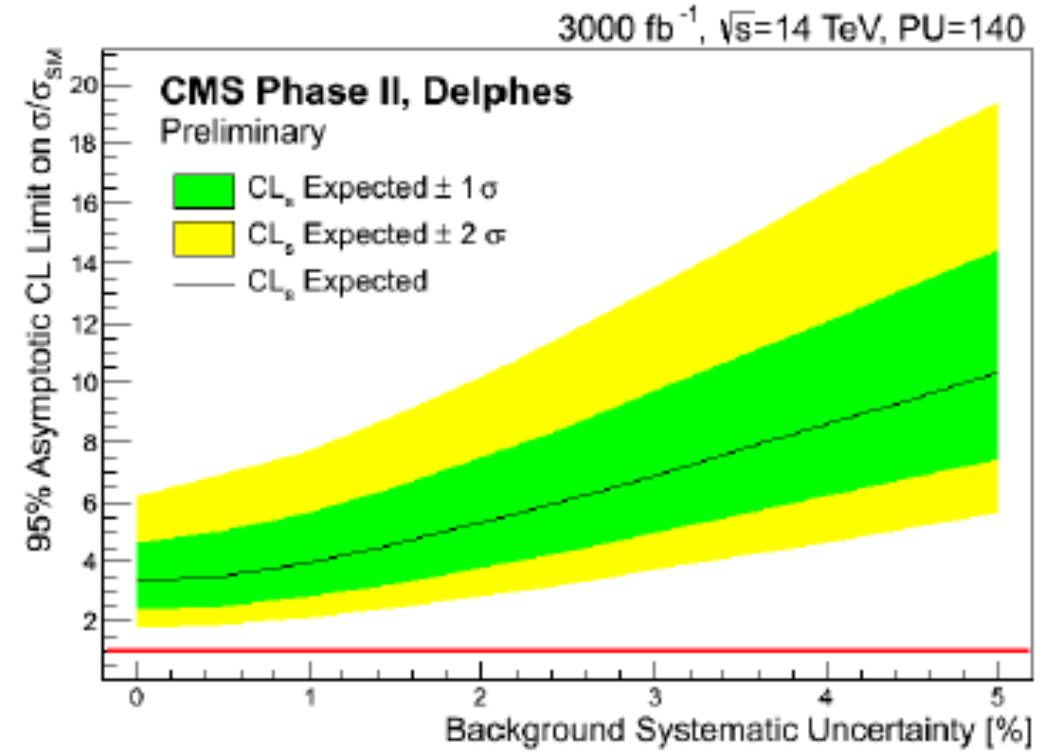
Higgs pair production

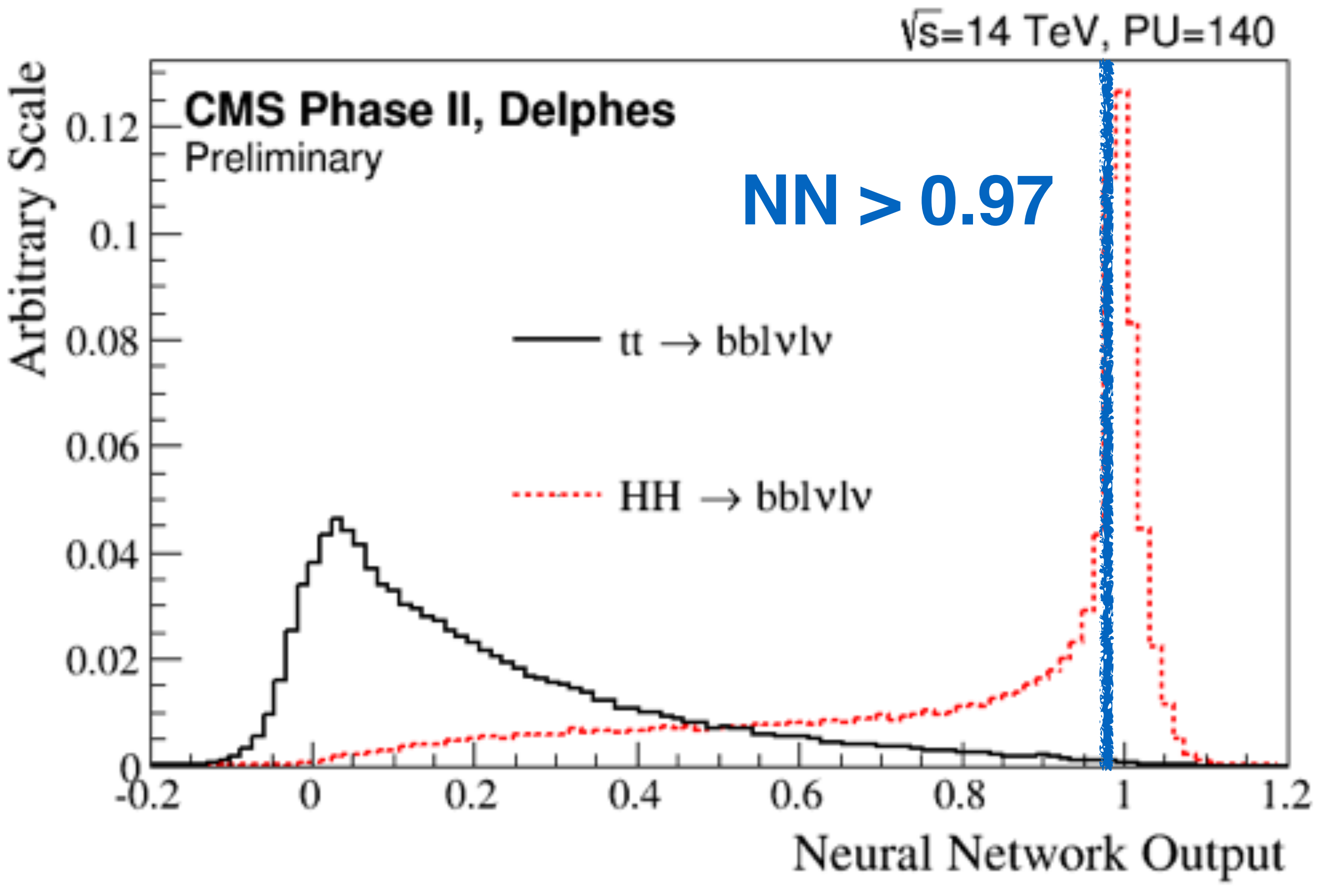
— H(bb) H(WW) —

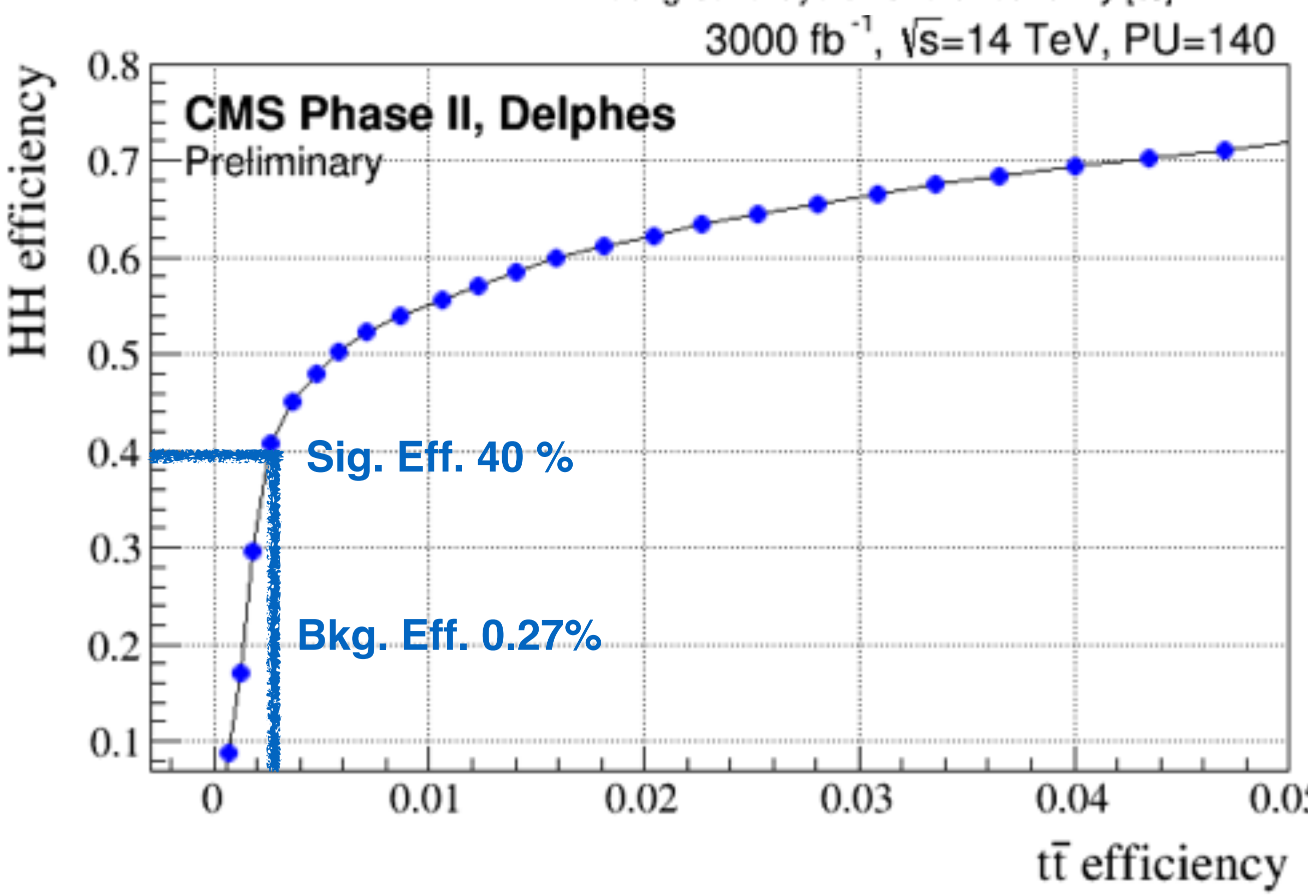
* background contributions mainly from tt events

* Neural Network built on kinematic variables

* new data driven methods could be used to constrain uncertainties to percent level and increase sensitivity to deviations from SM







Higgs pair production

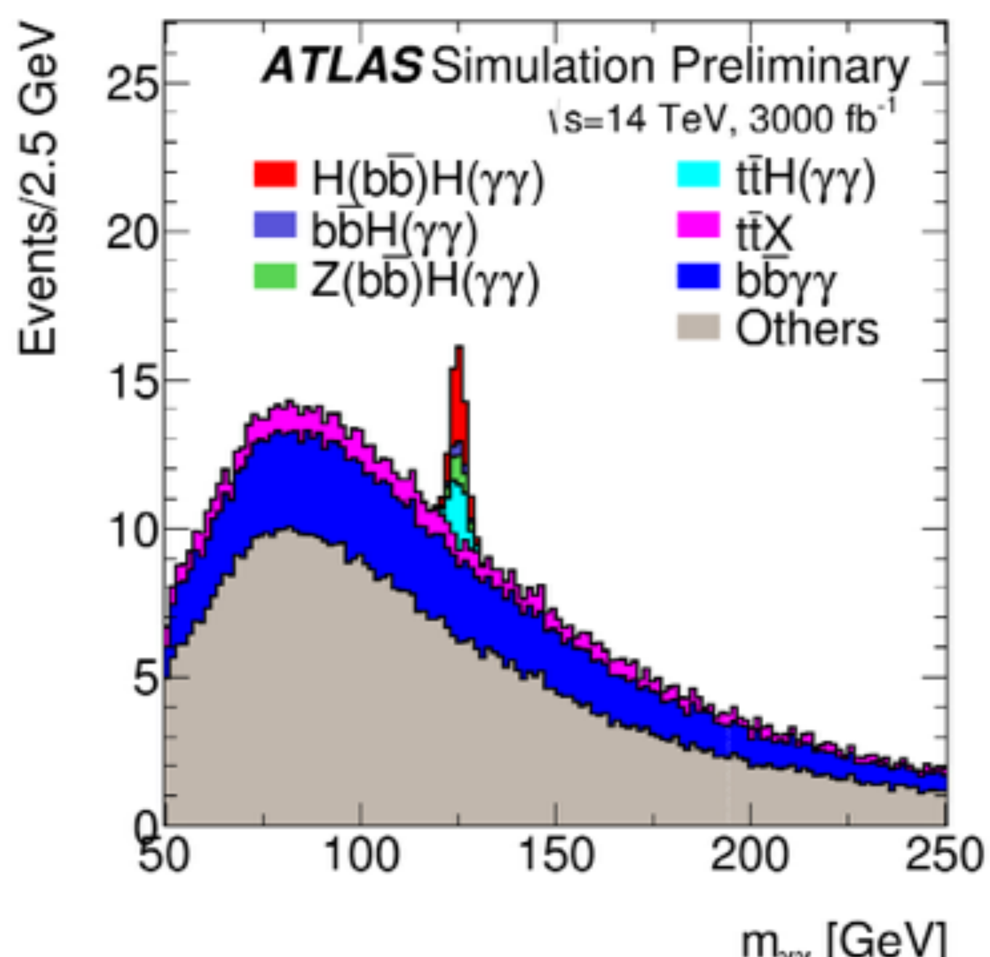
— H(bb) H(γγ) —

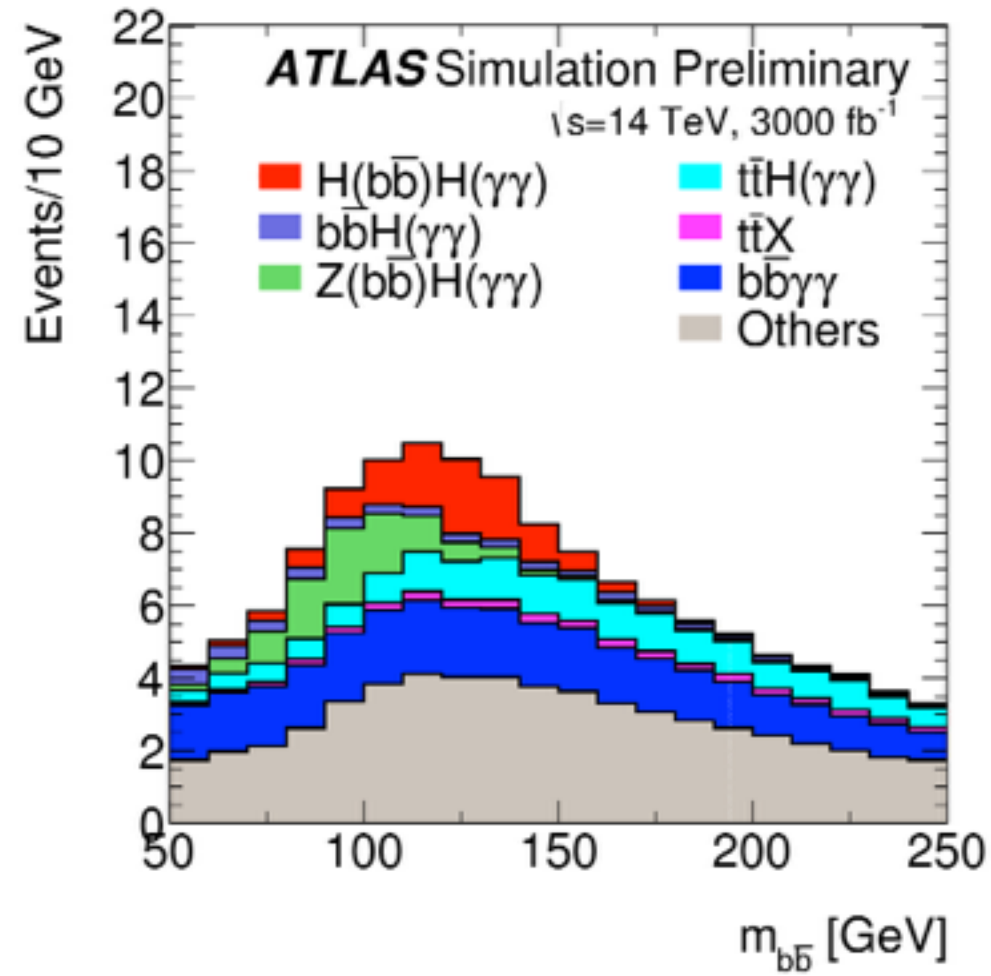
*** event selection**

$\geq$ 2 isolated photons, with $p_T > 30$ GeV, $\lvert\eta\rvert < 1.37$ or $1.52 < \lvert\eta\rvert < 2.37$
$\geq$ 2 jets identified as b-jets with leading/subleading $p_T > 40/25$ GeV, $\lvert\eta\rvert < 2.5$
No isolated leptons with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
< 6 jets with $p_T > 25$ GeV, $\lvert\eta\rvert < 2.5$
$0.4 < \Delta R^{b\bar{b}} < 2.0$, $0.4 < \Delta R^{\gamma\gamma} < 2.0$, $\Delta R^{\gamma b} > 0.4$
$100 < m_{b\bar{b}} < 150$ GeV, $123 < m_{\gamma\gamma} < 128$ GeV
$p_T^{\gamma\gamma}$, $p_T^{b\bar{b}} > 110$ GeV

*** expected events for SM**
— before (320) and after selection (8)

*** SM scenario: 1.3 σ significance**





Higgs pair production

— H(bb) H(ττ) —

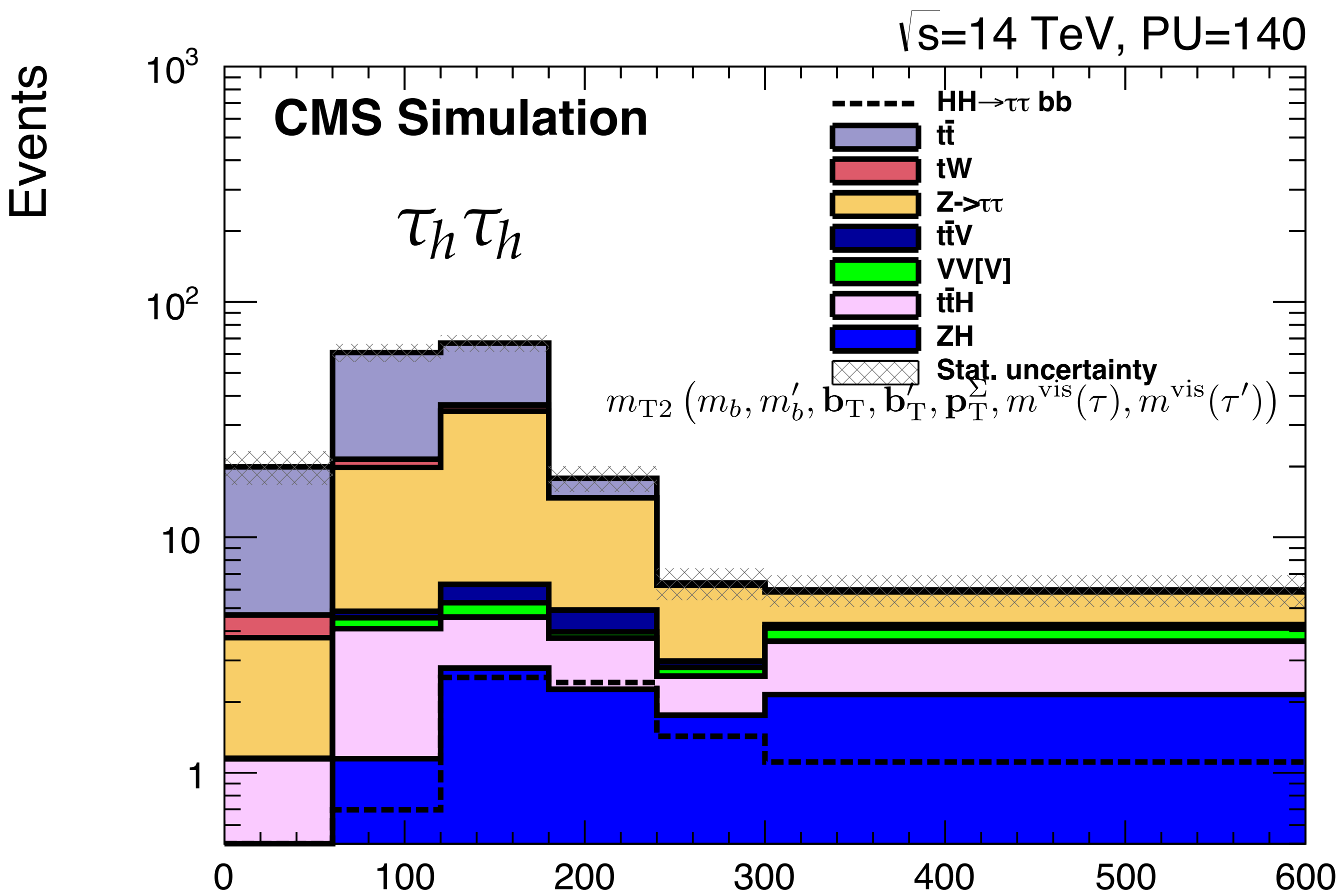
* $\tau_h\tau_h$

— with m_{2T} specially designed (arXiv 1309.6318) to remove tt
— both taus with $p_T > 60$ GeV or leading tau with $p_T > 90$ GeV and sub-leading tau $p_T > 45$ GeV

* $\tau_\mu\tau_h$

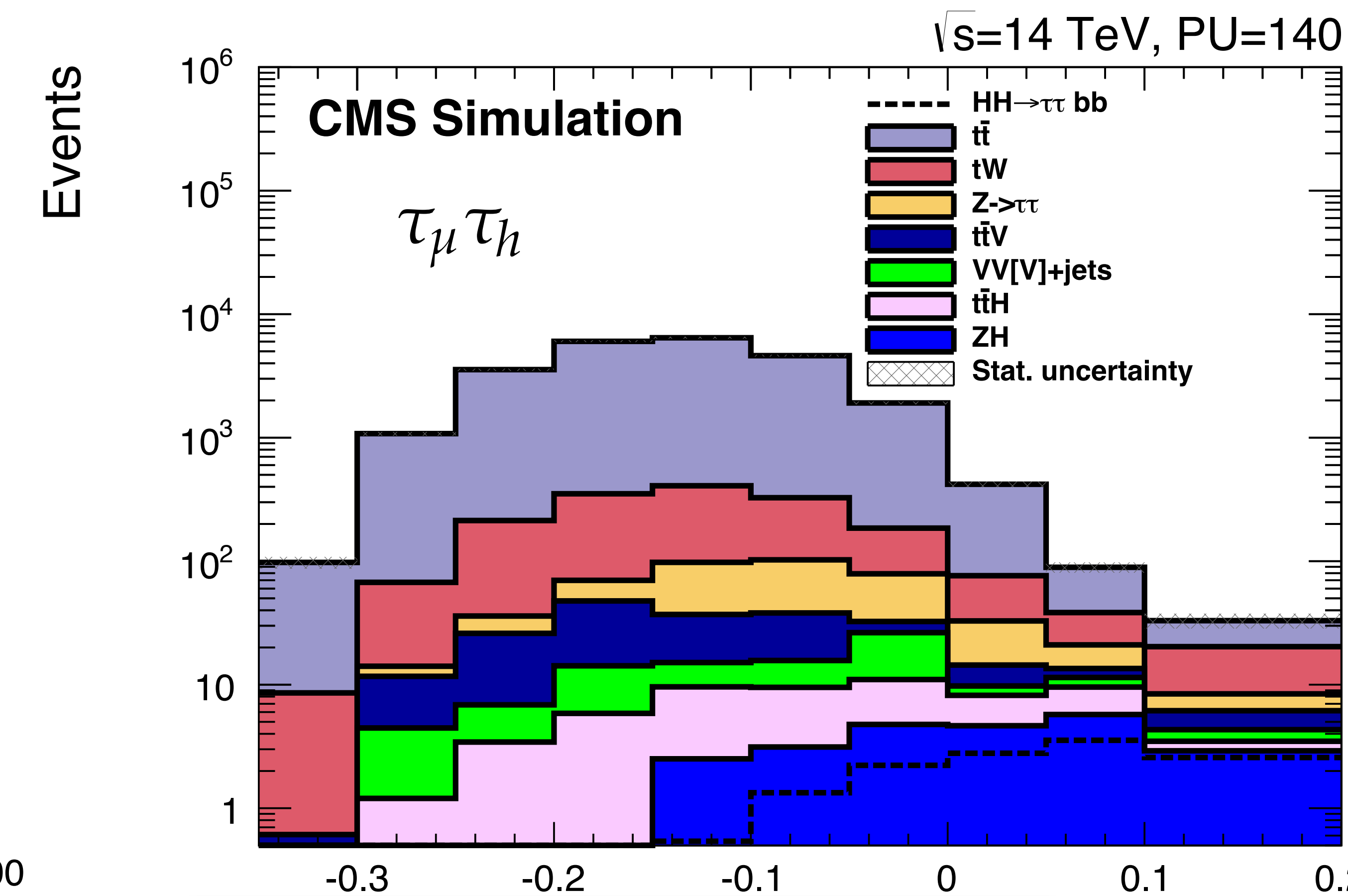
— muon with $p_T > 30$ GeV and tau with $p_T > 30$ GeV

* SM scenario — combination: 0.9 σ significance



* SM scenario: 0.7 σ significance

m_{T2} [GeV/c^2]



* SM scenario: 0.5 σ significance

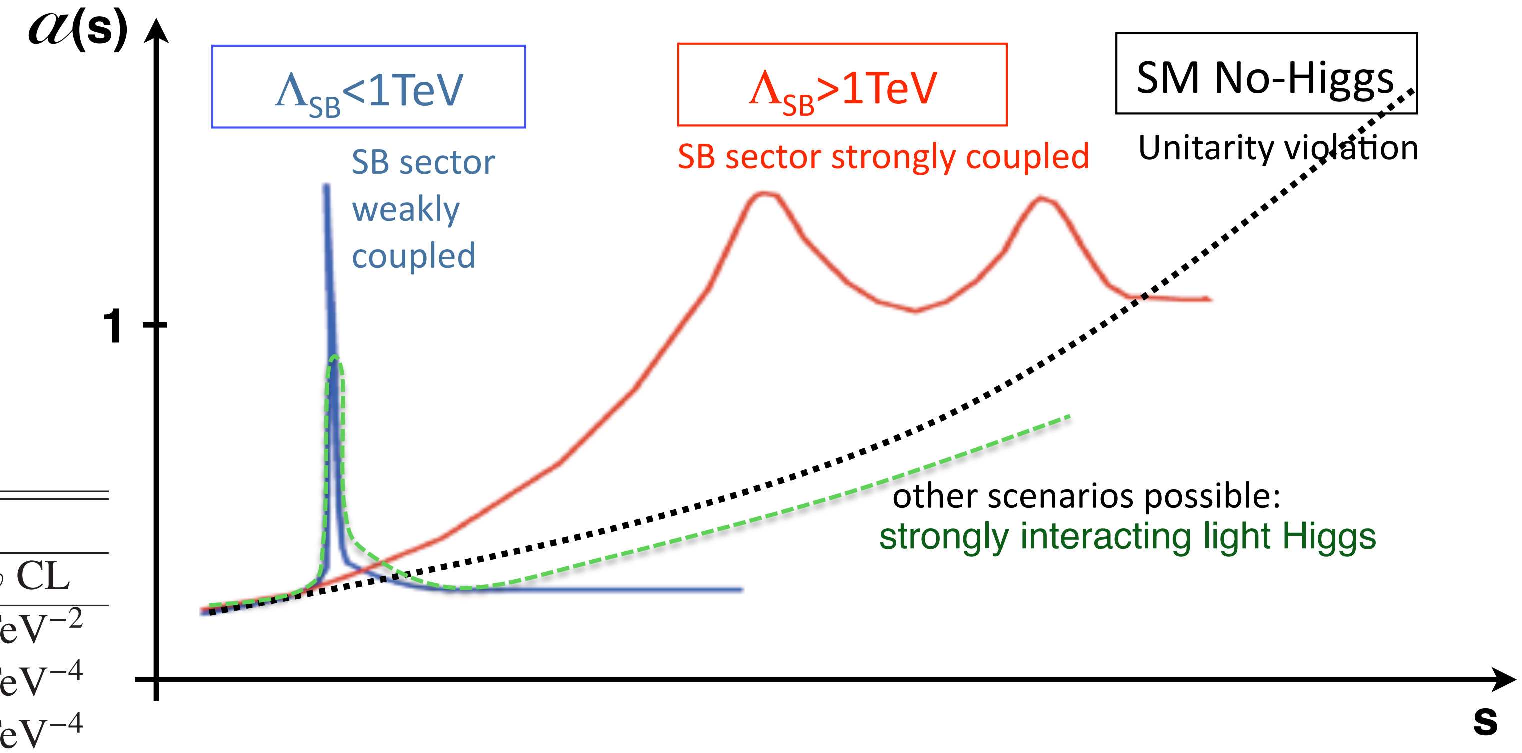
BDT

still in the "visible" range

— VV scattering —

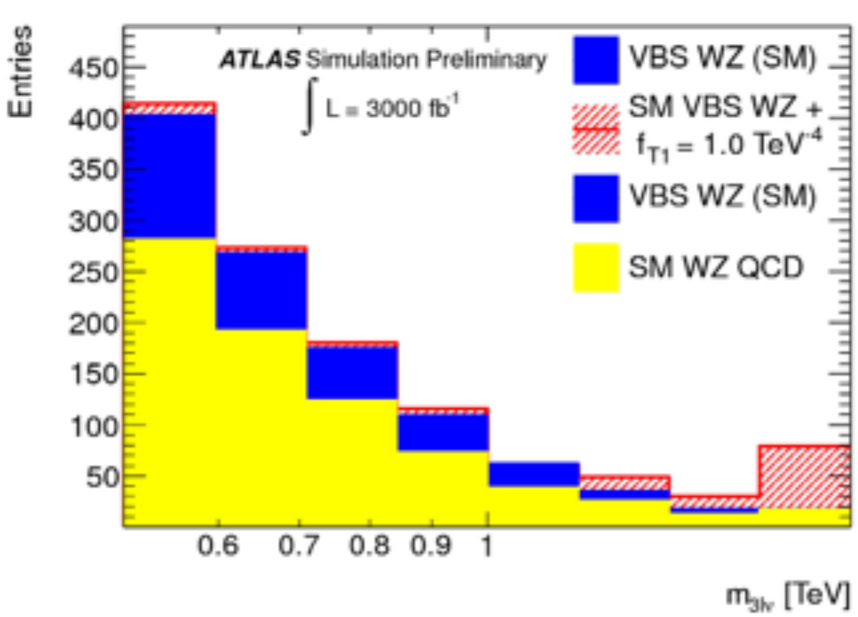
never say never

* σ (VV > VV) vs. M(VV)
* test nature of Higgs boson or
* find alternative EWSB mechanism

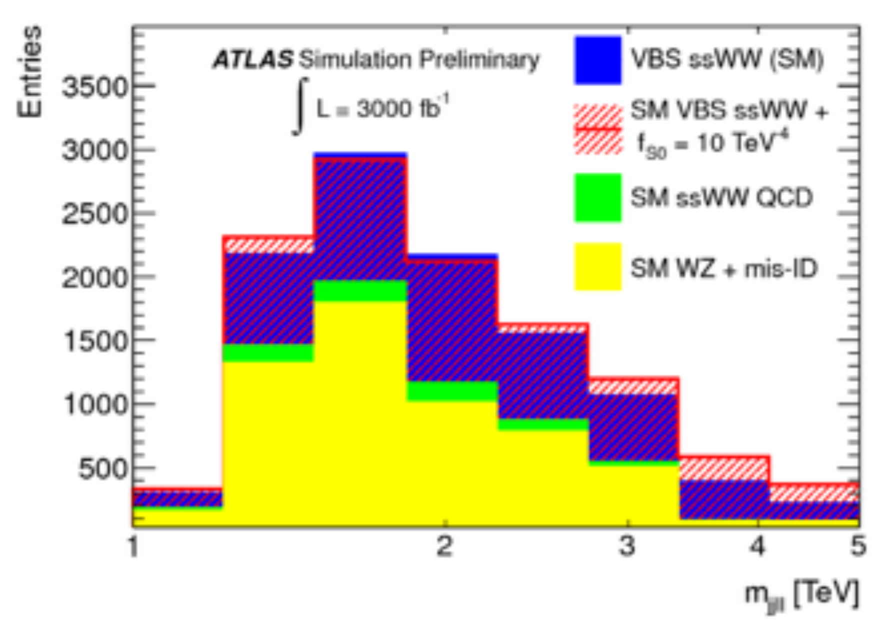


Parameter	dimension	channel	Λ_{UV} [TeV]	3000 fb^{-1}	
				5σ	95% CL
$c_{\phi W}/\Lambda^2$	6	ZZ	1.9	16 TeV^{-2}	9.3 TeV^{-2}
f_{S0}/Λ^4	8	$W^{\pm}W^{\pm}$	2.0	4.5 TeV^{-4}	0.8 TeV^{-4}
f_{T1}/Λ^4	8	WZ	3.7	0.6 TeV^{-4}	0.3 TeV^{-4}

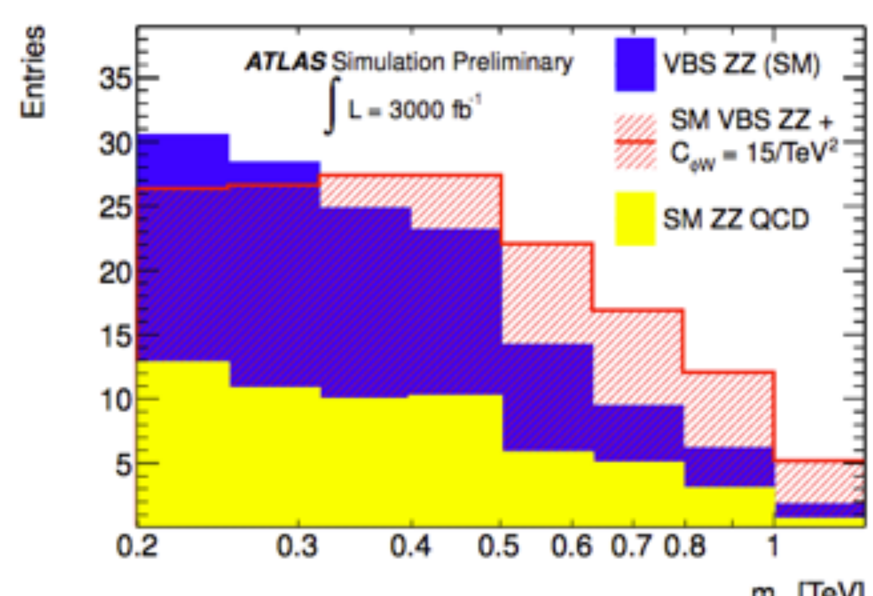
WZ



WW



ZZ



some of us will remain incurable dreamers

future cannot have conclusions…

nor summaries,
only ideas…
that you could take home

* HL LHC upgrade is well defined and scheduled
* we have very good plans how to update our detectors
— let's hope that no external calamity will happen

* with the new detectors:
— we can measure signal strengths and relative couplings to percent level
— we can access the 2nd lepton and quark generations
— combining ATLAS and CMS results we can probably reach 3 σ significance for the diHiggs production

* with a bit of chance we could even talk after HL LHC about VV scattering

in the end is not looking so bad…

backup

back into the future…

*** this is how the pier looks nowadays — guys, don't make a 2nd Baikal lake**

back to physics…

*** we like drawing plans and setting/checking up theories**
*** but we often forget how small are the “new” signals that we are looking for**

back to physics…

* on the way back…

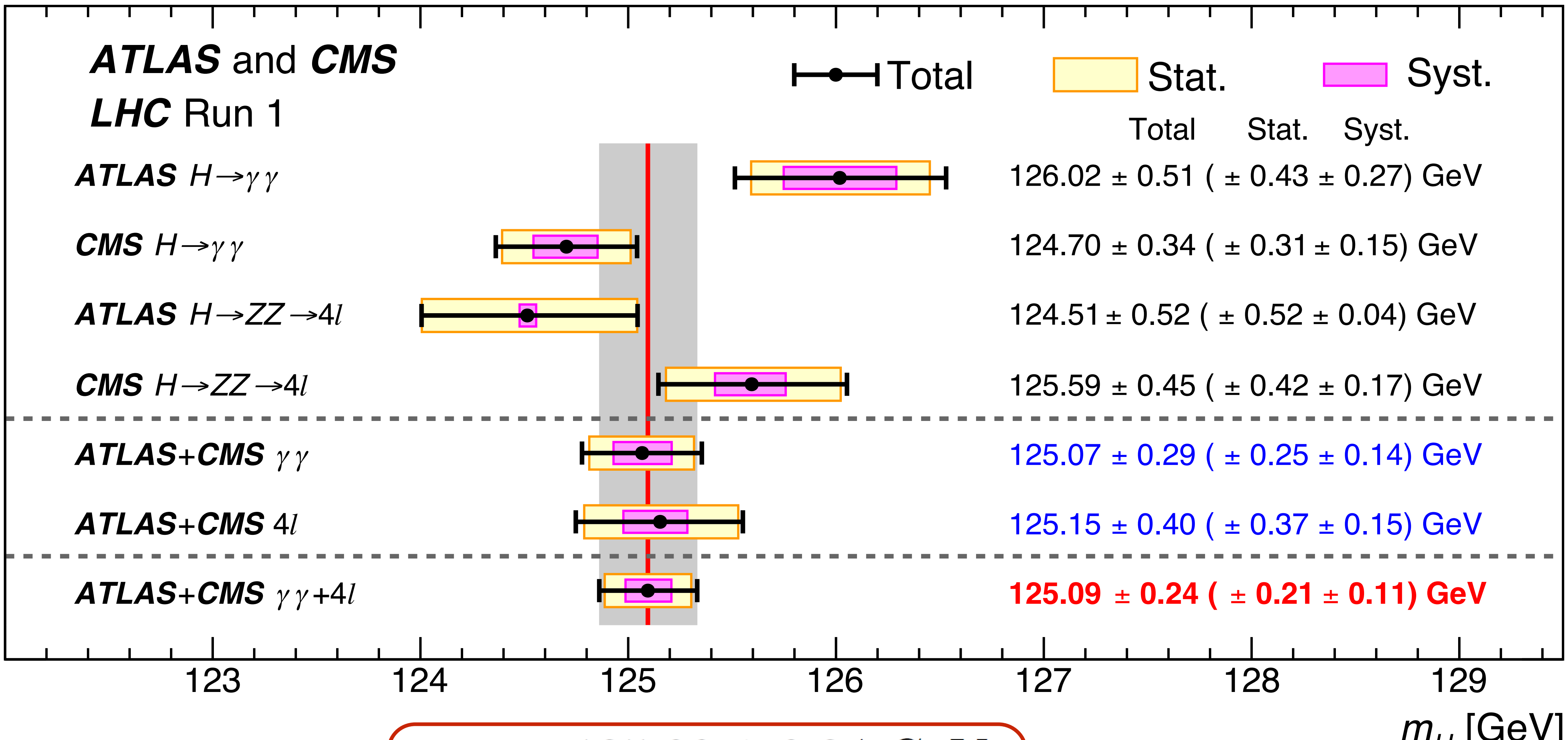
* and even more often, when we see a discrepancy from what we expect we hit it with “conservative attitude” blowing up the errors…
* is time to stop doing this.

a historical combination
ATLAS + CMS: Higgs mass after Run I

* statistic uncertainty

$$m_H = 125.09 \pm 0.21(\mathrm{stat.}) \pm 0.11(\mathrm{scale}) \pm 0.02(\mathrm{other}) \pm 0.01(\mathrm{theory})\ \mathrm{GeV}$$

* energy scale and resolution

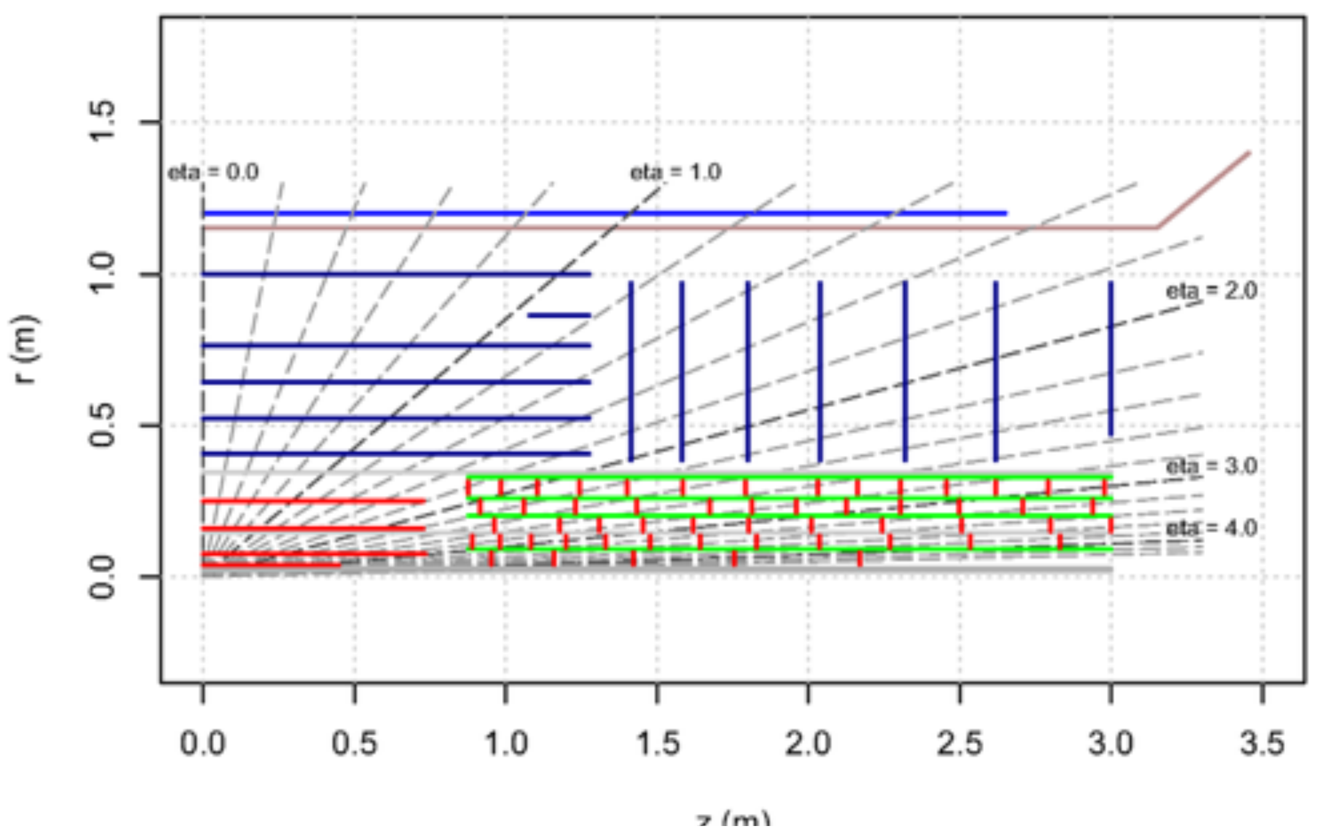


$$m_H = 125.09 \pm 0.24\ \mathrm{GeV}$$

* overall: 0.19% precision

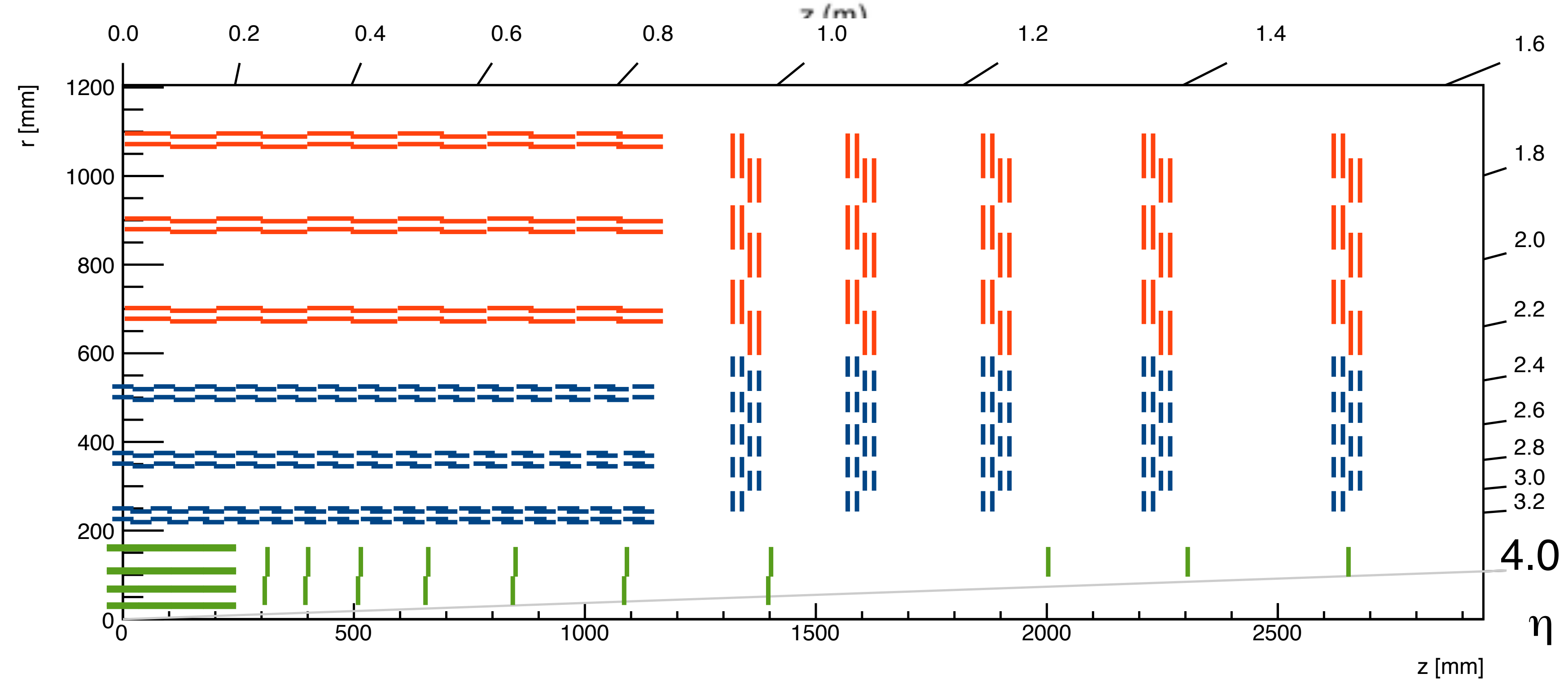
new ATLAS vs. CMS Tracker

ATLAS



few more adjustments and they look alike

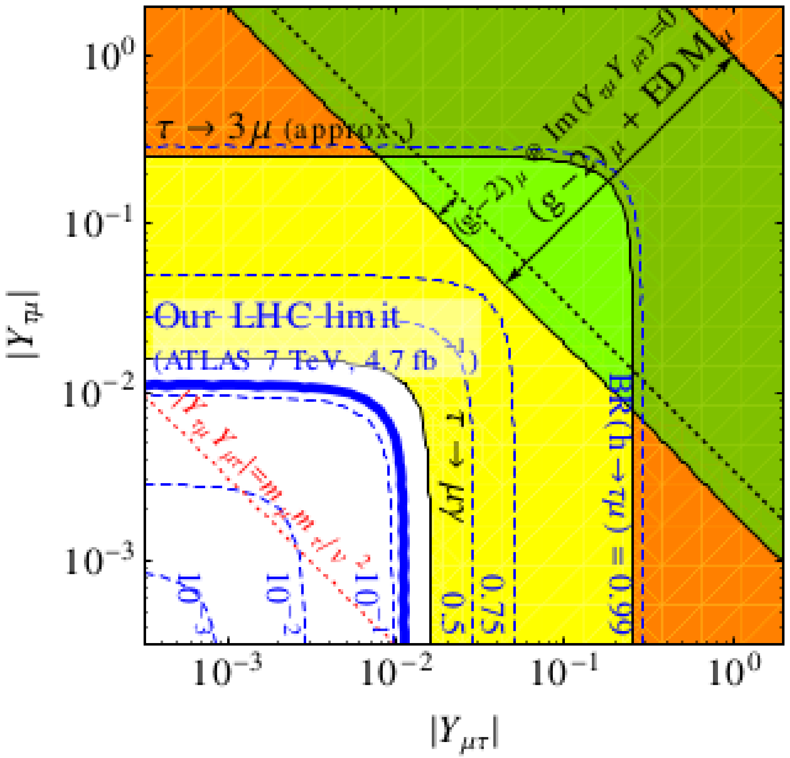
CMS



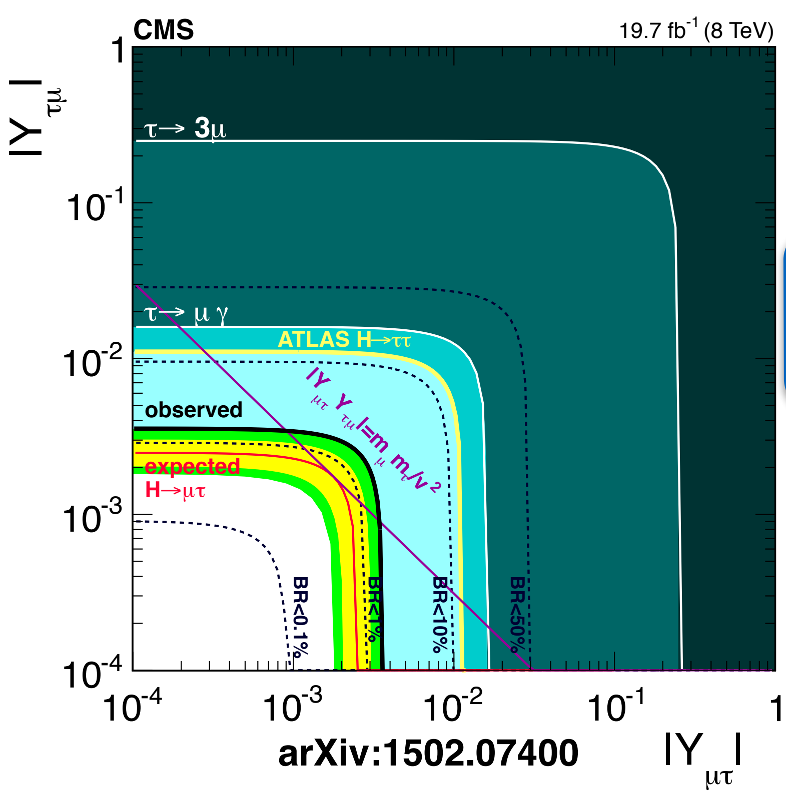
Higgs LFV decay modes

UniHH group

arXiv: 1209.1397



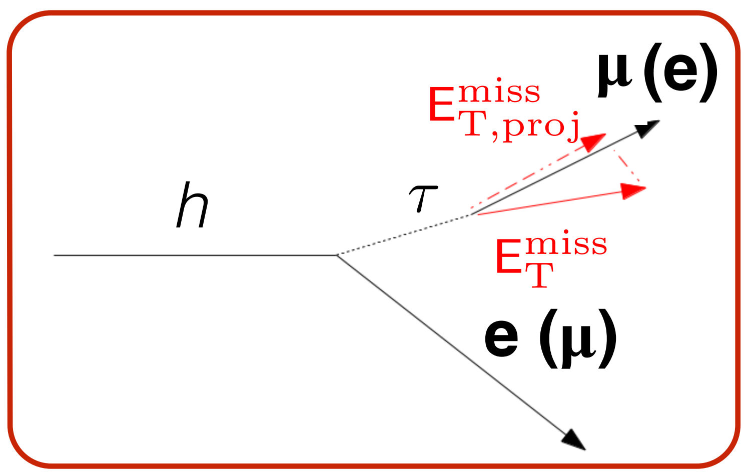
one order of magnitude improvement



arXiv:1502.07400

Yukawa Matrix:

$$Y = \begin{pmatrix} Y_{ee} & Y_{e\mu} & Y_{e\tau} \\ Y_{\mu e} & Y_{\mu\mu} & Y_{\mu\tau} \\ Y_{\tau e} & Y_{\tau\mu} & Y_{\tau\tau} \end{pmatrix}$$

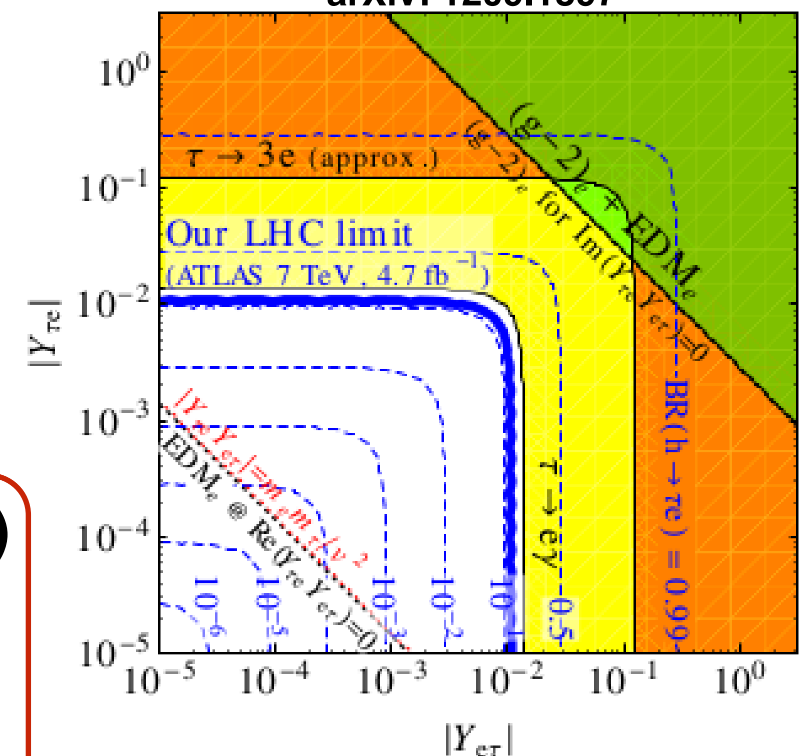


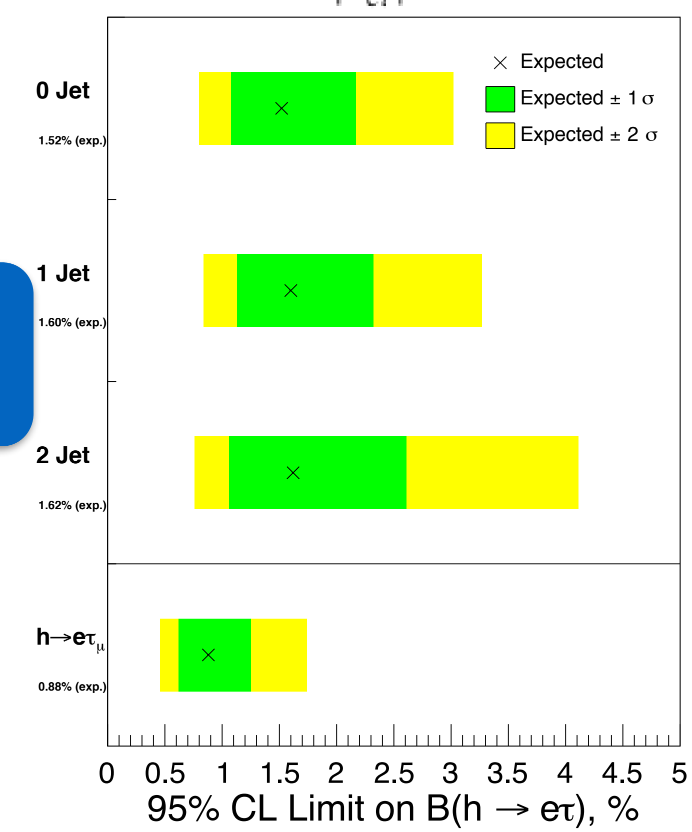
*** observed limit on h → μ τ: 1.57%**
*** Yukawa coupling constraint**

$$\sqrt{|Y_{\mu\tau}|^2 + |Y_{\tau\mu}|^2} < 3.6 \times 10^{-3}$$

*** new expected limit on h → e τ is at 1%**

arXiv: 1209.1397





and after 2015

hunt exotic decay modes and models

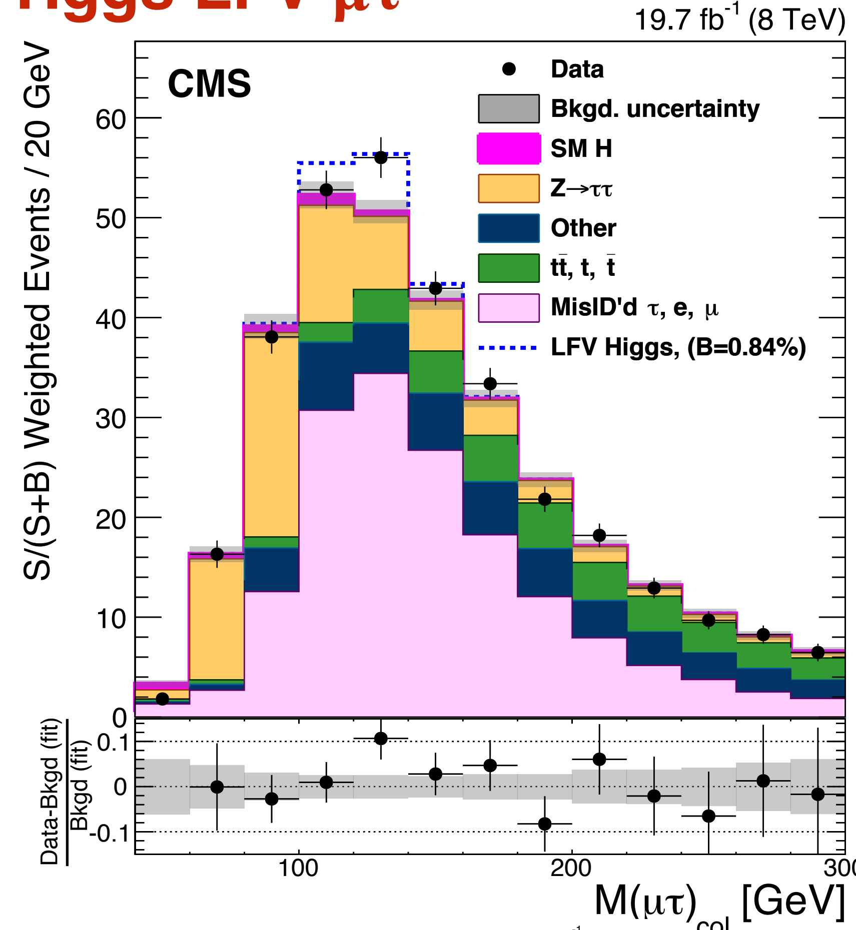
complete SM picture

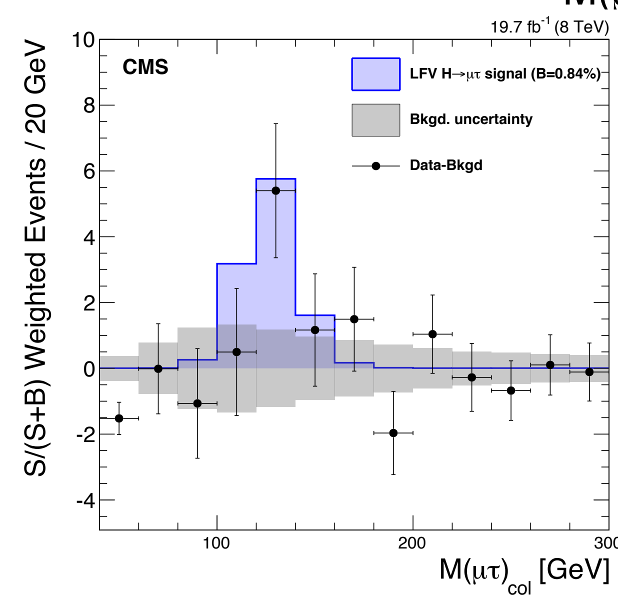
	signal strength μ (combination)	σ/σ_{SM}
h(125 GeV) ➛ $\tau\,\tau$ (2nd generation fermions)	0.91 ± 0.27	3.2
h(125 GeV) ➛ WW	0.83 ± 0.21	4.3
h(125 GeV) ➛ b b (2nd generation quarks)	0.93 ± 0.49	2.1
h(125 GeV) ➛ $\mu\mu$ (3rd generation fermions)	0.8 ± 3.45	0.4

2015

after 2015

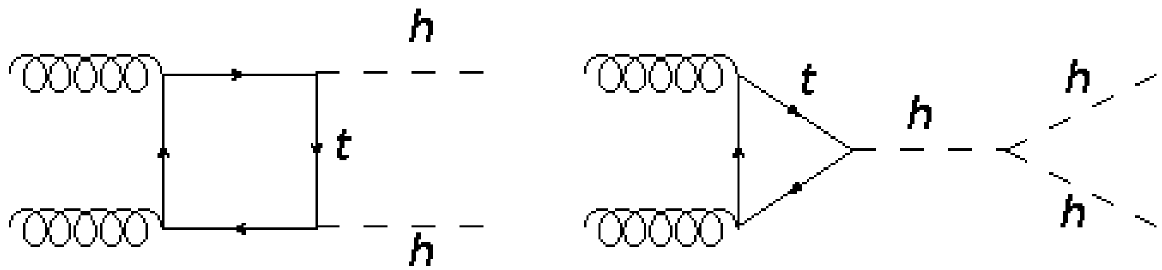
Hggs LFV $\mu\tau$



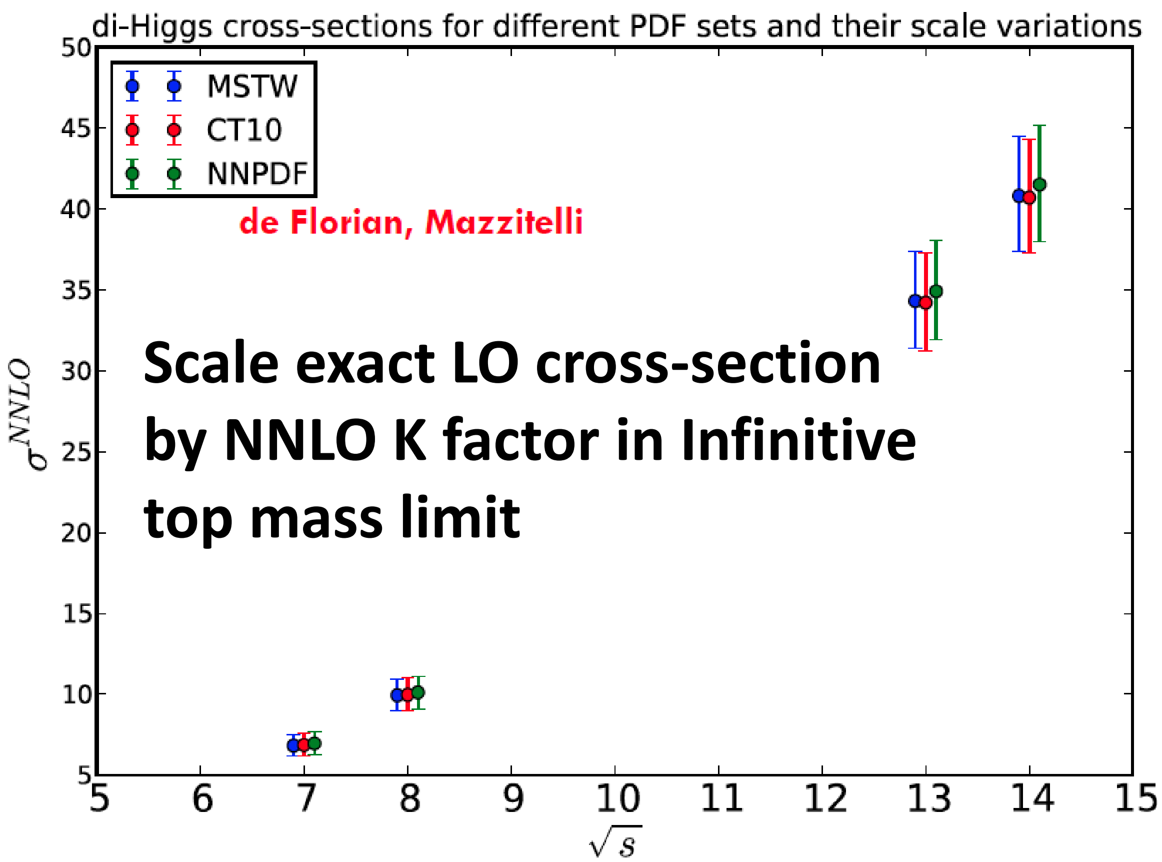


investigate the 2.4 σ excess

SM double Higgs production



LHCHXSWG prospects



NNLO σ in fb with CTEQ10

Scale	√s			
	7	8	13	14
$\mu = m_{HH}/2$	7.52	10.9	37.2	44.1
$\mu = m_{HH}$	**6.85**	**9.96**	**34.3**	**40.7**
$\mu = 2m_{HH}$	6.12	8.94	31.1	37.1
"+" [%]	10%	9%	8%	8%
"-" [%]	11%	10%	9%	9%

some of us will remain incurable dreamers