Tohoku Workshop on "Higgs and Beyond",
5-9 June 2013, Tohoku University, Sendai, Japan

Physics Potential at the HL-LHC

i.e. what we can learn by collecting ∫L~ 3000 fb^{-1}
in pp collisions at √S ~ 14 TeV

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Outline

- pp collision reach: where we stand today (!!!)
- High-Luminosity (HL) at LHC: generalities
- HL-LHC Physics potential (3000 fb^{-1} vs 300 fb^{-1}):
  - Higgs Physics (+ VV scattering → EWSB closure test)
  - Rare processes
  - New heavy resonances (reach)
  - SUSY states (reach)
- Summary

focus on ATLAS+CMS physics

Warning !

Provisional scenario presented here
for HL-LHC !

Could be much affected after further
LHC discoveries/findings at 14 TeV
before HL-phase start-up !

(just think of our expectations for next LHC phase in case Higgs resonance had not yet been observed at 7-8 TeV...)

(here, not an exhaustive review of present studies anyway...)

main references

- Contributions to the

  Update of the European Strategy for Particle Physics,
  CERN Council Open Symposium,
  Kracow, 10-12 September 2012

  [notes submitted by ATLAS and CMS
  + subsequent updates (Oct-Nov 2012) for
  Physics Briefing Book (Jan. 2013)]

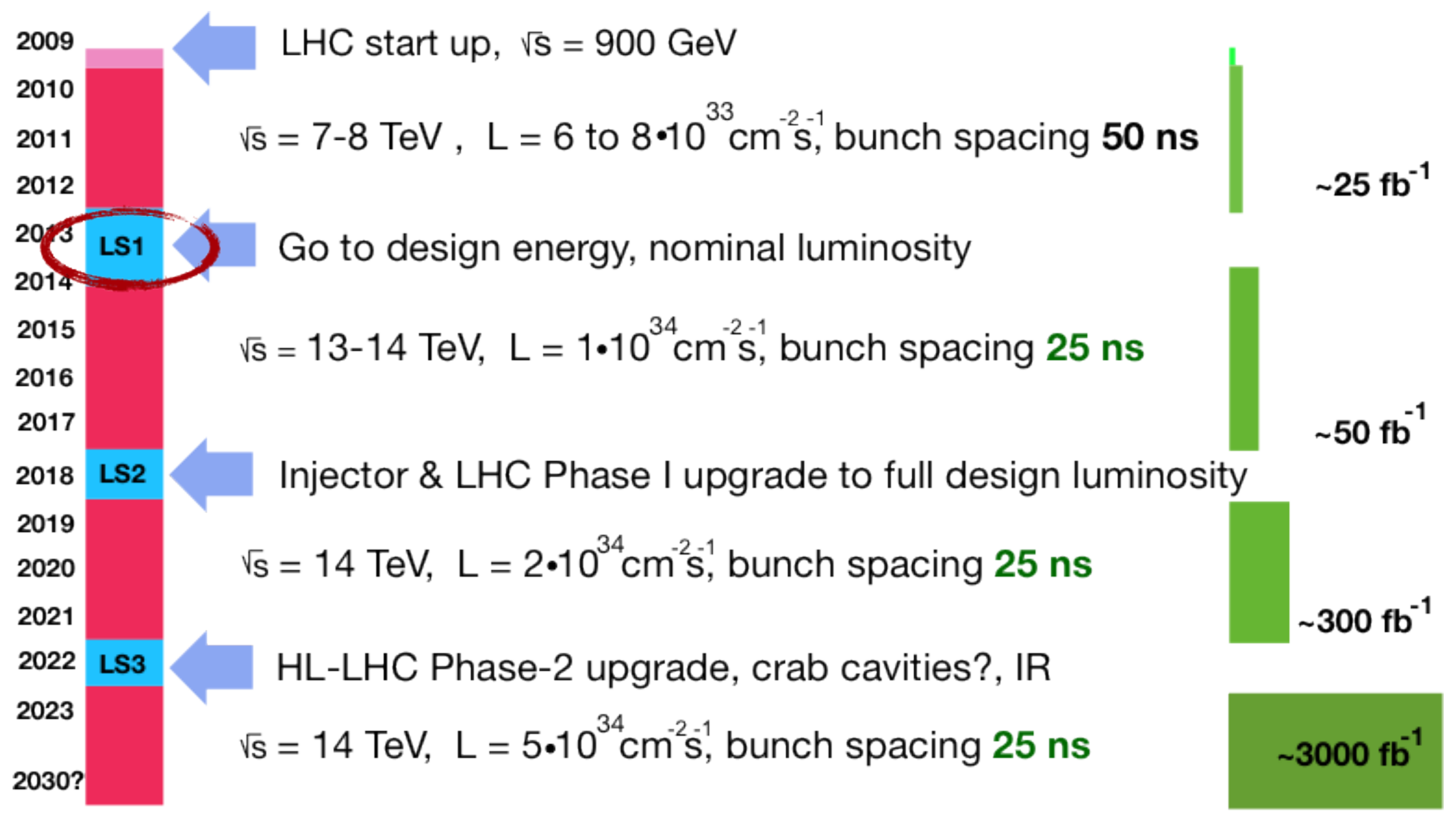
  HL-LHC Physics Potential Section :

  - Higgs couplings, confirm spin, CP and self-couplings
  - Vector Boson Scattering
  - SUSY
  - Exotics
  - SM: Vector Boson TGCs and top quark FCNC
- talks by R. Aleksan and A. Nisati

pp collisions: where we stand today

- LHC run at 7-8 TeV [$\int L \sim 5 + 20\ \mathrm{fb}^{-1}$] (just initial LHC phase !) ➜ results well above expectations...
- SM tested at high accuracy in a new √s range : QCD (many regimes), top physics, EW processes, flavor
- "direct" exploration of SM EWSB sector started up with observation of a (quite light) Higgs-like resonance !!!
- still a lot of room for a non-SM EWSB sector
- bounds on new heavy states predicted by many BSM models widely extended wrt pre-LHC era
- no real hint of BSM physics !
- SM hierarchy-problem solution getting harder...

LHC upgrade schedule → HL-LHC



LHC start up, $\sqrt{s} = 900$ GeV

$\sqrt{s} = 7\text{-}8$ TeV , $L = 6$ to $8 \cdot 10^{33}\ cm^{-2}s^{-1}$, bunch spacing **50 ns**

Go to design energy, nominal luminosity

$\sqrt{s} = 13\text{-}14$ TeV, $L = 1 \cdot 10^{34}\ cm^{-2}s^{-1}$, bunch spacing **25 ns**

Injector & LHC Phase I upgrade to full design luminosity

$\sqrt{s} = 14$ TeV, $L = 2 \cdot 10^{34}\ cm^{-2}s^{-1}$, bunch spacing **25 ns**

HL-LHC Phase-2 upgrade, crab cavities?, IR

$\sqrt{s} = 14$ TeV, $L = 5 \cdot 10^{34}\ cm^{-2}s^{-1}$, bunch spacing **25 ns**

aim: collect ~ 3000 fb^{-1} at $\sqrt{S}$ ~ 14 TeV in 10-12 years

major detector upgrades needed at HL-LHC

- harsher running conditions :
  - higher rates
  - 4-5 times higher pile-up than today (~140 events/bunch-crossing)
- want to keep performance on Physics Objects similar to present one !
- needed:
  - improved trigger
  - new tracking
  - improved forward detectors
  - . . . faster inner detector, with high granularity and redundancy, to cope with large occupancy
- HL-LHC physics potential will crucially depend on final trigger + detector performance (not yet known...) !

how does 10 × ∫L impact on Physics?

- all rare processes (of course) benefits from that

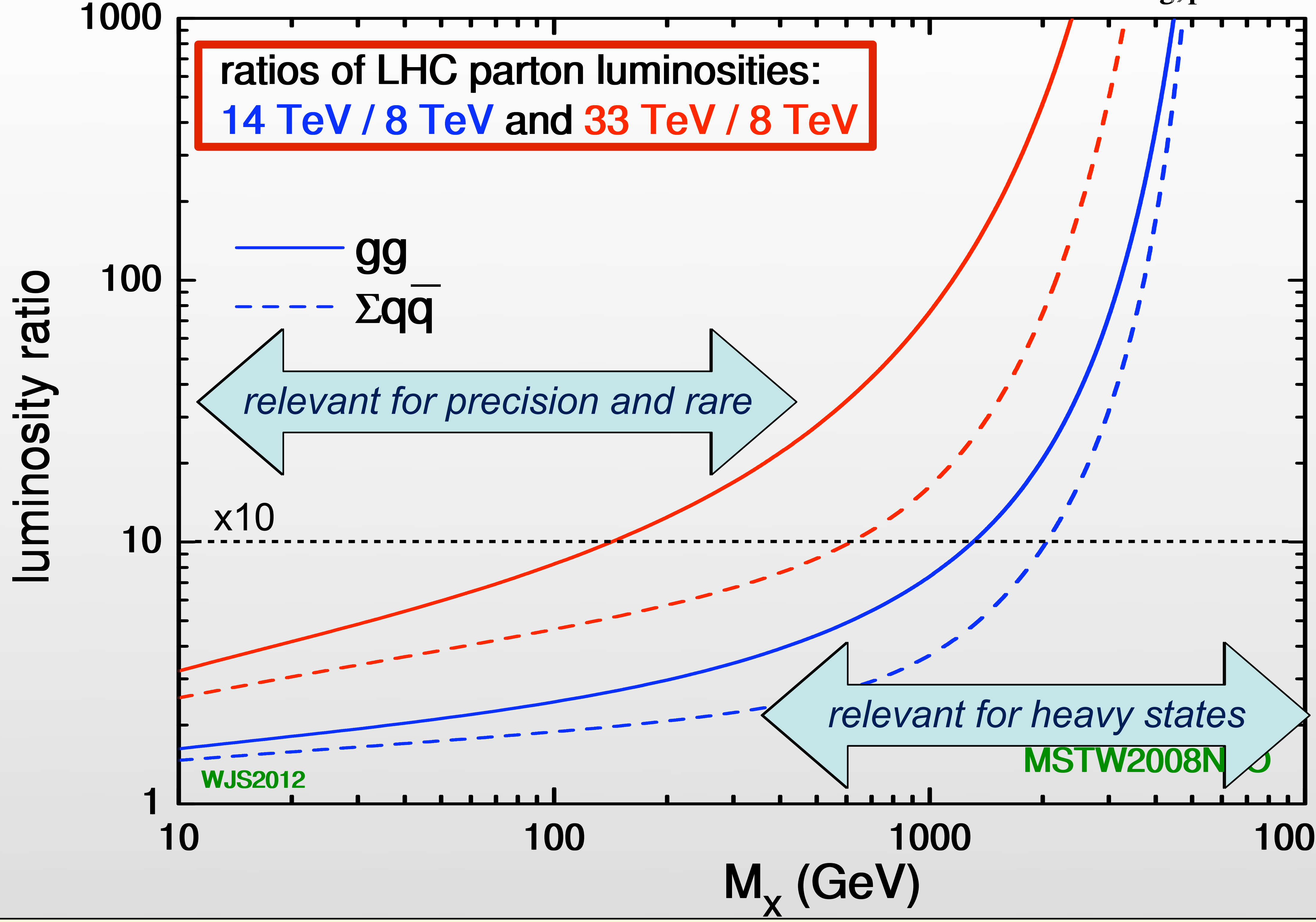
- moderate-to-small-σ processes benefit a lot, too
  [➜ higher sensitivity in Higgs physics,
  and EW (SM+BSM) sectors]

- precision physics !

- (milder) gain in extending phase-space for heavy state production
  (latter benefit more from higher √S) ➜ ➜ ➜

10 x ∫ L increase versus ~ 2 x √s increase

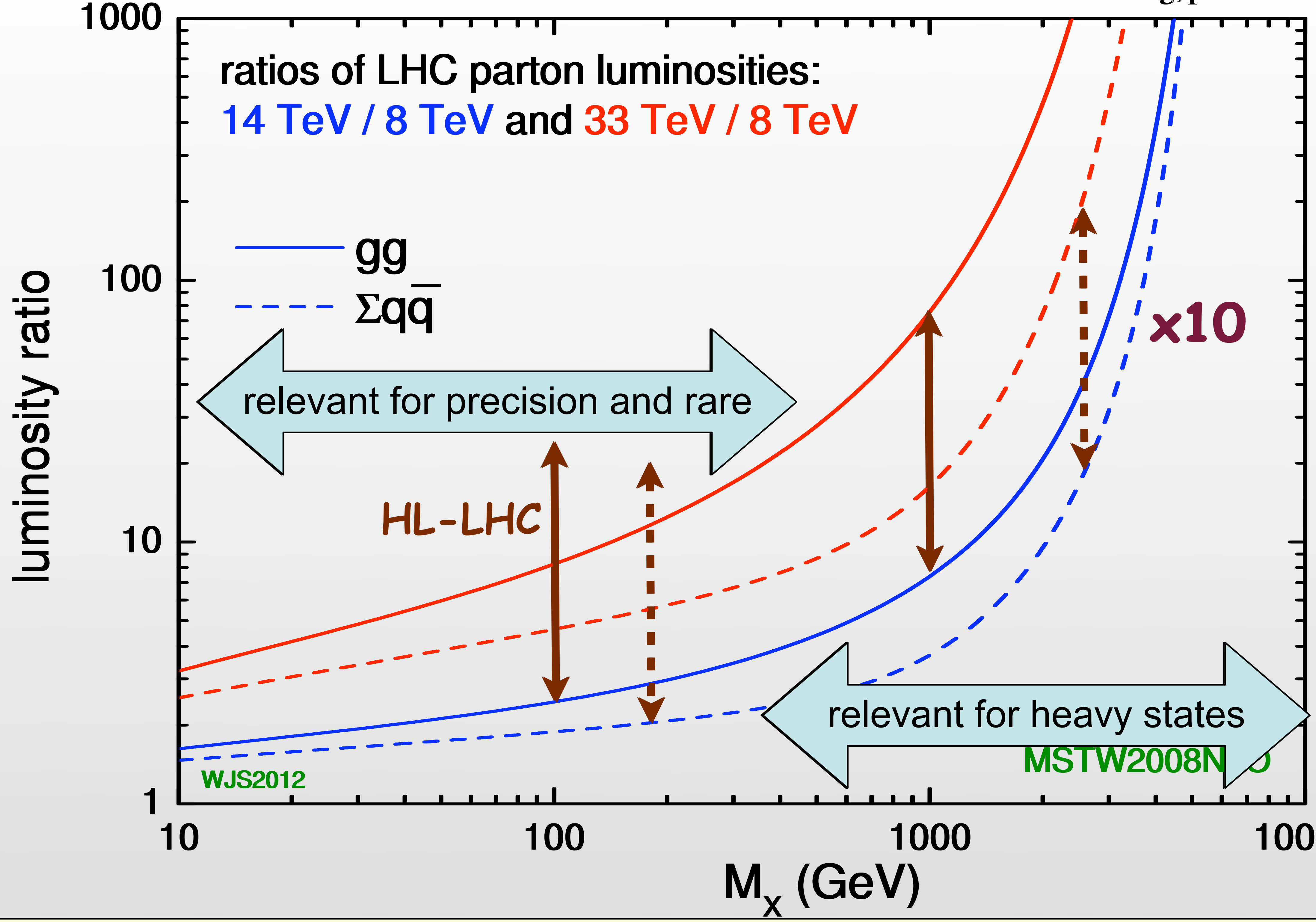
W.J. Stirling, private communication



HE-LHC$_{33TeV}$ versus LHC$_{14TeV}$ ➜ effective lumi increase

10 x ∫ L increase versus ~ 2 x √s increase

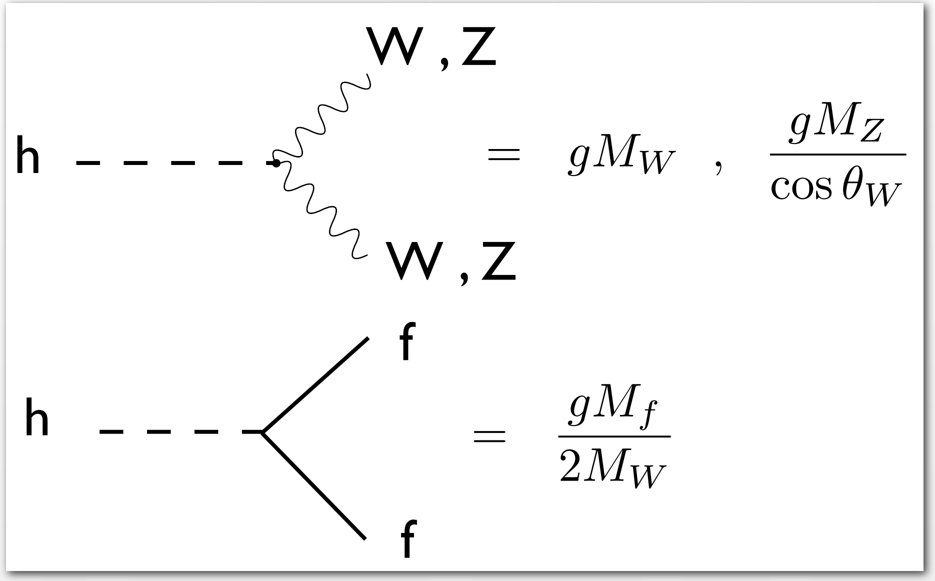
W.J. Stirling, private communication

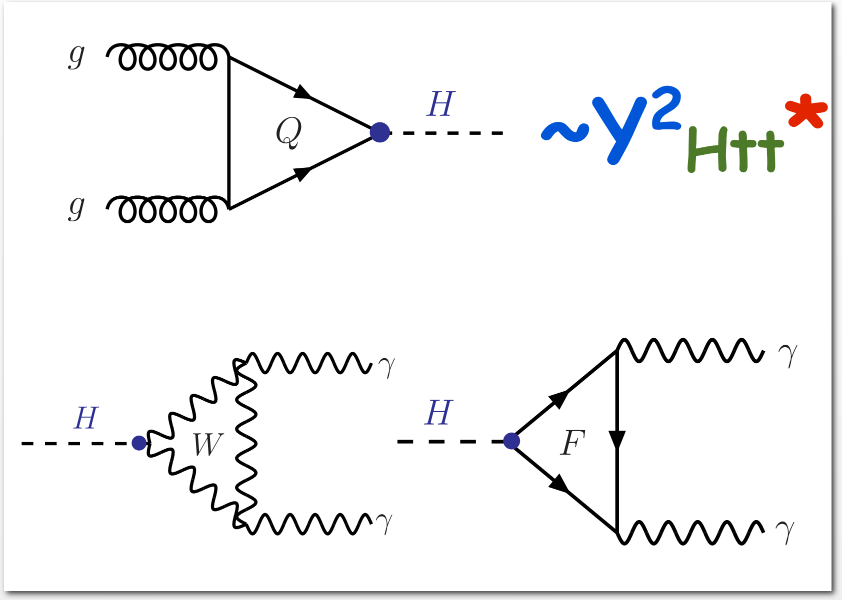


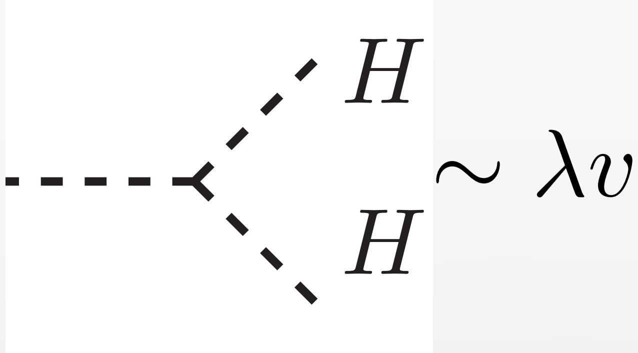
in gg (qq) at $M_X <$ 1(3)TeV, HL-LHC better than HE-LHC$_{33TeV}$

how close is the LHC signal to a SM Higgs ?

- test g_{HXX} (magnitude and structure) to vector bosons (EWSB), fermions and selfcouplings







m_H ~ 126 GeV

Γ_H = 4.2 MeV

$\lambda = (m_H/v)^2/2 = 0.131$

$H \to WW^*$ 23%*

$H \to ZZ^*$ 2.9%*

H → bb 56%*

H → cc 2.8%

$H \to \tau\tau$ 6.2%*

$H \to \mu\mu$ 0.21‰

H → gg 8.5%*

$H \to \gamma\gamma$ 2.3‰*

$H \to \gamma Z$ 1.6 ‰*

new set of reference SM parameters

many couplings accessible at LHC (*) !

top priority at Future Accelerators : test H sector

a) precision measurement of m_H and Γ_H

b) determination of spin and parity, J^P, and CP properties

c) measurement of g_{HVV}'s and g_{Hff}'s

d) measurement of self-coupling strength g_{HHH} (hard !)

e) Extended Higgs sector ? Search for possible partners (neutral/charged) of this boson

f) is this particle a fundamental object, or is it composite?

g) dependence with energy of Vector Boson Scattering cross sections (WW, WZ and ZZ)

h) Hierarchy problem → search for effects beyond SM, such as SUSY, Extra-Dims, Technicolor models...

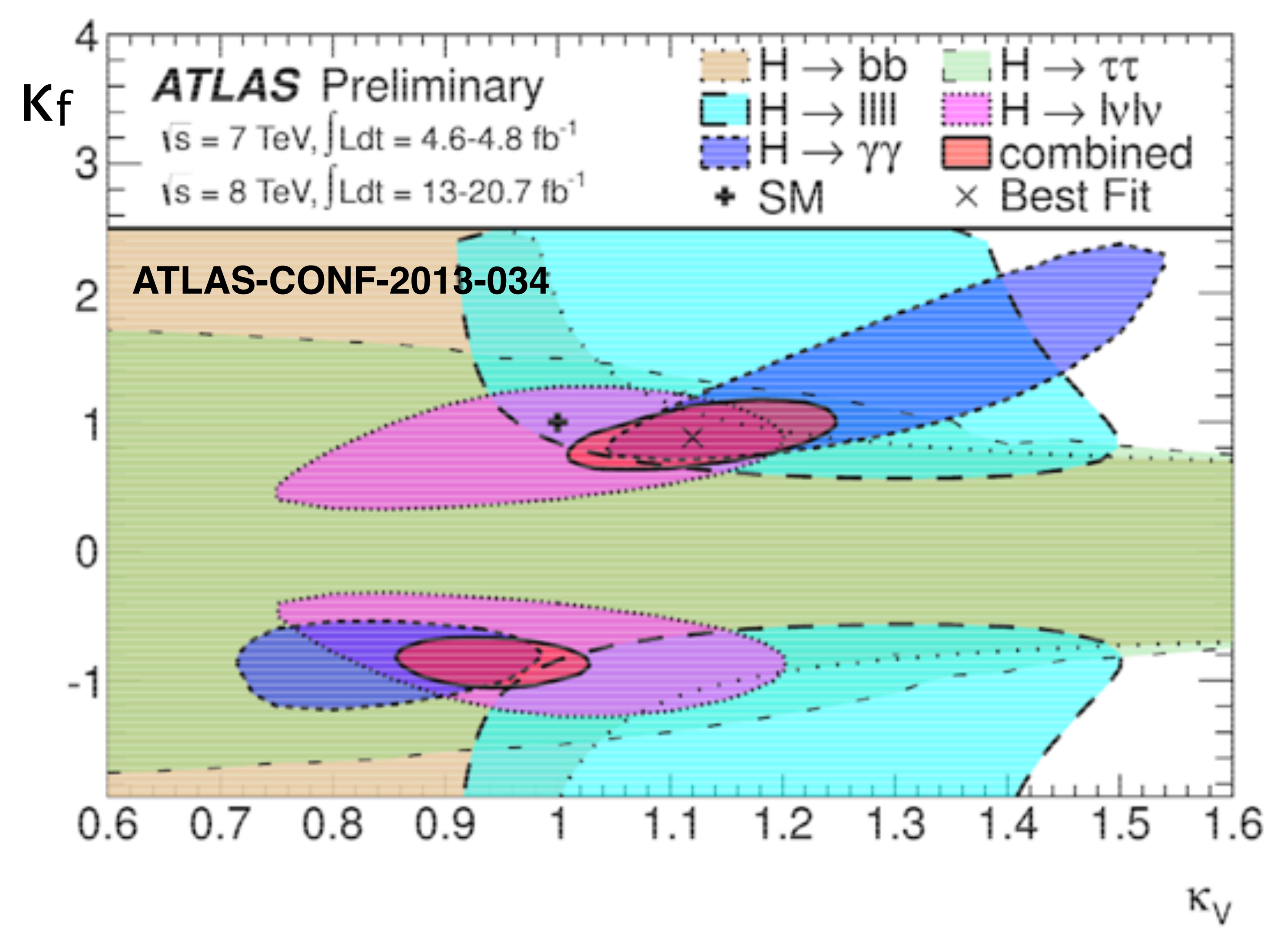
present (2-param) gHXX determination

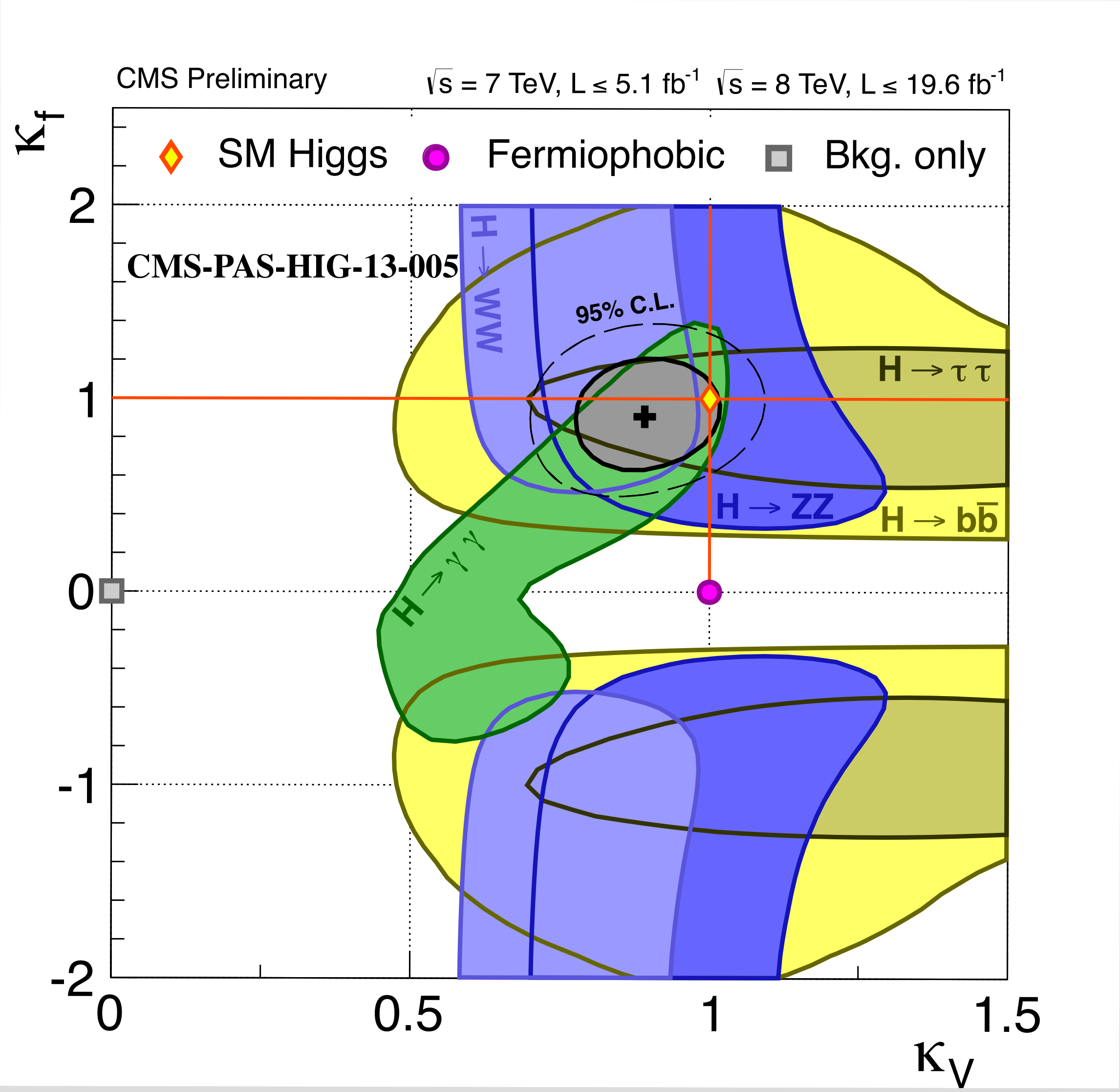
$$g_{HVV} = K_V \, g_{HVV}^{SM}$$

universal modifier of HWW and HZZ couplings

$$Y_f = K_f \, Y_f^{SM}$$

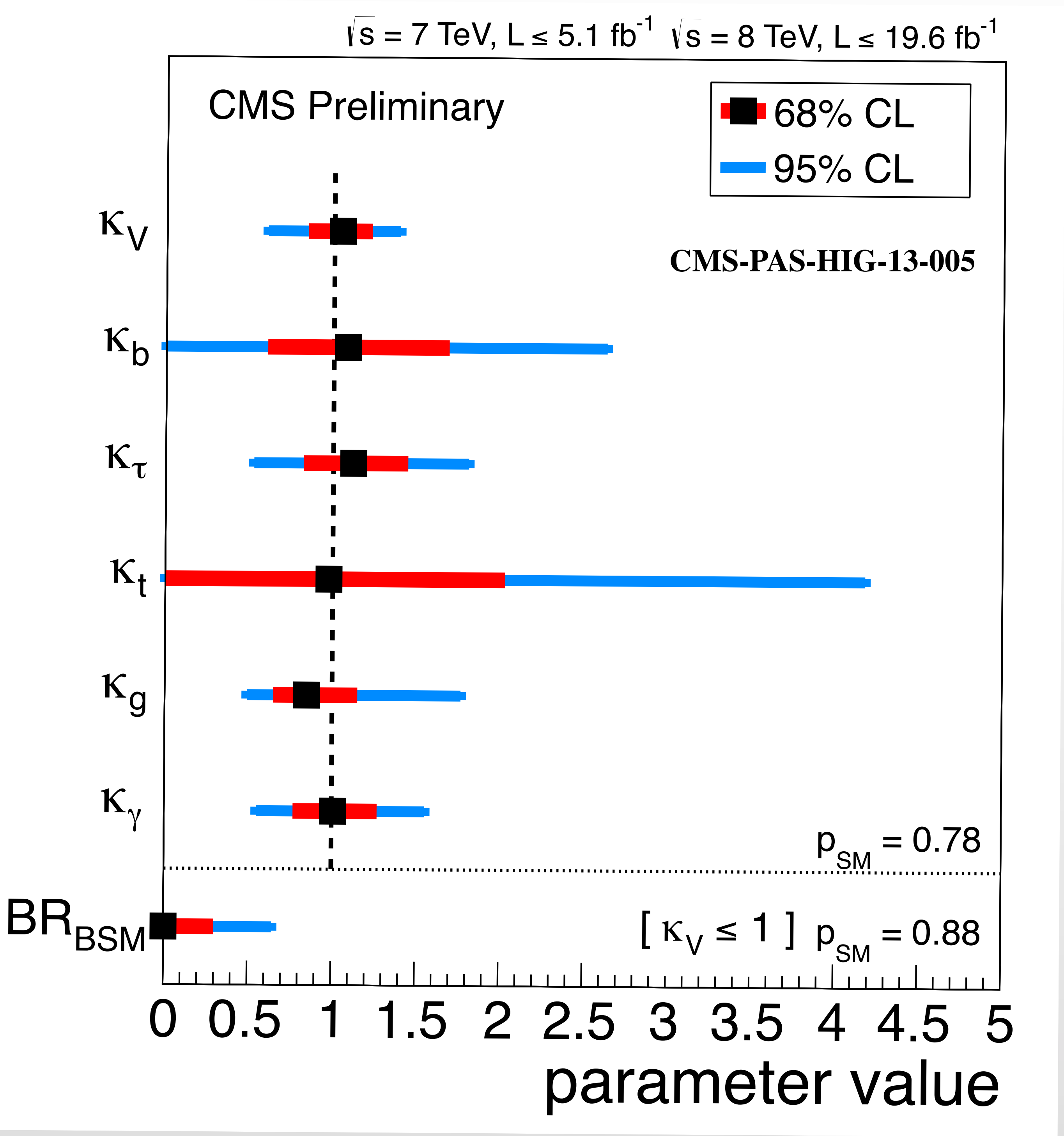
universal modifier of Hff couplings



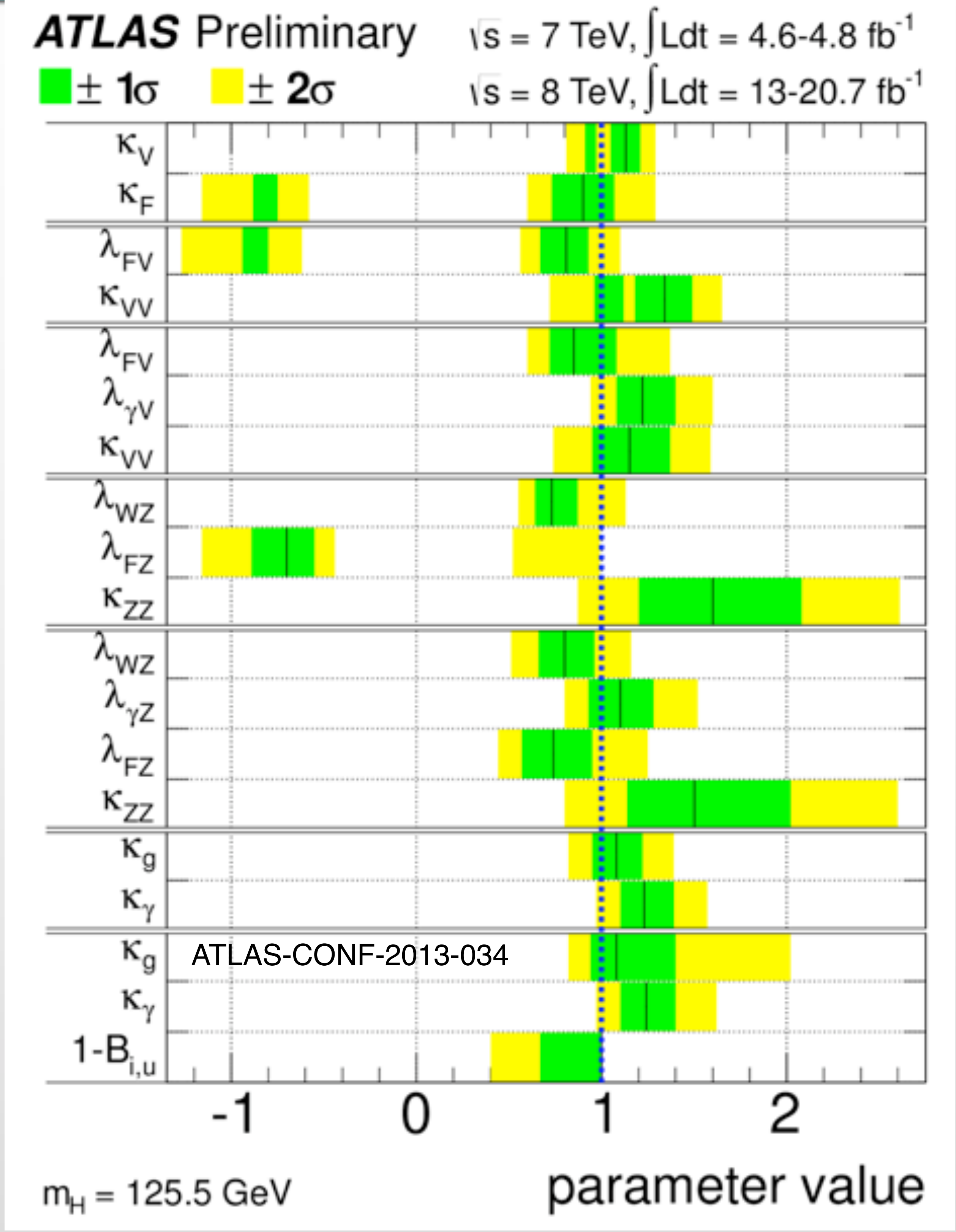


Kv and Kf compatible with SM values !

more statistics → more d.o.f.'s in the g_{HXX} fits



(6 parameter fit)



(Higgs x-section WG benchmarks)

present accuracy : $\Delta g_{HXX} \sim 20\%$!

- starting phase of new exciting chapter of experimental measurements (regardless of possible further new-state discoveries at the LHC !)
- new generation of Precision Tests opened up with excellent sensitivity to BSM effects

  (→ cf. EWPT's at LEP)

  i.e., one-loop decays ($H \to \gamma\gamma$) and production ($gg \to H$) are very sensitive to new heavy degrees of freedom that do not decouple !
- **ability** to reach accuracies on g_{HXX}'s as large as possible **crucial** to test the theory !

HL-LHC projection on Δg_{HXX} by ATLAS and CMS

ASSUME: same (2012) level of detector and trigger performances !

(i.e. upgraded detector and trigger will offset radiation damage and complications due to larger instantaneous lumi and larger event pileup)

ATLAS : fast simulation (parametrize trigger and detector response to different physics objects). Functions describing resolution, and reconstruction and trigger efficiencies defined by extrapolations from the existing data sample, and MC simulations that include up to an average pileup of 69

QUITE CONSERVATIVE !

(CMS)	Δ_{TH}	other syst Δ
Scenario 1	as now	as now
Scenario 2	scaled by 1/2	scaled as √ L
Scenario 3	0	. . .

realistic range

substantial simulation effort, taking into account realistic pile-up conditions

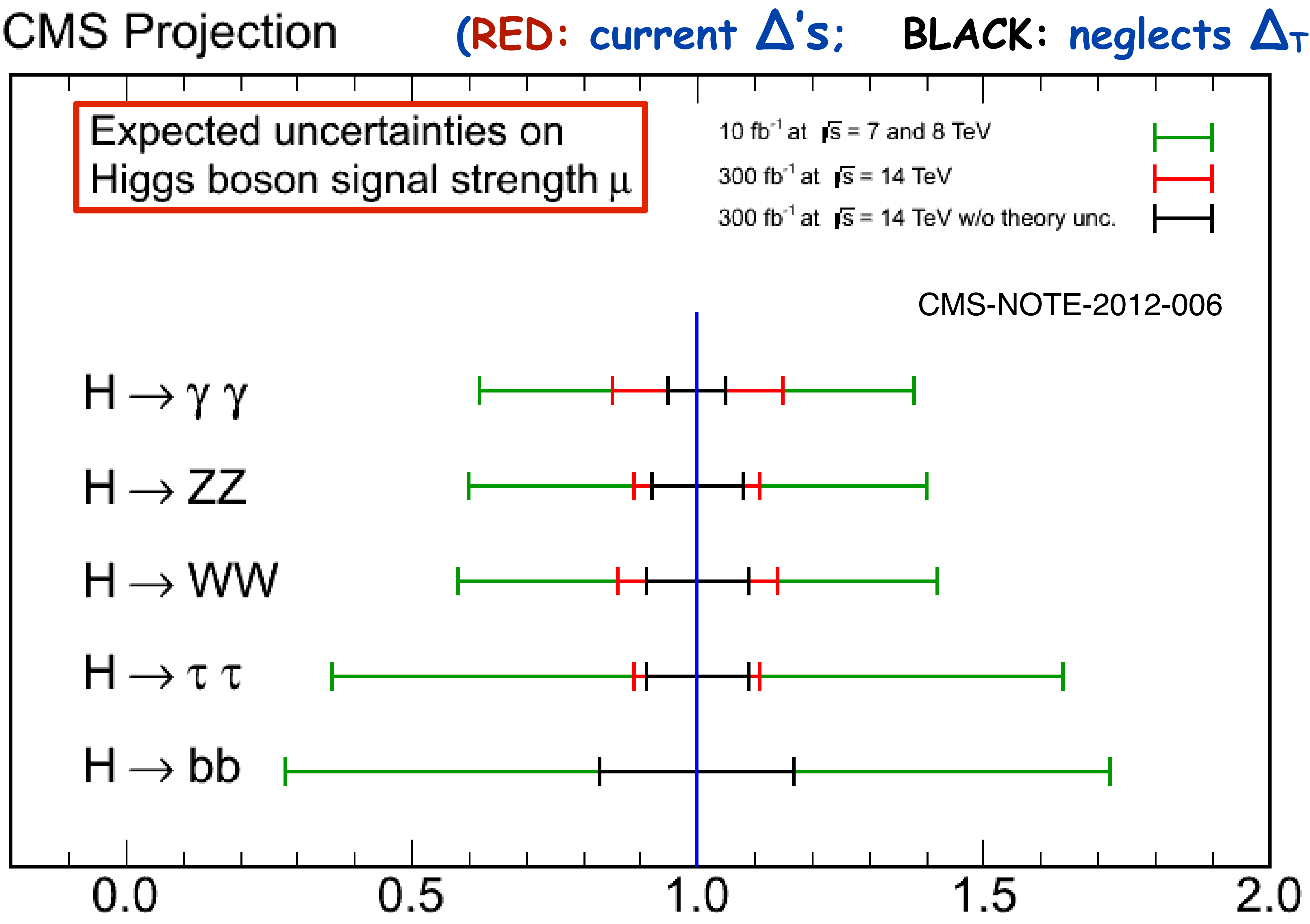
Scenario 1: all syst. uncertainties kept unchanged.

Scenario 2: th. uncertainties scaled by 1/2, other syst uncertainties scaled by √L

Scenario 3: th. uncertainties set to zero, to show interplay with the exp. uncertainties.

10 fb^{-1} (7-8 TeV) ➜ 300 fb^{-1} (14 TeV)

(**RED**: current Δ's; **BLACK**: neglects Δ_{TH})



CMS ultimate Δg_{HXX} ($\Rightarrow \Delta k_X$)

Coupling	Uncertainty (%)			
	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

CMS-NOTE-2012-006

Scenario 1 : all syst. uncertainties are kept unchanged.

Scenario 2 : theoretical uncertainties scaled by 1/2,
other syst. uncertainties scaled by $\sqrt{L}$

ATLAS projection on Δg_{HXX}

- focus on main channels under study with present data, plus a few rare decay channels sensitive to g_{Htt} and $g_{H\mu\mu}$ couplings

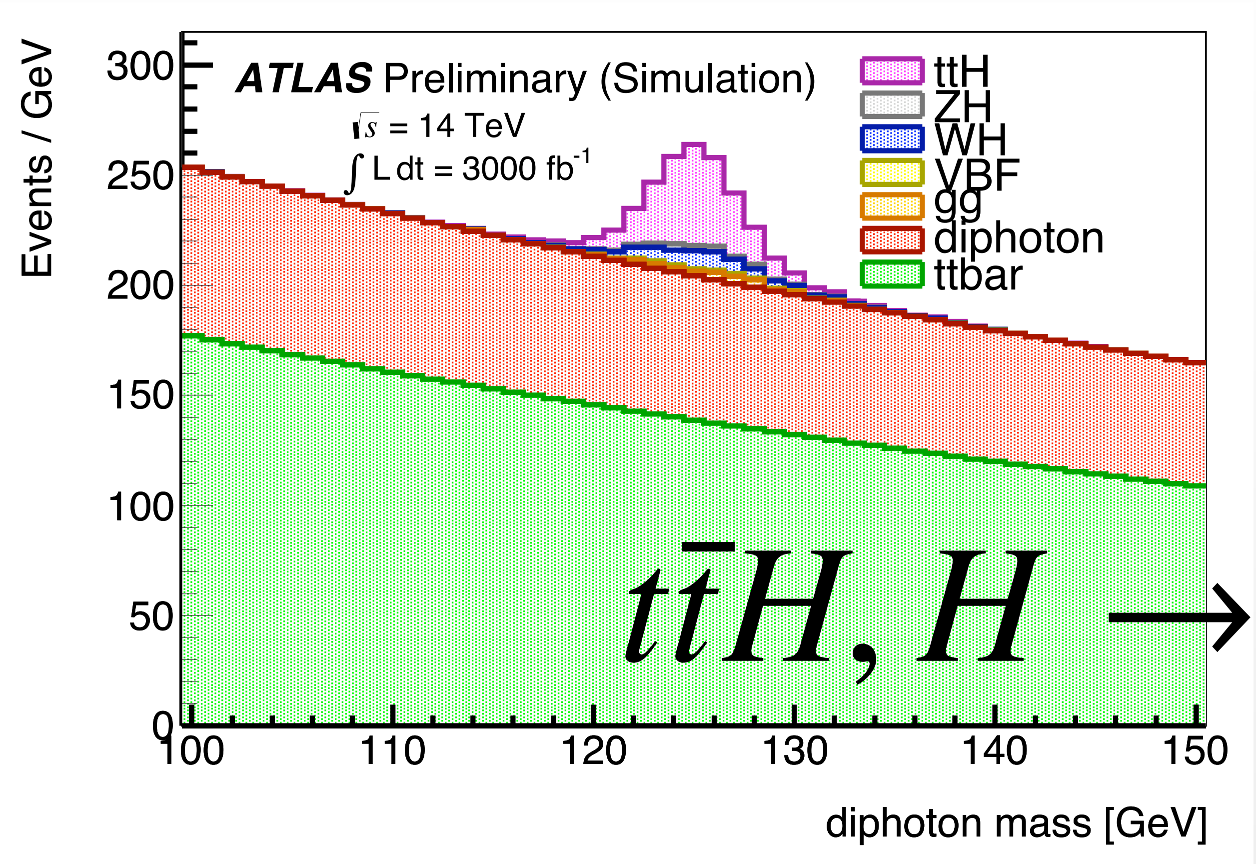
	ggF	VBF H	WH	ZH	ttH
H→γγ	✓	✓	✓	✓	✓
H→ZZ*	✓				
H→WW*	✓	✓	✓		
H→ττ	extrap.	✓			
H→μμ	✓				✓

ZH,H→bb considered ⇒ bad S/B and syst. uncertainties for 3000 fb^{-1} difficult to estimate today

⇒ not included in present ATLAS Eur.Str. studies

rare processes

ATLAS-PHYS-PUB-2012-004



$WH/ZH, H \to \gamma\gamma$

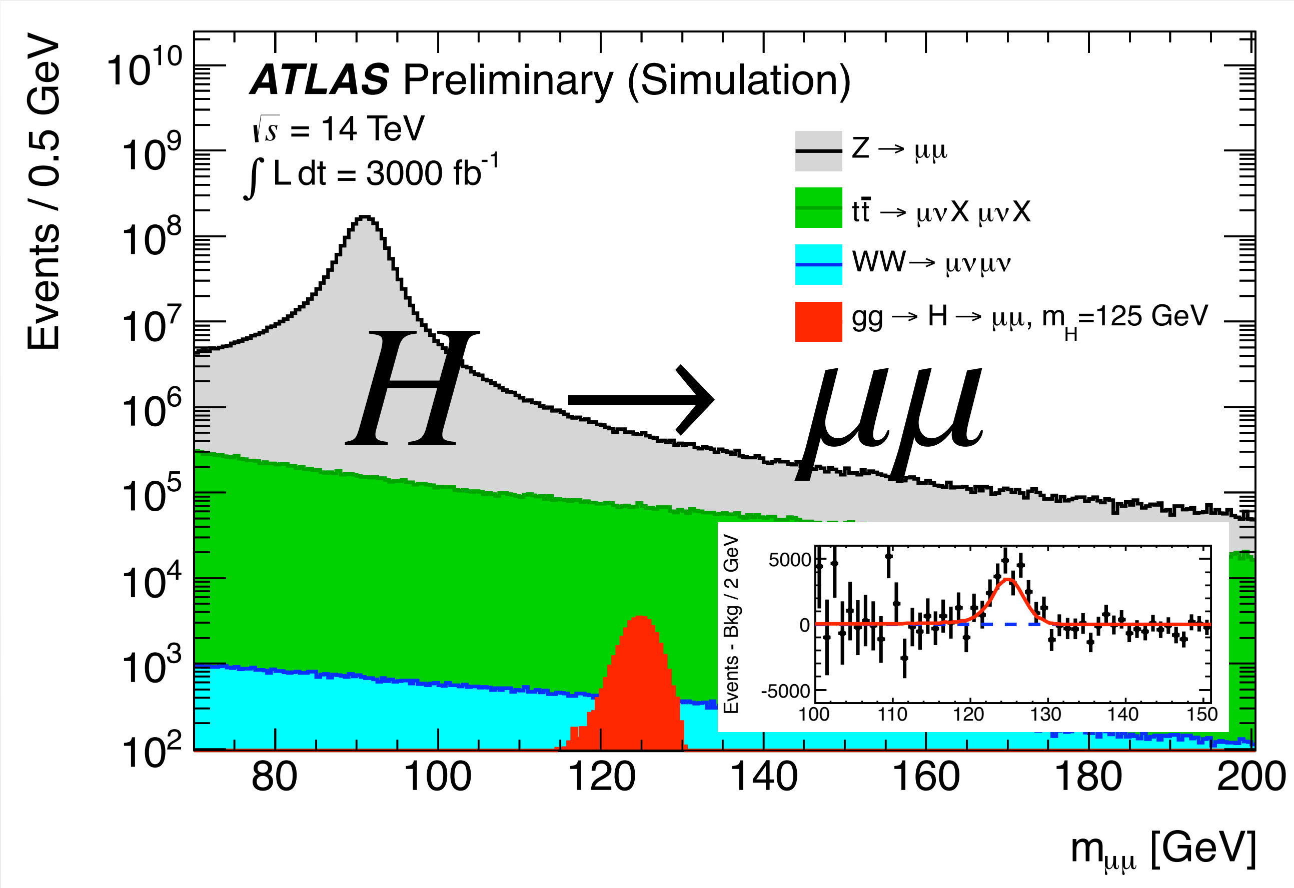
S/B~2%   S/B~10%

inclusive: S($\gamma\gamma$) >100

$t\bar{t}H, H \to \gamma\gamma$ cleanest: S/B ~ 20%

S/√B~ 6

sensitive to g_{Htt}



$H \to \mu\mu$

inclusive :

sensitive to $g_{H\mu\mu}$

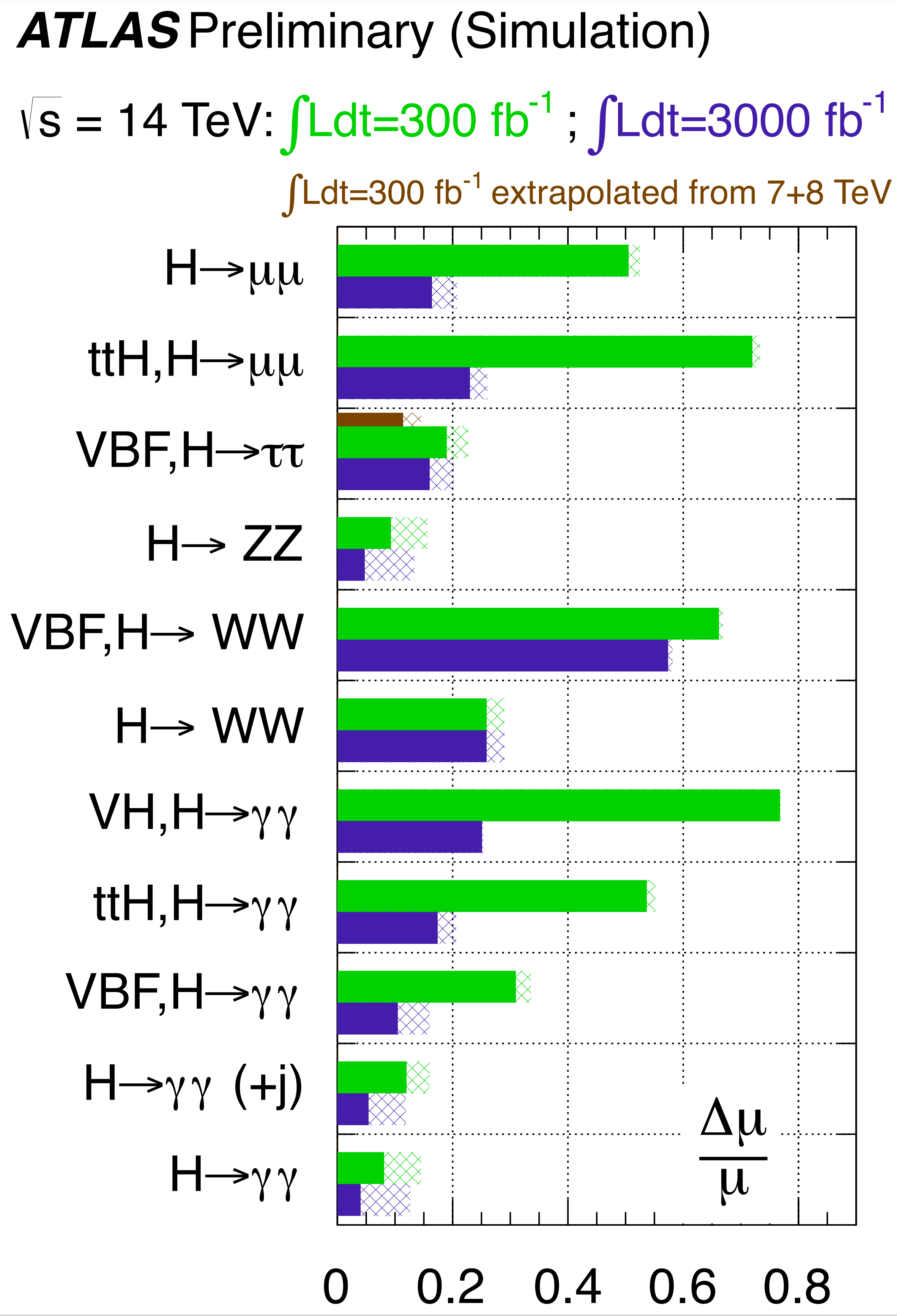
S/B ~ 0.2% but narrow reson.

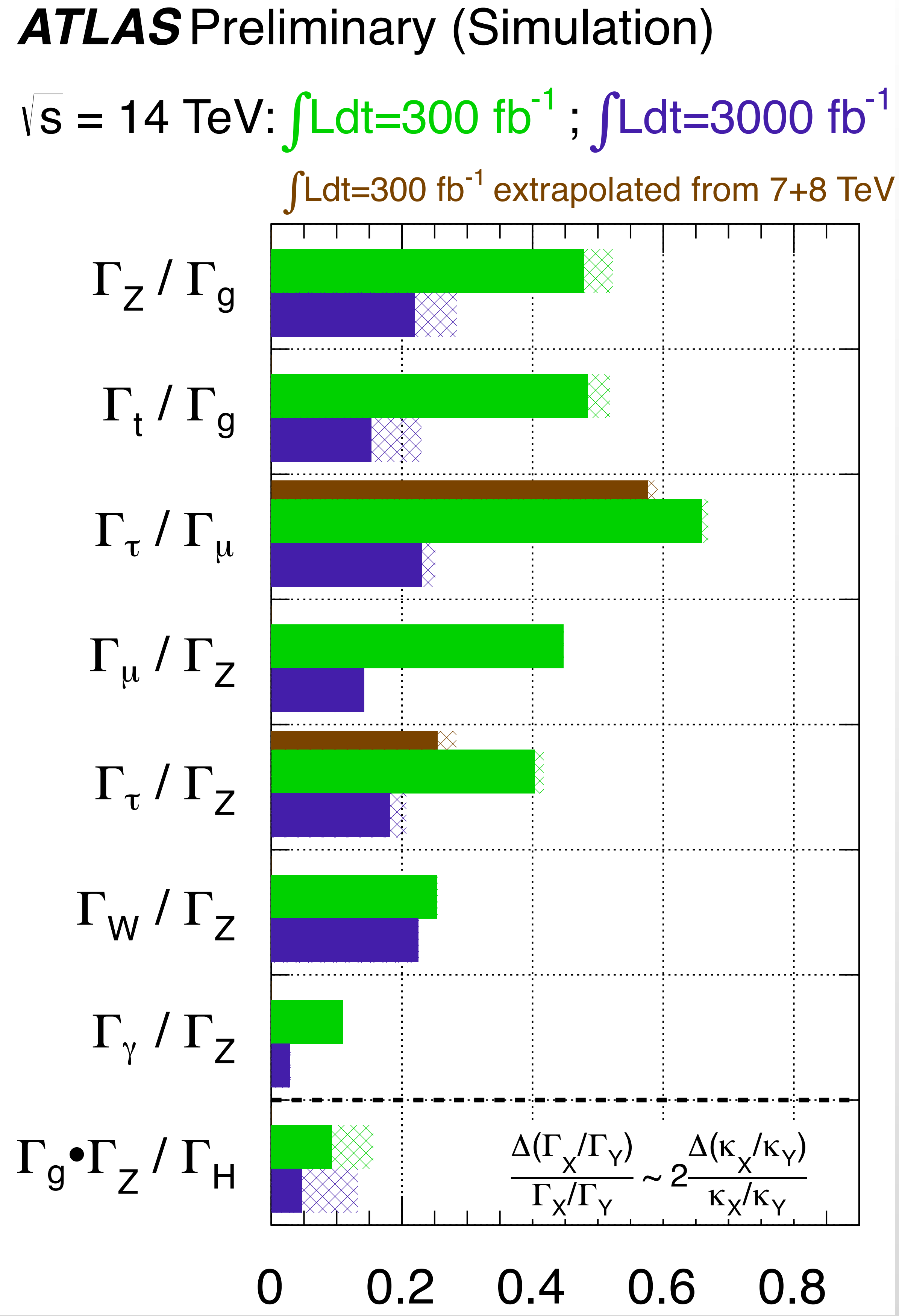
S/√B > 6

$t\bar{t}H, H \to \mu\mu$ δμ~25%

S/B>1 (S>30)

$\mu = (\sigma \times BR)/(\sigma \times BR)_{SM}$ ($\Delta\mu$ for SM g_{HXX})





ATLAS-PHYS-PUB-2012-004

ATLAS ultimate Δg_{HXX} ($\Rightarrow \Delta k_X$)

ATLAS-PHYS-PUB-2012-004

- universal g_{HVV} and g_{Hff} scenario

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

(…) include current Δ_{TH}

(in case no additional BSM contributions allowed either in loops or in Γ_H)

Higgs self-coupling $\lambda = \lambda' = M_H^2/(2v^2)$

tiny σ's !

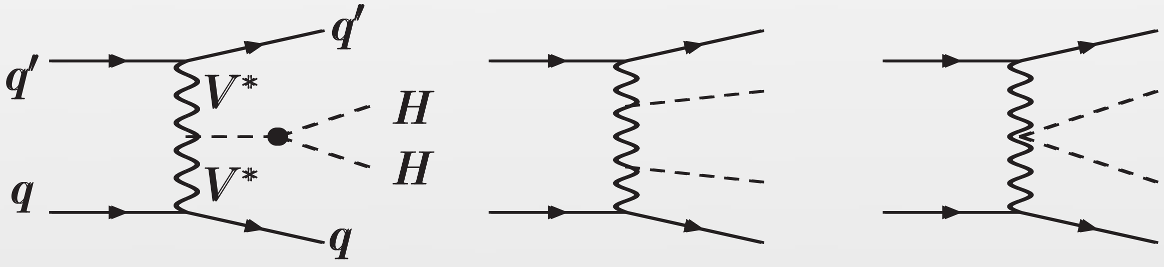
$\sqrt{s}$ [TeV]	$\sigma^{\rm NLO}_{gg\to HH}$ [fb]	$\sigma^{\rm NLO}_{qq'\to HHqq'}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}'\to WHH}$ [fb]	$\sigma^{\rm NNLO}_{q\bar{q}\to ZHH}$ [fb]	$\sigma^{\rm LO}_{q\bar{q}/gg\to t\bar{t}HH}$ [fb]
8	8.16	0.49	0.21	0.14	0.22
14	33.89	2.01	0.57	0.42	1.09

gg double-Higgs fusion: $gg \to HH$

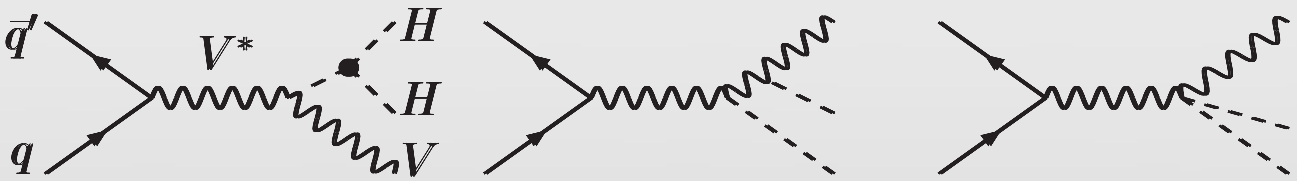
$$V(H) = \frac{1}{2}M_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda' H^4$$

fundamental test of SM potential

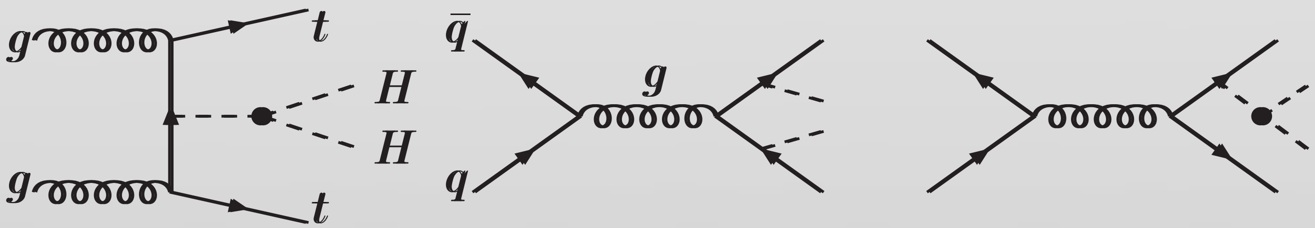
) WW/ZZ double-Higgs fusion: $qq' \to HHqq'$

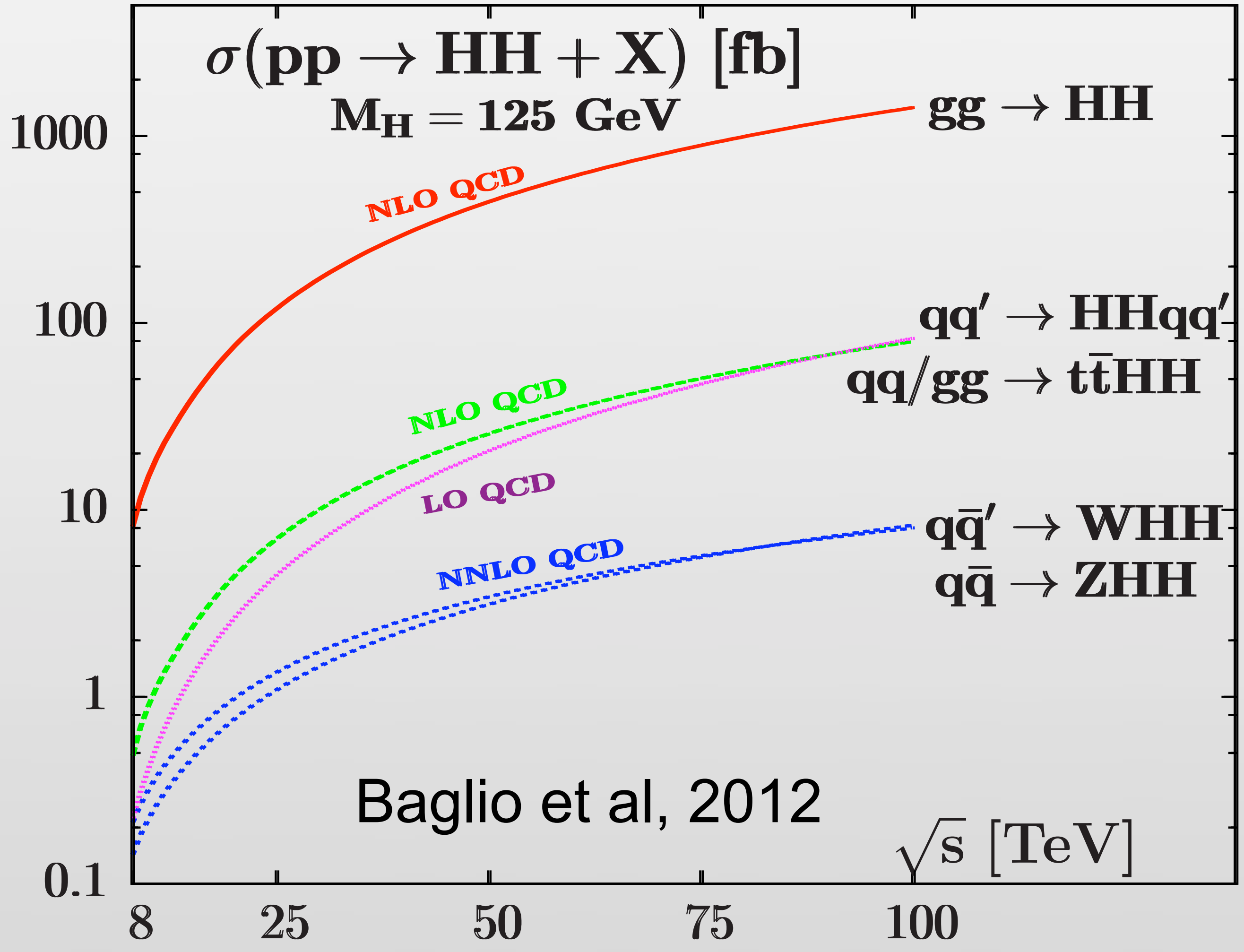


Double Higgs-strahlung: $q\bar{q}' \to ZHH/WHH$



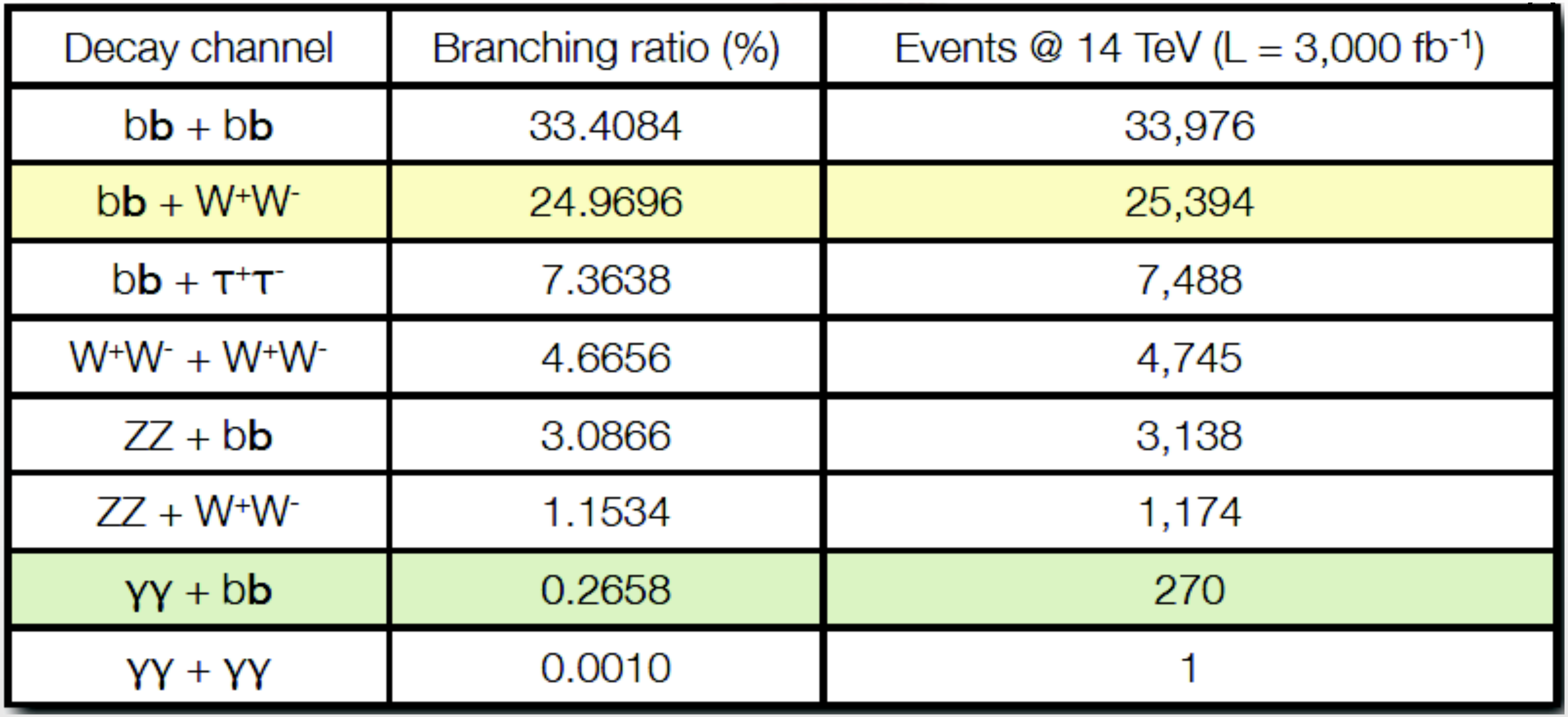
) Associated production with top-quarks: $q\bar{q}/gg \to t\bar{t}HH$





Baglio et al, 2012

Higgs self-coupling : ev/3000fb^{-1}



Decay channel	Branching ratio (%)	Events @ 14 TeV (L = 3,000 fb^{-1})
bb + bb	33.4084	33,976
bb + W^+W^-	24.9696	25,394
bb + $\tau^+\tau^-$	7.3638	7,488
W^+W^- + W^+W^-	4.6656	4,745
ZZ + bb	3.0866	3,138
ZZ + W^+W^-	1.1534	1,174
γγ + bb	0.2658	270
γγ + γγ	0.0010	1

selection of HH processes has to account for:

- final states experimentally clear and robust
- final states with large enough production rates

ATLAS studied HH → bbWW [challenging ! S(~10^3)/B(tt pairs)~10^{-4}]

and HH → bbγγ for Eur.Str.

HH → bbγγ (BR~0.27%)

sample	$\sigma\times$BR (fb)	simulated events	events passing selection	events expected in 3000 fb^{-1}
$HH \to b\bar{b}\gamma\gamma$ ($\lambda_{HHH} = 1$)	0.09	1020	42	10.7 (SM)
$HH \to b\bar{b}\gamma\gamma$ ($\lambda_{HHH} = 0$)	0.19	1020	32	17.9
$HH \to b\bar{b}\gamma\gamma$ ($\lambda_{HHH} = 2$)	0.04	1230	66	6.4
$\gamma\gamma b\bar{b}$	111	3.1×10^4	1	1.1
$ZH(Z\to b\bar{b}, H\to\gamma\gamma)$	0.04	5×10^5	11600	2.8
$b\bar{b}H(H\to\gamma\gamma)$	0.124	5×10^4	71	0.5
$\gamma\gamma jj$	2×10^3	5×10^5	0.004	0.1
$jjjj$	1.8×10^8	4.6×10^6	0	0
$t\bar{t}H(H\to\gamma\gamma)$	1.71	1.2×10^5	379	13.6
$t\bar{t}$ ($\geq$ 1 leptonic W decay)	5.0×10^5	1×10^7	$74^\dagger$	1.1
Total Background	-	-	-	19.2

ATLAS-PHYS-PUB-2013-001

combining with another channel with similar performances (HH→ττbb ?) and 2 exp.s, one should reach Δg_{HHH} ~30% !

EW Precision at HL-LHC : Summary

Accelerator → quantity ↓	LHC 300 fb^{-1}/exp	HL-LHC 3000 fb^{-1}/exp
Approx. date	2021	2030-35 ?
N_H	1.7 x 10^7	1.7 x 10^8
Δm_H (MeV)	100	50
$\Delta\Gamma_H/\Gamma_H$	--	--
$\Delta\Gamma_{inv}/\Gamma_H$	Indirect (?)	Indirect (?)
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	6.5 – 5.1%	5.4 – 1.5%
$\Delta g_{Hgg}/g_{Hgg}$	11 – 5.7%	7.5 – 2.7%
$\Delta g_{Hww}/g_{Hww}$	5.7 – 2.7%	4.5 – 1.0%
$\Delta g_{HZZ}/g_{HZZ}$	5.7 – 2.7%	4.5 – 1.0%
$\Delta g_{HHH}/g_{HHH}$	--	< 30% (2 exp.)
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<30%	<10%
$\Delta g_{H\tau\tau}/g_{H\tau\tau}$	8.5 – 5.1%	5.4 – 2.0%
$\Delta g_{Hcc}/g_{Hcc}$	--	--
$\Delta g_{Hbb}/g_{Hbb}$	15 – 6.9%	11 – 2.7%
$\Delta g_{Htt}/g_{Htt}$	14 – 8.7%	8.0 – 3.9%
Δm_t (MeV)	800-1000	500-800
Δm_W (MeV)		~10

Δg_{HXX} ~ 3-9% for 300 fb^{-1}

~ 1-4% for 3000 fb^{-1}

with scaling of syst. errors

Aleksan

EW Precision at Future Colliders

Accelerator→ Quantity ↓	HL-LHC 3000fb^{-1} /exp	ILC (250) 250 fb^{-1}	ILC (250+350+1000)	LEP3 240 4 IP	TLEP 240 +350 4 IP
Approx. date	2030-35	2030-35?	>2045?	2035?	2035?
N_H	1.7 x 10^8	5 10^4 ZH	(10^5 ZH) (1.4 10^5 Hvv)	4 10^5ZH	2 10^6 ZH
Δm_H (MeV)	50	35	35	26	7
$\Delta\Gamma_{H/}\Gamma_H$	--	10%	3%	4%	1.3%
$\Delta\Gamma_{inv/}\Gamma_H$	Indirect (?)	1.5%	1.0%	0.35%	0.15%
$\Delta g_{H\gamma\gamma}/g_{H\gamma\gamma}$	1.5%	--	5%	3.4%	1.4%
$\Delta g_{Hgg}/g_{Hgg}$	2.7%	4.5%	2.5%	2.2%	0.7%
$\Delta g_{Hww}/g_{Hww}$	1.0%	4,3%	1%	1.5%	0.25%
$\Delta g_{HZZ}/g_{HZZ}$	1.0%	1.3%	1.5%	0.65%	0.2%
$\Delta g_{HHH}/g_{HHH}$	< 30% (2 exp.)	--	~30%	--	--
$\Delta g_{H\mu\mu}/g_{H\mu\mu}$	<10%	--	--	14%	7%
$\Delta g_{H\tau\tau}/g_{H\tau\tau}$	2.0%	3,5%	2.5%	1.5%	0.4%
$\Delta g_{Hcc}/g_{Hcc}$	--	3,7%	2%	2.0%	0.65%
$\Delta g_{Hbb}/g_{Hbb}$	2.7%	1.4%	1%	0.7%	0.22%
$\Delta g_{Htt}/g_{Htt}$	3.9%	--	15%	--	30%
Δm_t (MeV)	500-800	--	20	--	20
Δm_W (MeV)	~10	--	~6	--	< 1

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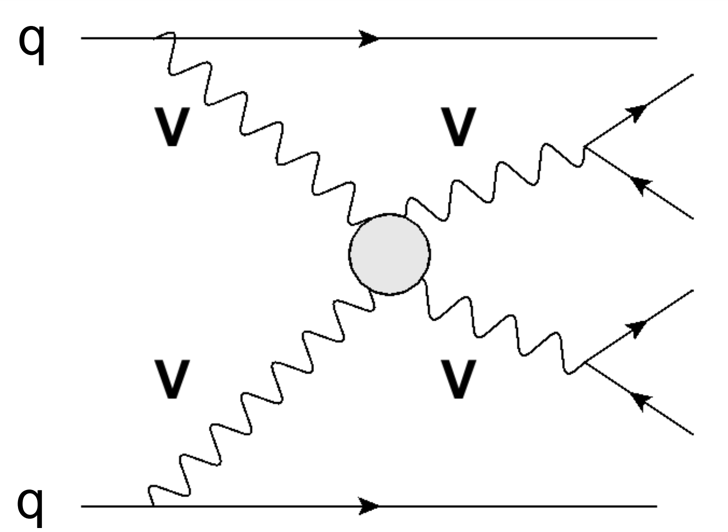
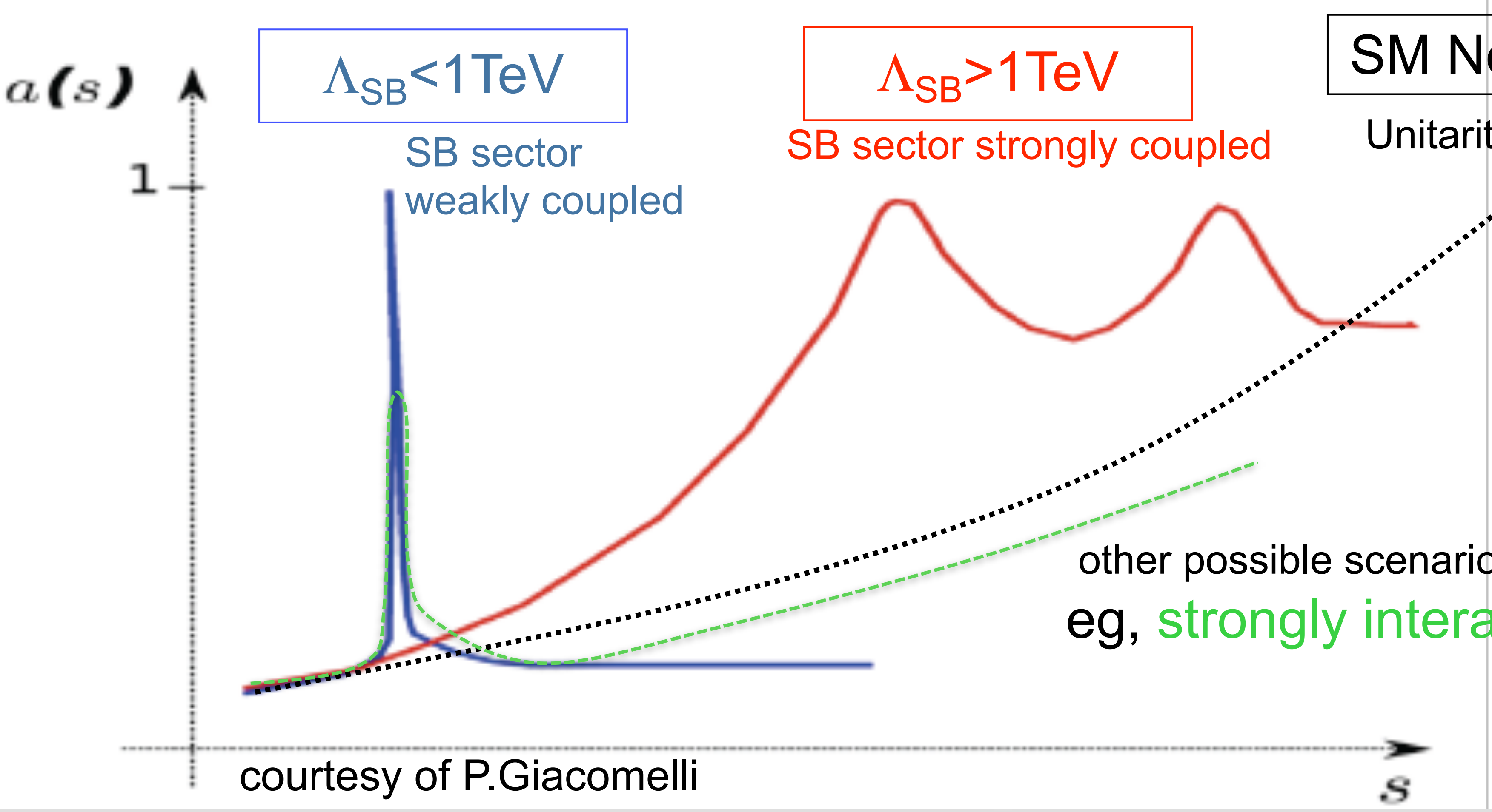
Vector Boson Scattering (VBS)



-unitarity restoration in VBS amplitudes strictly linked to EWSB mechanism.

-a SM Higgs does the job exhaustively.

-a non-SM Higgs needs further mechanism (heavy VV resonances ?)



courtesy of P.Giacomelli

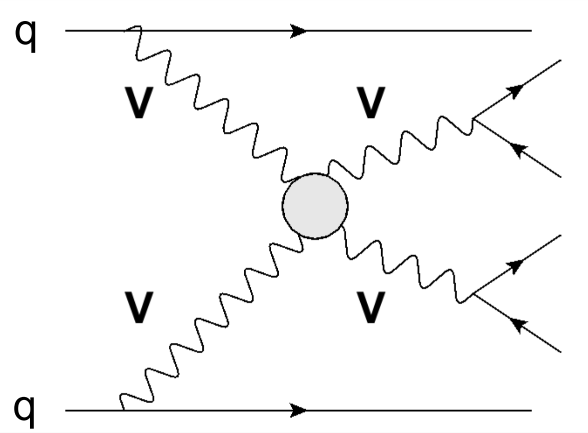
BSM models predict TeV-scale resonances “paired” with a light scalar particle

other possible scenarios:

eg, strongly interacting light Higgs (SILH)

Challenging ! both for TH (interferences with qq→6f amplitudes) and EXP.s (small yields, wide y coverage, many channels) !!!

Search for resonances in VBS spectrum



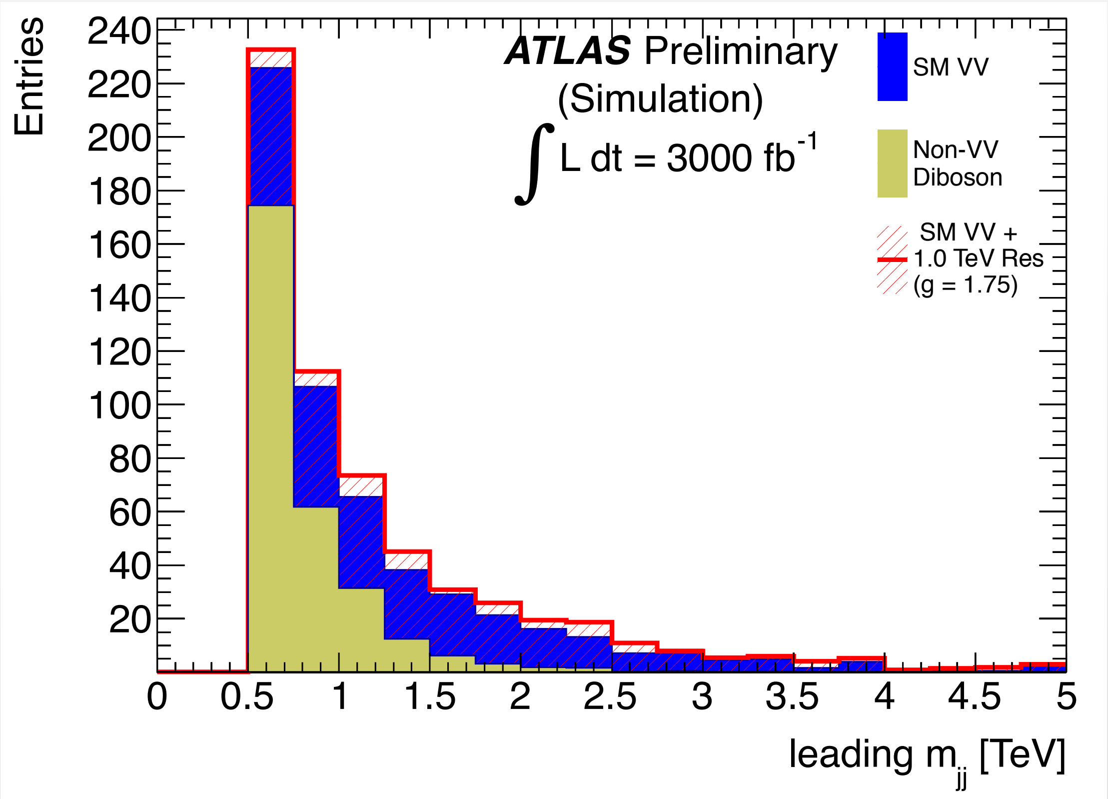
$$ZZjj \rightarrow \ell\ell\ell\ell jj$$

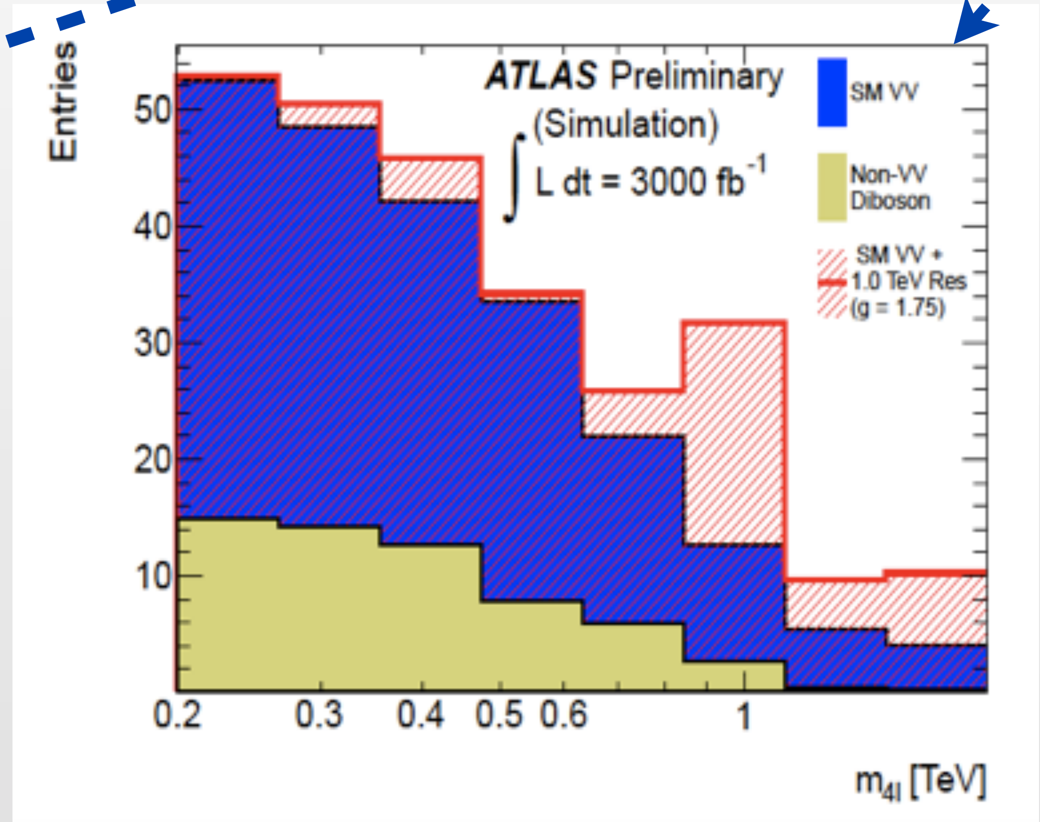
ATLAS-PHYS-PUB-2012-005

fully reconstructed ZZ resonance peak !

WHIZARD → generates VBS mediated by a heavy resonance in presence of a Higgs boson

a forward m(jj) >1 TeV requirement reduces events from jets accompanying non-VBS diboson production





model	$300\ \mathrm{fb}^{-1}$	$3000\ \mathrm{fb}^{-1}$
$m_{\mathrm{resonance}} = 500$ GeV, $g = 1.0$	2.4σ	7.5σ
$m_{\mathrm{resonance}} = 1$ TeV, $g = 1.75$	1.7σ	5.5σ
$m_{\mathrm{resonance}} = 1$ TeV, $g = 2.5$	3.0σ	9.4σ

15% statistical precision on the SM VV contribution with 3000 fb^{-1}

New Di-lepton and Di-top Resonances

ATLAS-PHYS-PUB-2013-003

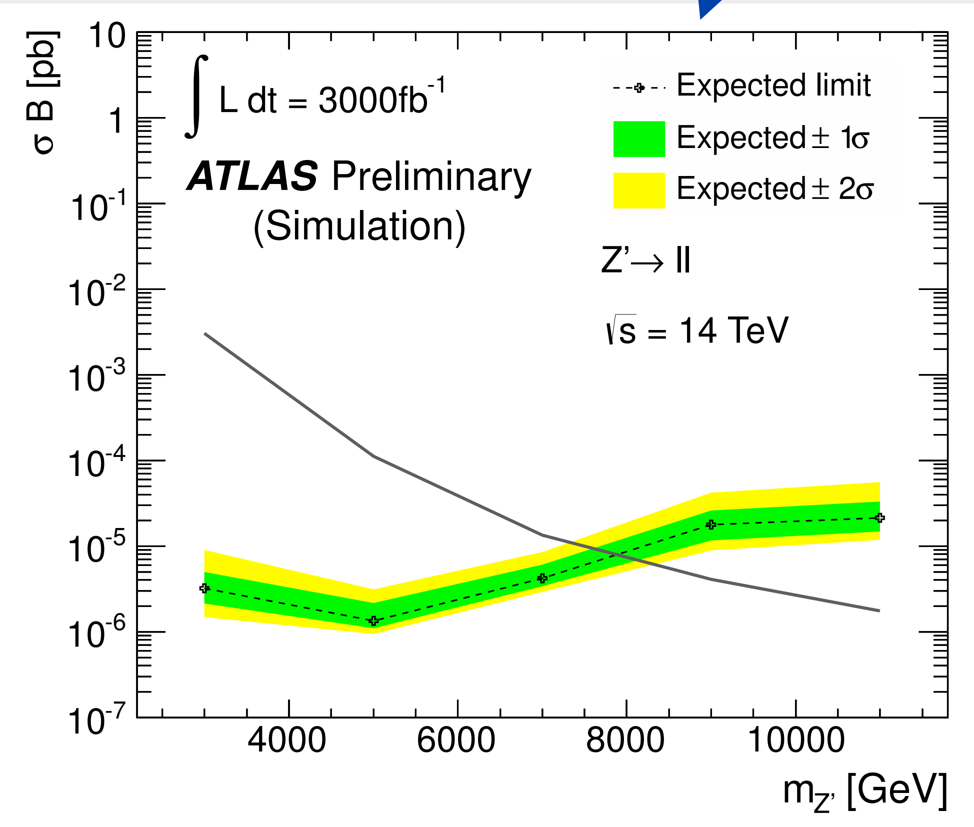
Strongly (g_{KK})- and weakly ($Z'_{Topcolor}$)-produced tt resonances

pp → g_{KK}, $Z'_{Topcolor}$ → t t

- benchmarks for cascade decays containing leptons, (b-)jets and E_{miss}
- provide opportunity to study highly boosted topologies

pp → Z'_{SSM} → ee, μμ

- need lepton measur. at very high p_T



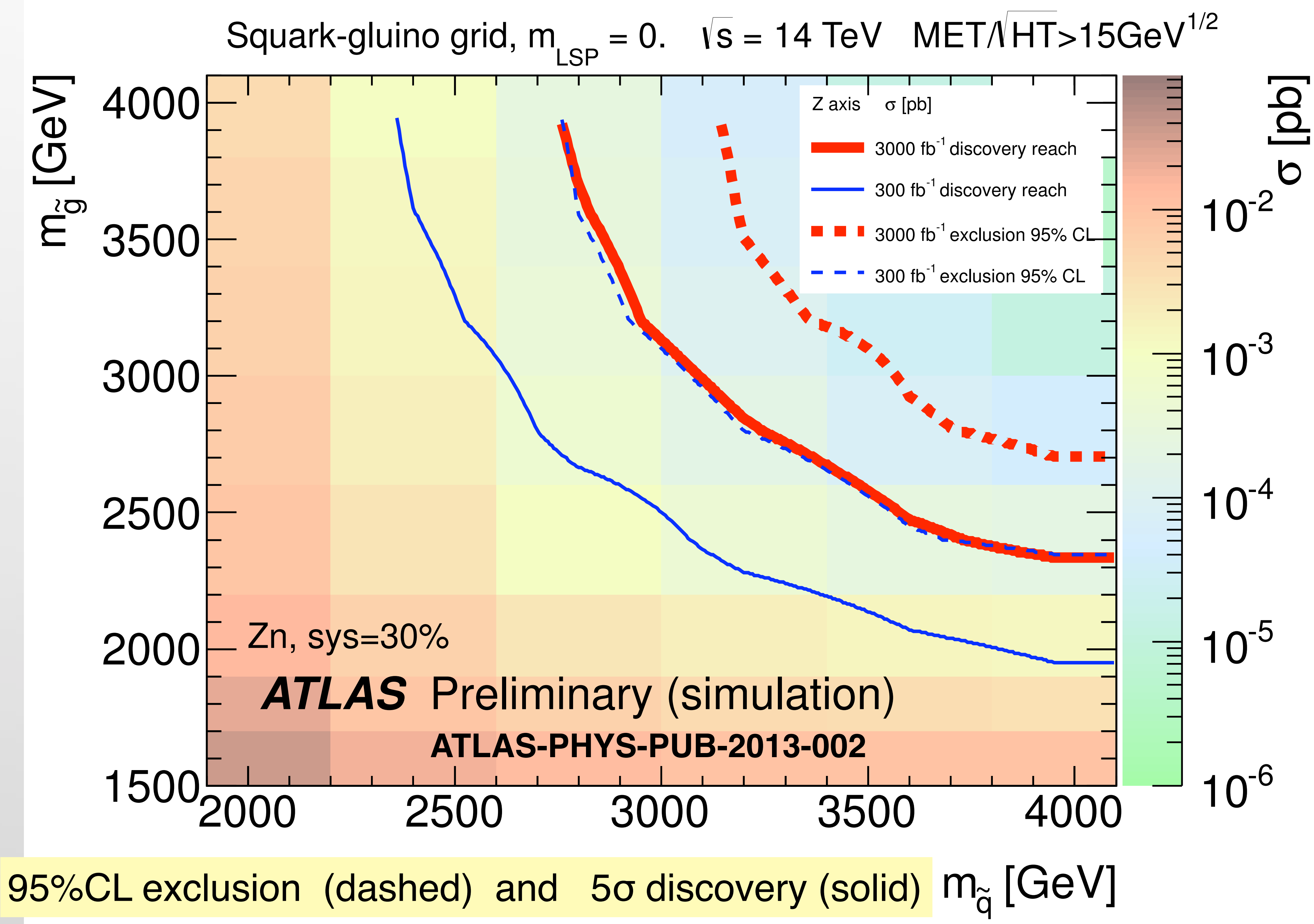
(lep+jets) *(2 lep)*

model	300 fb^{-1}	1000 fb^{-1}	3000 fb^{-1}	
g_{KK}	4.3 (4.0)	5.6 (4.9)	6.7 (5.6)	*TeV*
$Z'_{topcolor}$	3.3 (1.8)	4.5 (2.6)	5.5 (3.2)	*TeV*
$Z'_{SSM} \to ee$	6.5	7.2	7.8	*TeV*
$Z'_{SSM} \to \mu\mu$	6.4	7.1	7.6	*TeV*

ΔM up to 2.4 TeV !

Searches for squarks and gluinos

- 400-500 GeV rise in $M_{(squark,gluino)}$ sensitivity wrt L=300 fb^{-1}
- $M_{(1st,2nd\ gen.\ squark)}$ up to 3 TeV ; $M_{(gluino)}$ up to 2.5 TeV



95%CL exclusion (dashed) and 5σ discovery (solid)

$$H_T = \sum_{p_T > 30\text{GeV}}^{\text{jets}} |\boldsymbol{p}_T|.$$

$$E_T^{\text{miss}} / \sqrt{H_T} > 15\ \text{GeV}^{1/2}$$

select true E_{miss} from jet mis-measurement

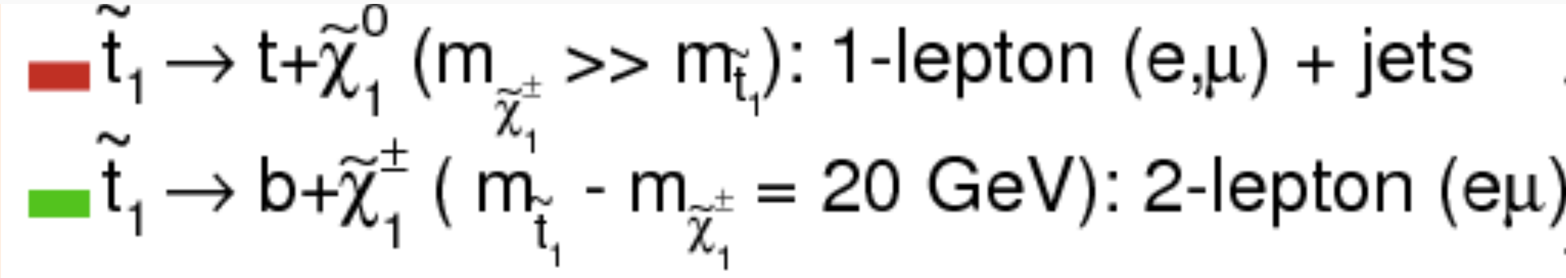
larger relat. impact when moving from 8 TeV to 14 TeV !

(phase-space saturation matters in strongly produced states !)

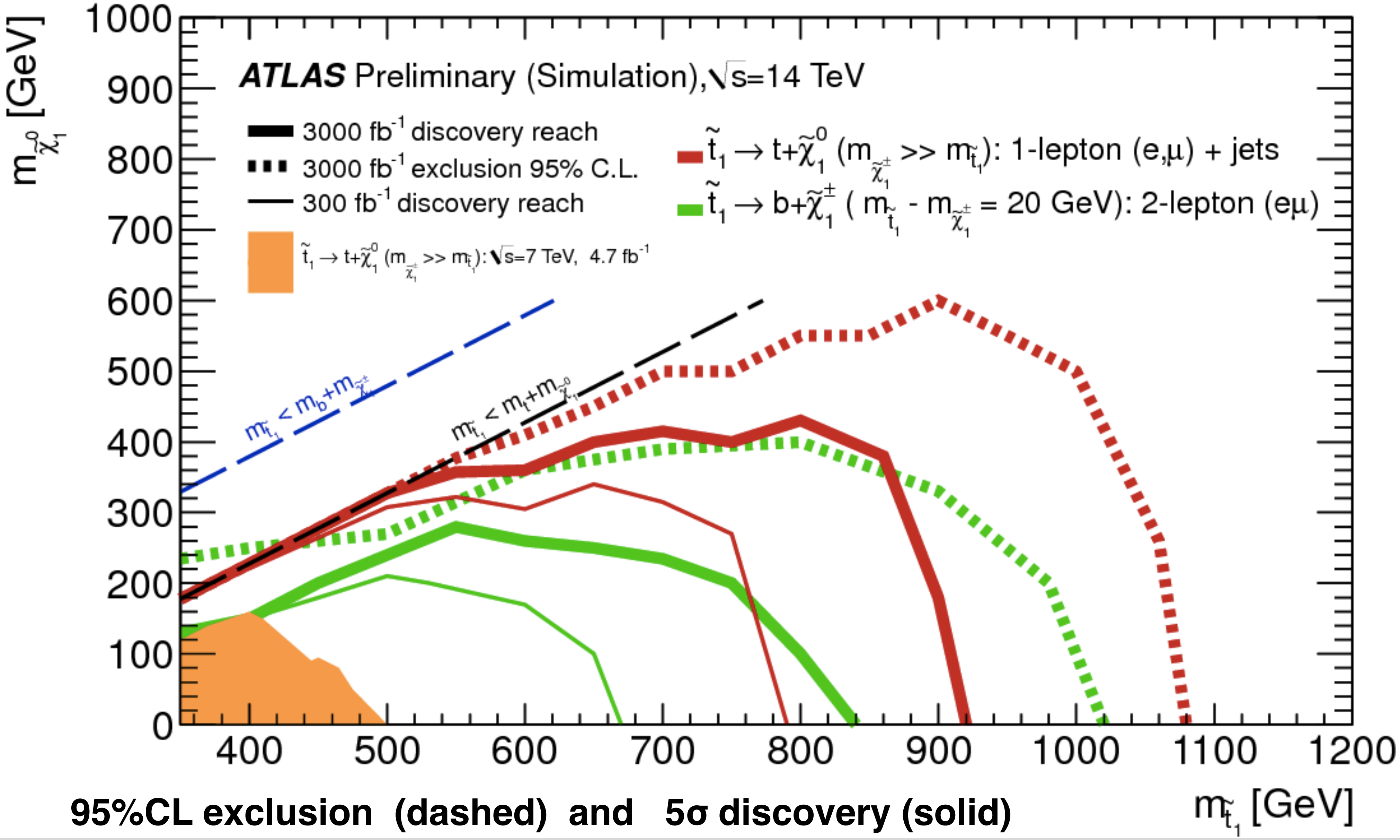
stop-pair searches

M(stop) ≲ 1TeV could alleviate EWSB hierarchy problem !

σ~10 fb



ATLAS-PHYS-PUB-2013-002



95%CL exclusion (dashed) and 5σ discovery (solid)

final states containing t,b,W,Z,h,E_{miss}

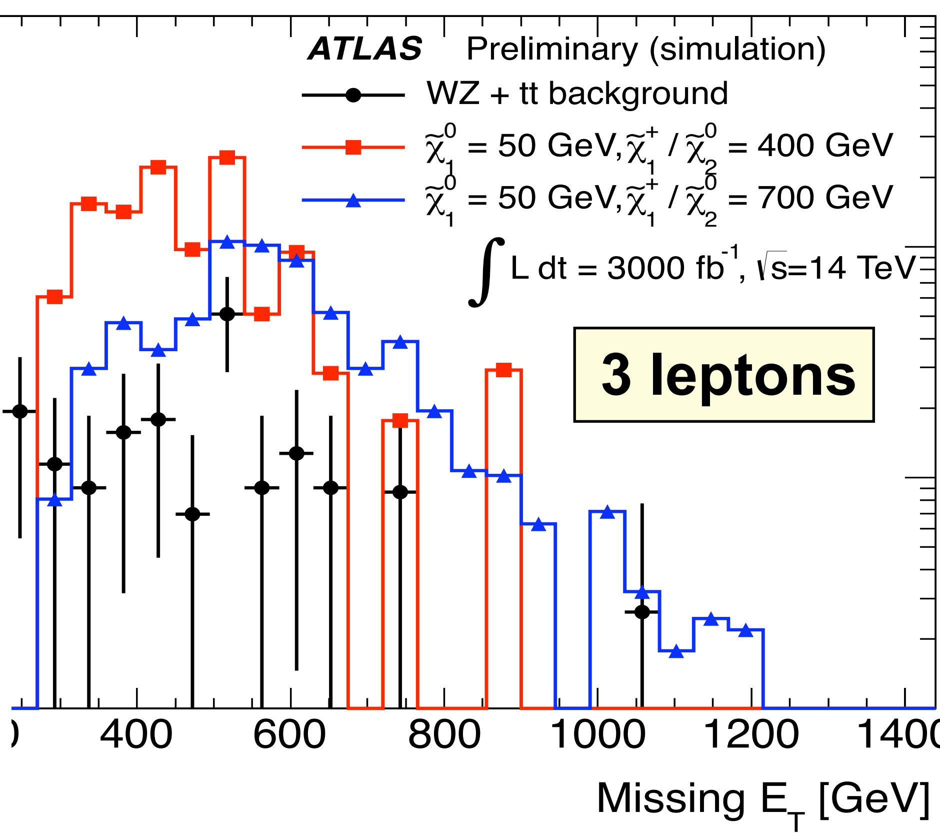
reach in $m(\tilde{t})$ for 10xL increases by 100-150 GeV ; ➜ 3000 fb^{-1} tests up to ~ 1 TeV !

direct chargino/neutralino production

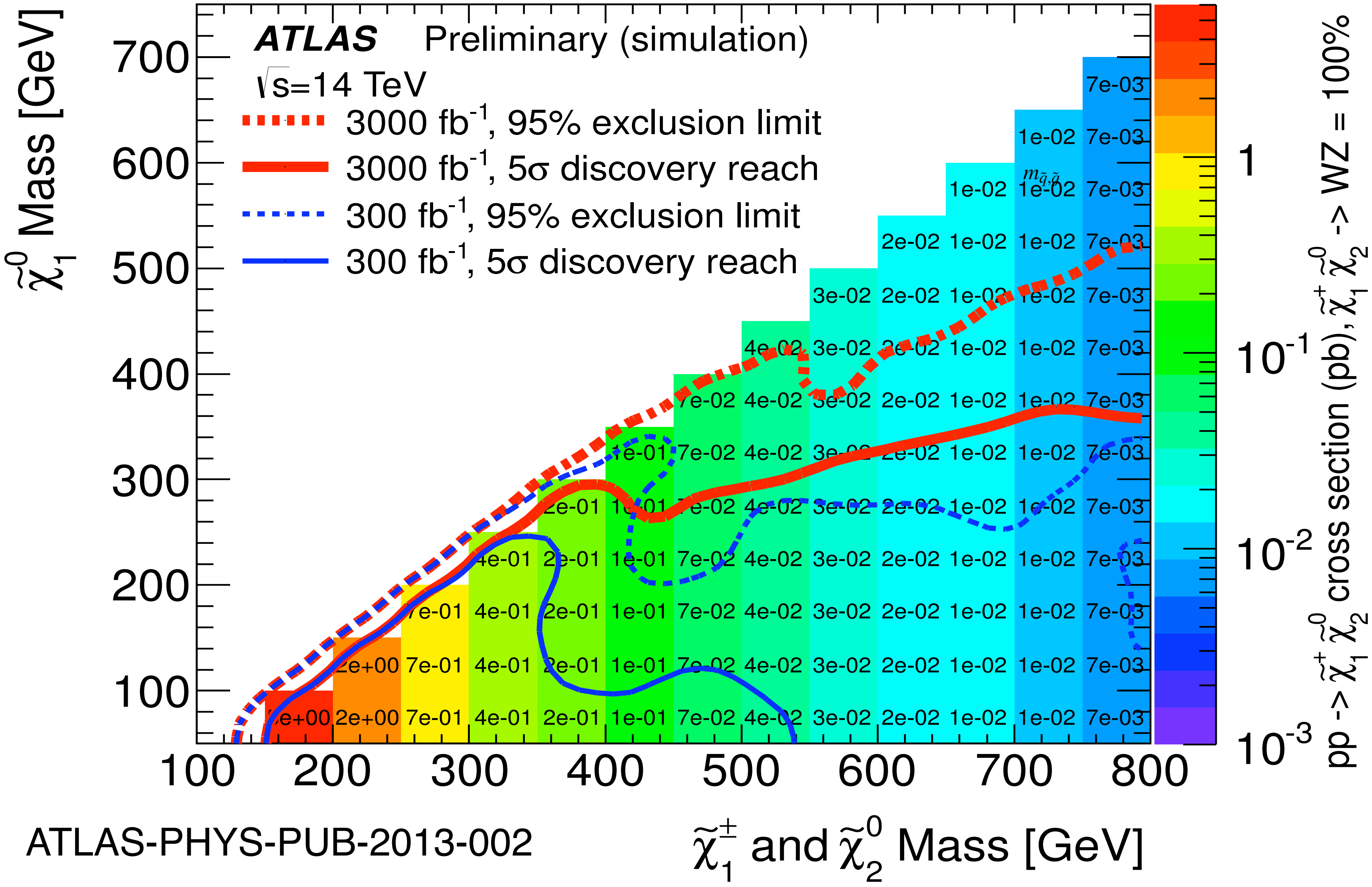
dominant SUSY process for heavy $m_{\tilde{q},\tilde{g}}$

$$\chi^{\pm}_1\,\chi^0_2 \rightarrow W\,\chi^0_1\,Z\,\chi^0_1 \quad (100\%)$$

EW σ → HL-LHC makes a real difference!



95%CL exclusion (dashed) and 5σ discovery (solid)

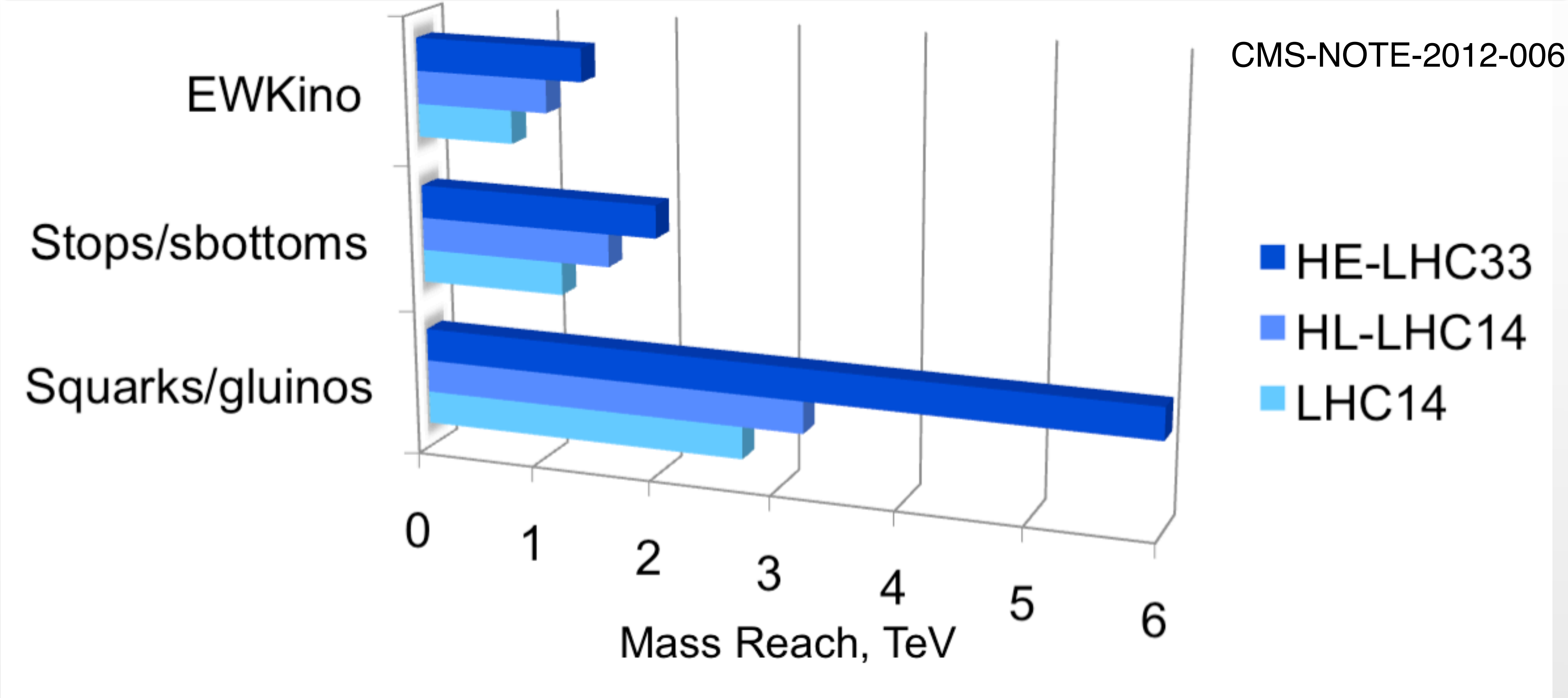


ATLAS-PHYS-PUB-2013-002

- benefits a lot from 300 → 3000 fb^{-1} !
- discovery reach for chargino masses: 500 → 1000 GeV !
- similar reach for $\chi^{\pm}_1\,\chi^0_2 \rightarrow W\,\chi^0_1\,h\,\chi^0_1$

Baer et al, 2012

SUSY : HL-LHC versus HE-LHC



- going to higher energy, sensitivity increase is more pronounced for heavy squark-gluinos ;

- recall parton luminosity behavior vs $\sqrt{S}$:

in gg (qq) at $M_X > 1(3)$TeV, HE-LHC$_{33TeV}$ better than HL-LHC !

Summary

- substantial gain in LHC Physics Reach for 300→3000 fb^{-1} (assuming constant trigger + detector performance)
- accuracy on signal strengths for main Higgs channels better by factor 2-3
- $\Delta g_{HVV,Hff} \sim 1\text{-}4\%$, $\Delta g_{HHH} \sim 30\ \%$
- access to rare H decays
- HL crucial in VBS for measuring SM VV rates
- increased sensitivity to new heavy states
- last but not least : HL valuable asset in case of new findings at LHC with 300 fb^{-1} !