Higgs physics at the HL-LHC and complementarity to FCC-ee

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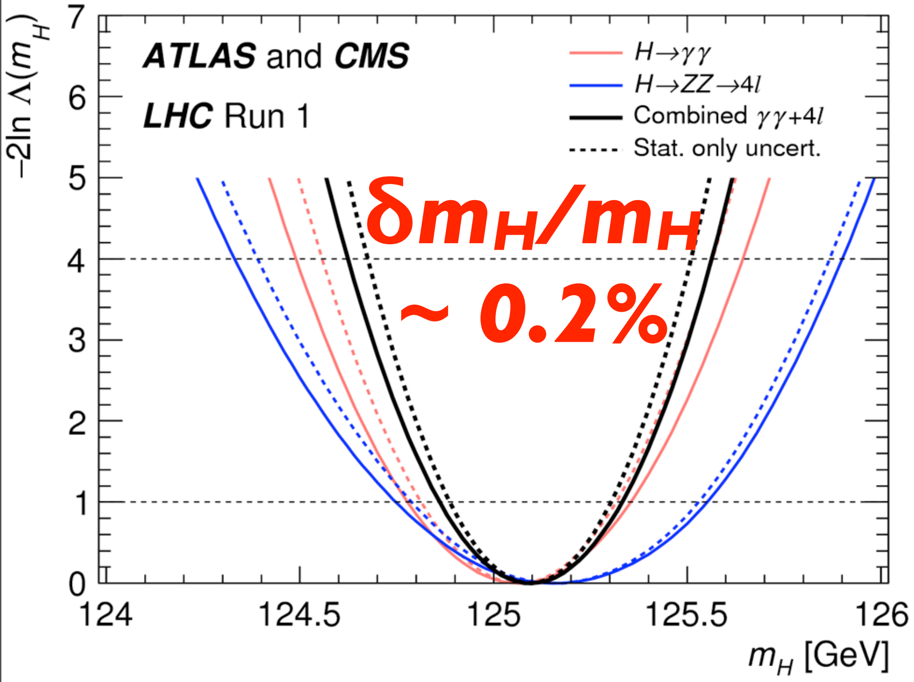
FCC-ee Workshop, Sept. 23 2015, CERN

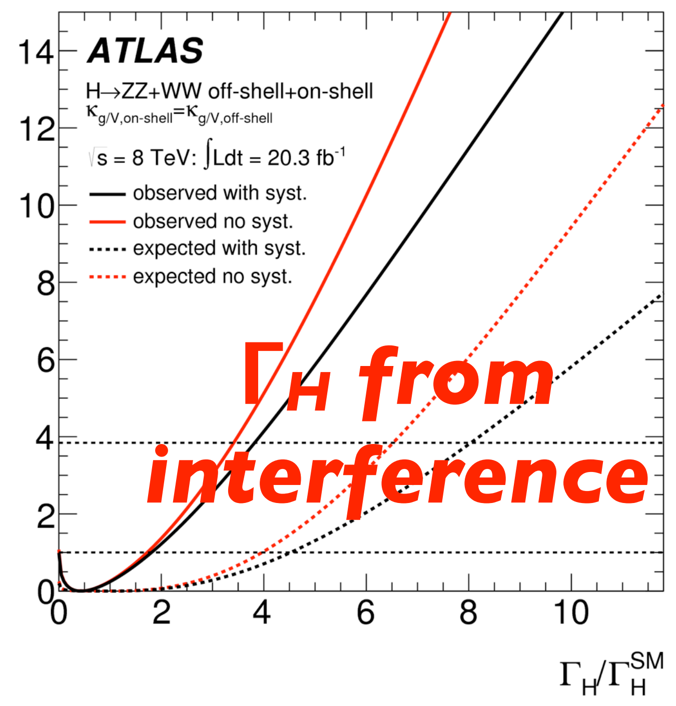
Run I legacy

ATLAS+CMS, PRL 117 191803



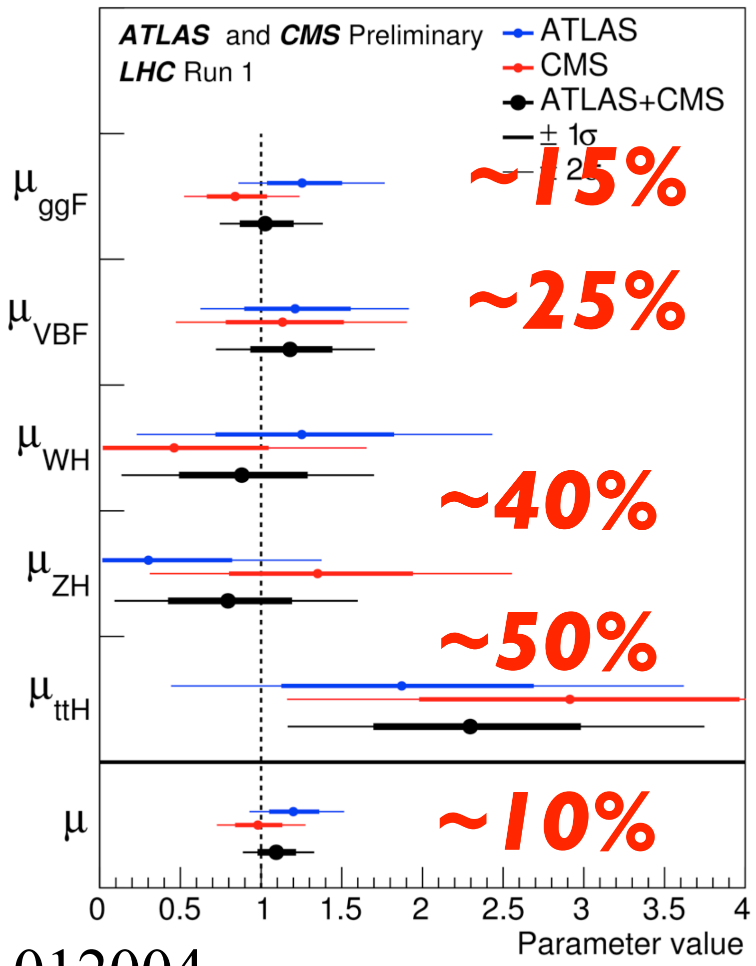
$\delta m_H/m_H$ ~ 0.2%

ATLAS, EPJC 75 (2014) 335



Γ_H from interference

CMS-PAS-HIG-15-002,
ATLAS-CONF-2015-044



~15%

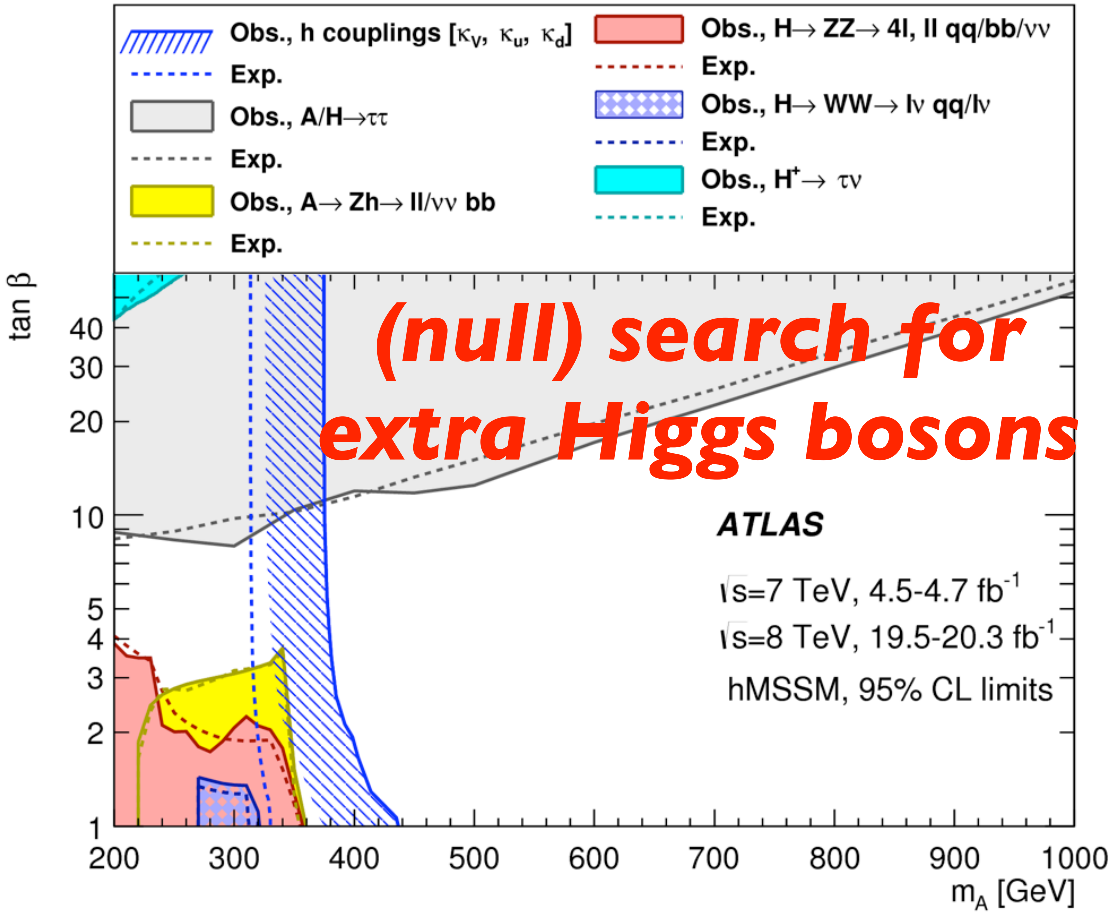
~25%

~40%

~50%

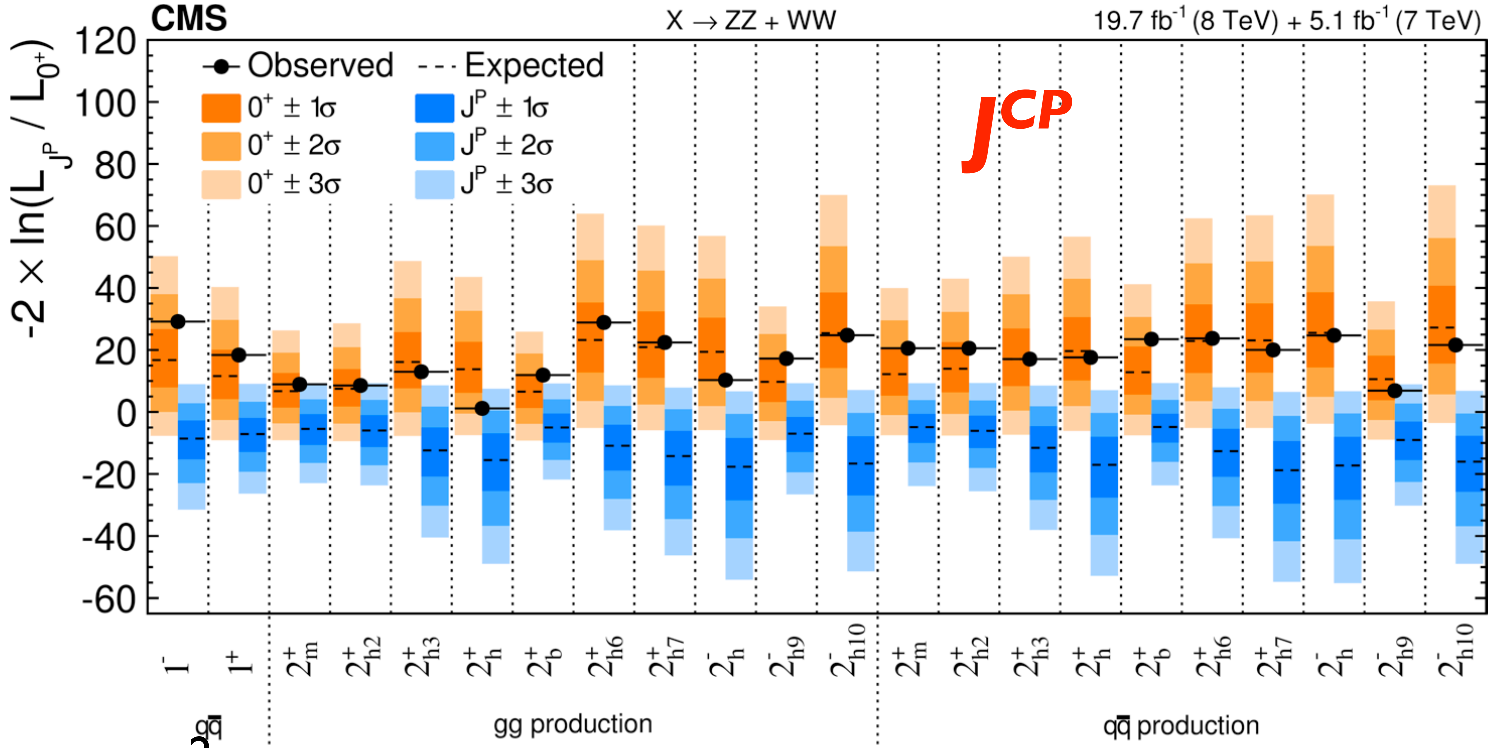
~10%

ATLAS, arXiv:1509.00672



(null) search for extra Higgs bosons

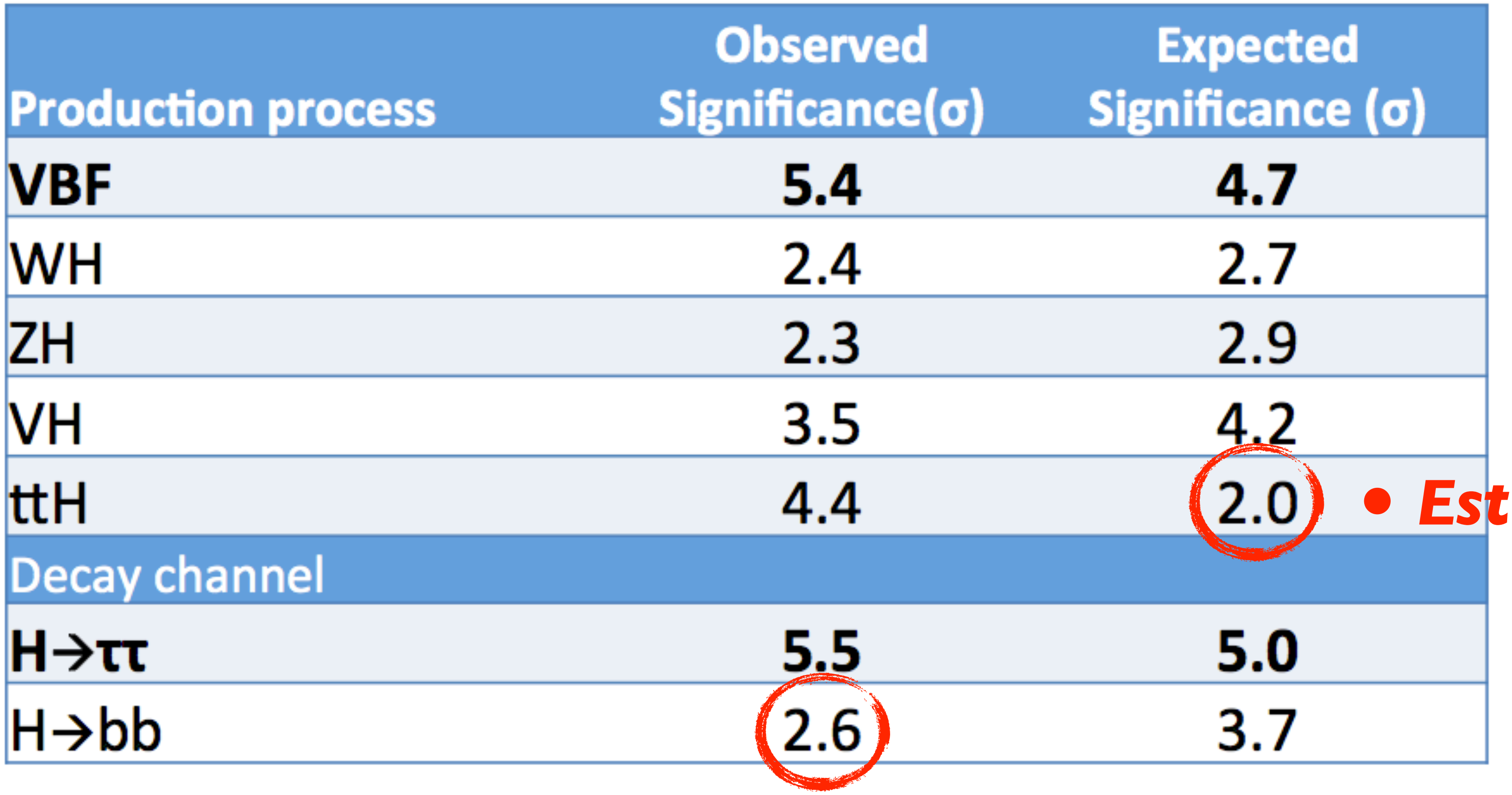
CMS, PRD 92 (2015) 012004



J^{CP}

What is still missing

CMS-PAS-HIG-15-002, ATLAS-CONF-2015-044



Production process	Observed Significance(σ)	Expected Significance (σ)
VBF	**5.4**	**4.7**
WH	2.4	2.7
ZH	2.3	2.9
VH	3.5	4.2
ttH	4.4	2.0
Decay channel		
H→ττ	**5.5**	**5.0**
H→bb	2.6	3.7

- ***Estabilsh ttH***
- ***Observe H→bb***

Some “distinguished” processes still lurking in the background

- as it should be if they are SM-like
- need full HL-LHC program to dig them out
  - for some, it may be not enough...

⇨

- ***bbH, ggHZ, tH, HH***
- ***H→cc, Zγ, μμ***

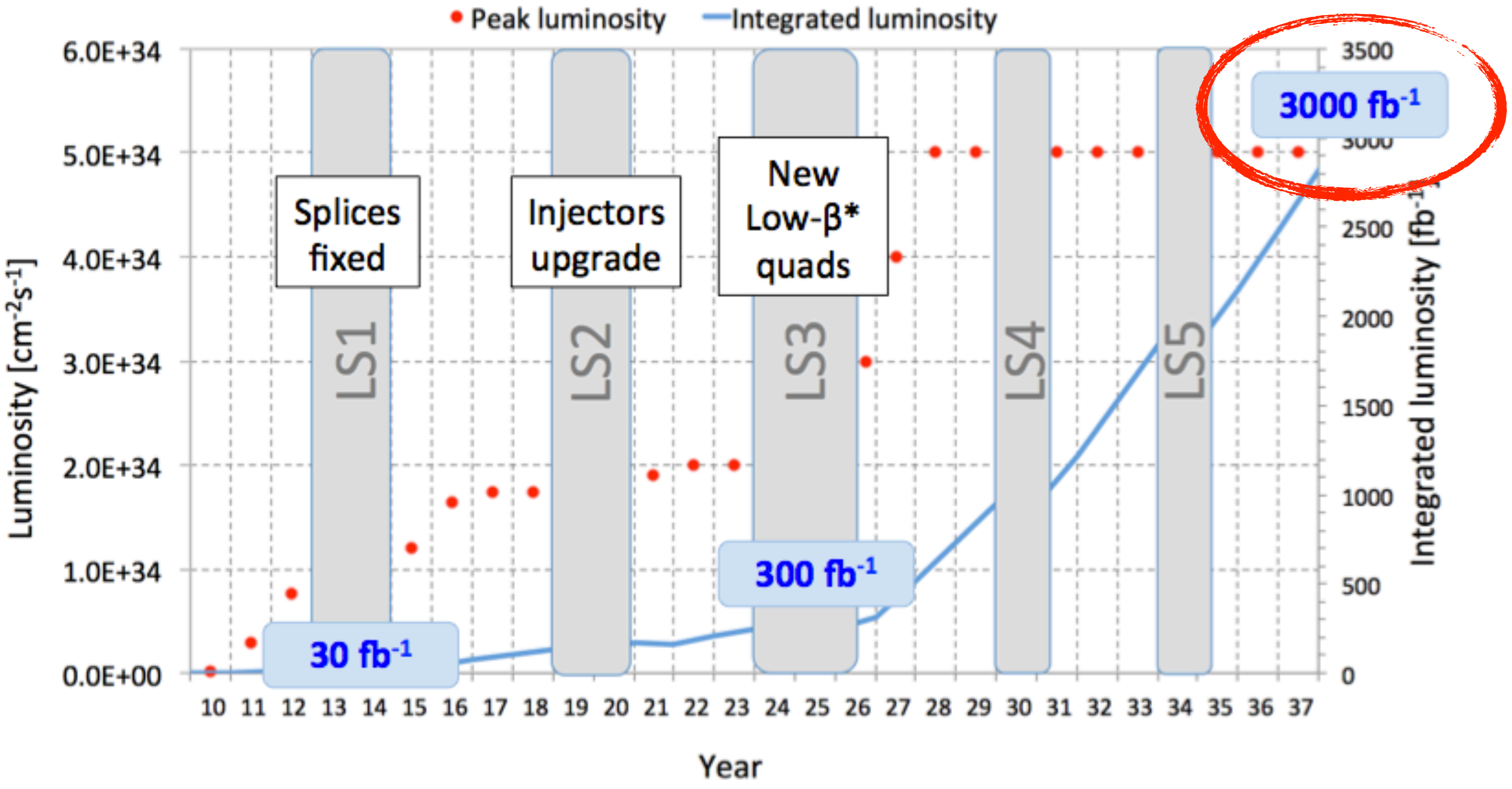
Framework for HL-LHC projections

- Projections for HL-LHC:
  - ATLAS:

    "***Simulation smeared by HL-LHC resolution functions. Repeat Run 1-like analyses.***"
  - CMS:

    "***Project Run I analyses data cards (2013) to high-lumi. Full detector simulation validates projection.***"
- A few caveats:
  - Not always best analyses projected
  - Theory uncertainties as of the time of projections
    - theoretical calculation is an evolving field
    - LHC data can give constraints (e.g. PDF)
  - Run I analyses optimised for early discovery
  - Systematic-free analyses not yet addressed
    - e.g.: $\sigma(ttH)/\sigma(ttZ)$, $\sigma(VH\rightarrow\tau\tau)/\sigma(VH\rightarrow bb)$ in same phase-space

Physics reach with 3 ab^{-1}



Luminosity:
~30 fb^{-1} → ~3000 fb^{-1}

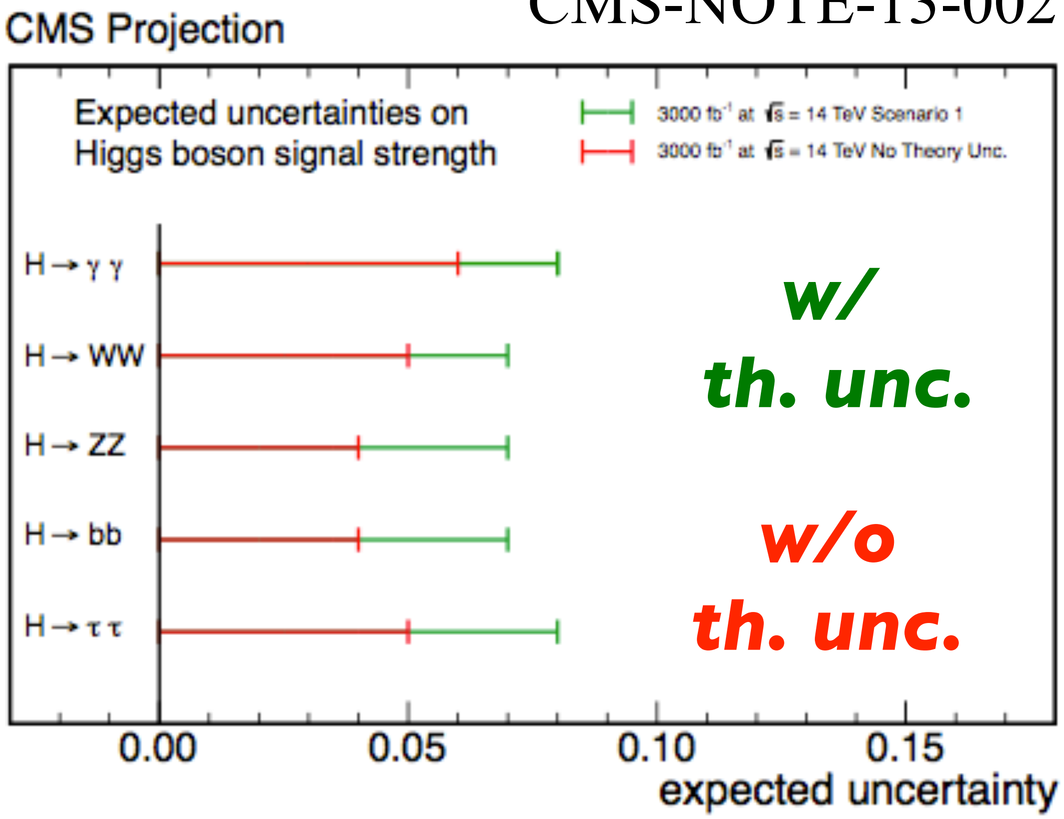
⇩

δμ:
~10% → ~1%

Naive scaling challenged by:

- luminosity uncertainty
  - common to all measurements (~3%)
- detector performances
  - e.g. pile-up (<μ>~128)
- theory uncertainties
  - $\sigma_{SM} \times BR_{SM} \times A_{SM}$ known up to some accuracy (~ NLO+PS)

CMS-NOTE-13-002



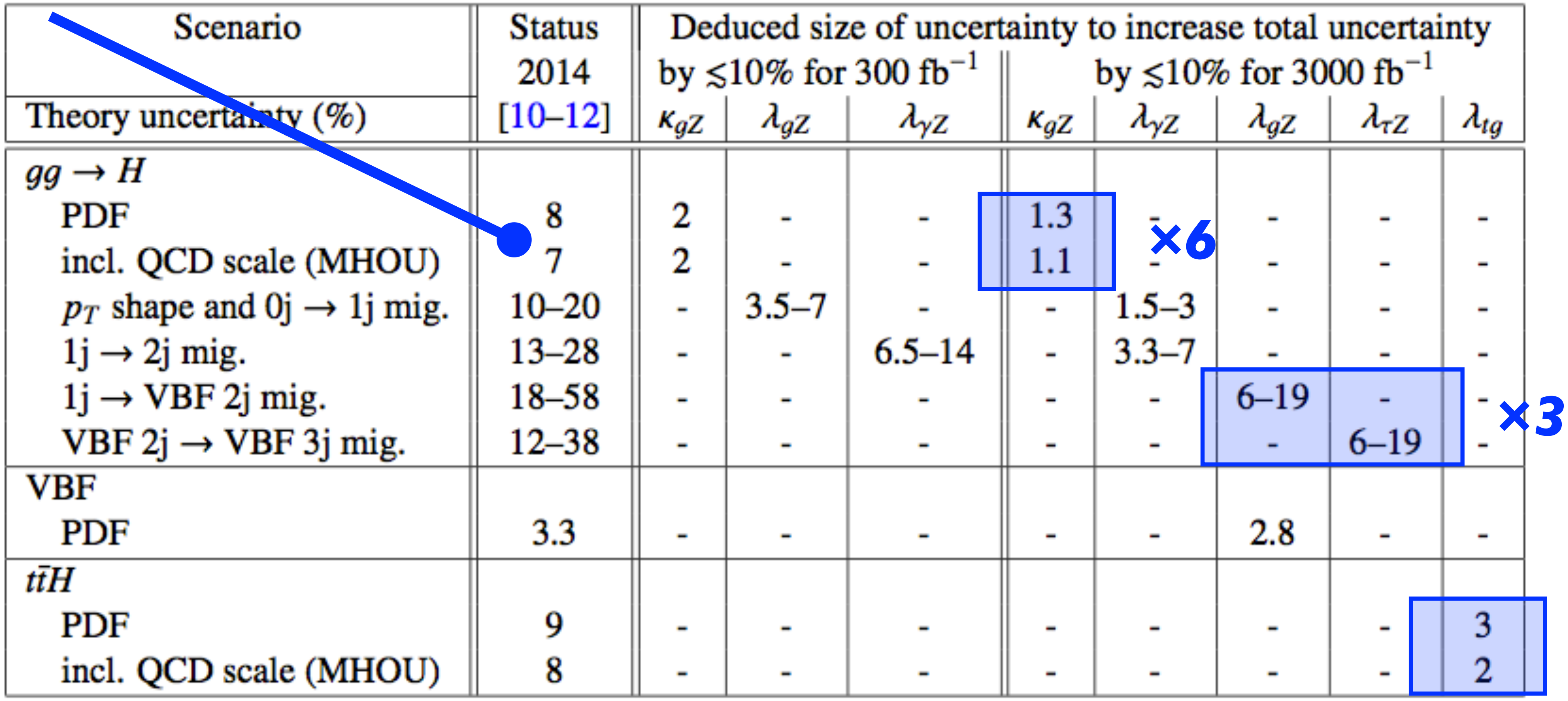
w/ th. unc.

w/o th. unc.

Targets for the HL-LHC

Now:
3% (N^3LO)

ATL-PHYS-PUB-2014-016



Scenario Theory uncertainty (%)	Status 2014 [10–12]	Deduced size of uncertainty to increase total uncertainty by $\lesssim$10% for 300 fb^{-1} κ_{gZ}	λ_{gZ}	$\lambda_{\gamma Z}$	by $\lesssim$10% for 3000 fb^{-1} κ_{gZ}	$\lambda_{\gamma Z}$	λ_{gZ}	$\lambda_{\tau Z}$	λ_{tg}
$gg \to H$									
PDF	8	2	-	-	1.3	-	-	-	-
incl. QCD scale (MHOU)	7	2	-	-	1.1	-	-	-	-
p_T shape and 0j → 1j mig.	10–20	-	3.5–7	-	-	1.5–3	-	-	-
1j → 2j mig.	13–28	-	-	6.5–14	-	3.3–7	-	-	-
1j → VBF 2j mig.	18–58	-	-	-	-	-	6–19	-	-
VBF 2j → VBF 3j mig.	12–38	-	-	-	-	-	-	6–19	-
VBF									
PDF	3.3	-	-	-	-	-	2.8	-	-
$t\bar{t}H$									
PDF	9	-	-	-	-	-	-	-	3
incl. QCD scale (MHOU)	8	-	-	-	-	-	-	-	2

×6

×3

×3

Target precision challenges theory prediction

- PDF: need 3÷6 times reduction in uncertainty
- NNLO + PS needed (e.g. ttH)
- role of non perturbative QCD?
- need to minimise impact of theory uncertainty

O(1%) precision remains a challenging task

HL-LHC: Higgs factory

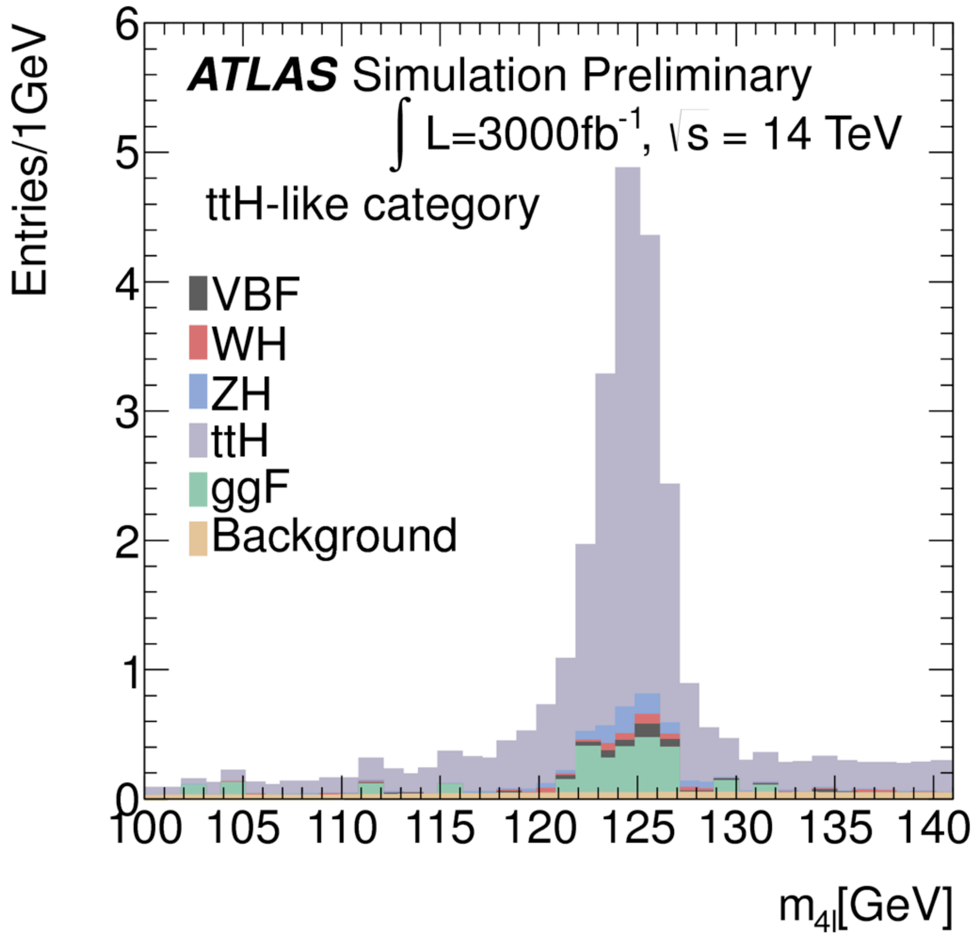
3 ab^{-1} ⇔ 150M (ggF+ttH) + 10M (VH+VBF)

- each production mode from golden channels
- rare production & decay modes

ATL-PHYS-PUB-2013-004
ATL-PHYS-PUB-2014-016
CMS-NOTE-13-002
CMS, CERN-LHCC-P-008

H→ZZ ⇒

Category	Rate	Purity
ttH-like	**37**	**80%**
ZH-like	**5.7**	**75%**
WH-like	**80**	**30%**
VBF-like	**100**	**50%**
ggF-like	**6000**	**60%**

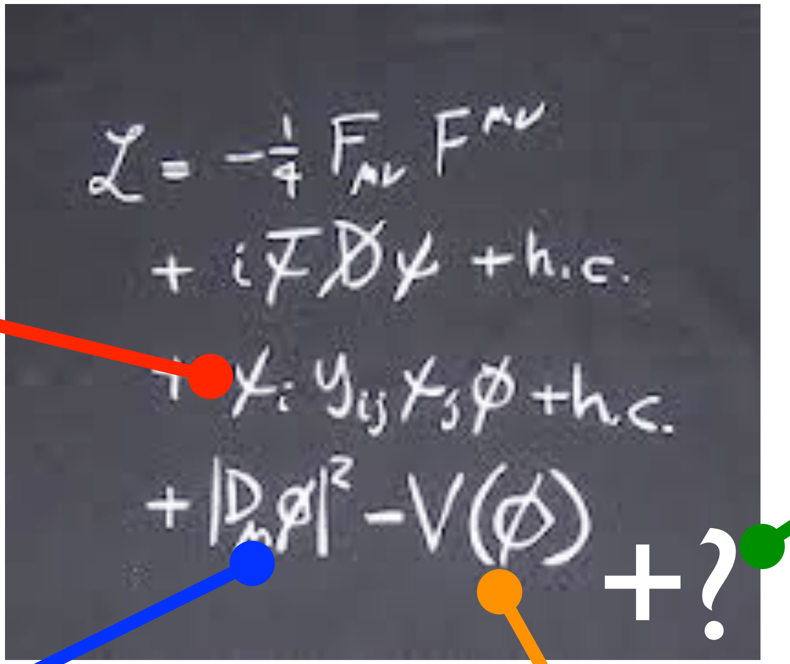


Production	δμ	significance
VBF	**[9,15]%**	**observed**
ttH	**[10,16]%**	**observed**
HH	**~50%**	**2÷3σ**

Decay	δμ	significance
H→μμ	**[10,16]%**	**~7σ**
H→Zγ	**[20,30]%**	**~4σ**

What can we learn from this?

- What information can be extracted from this data?
  - (in lack of direct evidence...) which implications on new physics?
- How does it compare with a concurrent FCC-ee?
  - is there complementarity? or redundancy ($1/\sqrt{N_{exp}}$)? or none?



- ***Coupling to fermions***
- ***CP-violation***
- ***Flavour structure***

- ***BR$_{BSM}$***
- ***Dim-6 operators***
- ***Extra Higgs bosons***

- ***Coupling to gauge boson***

- ***Mass and self-coupling***

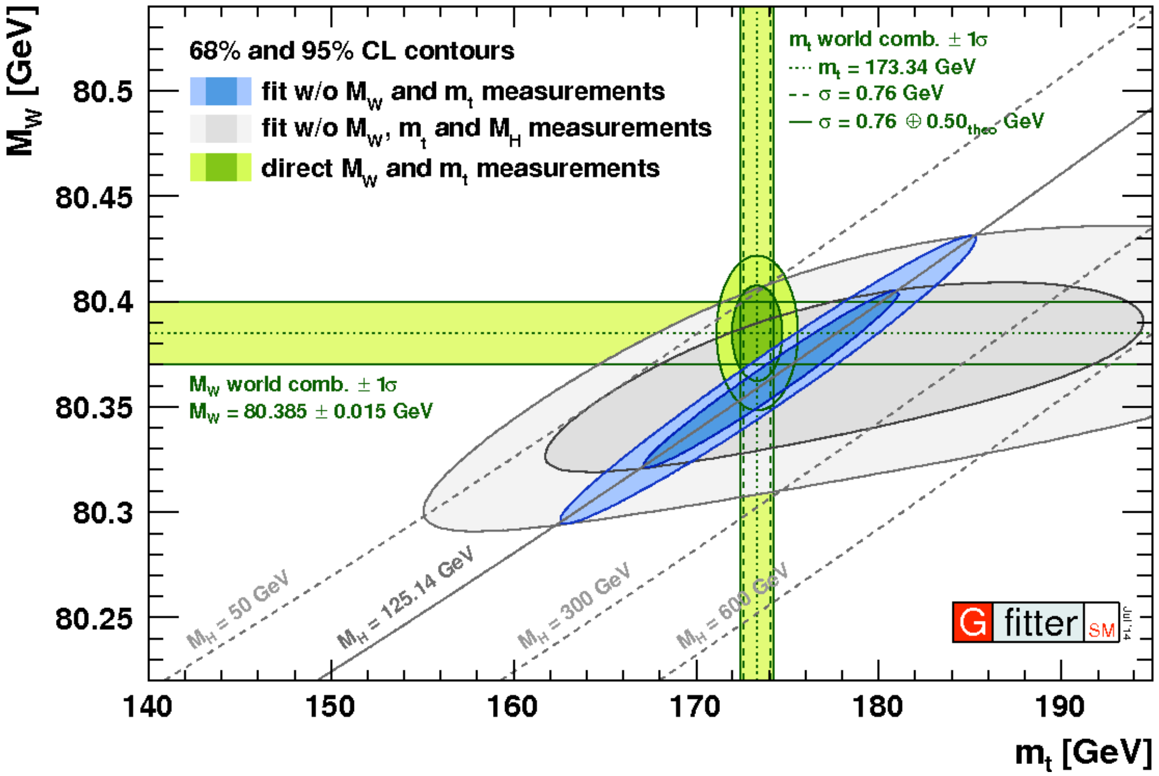
Mass (m_H)

	δm_H
HL-LHC	***~50 MeV***
TLEP	***~10 MeV***

No compelling theoretical need for such a precision. (but who knows...)

Top, W mass:

Gfitter, 2015



Stability bound:

$$m_h > 129.4\,\mathrm{GeV} + 1.4\,\mathrm{GeV}\left(\boxed{\frac{m_t - 173.2\,\mathrm{GeV}}{0.7\,\mathrm{GeV}}}\right) - 0.5\,\mathrm{GeV}\left(\frac{\alpha_s(M_Z) - 0.1184}{0.0007}\right) \pm 1\,\mathrm{GeV}$$

Snowmass, arXiv:1310.8361
Gupta et al. PRD 88 055024 (2013)

Width (Γ_H)

ATL-PHYS-PUB-2014-016
CMS-NOTE-13-002

No direct measurement if $\Gamma_H \sim \Gamma_{SM}$ = 4.2 MeV

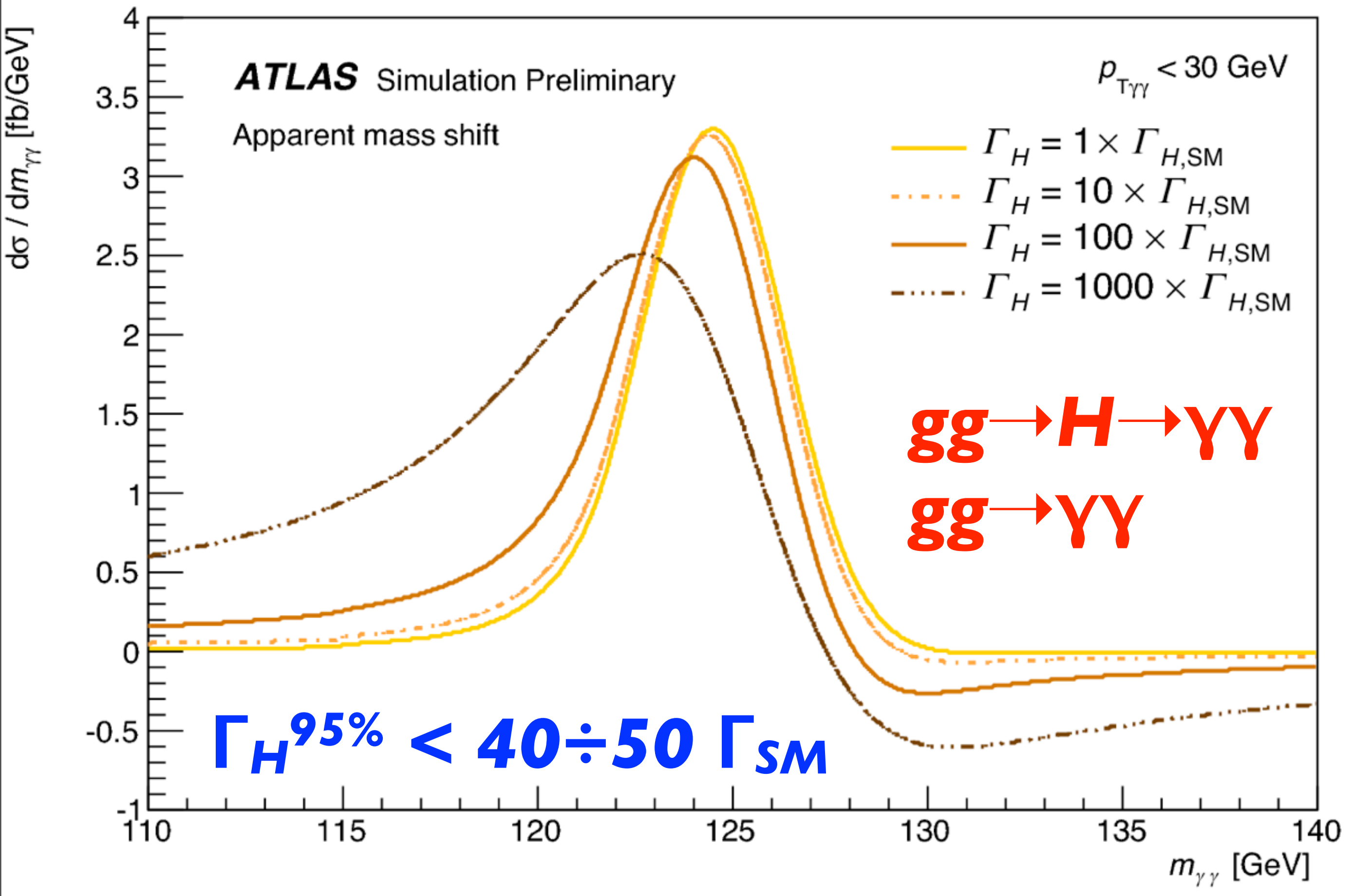
- only lower bounds allowed from $\sigma \times BR$:

$$(1 \pm \delta\mu) \cdot (\Gamma_i \times \mathrm{BR}_f)_{\mathrm{SM}} = \Gamma_i \times \mathrm{BR}_f \leq \Gamma_i$$

- need extra model assumptions
- constraint from bkg interference:

	95% U.L.
Invisible only	**[6,17]%**
Constrained fit ($\kappa_V \leq 1$)	**[7,14]%**

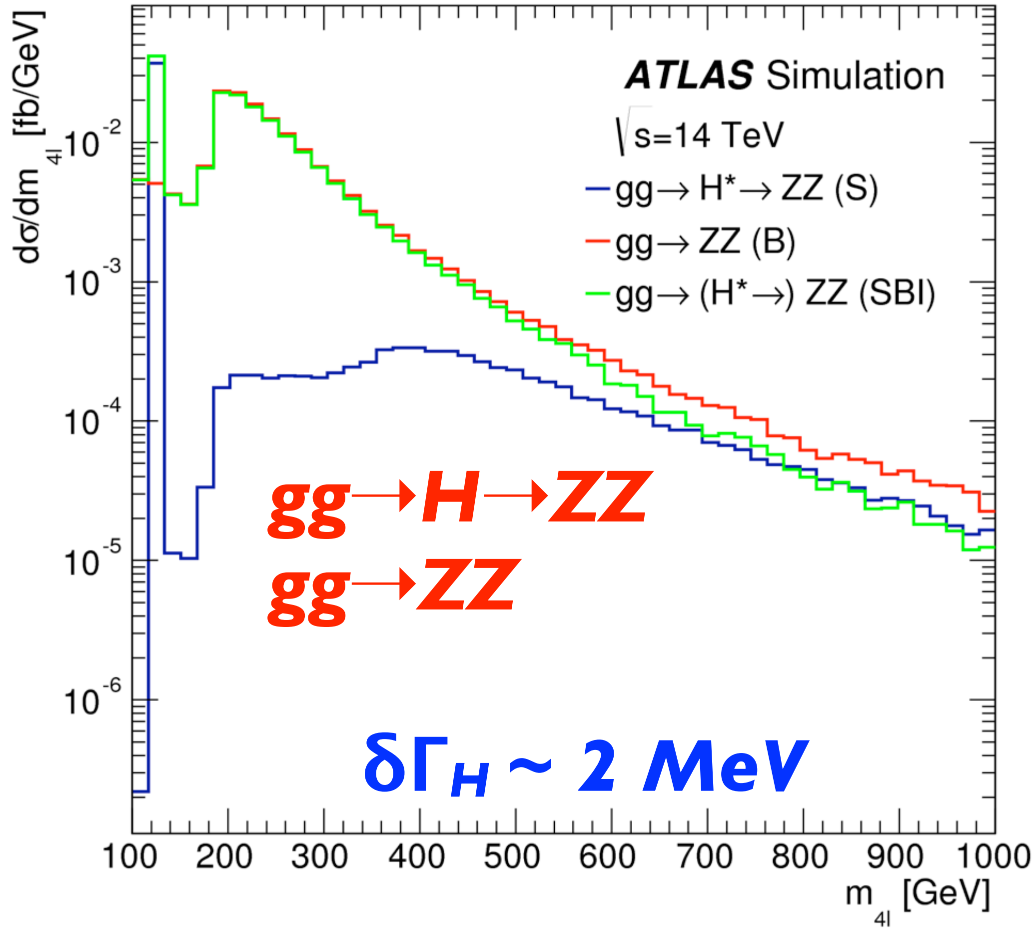
ATL-PHYS-PUB-2014-016



gg→H→γγ
gg→γγ

$\Gamma_H^{95\%} < 40 \div 50\ \Gamma_{SM}$

ATL-PHYS-PUB-2015-024



gg→H→ZZ
gg→ZZ

$\delta\Gamma_H \sim 2$ MeV

Width (Γ_H)

ATL-PHYS-PUB-2014-016
CMS-NOTE-13-002

No direct measurement if $\Gamma_H \sim \Gamma_{SM}$ = 4.2 MeV

- only lower bounds allowed from σ×BR:

$$(1 \pm \delta\mu) \cdot (\Gamma_i \times \mathrm{BR}_f)_{\mathrm{SM}} = \Gamma_i \times \mathrm{BR}_f \leq \Gamma_i$$

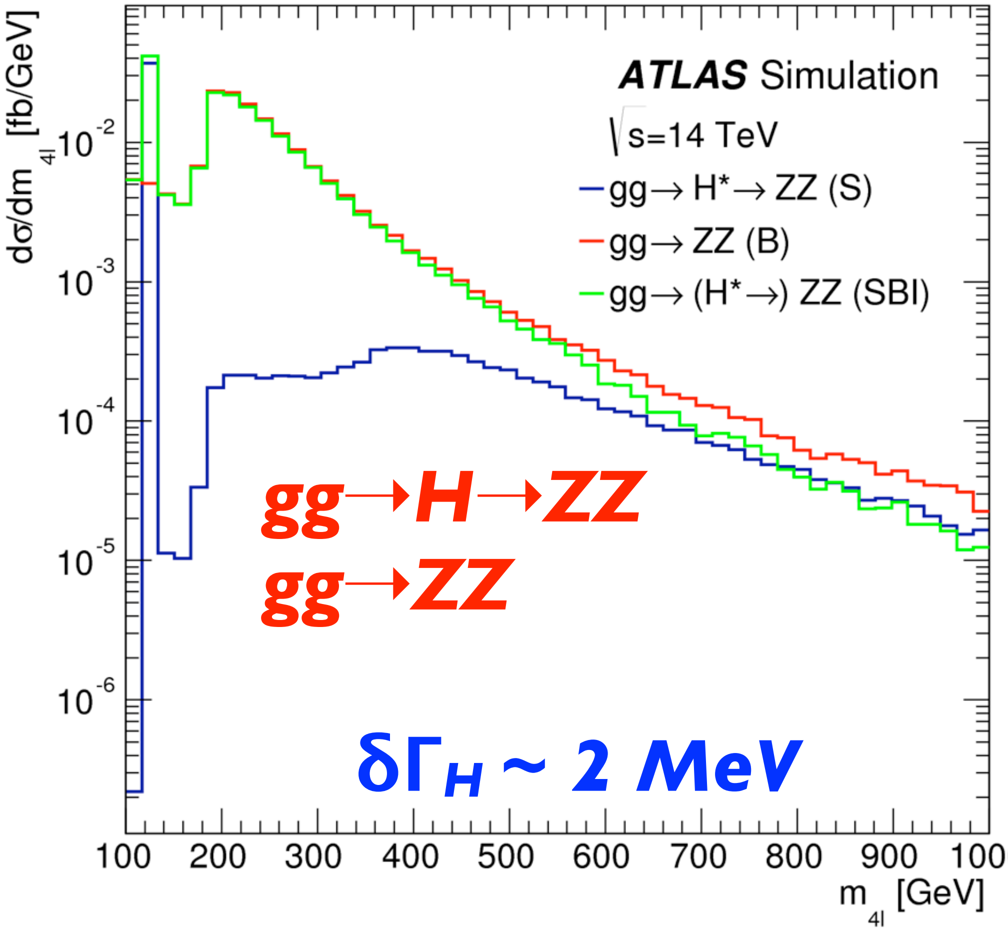
- need extra model assumptions
- constraint from bkg interference:

	95% U.L.
Invisible only	**[6,17]%**
Constrained fit ($\kappa_V \leq 1$)	**[7,14]%**

@FCC-ee:
model-independent
measurement of Γ_H
from σ(ZH) and σ(ZH)BR_{ZZ}
[~1% precision]

⟺ constrain Γ_{undet}

ATL-PHYS-PUB-2015-024



gg→H→ZZ
gg→ZZ

$\delta\Gamma_H \sim$ 2 MeV

From μ's to couplings

- Parametrise μ_i^f with coupling constant modifiers (κ)

$$\left\{\begin{array}{l} g_i = \kappa_i g_i^{\rm SM} \\ \\ \Gamma_H = \left[\sum_i \kappa_i^2 {\rm BR}_i^{\rm SM}/(1-{\rm BR}_{\rm BSM})\right]\Gamma_H^{\rm SM} = \kappa_H^2\Gamma_H^{\rm SM} \end{array}\right. \Rightarrow \boxed{\mu_i^f = \frac{\kappa_i^2\kappa_f^2}{\kappa_H^2}}$$

  - extract from combined fit

μ's unchanged by $\kappa_i \to \varsigma\kappa_i \quad \kappa_H \to \varsigma^2\kappa_H$

- Only ratios of κ's + one μ can be fitted
  - to remove flat direction need assumptions.
    - e.g. $\mathrm{BR}_{\mathrm{BSM}} = 0$
    - e.g. upper limit on vector coupling
    - e.g. symmetrise unobservable couplings (e.g. $\kappa_t = \kappa_c = \kappa_u$)

Couplings: global fit

ATL-PHYS-PUB-2014-016
CMS-NOTE-13-002

* [no theory, full theory]

**[1/2 theory & 1/√L sys., Run 1 syst.]

	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{BSM}
*ATLAS**	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]	[10,14]
*CMS***	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]	[7,11]

Couplings: global fit

* [no theory, full theory]

**[1/2 theory & 1/√L sys., Run 1 syst.]

ATL-PHYS-PUB-2014-016
CMS-NOTE-13-002

	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{BSM}
*ATLAS**	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]	[10,14]
*CMS***	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]	[7,11]

Not best ttH/VH(bb) analysis
projected by ATLAS
No VBF(bb)

ttH(bb) + ttH(γγ)
Adding ttH(WW): 7%→4%

C. Botta, Moriond2013

Only VBF(ττ)
projected by ATLAS
(x2 from ggF)

New CMS
projection: 5%

CMS, CERN-LHCC-P-008

Couplings: global fit

ATL-PHYS-PUB-2014-016
CMS-NOTE-13-002

* [no theory, full theory]

**[1/2 theory & $1/\sqrt{L}$ sys., Run 1 syst.]

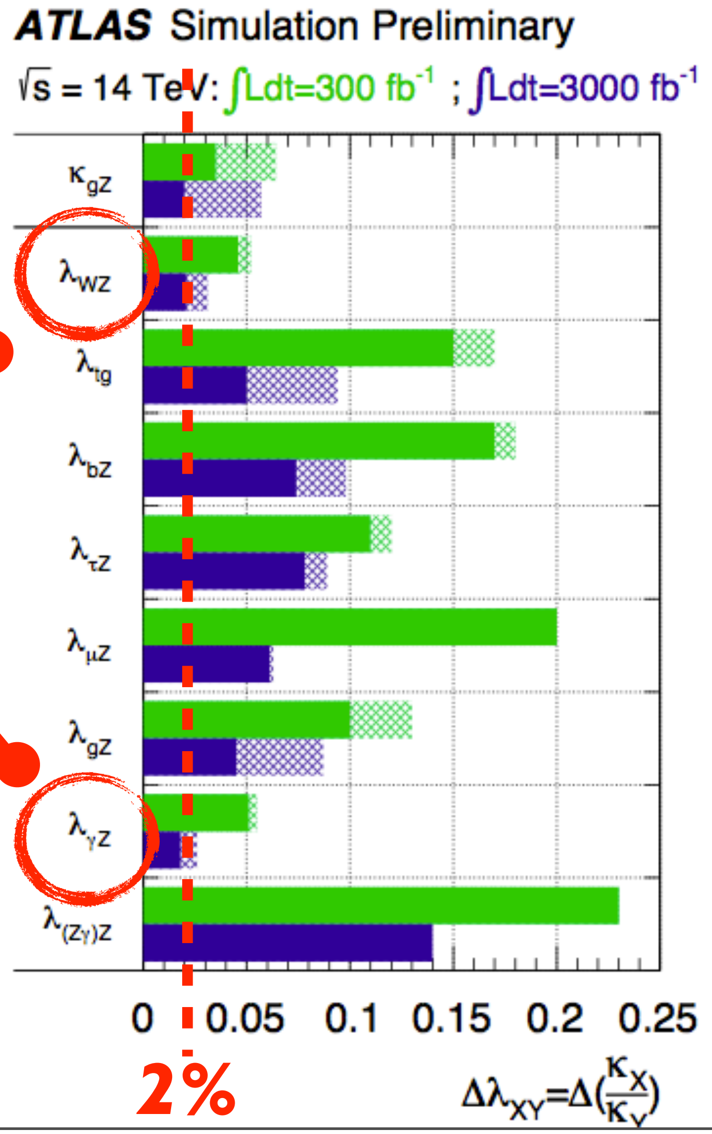
	κ_γ	κ_W	κ_Z	κ_g	κ_b	κ_t	κ_τ	$\kappa_{Z\gamma}$	κ_μ	BR_{BSM}
*ATLAS**	[4,5]	[4,5]	[4,4]	[5,9]	[10,12]	[8,11]	[9,10]	[14,14]	[7,8]	[10,14]
*CMS***	[2,5]	[2,5]	[2,4]	[3,5]	[4,7]	[7,10]	[2,5]	[10,12]	[8,8]	[7,11]

Optimistic scenario:

	$\delta\kappa/\kappa$	
κ_V, κ_γ	**3%**	**Gauge bosons**
κ_b	**4%**	**Bottom Yukawa**
κ_t	**5%**	**Top Yukawa**
κ_τ	**3%**	**Leptons**
κ_μ	**5%**	**2nd family**

Similar for $\lambda_{ij} = \kappa_i/\kappa_j$:

$\sigma(ggF)$ cancels

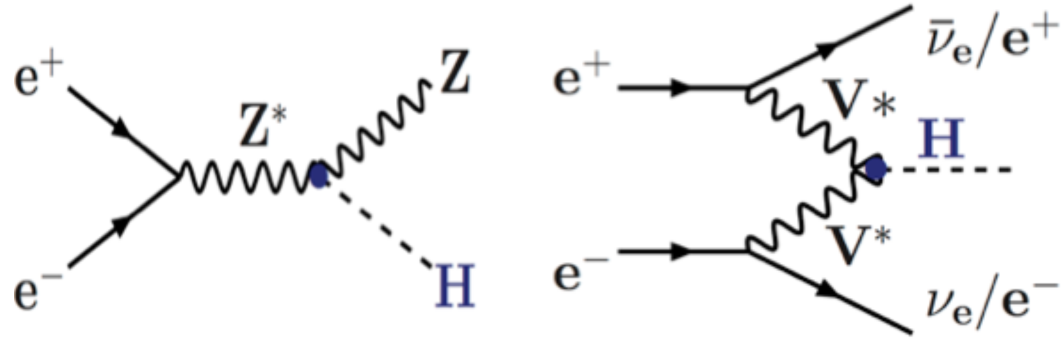


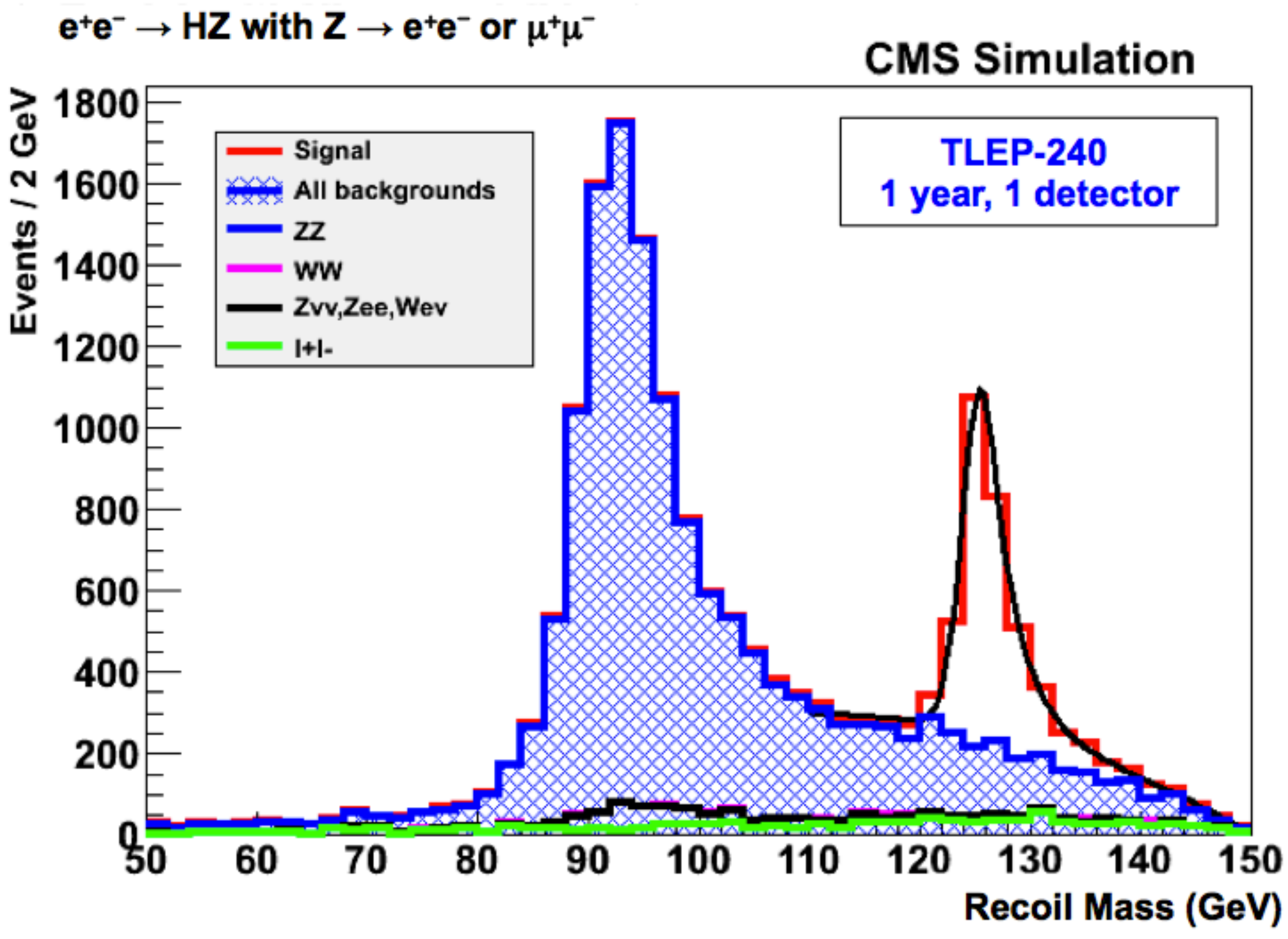
Coupling measurements at FCC-ee

Comparing to FCC-ee with 2.5×4 ab^{-1} at 240 GeV (TLEP)

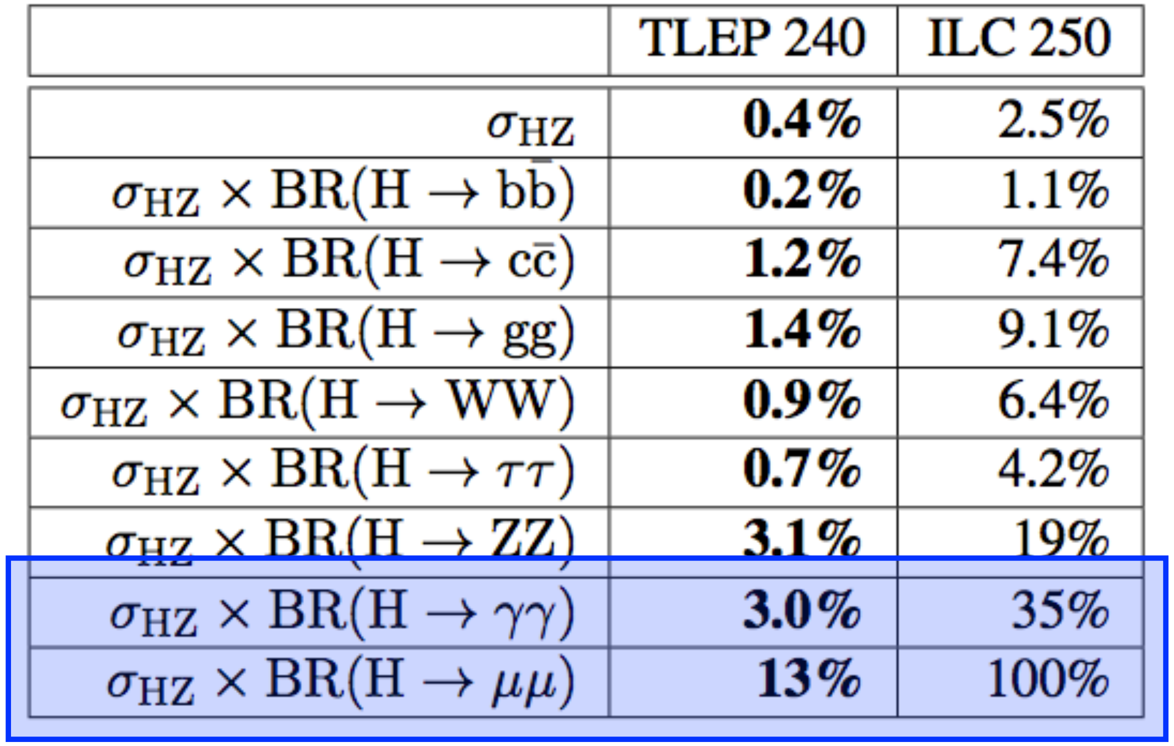
- inclusive production cross section measurable to ~1%
- all decay modes accessible
  - good b/c separation from vertex detector

Direct measurement of κ's from $\sigma(ZH)$, $\sigma(ZH)BR_X$, Γ_H





arXiv:1308.6176

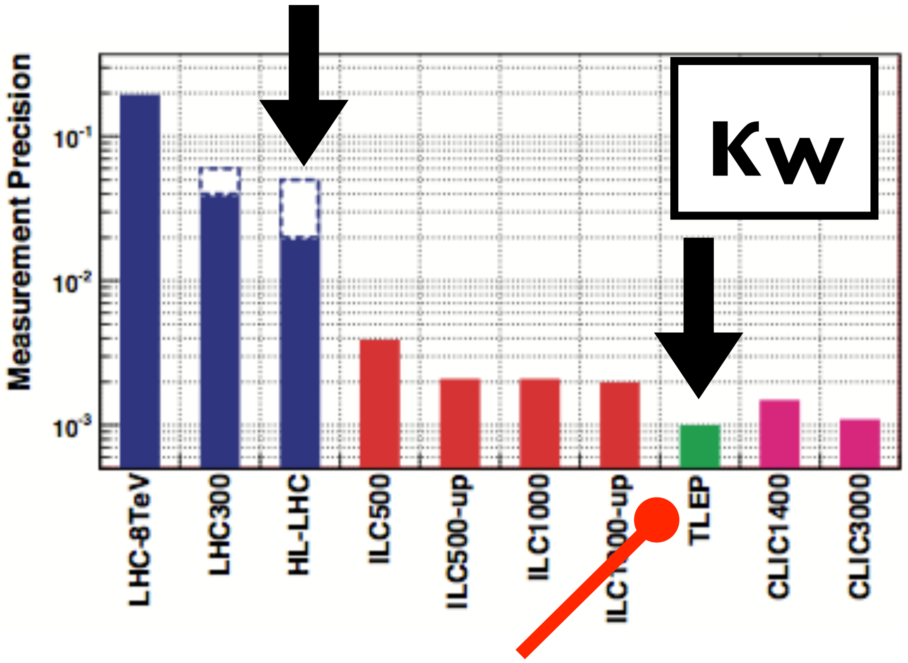


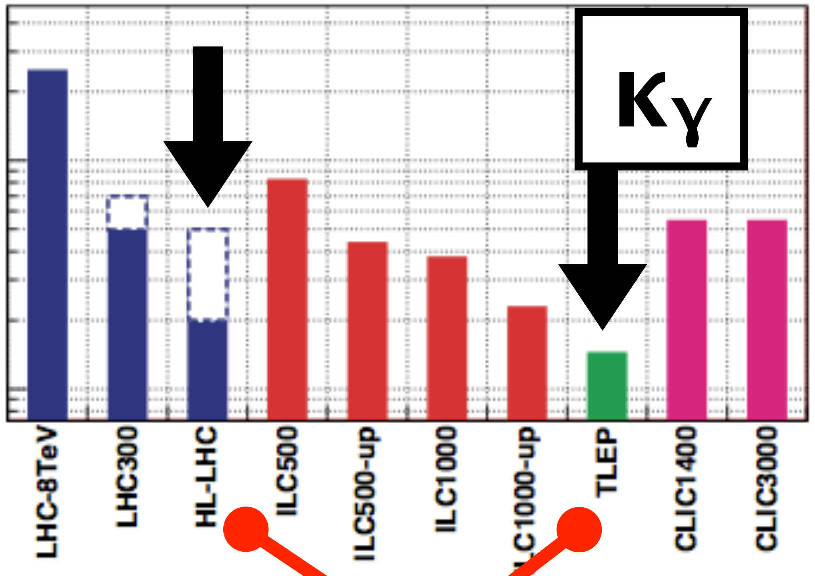
	TLEP 240	ILC 250
σ_{HZ}	**0.4%**	2.5%
$\sigma_{HZ} \times BR(H \to b\bar{b})$	**0.2%**	1.1%
$\sigma_{HZ} \times BR(H \to c\bar{c})$	**1.2%**	7.4%
$\sigma_{HZ} \times BR(H \to gg)$	**1.4%**	9.1%
$\sigma_{HZ} \times BR(H \to WW)$	**0.9%**	6.4%
$\sigma_{HZ} \times BR(H \to \tau\tau)$	**0.7%**	4.2%
$\sigma_{HZ} \times BR(H \to ZZ)$	**3.1%**	19%
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	**3.0%**	35%
$\sigma_{HZ} \times BR(H \to \mu\mu)$	**13%**	100%

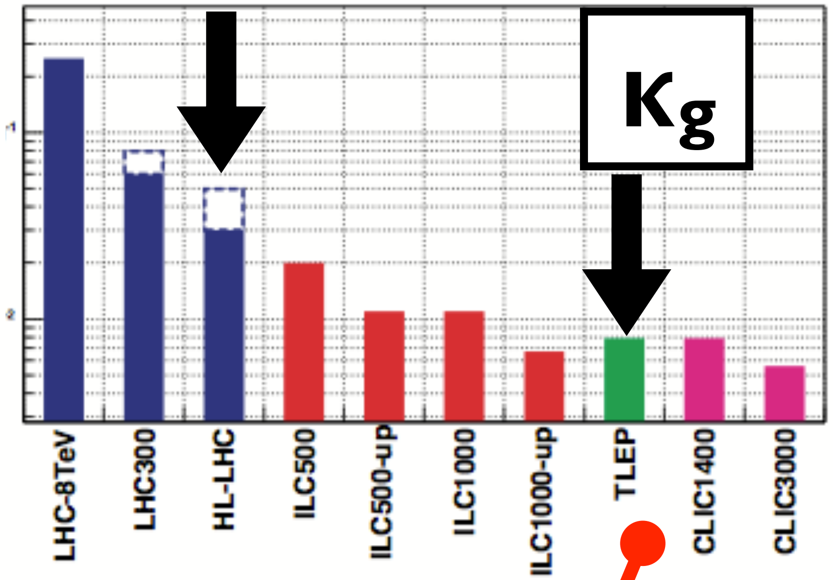
Limited by BR

Snowmass, arXiv:1310.8361

Results







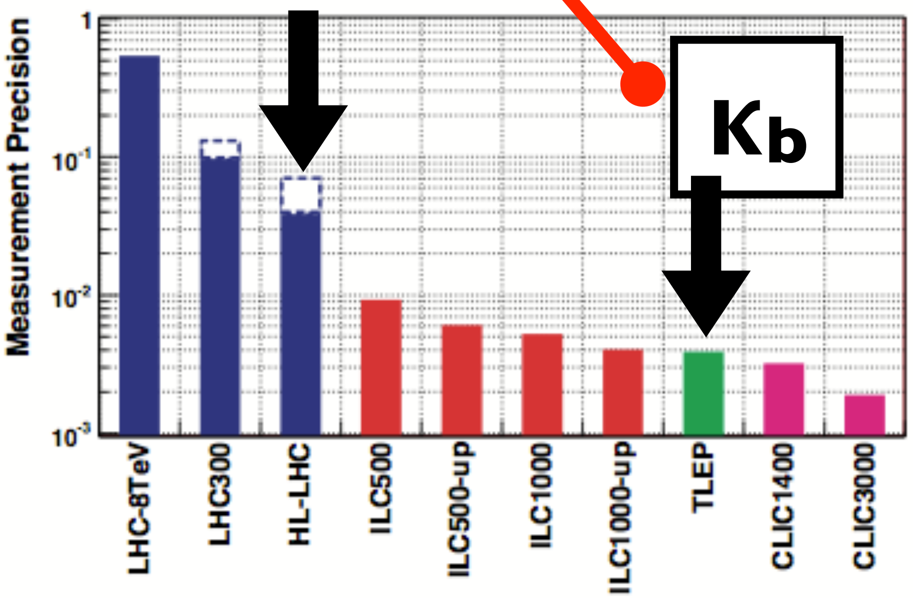
κ_V to permill level

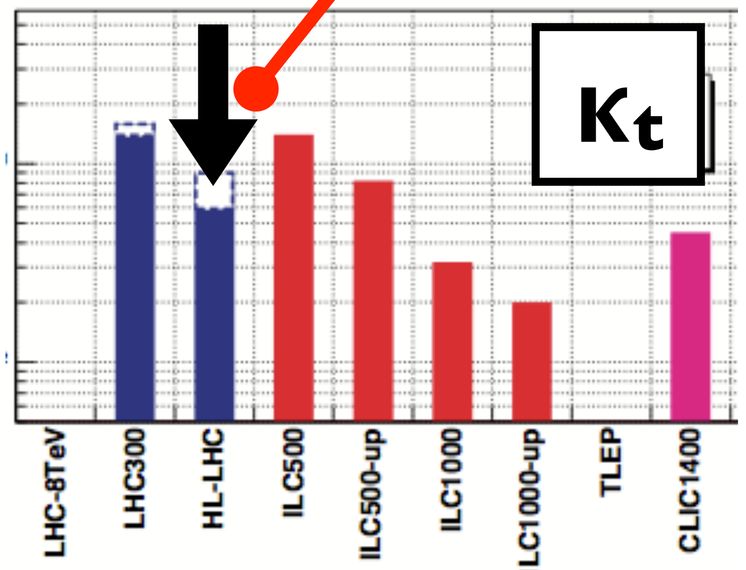
similar precision on κ_γ (and κ_μ)

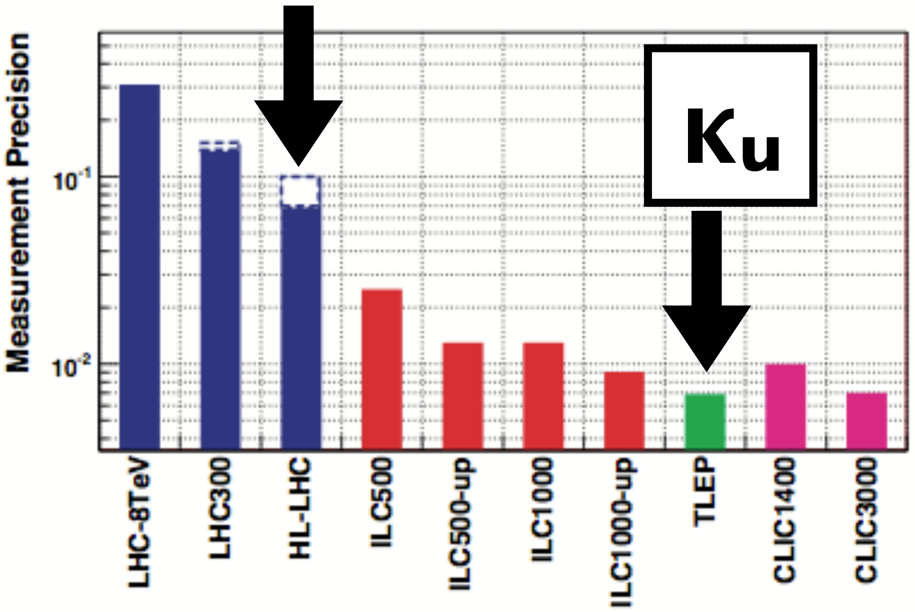
κ_g/κ_c separation

κ_b to <1%

κ_t (direct) only at HL-LHC







Light quarks Yukawa

- H → cc challenging at LHC
  - recast VH→bb analysis into VH→cc

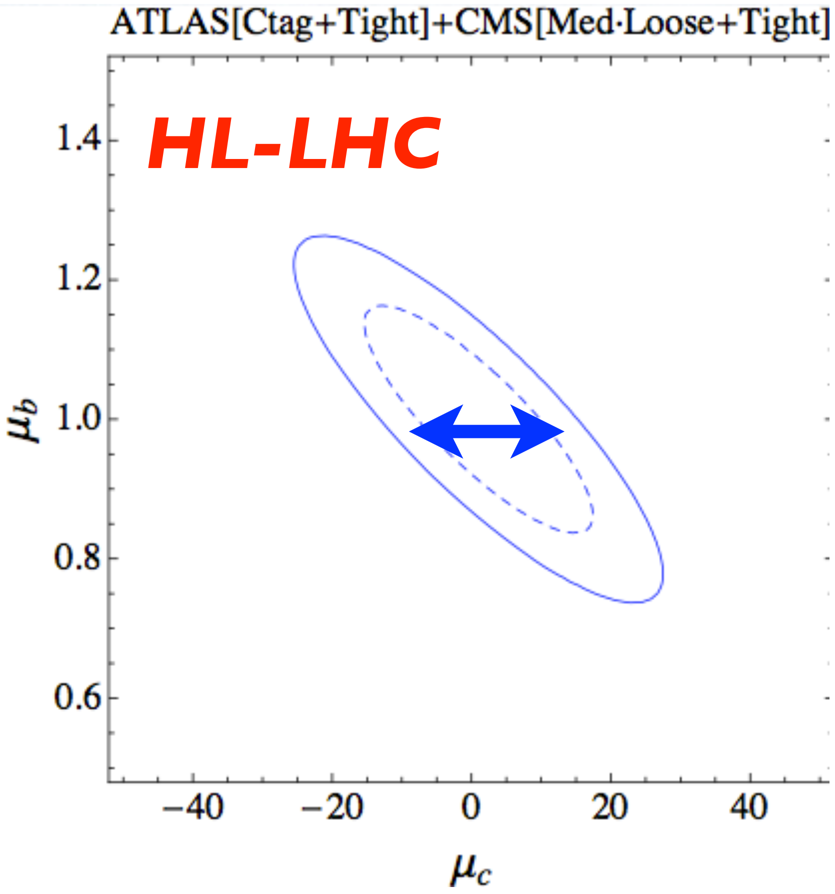
$$\mu_b = \frac{\sigma \mathrm{BR}_b}{[\sigma \mathrm{BR}_b]^{\mathrm{SM}}} \rightarrow \mu_b + \left(\frac{\epsilon_{c_1}\epsilon_{c_2}}{\epsilon_{b_1}\epsilon_{b_2}}\right)\frac{\mathrm{BR}_c^{\mathrm{SM}}}{\mathrm{BR}_b^{\mathrm{SM}}}\,\mu_c$$

  - from radiative decay H → J/ψ γ
    ↳ μμ

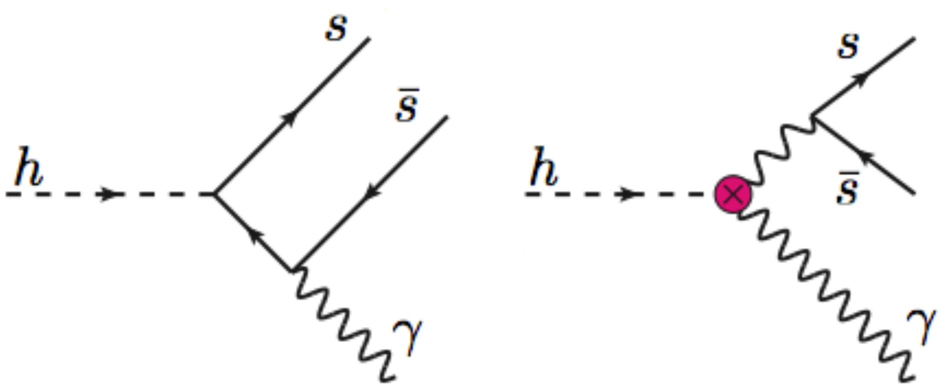
B(H→J/ψγ)	SM	Obs. (Exp.) *
95% CL U.L.	~3 · 10^{-6}	1.5 (1.2) · 10^{-3}

[* ATLAS, PRL 114 121801 (2015)]

Y. Soreq, FCCee Workshop



- What about even-lighter quarks?
  - radiative decays e.g. H→Φγ
    - sensitive to κ_s through interference



$$\frac{\mathrm{BR}_{h\to\phi\gamma}}{\mathrm{BR}_{h\to b\bar{b}}} = \frac{\kappa_\gamma[(3.0\pm0.3)\kappa_\gamma - \boxed{0.78\bar{\kappa}_s]}\times 10^{-6}}{0.57\bar{\kappa}_b^2}$$

FCC-ee: 2nd generation quark Yukawa.
Lighter quarks out-of-reach.

Implications on BSM

Coupling measurements can constrain BSM

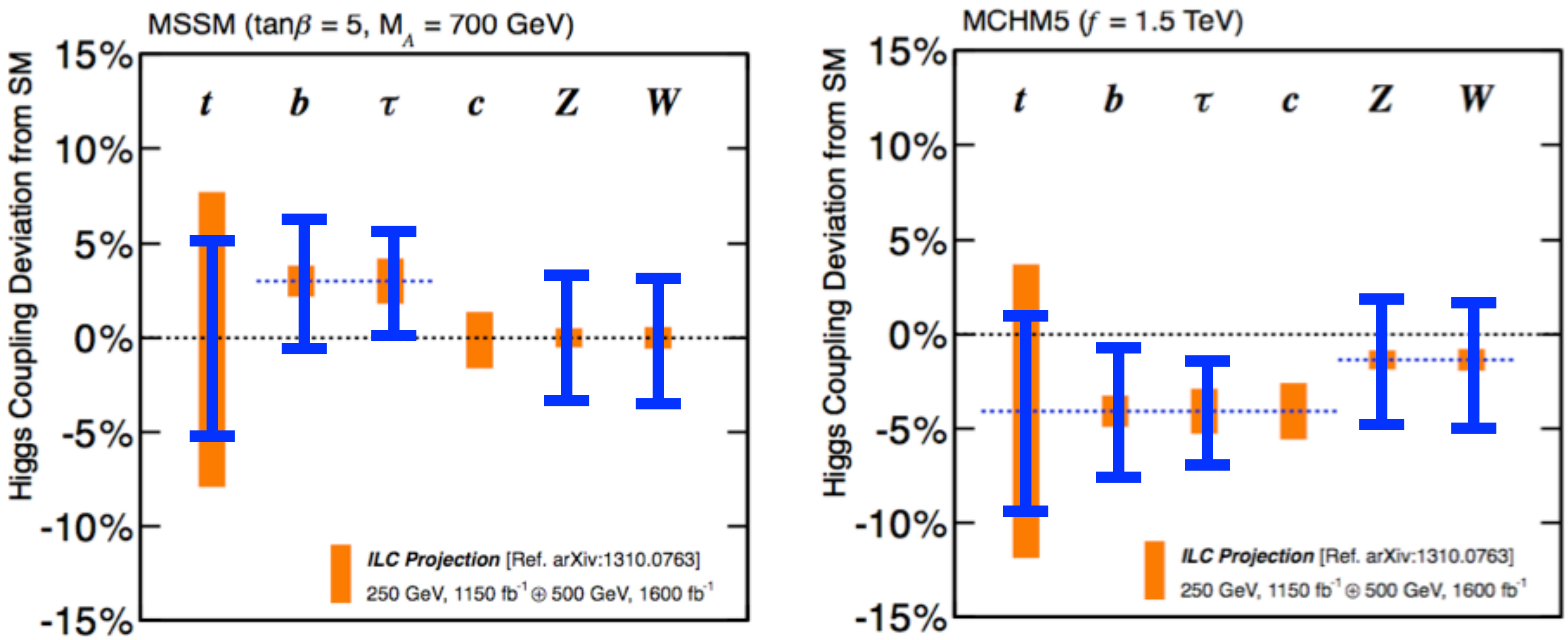
- need enough accuracy to identify deviations
- each model has its own pattern of deviations

Gupta et al. PRD 86 095001 (2012)
Peskin, HL-LHC Workshop May15

I = *HL-LHC.*

SUSY

Composite Higgs

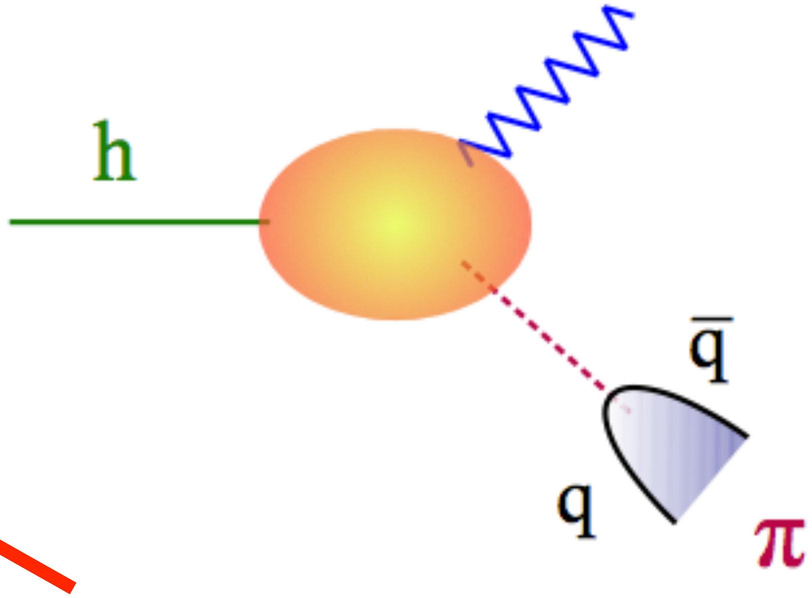


HL-LHC may just slightly miss the signature of new physics

Rare processes: semi-hadronic decays

Exclusive semi-hadronic decays (Z/W+meson)

- suppressed by $(f_P/v)^2$
- complementary to H→VV*



$$\mathcal{A}_V^{\mathcal{F}} = C_V g_V^2 m_V \frac{\varepsilon_\mu J_\nu^{\mathcal{F}}}{(q^2 - m_V^2)} [f_1^V(q^2) g^{\mu\nu} + f_2^V(q^2) q^\mu q^\nu$$
$$+ f_3^V(q^2)(p \cdot q\, g^{\mu\nu} - q^\mu p^\nu) + f_4^V(q^2) \epsilon^{\mu\nu\rho\sigma} p_\rho q_\sigma]$$

f_2^V only in A^P_V

BR_{SM} (W^-D^*) ~10^{-5} ⇒ O(100) events in VBF

VP mode	$\mathcal{B}^{\mathrm{SM}}$	VP^* mode	$\mathcal{B}^{\mathrm{SM}}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	$Z^0 J/\psi$	2.2×10^{-6}

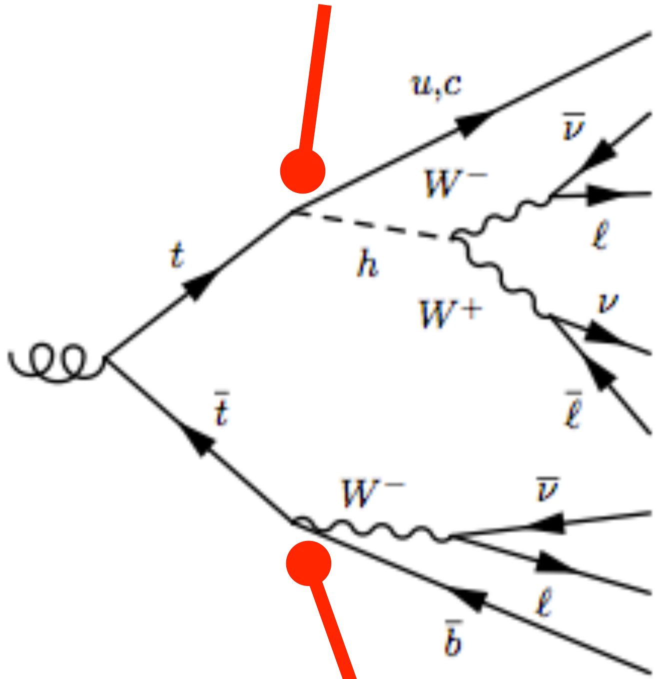
G. Isidori et al. PLB 728 (2014) 131

No conclusive studies yet. BR ~10^{-5} may be detectable at HL-LHC

FCNC from the Yukawa sector

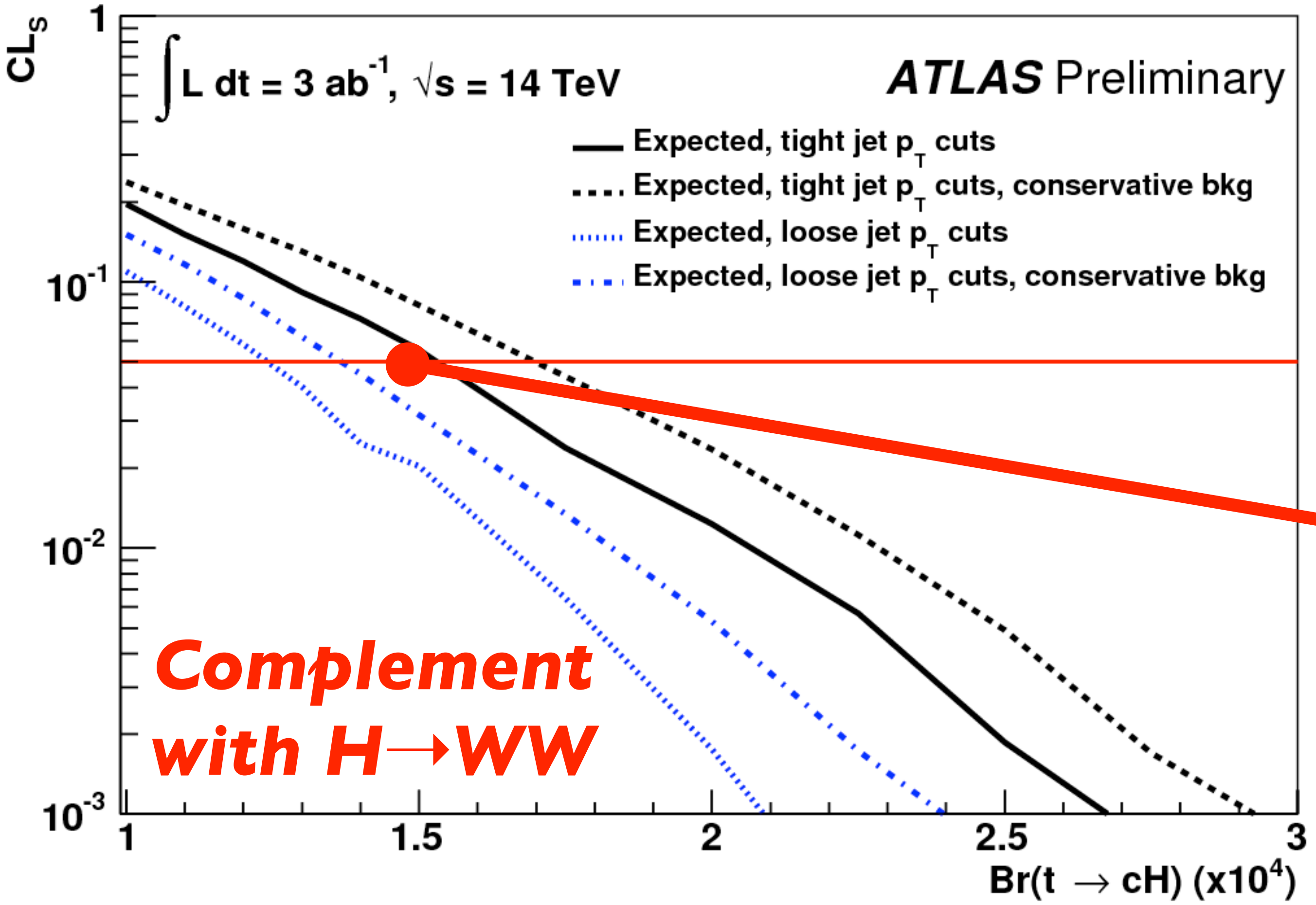
- FC currents from Htq interaction highly suppressed in SM
    - $BR(t \to cH) < 10^{-15}$
    - appear naturally in BSM (QS, 2HDM)
- Search for FC decays of top quarks
    - profit from large σ(pp → tt)
        - 3×10^{9} top pairs ⇒ $BR\sim10^{-6}$ with ~10%

$$\lambda_{t(u,c)H}\ \bar{t}(u,c)\ H$$



$$-\frac{g}{\sqrt{2}}V_{tb}\ \bar{t}_L\gamma^\mu b_L\ W^+_\mu$$

ATL-PHYS-2013-012



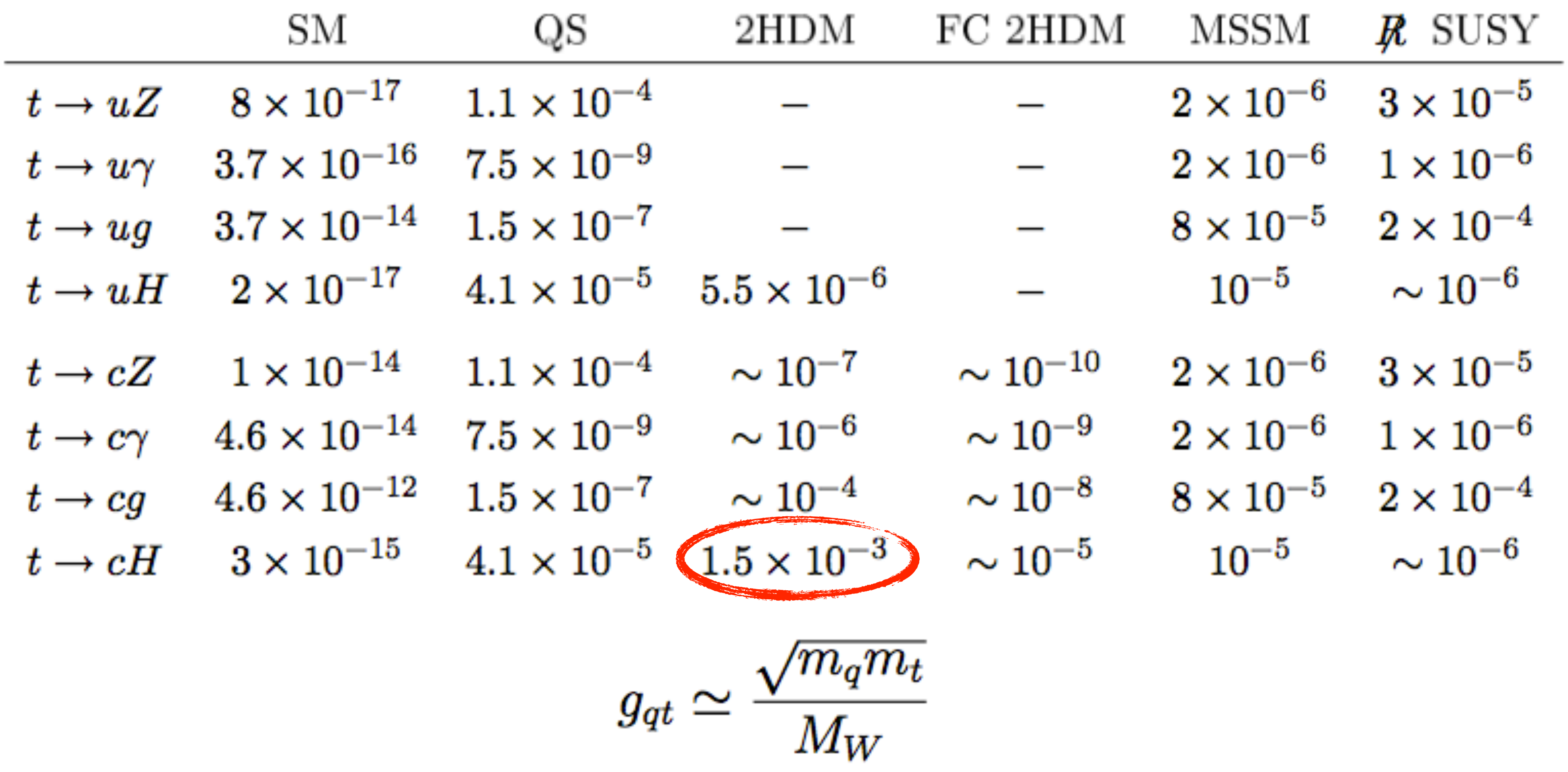
Complement with H→WW

$BR\sim10^{-4}$ could be detectable.
[FCC-ee: higher sensitivity to Ztq]

P. Azzi, FCC-ee Workshop, Pisa 2015

FCNC from the Yukawa sector

Aguilar-Saavedra, Acta Phys.Polon. B35:2695-2710 (2004)



	SM	QS	2HDM	FC 2HDM	MSSM	$\not{R}$ SUSY
$t \to uZ$	8×10^{-17}	1.1×10^{-4}	–	–	2×10^{-6}	3×10^{-5}
$t \to u\gamma$	3.7×10^{-16}	7.5×10^{-9}	–	–	2×10^{-6}	1×10^{-6}
$t \to ug$	3.7×10^{-14}	1.5×10^{-7}	–	–	8×10^{-5}	2×10^{-4}
$t \to uH$	2×10^{-17}	4.1×10^{-5}	5.5×10^{-6}	–	10^{-5}	$\sim 10^{-6}$
$t \to cZ$	1×10^{-14}	1.1×10^{-4}	$\sim 10^{-7}$	$\sim 10^{-10}$	2×10^{-6}	3×10^{-5}
$t \to c\gamma$	4.6×10^{-14}	7.5×10^{-9}	$\sim 10^{-6}$	$\sim 10^{-9}$	2×10^{-6}	1×10^{-6}
$t \to cg$	4.6×10^{-12}	1.5×10^{-7}	$\sim 10^{-4}$	$\sim 10^{-8}$	8×10^{-5}	2×10^{-4}
$t \to cH$	3×10^{-15}	4.1×10^{-5}	1.5×10^{-3}	$\sim 10^{-5}$	10^{-5}	$\sim 10^{-6}$

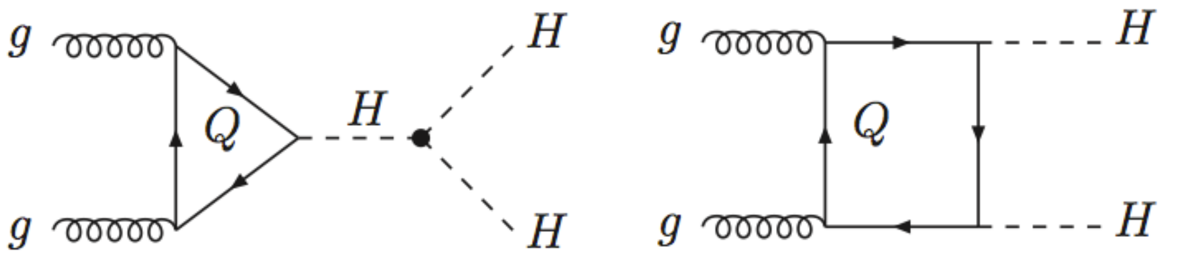
$$g_{qt} \simeq \frac{\sqrt{m_q m_t}}{M_W}$$

BR~10^{-4} maybe not enough...

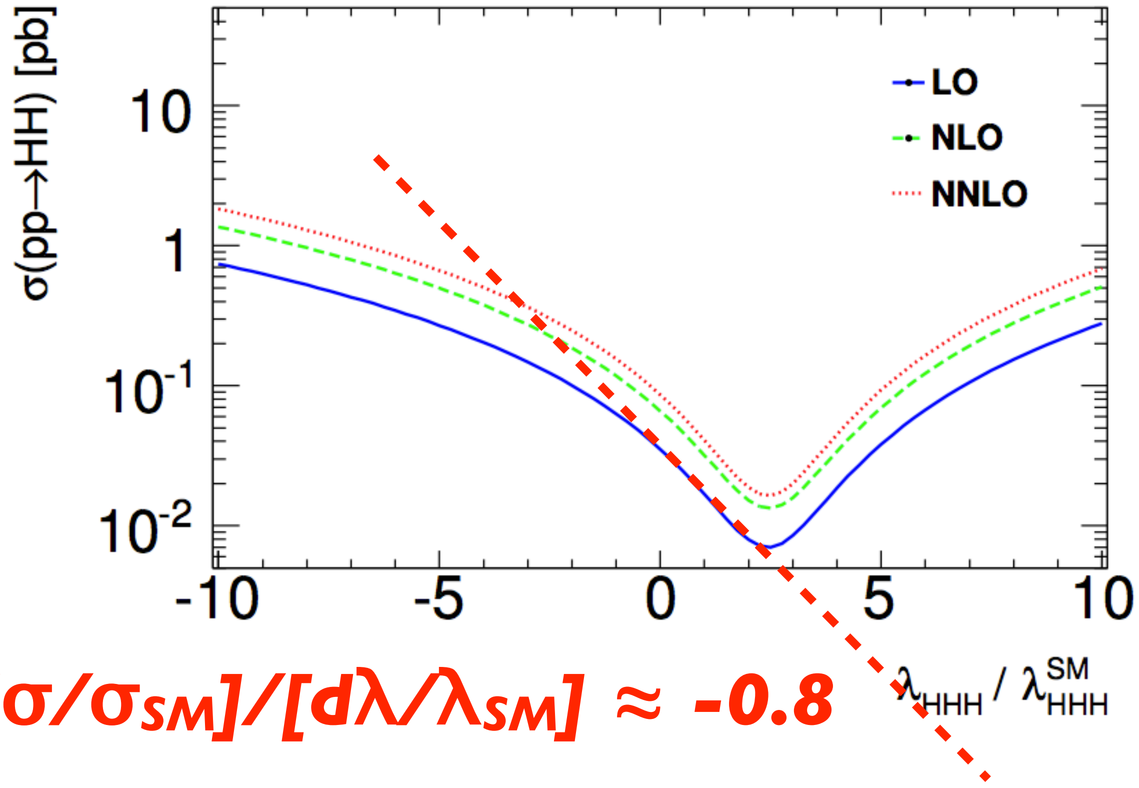
HH production

Unique access to self-coupling

- σ_{SM} ~ 40 fb
- destructive interference with Yukawa-mediated diagrams
  - reduced sensitivity to λ

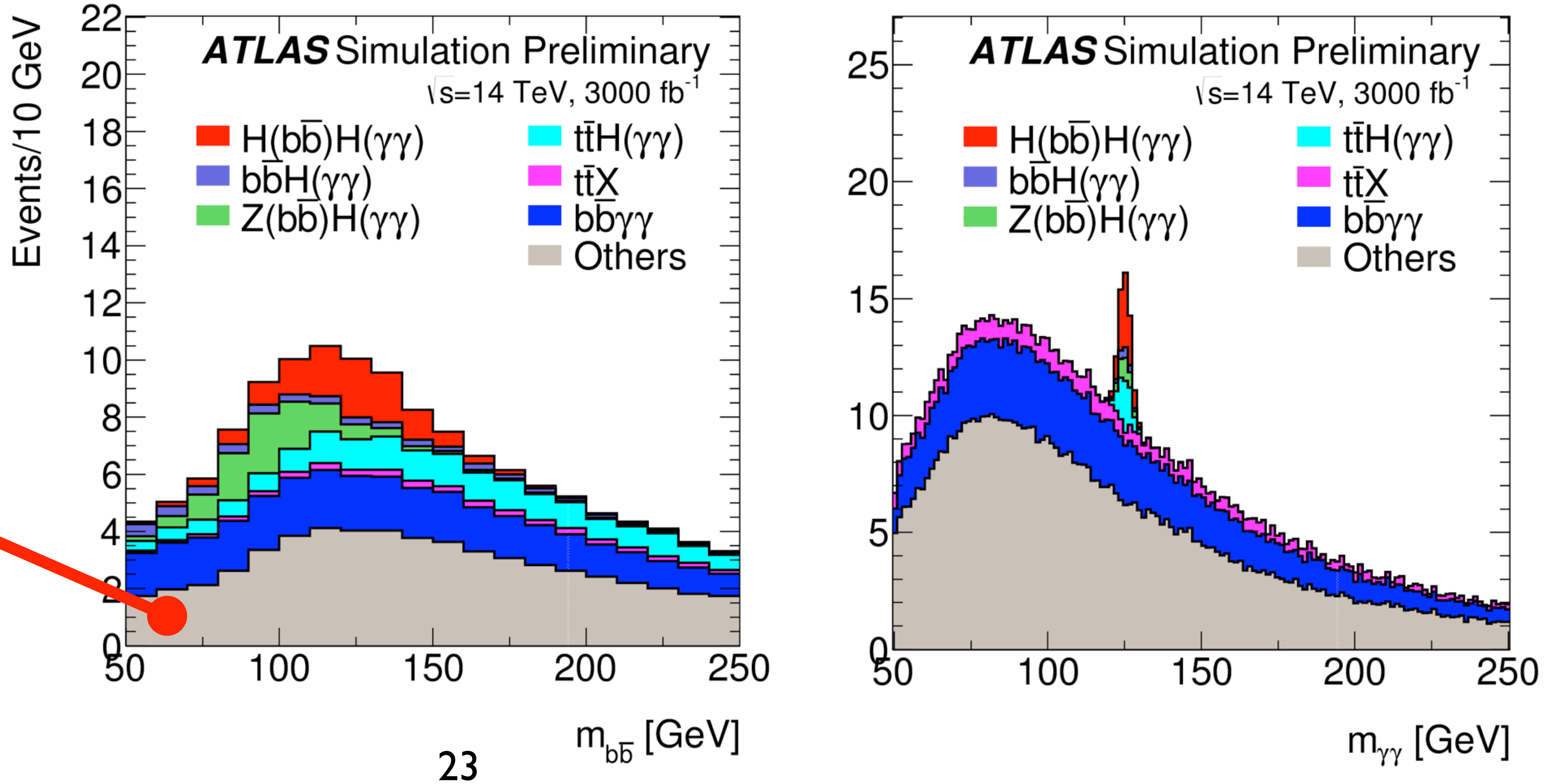


ATL-PHYS-PUB-2014-019



$[d\sigma/\sigma_{SM}]/[d\lambda/\lambda_{SM}] \approx -0.8$

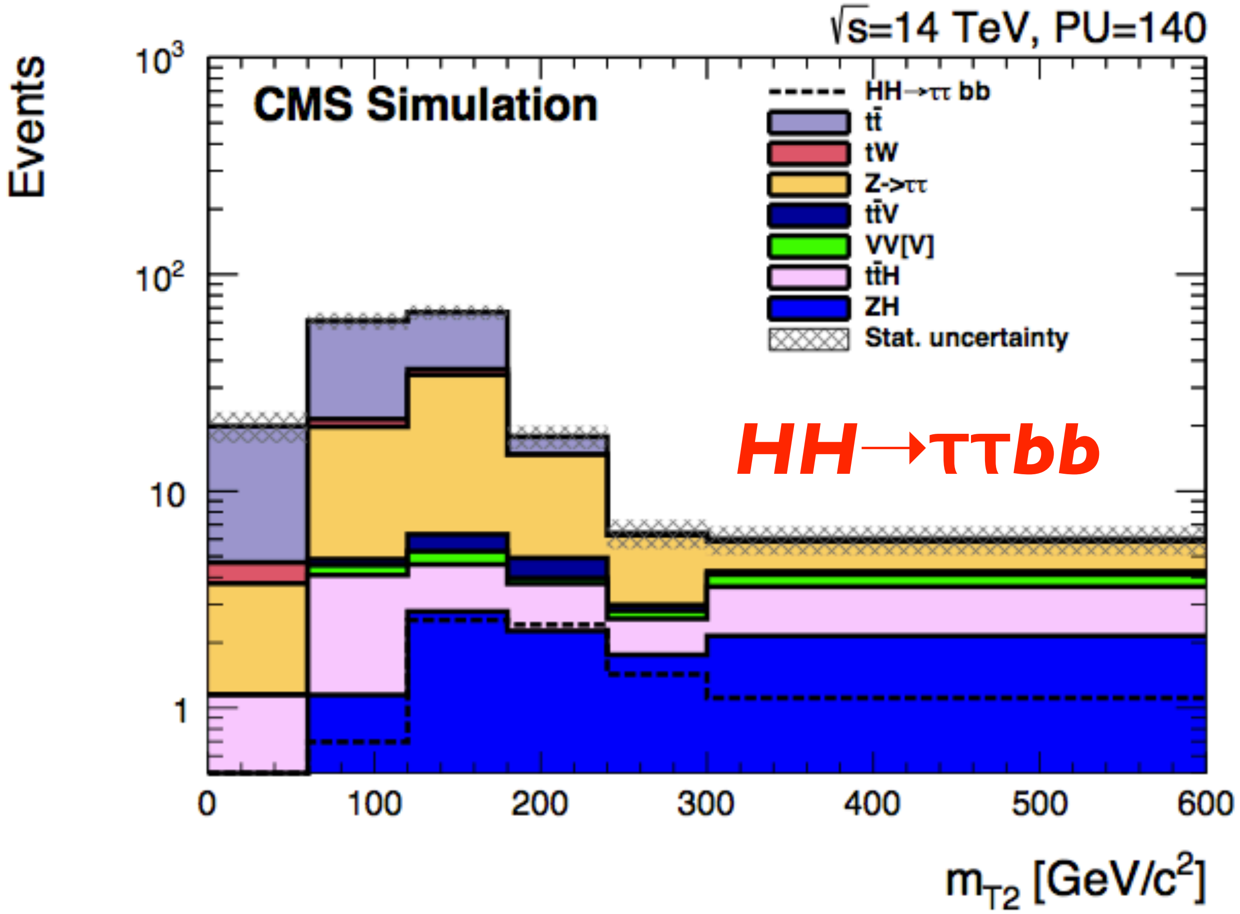
Signal extraction from 2D fit (m_{bb}, $m_{\gamma\gamma}$)



HH production

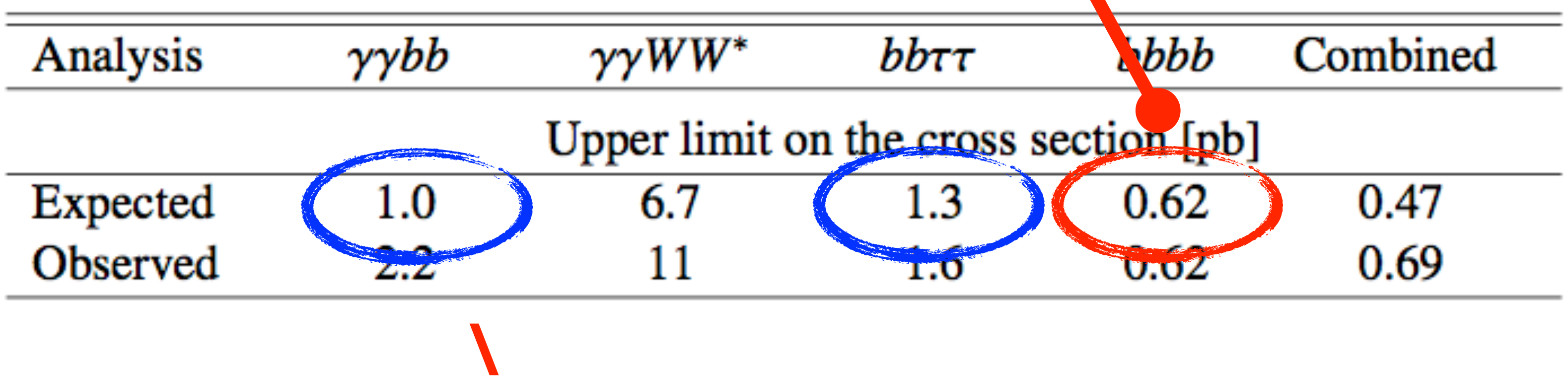
Channel	Sensitivity	δμ (≈1.3 δλ)
bbγγ	1.3σ	~80%
bbττ	0.9σ	~100%
bbWW	-	> 200%
bbγγ + bbττ	**1.9σ**	**54%**

CMS, CERN-LHCC-P-008



x2 improvements from HH→bbbb (but cuts enhance box)

ATLAS, arXiv:1509.0467



Analysis	$\gamma\gamma bb$	$\gamma\gamma WW^*$	$bb\tau\tau$	$bbbb$	Combined
			Upper limit on the cross section [pb]		
Expected	1.0	6.7	1.3	0.62	0.47
Observed	2.2	11	1.6	0.62	0.69

δλ ~50%
(per experiment)
possible @ HL-LHC

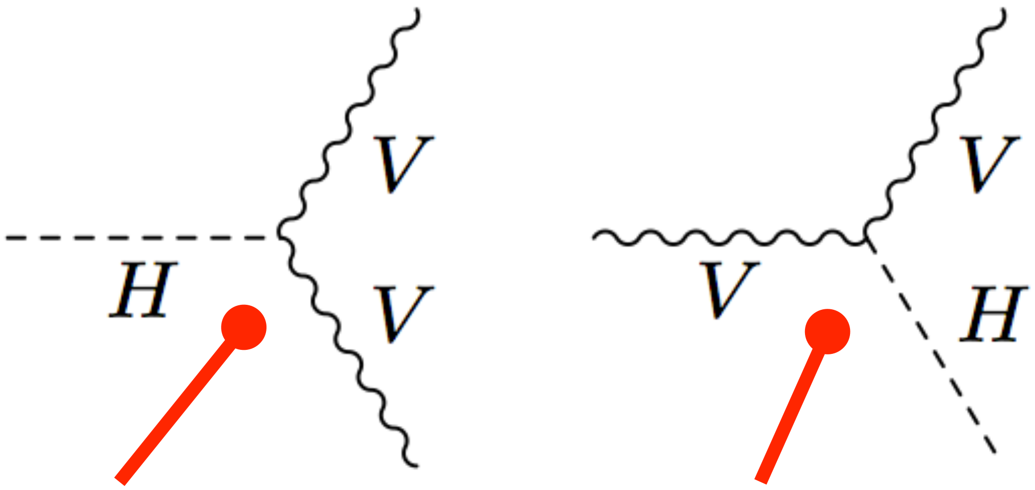
HVV tensor structure

Study of the HVV amplitude

- maximal usage of information
  - higher-dimensional operators can modify HVV
  - evidence of CP-violation from CP-odd amplitude

kinematically enhanced at high energies

$$A(X_{J=0} \to VV) = \frac{1}{v}\left(g_1 m_V^2 \epsilon_1^* \epsilon_2^* + g_2 f^{*(1)}_{\mu\nu} f^{*(2),\mu\nu} \boxed{+ g_4 f^{*(1)}_{\mu\nu} \tilde{f}^{*(2),\mu\nu}}\right)$$

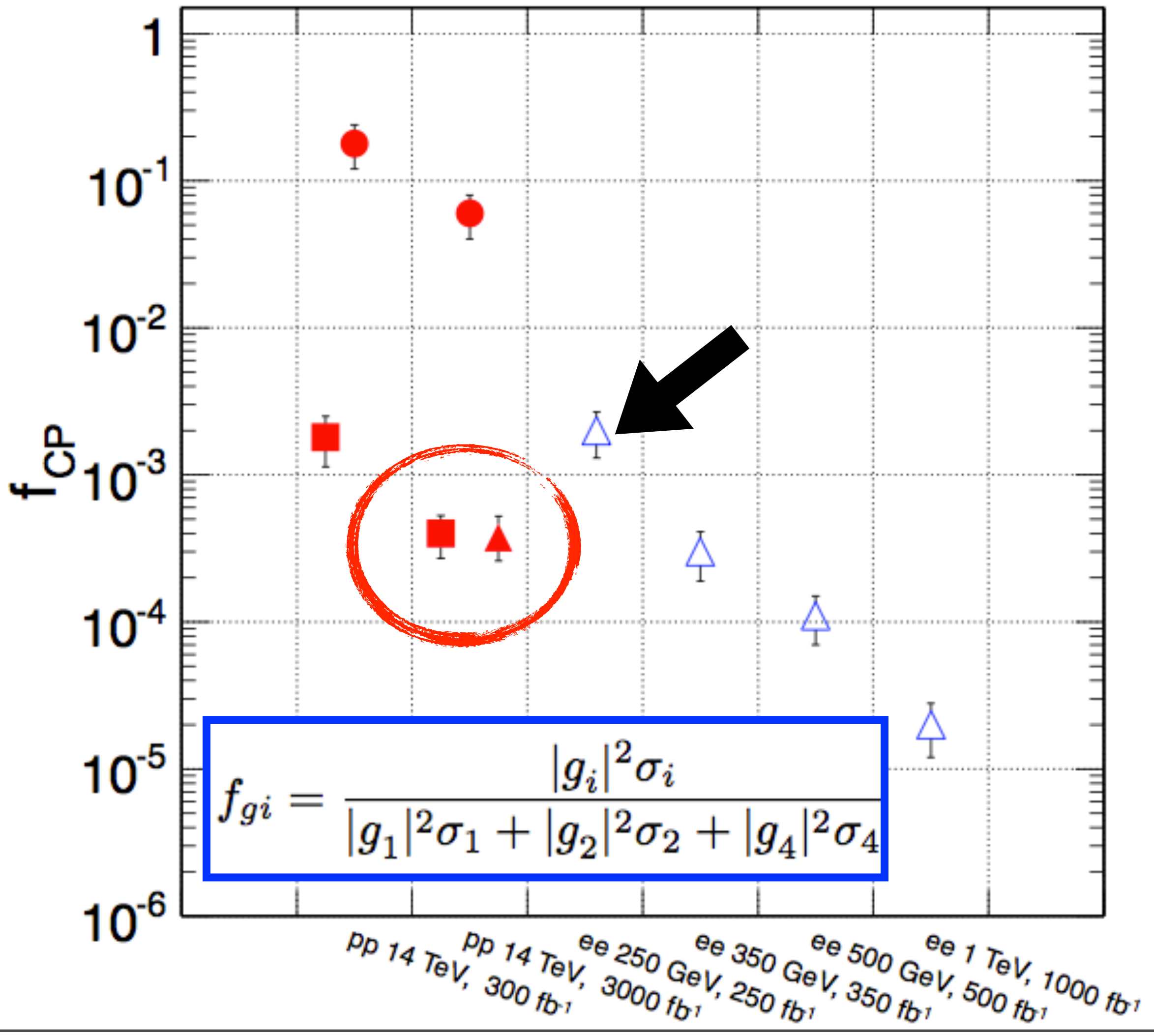


f_{CP} small in decay

f_{CP} enhanced for large M_{V*}

HL-LHC can probe large M_{V*}
FCC-ee limited by $\sqrt{s}$

Anderson et al., PRD 89 035007 (2014)



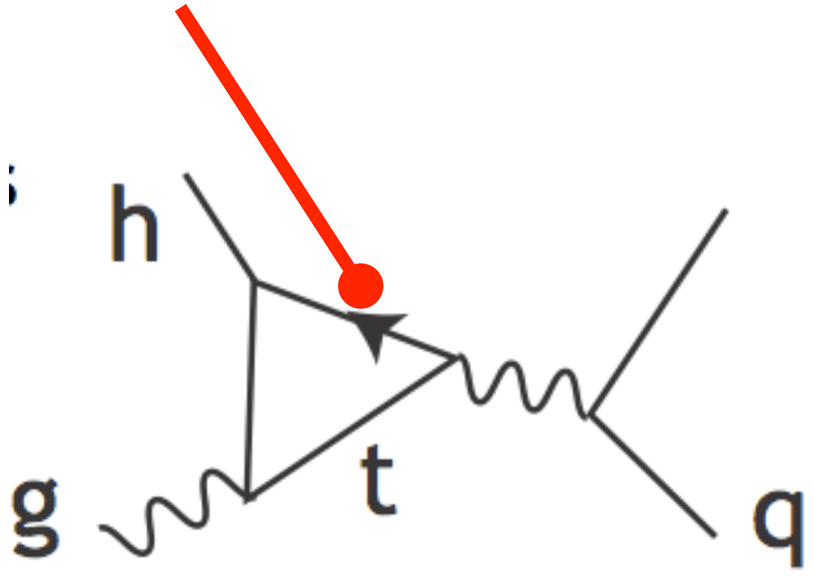
$$f_{gi} = \frac{|g_i|^2\sigma_i}{|g_1|^2\sigma_1 + |g_2|^2\sigma_2 + |g_4|^2\sigma_4}$$

Resolving the ggH vertex

Top-partners and anomalous y_t could compensate in $\Gamma(H\to gg)$

- disentangle top Yukawa and new T particles using high-p_T Higgs

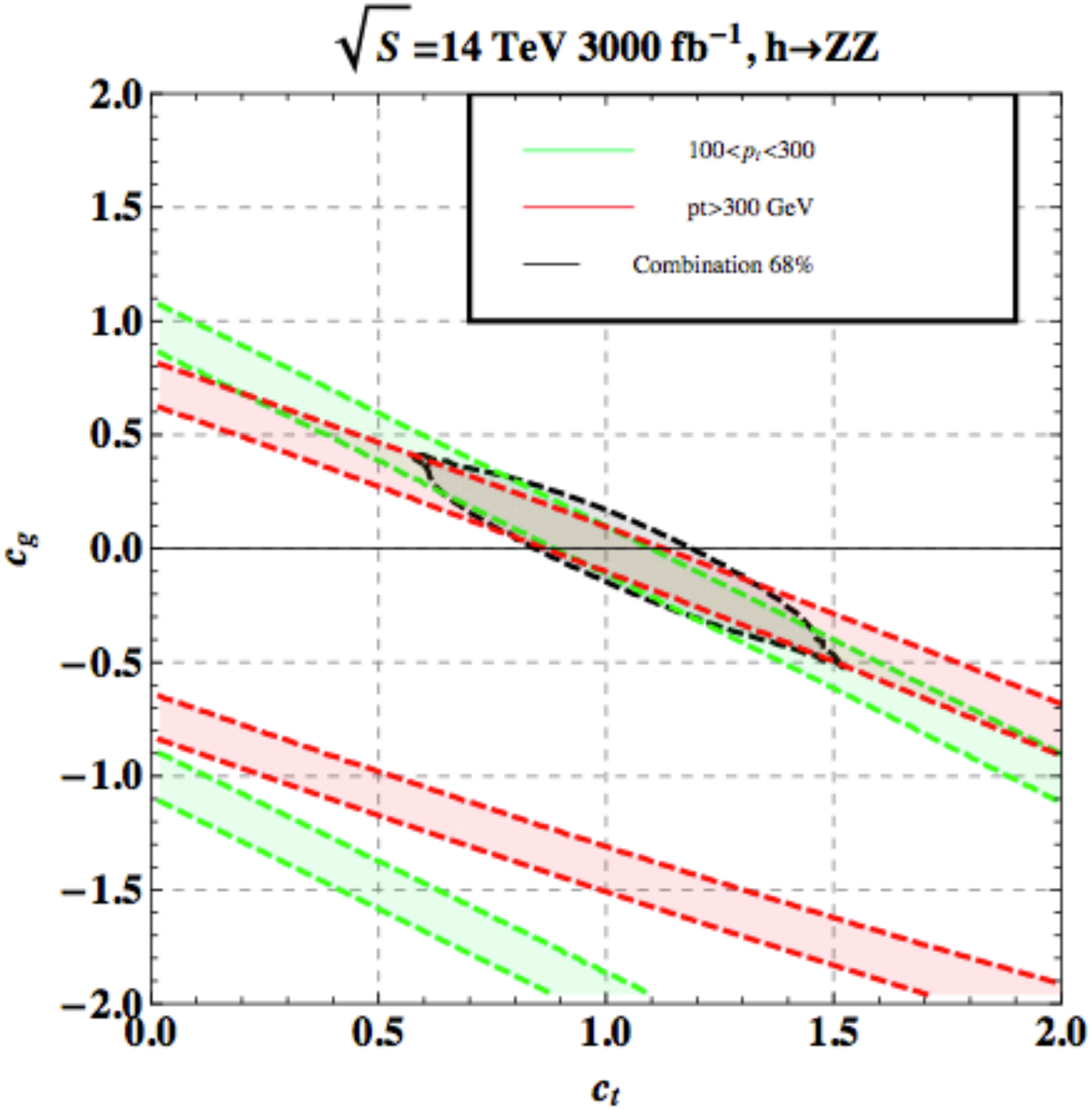
Top contribution suppressed at $p_T >> m_t \Rightarrow$ enhance T contribution



Peskin, HL-LHC Workshop May15

Can complement direct-κ_t (HL-LHC) and κ_{t+g} (FCC-ee)

Avatov et al., JHEP 01 (2014) 014



$G_{\mu\nu}G^{\mu\nu}$ modifier (T)

Top Yukawa modifier

Snowmass, arXiv:1310.8361

CP mixing

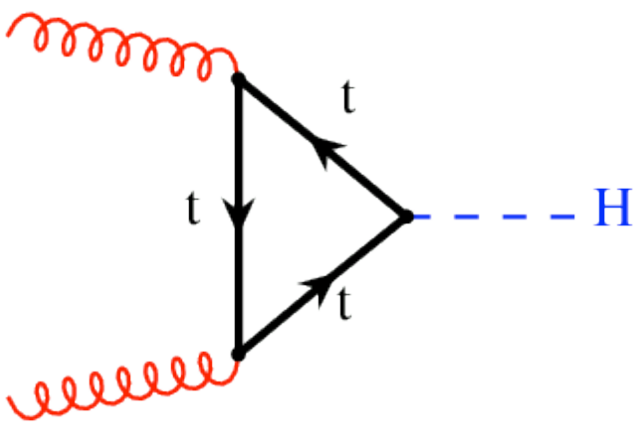
- CP-mixing better measurable in fermion decays
  - CP-odd component suppressed in H→VV
  - τ's are ideal polarimeters.
    [easier in cleaner e⁺e⁻ colliders]

$$\boxed{\cos\alpha\, y_f \bar{\psi}_f \psi_f h + \sin\alpha\, \widetilde{y}_f \bar{\psi}_f i\gamma_5 \psi_f h}$$

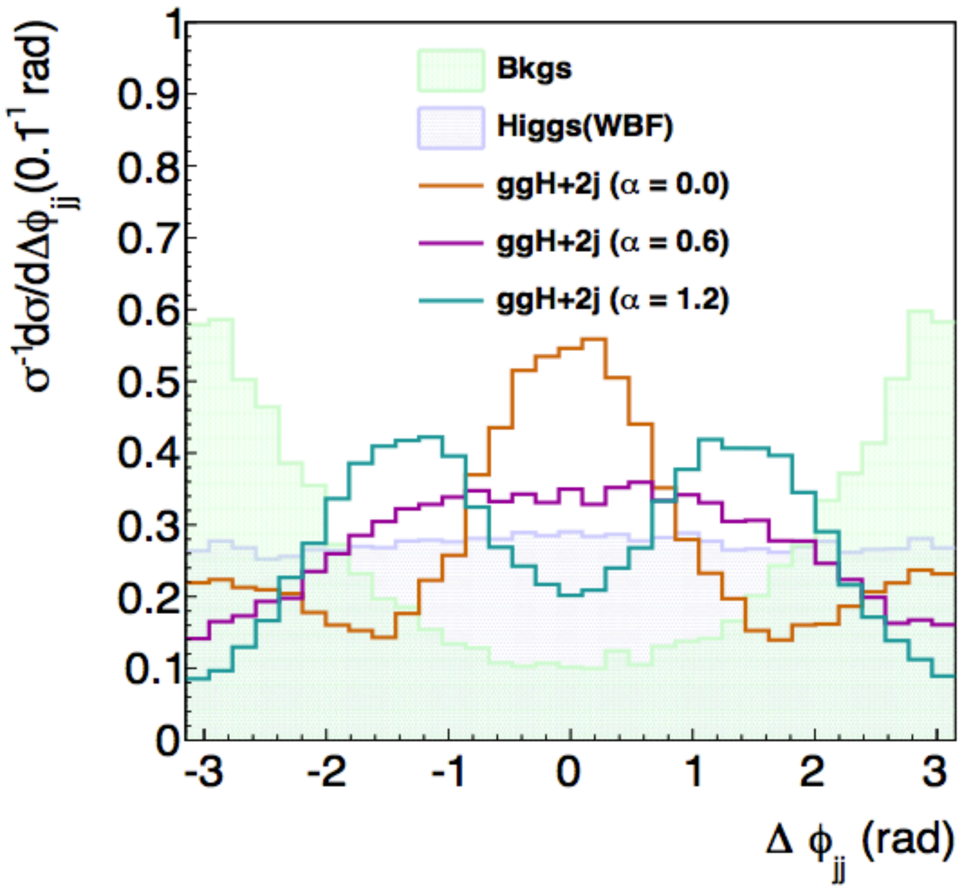
Collider	δα
ILC	***5°***
HL-LHC	***11°***

from ττ decays

- @LHC: use ggF+2j prodcution
  - CP-odd operator not suppressed in loop



Dolan et al., PRD 90 073008 (2014)

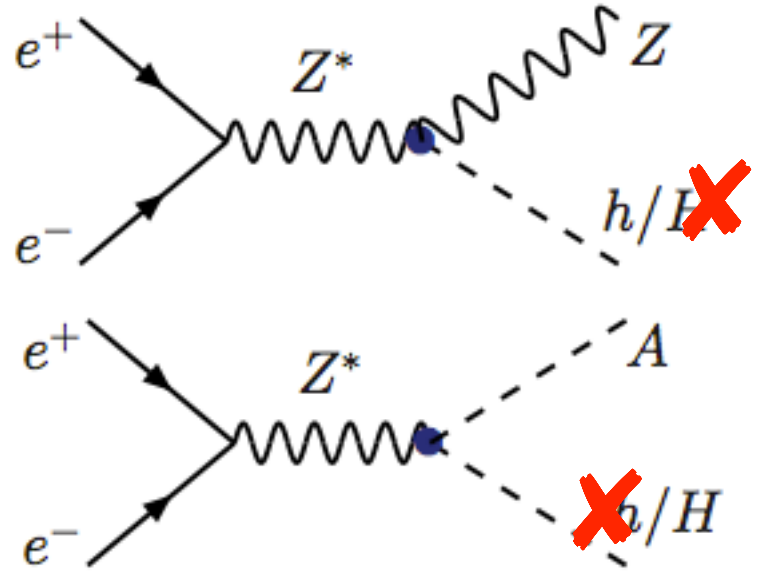


δα ~ 5÷10 deg could be achievable (no projections yet)

Extra Higgs bosons

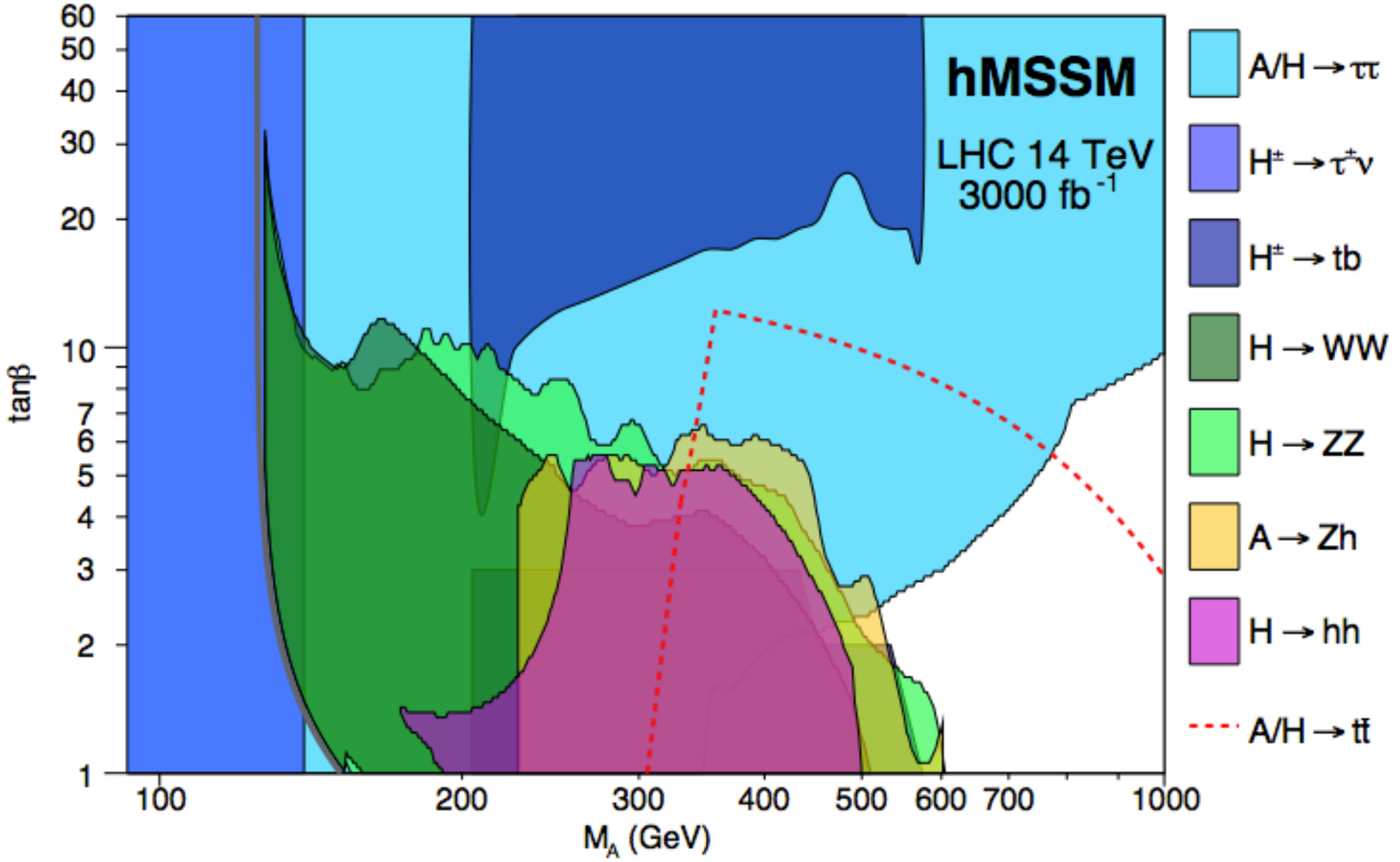
What if Higgs sector is not minimal (MSSM)?

- e^+e^- colliders limited in direct searches
- several channels open in pp collisions
  - interplay between channels



$\cos^2(\beta-\alpha) \rightarrow 0$

Djouadi et al., arXiv:1502.05653



Searches for H/A/H± decays

Decoupling regime ⇒

need for direct searches
FCC-ee limited by √s

Conclusions

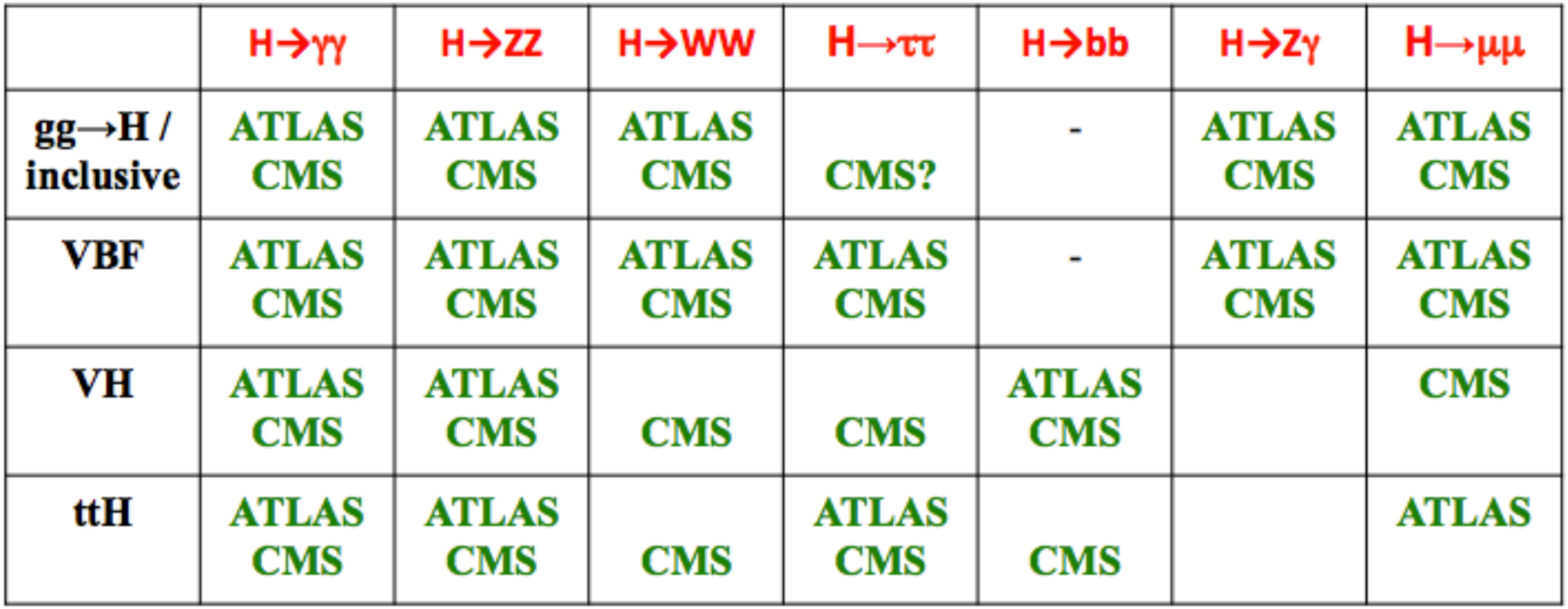
- HL-LHC will dramatically improve current Higgs measurements precision and open new channels
  - theoretical uncertainties (pQCD+PDF) will eventually saturate precision
  - superior performances a FCC-ee manifest in coupling extraction
    - most noteworth: model-independent measurement of Γ_H

- HL-LHC / FCC-ee are comparable for...
  - rare decays ($H \to \gamma\gamma$, $Z\gamma$, $\mu\mu$), HVV amplitude studies, CP-odd phase

- HL-LHC / FCC-ee are complementary for...
  - $2^{nd}/3^{rd}$ generation Yukawa
  - Higgs self-coupling
  - SM-suppressed processes (FCNC, LFV, semi-hadronic decays)
  - new Higgs particles

Thanks for your attention

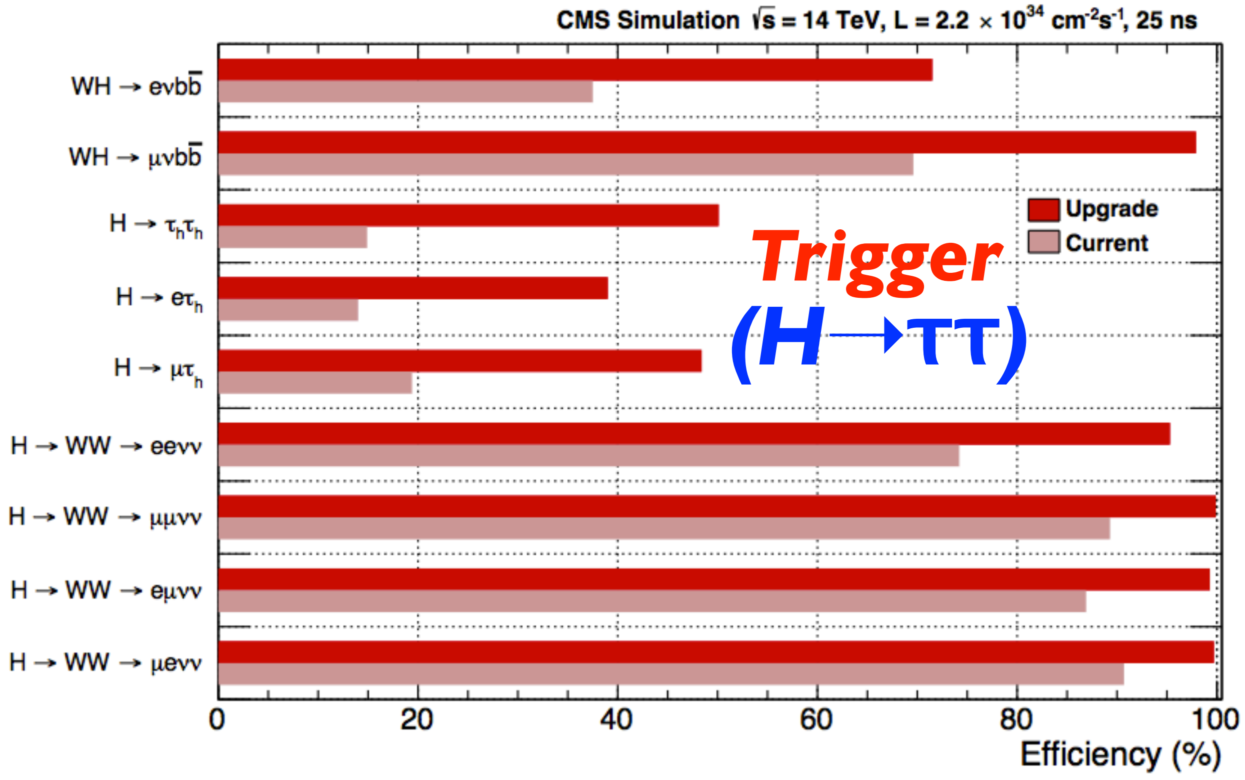
Framework for HL-LHC projections



	$H \to \gamma\gamma$	$H \to ZZ$	$H \to WW$	$H \to \tau\tau$	$H \to bb$	$H \to Z\gamma$	$H \to \mu\mu$
gg→H / inclusive	ATLAS CMS	ATLAS CMS	ATLAS CMS	CMS?	-	ATLAS CMS	ATLAS CMS
VBF	ATLAS CMS	ATLAS CMS	ATLAS CMS	ATLAS CMS	-	ATLAS CMS	ATLAS CMS
VH	ATLAS CMS	ATLAS CMS	CMS	CMS	ATLAS CMS		CMS
ttH	ATLAS CMS	ATLAS CMS	CMS	ATLAS CMS	CMS		ATLAS

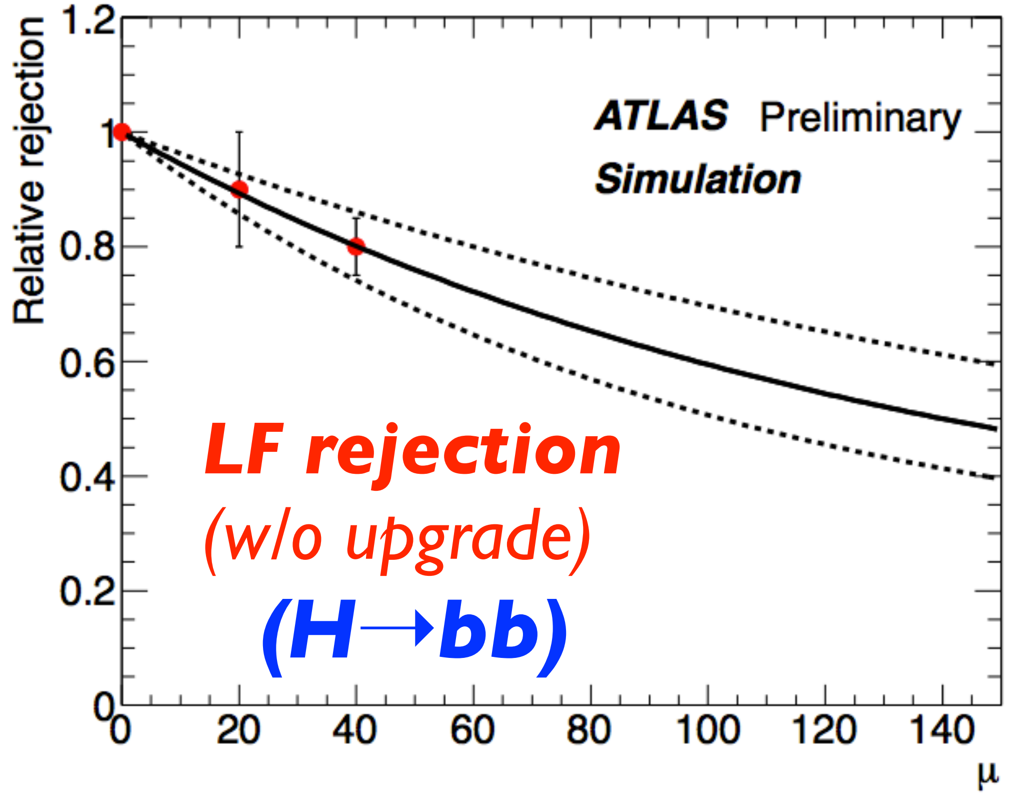
Experimental challenges

CMS-NOTE-13-002



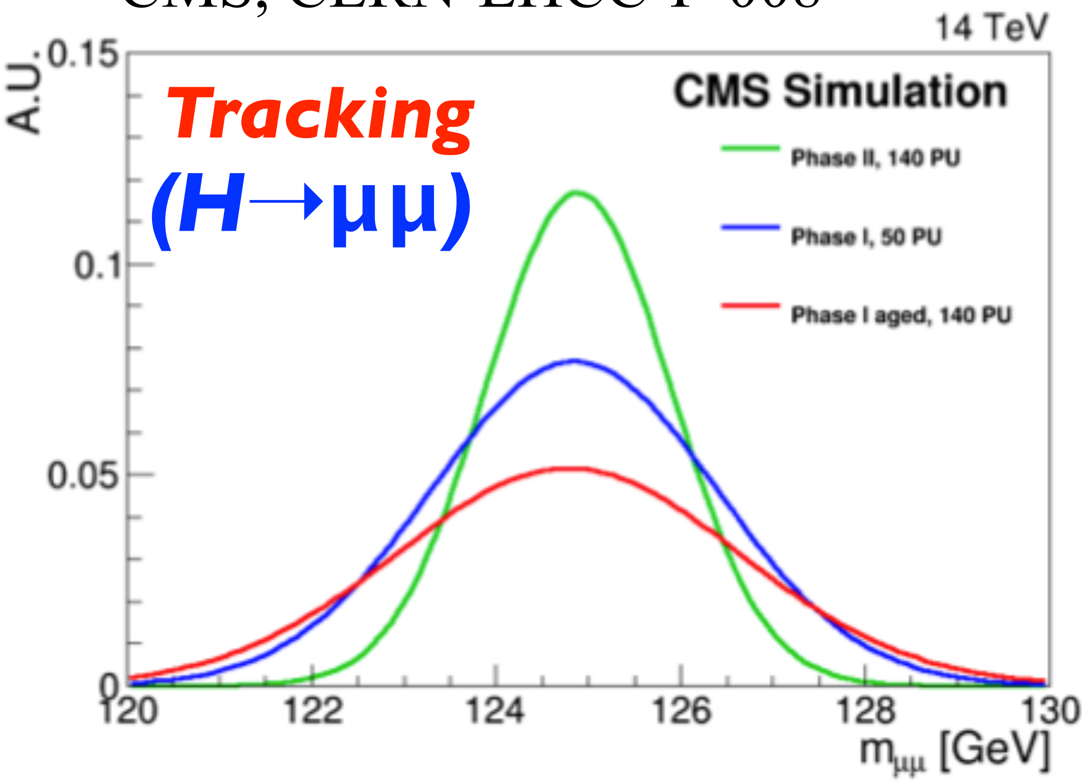
Trigger
(H→ττ)

ATL-PHYS-PUB-2013-004



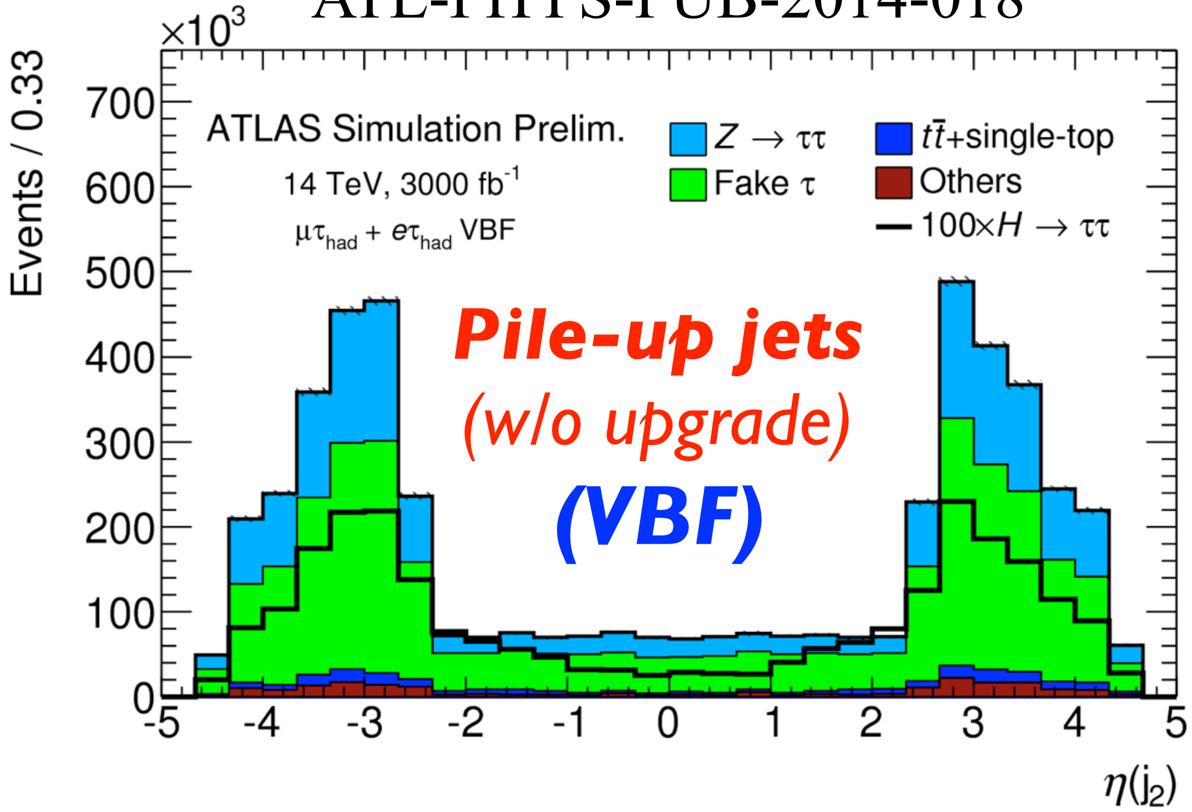
LF rejection
(w/o upgrade)
(H→bb)

CMS, CERN-LHCC-P-008



Tracking
(H→μμ)

ATL-PHYS-PUB-2014-018



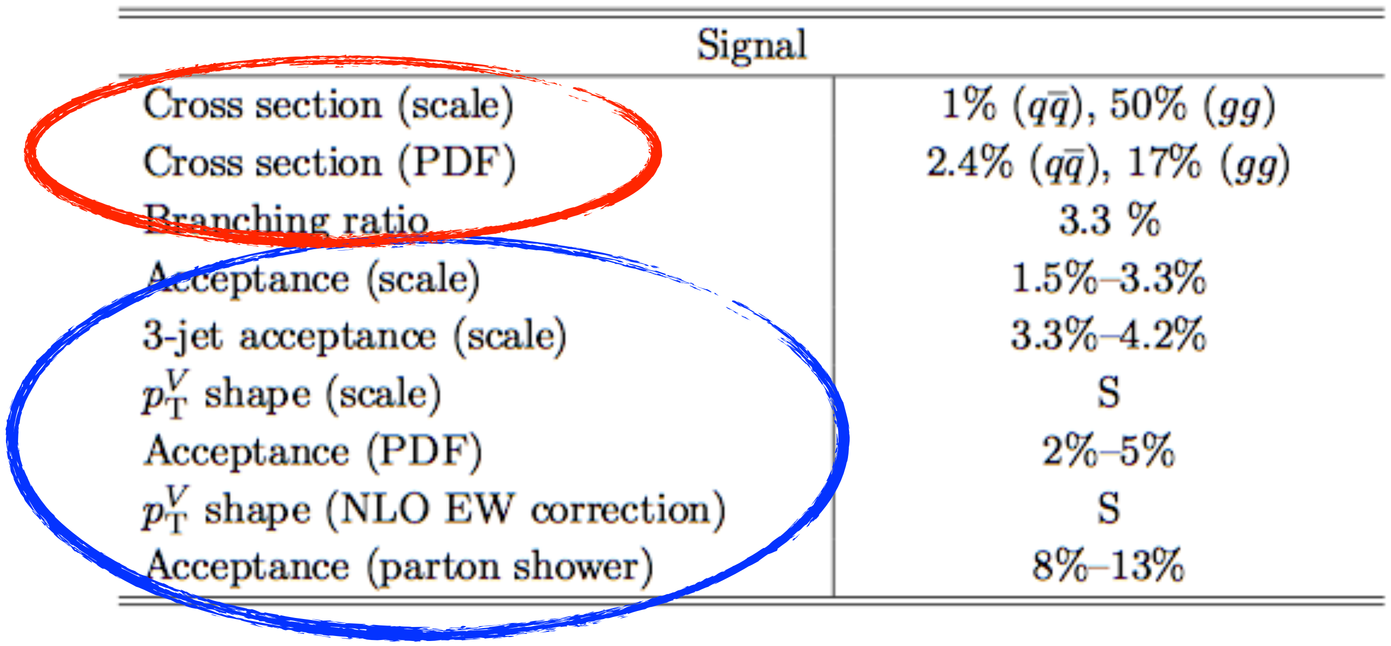
Pile-up jets
(w/o upgrade)
(VBF)

Theory uncertainty

ATLAS, JHEP 01 (2015) 069

QCD scale, PDF

Acceptance, Observables



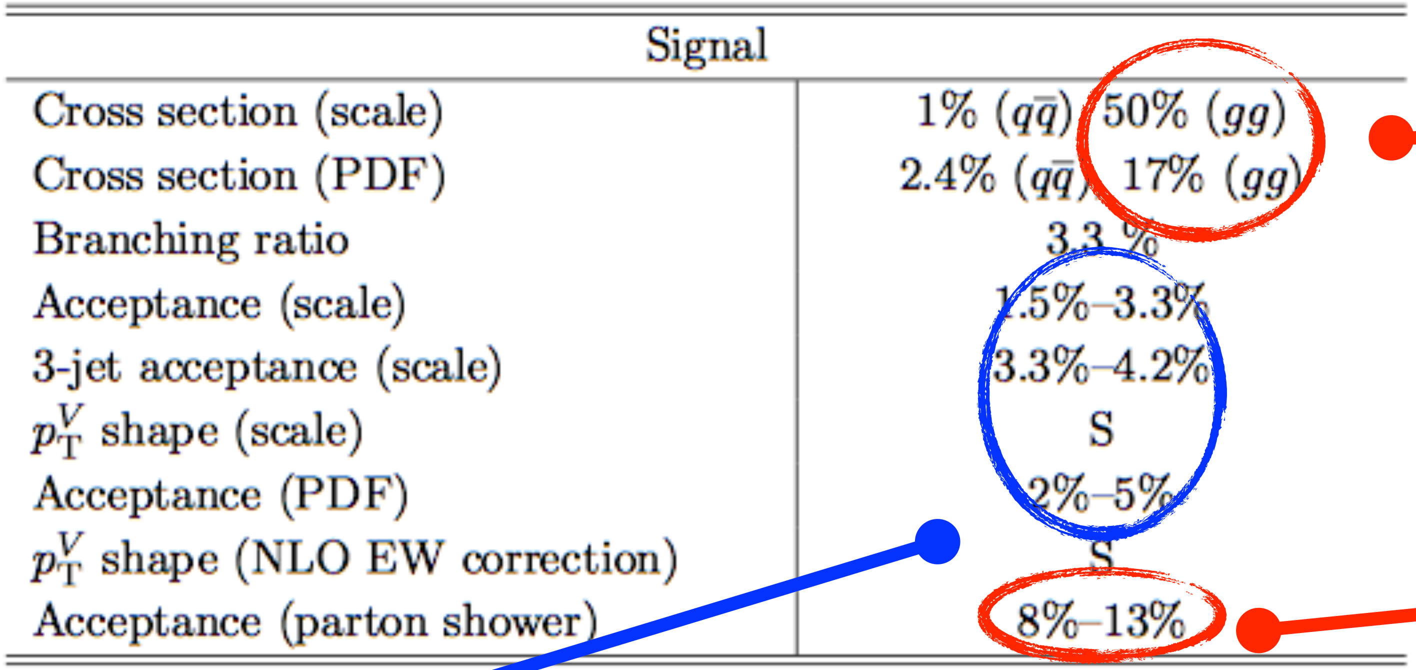
Signal	
Cross section (scale)	1% ($q\bar{q}$), 50% (gg)
Cross section (PDF)	2.4% ($q\bar{q}$), 17% (gg)
Branching ratio	3.3 %
Acceptance (scale)	1.5%–3.3%
3-jet acceptance (scale)	3.3%–4.2%
p_{T}^{V} shape (scale)	S
Acceptance (PDF)	2%–5%
p_{T}^{V} shape (NLO EW correction)	S
Acceptance (parton shower)	8%–13%

Theory uncertainties: VH

NLO MCs reweighted to best accuracy

- QCD @NNLO and EWK @NLO
- both qqVH and ggZH productions
- uncertainty on acceptance increased by analysis cuts (p_T^V, N_{jet})
  - further enhanced in most senitive BDT bins

ATLAS, JHEP 01 (2015) 069



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Acceptance (parton shower)	8%–13%

ggZH ~10%σ_{VH} @14 TeV

e.g. PYTHIA vs HERWIG

Can it be constrained by WZ/ZZ?

$\sigma_{stat}^{WZ/ZZ}$ ~ 2% at 3000 fb^{-1}

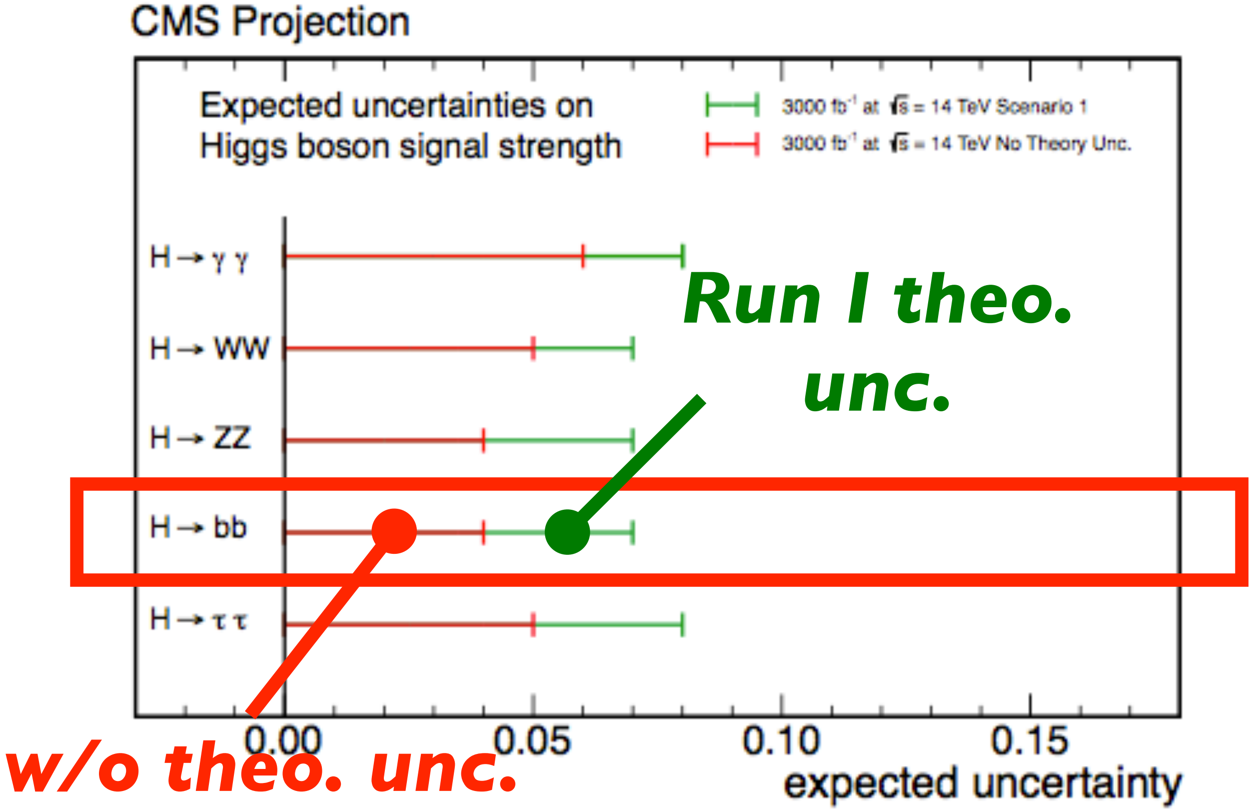
PDFs

Can be related to other
Drell-Yan measurements?

Projections: HL-LHC

Run I:	exp.	obs.
CMS	2.1σ	2.1σ
ATLAS	2.6σ	1.4σ

CMS, NOTE-13-02 (2013)



Run I theo. unc.

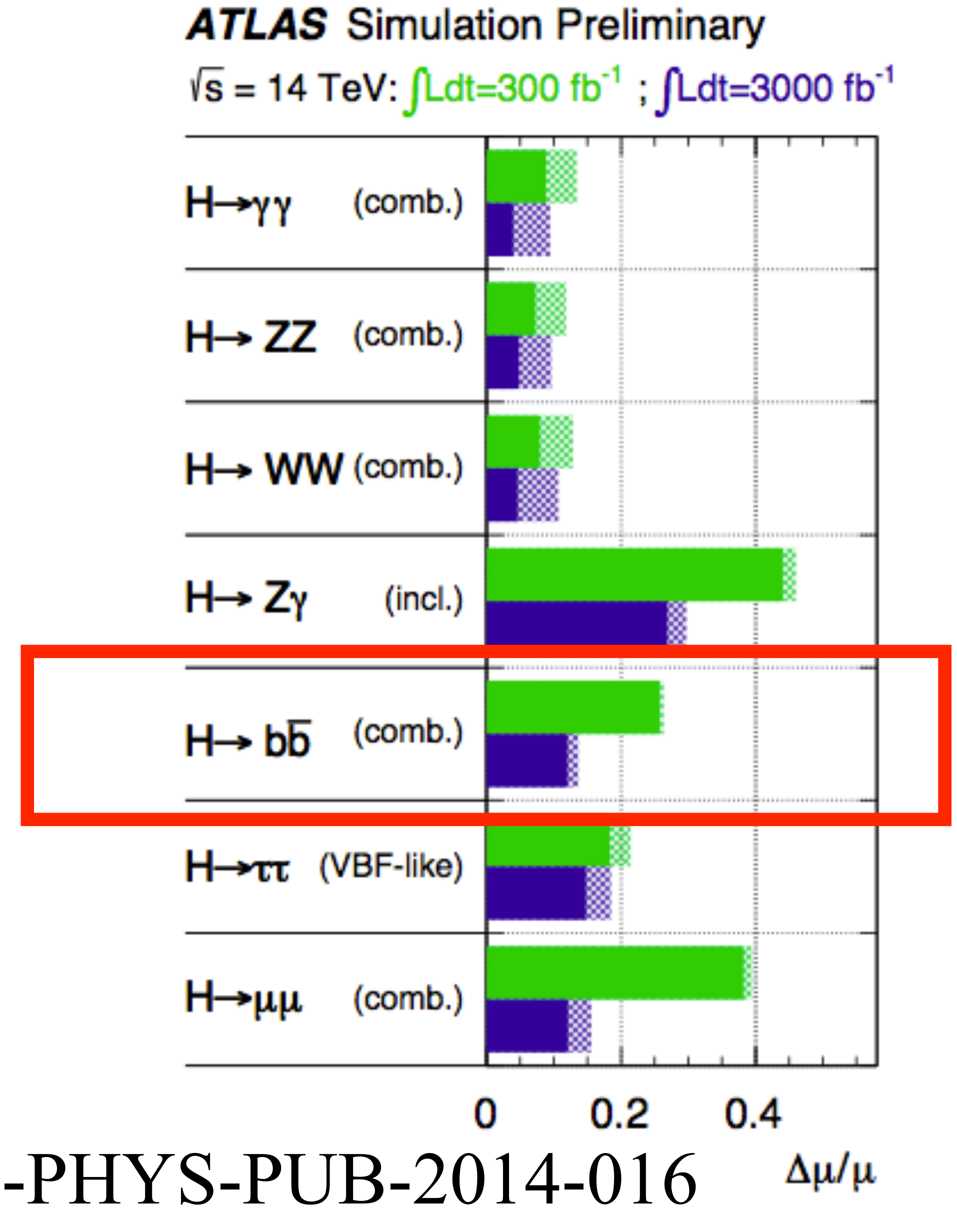
w/o theo. unc.

CMS projection:

- Δμ/μ: 7% → 4% w/o theo. unc.

ATLAS projection:

- at first sight, different conclusion, but:
  - not best analysis projected (x2 worse than RunI legacy)
  - no Z(νν) channel either
- largest uncertainties from:
  - signal acceptance (PDF, PS, scale)
  - ttbar and W+bb modeling



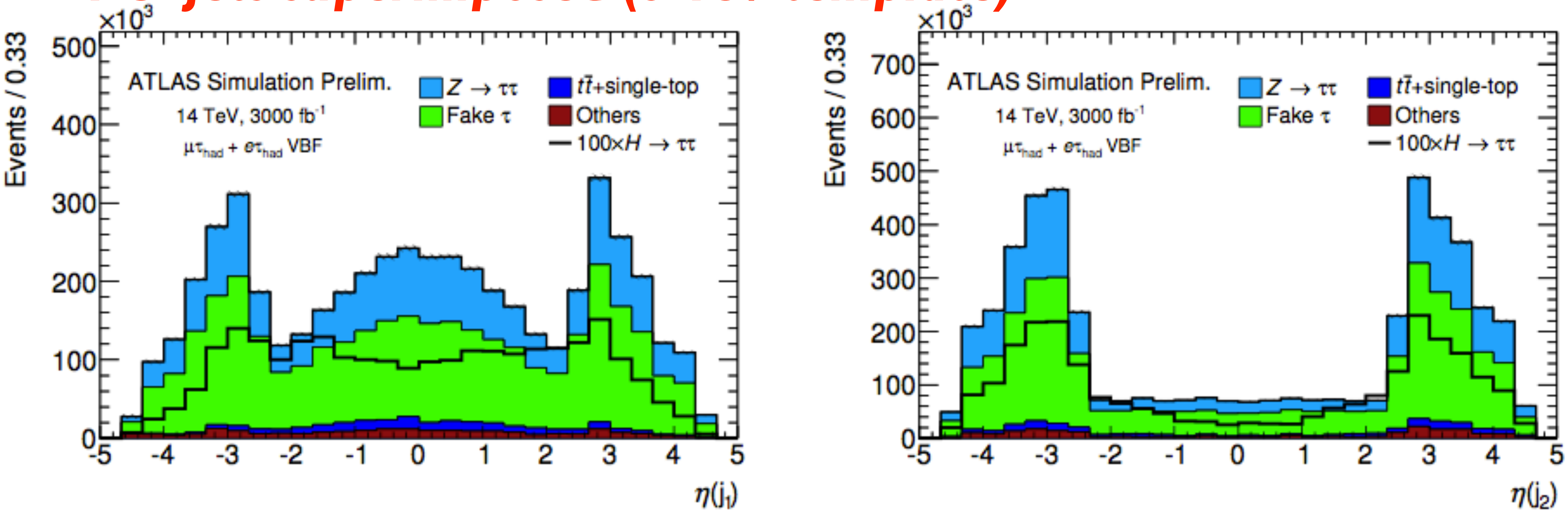
ATL-PHYS-PUB-2014-016

Experimental challenges: PU jets

VBF-like selection based on forward/backward di-jet pairs

- fake VBF signature from pile-up jets

PU-jets superimposed (8 TeV template)



	Leading jet	Trailing jet
% of events w/ a PU jet as...	42%	72%

Impact on Δμ from tracker extension:

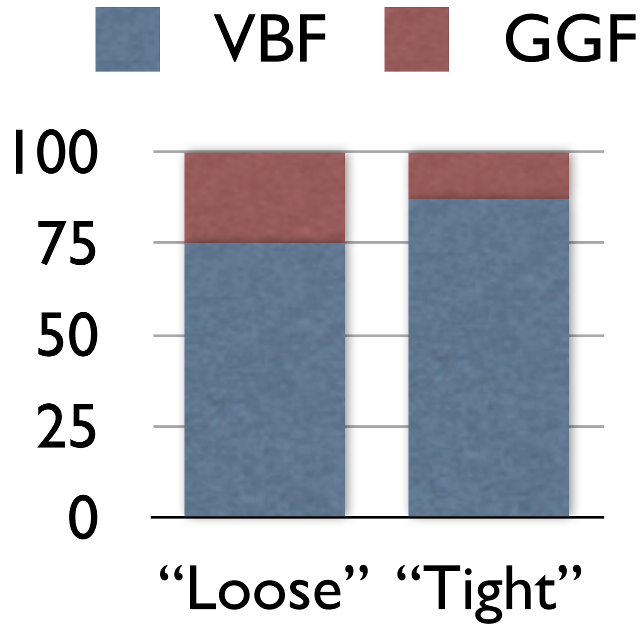
forward pile-up jet rejection	50%	75%	90%
forward tracker coverage		$\Delta\mu$	
Run-I tracking volume		0.24	
$\lvert\eta\rvert < 3.0$	0.18	0.15	0.14
$\lvert\eta\rvert < 3.5$	0.18	0.13	0.11
$\lvert\eta\rvert < 4.0$	0.16	0.12	0.08

ATL-PHYS-PUB-2014-018

Theory uncertainties

The VBF selection:

- cutting on $|\Delta\eta_{jj}|$ and/or m_{jj}
  - veto events w/ p_T^{j3} >30 GeV)
- ATLAS uses MVA
  - $\Delta\eta_{jj}$, m_{jj}, $\eta_{j1} \times \eta_{j2}$, ...



NLO MC	Scale	PDF	Parton shower (PYTHIA vs Herwig)	Generator modeling (powheg vs aMC@NLO)	TOT
VBF	•3% QCD •2% EWK	•3% (incl.) •1% (acc.)	up to 8%	2%	~6%
gg→H	23%	6%	up to 9%	4÷30%	~30÷ 40%

Increasing with $|\Delta\eta_{jj}|$ (high-x partons)

Sizable model-dependence

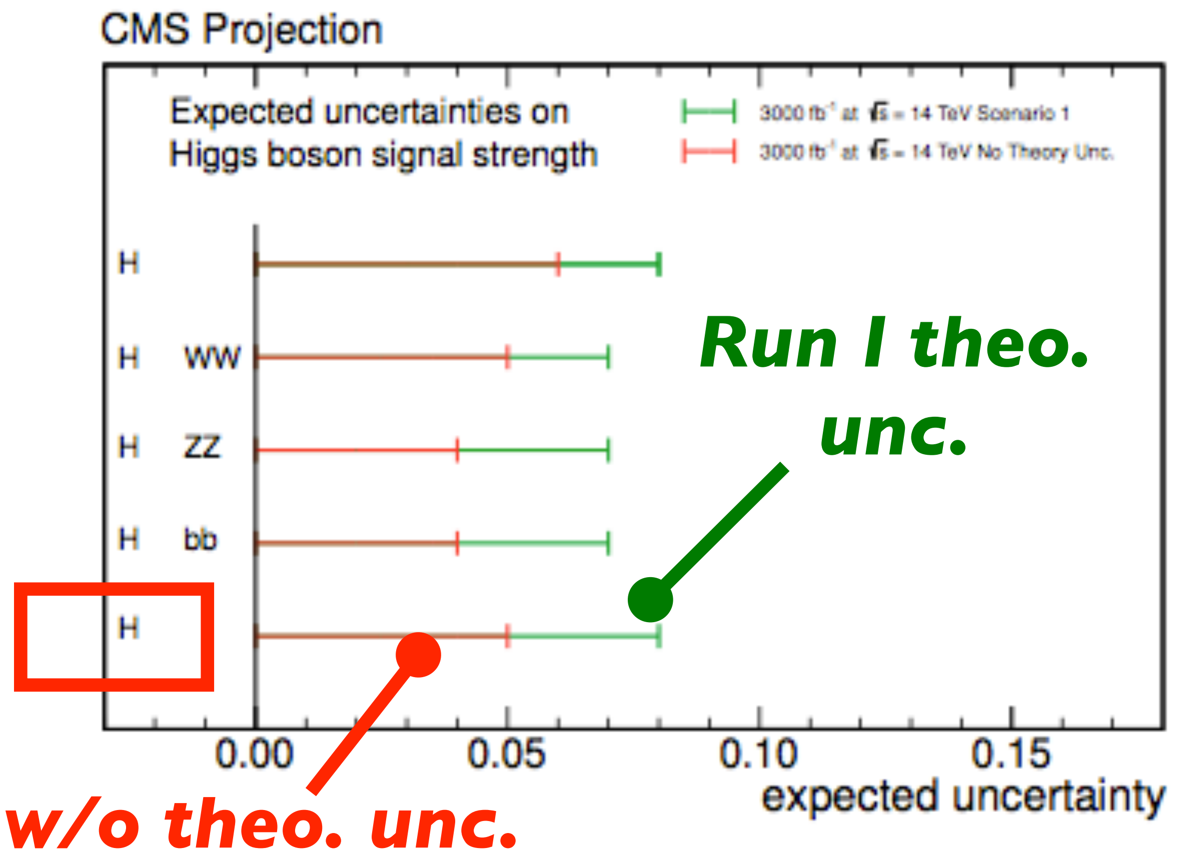
$\Delta\mu_{ggF} \sim \Delta\mu_{VBF}$

Tighter VBF cuts will help.

Can model dependence be reduced?

Projections: $H\to\tau\tau$

Run I:	exp.	obs.
CMS	3.7σ	3.2σ
ATLAS	3.4σ	4.5σ



Run I theo. unc.

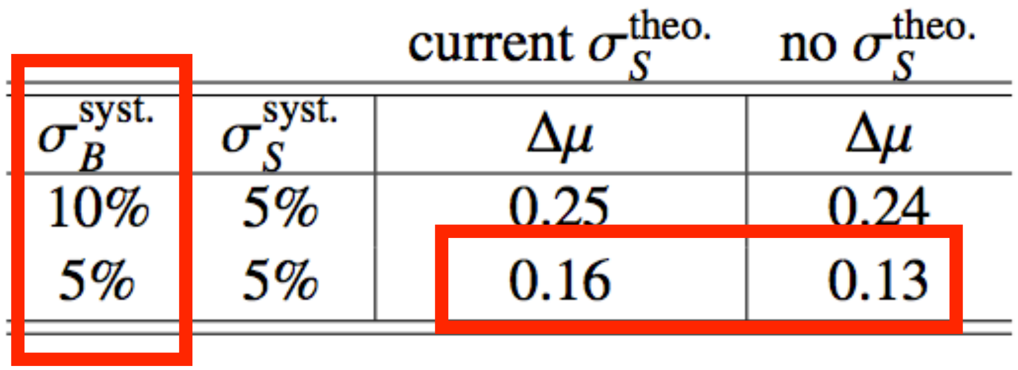
w/o theo. unc.

- CMS projections:
  - assume same cuts and efficiency
  - same di-tau mass resolution

$(\Delta\mu/\mu)_{\text{stat. + syst.}} \sim 5\%$

$(\Delta\mu/\mu)_{\text{theor.}} \sim 6\%$

- ATLAS projections:
  - consider only VBF $H\to\tau_h\tau_l$
    - ~2 worse than full result
    - PU jets from 8 TeV template
  - theor. unc. relevant ***if*** substantial PU mitigation is possible
    - otherwise limited by systematic



		current $\sigma_S^{\text{theo.}}$	no $\sigma_S^{\text{theo.}}$
$\sigma_B^{\text{syst.}}$	$\sigma_S^{\text{syst.}}$	$\Delta\mu$	$\Delta\mu$
10%	5%	0.25	0.24
5%	5%	0.16	0.13

The HL-LHC

Can reach O(5%) precision on most of the Higgs couplings

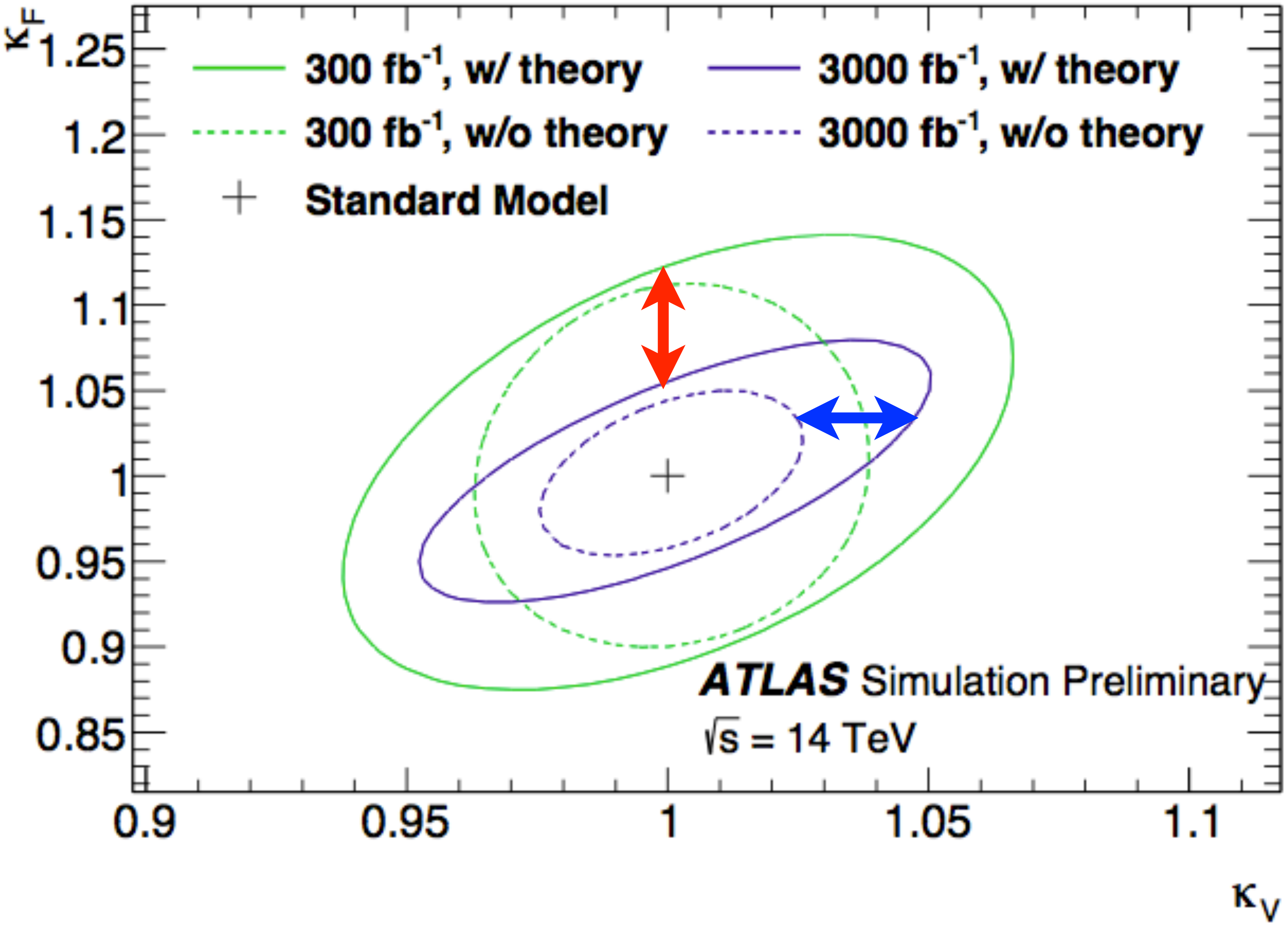
- necessary (but not sufficient) condition: maintain *detector performances*
- *luminosity* increase and reduction of *theory systematics* complementary

ATLAS-PHYS-PUB-2014-016

coupling to fermions

⇒

luminosity



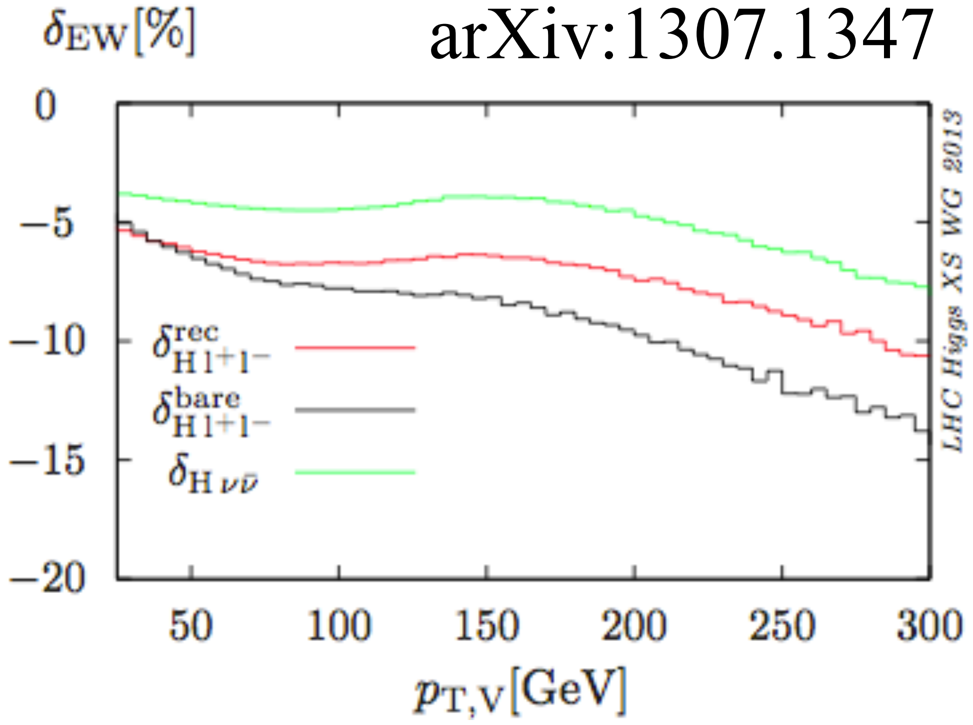
coupling to vectors

⇒

theory

Theory uncertainties: VH

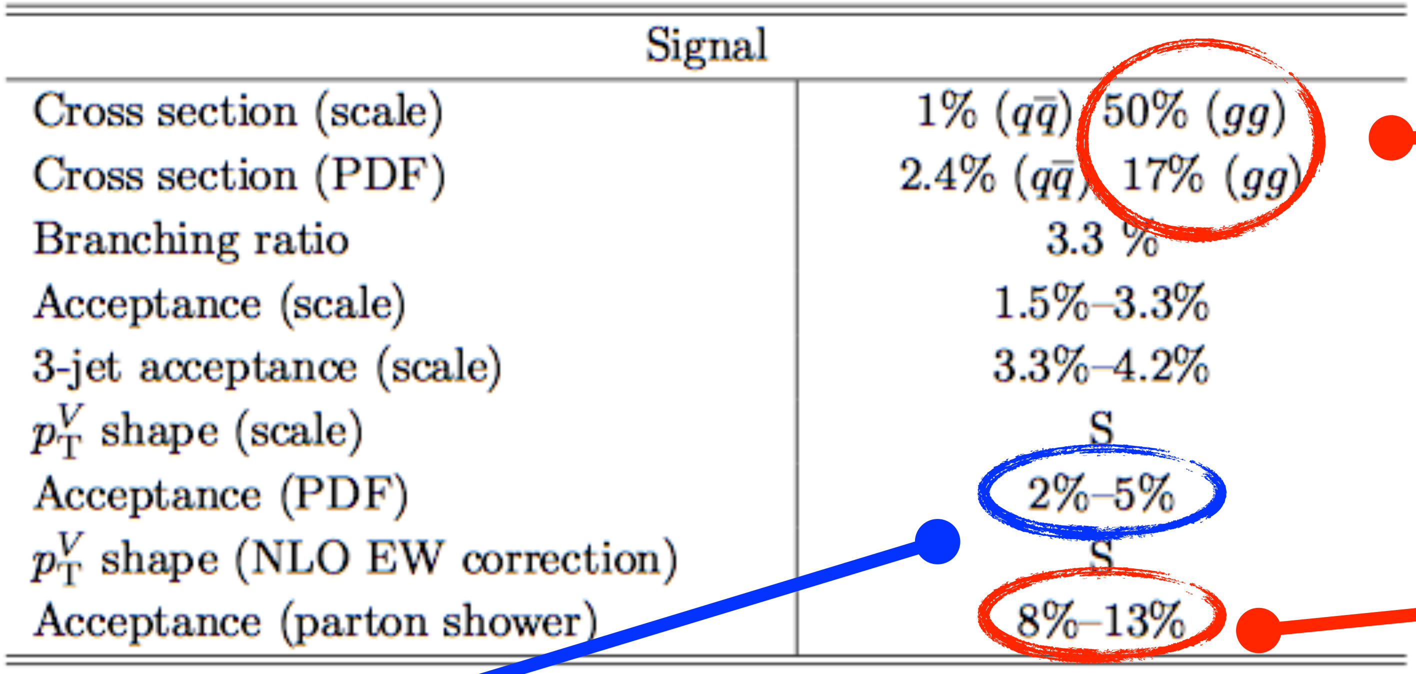
LHCXSWG,
arXiv:1307.1347



NLO MCs reweighted to best accuracy:

QCD	qqVH	NNLO	fully differential
	ggZH	NLO	inifinite-top mass
EWK	NLO		factorised

ATLAS, JHEP 01 (2015) 069



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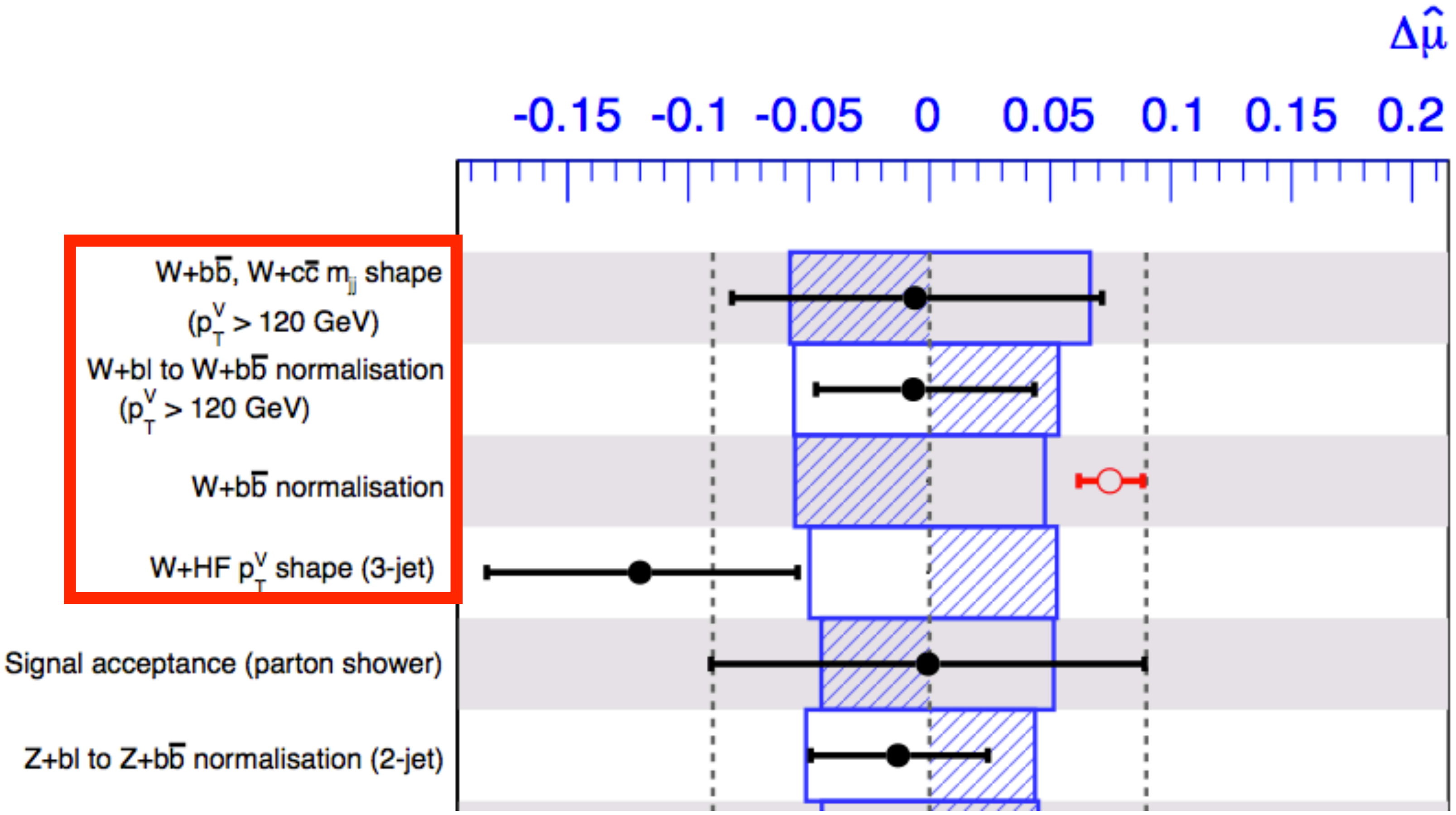
Can it be constrained by WZ/ZZ?

$\sigma_{stat}^{WZ/ZZ}$ ~ 2% at 3000 fb^{-1}

PDFs

Can be related to other
Drell-Yan measurements?

Run I systematics



ATLAS, JHEP 01 (2015) 069

Source	Type	Event yield uncertainty range (%)	Individual contribution to μ uncertainty (%)	Effect of removal on μ uncertainty (%)
b-tagging	shape	3–15	10.2	2.1
Signal cross section (scale and PDF)	norm.	4	3.9	0.3
Signal cross section (p_T boost, EW/QCD)	norm.	2/5	3.9	0.3
Monte Carlo statistics	shape	1–5	13.3	3.6
Backgrounds (data estimate)	norm.	10	15.9	5.2
Single-top-quark (simulation estimate)	norm.	15	5.0	0.5
Dibosons (simulation estimate)	norm.	15	5.0	0.5
MC modeling (V+jets and $t\bar{t}$)	shape	10	7.4	1.1

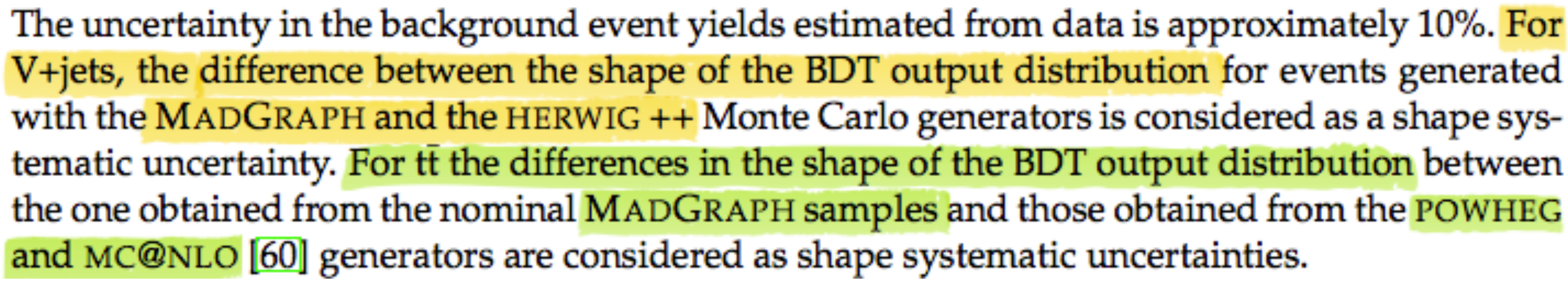
CMS, PRD 89 012003 (2014)

Background shape uncertainties

CMS:

- take envelope between BDT outputs from independent MCs

“



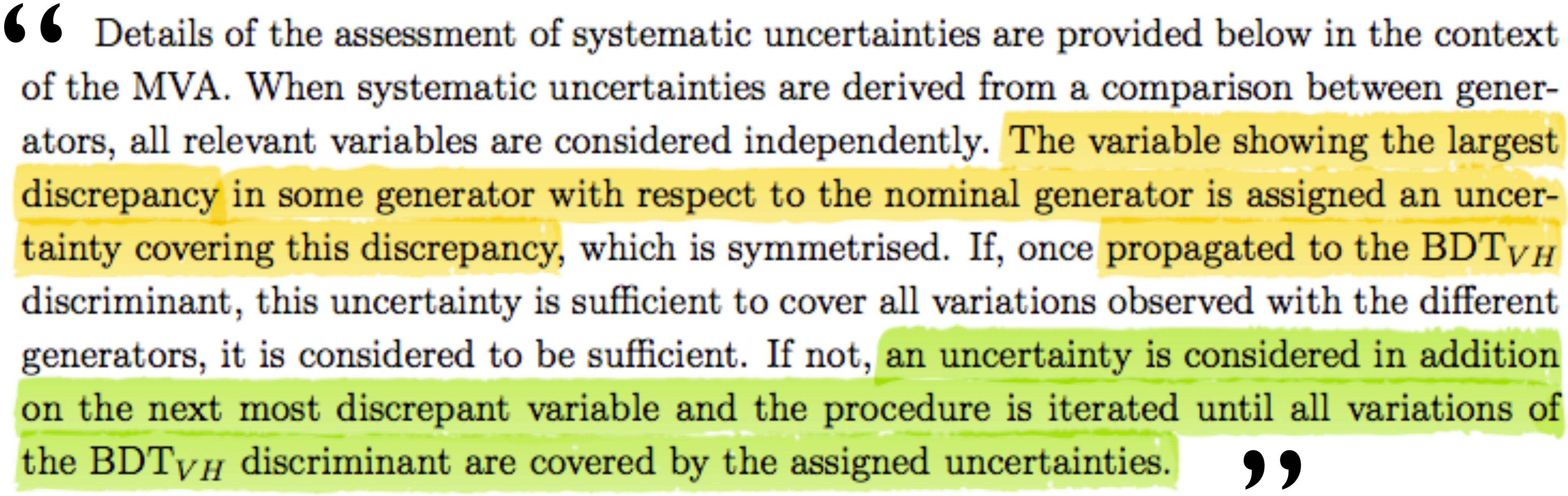
The uncertainty in the background event yields estimated from data is approximately 10%. For V+jets, the difference between the shape of the BDT output distribution for events generated with the MadGraph and the HERWIG ++ Monte Carlo generators is considered as a shape systematic uncertainty. For $t\bar{t}$ the differences in the shape of the BDT output distribution between the one obtained from the nominal MadGraph samples and those obtained from the POWHEG and MC@NLO [60] generators are considered as shape systematic uncertainties.

”

ATLAS:

- assess uncertainty on modeling of BDT input variables
  - m_{bb}, p_T^V, N_{jet}

“



Details of the assessment of systematic uncertainties are provided below in the context of the MVA. When systematic uncertainties are derived from a comparison between generators, all relevant variables are considered independently. The variable showing the largest discrepancy in some generator with respect to the nominal generator is assigned an uncertainty covering this discrepancy, which is symmetrised. If, once propagated to the BDT_{VH} discriminant, this uncertainty is sufficient to cover all variations observed with the different generators, it is considered to be sufficient. If not, an uncertainty is considered in addition on the next most discrepant variable and the procedure is iterated until all variations of the BDT_{VH} discriminant are covered by the assigned uncertainties.

”

PU jets suppression

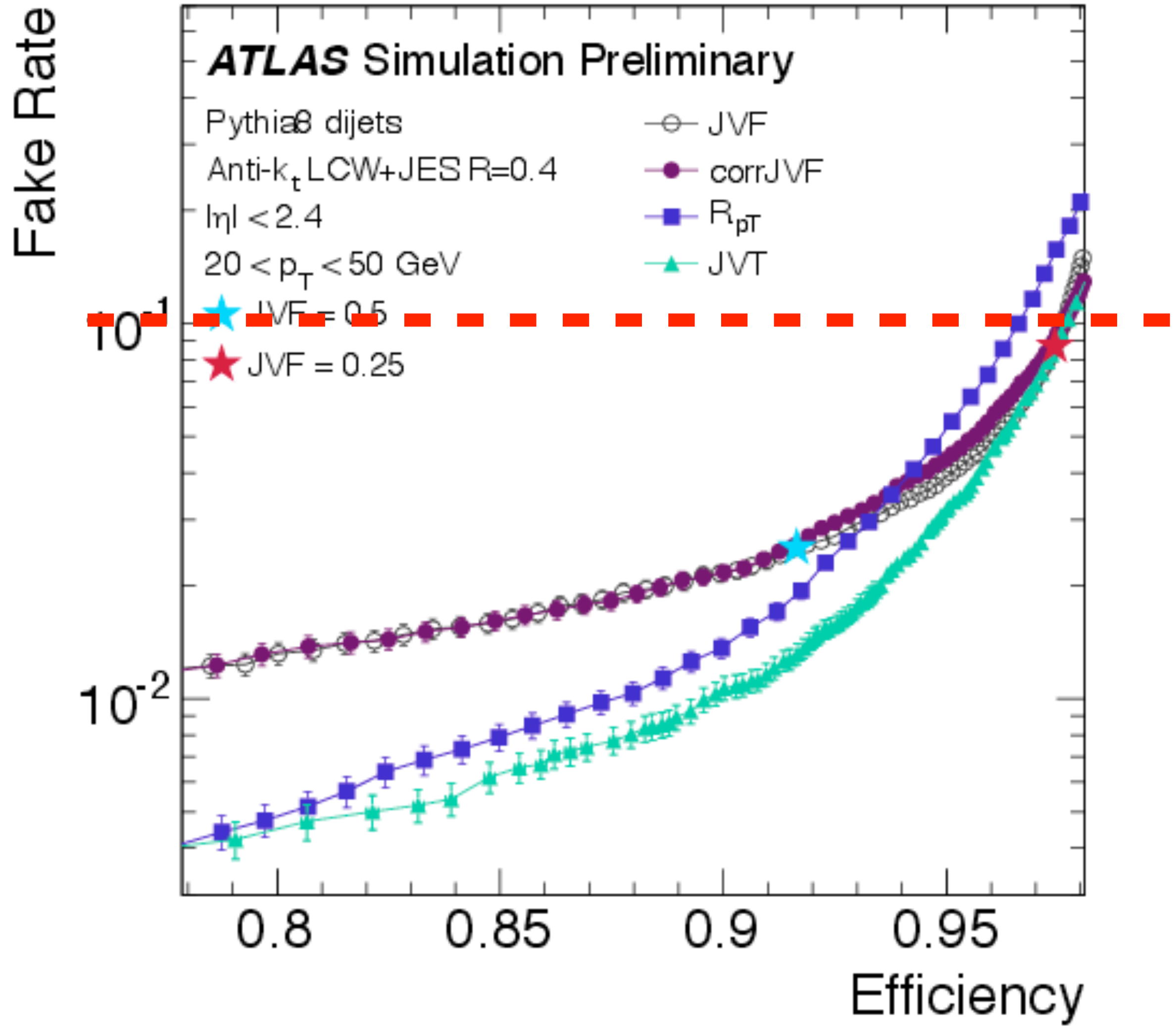
Already studied and deployed in Run I

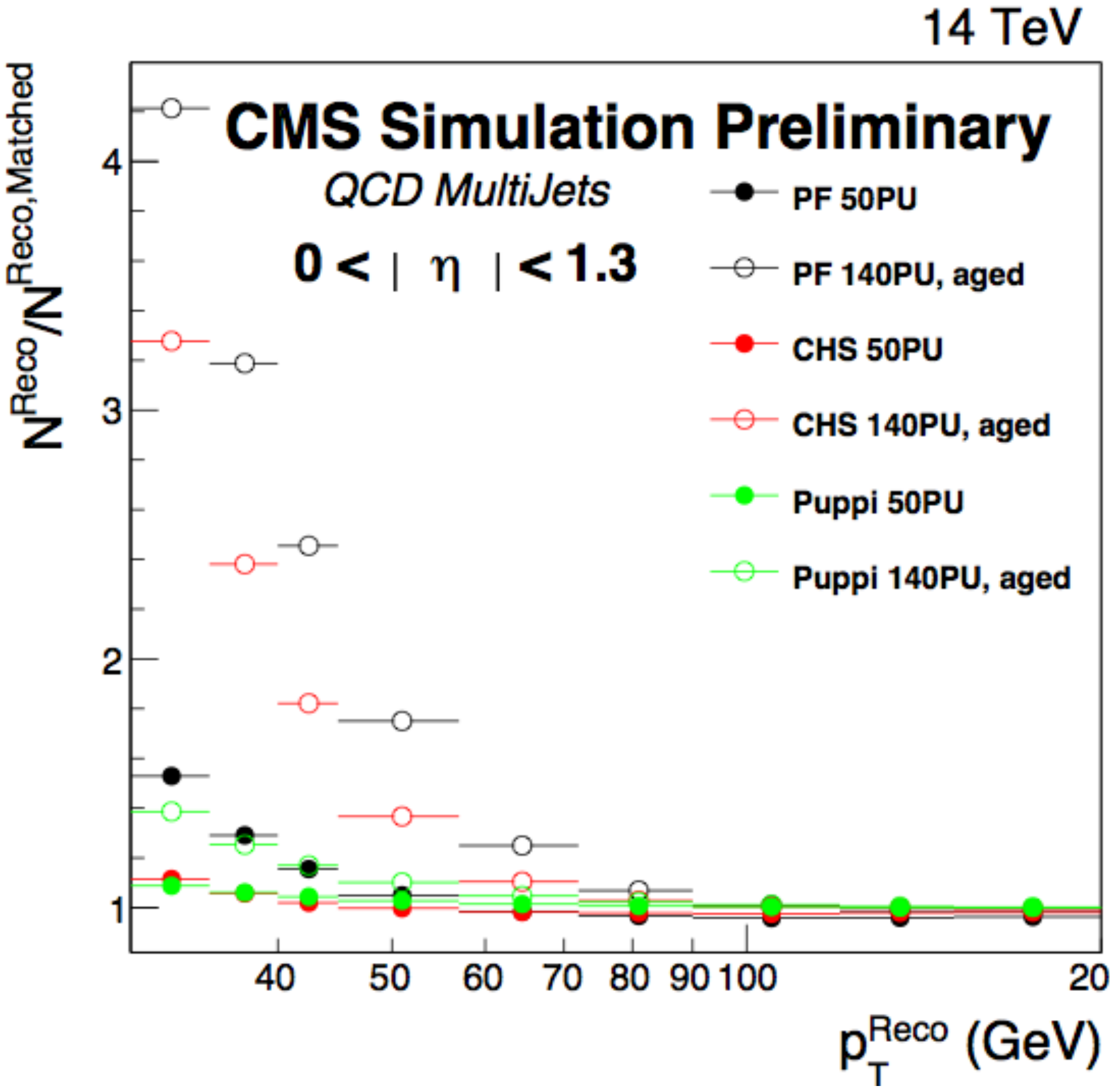
- PU-jet rejection mandatory to preserve acceptance
  - 90% bkg rejection at negligible signal loss within tracker

p_T cut for less than X% fake rate

Eta	10% (GeV)	1% (GeV)
0–2.1	60 (30)	80 (40)
2.1–2.8	50	80
2.8–3.2	50	80
3.2–4.5	30	50

ATLAS-CONF-2014-018

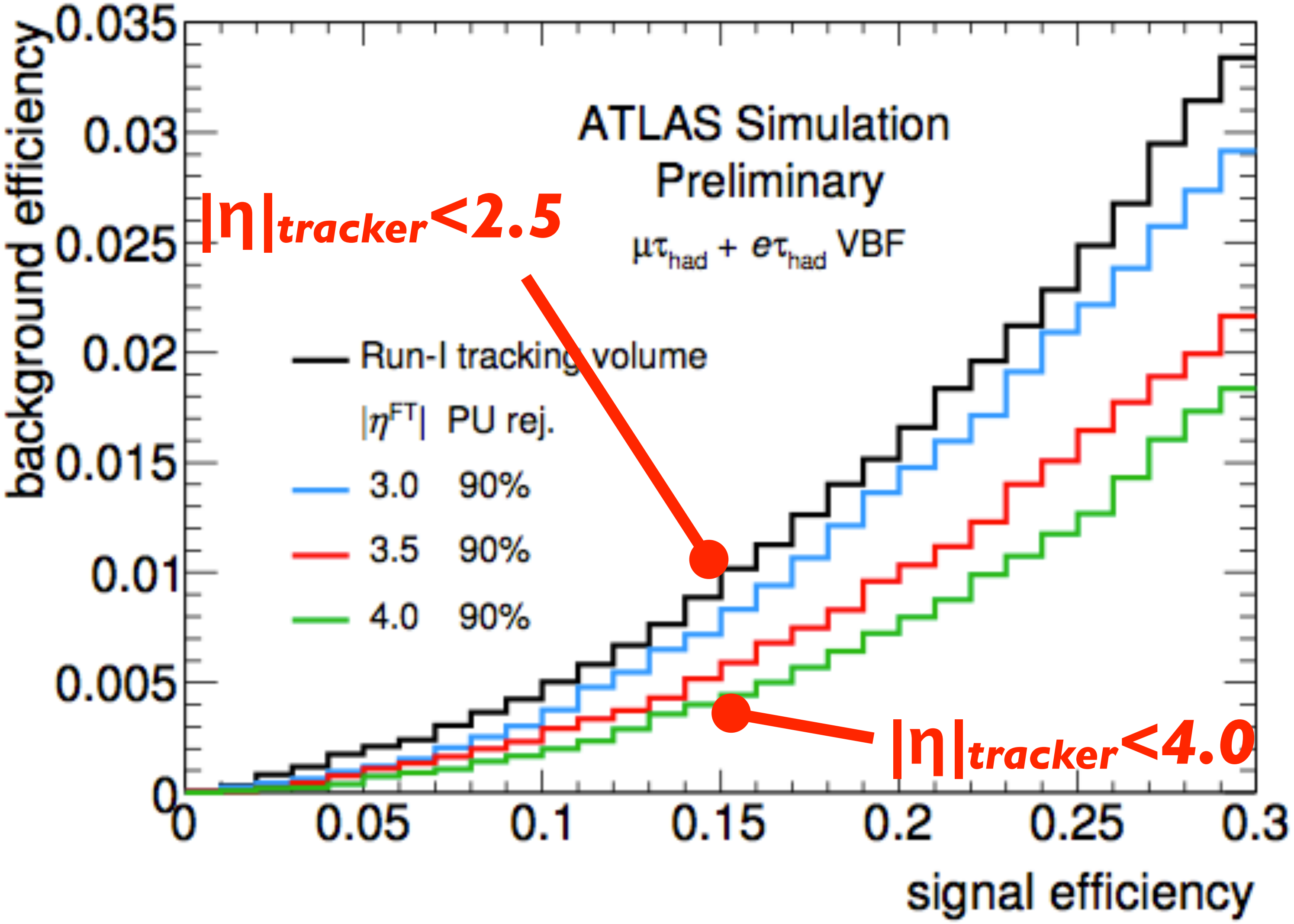




Impact of extended PU rejection

Extension of tracking to forward region

- performances dramatically improved by larger tracking coverage



ATL-PHYS-PUB-2014-018

forward pile-up jet rejection	50%	75%	90%
forward tracker coverage		$\Delta\mu$	
Run-I tracking volume		0.24	
$\lvert\eta\rvert < 3.0$	0.18	0.15	0.14
$\lvert\eta\rvert < 3.5$	0.18	0.13	0.11
$\lvert\eta\rvert < 4.0$	0.16	0.12	0.08

Extension of tracker coverage can provide up to 3 times smaller Δμ !!

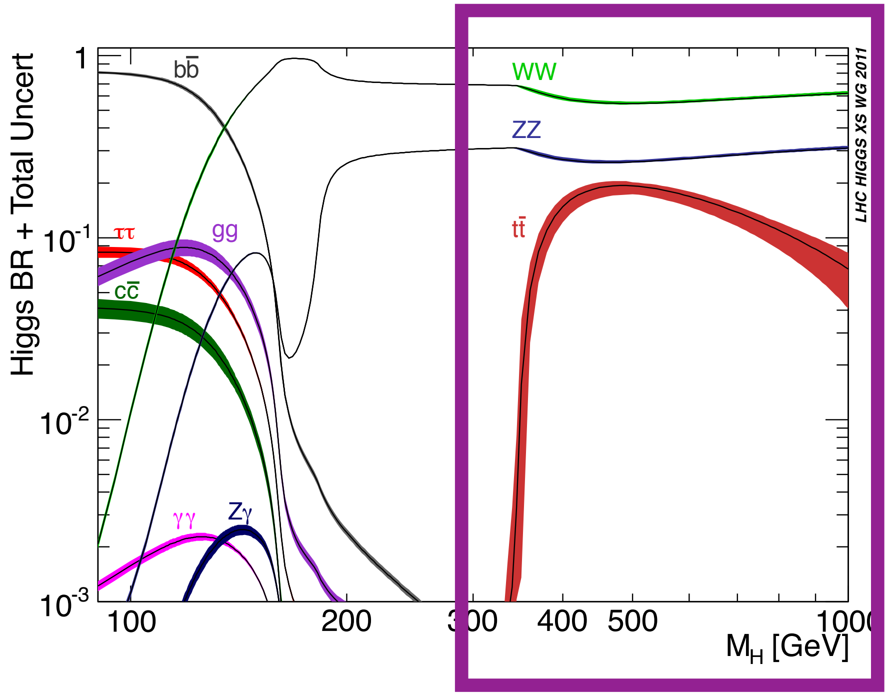
Also studied by CMS for Phase2 upgrade

- forward pixel disks and timing in pre-shower

The top quark Yukawa coupling

Precise knowledge of Yukawa coupling y_t crucial for characterization of H(125)

- no partial width $\Gamma_{H\to tt}$
  - off-shell H→tt through gg→tt interference? Maybe, but very hard



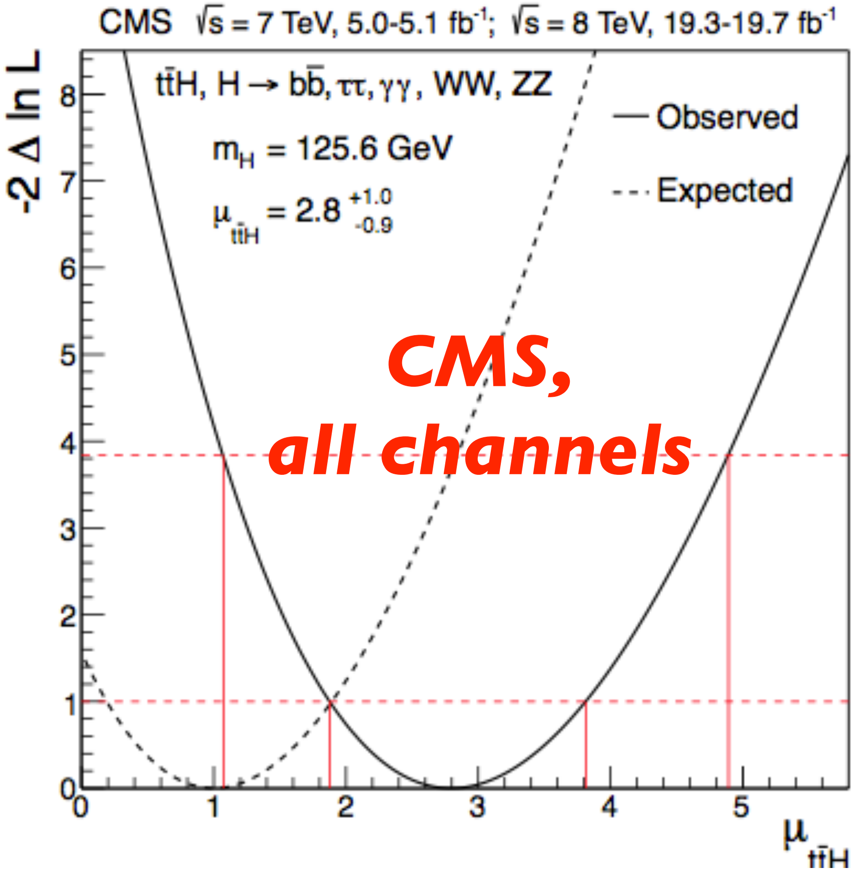
	H→ZZ*/WW*/ff	H→γγ
σ(pp→H)	κ_t^2 [*loop*]	$\lvert\kappa_t\mathcal{M}_a + \kappa_V\mathcal{M}_b\rvert^2$ [*loop*]
σ(pp→ttH)	κ_t^2 [*tree*]	
σ(pp→tH)	$\lvert\kappa_t\mathcal{M}_a + \kappa_V\mathcal{M}_b\rvert^2$ [*tree*]	

ttH: theoretical developments

	Accuracy	Some references
Signal modeling	NLO	PRL 87 (2001) 201805 NPB 653 (2003) PRD 68 (2003) 034022
	bkg interference	arXiv:1412.5290
	EWK corrections	arXiv:1504.03446
	NLO + PS	aMC@NLO+PYTHIA Sherpa+OpenLoops POWHEG+HELAC
Background modeling	tt+bb @NLO	PRL 103 (2009) 012002
	tt+bb @NLO + PS (4FS, 5FS)	PLB 734 (2014) 210 JHEP 07 (2014) 135 JHEP 1503 (2015) 083
	tt+jj @NLO	PRD 84 (2011) 114017
	tt+jj @NLO + PS	arXiv:1402.6293

Run I at a glance

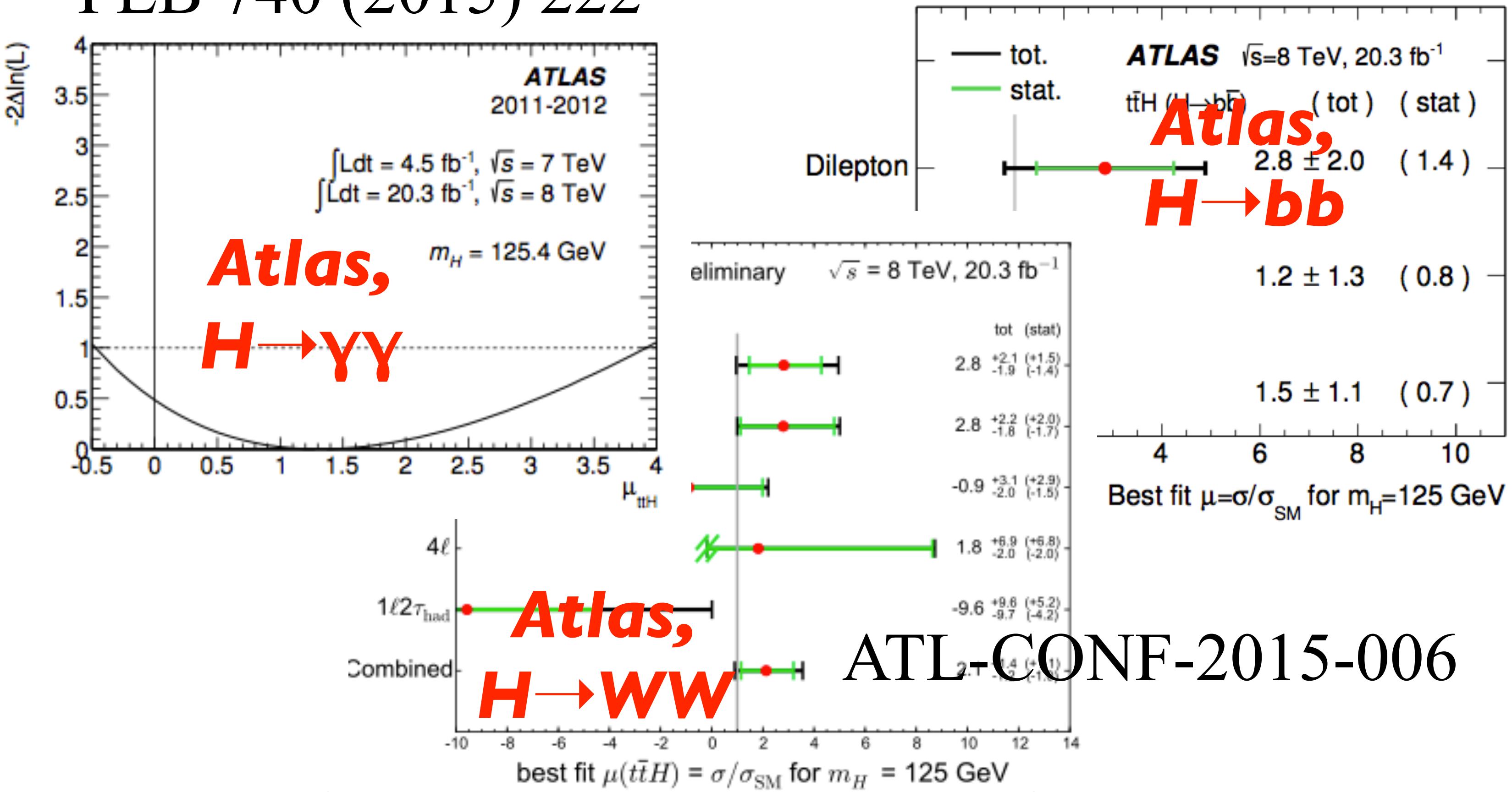
JHEP 09 (2014) 087



CMS, all channels

PLB 740 (2015) 222

ATLAS, arXiv:1503.05066



Atlas, H→γγ

Atlas, H→bb

Atlas, H→WW

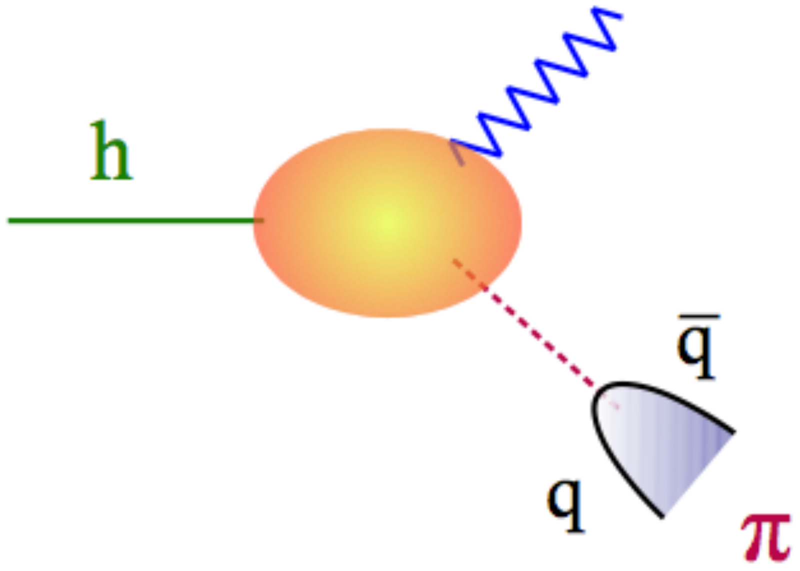
ATL-CONF-2015-006

	Experiment	obs. (exp.) limit 95% CL	best-fit value (±1σ)
H → hadrons	CMS	4.1 (3.5)	0.7 $^{+1.9}_{-1.9}$
	ATLAS	3.4 (**2.2**)	1.5 $^{+1.1}_{-1.1}$
H → photons	CMS	7.4 (**4.7**)	2.7 $^{+2.6}_{-1.8}$
	ATLAS	6.7 (4.9)	1.4 $^{+2.1}_{-1.4}$
H → leptons	CMS	6.6 (**2.4**)	3.7 $^{+1.6}_{-1.4}$
	ATLAS	7.7 (2.4)	2.1 $^{+1.4}_{-1.2}$

Rare processes: semi-hadronic decays

Exclusive semi-hadronic decays (V+meson)

- suppressed by $(f_P/v)^2$
- complementary to H→VV*
  - e.g. in EFT approach:



$$\frac{\Gamma(h\to VP)}{\Gamma(h\to VP)^{\rm SM}} = \left|c_1 + g_2^2(c_2+c_3)\right|^2$$

=1 (SM)

$$\mathcal{O}_W = \frac{g_2 c_2}{v} h D_\mu W_a^{\mu\nu}\, {\rm Tr}\left[\Sigma^\dagger i\tau^a \overleftrightarrow{D}_\nu \Sigma\right],$$

$$\mathcal{O}_{W\partial H} = \frac{g_2 c_3}{v} (\partial_\nu h) W_a^{\mu\nu}\, {\rm Tr}\left[\Sigma^\dagger i\tau^a \overleftrightarrow{D}_\mu \Sigma\right].$$

$BR_{SM} \sim 10^{-5}$ ⇒ O(100) events in VBF

VP mode	$\mathcal{B}^{\rm SM}$	VP^* mode	$\mathcal{B}^{\rm SM}$
$W^-\pi^+$	0.6×10^{-5}	$W^-\rho^+$	0.8×10^{-5}
W^-K^+	0.4×10^{-6}	$Z^0\phi$	2.2×10^{-6}
$Z^0\pi^0$	0.3×10^{-5}	$Z^0\rho^0$	1.2×10^{-6}
$W^-D_s^+$	2.1×10^{-5}	$W^-D_s^{*+}$	3.5×10^{-5}
W^-D^+	0.7×10^{-6}	W^-D^{*+}	1.2×10^{-6}
$Z^0\eta_c$	1.4×10^{-5}	Z^0J/ψ	2.2×10^{-6}

No conclusive studies yet, but BR ~10^{-5} may be detectable at HL-LHC

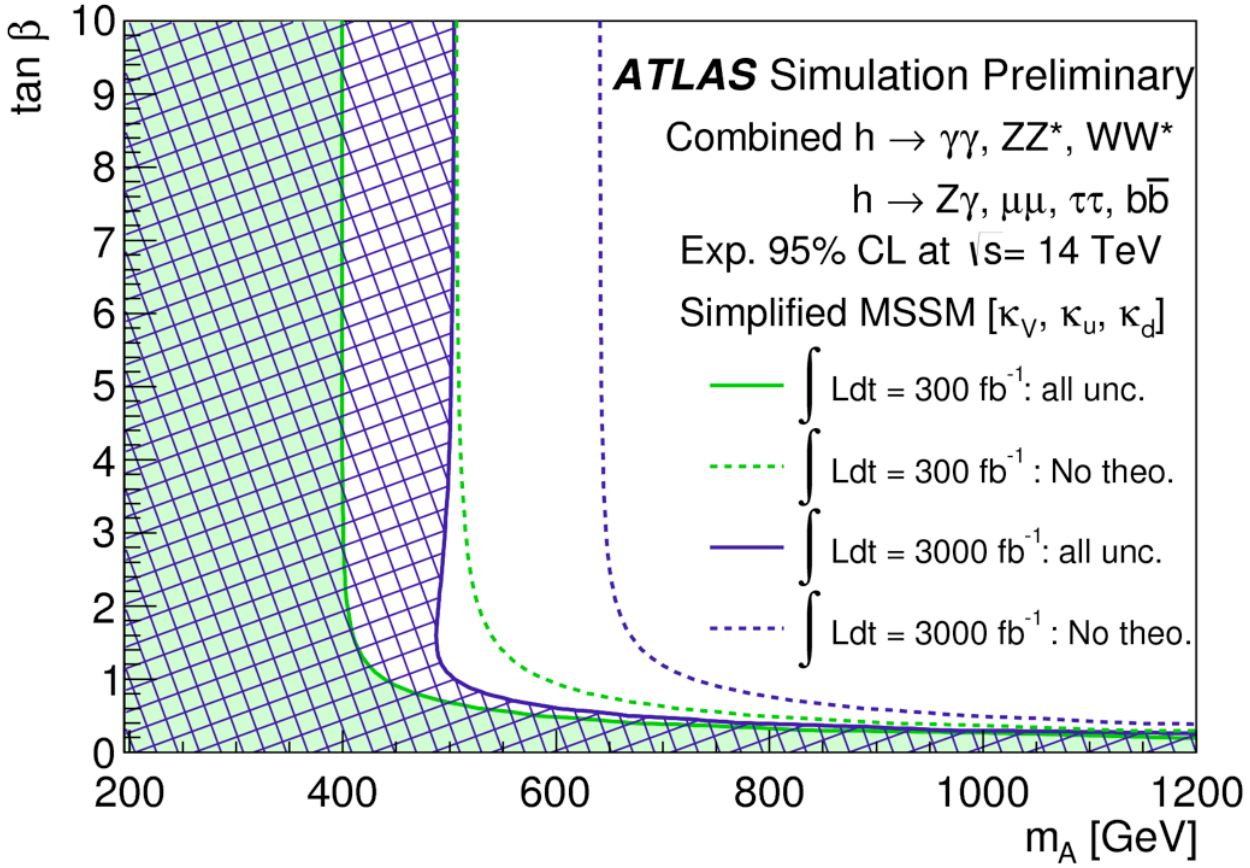
G. Isidori et al. PLB 728 (2014) 131

Extra Higgs bosons

h(125)
coupling fit

Direct H/A/H±
searches

ATL-PHYS-PUB-2014-017



Djouadi et al., arXiv:1502.05653