Prospects for Higgs Physics at the (HL-)LHC

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on behalf of the CMS and ATLAS experiments

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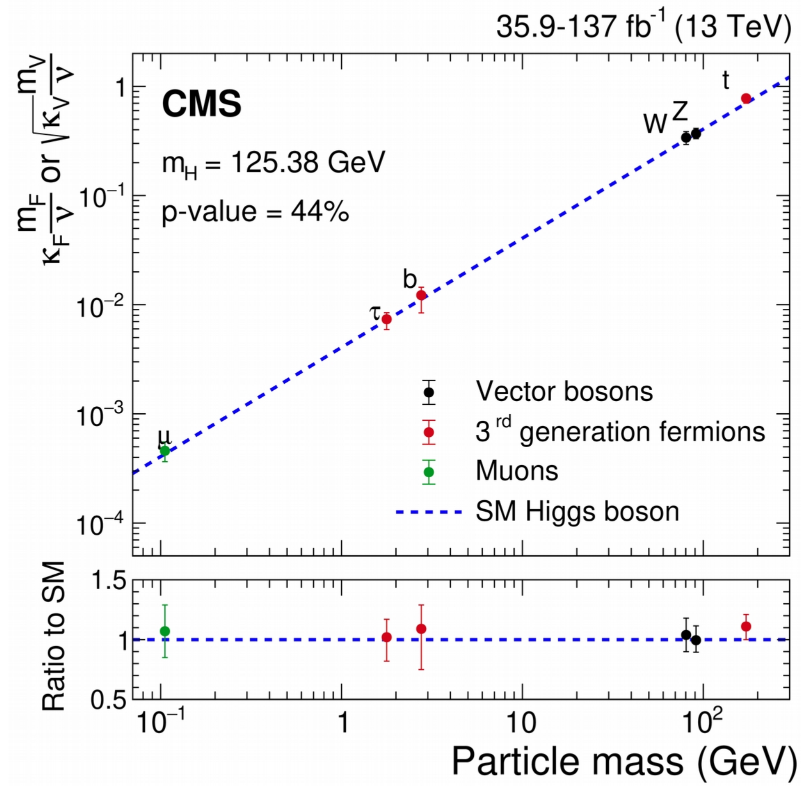
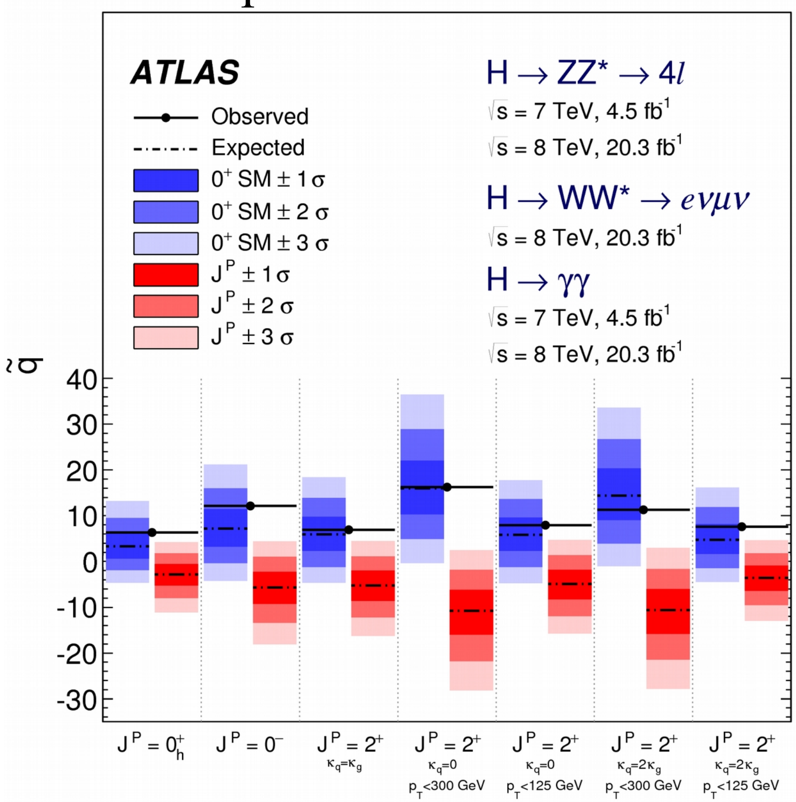
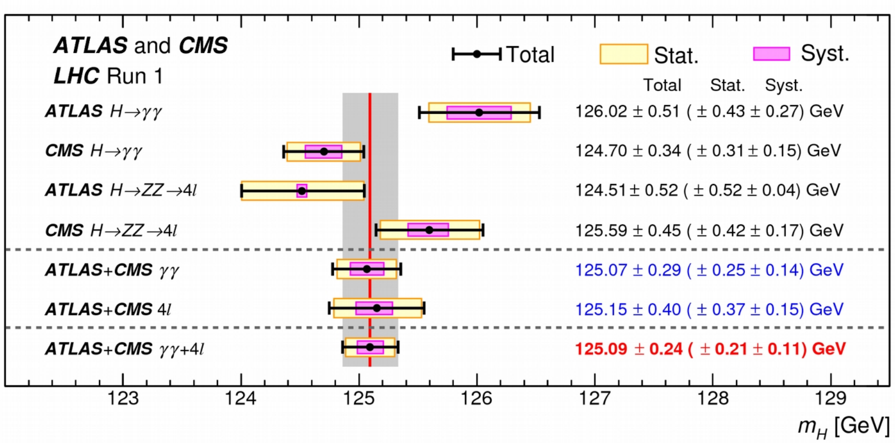
Introduction

- 10 years after the Higgs boson discovery
- All main production modes observed
  - couplings measured with 10-50% precision
- Spin/parity: $J^{PC} = 0^{++}$
  - spin 1 and 2 excluded at > 99% CL



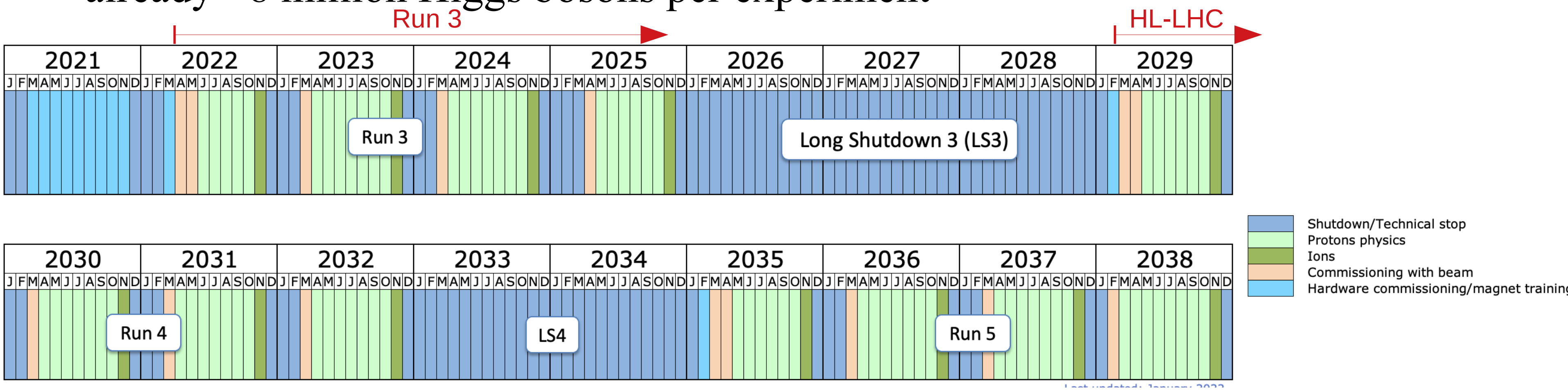


- Mass: precision < 0.2% (140 MeV)



Context

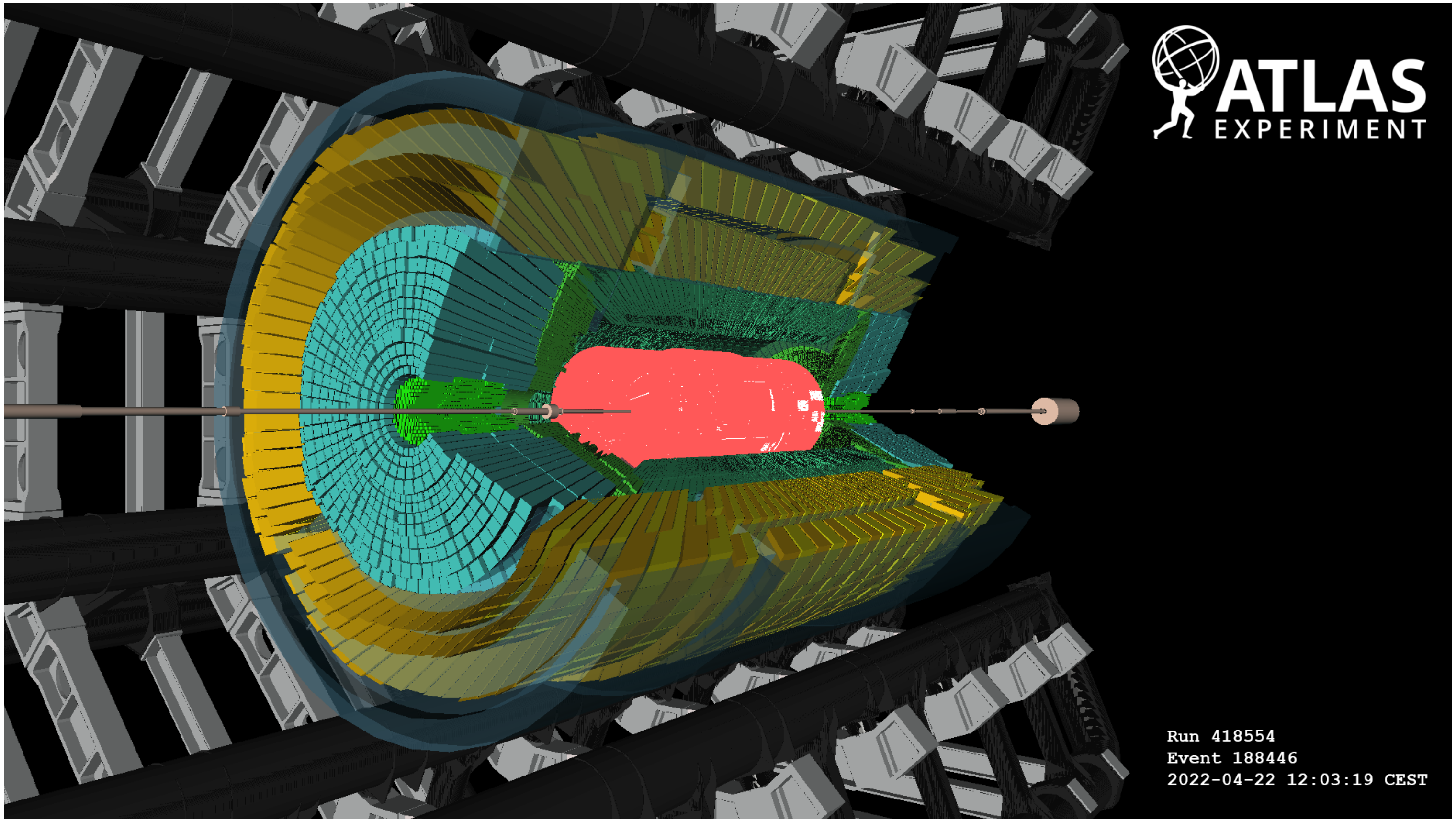
- Only 5% of total LHC dataset delivered
  - already ~8 million Higgs bosons per experiment



- Propects studies done by the ATLAS and CMS collaborations in the past years
- European Strategy for Particle Physics 2018-2020
  - CERN Yellow Report on the Physics at the HL-LHC, and Perspectives for the HE-LHC (link)
  - symposium in 2019 + briefing book (link) + conclusions (link)
- US Snowmass process 2020-2022
  - to identify the most important questions in HEP and the tools and infrastructure required to address them
  - meeting in July 2022, book end of 2022
  - White paper by ATLAS and CMS (link)

Run 3 of the LHC

- First beam on the 22nd of April!



- Expected integrated luminosity: ~350 fb^{-1}
  - pile-up similar to Run 2 + upgraded muons system, but generally radiation damaged detectors
- Centre-of-mass energy: 13.6 TeV

Higgs boson at Run 3

- Increase in Higgs boson production cross-section from the centre of √s:

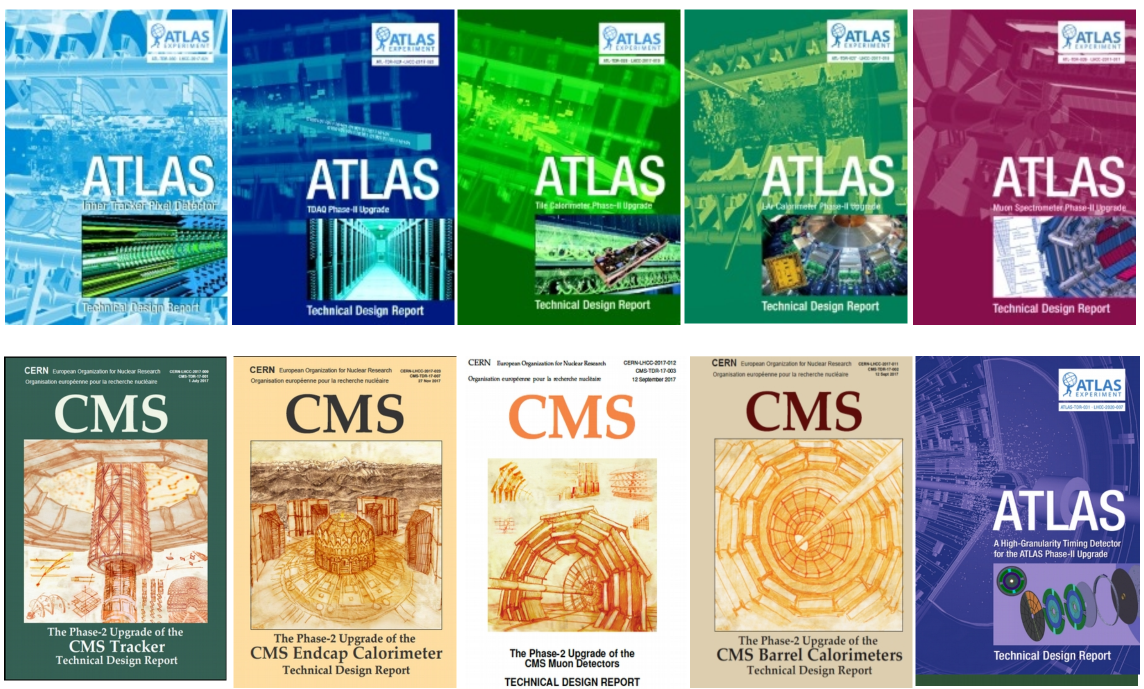
ggF	+7.5%
VBF	+7.9%
WH	+6.2%
ZH	+6.9%
ttH	+12.6%
HH	+11%

- In general: measurements that are still statistically limited with Run 2 dataset
- Differential cross-section measurements
- Couplings to 2nd generation
  - $H \rightarrow \mu\mu$: first evidence by the CMS collaboration with Run 2 dataset: observed (expected) signal significance of 3.0σ (2.5σ)
    - ATLAS Run2 : observed (expected) signal significance of 2.0σ (1.7σ)
    - projected CMS analysis: 5σ can be achieved with $L \approx 300\ fb^{-1}$ of data (at = 14 TeV)
  - also sensitivity to $VH(\rightarrow c\bar{c})$
- Rare decay: $H \rightarrow Z(\rightarrow ee/\mu\mu)\gamma$:$BR = 0.1\times10^{-3}$
  - full Run 2 significance:
    - ATLAS: 2.2σ (expected 1.2σ)
    - CMS: 2.7σ (expected 1.2σ) NEW
  - 5σ expected at HL-LHC ⇒ evidence could be expected by the end of Run 3

HL-LHC (Run 4+)

- From 2029 to ~2040
- Total integrated luminosity: 3000 fb^{-1} /experiment
  - peak luminosity *5-7 wrt Run 2-3
- Center-of-mass energy: 14 TeV

- Upgrades of ATLAS and CMS to cope with aging, pile-up, radiation
  - 2017-2019: >4500 pages of Technical Design Reports

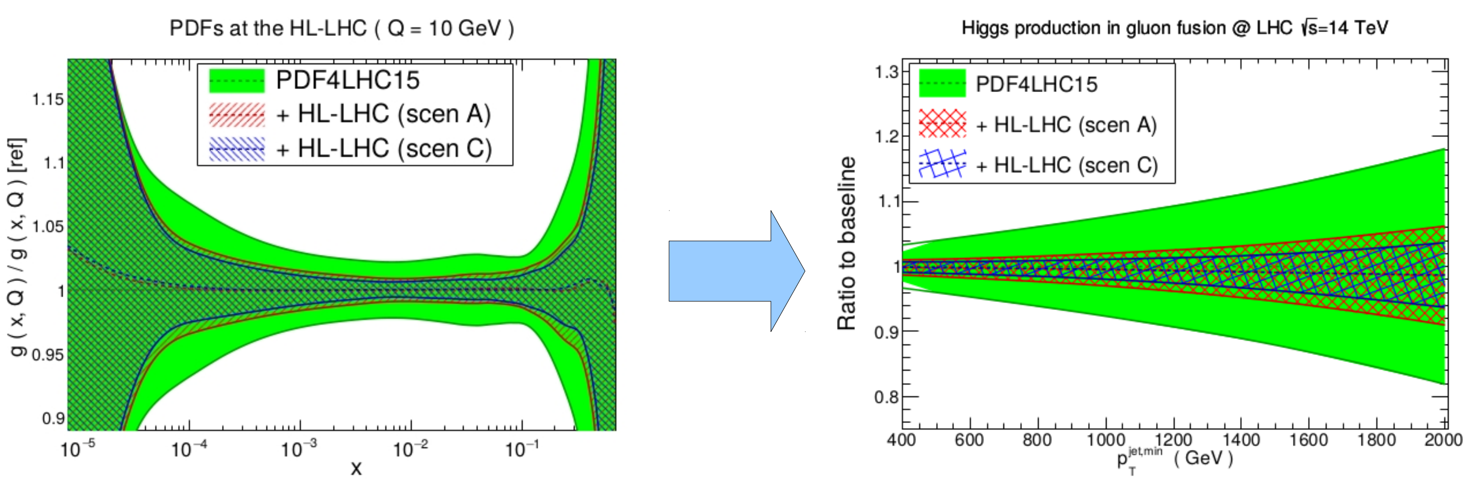


  - possible to maintain (or even improve!) Run 2 performance (reconstruction efficiencies, calibration, etc) despite harder environment

HL-LHC analyses

CERN-2019-007

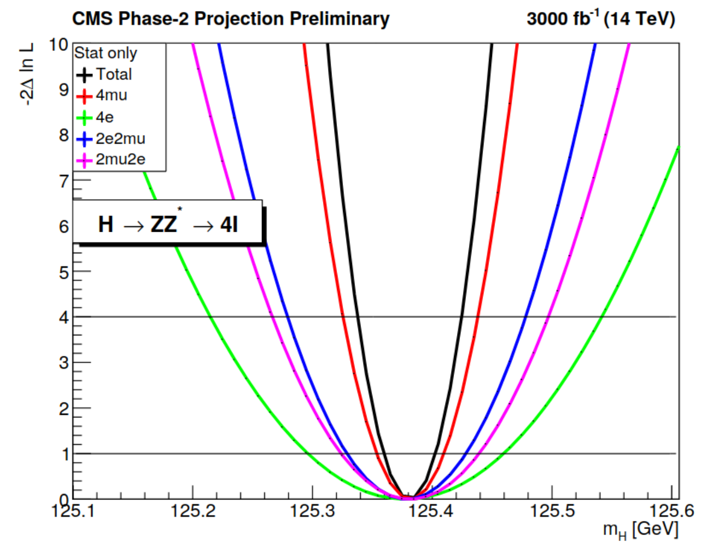
- Extrapoled from Run-2, or dedicated analyses with parameterised performance
- Assumption on systematics: Run 2 or 'YR2018':
  - statistics-driven sources: data → √L, simulation → 0
  - theory uncertainties typically halved
  - intrinsic detector limitations stay ~constant
  - luminosity uncertainty 1%
  - PDF uncertainties: pseudo-data generated for various inputs: top Drell-Yan, iso photons, W+charm, W and Z in the forward region, inclusive jets, etc
    - optimistic (A) and conservative (C) scenarios



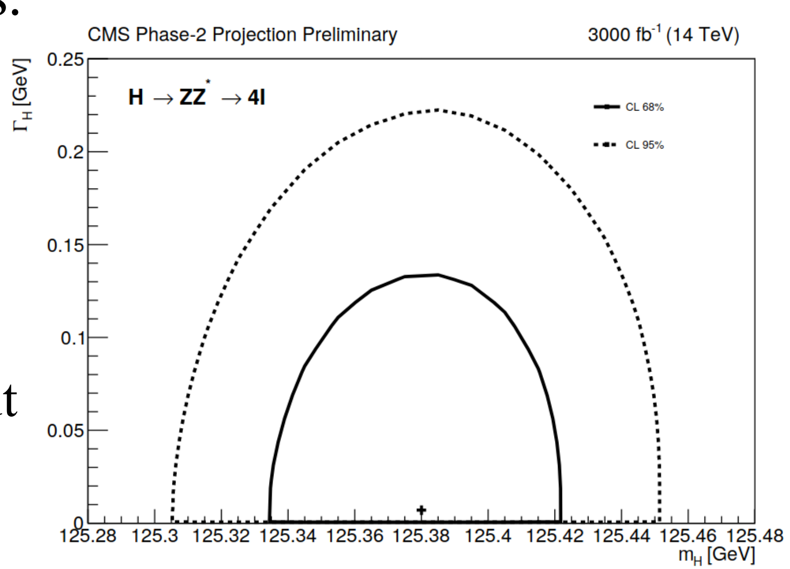
- reduction of PDF uncertainties by almost a factor 4 in the optimistic scenario in the gg channel, and around a factor 3 in the $q\bar{q}$ and qq channels
  - VH(→ bb) and H(→ ττ) studies for Snowmass2021 showed that 'YR2018' assumptions could be achieved

Higgs boson mass and width at HL-LHC

- **Mass**: new projection of CMS measurements
  - $H \rightarrow \gamma\gamma$: 20 (stat) ⊕ 70 (syst) MeV
  - $H \rightarrow ZZ \rightarrow 4l$: 30 = 22 (stat) ⊕ 20 (syst) MeV
  - reach of 10-20 MeV precision plausible goal, dependent on future improvements of muon momentum measurements



- **Width** (SM = 4.07 MeV): Direct measurement will be challenging also with HL-LHC statistics.
  - new CMS 4lepton onshell: upper limit of 177 MeV at 95% CL
  - 4lepton onshell+offshell: 20% precision at 68% CL combining CMS+ATLAS (assumption that ratio from SM)
  - from couplings: Γ_H 5% precision at 95% CL, but model dependent
  - diphoton interference study, only weaker constraints



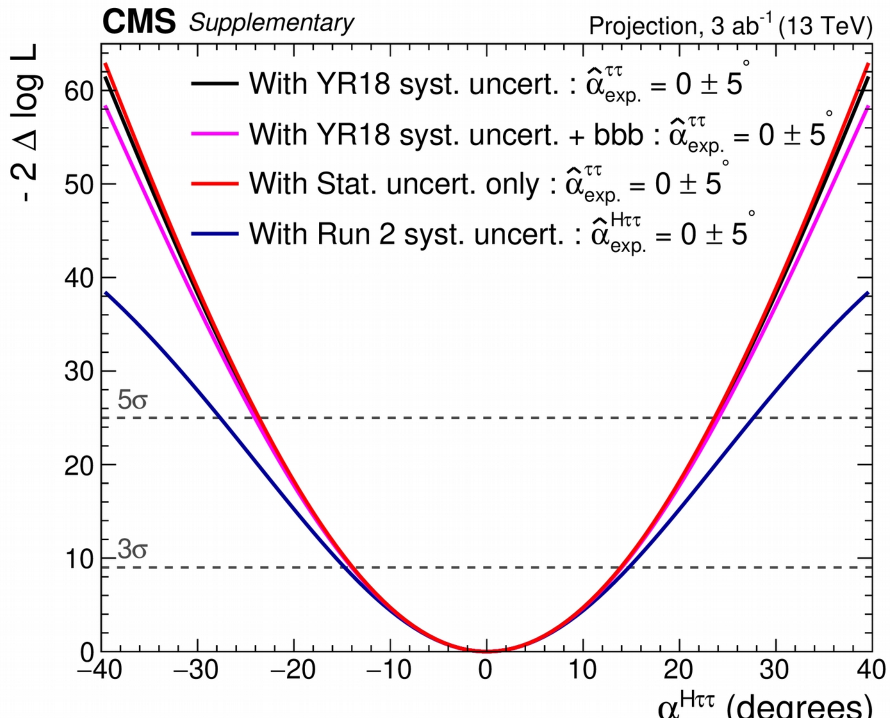
Higgs boson spin/CP at HL-LHC

ATL-PHYS-PUB-2022-018/
CMS-PAS-FTR-22-001

- Modification of CP-structure to the couplings to τ leptons could account for the observed baryon asymmetry of the universe in certain baryogenesis models
  - described in terms of an effective mixing angle $\alpha^{H\tau\tau}$

$$\tan(\alpha^{H\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

    - 0° = pure scalar coupling, 90° = pure pseudoscalar coupling
    - any other value = mixed couplings between CP-even and CP-odd components



- If $\alpha^{H\tau\tau} = 0°$, expected uncertainty of 5%
  - ~independent from the systematic uncertainty assumptions
  - 20% uncertainty with Run-2 data

Higgs couplings at HL-LHC (1)

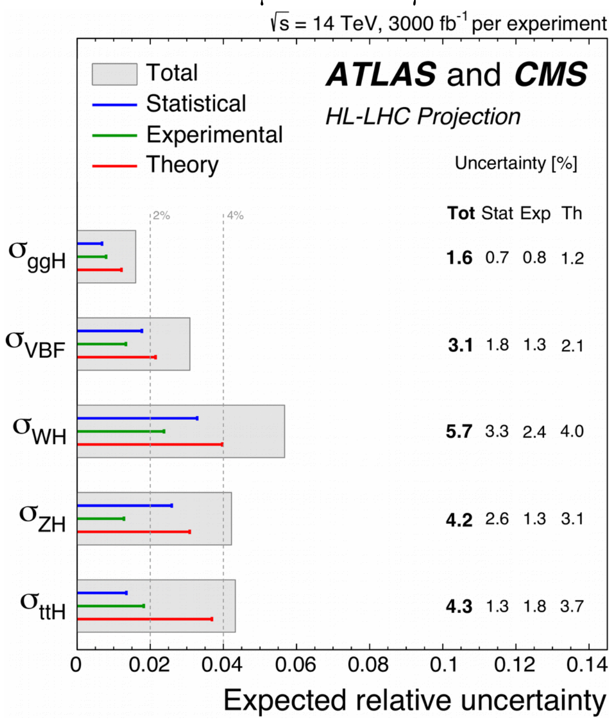
CERN-2019-007
ATL-PHYS-PUB-2022-018/
CMS-PAS-FTR-22-001

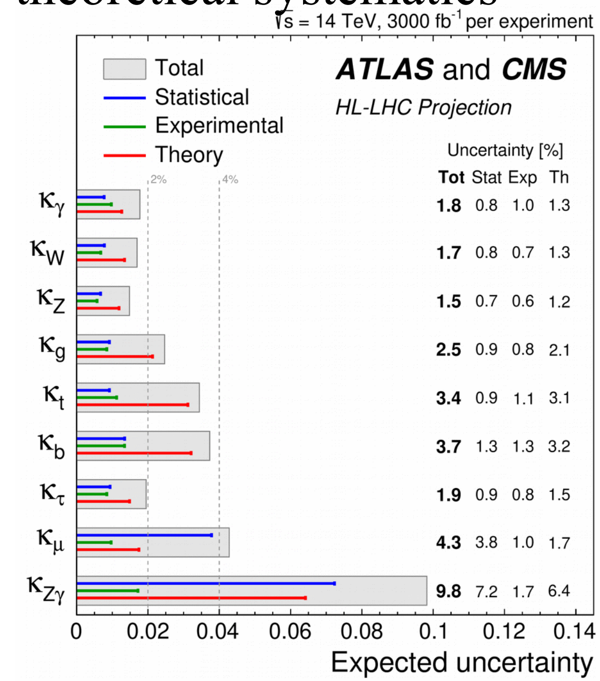
- Precision on cross-sections and κ modifiers between 2 and 4%
  - limited by experimental and mostly theoretical systematics
    - except for κ_μ and $\kappa_{Z\gamma}$

$$\mu_i^f \equiv \frac{\sigma . BR}{\sigma_{SM} . BR_{SM}} = \frac{\kappa_i^2 . \kappa_f^2}{\kappa_H^2}$$

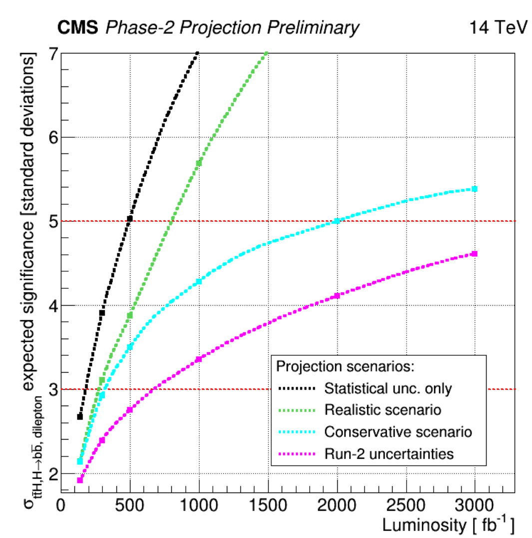
$$(\sigma . BR)(i \rightarrow H \rightarrow f) = \frac{\sigma_i . \Gamma_f}{\Gamma_H}$$

more information on the κ framework in the talk by P. Windischhofer





- Importance of systematic uncertainties, example of ttH(→ $b\bar{b}$, dilepton) channel:



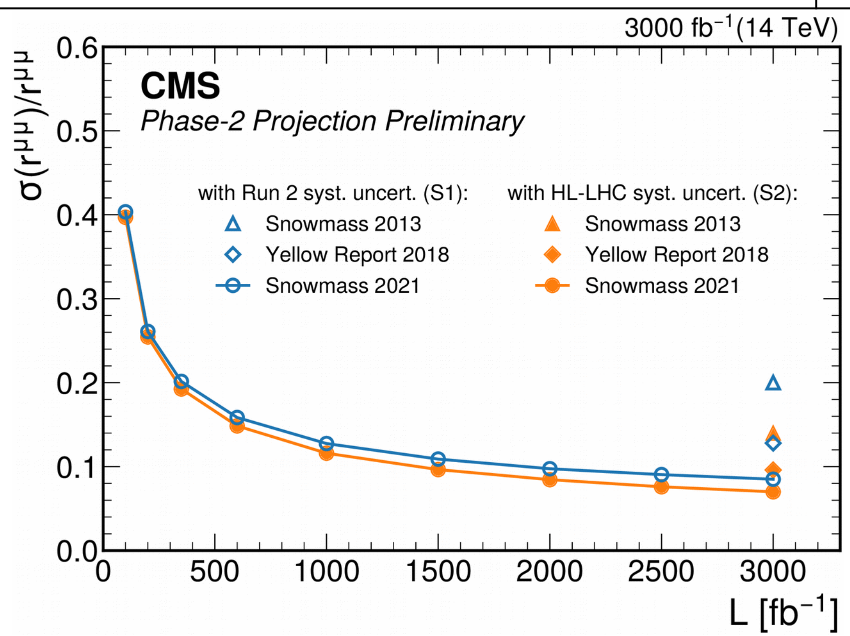
Higgs couplings at HL-LHC (2)

ATL-PHYS-PUB-2022-018/
CMS-PAS-FTR-22-001

- 2^{nd} generation: Coupling to muons through $H \rightarrow \mu\mu$
- Extrapolations of Run 2 analyses
  - improvement of the acceptance and resolution thanks to the extension of the coverage of the CMS muon system ($|\eta| < 2.8$) and ATLAS inner tracker ($|\eta| < 4$)
- Expected precision on signal strength (YR2018 uncertainties):

	Statistical	Experimental	Theoretical	Total
ATLAS YR2018	$^{+12\%}_{-13\%}$	2.00%	$^{+5\%}_{-4\%}$	**13%**
CMS Snowmass2013				**14%**
CMS YR2018	9%	2%	3%	**10%**
CMS Snowmass2021	6%	2%	2%	**7%**

factor 2 in 8 years!



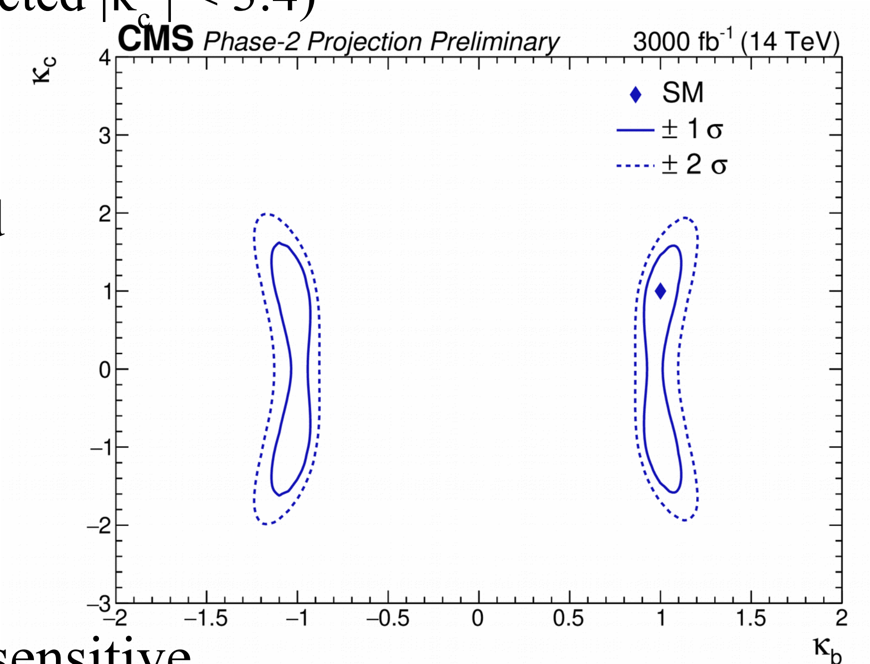
- Expected precision on κ_μ (CMS Snowmass2021): 3.5%

Higgs couplings at HL-LHC (3)

- 2^{nd} generation: Coupling to charm through VH ($H\rightarrow c\bar{c}$)

- CMS Run2 (most stringent limits up to date):
  - both resolved and boosted jets, and new c-taggers
  - observed (expected) upper limit on cross-section: 14 ($7.6^{+3.4}_{-2.3}$) times the SM
  - observed limit on κ_c: $1.1 < |\kappa_c| < 5.5$ (expected $|\kappa_c| < 3.4$)

- CMS HL-LHC:
  - 3 $c\bar{c}$-enriched categories and 3 $b\bar{b}$-enriched categories
  - expected best fit values:
    - $\mu_{VH(H\rightarrow b\bar{b})} = 1.00 \pm 0.03\ (\text{stat}) \pm 0.04\ (\text{syst})$
    - $\mu_{VH(H\rightarrow c\bar{c})} = 1.00 \pm 0.60\ (\text{stat}) \pm 0.5\ (\text{syst})$



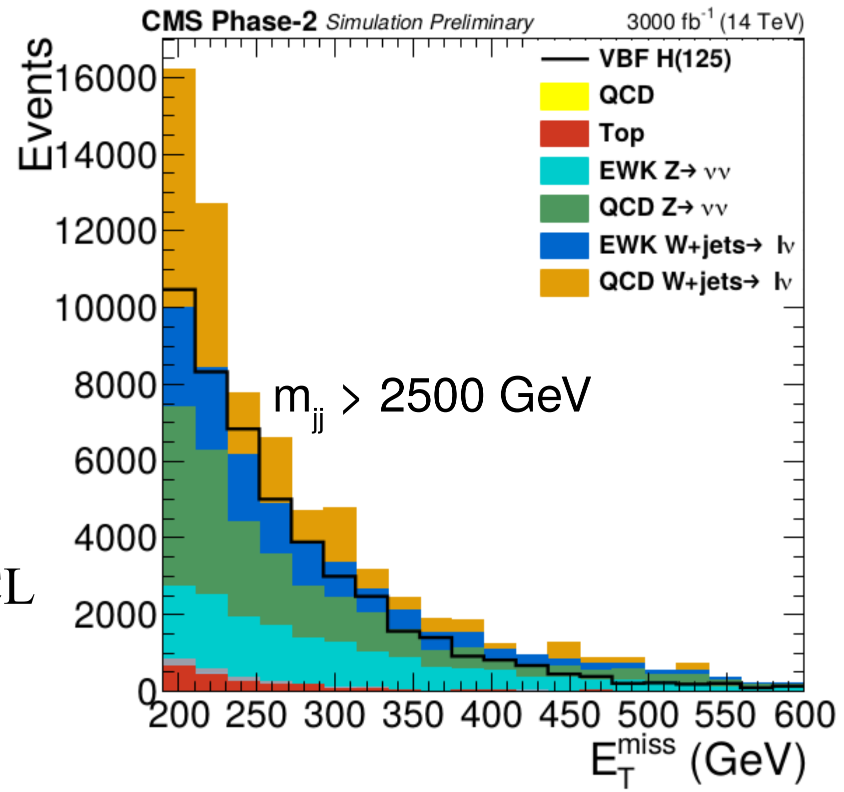
- Also ATLAS HL-LHC projection but less sensitive
  - only resolved jets in this extrapolation
  - boosted H(bb) analyses using substructure methods, developed in Run 2

Higgs couplings at HL-LHC (4)

- Higgs invisible width

- Current ATLAS and CMS Run 2:
  - global coupling fit BR(H→inv) < 4.2% @ 95% CL if BR(BSM) ≥ 0 (any invisible or undetected states)
  - direct searches: BR(H→inv) < 10% at 95% CL

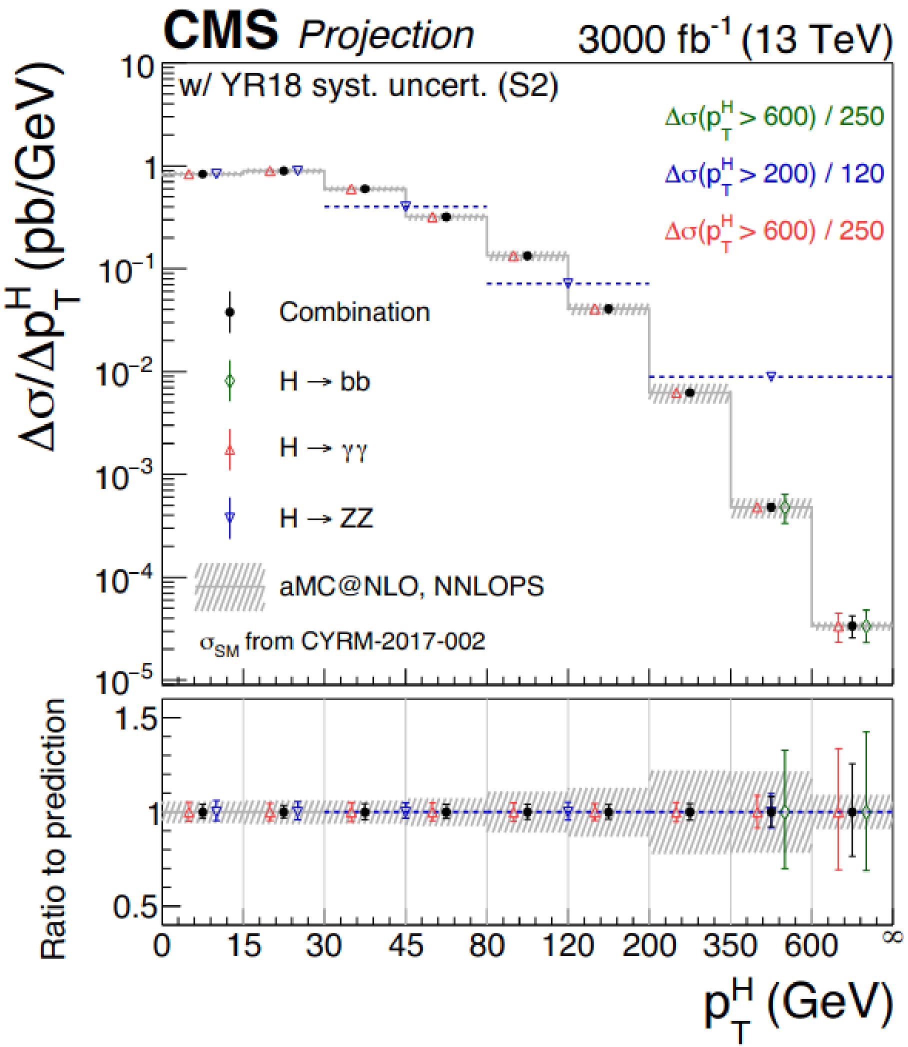
- Prospects of direct searches @14TeV:
  - VH: ATLAS, 2013: <8% @ 95%CL
  - VBF: CMS, 2018: <3.8% @ 95%CL
    - full reoptimization of the analysis at 200 pile-up to study how to handle the impact of pile-up in E_T^{miss}
  - combination: BR(H→inv) < 2.5% @ 95% CL

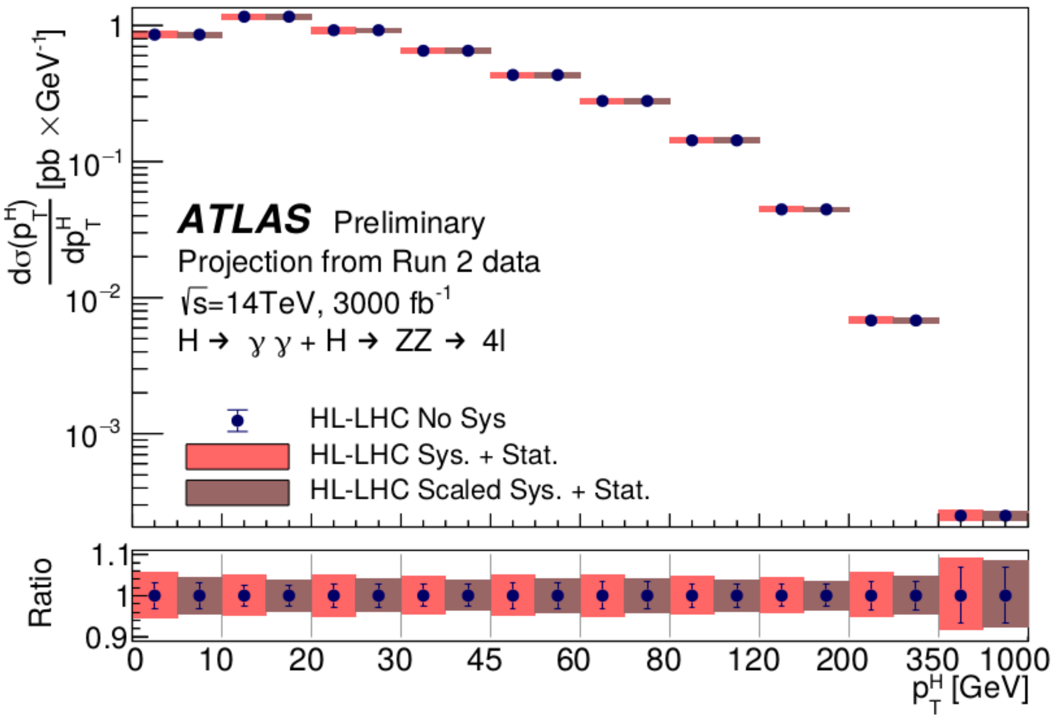


Differential cross-sections at HL-LHC (1)

more information on the differential cross-section measurements in the talk by S. Addepalli

- Sensitive to κ_b/κ_c at low p_T^H and κt /BSM at high p_T^H

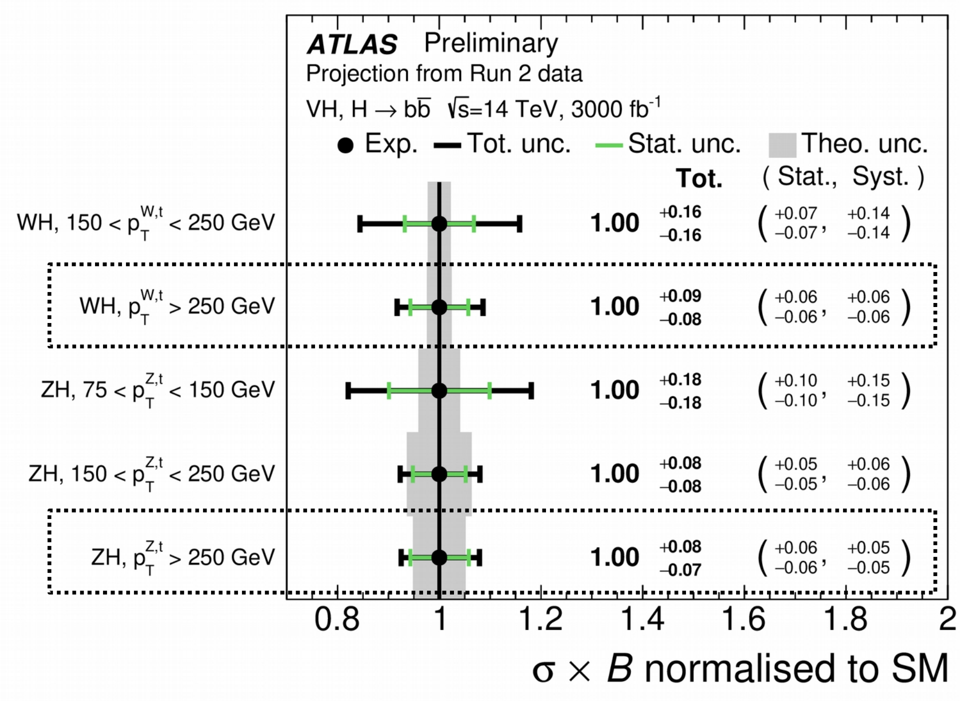


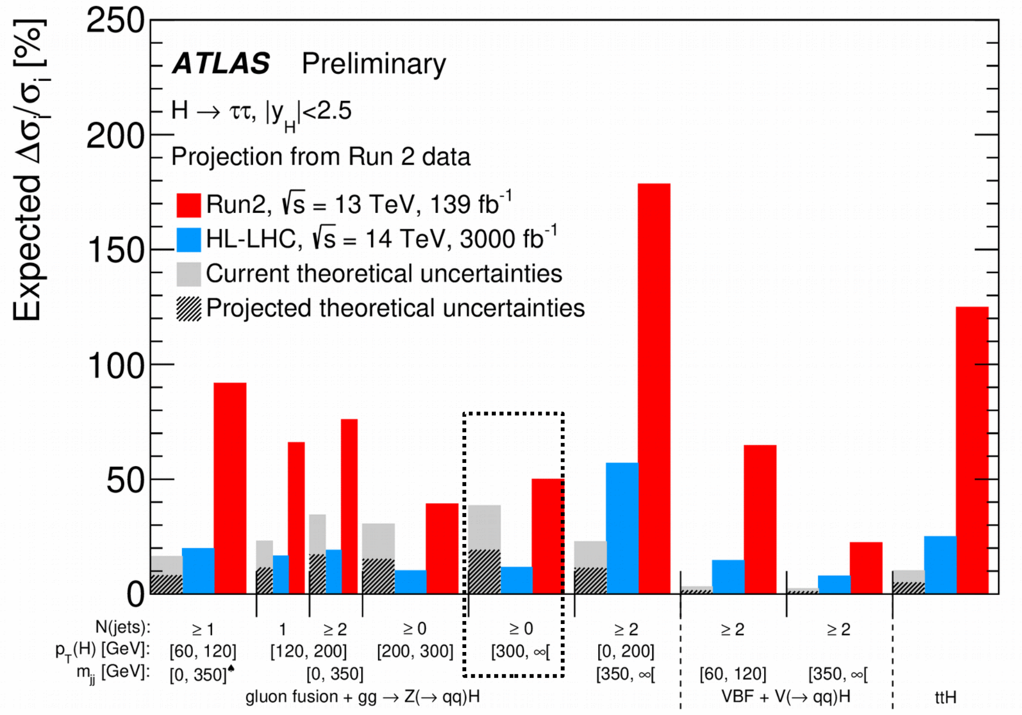


- Expected precision of ~ 10% for p_T^H > 350 GeV, statistically limited

Differential cross-sections at HL-LHC (2)

- For Snowmass2021: couplings in Simplified Template Cross Section framework for
  - measurements into bins of key variables such as Higgs transverse momentum (p_T^H), jet multiplicity (Njets), and dijet invariant mass (mjj)
- VH($\rightarrow b\bar{b}$) and $H \rightarrow \tau\tau$

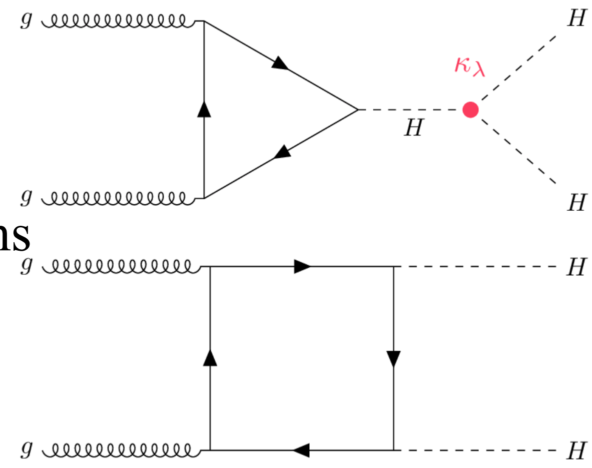




- p_T^H > 250-300 GeV (sensitive to BSM) could be measured with a precision of ~10%
  - better than theoretical uncertainties for $H \rightarrow \tau\tau$

Higgs self-coupling at HL-LHC (1)

more information on the HH search in the talk by J. Schaarschmidt



- Through the HH production
  - rare process of the Standard Model (σ(HH)/σ(H) = 0.1%)
  - destructive interference between triangle and box diagrams

- Summary of channels/methods for the YR2018 studies:

	ATLAS	CMS	
bbbb	extrapolation	parametric	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	extrapolation	parametric	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	smearing	parametric	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→lνlν)		parametric	Large BR ☺ Large bkg ☹
bbZZ (→4l)		parametric	Very small BR ☹ Very small bkg ☺

Updated for Snowmass2021

- New for Snowmass 2021:

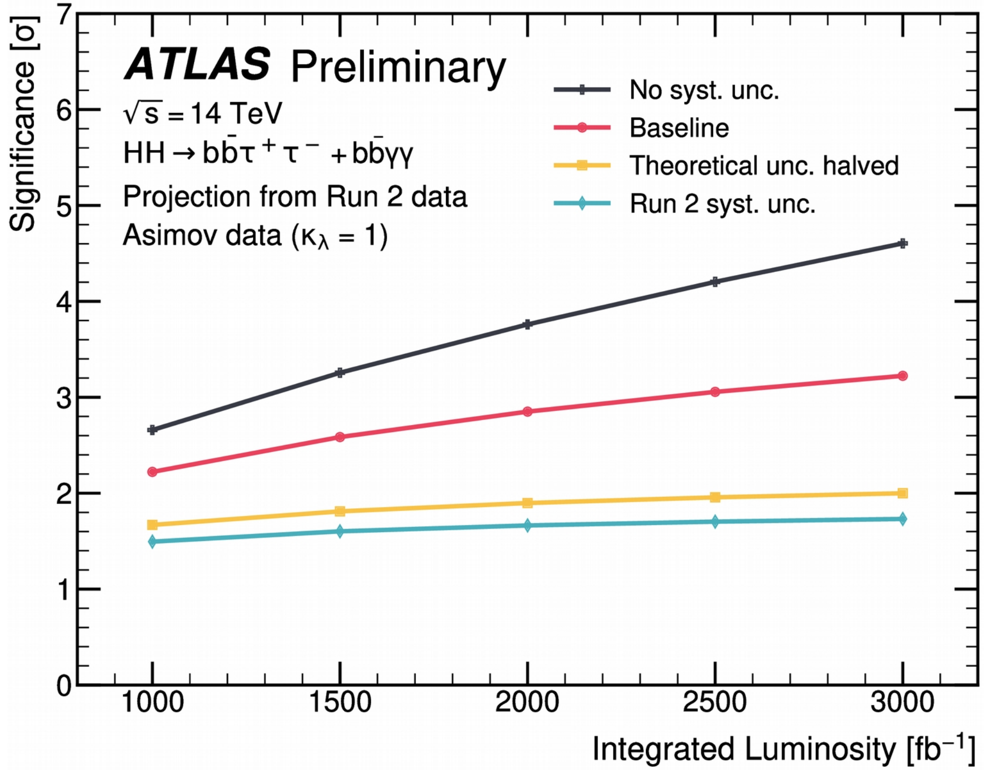
WWγγ+τγγ		parametric	Clean channel ☺ Large bkg ☹
ttHH		parametric	Very small cross-section ☹ Highly sensitive to BSM ☺

Higgs self-coupling at HL-LHC (2)

- Expected significance for SM HH production in YR2018 (→ Snowmass2021):

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5 → 4.0	1.6	2.1 → 2.8	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1 → 2.3	1.8	2.0 → 2.2	1.8 → 2.2
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0 → 3.2	2.6
	Combined 4.5		Combined 4.0	

- … as a function of int. luminosity:



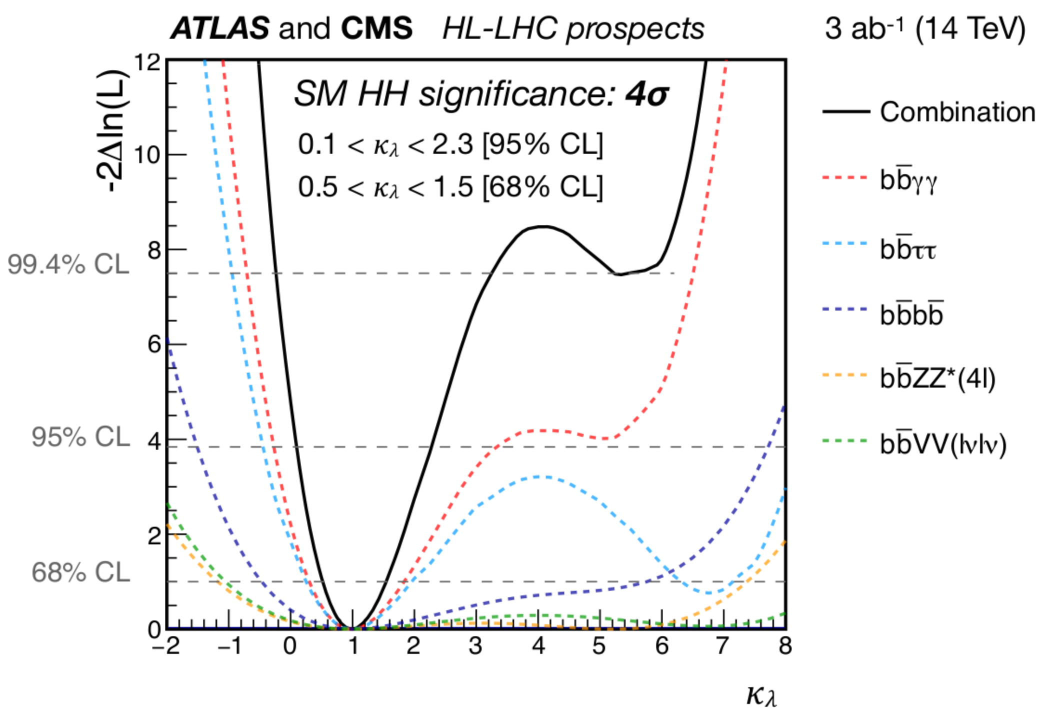
- $t\bar{t}HH$: upper limit of $3.14^{+1.27}_{-0.9}$ *SM

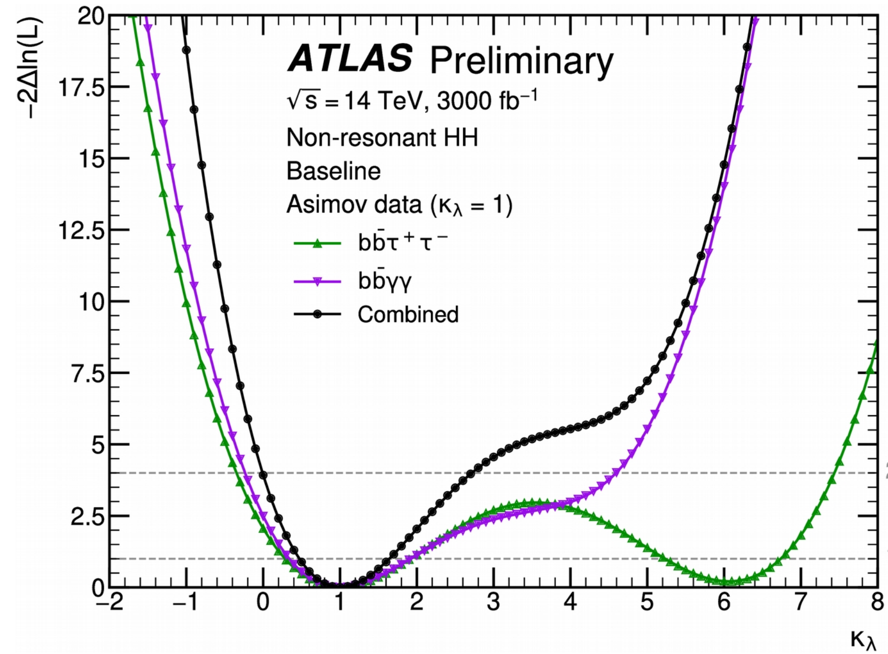
CERN-2019-007
ATL-PHYS-PUB-2022-018/
CMS-PAS-FTR-22-001

Higgs self-coupling at HL-LHC (3)

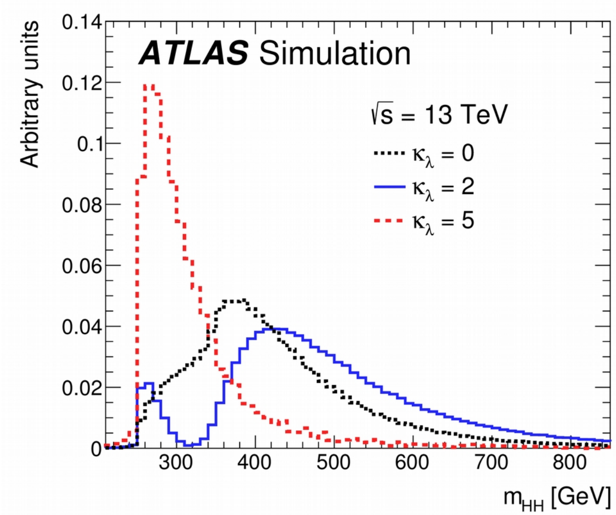
$$\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$$

- Measurement of κ_λ:



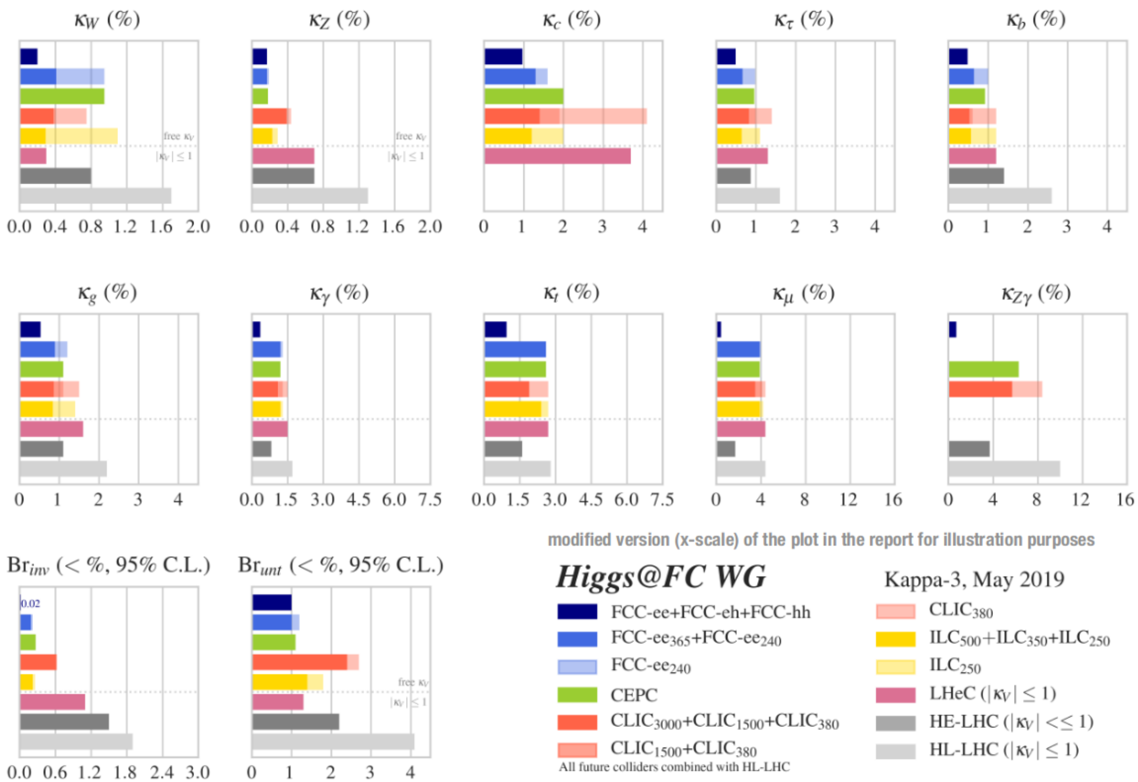


- YR2018 (ATLAS+CMS): [0.5; 1.5] at 68% CL
- Snowmass2021 (ATLAS bbττ+bbγγ only!): [0.5; 1.6]
- importance of measurements sensitive to m_{HH} to remove the second minimum (degeneracy of the HH production cross-section)



Higgs boson studies at Future Colliders

- After HL-LHC: Electron-positron (FCC-ee, CEPC, CLIC, ILC), proton-proton (HE-LHC, FCC-hh), electron-proton (LHeC)
- Precision on κ coupling modifiers:



- Precise measurements of Higgs couplings (large gain in κ_W, κ_Z, κ_b, access to κ_c), invisible decays and CP properties, and the opportunity to measure the Higgs width
- Several of the proposed FCs will establish the existence of the self-coupling at 5σ

Conclusion

- Already well defined physics program for the HL-LHC
  - mostly extrapolated from the Run-2 results
  - based on the foreseen detector improvements

- Higgs mass could be measured with an uncertainty of 10-20 MeV
- Higgs couplings will be measured with percent precision
- Higgs self-couplings could be measured with a precision betten than 50%, expected significance for the HH process >4σ

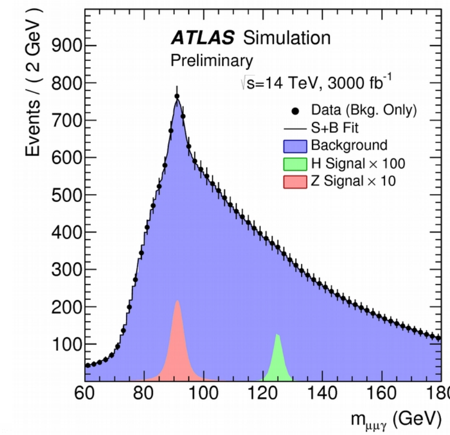
- Already improvements between the YR2018 and Snowmass2021 projections
  - ex. uncertainty on κ_c:
    - Snowmass2013: 7.5%
    - YR2018: 5.0%
    - Snowmass2021: 3.5%
  - Stay tuned! Ultreia!

Back-up

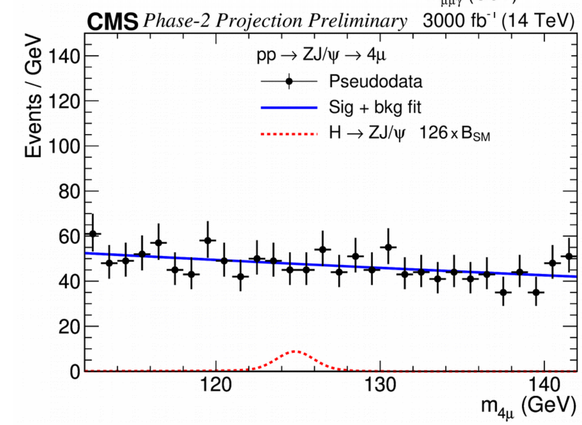
Higgs couplings at HL-LHC (4)

ATL-PHYS-PUB-2015-043
CMS-PAS-FTR-21-009

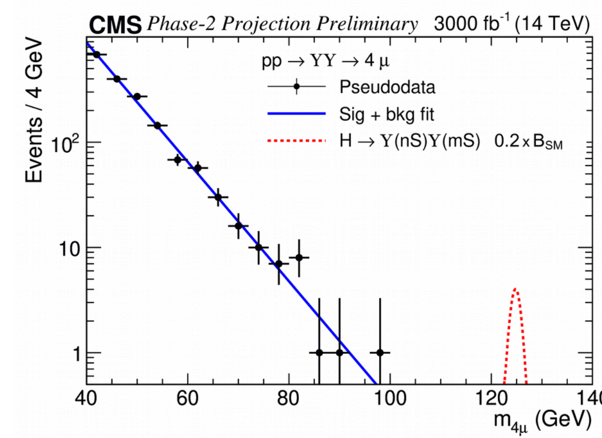
- 2^{nd} generation: Coupling to charm through rare decays with quarkonium mesons
  - low branching ratios in the SM, can be largely enhanced by BSM
- $H \rightarrow J/\Psi+\gamma$ (BR = $2.9 \pm 0.2 \times 10^{-6}$)
  - ~3 expected signal events
  - expected 95% CL upper limits: 15*SM



- $H \rightarrow J/\Psi+Z$ (BR = 2.3×10^{-6})
  - search in the 4 muon invariant mass
  - expected 95% CL upper limits: 126*SM

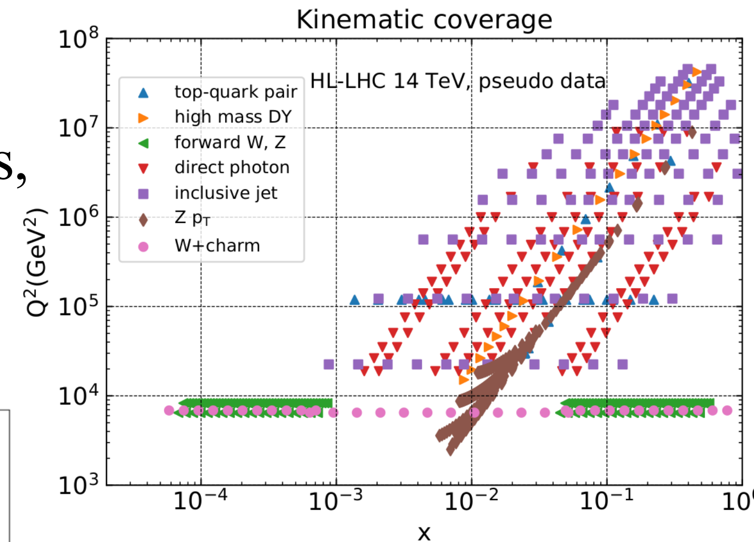


- $H \rightarrow \Upsilon(mS)\Upsilon(nS)$ (BR = 6.5×10^{-5})
  - search in the 4 muon invariant mass
  - expected 95% CL upper limits: 0.2*SM
  - predicted background negligible
    ⇒ 1 event = evidence
    ⇒ 3 events = observation



PDF at HL-LHC (1)

- Constraints of the HL–LHC pseudo-data on the PDF4LHC15 set by means of the Hessian Profiling method
  - PDF4LHC15 set broadly represents the state-of-the-art understanding of the proton structure
- HL-LHC coverage of the large-x region, where current PDF fits exhibit large uncertainties, is markedly improved as compared to available LHC measurements



- Example:

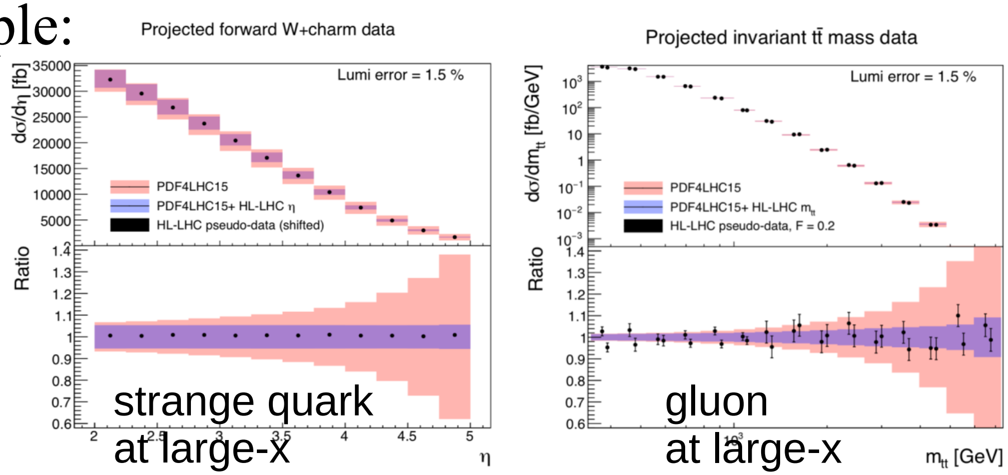
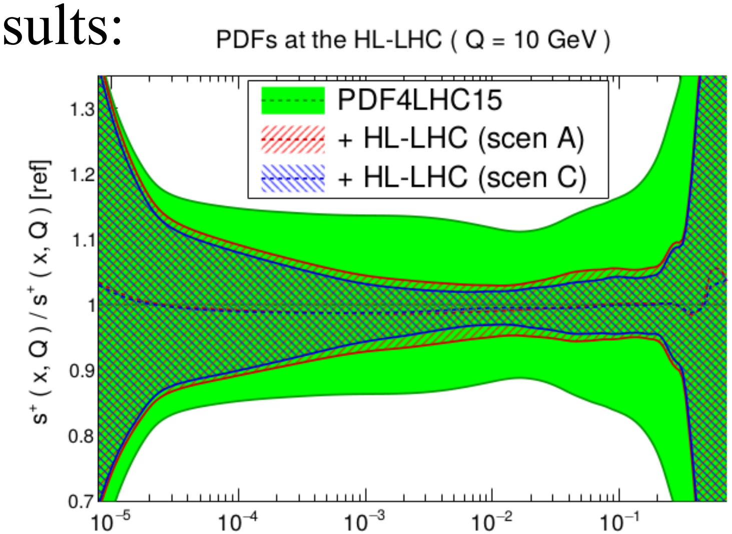


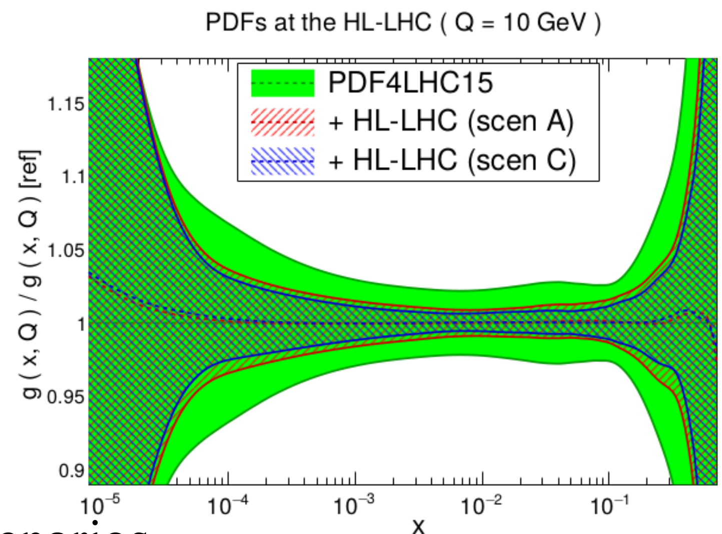
Fig. 6: Comparison between the HL–LHC pseudo-data and the theoretical predictions for forward W+charm production (left) and for the invariant mass $m_{t\bar{t}}$ distribution in top-quark pair production (right). The theory calculations are shown both before (PDF4LHC15) and after profiling.

  - expected precision of the HL-LHC measurements is rather higher than the current PDF uncertainties ⇒ marked improvement once they are included in PDF4LHC15 via the Hessian profiling

PDF at HL-LHC (2)

- Scenarios: reduction factor applied to the systematic errors of the reference 8 TeV or 13 TeV measurements
  - optimistic (C): reduction of the systematic errors by a factor 2.5 (5) as compared to the reference 8 TeV (13 TeV) measurements
  - conservative (A): no reduction in systematic errors with respect to the 8 TeV reference
- Results:





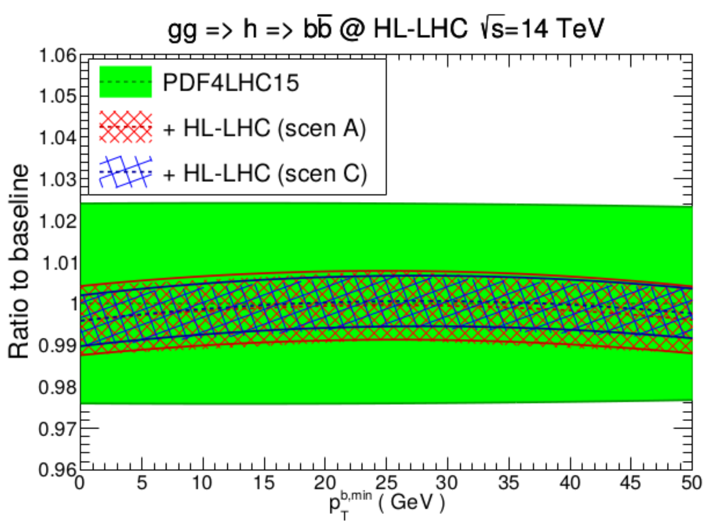
  - impact reasonably similar in both scenarios
    - use of processes which will benefit from a significant improvement in statistics
    - they tend to lie in kinematic regions where the PDFs themselves are generally less well determined
  - marked reduction of the PDF uncertainties in all cases
    - gluon PDF: improvement in the complete relevant range of momentum fraction x

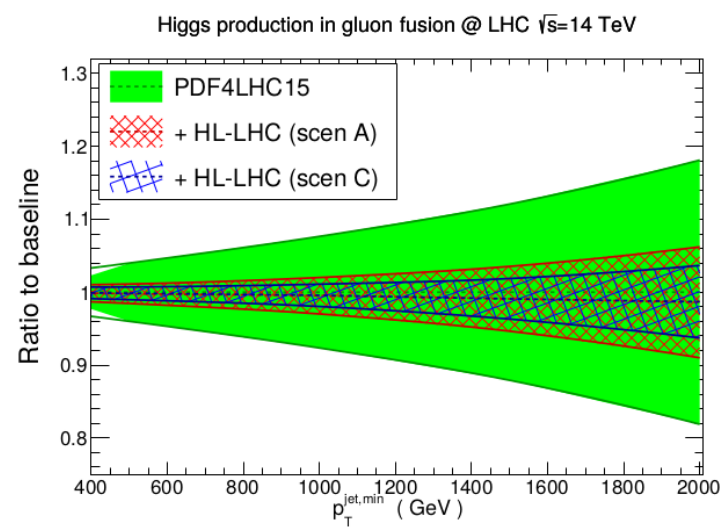
PDF at HL-LHC (3)

- Reduction of the PDF uncertainties as compared to the PDF4LHC15 baseline:

Ratio to baseline	$10\ \mathrm{GeV} \leq M_X \leq 40\ \mathrm{GeV}$	$40\ \mathrm{GeV} \leq M_X \leq 1\ \mathrm{TeV}$	$1\ \mathrm{TeV} \leq M_X \leq 6\ \mathrm{TeV}$
gluon-gluon	0.50 (0.60) ggH - ttH	0.28 (0.40)	0.22 (0.34)
quark-quark	0.74 (0.79)	0.37 (0.46) VBF	0.43 (0.59)
quark-antiquark	0.71 (0.76)	0.31 (0.40)	0.50 (0.60) ZH WH

- Predictions for SM Higgs production at √s = 14 TeV:





- Two caveats:
  - only a subset of all possible measurements of relevance for PDF fits at HL–LHC
  - possible data incompatibility has not been accounted for fully

Theoretical uncertainties ('YR2018')

- Theoretical uncertainties are assumed to be reduced by a factor of two with respect to the current knowledge
  - higher-order calculation
  - reduced parton distribution functions uncertainties
- Gluon fusion:

[Czakon, Harlander, Klappert, Niggetiedt '20]

Remove one source of uncertainty!

Future:

- light-quark mass effects
  - large logs to resum?

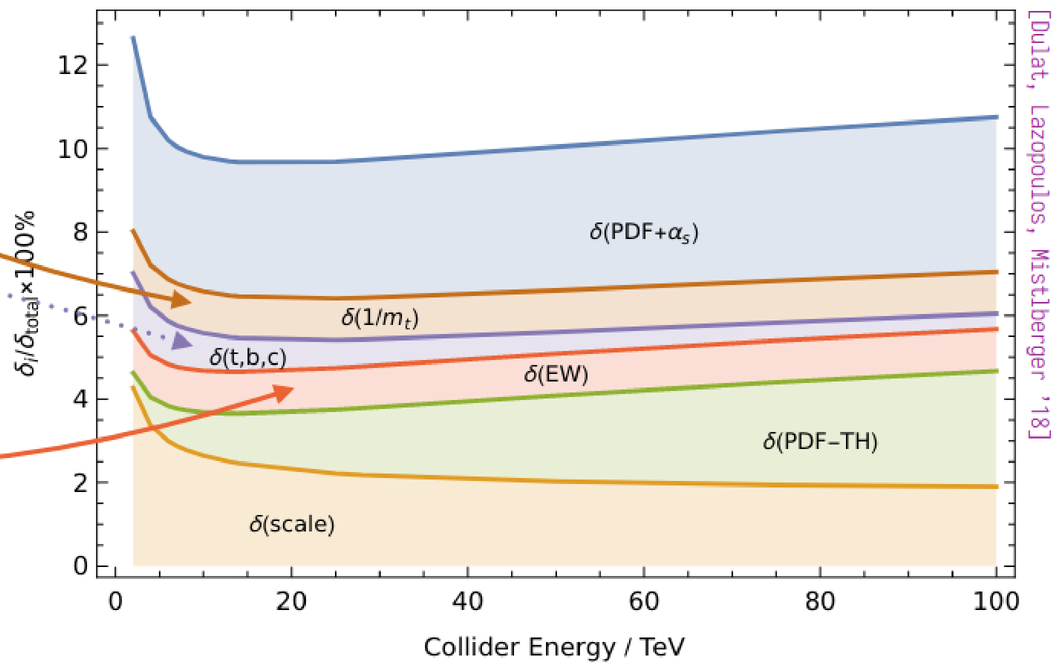
[Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer '20]

Reduce uncertainty: $\sim 1\,\% \rightarrow 0.6\,\%$

Future:

- quark-induced EW contributions
- large p_T^H?
- m_t dependence in QCD amplitude?

Sources of Uncertainties:

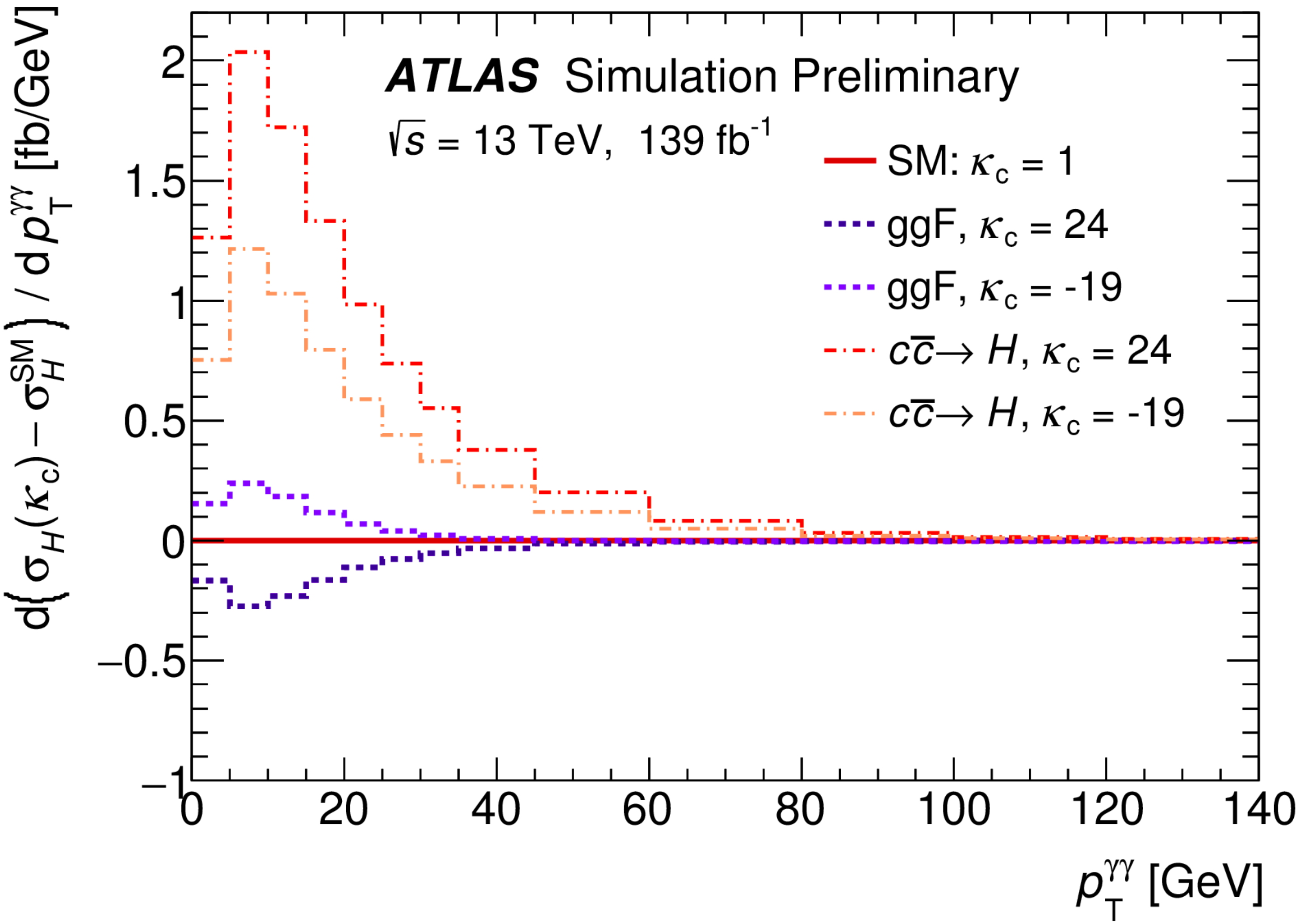


G. Salam

- $\delta(\mathrm{PDF}+\alpha_s)$ — more data & accurate determinations
- $\delta(\mathrm{PDF}-\mathrm{TH})$ — missing N³LO PDFs (AP kernels)

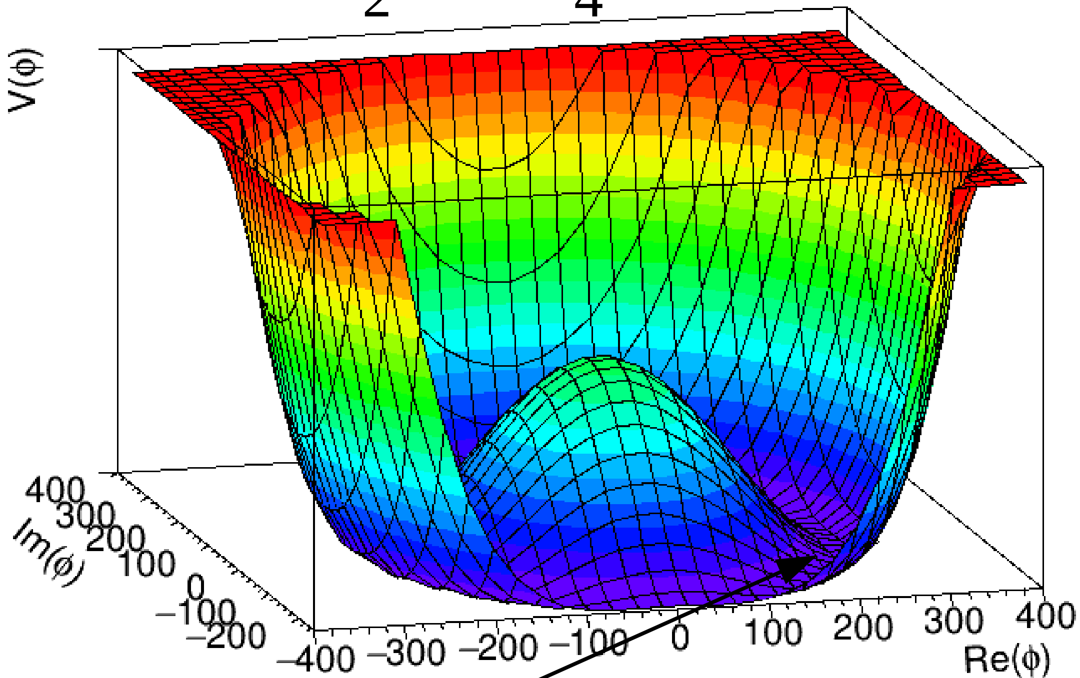
Differential cross-sections

- Effect of κ_c variations on p_T^{Higgs}:



Higgs self-couplings

- Higgs potential: $V(\Phi) = \frac{1}{2}\mu^2\Phi^2 + \frac{1}{4}\lambda\Phi^4$



- Approximation around the v.e.v:

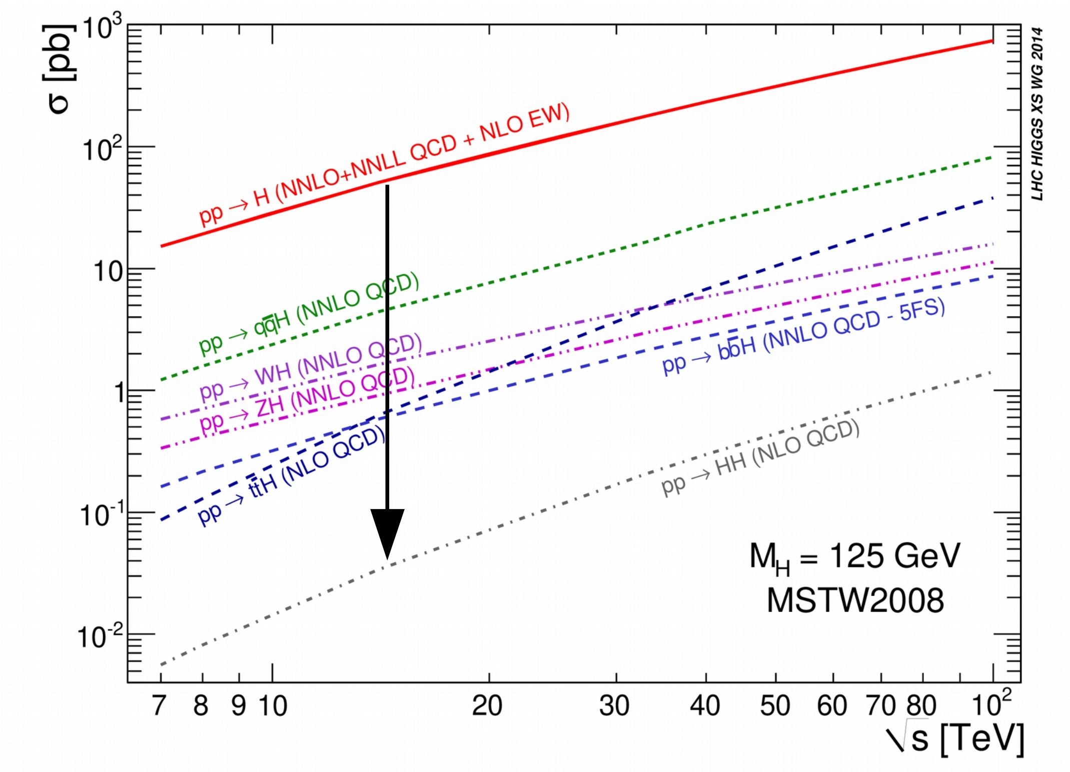
$$V(\Phi) \approx \underbrace{\lambda v^2 h^2}_{\text{mass term}} + \underbrace{\lambda v h^3 + \frac{1}{4}\lambda h^4}_{\text{self-coupling terms}}$$

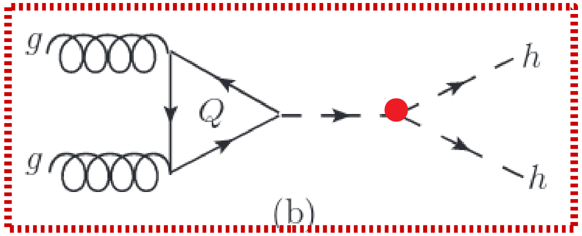
mass term self-coupling terms

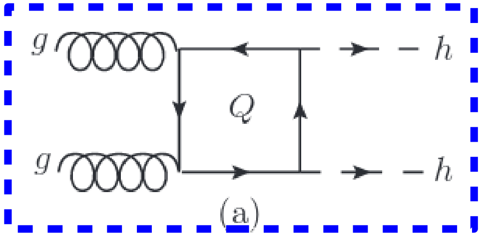
- λ known from v.e.v and Higgs mass: $\lambda = \frac{m_H^2}{2 \cdot v^2} \approx 0.13$
- BSM effects could change $\lambda \Rightarrow$ define deviation of tri-linear term: $\kappa_\lambda = \frac{\lambda_{HHH}}{\lambda_{HHH}^{SM}}$
  - no quartic terms considered here

Di-Higgs production at hadronic colliders (1)

- Main production mode: ggF
- Rare process of the Standard Model
  - destructive interference between triangle and box diagrams
  - σ(HH)/σ(H) = 0.1%



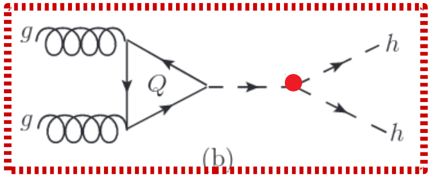


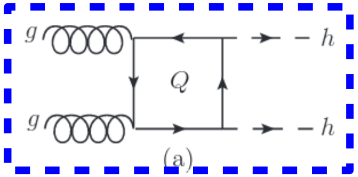


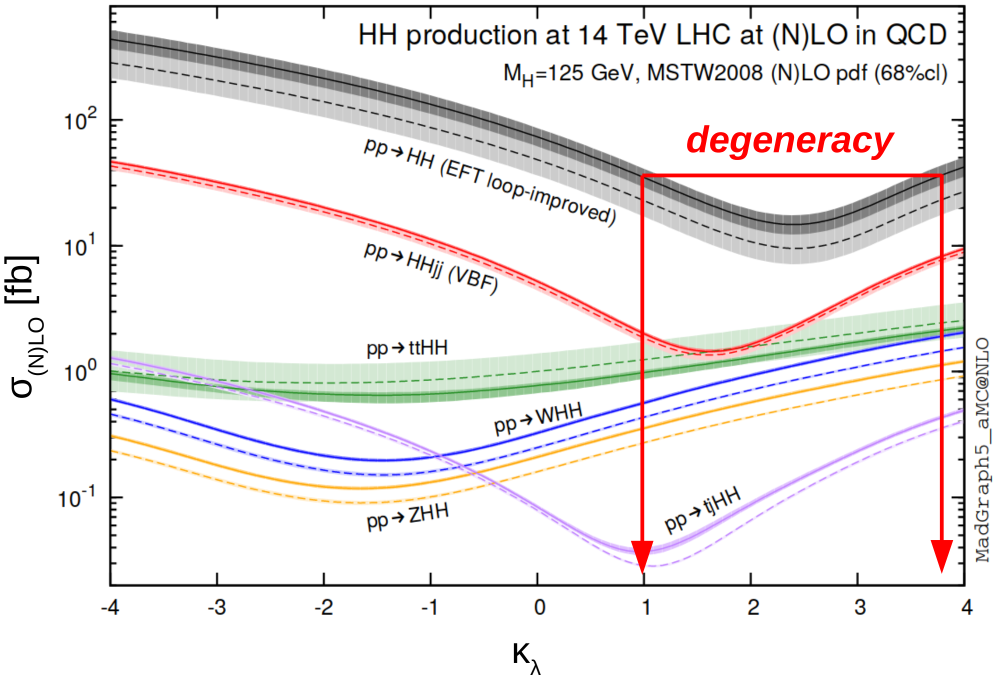
- State of the art NNLO calculation with finite m_t effects at NLO

Di-Higgs production at hadronic colliders (2)

- Self-couplings through
  - total HH cross section
  - differential cross section $d\sigma/dm_{HH}$







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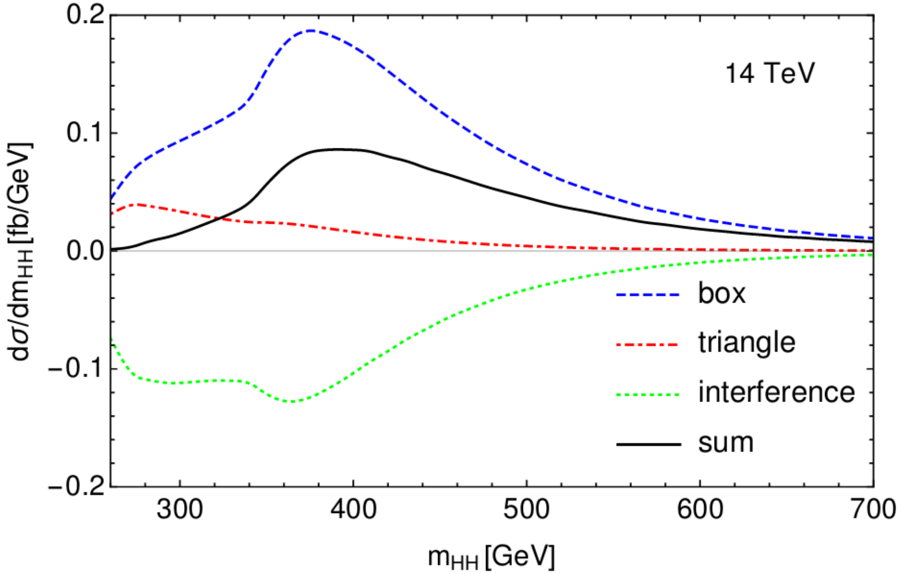

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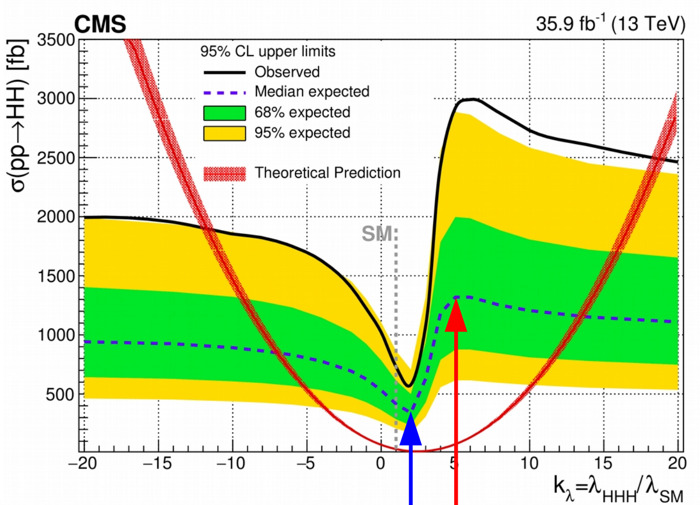
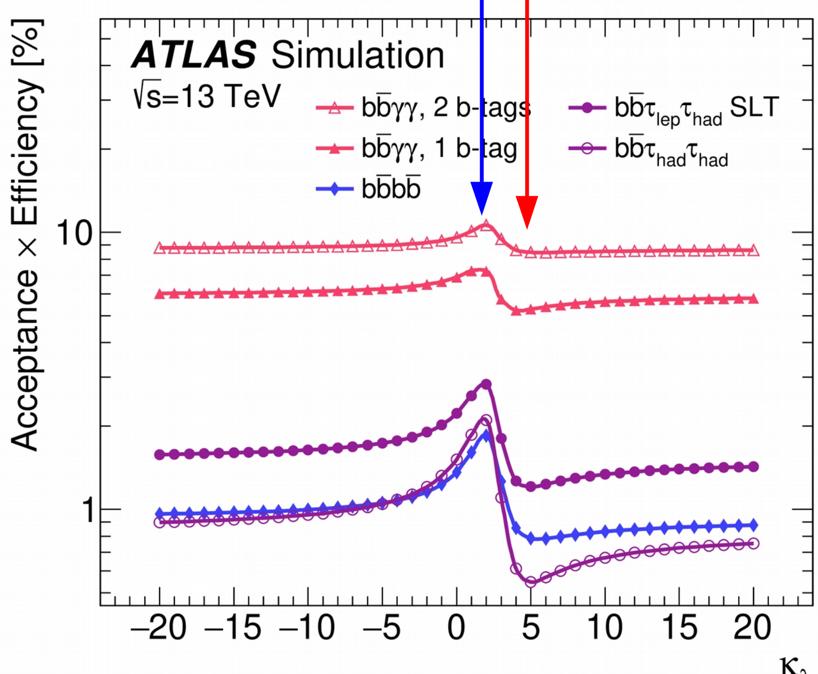
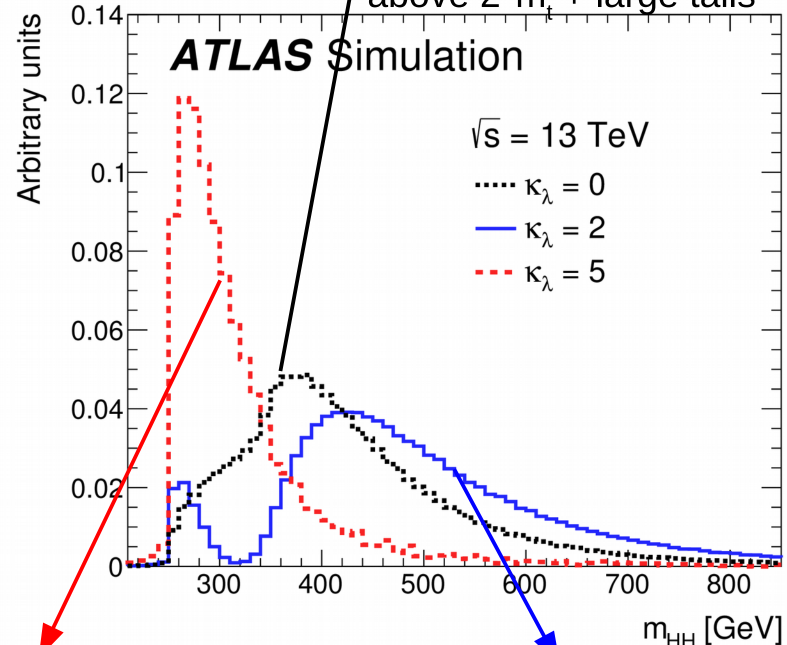
Di-Higgs production at hadronic colliders (3)

- Sensitivity to κ_λ directly related to the acceptance, so to the m_{HH} shape







κ_λ=0: no triangle ⇒ increase of cross-section above 2*m_t + large tails

κ_λ=5: interference at high m_{HH} ⇒ soft spectrum

κ_λ=2: max interference ⇒ deficit between 2*m_H and 2*m_t + large tails

$|\kappa_\lambda|$>10: trilinear dominant ⇒ peaks at 2*m_H

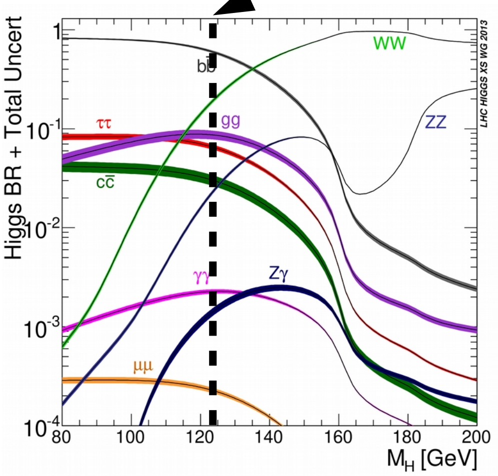
- NB: most analyses optimised for κ_λ=1

HH decays

- Many decay channels!

CERN seminar, 13th of Dec. 2011

It would be a very nice region for the Higgs to be → accessible at LHC in γγ, 4l, lνlν, bb, ττ



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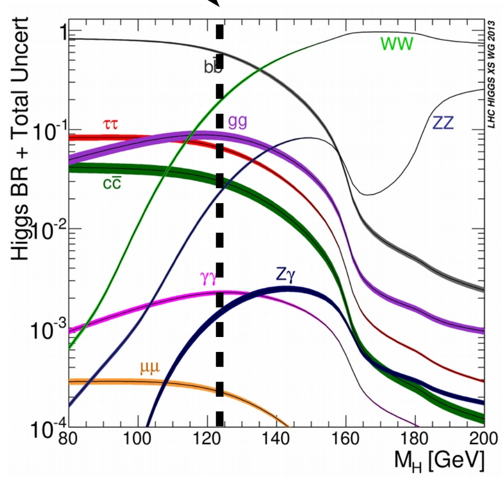

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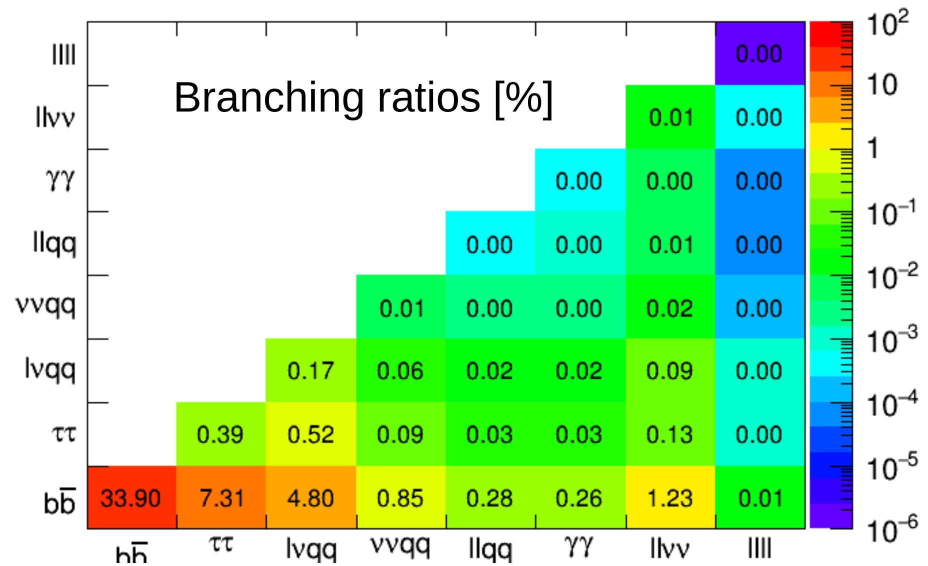
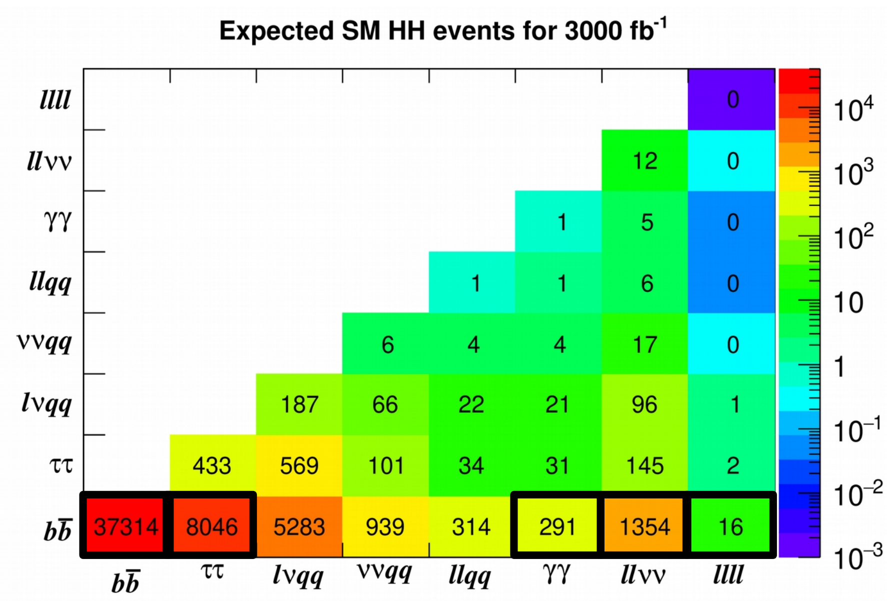


- In practice consider channels with $b\bar{b}$ (BR = 59%) to maximise the rate

Di-Higgs search

- Summary of channels/methods for HL-LHC studies:

	ATLAS	CMS	
bbbb	extrapolation	parametric	Largest BR ☺ Large multijet and tt bkg ☹
bbττ	extrapolation	parametric	Sizeable BR ☺ Relatively small bkg ☺
bbγγ	smearing	parametric	Small BR ☹ Good diphoton resolution ☺ Relatively small bkg ☺
bbVV (→lνlν)		parametric	Large BR ☺ Large bkg ☹
bbZZ (→4l)		parametric	Very small BR ☹ Very small bkg ☺



- Benefit from performance work of Technical design reports

- New analyses, either
  - extrapolations from Run-2 analyses
  - dedicated studies with smeared/parametric detector response, corresponding to pile-up of 200