Future prospects for Higgs physics at the LHC and beyond

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A results explosion!

In last year, big push to update prospects for high luminosity physics program at LHC

A large part of these projections relate to Higgs physics

Intense collaboration between ATLAS and CMS to create coherent picture

For CMS, public results can be found here

http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html

FTR-18-011 couplings, width, differential cross section

FTR-18-016 $H\rightarrow$invisible

FTR-18-017 $H\rightarrow\tau\tau$ in MSSM

FTR-18-019 Double Higgs production

FTR-18-020 ttH, $H\rightarrow\gamma\gamma$ and self-coupling constraints

FTR-18-035 Exotic decays

FTR-18-040 $H\rightarrow ZZ$ at high mass

This talks uses many results from these documents

Systematic uncertainties

This is the crucial aspect of these projections

CMS mostly considering two scenarios:

- S1: "Run-2" systematics
  - Independent on integrated luminosity
  - CMS performance unchanged
- S2: "YR18" systematics
  - Theory scaled by ½
  - Experimental scaled by 1/sqrt(L)
    - With a cut-off to a reasonable expected limit on uncertainty with CMS upgrades

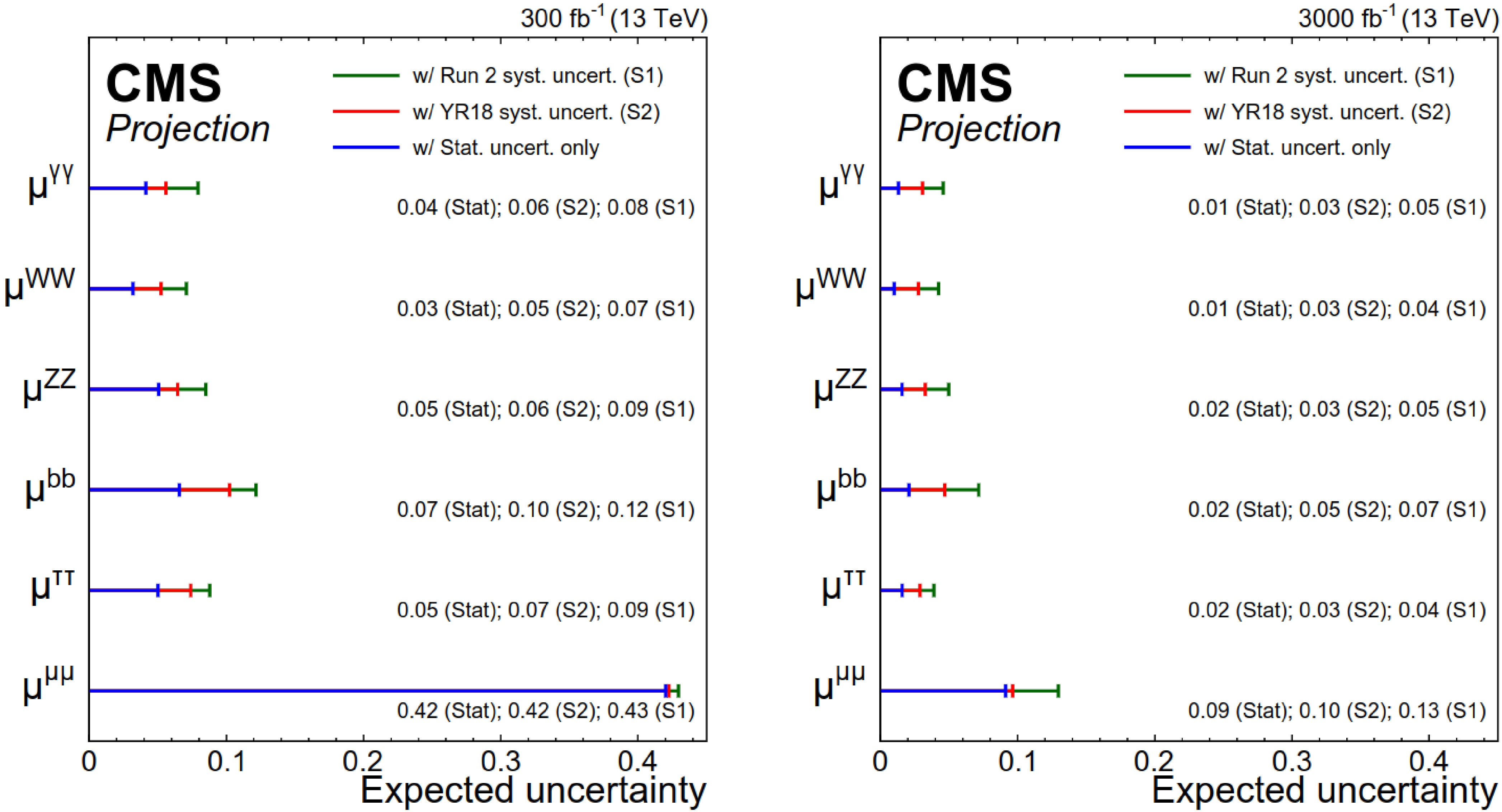
A pinch of pessimism: 13 TeV (but not much different for h_{125})

Limits to systematics at high lumi

Source	Component	Run 2 uncertainty	Projection minimum uncertainty
Muon ID		1–2%	0.5%
Electron ID		1–2%	0.5%
Photon ID		0.5–2%	0.25–1%
Hadronic tau ID		6%	2.5%
Jet energy scale	Absolute	0.5%	0.1–0.2%
	Relative	0.1–3%	0.1–0.5%
	Pileup	0–2%	Same as Run 2
	Method and sample	0.5–5%	No limit
	Jet flavour	1.5%	0.75%
	Time stability	0.2%	No limit
Jet energy res.		Varies with p_T and η	Half of Run 2
MET scale		Varies with analysis selection	Half of Run 2
b-Tagging	b-/c-jets (syst.)	Varies with p_T and η	Same as Run 2
	light mis-tag (syst.)	Varies with p_T and η	Same as Run 2
	b-/c-jets (stat.)	Varies with p_T and η	No limit
	light mis-tag (stat.)	Varies with p_T and η	No limit
Integrated lumi.		2.5%	1%

Signal strength: decay modes

$$\mu = \frac{\sigma_{meas}}{\sigma_{SM}}$$



With 3 ab^{-1}, systematics are the limiting factor for *most* of the final states

Not really a surprise, but...

Systematics: theory vs experiment

		300 fb^{-1} uncertainty [%]					3000 fb^{-1} uncertainty [%]				
		Total	Stat	SigTh	BkgTh	Exp	Total	Stat	SigTh	BkgTh	Exp
$\mu^{\gamma\gamma}$	S1	7.9	4.1	4.8	0.3	4.8	4.6	1.3	3.5	0.3	2.6
	S2	5.6	4.1	2.7	0.3	2.6	3.1	1.3	2.1	0.3	1.7
μ^{WW}	S1	7.1	3.2	4.9	1.8	3.5	4.2	1.0	3.7	1.0	1.4
	S2	5.2	3.2	2.7	1.4	2.8	2.8	1.0	2.2	0.9	1.1
μ^{ZZ}	S1	8.5	5.1	5.1	0.4	4.5	5.0	1.6	3.5	1.9	2.5
	S2	6.4	5.1	2.9	0.3	2.7	3.3	1.6	2.1	0.7	1.7
μ^{bb}	S1	12.2	6.6	4.8	7.0	5.6	7.2	2.1	5.4	3.6	2.3
	S2	10.2	6.6	2.4	5.6	4.9	4.7	2.1	2.5	2.9	1.7
$\mu^{\tau\tau}$	S1	8.8	5.0	5.1	0.9	5.0	3.9	1.6	2.6	1.5	1.9
	S2	7.4	5.0	3.3	0.9	4.3	2.9	1.6	1.8	0.6	1.4
$\mu^{\mu\mu}$	S1	43.0	42.0	5.7	0.8	5.9	13.0	9.1	5.2	0.8	7.6
	S2	42.2	42.0	3.0	0.8	2.6	9.6	9.1	2.6	0.8	1.7

Systematics: theory vs experiment

		300 fb^{-1} uncertainty [%]					3000 fb^{-1} uncertainty [%]				
		Total	Stat	SigTh	BkgTh	Exp	Total	Stat	SigTh	BkgTh	Exp
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μ^{WW}	S1	7.1	3.2	4.9	1.8	3.5	4.2	1.0	3.7	1.0	1.4
	S2	5.2	3.2	2.7	1.4	2.8	2.8	1.0	2.2	0.9	1.1
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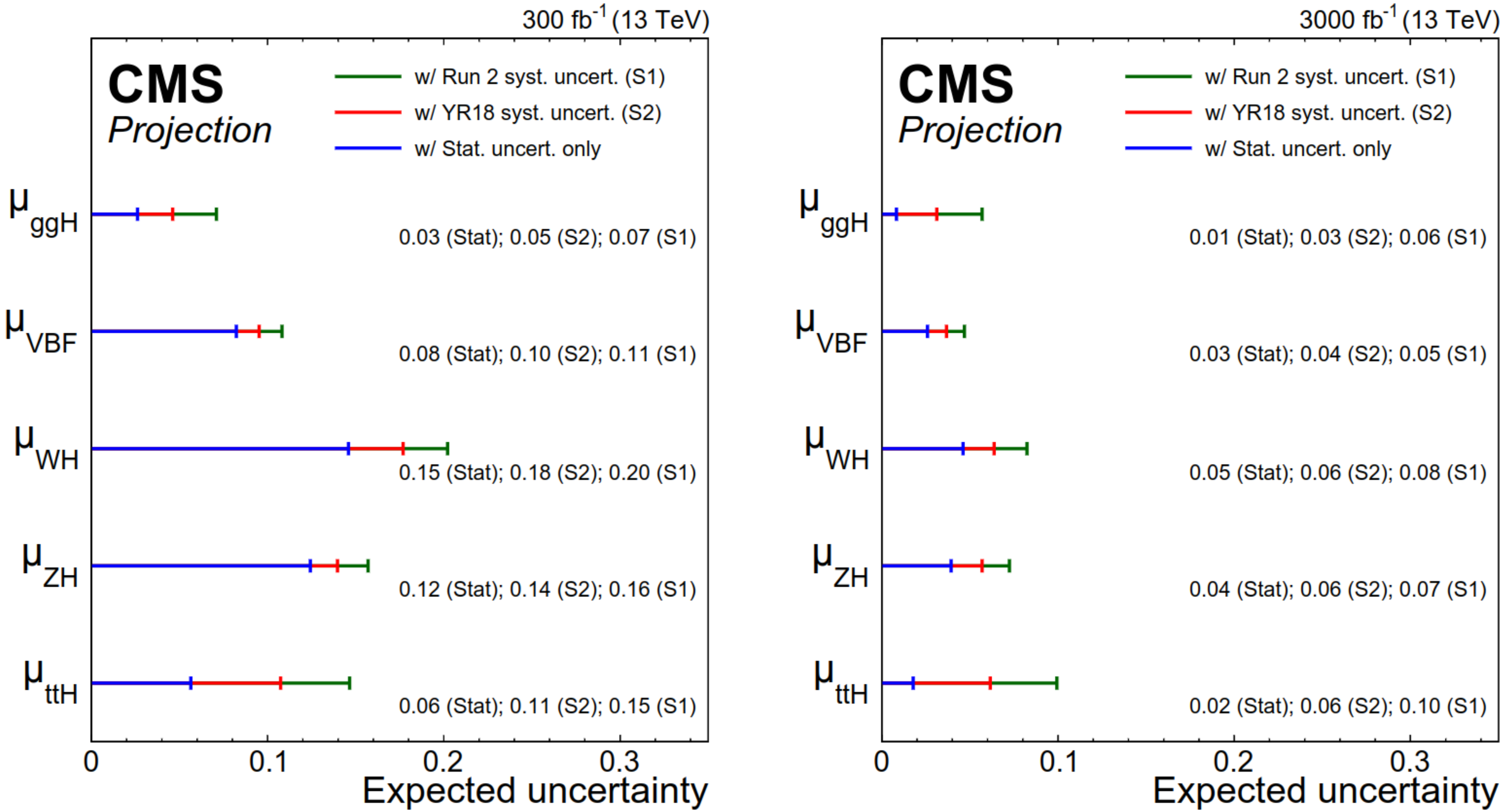
	S2	42.2	42.0	3.0	0.8	2.6	9.6	9.1	2.6	0.8	1.7

Target of few % uncertainty at end of LHC seems feasible in S2
Theory uncertainties become dominant at high lumi (apart from μμ)
Beware: high correlations arise at 3 ab^{-1}

Signal strength: production channels

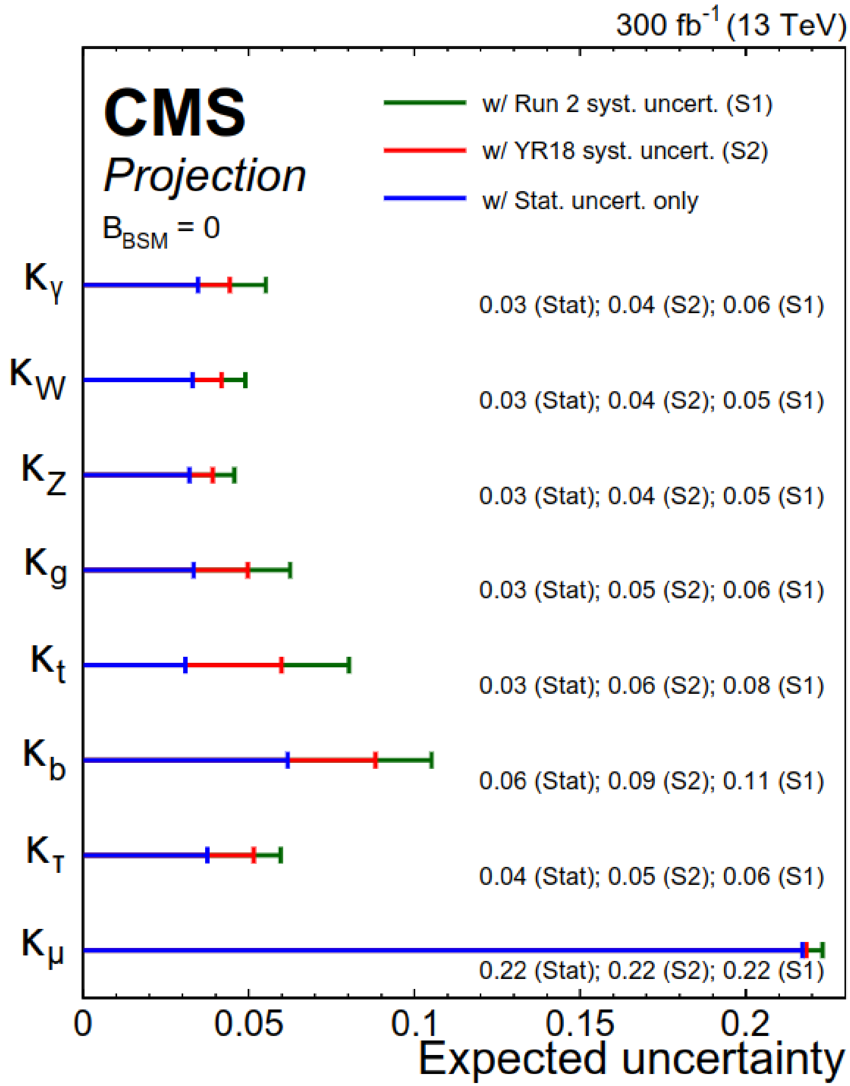
$\mu = \frac{\sigma_{meas}}{\sigma_{SM}}$

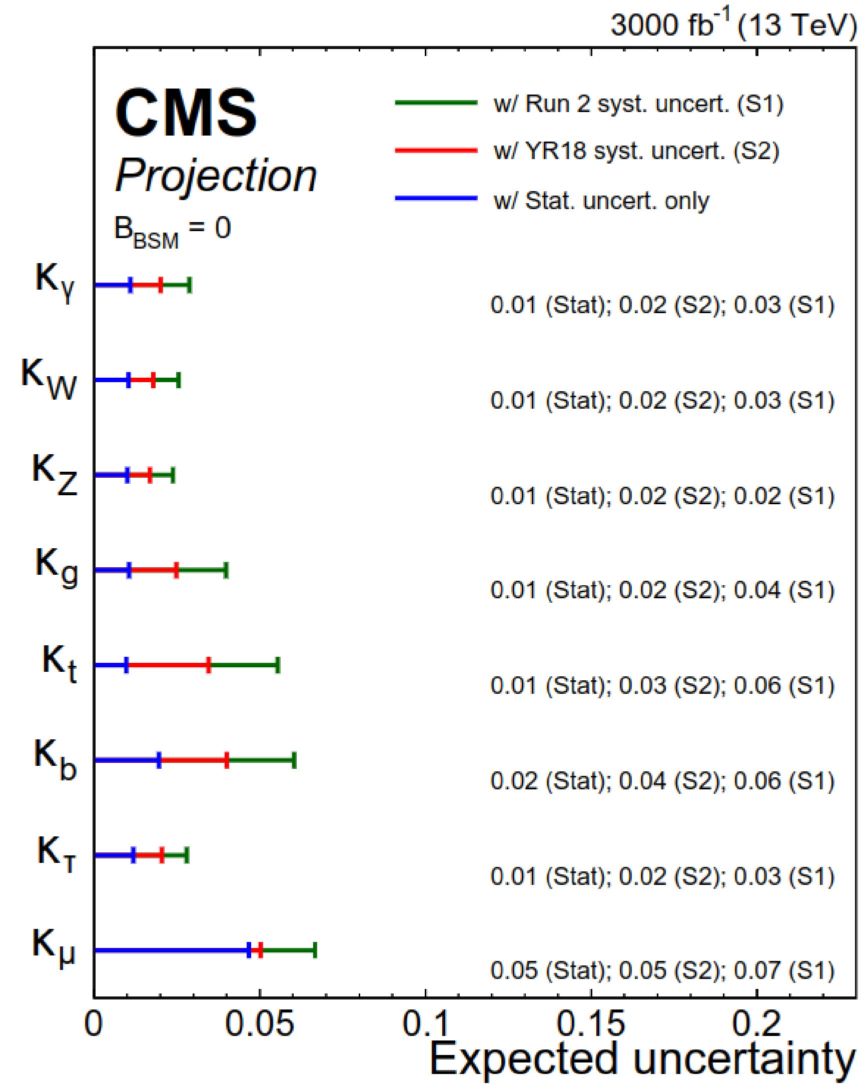


At 3 ab^{-1}, still statistically limited in all but ggH and ttH
This information on signal strength can be further processed...

Higgs coupling modifiers

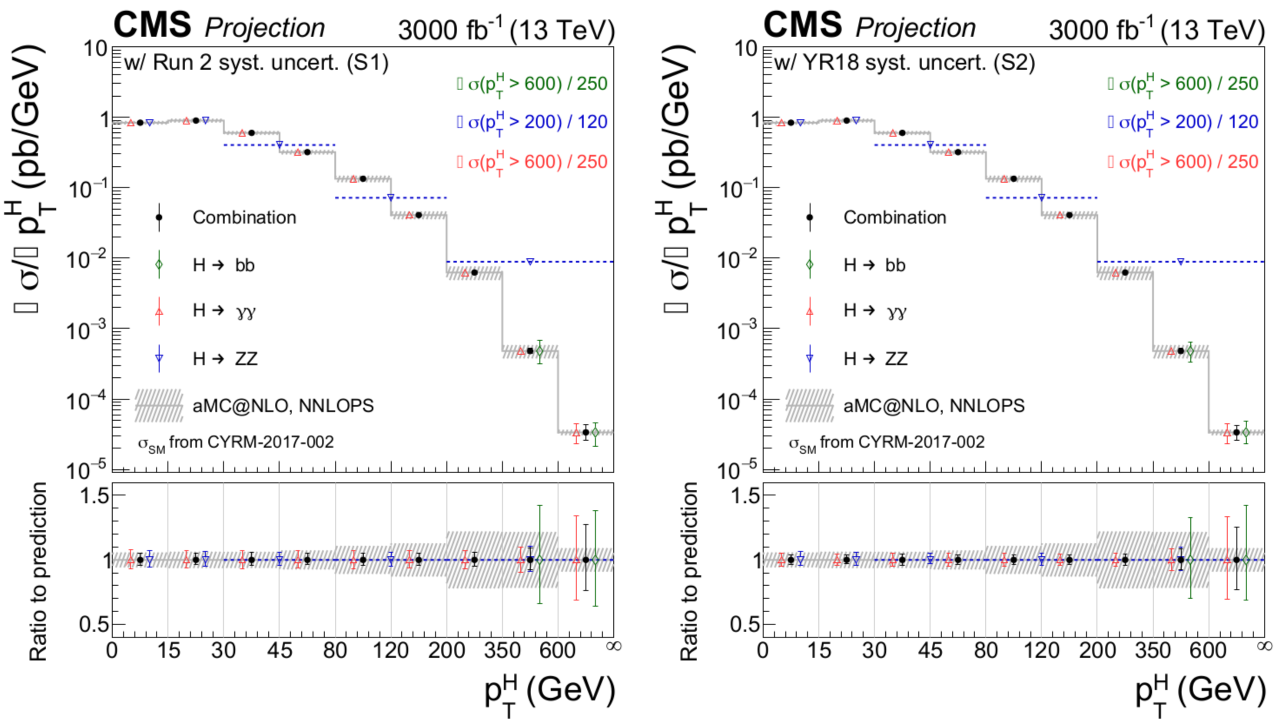
$$\kappa = \frac{g_{meas}}{g_{SM}}$$





All coupling uncertainties with a few % at 3 ab^{-1}
Muon coupling < 10% in both scenarios
"Signal theory" generally the largest uncertainty at 3 ab^{-1}
Caveat: larger correlations wrt signal strength
Reminder: quark/lepton couplings within $2^{nd}/3^{rd}$ families crucial for NP searches..

Differential cross sections

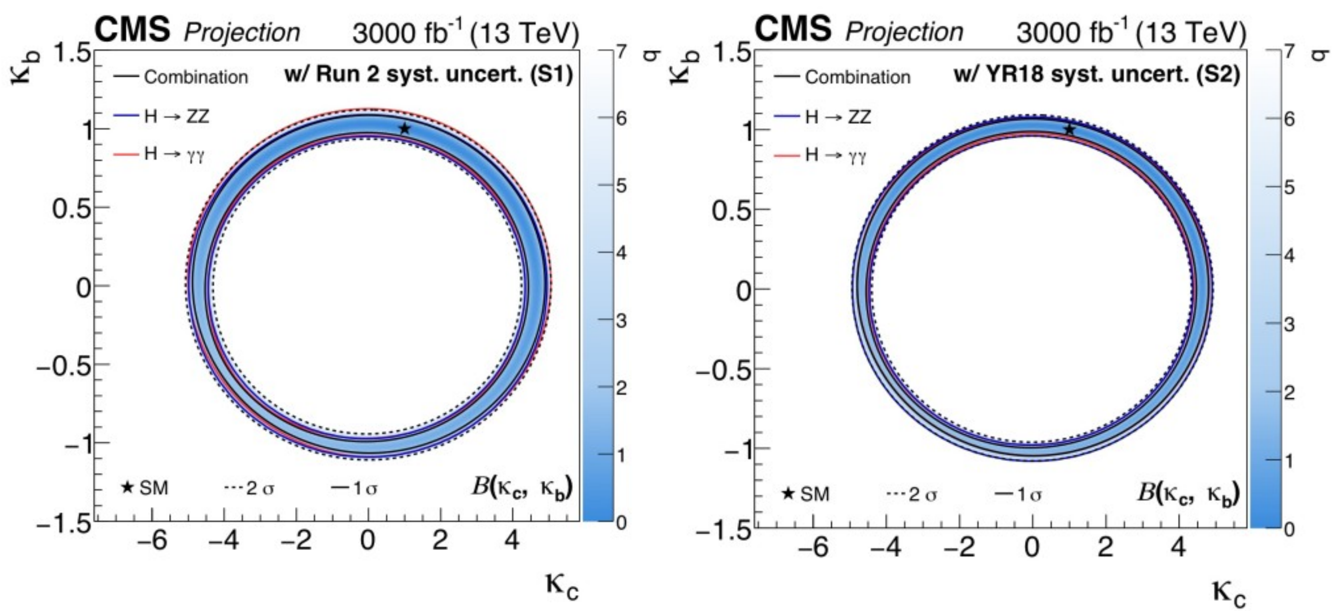


Main conclusions:

- At 3 ab^{-1} uncertainties reduced by factor 10 wrt now
- Higher p_T bins still statistically Dominated
- Lower p_T bins theory limited

Can use the p_T distribution to Constrain couplings: (b,c) or (g,t)

Additional information that can be used in a global fit



Higgs width

Remind: direct measurement "impossible" at LHC

Workaround: measure the ration between on-shell and off-shell cross sections

➔ Only one depends on Γ_H, and great reduction of systematics

CMS in $H \rightarrow VV$

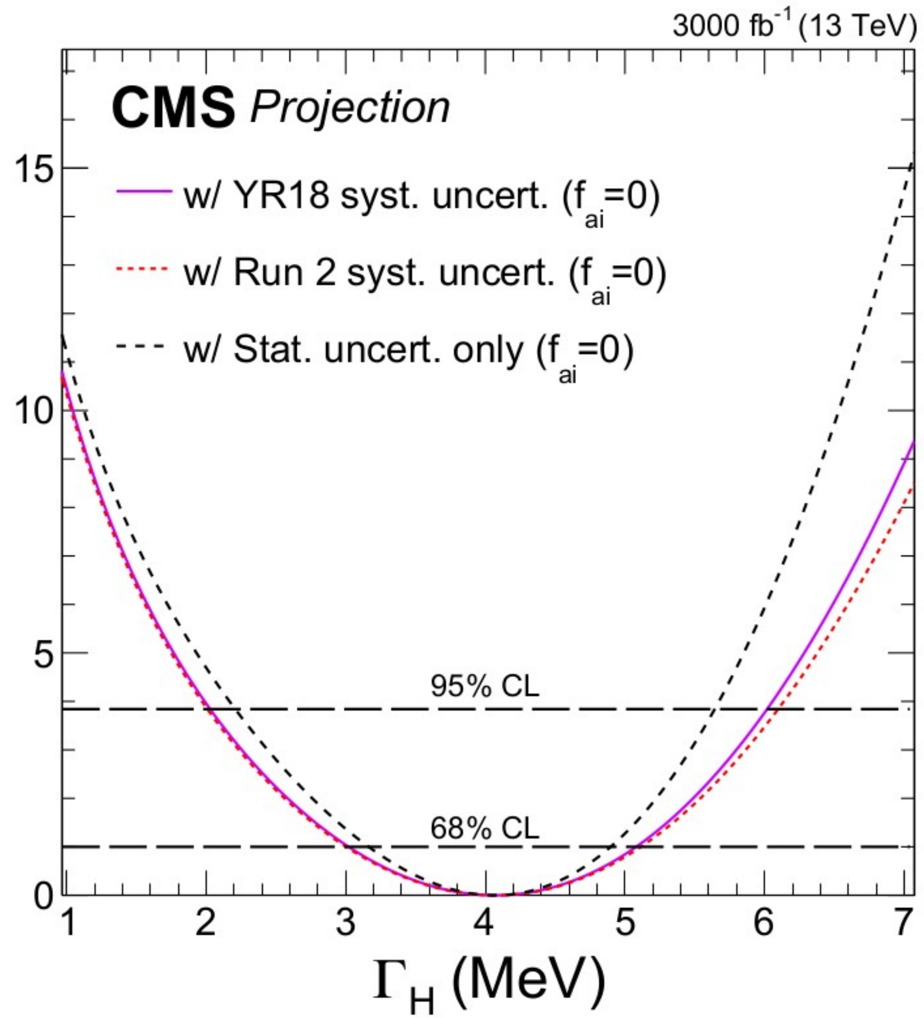
➔ Current limit is 9 MeV @ 95% CL

Still statistically limited

Caveat: assumptions…

One can also put limits on

anomalous couplings



H → invisible

Projections to 3 ab^{-1} show search limited by systematic uncertainties

Not the biggest surprise: tough analysis in pp environment, with great experimental challenges

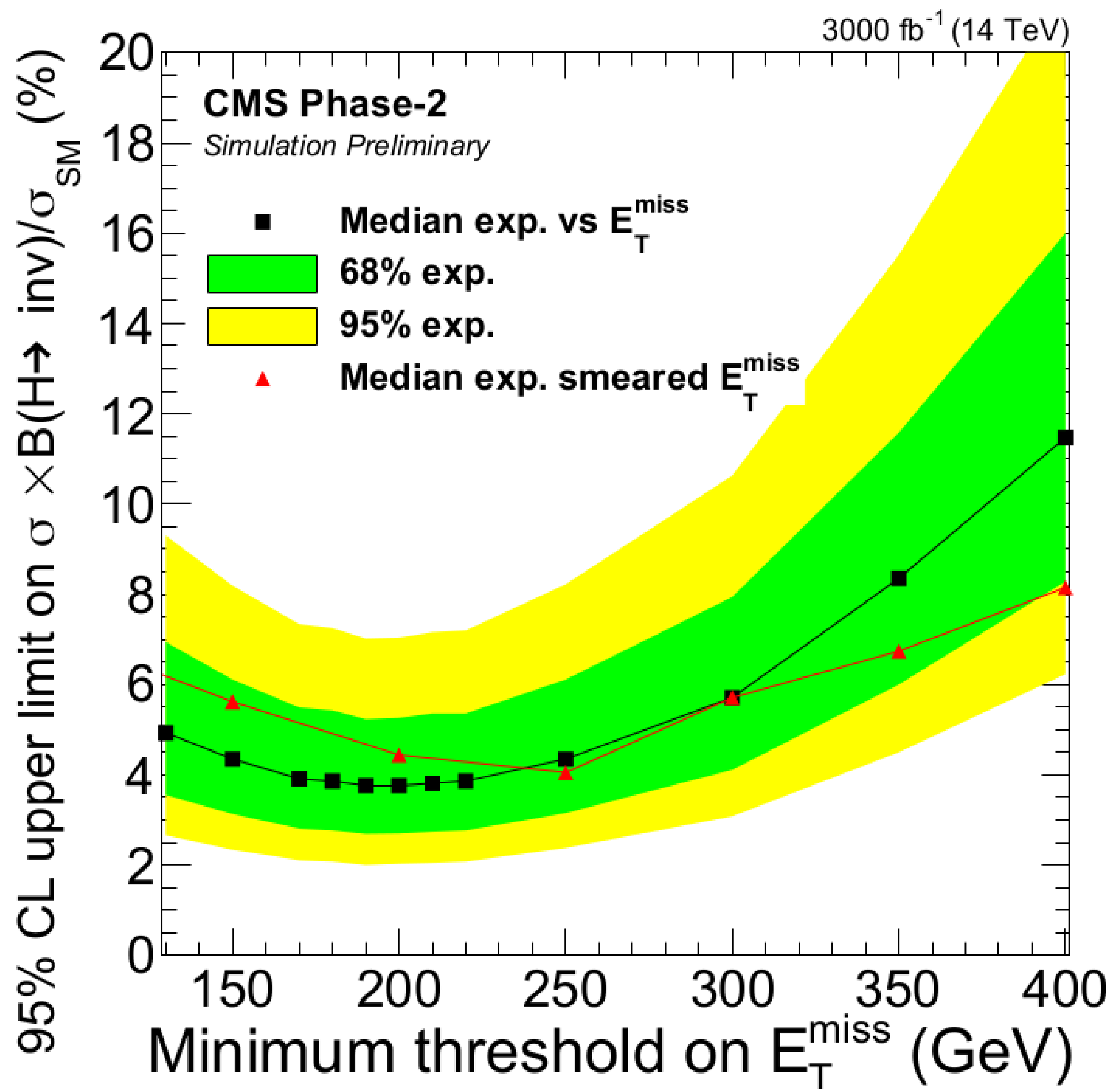
Interesting exercise:

Test scenario with missing mass resolution worse by factor 2

- Case of *extreme* PU conditions

Conclusion:

Analysis is flexible enough to yield similar limits with selection re-optimization



Di-Higgs production

H-H production naturally emerges from the Standard Model

Potential near minimum:

$$V^{SM}(h) = \frac{m_h^2}{2} h^2 + \lambda_3^{SM} v h^3 + \lambda_4^{SM} h^4$$

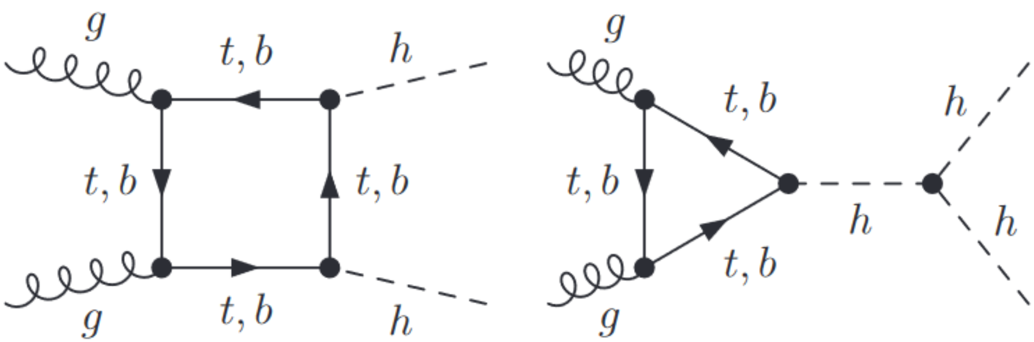
m_H → mass term

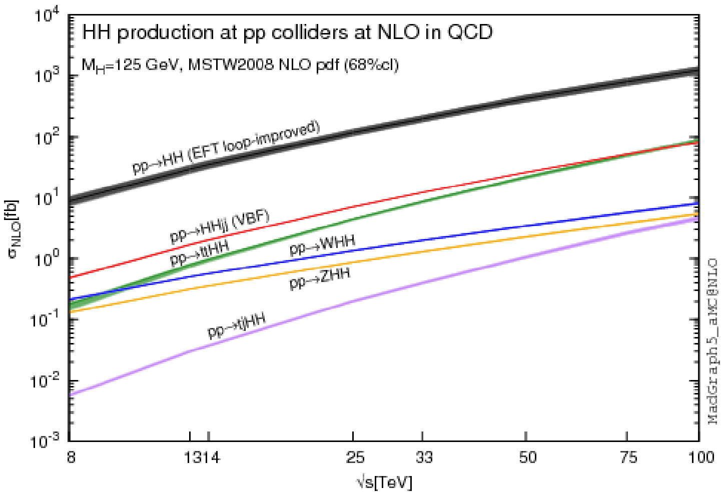
$$\lambda_4 = \frac{m_H^2}{8 v^2}$$ Quartic self-coupling

$$\lambda_3 = \frac{m_H^2}{2 v}$$ Trilinear self-coupling

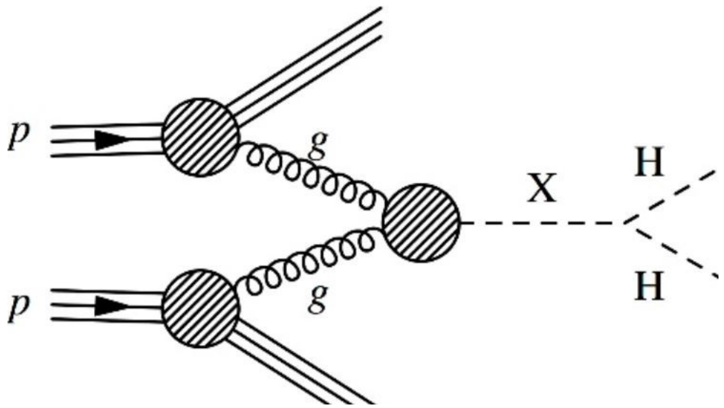
H-H production at LHC

In SM, typically non-resonant

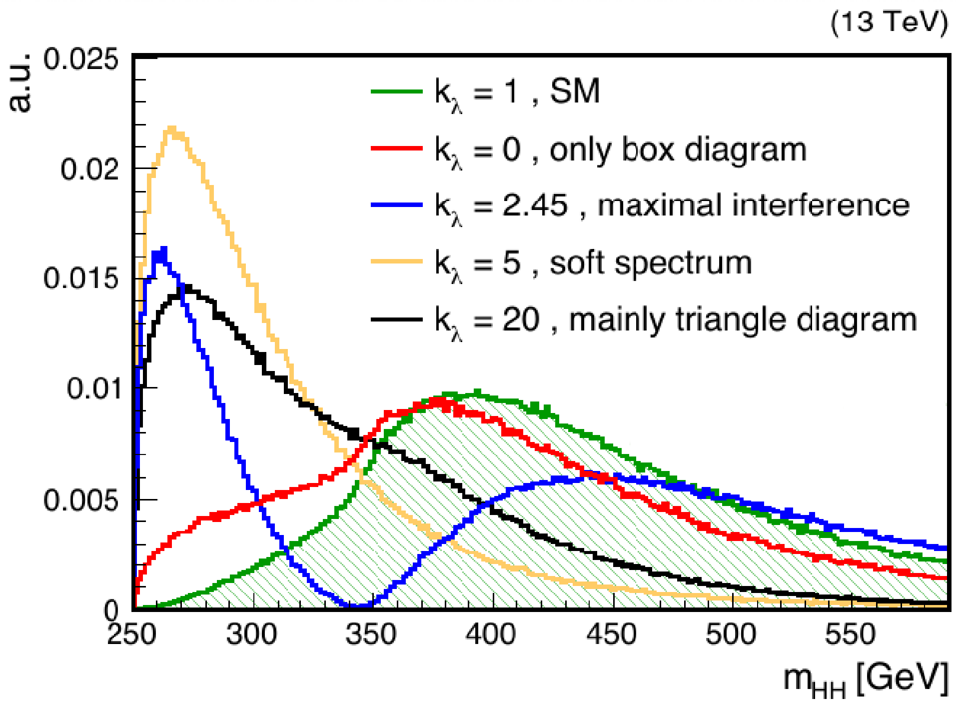




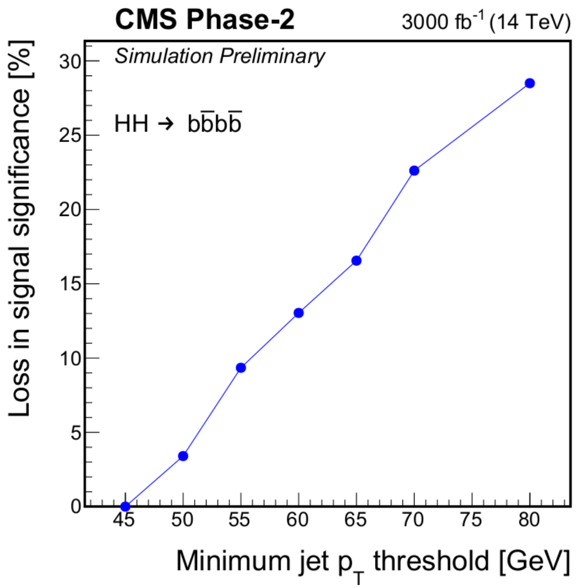
Nature doesn't help: destructive interference

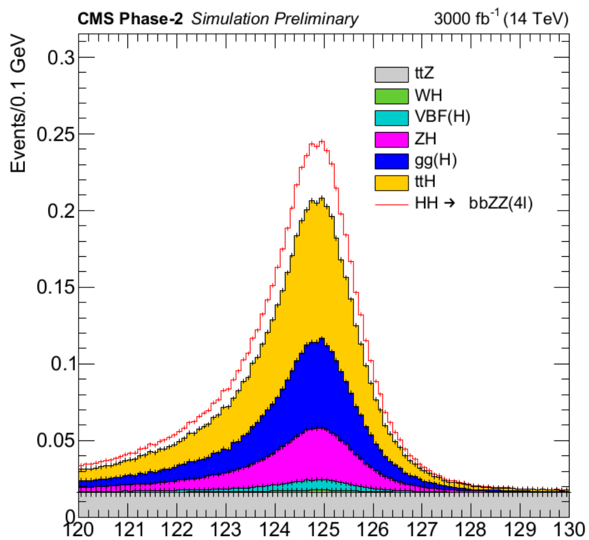


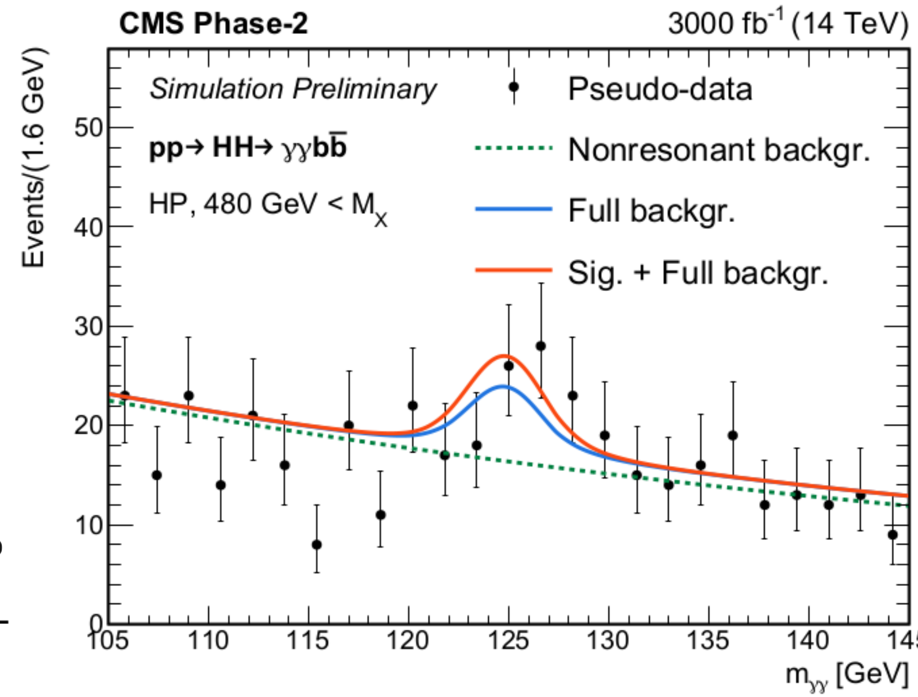
NP can be resonant or non-resonant
(expansion on higher dim operators)

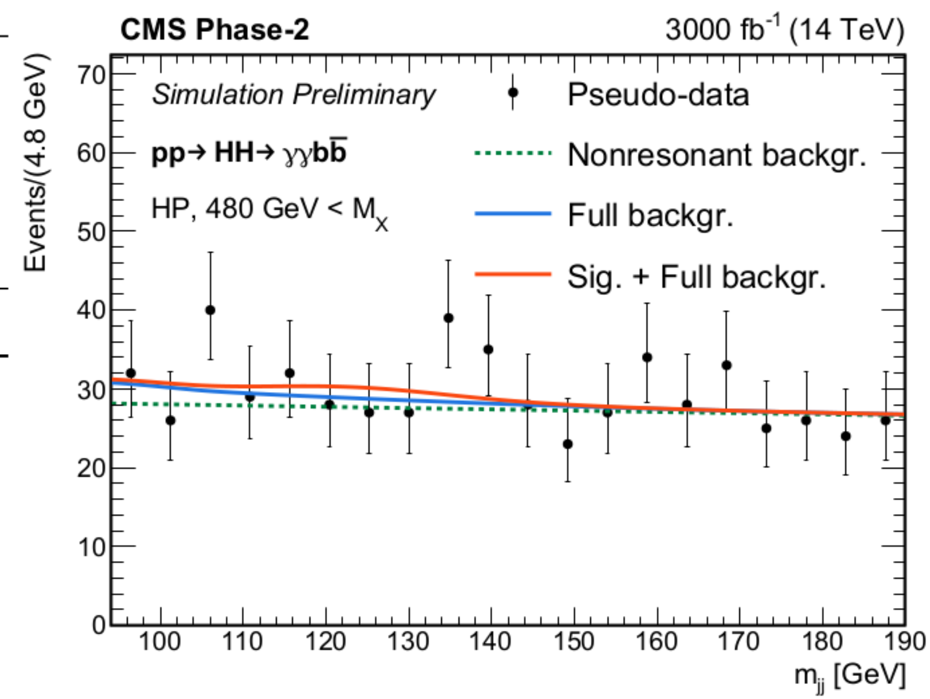


A plethora of final states







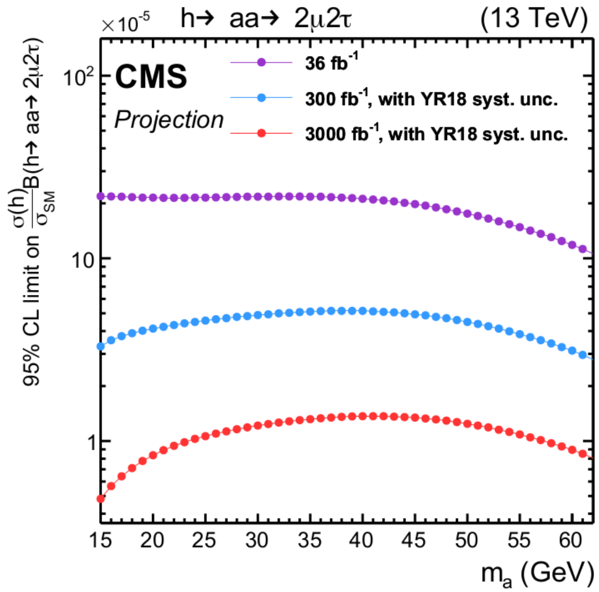


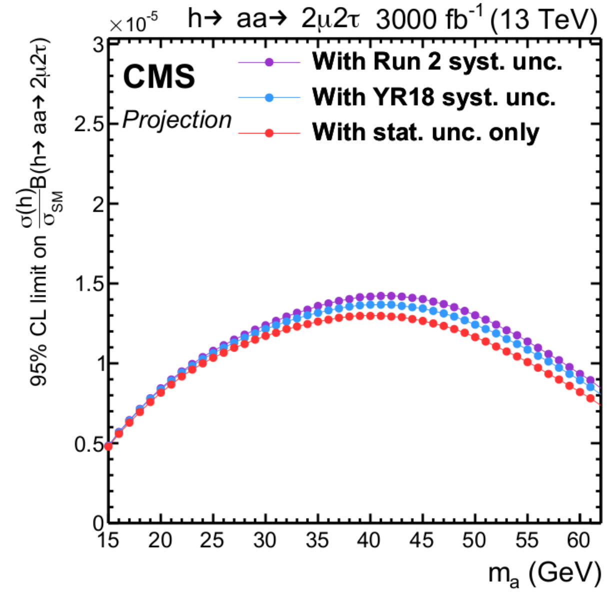
Channel	Significance		95% CL limit on $\sigma_{HH}/\sigma_{HH}^{SM}$	
	Stat. + syst.	Stat. only	Stat. + syst.	Stat. only
bbbb	0.95	1.2	2.1	1.6
bb$\tau\tau$	1.4	1.6	1.4	1.3
bbWW($\ell\nu\ell\nu$)	0.56	0.59	3.5	3.3
bb$\gamma\gamma$	1.8	1.8	1.1	1.1
bbZZ($\ell\ell\ell\ell$)	0.37	0.37	6.6	6.5
Combination	2.6	2.8	0.77	0.71

Combination shows LHC won't provide a complete picture on di-Higgs physics

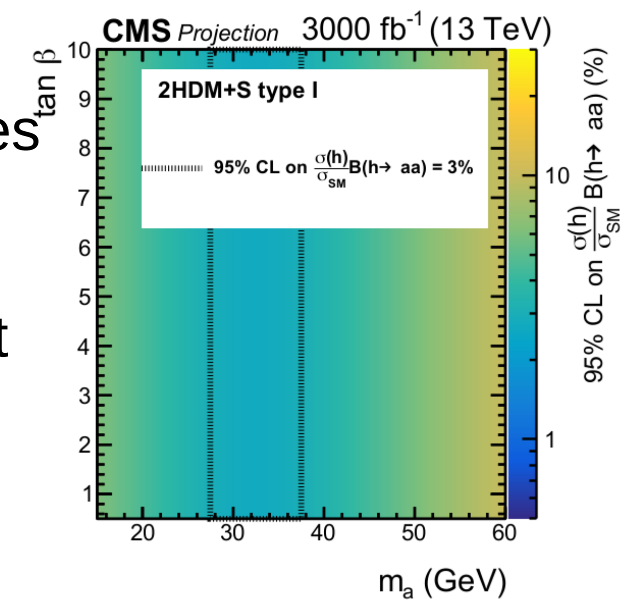
Exotic decays

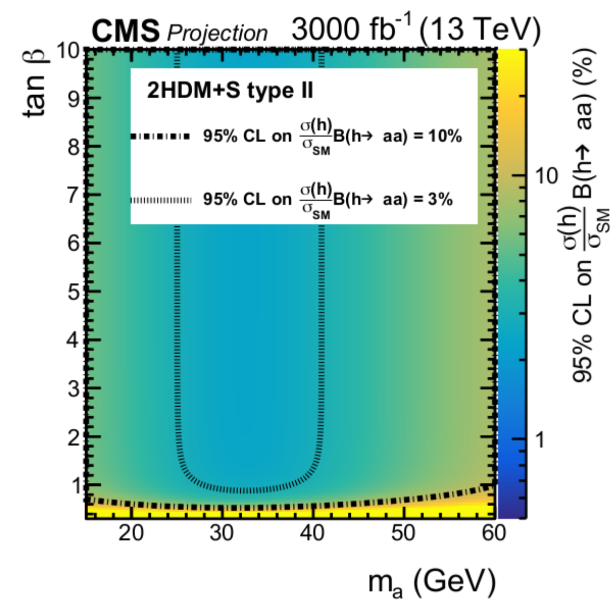
- Lots of possible decays to be studied at HL-LHC
  - H → meson + γ
  - H → quarkonium
  - H → aa
  - H → hh, Zh, Ah
  - LFV





- For now, projections mostly for light pseudoscalar searches
- Some analyses need to be re-thought for HL environment





Higgs at future colliders

Studies emerging to provide more complete view on Higgs perspectives in future colliders

Fundamental step into decision making process for next generation accelerators

Many scenarios, difficult to summarize all considerations

Expected relative precision

kappa-0	HL-LHC	LHeC	HE-LHC	ILC_{250}	ILC_{500}	$CLIC_{380}$	$CLIC_{1500}$	$CLIC_{3000}$	CEPC	FCC-ee_{240}	FCC-ee_{365}	FCC-ee/eh/hh
κ_W (%)	1.9	0.75	1.0	1.8	0.29	0.86	0.17	0.11	1.3	1.3	0.43	0.15
κ_Z (%)	1.6	1.2	0.95	0.29	0.23	0.5	0.26	0.23	0.13	0.2	0.17	0.12
κ_g (%)	2.4	3.6	1.5	2.3	0.97	2.5	1.3	0.9	1.5	1.7	1.0	0.52
κ_γ (%)	1.9	7.5	1.2	6.7	3.4	98⋆	5.0	2.2	3.7	4.7	3.9	0.35
$\kappa_{Z\gamma}$ (%)	10.6	–	4.0	99⋆	86⋆	120⋆	15	6.9	8.2	81⋆	75⋆	0.7
κ_c (%)	–	4.0	–	2.5	1.3	4.3	1.8	1.4	2.2	1.8	1.3	0.95
κ_t (%)	2.8	–	2.1	–	6.9	–	–	2.6	–	–	–	1.0
κ_b (%)	3.5	2.1	2.3	1.8	0.58	1.9	0.48	0.38	1.2	1.3	0.67	0.45
κ_μ (%)	4.6	–	1.9	15	9.4	320⋆	13	5.8	8.9	10	8.9	0.42
κ_τ (%)	1.8	3.3	1.3	1.9	0.7	3.0	1.3	0.89	1.3	1.4	0.73	0.49

collider	(1) di-H excl.
HL-LHC	$^{+60}_{-50}$% (50%)
HE-LHC	10-20% (n.a.)
ILC_{250}	–
ILC_{350}	–
ILC_{500}	27% (27%)
$CLIC_{380}$	–
$CLIC_{1500}$	36% (36%)
$CLIC_{3000}$	$^{+11}_{-7}$% (n.a.)
FCC-ee_{240}	–
FCC-ee_{365}	–
FCC-ee/eh/hh	5% (5%)
CEPC	–

Di-Higgs: cubic self-coupling

Upper bounds from rarer decays

	HL-LHC	+LHeC	+HE-LHC	+ILC_{500}	+$CLIC_{3000}$	+CEPC	+FCC-ee_{240}	+FCC-ee/eh/hh
κ_u	570.	320.	420.	330.	430.	290.	310.	280.
κ_d	270.	150.	200.	160.	200.	140.	140.	130.
κ_s	13.	7.3	9.4	7.5	9.9	6.6	7.	6.4
κ_c	1.2		0.87	measured directly				

from arXiv:1905.03764

Conclusions

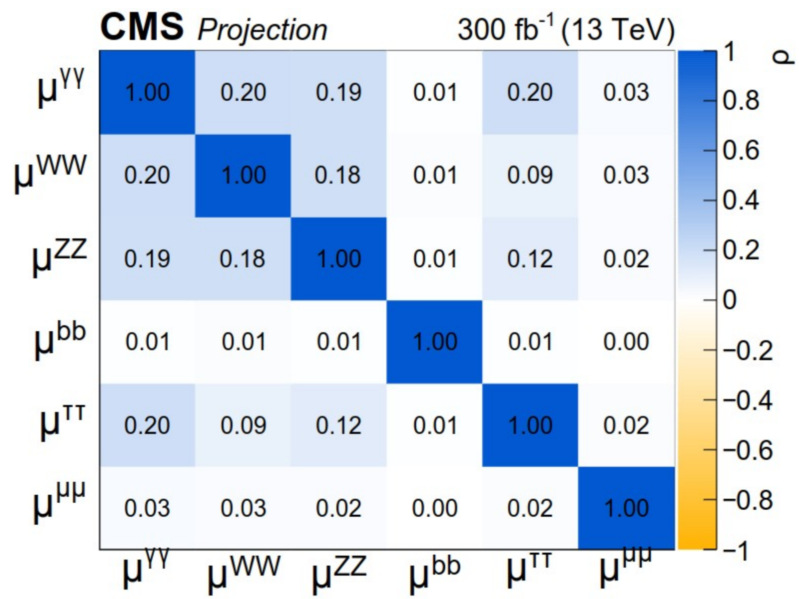
- CMS on track to provide coherent view on Higgs perspectives during the lifetime of the experiment
- Capitalized on Run-II experience
  - What are the critical areas?
  - Where will theory uncert. *hit us the most*?
    - Cross-collaboration dialogue with theory community fundamental
  - Positive message: in some way, we are always pessimistic
    - Difficult to account for new ideas

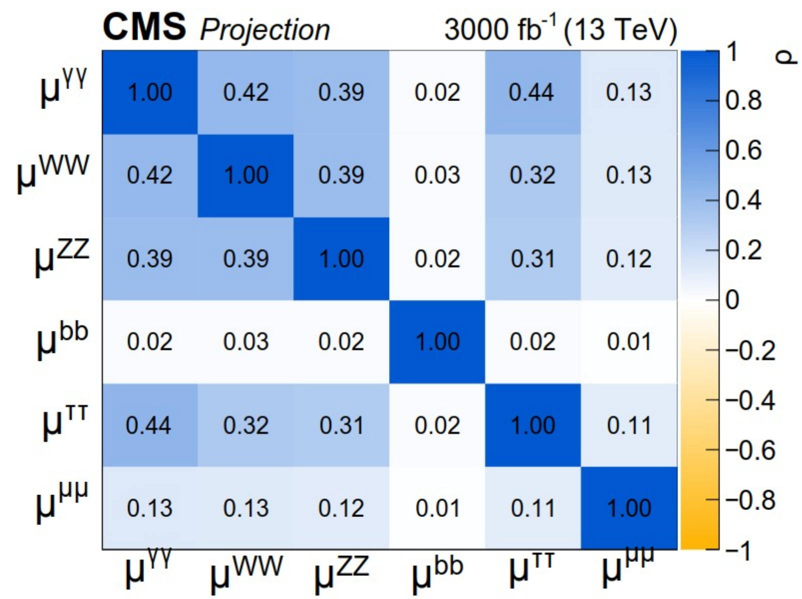
Single-Higgs physics will see it’s natural conclusion at LHC with a 3 ab^{-1} dataset

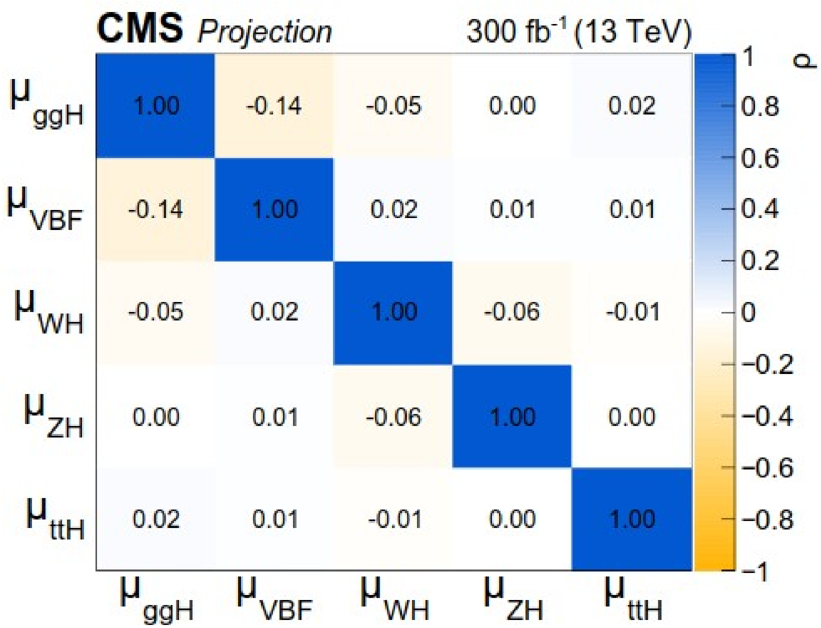
Double-Higgs physics will require a new project…!

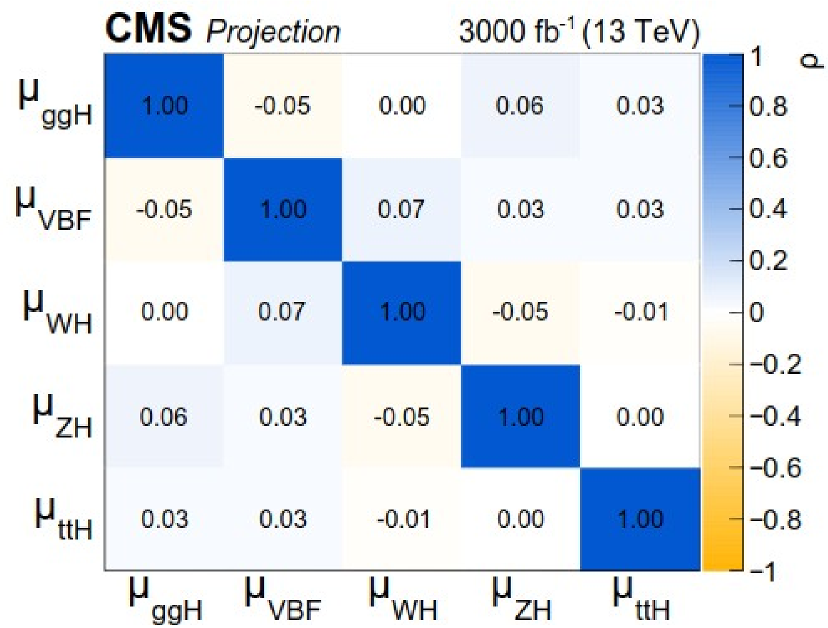
Backup

Signal strength correlations

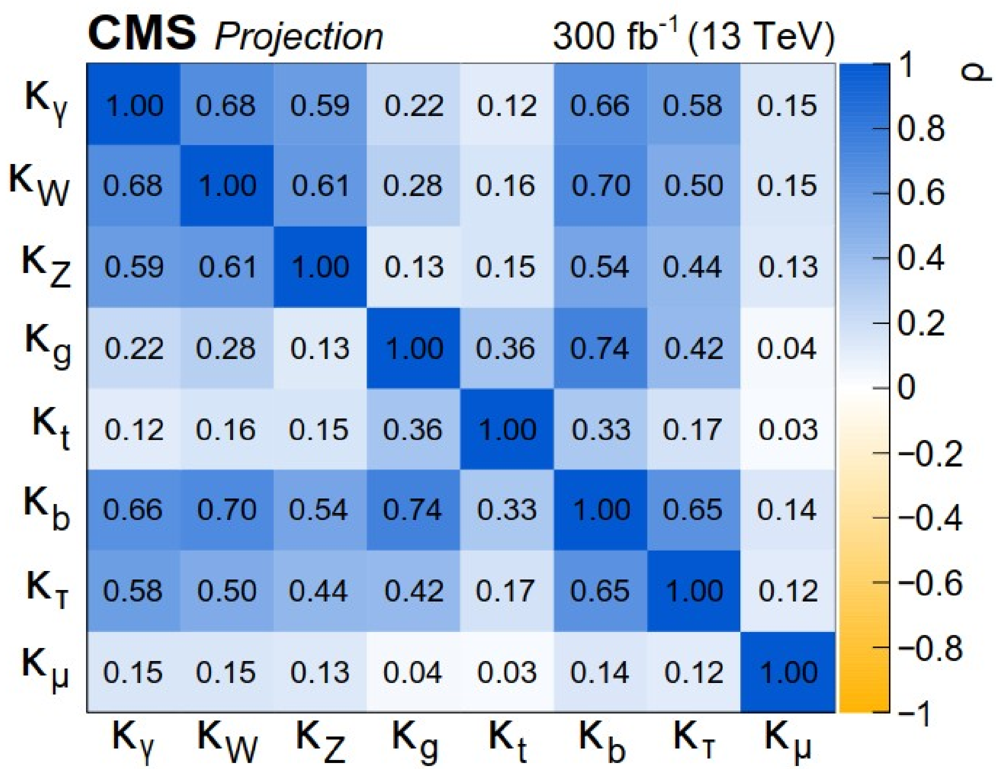


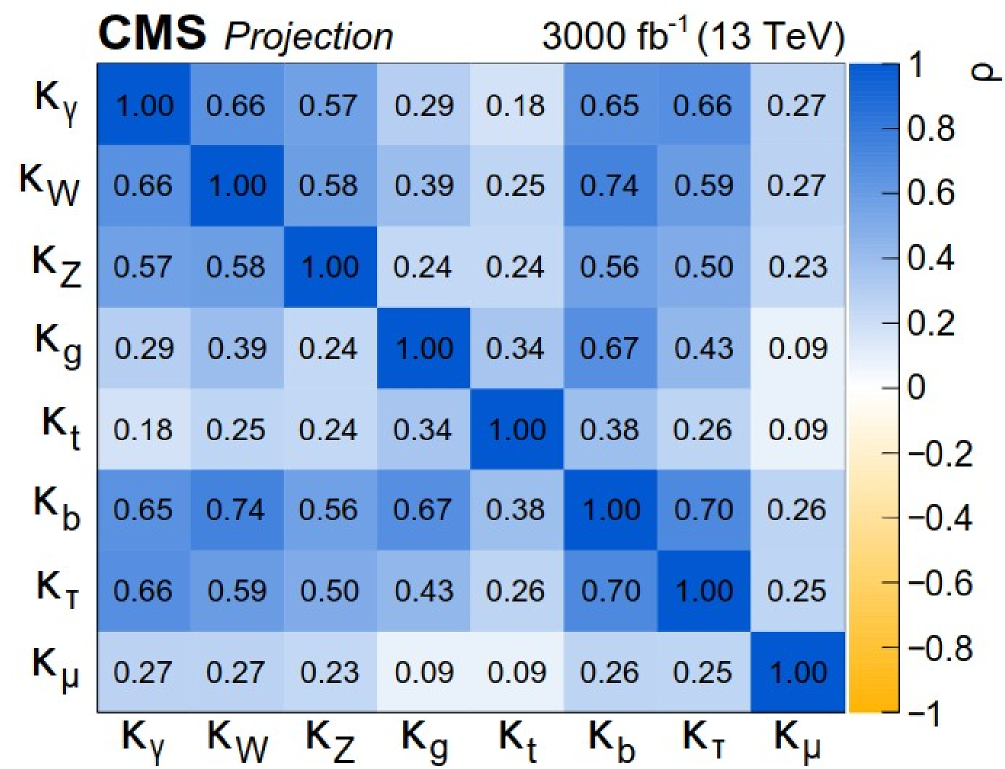






Couplings correlations





Couplings: uncertainties breakdown

		300 fb^{-1} uncertainty [%]					3000 fb^{-1} uncertainty [%]				
		Total	Stat	SigTh	BkgTh	Exp	Total	Stat	SigTh	BkgTh	Exp
$B_{BSM} = 0$											
κ_γ	S1	5.5	3.5	2.0	1.8	3.3	2.9	1.1	1.8	1.0	1.7
	S2	4.4	3.5	1.1	1.2	2.2	2.0	1.1	0.9	0.8	1.2
κ_W	S1	4.9	3.3	1.8	2.0	2.5	2.6	1.0	1.7	1.1	1.1
	S2	4.2	3.3	1.0	1.3	2.0	1.8	1.0	0.9	0.8	0.8
κ_Z	S1	4.6	3.2	1.9	1.7	2.0	2.4	1.0	1.7	0.9	0.9
	S2	3.9	3.2	1.0	1.1	1.7	1.7	1.0	0.9	0.7	0.7
κ_g	S1	6.3	3.3	3.6	2.5	3.0	4.0	1.1	3.4	1.3	1.2
	S2	5.0	3.3	1.9	2.0	2.5	2.5	1.1	1.7	1.1	1.0
κ_t	S1	8.0	3.1	4.3	4.6	3.8	5.5	1.0	4.4	2.7	1.6
	S2	6.0	3.1	2.2	3.5	3.0	3.5	1.0	2.2	2.1	1.2
κ_b	S1	10.5	6.2	3.9	5.2	5.4	6.0	2.0	4.3	2.9	2.3
	S2	8.8	6.2	1.9	4.0	4.5	4.0	2.0	2.0	2.2	1.8
κ_τ	S1	6.0	3.8	2.6	1.9	3.3	2.8	1.2	1.8	1.1	1.4
	S2	5.2	3.8	1.7	1.4	2.8	2.0	1.2	1.0	0.9	1.0
κ_μ	S1	22.3	21.7	2.7	1.8	3.6	6.7	4.7	2.5	1.0	3.9
	S2	21.8	21.7	1.4	1.4	1.8	5.0	4.7	1.3	0.8	1.1
$B_{BSM} \geq 0, \lvert\kappa_V\rvert \leq 1$											
B_{BSM} $(+1\sigma)$	S1	8.2	6.0	2.7	3.1	3.7	3.8	1.9	2.4	1.5	1.7
	S2	7.2	6.0	1.5	2.3	3.1	2.7	1.9	1.0	1.2	1.3
Γ/Γ_{SM}	S1	12.7	8.6	4.1	4.8	6.7	5.8	2.7	3.6	2.4	2.7
	S2	11.2	8.6	2.3	3.9	5.5	4.3	2.7	1.9	1.8	2.1