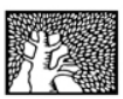


מכון ויצמן למדע
WEIZMANN INSTITUTE OF SCIENCE

ATLAS BSM Higgs

Lessons from Run-1 and Wishlist for Run-2

Jana Schaarschmidt (Weizmann) on behalf of the ATLAS BSM Higgs group

With contributions from:

L. Barak, N. Edwards, C. Gwilliam, H. Hadavand, S. Jabbar, N. Kauer,
A. Madsen, C. O'Brian, N. Rompotis, M. Stanescu-Bellu, and others

MC studies presented can be found in ATL-PHYS-PUB-2014-022

Higgs (N)NLO MC Workshop 19.12.2014

ATLAS has a very rich BSM Higgs boson search program.
In this talk we highlight the issues where we would like feedback from the theorists.

Topics covered in this talk: Charged Higgs, bbA production, H → $t\bar{t}$ Interference study, and more

Neutral Heavy Higgs to Fermions	H/A→(b)ττ (LL,LH,HH)
	H/A→(b)μμ
	H/A→(b)bb
	H/A→tt
Neutral Heavy Higgs to Bosons	H→γγ
	H→ZZ→4l
	H→ZZ→llνν
	H→ZZ→llqq
	H→ZZ→ννqq
	H→WW→lνlν
	H→WW→lνqq
Neutral Heavy Higgs to Bosons, including light Higgs	(H→)hh→γγbb
	(H→)hh→4b
	(H→)hh→bbττ
	(H→)hh→VVγγ→4jγγ,
	(H→)hh→WWγγ→lνqqγγ
	A→Zh→llττ (LL,LH,HH)
	A→Zh→(ll/νν)bb

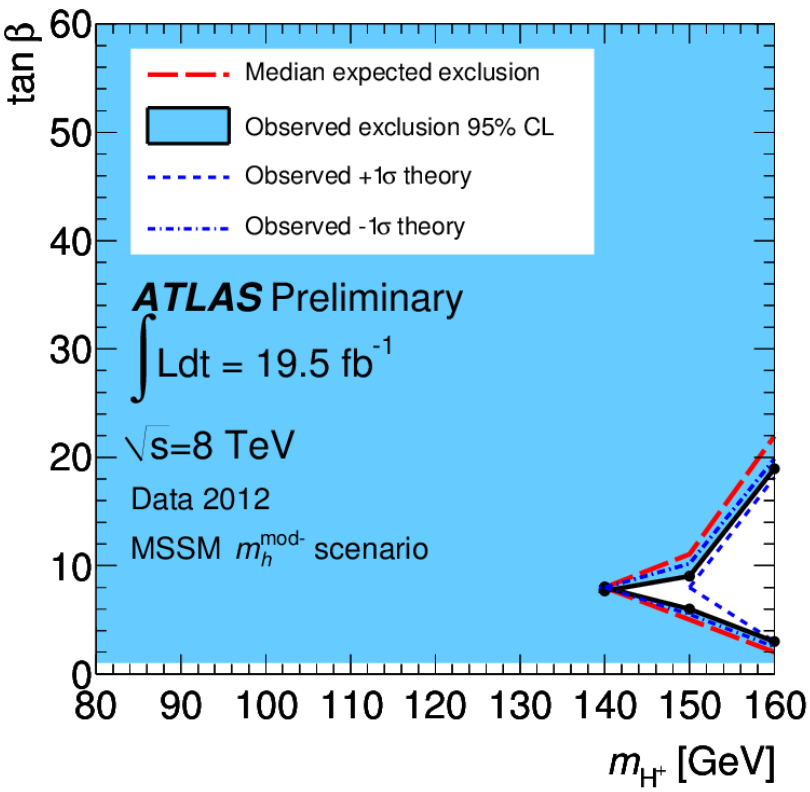
Heavy and light Charged Higgs	H+→τν+jets
	H+→tb (resolved)
	H+→tb s-chan (had, L+j)
	H+→τν+lep(s)
	H+→μν
	H+→cs
	H+→cb
	- AW
	H+→Wh (WH, WA)
	H+→Wγ
	H+→tb (boosted)
	H+→WZ→tb (lνqq, qqll)
	H++
LFV / FCNC / rare decays	H→τμ, τe
	H→eμ
	H→J/ψγ, Υγ
	H→ZJ/ψ, ZΥ
	H→ϕγ
	t→cH (various

Exotics decays with MET, Dark-sector Inspired	mono H (→γγ+MET)
	mono H (→bb+MET)
	mono H (→4l+MET)
	H→γγdark
	ZH→(ll)INV
	VBF H→INV
	VH→(jj)INV
	ttH→INV (various
	ggF H→INV (monojet).
Exotics decays with no MET, Dark-sector / NMSSM Inspired	H→ZdarkZ(dark)→4l
	h→2a→μμμμ
	h→Za→llμμ
	a→μμ
	h→2a→4γ(multiphoton)
	h→2a→bbμμ
	h→2a→bbττ
	(bb)a→(bb)ττ→(bb)eμ
	h→2a→4τ
	H+→aW

Charged Higgs Bosons

ATLAS has a strong H^+ program
Our most prominent channel: $H^+ \to \tau\nu$ („τ + jets“), one of the high-priority channels in Run-II

Most recent $H^+ \to \tau\nu$ exclusions in the m_h^{mod-} scenario:



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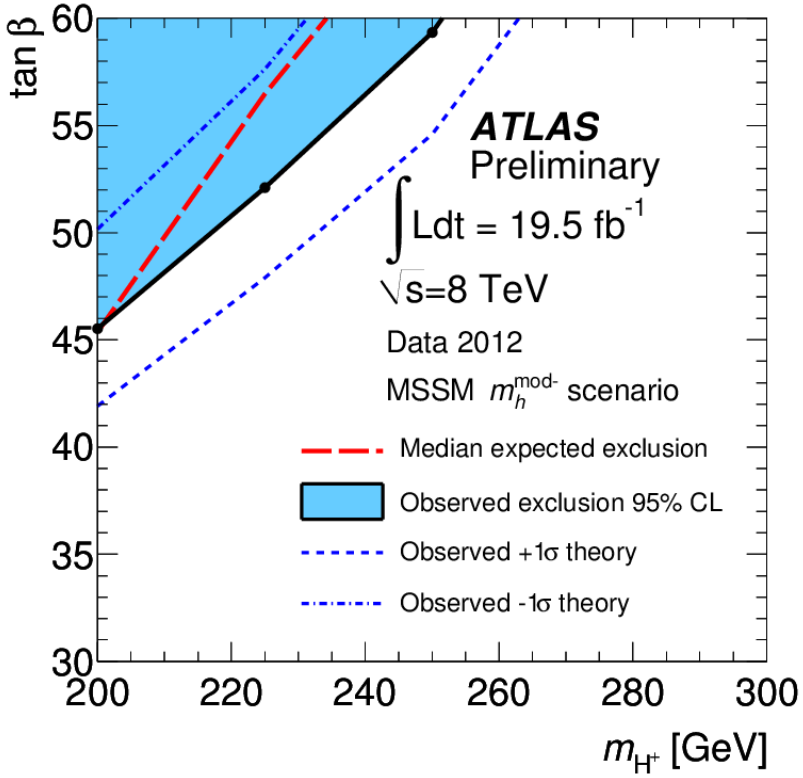
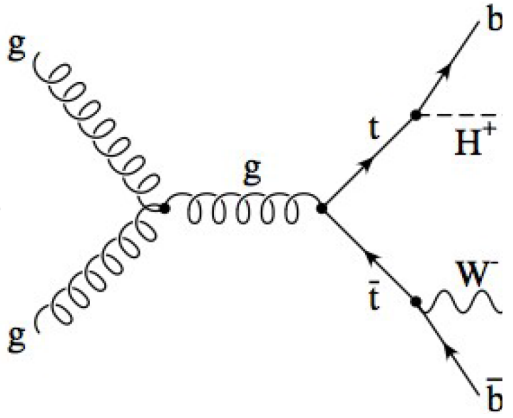


The intermediate region has not been studied in Run-I.

We wish to close this gap in Run-II. We need a MC generator for the signal that can handle this.

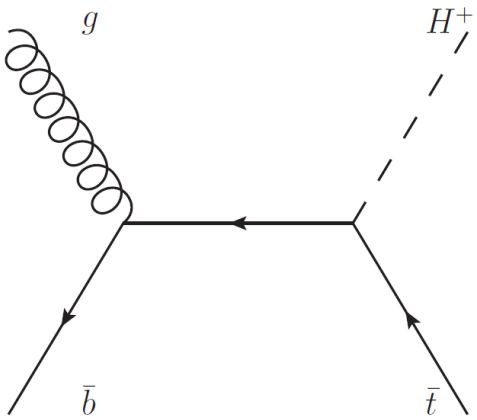
Intermediate mass region

Low mass $m_{H+} < m_{top}$: $pp \rightarrow tt \rightarrow bWbH^+$



See also talk by M. Flechl of the WG3

High mass $m_{H+} > m_{top}$: $pp \rightarrow tH^+ + X$



Intermediate mass region: 160-200 GeV:

- Contributions from both processes, comparable size
- Interference effects, processes cannot simply be added up
- We need a coherent cross section calculation with not too large uncertainties,
- We also need MC generator which models the signal in this region.
  First studies with MG LO are ongoing, we'd like to have NLO MC generator

H^+ Production: Intermediate mass region

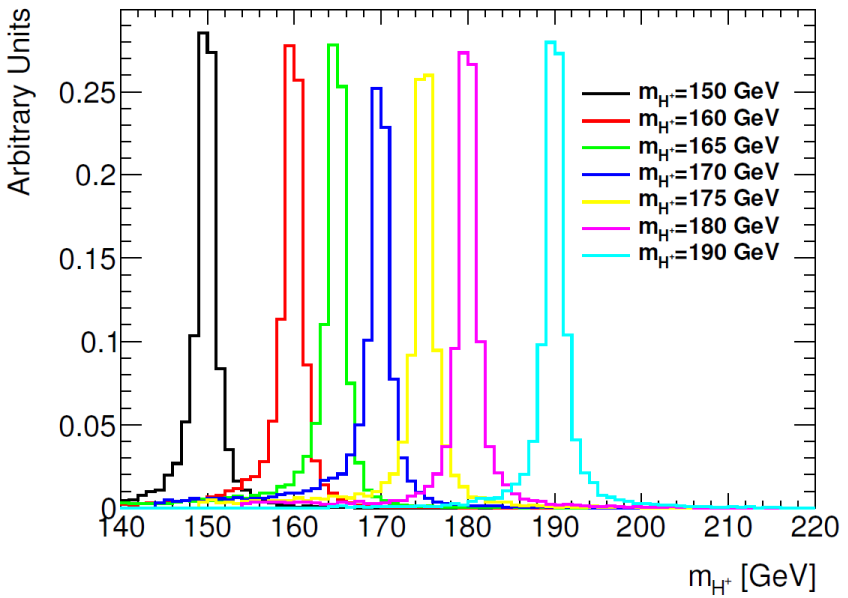
A very first look at MadGraph5 LO v2.2.0 H^+ in the intermediate mass region:

We generated events (process pp → WbH^+b) for H^+ masses between 150-190 GeV to bridge the difficult region (160-180 GeV).

Generator details:

	H^+ $\sqrt{s}$=13 TeV
ME gen.	MadGraph5_aMC@NLO v2.2.0
PS/UE	Pythia8 v8.175
Ren/Fac. scale	m_Z
ME & PS/UE PDF	CTEQ6L1
Tune	AU

Reconstructed H^+ mass ($H^+ \to \tau\nu$)



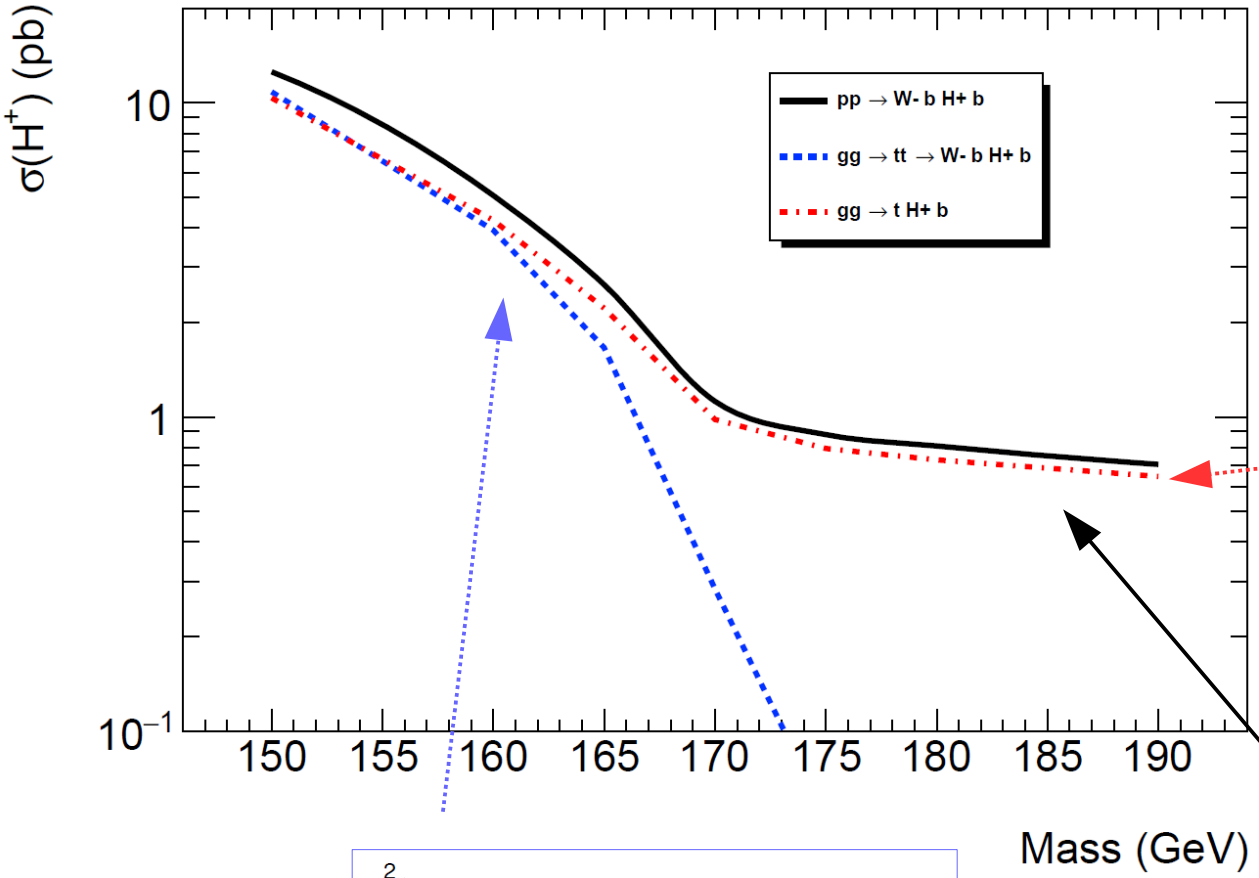
No simulation or smearing applied

Wishlist:

We are looking forward to the NLO implementation. We want to use the NLO signal modell for our Run-2 studies.

H^+ Production: Intermediate mass region

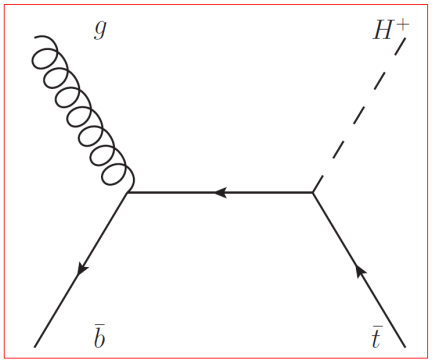
A very first look at MadGraph5 LO v2.2.0 H^+ in the intermediate mass region:



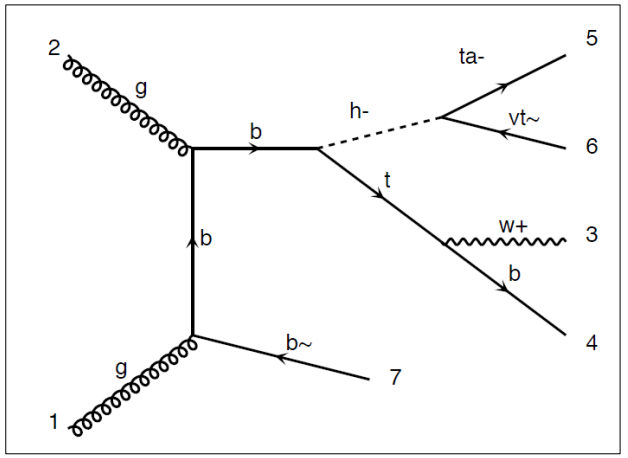
Example diagrams

High mass:

$gb \rightarrow H^+t$

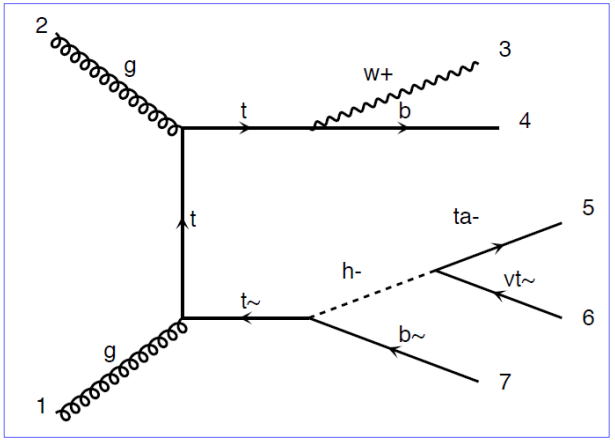


$pp \rightarrow WbH^+b$, gauge invariant over the whole mass range



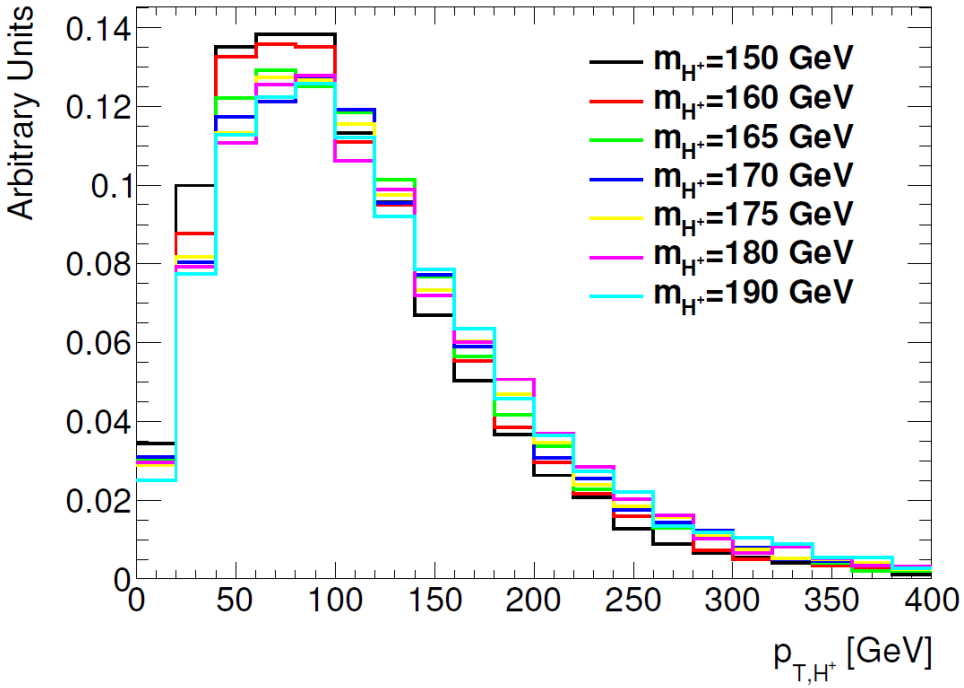
low mass:

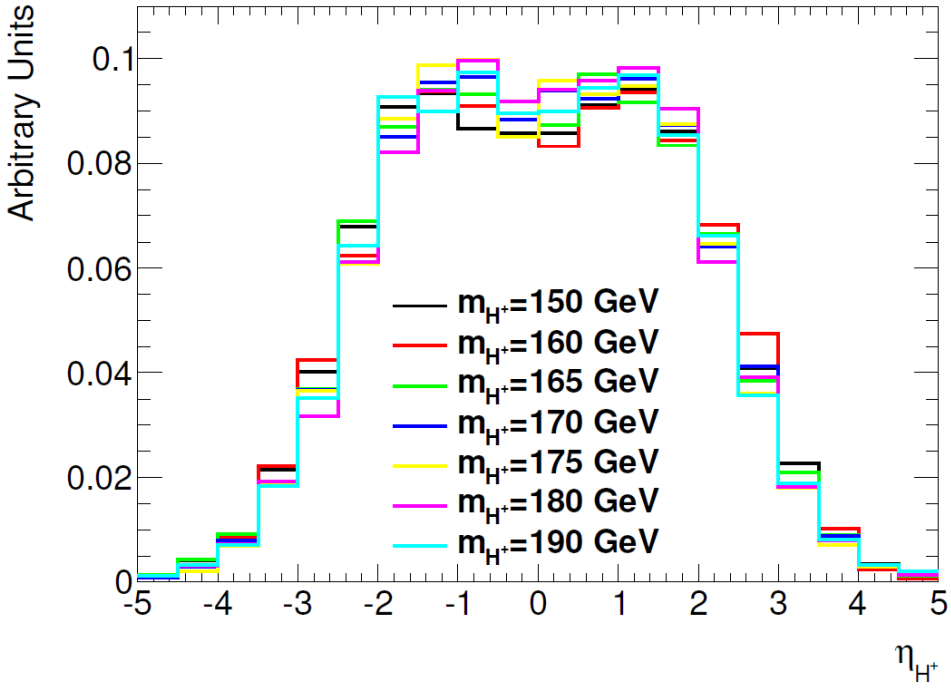
$tt \rightarrow WbH^+b$



H^+ Production: Intermediate mass region

A very first look at MG LO H^+ in the intermediate mass region:
Kinematics of $pp \rightarrow WbH^+b$



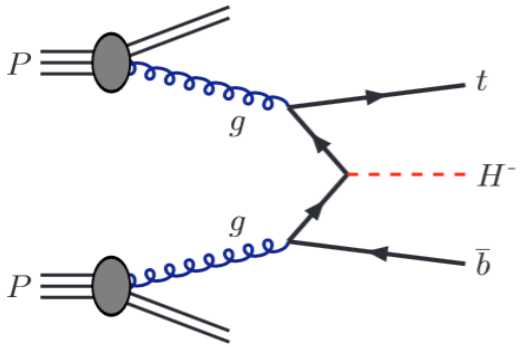


We need to study the particle kinematics and event characteristics and how they change throughout the transition region, to find an optimal event selection.

H^+ Production: 4 Flavor vs. 5 Flavor Scheme

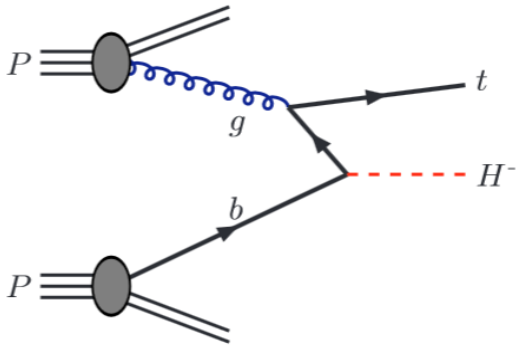
There are two schemes to calculate the charged Higgs cross section:

the 4-flavour scheme **$gg \to tbH^+$**



+ exact $g \to b\bar{b}$ splitting & mass effects
− no summation of $\ln(M_H/M_b)$ terms

and the 5-flavour scheme **$gb \to tH^+$**



+ summation of $\ln(M_H/M_b)$ terms
− LL approx. to $g \to b\bar{b}$ splitting

The 4- and 5-flavour schemes

- are both theoretically consistent & well-defined
- represent different ways of ordering perturbation theory
- should agree at sufficiently high order
- do not match exactly at finite order

Completely valid in the asymptotics limits:

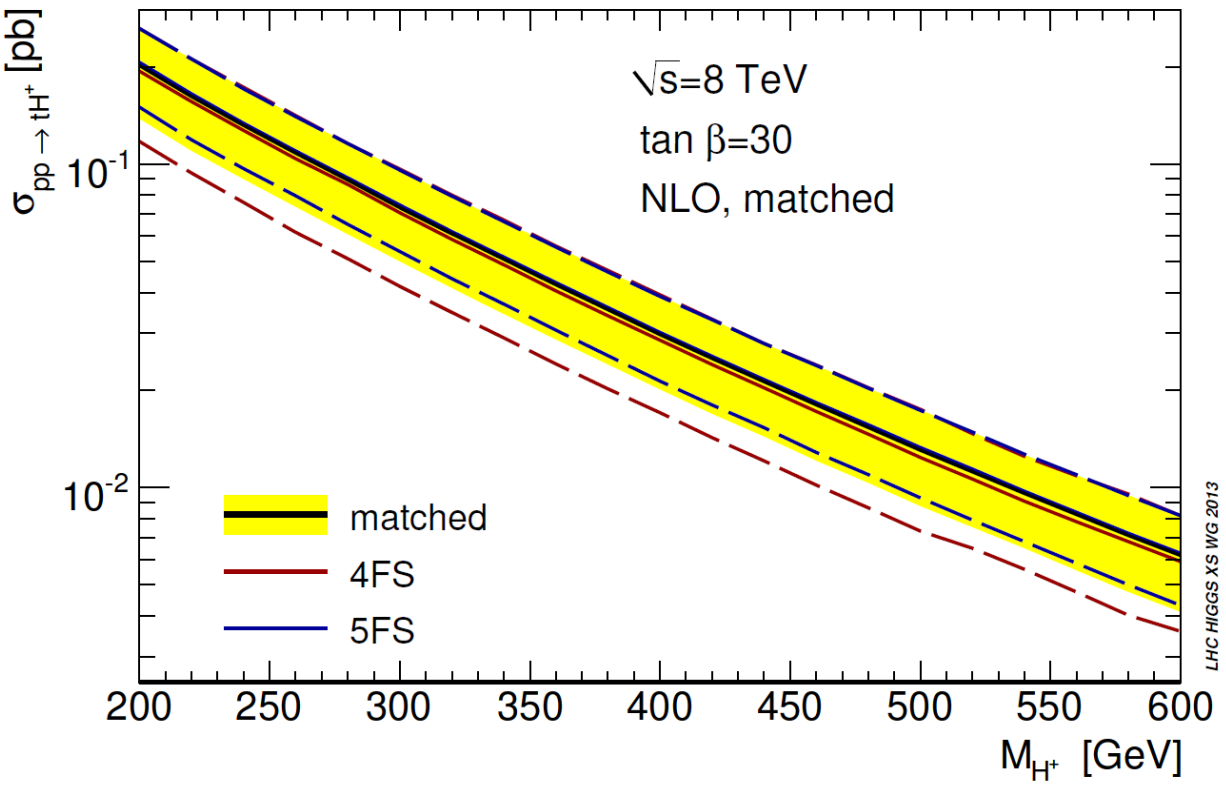
$$m_{\mathrm{H}}/m_{\mathrm{b}} \to 1 \quad : \quad 4\mathrm{FS}$$

$$m_{\mathrm{H}}/m_{\mathrm{b}} \to \infty \quad : \quad 5\mathrm{FS}$$

H^+ Production: 4 Flavor vs. 5 Flavor Scheme

Santander matching:

$$\sigma^{\text{matched}} = \frac{\sigma^{4FS} + w\,\sigma^{5FS}}{1+w} \qquad w = \ln\frac{m_H}{m_b} - 2$$



Santander matching agrees well for inclusive cross sections, but what about exclusive events?

Our wish for Run-II:

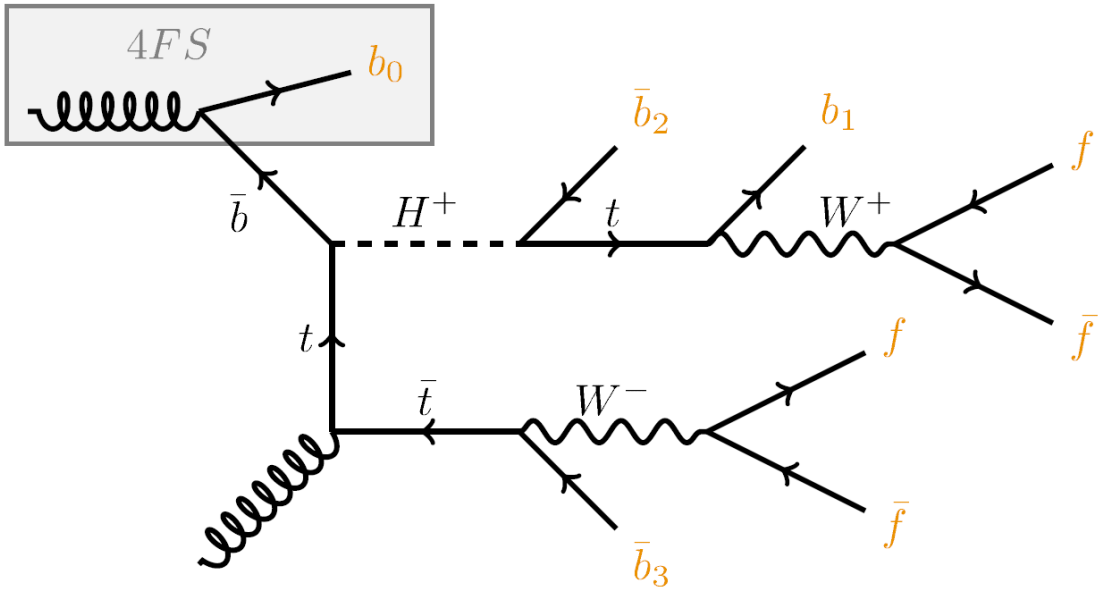
We need the cross sections and uncertainties at 13 TeV for H^+ masses well above 600 GeV, and for all sorts of models/benchmarks.

H^+ Production: 4 Flavor vs. 5 Flavor Scheme

The two FS have huge impact on the signal acceptance, esepcially in final states with many b-jets:

4FS $H^+ \rightarrow$ tb:

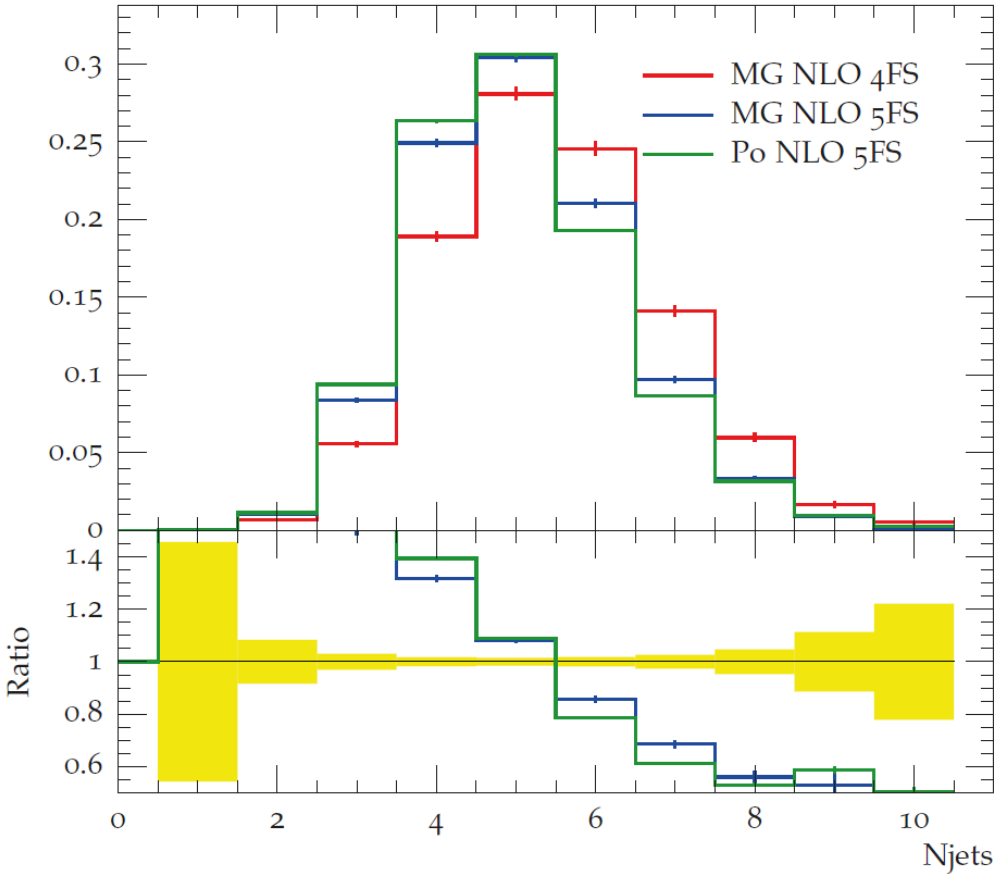
In principle the 4FS gives one more bjet.



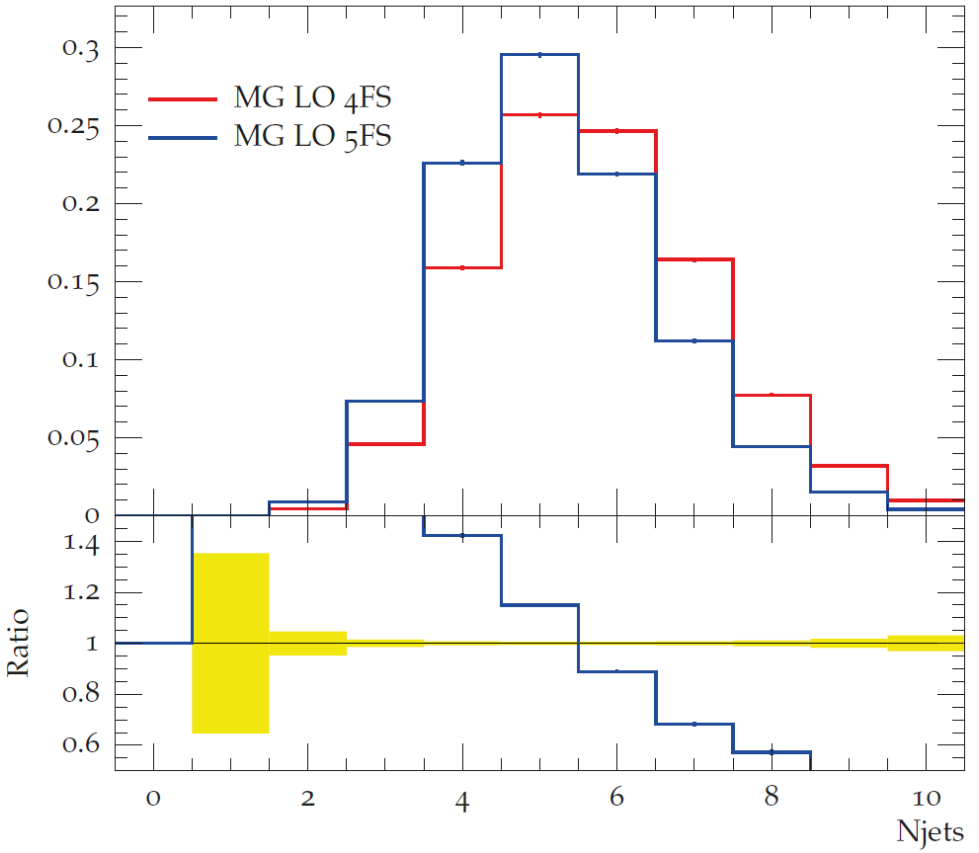
	H^+, $\sqrt{s}$=8 TeV		
ME gen.	MadGraph5_aMC@NLO NLO	MadGraph5 LO	Powheg
	v2.1.1	v1.5.12	v1.0
PS/UE gen.	Pythia8	Pythia8	Pythia8
	v8.175	v8.175	v8.175
Ren./Fac. scale	$(m_t + m_H)/3$	$(m_t + m_H)/3$	$(m_t + m_H)/2$
ME & PS/UE PDF	CTEQ6L1	CTEQ6L1	CT10
Tune	AU2	AU2	AU2
m_H	200/400/600 GeV	400 GeV	400 GeV

H^+ Production: 4 Flavor vs. 5 Flavor Scheme

Comparison of MG5_aMC@NLO for 4FS and 5FS,
and overlayed with PowhegPythia 5FS:



MG5 LO samples:

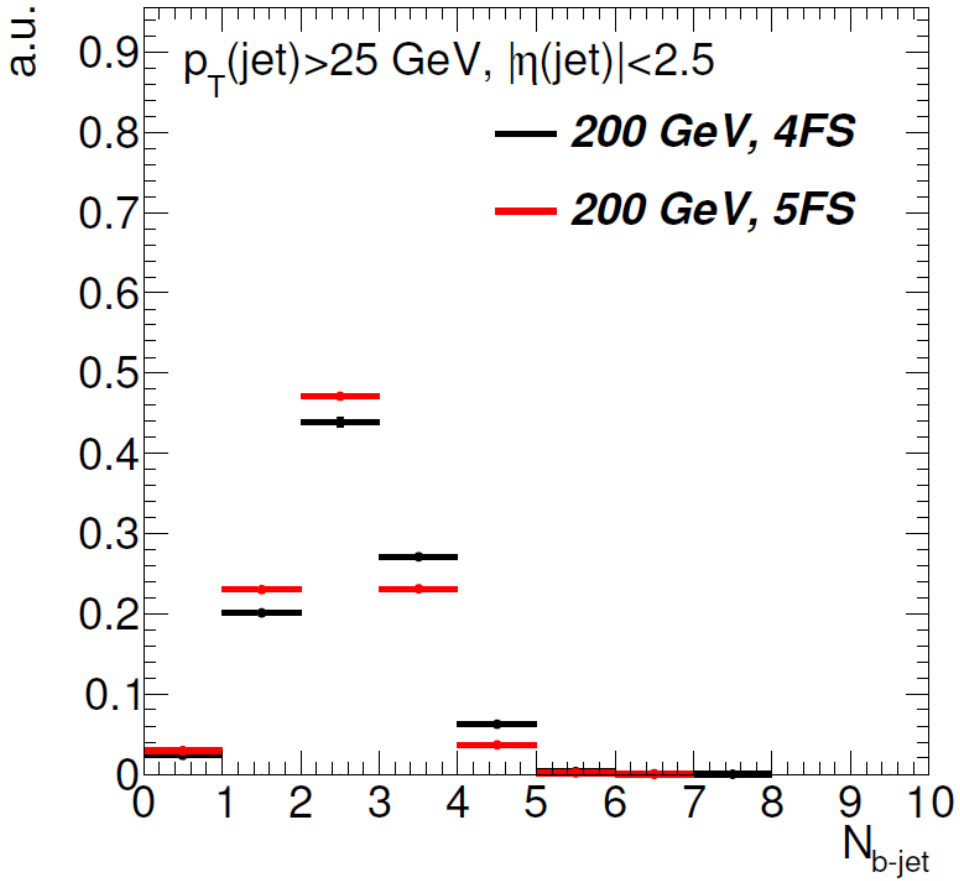


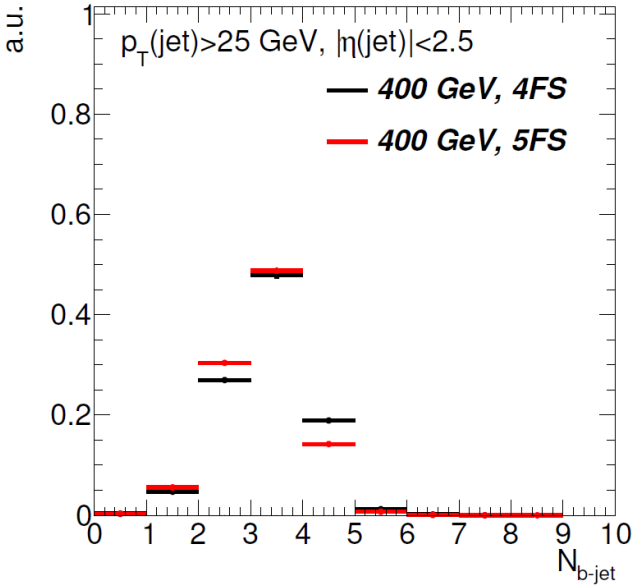
All samples showered with Pythia8.

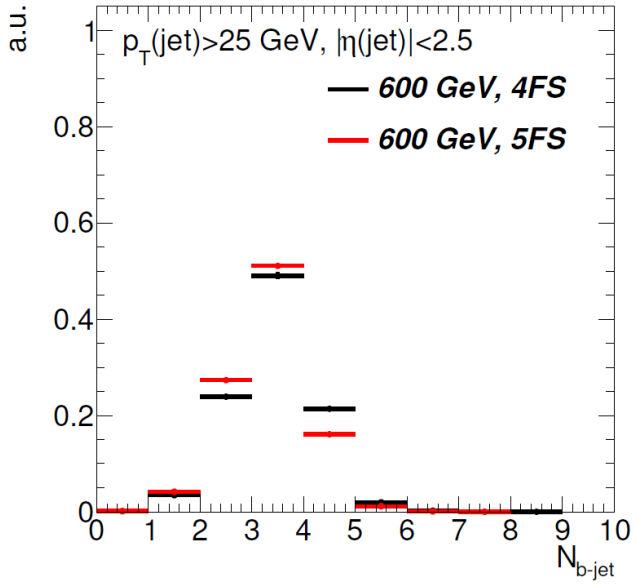
We are puzzled to find about the same differences with NLO as with LO samples.
→ Will be discussed in talk by Maria Ubiali later today.

H^+ Production: 4 Flavor vs. 5 Flavor Scheme

b-jet multiplicity for 200, 400 and 600 GeV H^+ mass, $tH^+ \rightarrow tb$ MG5_aMC@NLO:



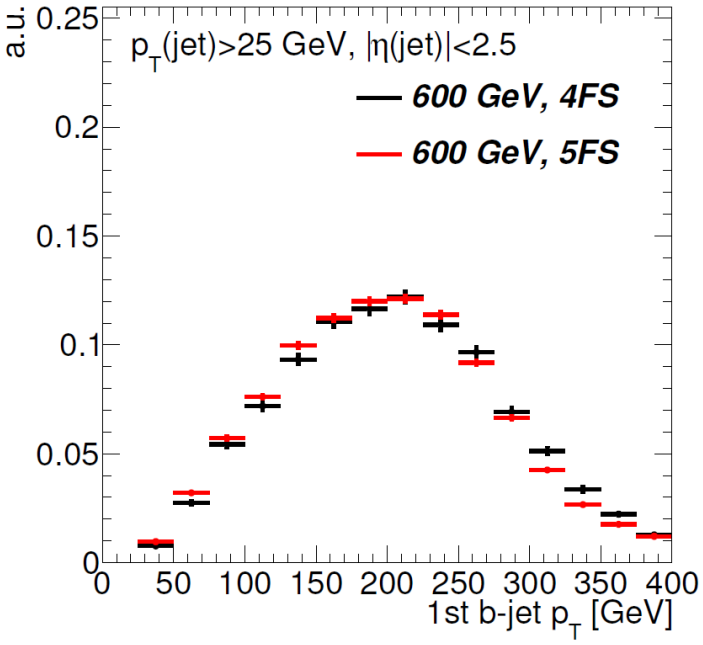


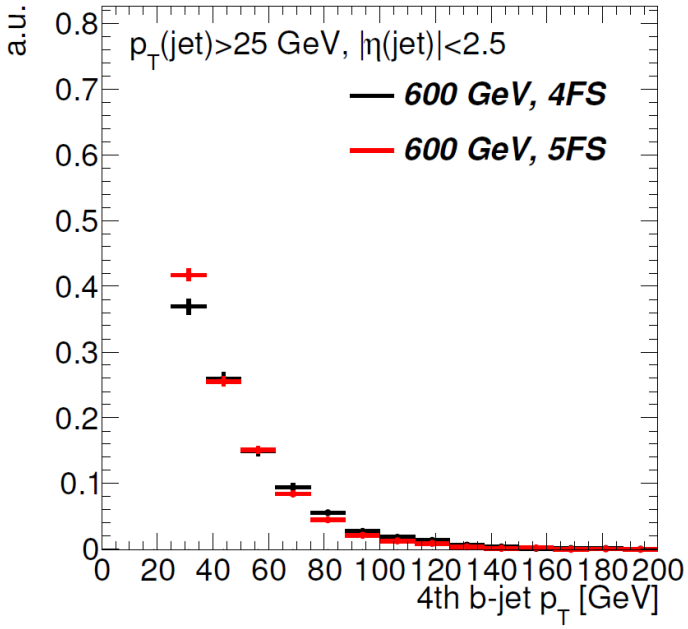


H^+ Production: 4 Flavor vs. 5 Flavor Scheme

pT of the 1st and 4th b-jet for m_{H+}=600 GeV:

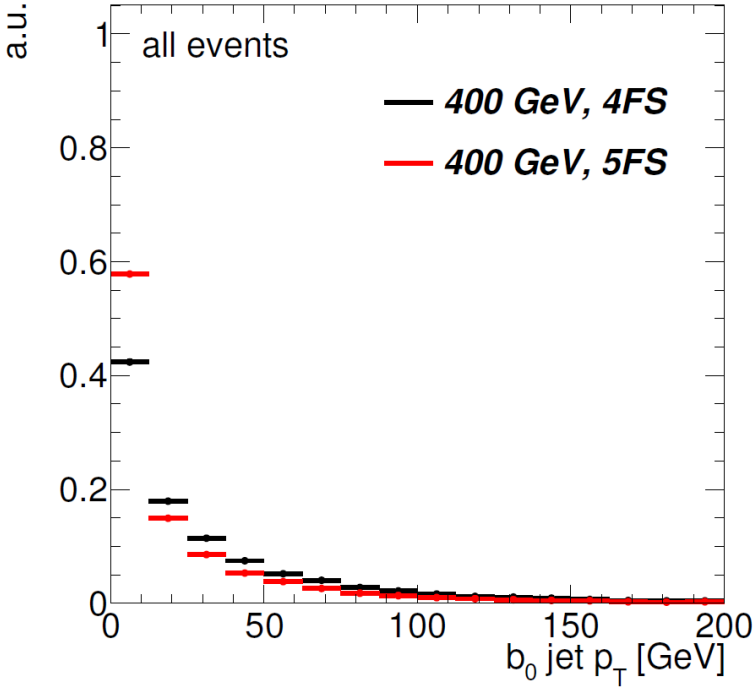
→ 4FS has more and harder b-jets.

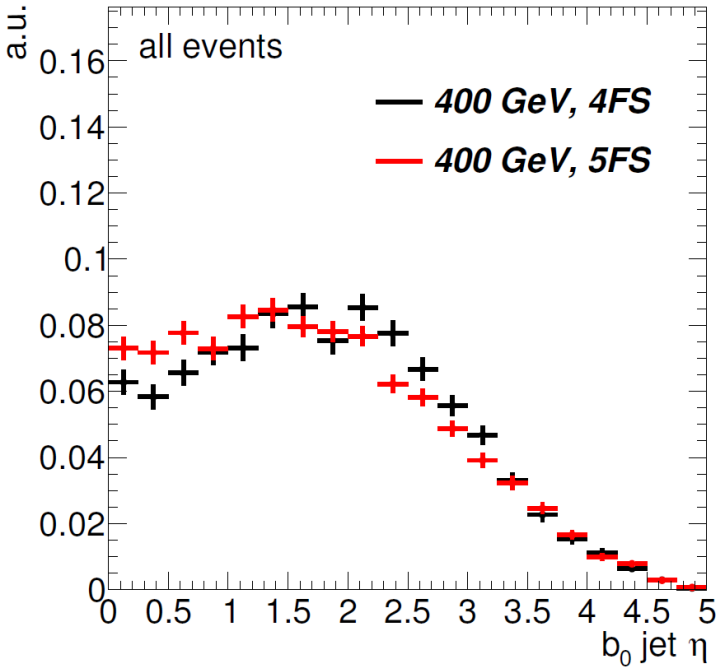




p_T and η of bjets that don't come from the H^+ or top decay:

→ Large differences





H^+ Production: 4 Flavor vs. 5 Flavor Scheme

Number of signal events of tH+> tb in jet and b-tag categories (on truth level),
And relative differences between 4FS and 5FS. Numbers in arbitrary units,
Samples are MG5_aMC@NLO.

Events in the 6jet-inclusive signal region:

Sample	2b	3b	4b	3b+4b
4 FS 200 GeV	0.798	1.071	0.400	1.471
5 FS 200 GeV	0.585	0.796	0.260	1.056
rel. difference	-27%	-26%	-35%	-28%
4 FS 400 GeV	0.622	1.927	1.057	2.984
5 FS 400 GeV	0.581	1.714	0.803	2.518
rel. difference	-7%	-11%	-24%	-16%
4 FS 600 GeV	0.643	2.088	1.268	3.356
5 FS 600 GeV	0.638	2.000	0.935	2.931
rel. difference	-1%	-4%	-26%	-13%

Huge differences, mass dependent,

Differences increase with b-jet multiplicity

H^+ Production: 4 Flavor vs. 5 Flavor Scheme

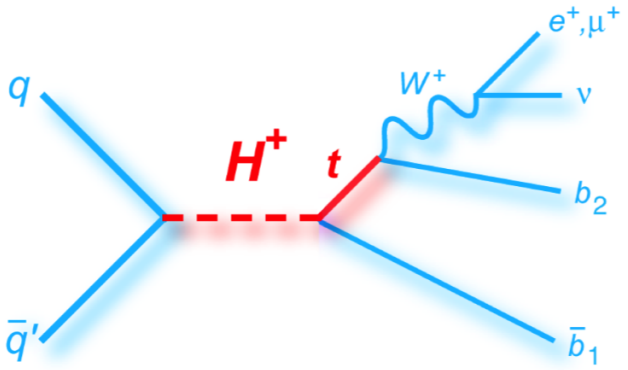
In Run-I, we use 5FS Powheg+Pythia8 samples to model our signal,
and we use an inclusive signal region: >=5jets, >=3 btags.

Our wishes for Run-2:

- We want to switch to 4FS nominal signal samples at NLO
- In particular for the $H^+ \rightarrow tb$ search:
  We want to separate our signal regions into various jet and bjet multiplicity categories
- We would also like to assess the difference to the 5FS prediction,
  and the uncertainty on this difference
- We need to know how to deal with this difference between 4/5 FS
  (eg. should we treat it like an uncertainty in the statistical analysis),
  this recipe should be written down in a citable document

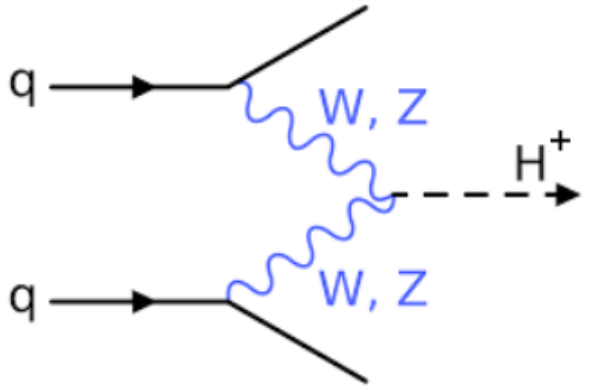
s-channel $H^+ \rightarrow tb$

- Currently studied in the mass range 0.4-3 TeV
- Identical to W' → tb search except the signal model
- Experimentally nice: Less complicated final state than $tH^+ \rightarrow tb$



VBF $H^+ \rightarrow WZ$

- Searched for with ATLAS in the WZ fusion production mode (imposing dedicated VBF cuts), in mass range 200 -1000 GeV
- Predicted at loop level in multi-scalar doublet models, but can appear at tree level in scalar triplet models (eg. Littlest Higgs), or fermiophobic models.



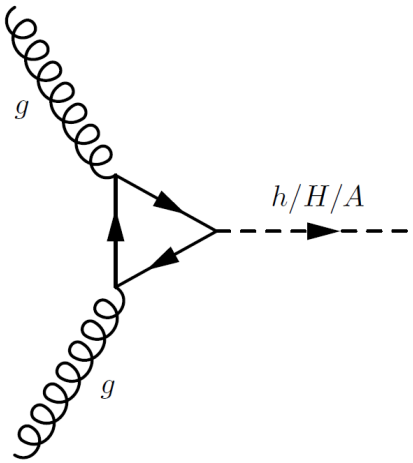
Wishlist:

We would like to have bechmark models for these new channels (cross sections and BR)

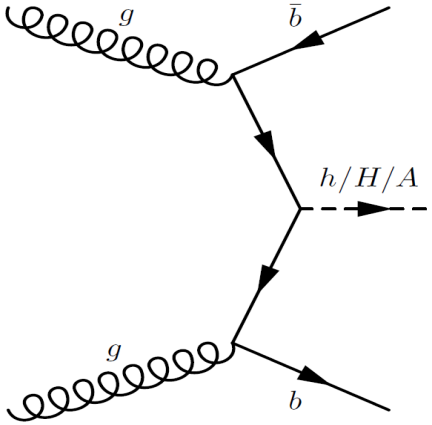
b-associated Higgs Production

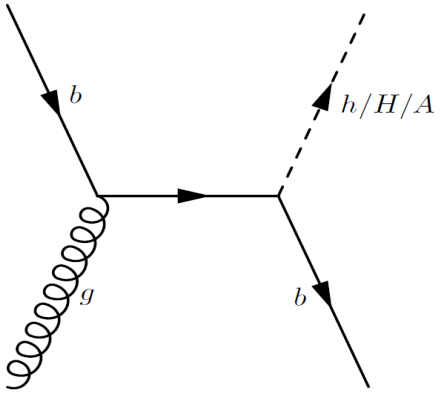
Neutral BSM Higgs production

Gluon fusion:



b-associated production:





→ negligible in the SM, but enhanced with tanβ in the MSSM, therefore dominating at high tanβ

→ experimentally nice: a b-tag can reduce backgrounds, one can define categories in b-jet multiplicity and increase sensitivity

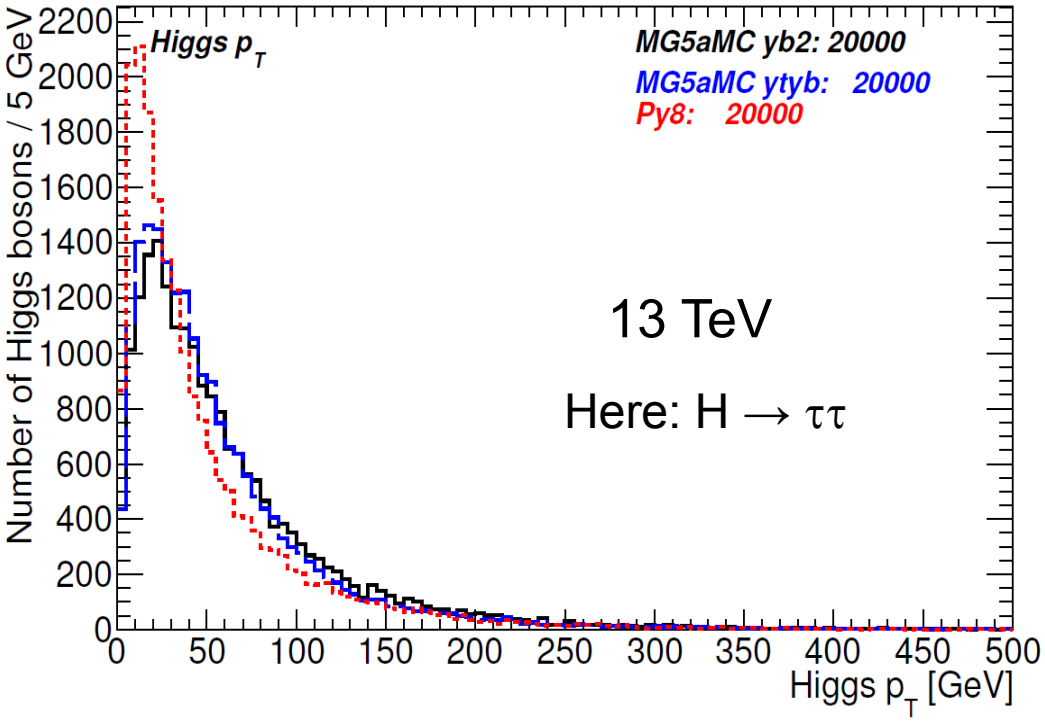
→ can be used to distinguish models in case of a signal

Very relevant for searches for H/A → ττ, or H/A → VV

- Comparison of **Pythia8** (LO) to **MG5 NLO in the 4FS**, hadronized with Herwig++.
  MG5 calculation either with terms proportional to y_b^2 or $y_t * y_b$

$$\sigma = \left(\alpha_S^2 y_b^2 \Delta_b^{(0)} + \alpha_S^3 y_b^2 \Delta_b^{(1)}\right) + \alpha_S^3 y_b y_t \Delta_b^{(1)} + \mathcal{O}(\alpha_S^4) = \sigma(y_b^2) + \sigma(y_b \cdot y_t) + \mathcal{O}(\alpha_S^4)$$

As expected, the Higgs boson p_T of Pythia8 is softer
Than that of MG5, expected since Pythia8 is LO.

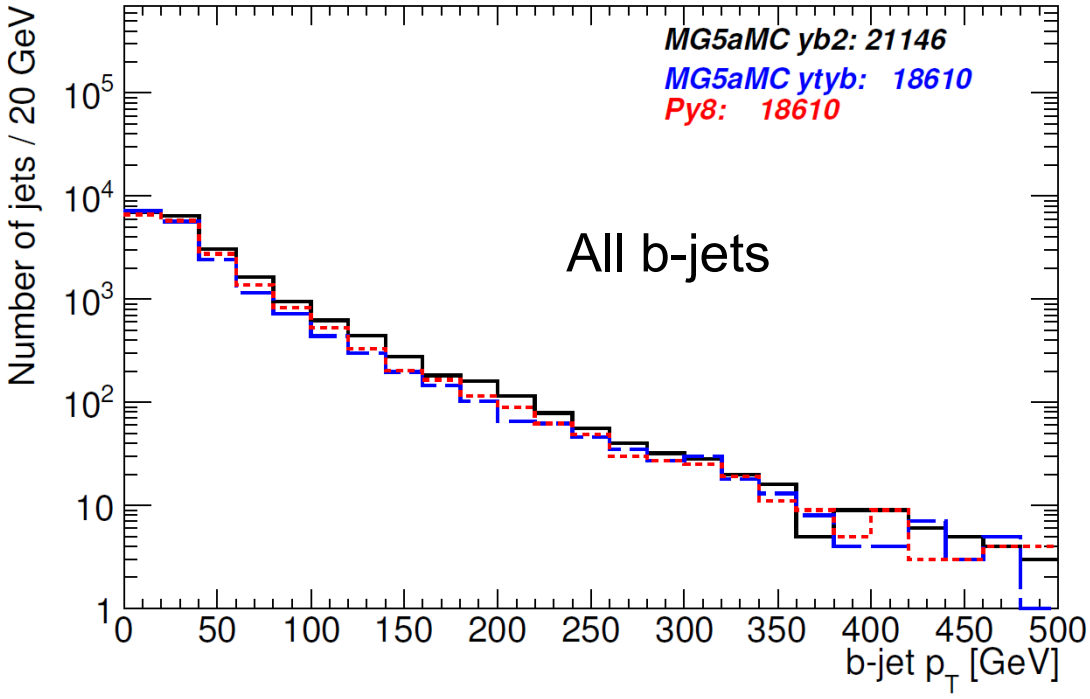


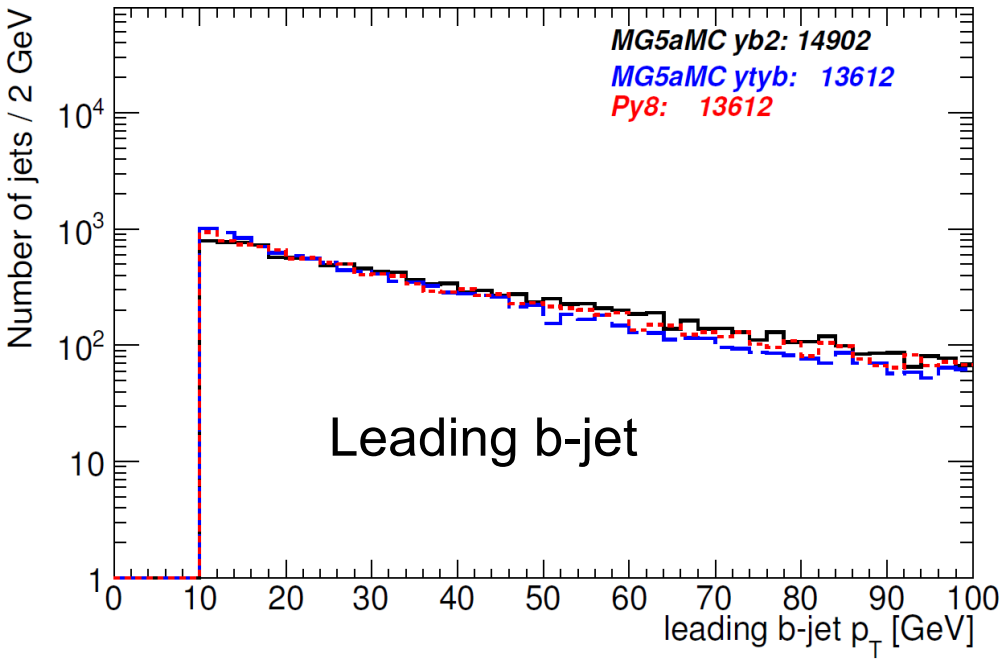
Generator details:

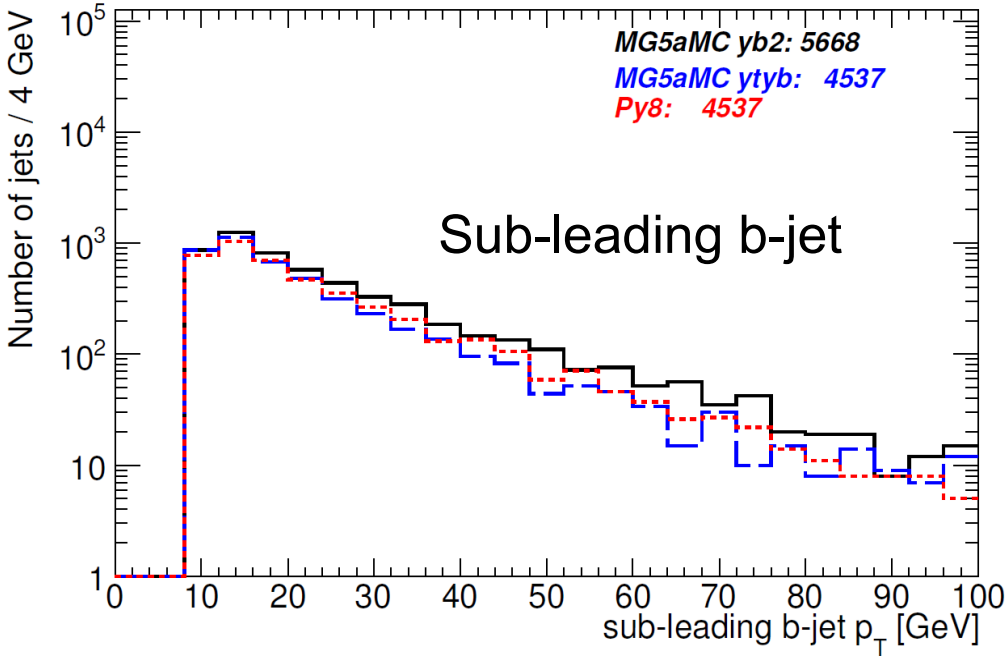
	bbH, $\sqrt{s}$=13 TeV	
ME gen.	MadGraph5_aMC@NLO v2.1.2	Pythia8 v8.175
PS/UE gen.	Herwig++ v2.7.0a	Pythia8 v8.175
Ren./Fac. scale	$H_T/4$	*default*
ME & PS/UE PDF	CT10	CTEQ6L1
Tune	UE-EE-4	AU2
m_H	500 GeV	500 GeV

We study the bjets that come from the b-associated production vertex for the same samples as before.

For each sample 20k events generated, no extra normalization applied here.







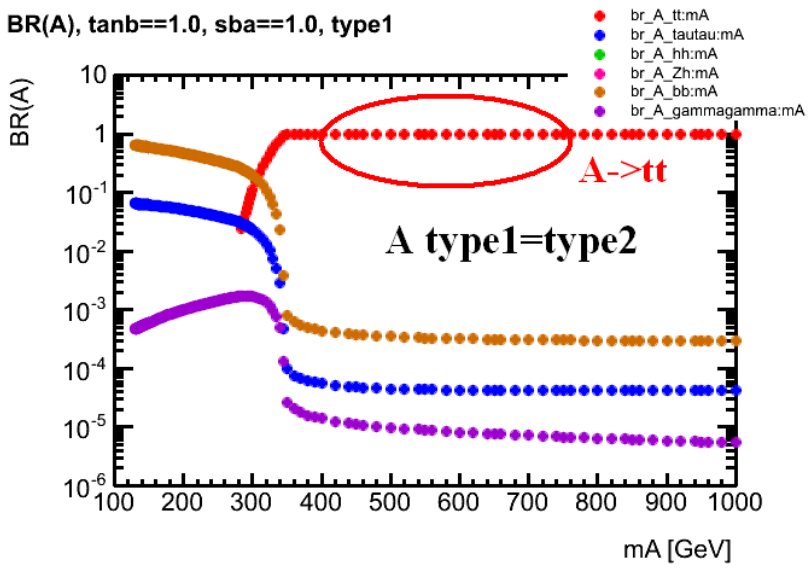
The distributions we studied look fine with MG5_aMC@NLO.

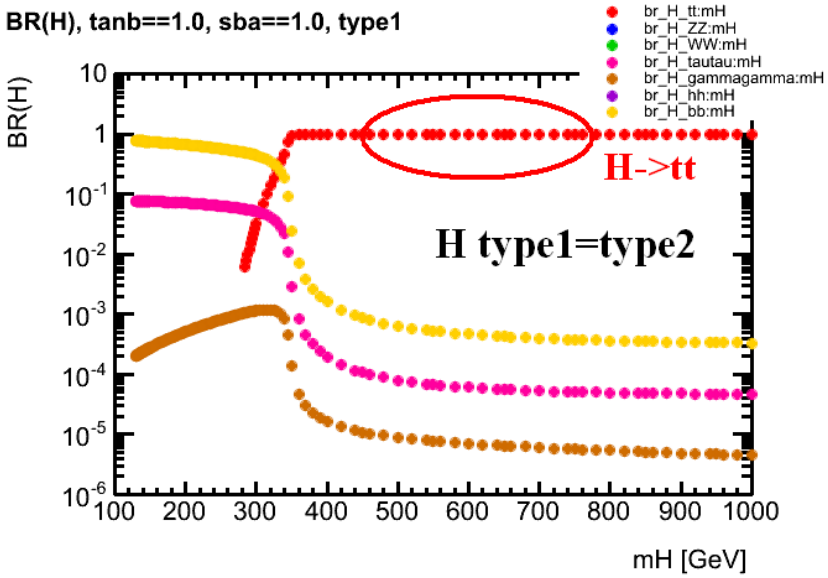
We are considering to use MG5_aMC@NLO for the production of our bbA/H signal samples in Run-2.

We thank Marius Wiesemann from the MG5_aMC@NLO team for his continous and patient support.

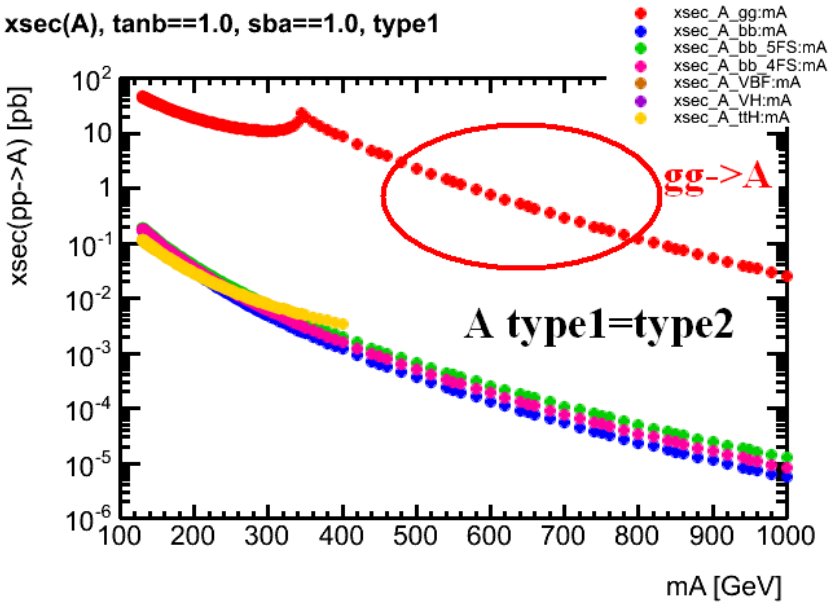
Interference of $gg \to H \to tt$ with $gg \to tt$

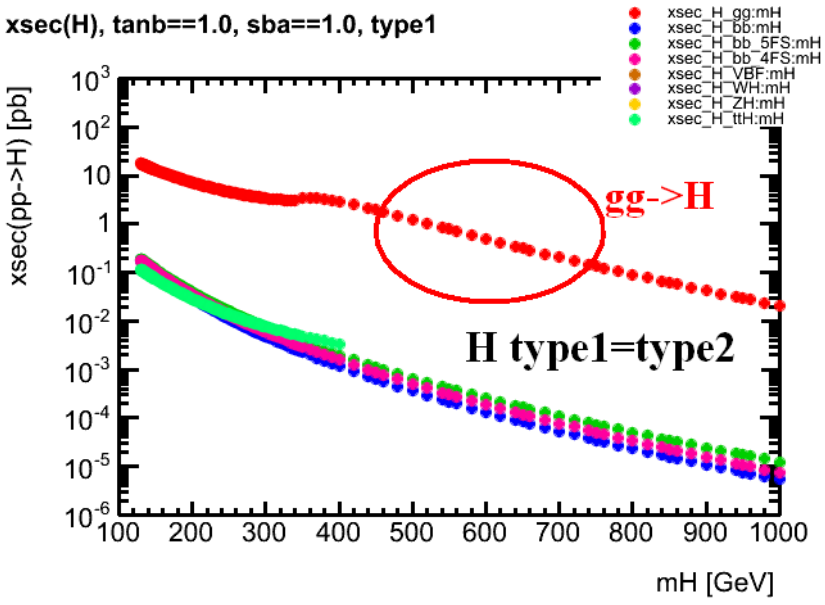
Dominant decay for $m_H > 2 * m_{top}$ (350 GeV)



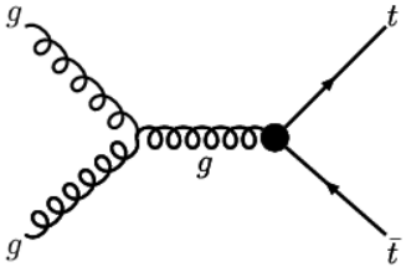


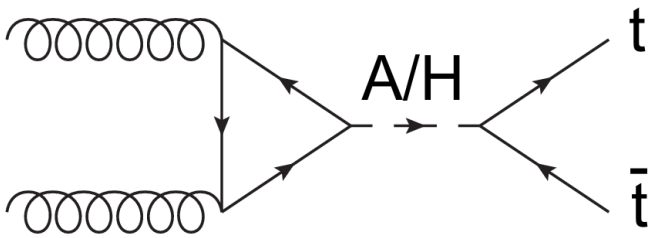
Production via gluon fusion dominant over the entire mass range:





Study of interference of gg → tt with gg → A/H → tt





Three samples are produced with MG5 at LO:

- Signal gg → A/H → tt
- Background gg → tt
- „All“ (Signal + background + interference)

	$A/H \to t\bar{t}$, $gg \to t\bar{t}$, $\sqrt{s}$=8 TeV
ME gen.	MadGraph5_aMC@NLO v2.0.1
ME PDF	CTEQ6L1
Ren./Fac. scale	m_Z
PS/UE gen.	*none*

Benchmark points:

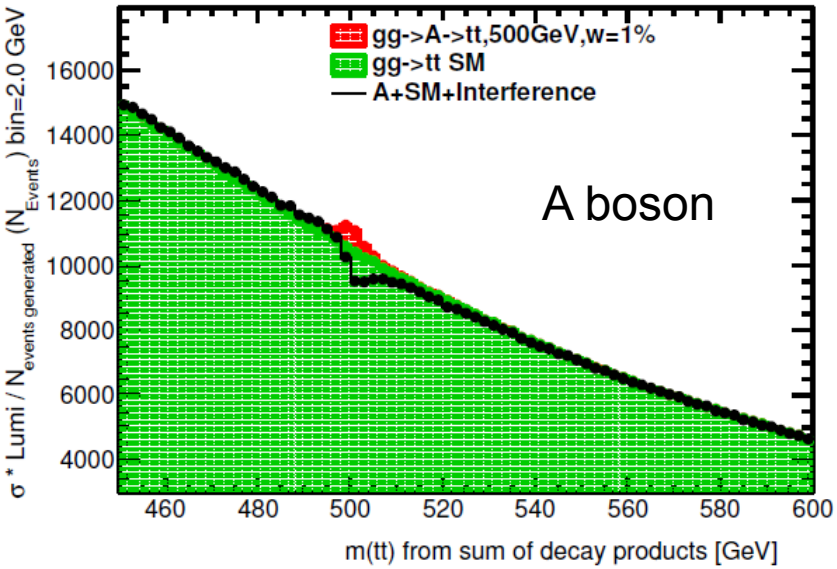
LO Cross sections from Madgraph (MG)

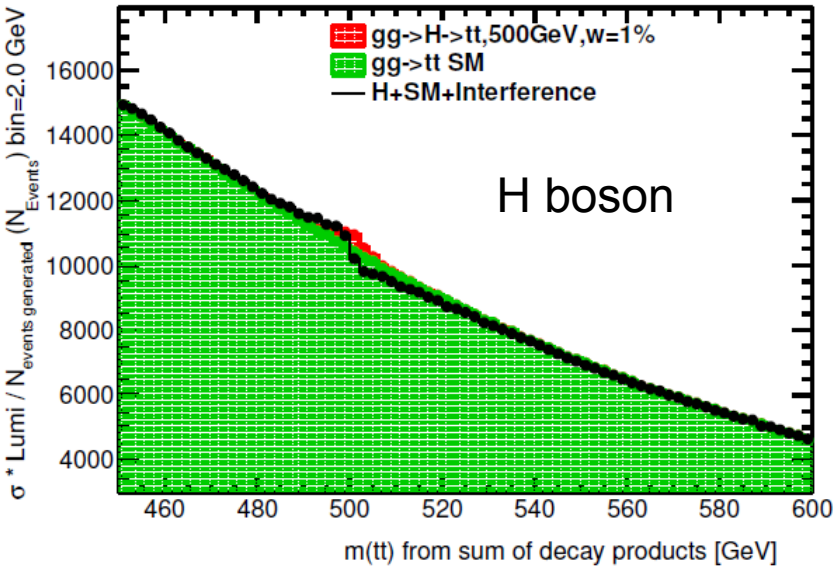
σ(gg→tt)= 92.18 pb (from MadGraph)

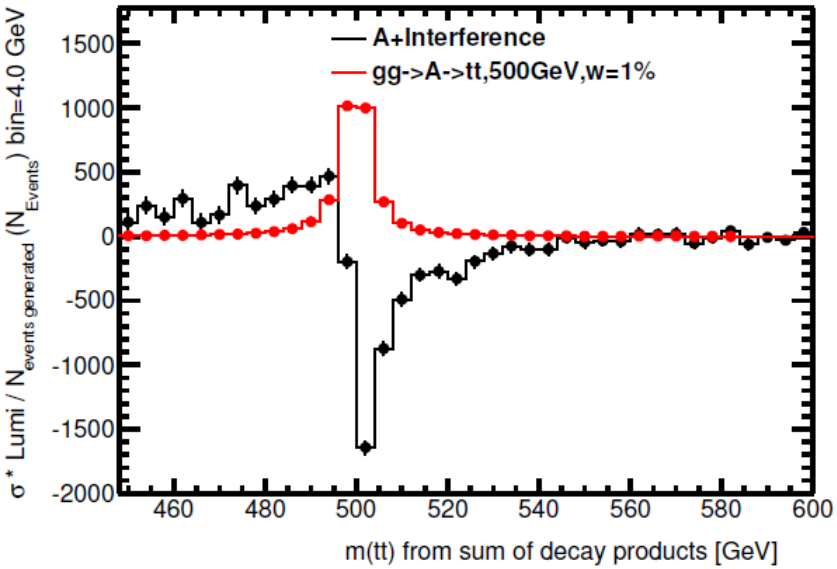
Mass	Width	tan β A	MG σ_{ggA} [fb]	tan β H	MG σ_{ggH} [fb]
400 GeV	5%	0.8	2964	0.5	2686
400 GeV	10%	0.58	4672	0.37	3273
500 GeV	1%	2.0	159	1.7	116
500 GeV	5%	0.9	795	0.73	593
500 GeV	10%	0.65	1422	0.51	1148
600 GeV	1%	2.1	51	1.9	39
600 GeV	5%	0.9	288	0.82	198
600 GeV	10%	0.67	484	0.6	339

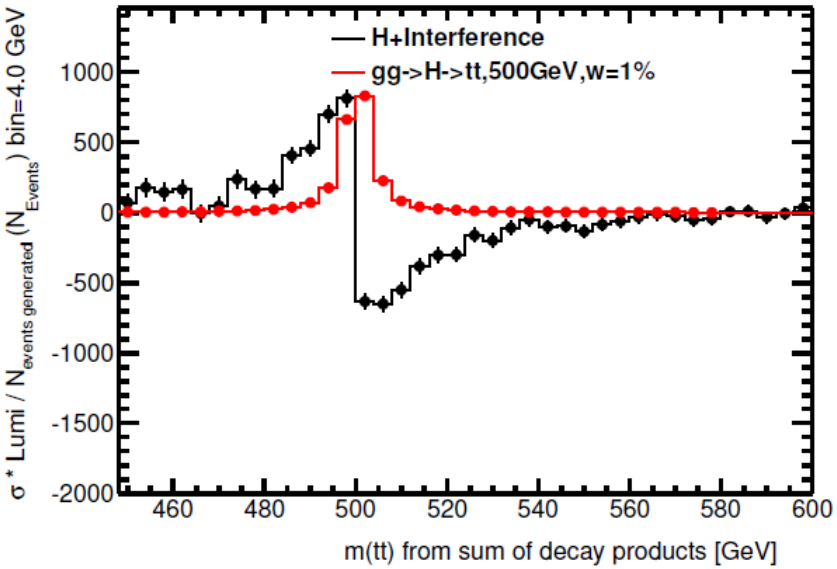
Interference for $m_{A/H}$=500 GeV, width=1%

The impact of the interference is checked on truth level, after reconstructing the tt mass from the decay products.

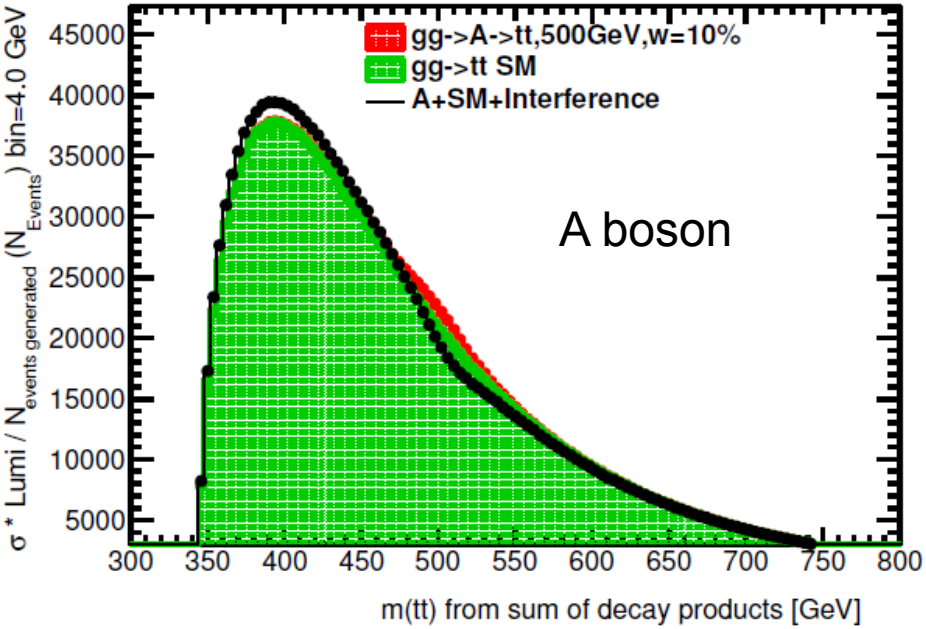


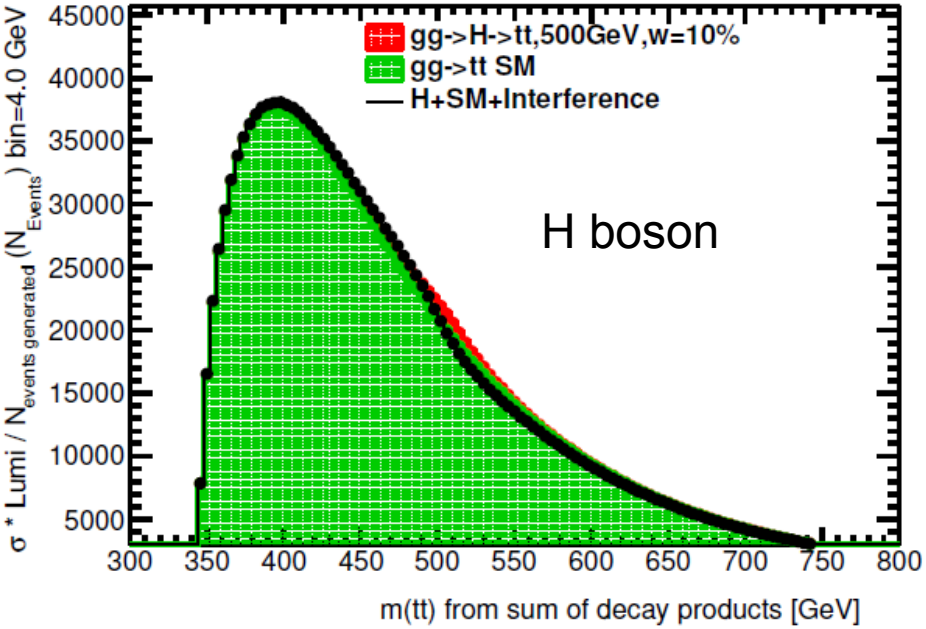


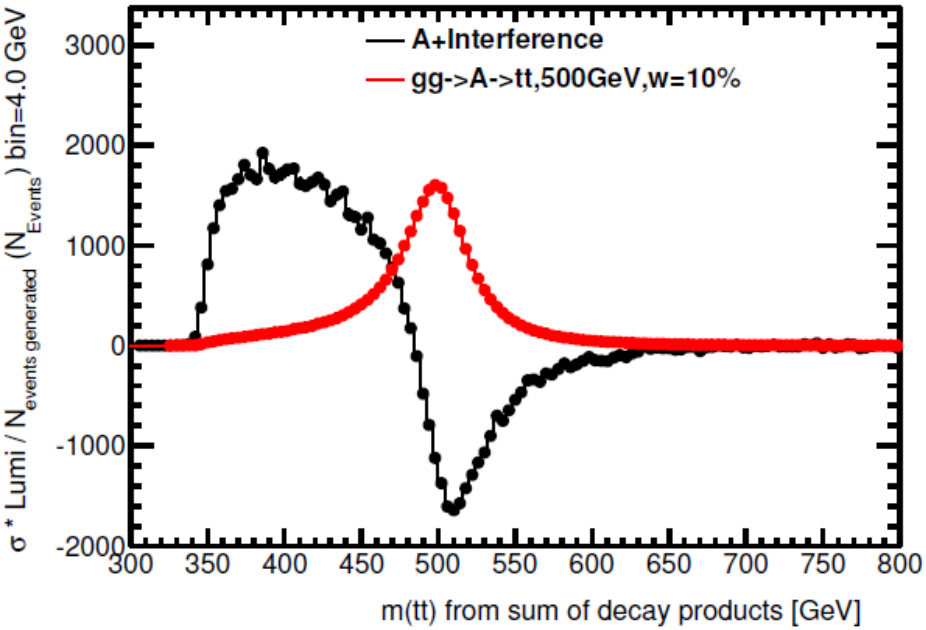


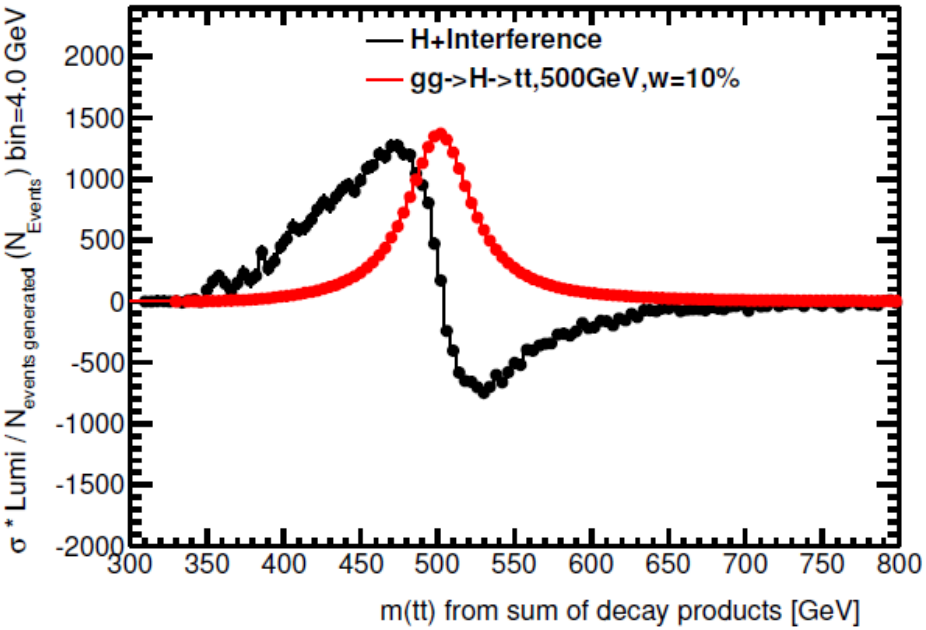


Interference for $m_{A/H}$=500 GeV, width=10%



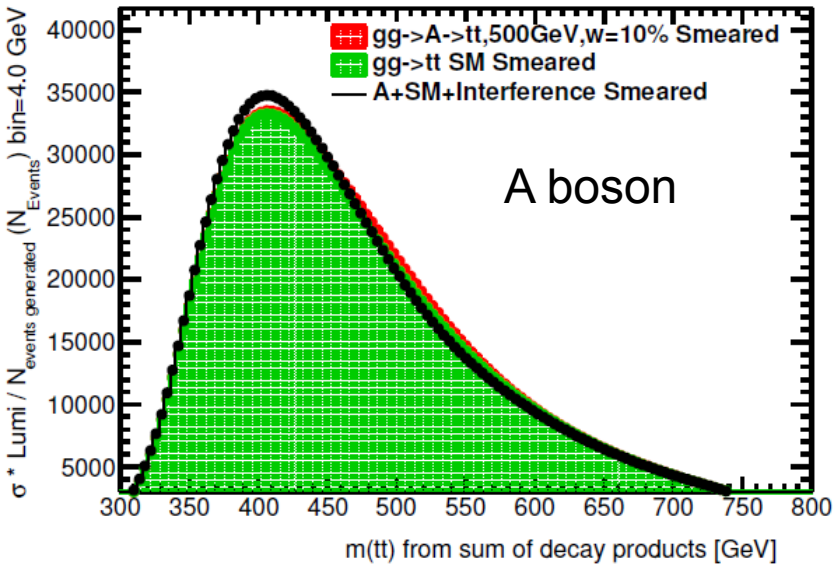


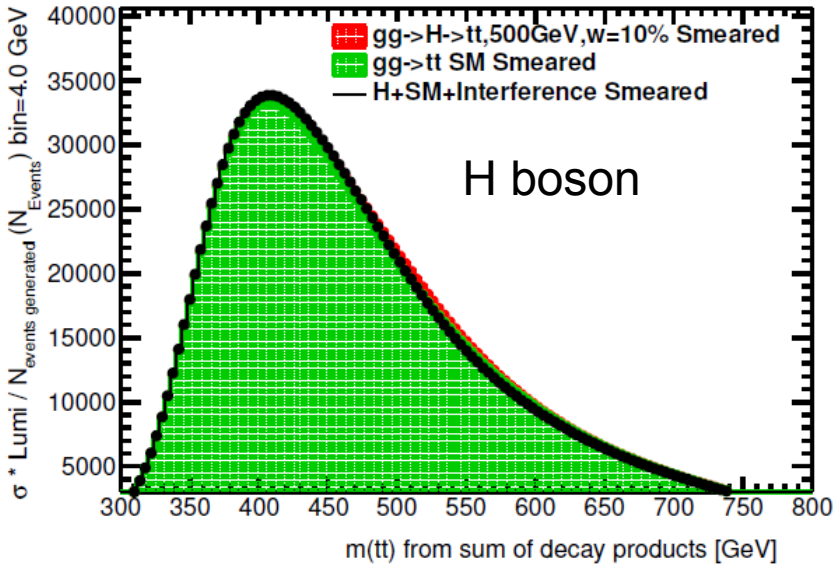


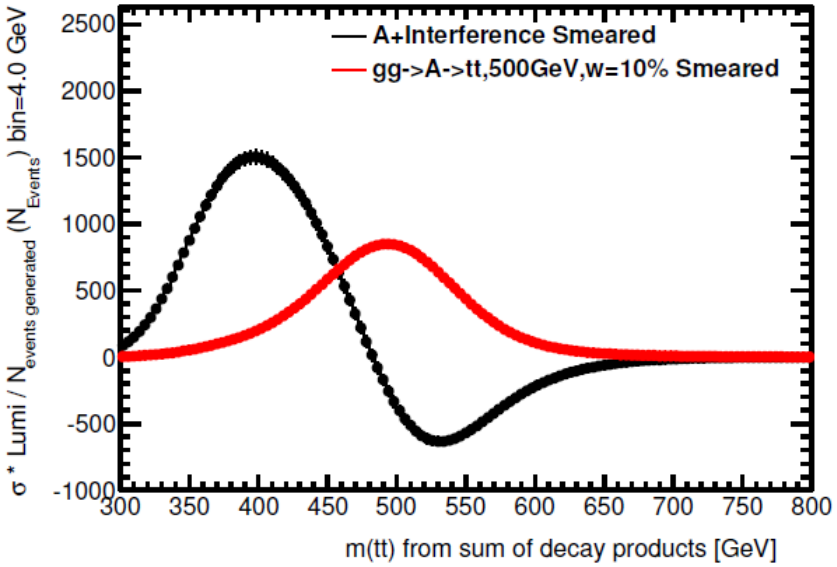


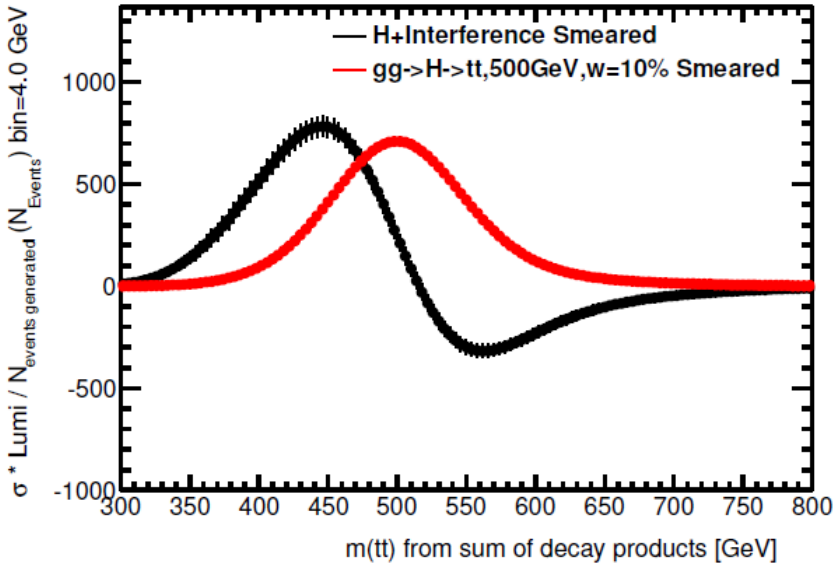
Interference for $m_{A/H}$=500 GeV, width=10%, with $m_{t\bar{t}}$ Smearing

As a refinement, the reconstructed tt mass is optionally smeared according to the detector resolution: 8% of m_{tt} for m_{tt}<400GeV to 6.5% of m_{tt} for m_{tt}>1000 GeV

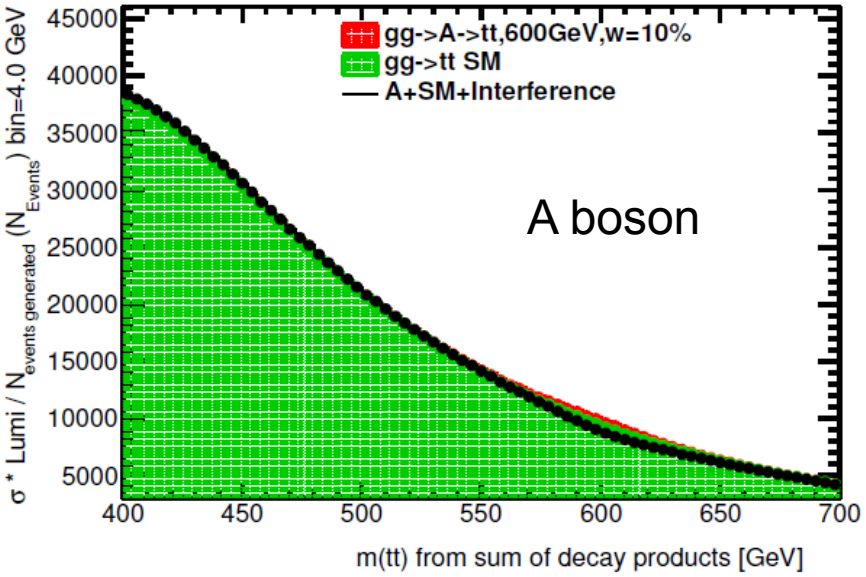


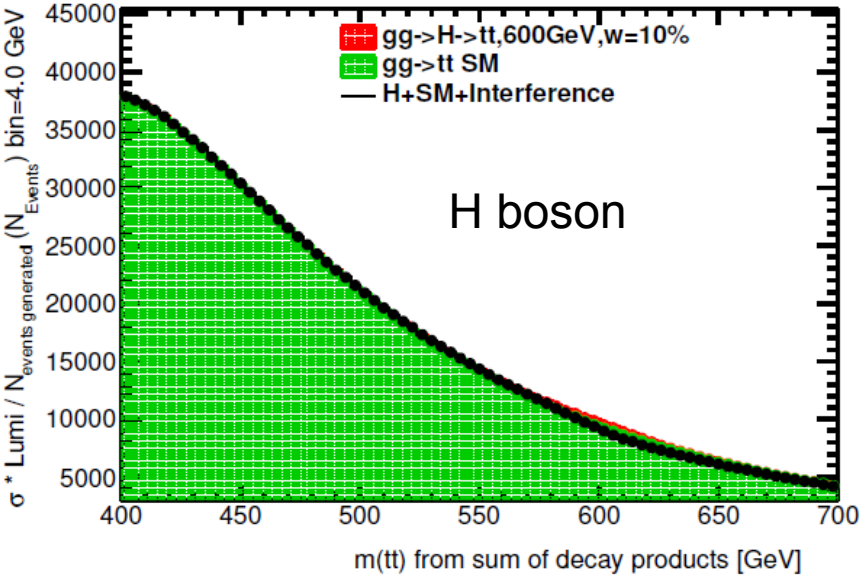


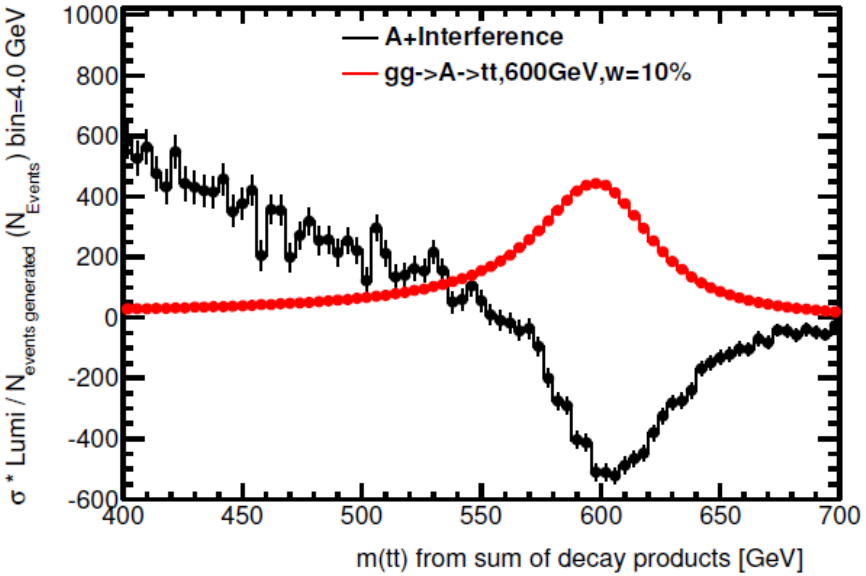


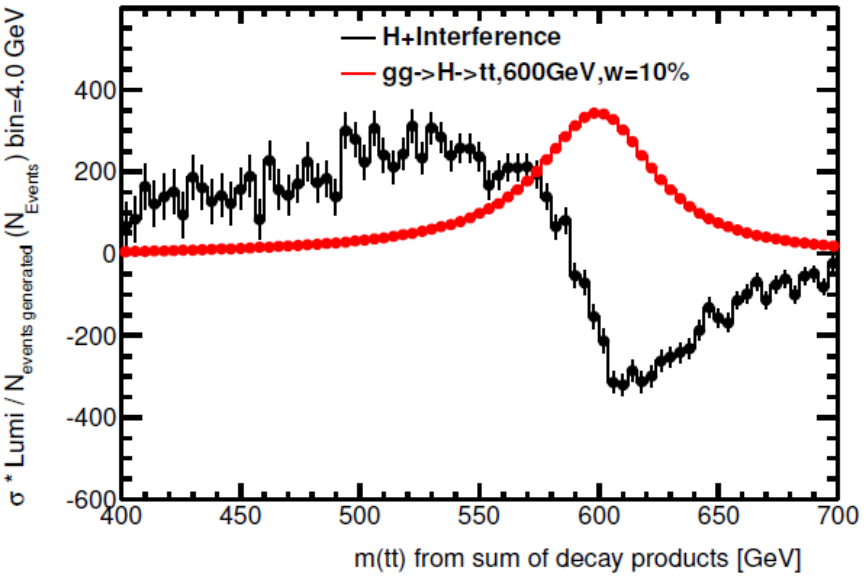


Interference for $m_{A/H}$=600 GeV, width=10%





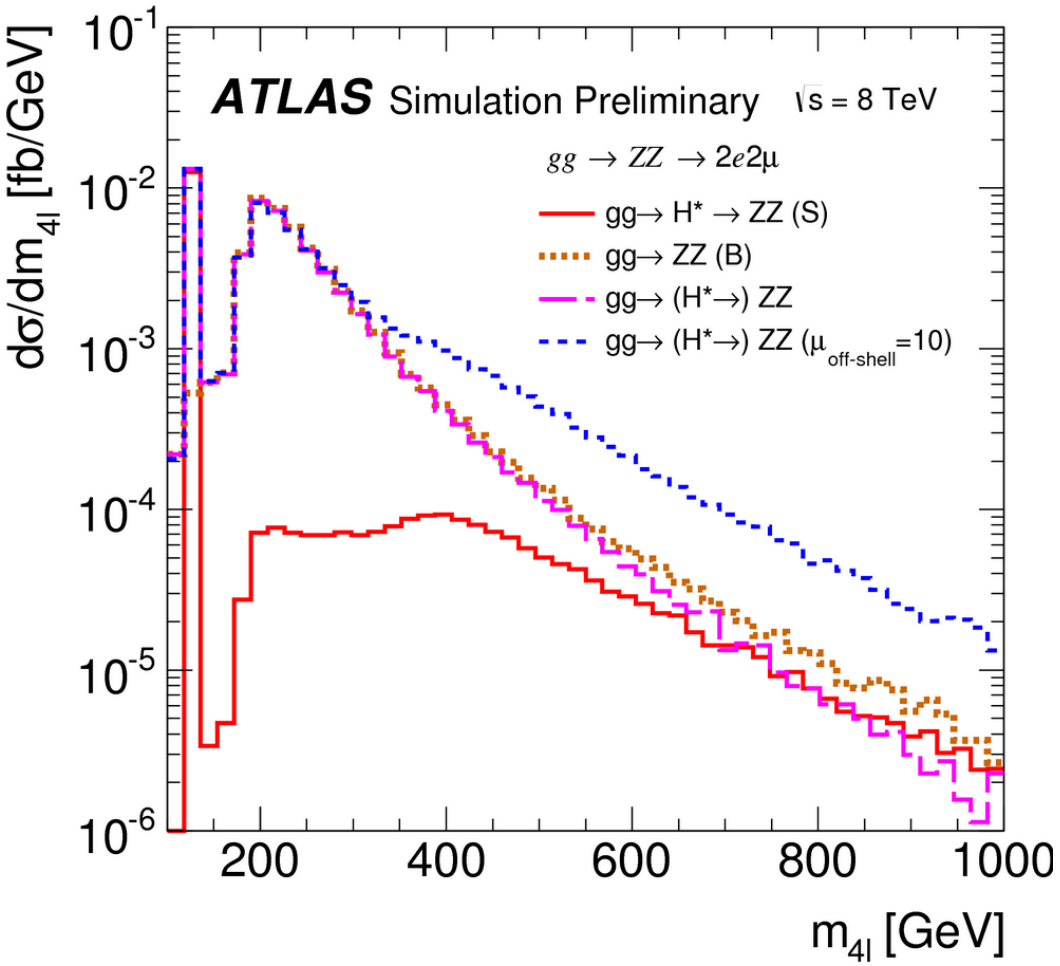




→ These effects are non-negligible. They have to be taken into account in the search.
One could even modify the search and look for dips instead of bumps.

Interference of $gg \to H \to VV$ with $gg \to VV$ and $h \to VV$ with $H \to VV$

The SM Higgs boson has a non-negligible off-shell component:



→ Relevant implications for BSM Higgs searches:

The heavy BSM H can interfere with the background just as the h does now.

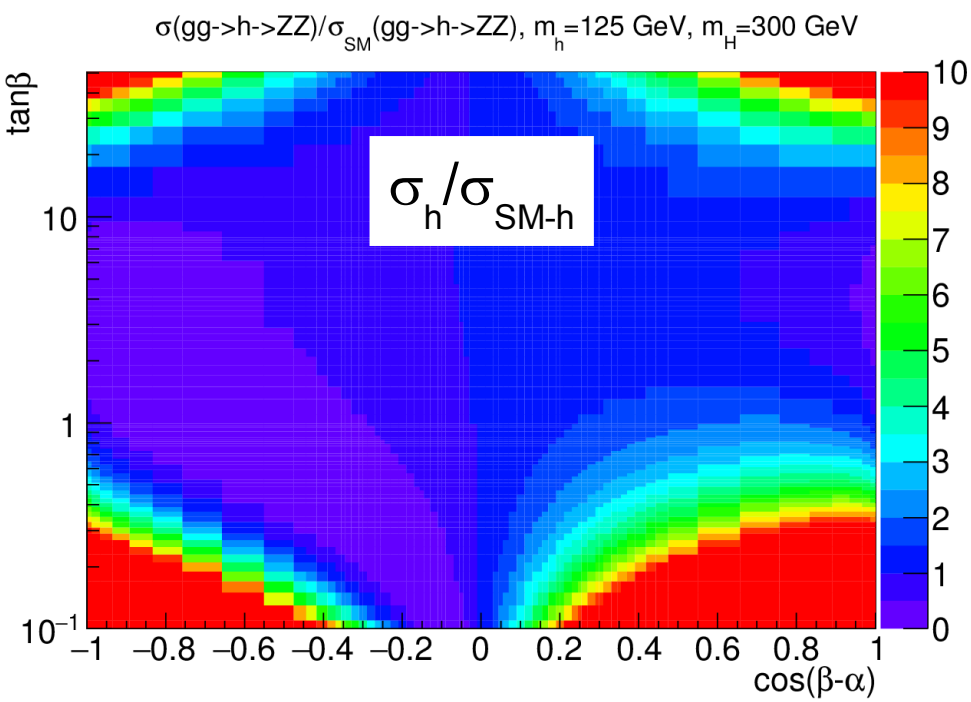
The h can interfere with heavy Higgs at high masses.

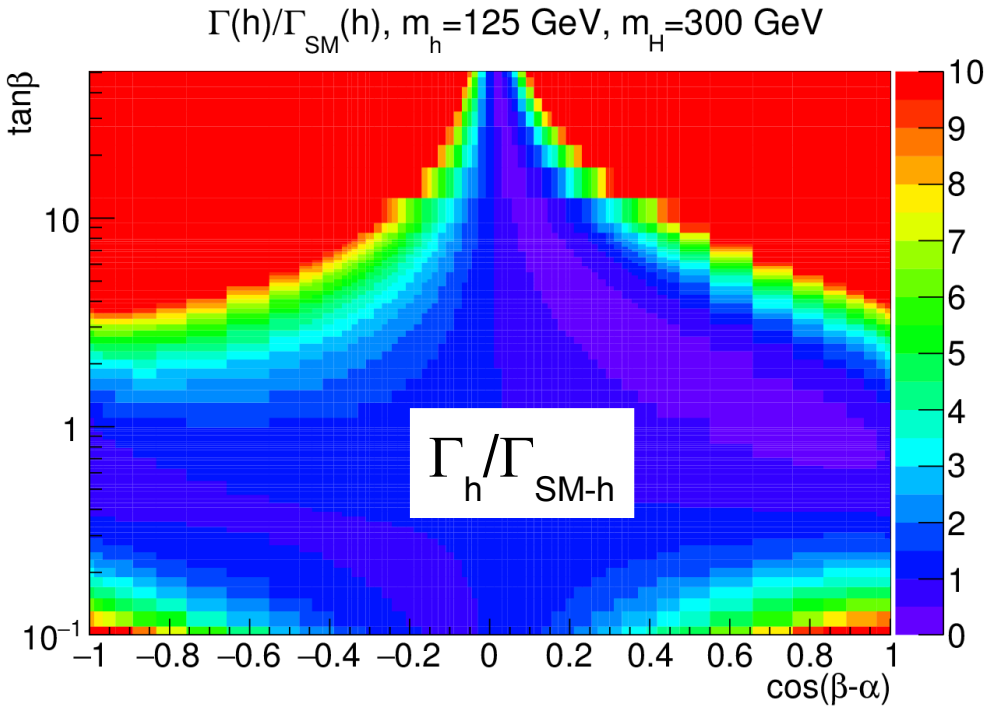
Offshell component of h becomes a background for heavy H searches, especially if $\mu_{offshell}$ is large.

ATLAS prelim: $\mu_{offshell} < 6.7$ (obs..)

The cross section and width of the light h in the 2HDM depend on the model parameters, such as the mass of the heavy H or A, or the tanβ.

2HDM Type-II



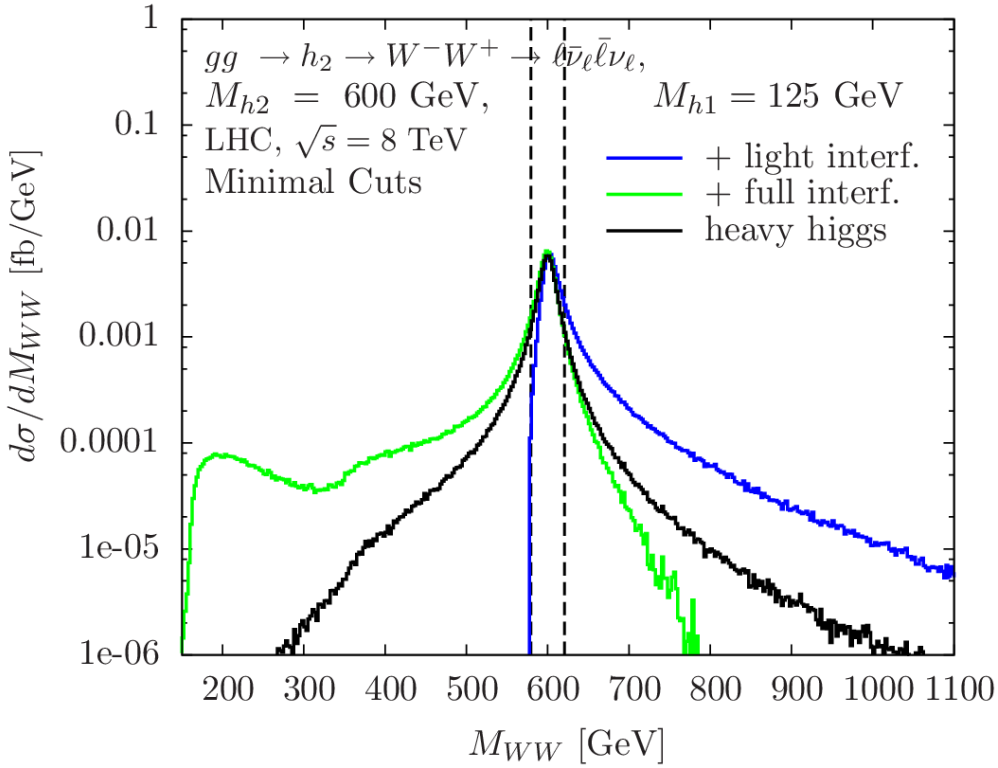


→ Need to consider interference effects in our searches and interpretations.
We started only recently to do so.
→ Width of the Higgs boson is another degree of freedom which we need to consider

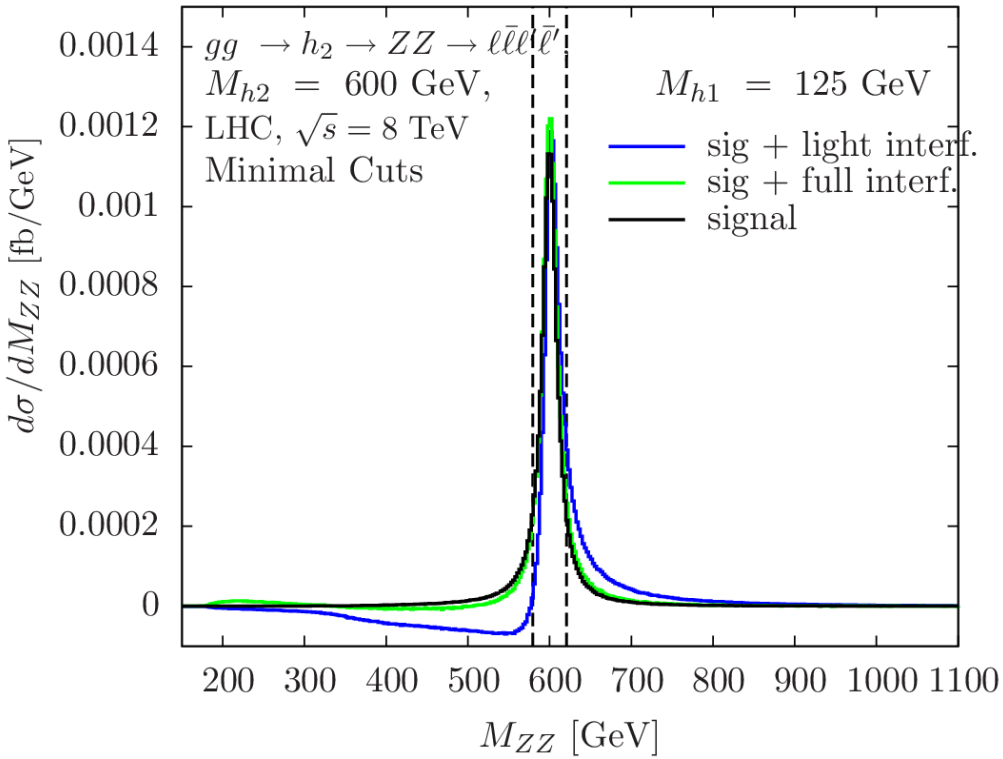
Interference of H → VV with h → VV and gg → VV

MC: gg2VV

H → WW, m_H=600 GeV, m_h=125 GeV:



H → ZZ, m_H=600 GeV, m_h=125 GeV:



The mass lineshape of the heavy Higgs boson changes when taking into account interference with the light h and the continuum background.

→ For further details please see the talk by Nikolas on Thursday (LINK)

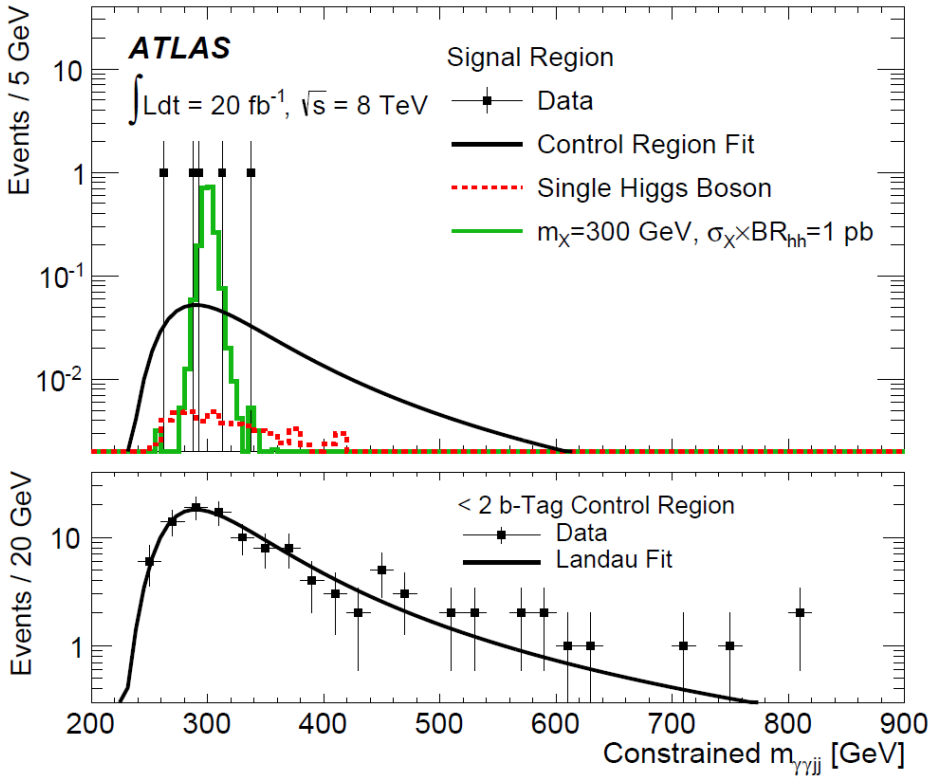
Other BSM Higgs Channels
&
More items on our Wishlist

Higgs Boson Pair Production

Will become very relavant for high-lumi LHC. But we do search for HH already now (eg. HH → bbbb, HH → bbττ, HH → bbγγ), because the HH cross section could be enhanced.

HH → bbγγ:

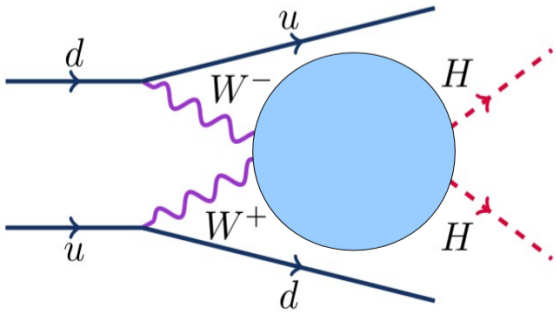
(Paper)



Wish:

We would like to have VBF MC event generators for HH and ttHH final states

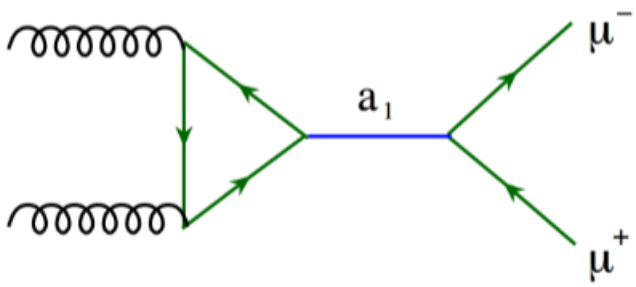
→ Searches for such new signatures could already be tried in Run-II.



Channels being looked at in ATLAS:

- (bb)a → ττ
- h → aa → 4l
- h → aa → 2μ2τ
- t → bH$^+$ → ba$_1$W, a$_1$ → 2μ
- a$_1$ → μμ
- h → aa → 2b2μ
- h → aa → 4γ

Example:



Signal MC samples usually generated with MG5, Powheg + Pythia, or Pythia standalone.

Wish:

We'd like a dedicated NLO generator for the NMSSM.

For example Madgraph5_aMC@NLO with fully implemented NLO would be nice. Please also include the a$_1$ → μμ channel.

Summary of BSM Higgs Issues for Run-2

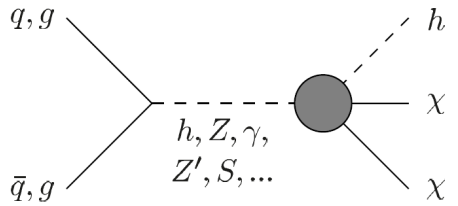
- BSM Higgs boson production:
  - b-associated production
  - Charged Higgs production in different flavor schemes
  - Recipes to evaluate uncertainties
  - Production rates and relative fractions depend on the model

- Interference and width effects:
  - light Higgs boson with BSM Heavy Higgs bosons
  - Higgs bosons with continuum background

- MC generators at NLO:
  For all sort of signals (eg. NMSSM channels, VBF HH, H^+ in intermediate region, ...)

- Input for model-dependent interpretations:
  - Preferably we like „offical numbers“ from the LHC XS WG that allow comparisons with other experiments
  - Please give us cross sections and BR in a dense grids of the parameters
  - We need cross sections and BR for new searches, rare decay modes and for high masses
  - The more models, the better! Eg. we are looking forward getting „low tanβ“ benchmarks.

- EFT validity
  Relevant for dark matter („Higgs+MET“) searches for example

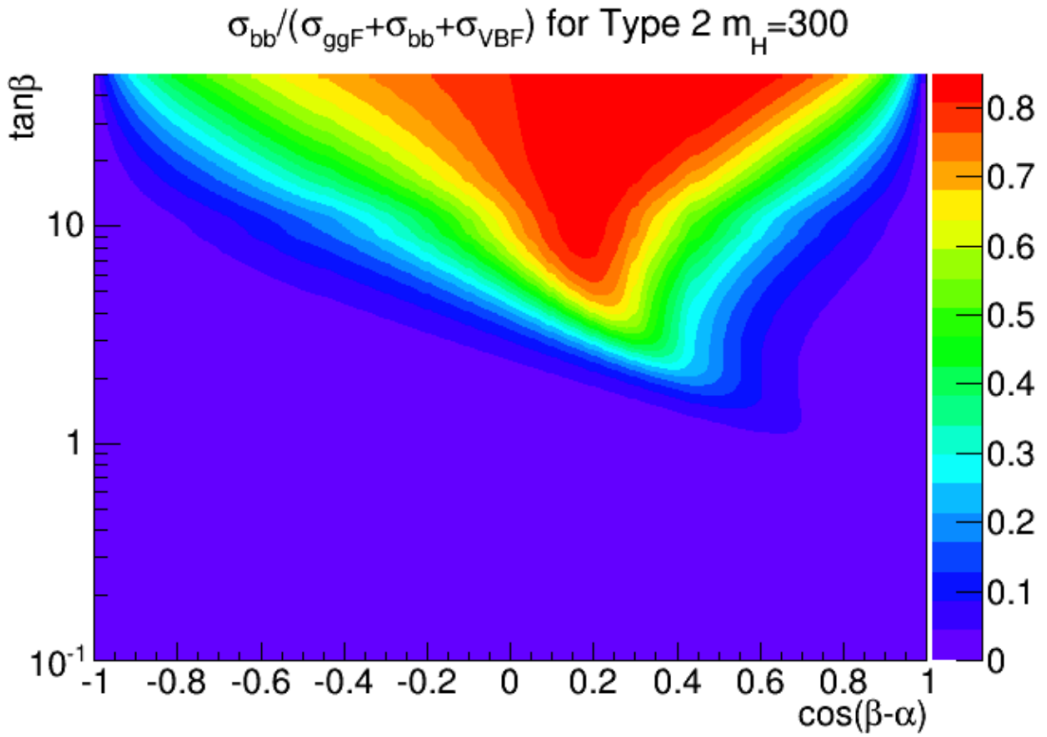


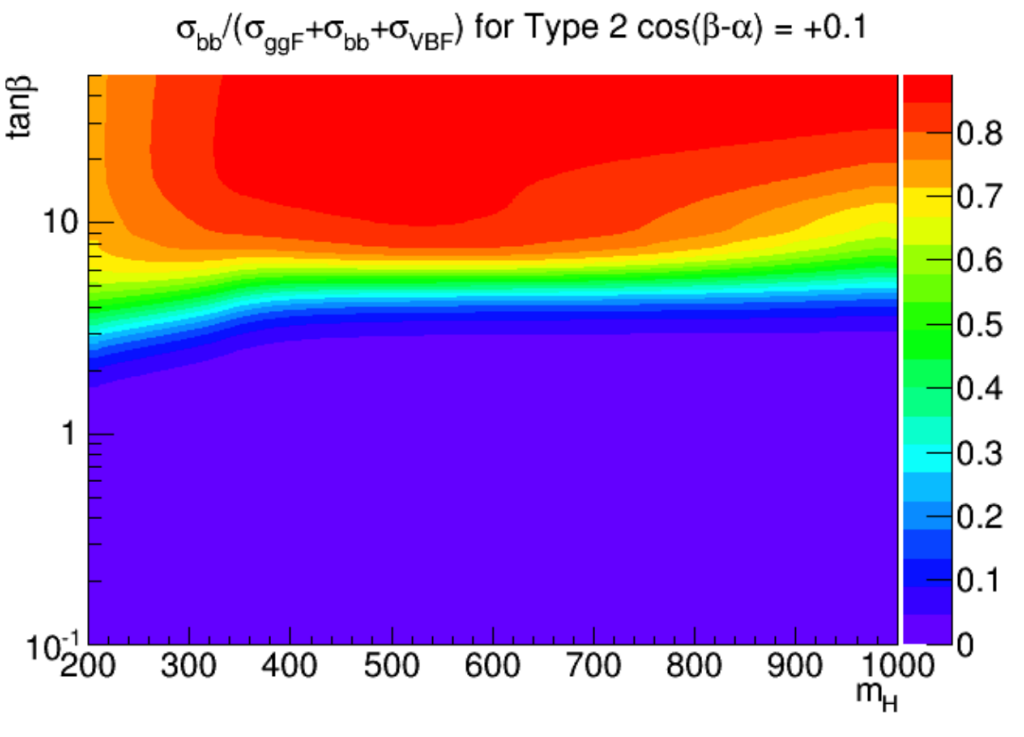
Next year will be the year of the BSM Higgs searches, we look forward to the 13 TeV data!

Backup

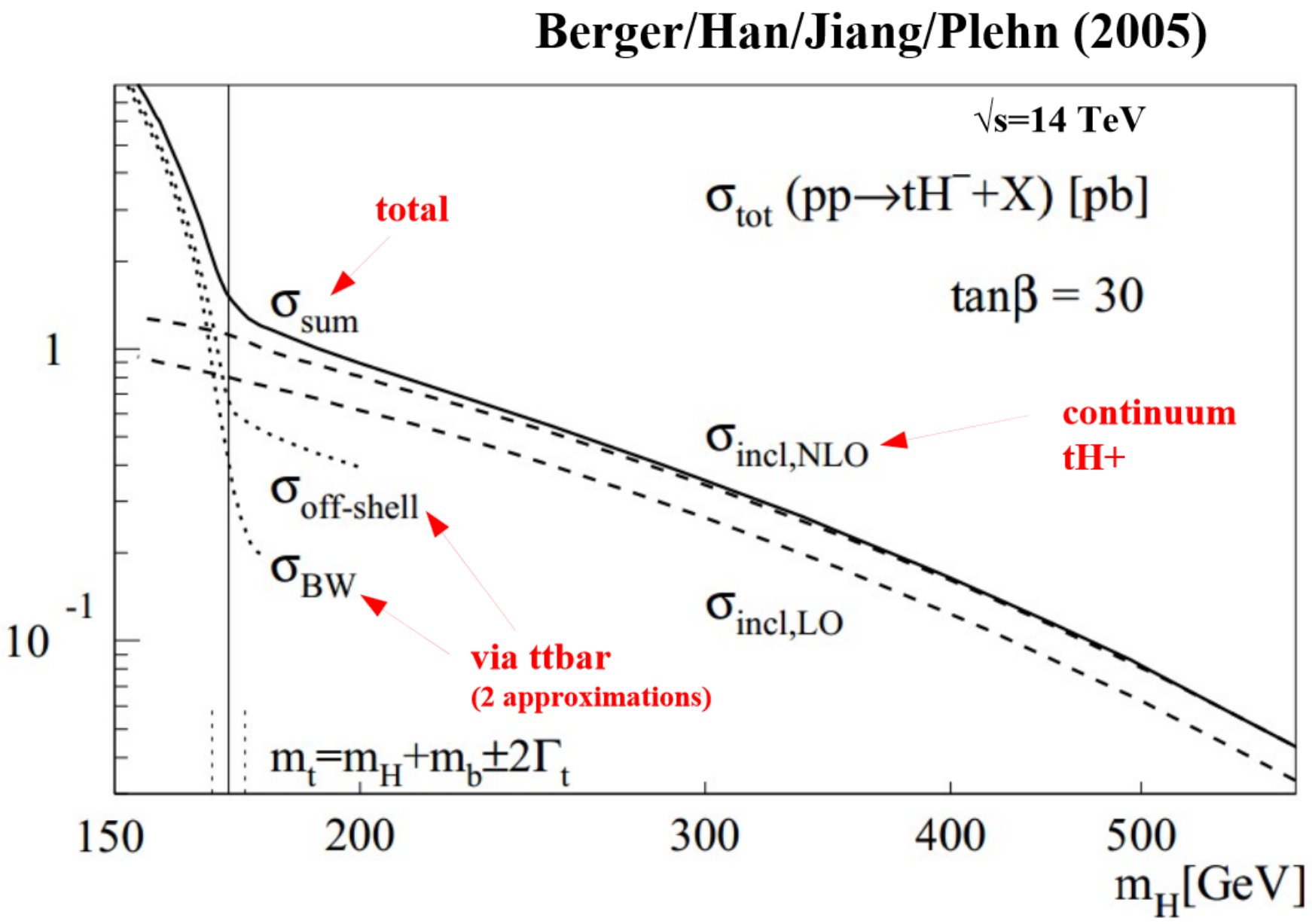
b-associated production becomes relevant for large tanβ

Needs to be taken into account in the model-dependent interpretations





H^+ Production cross section:



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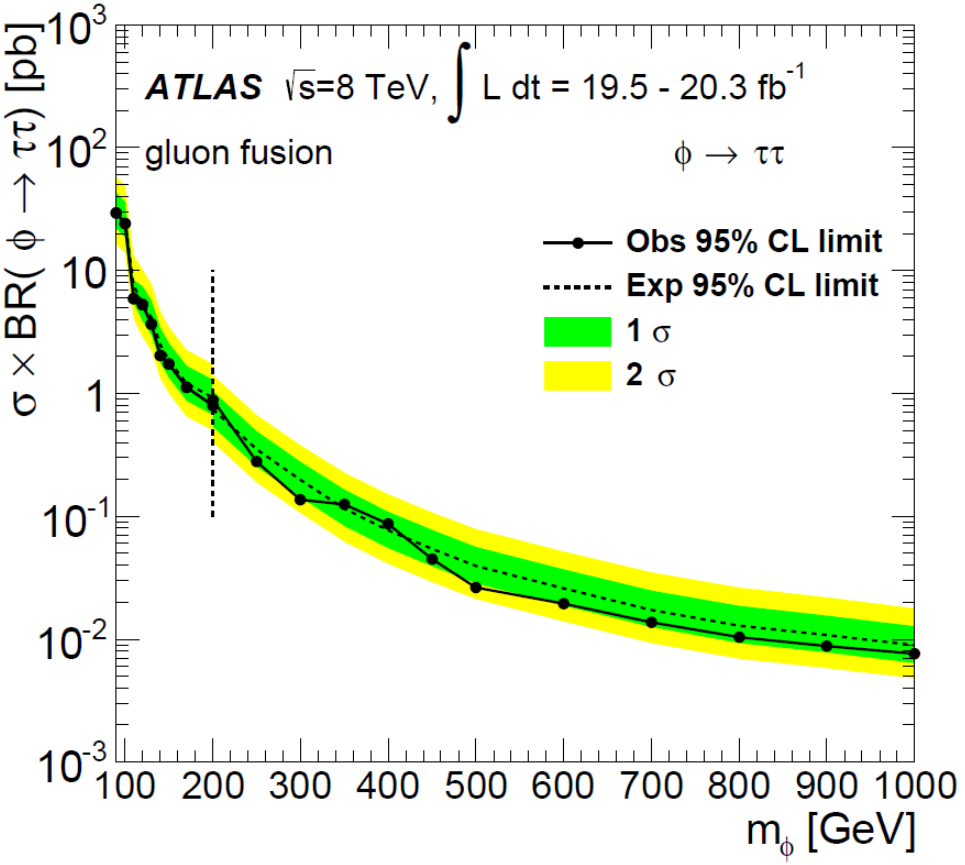

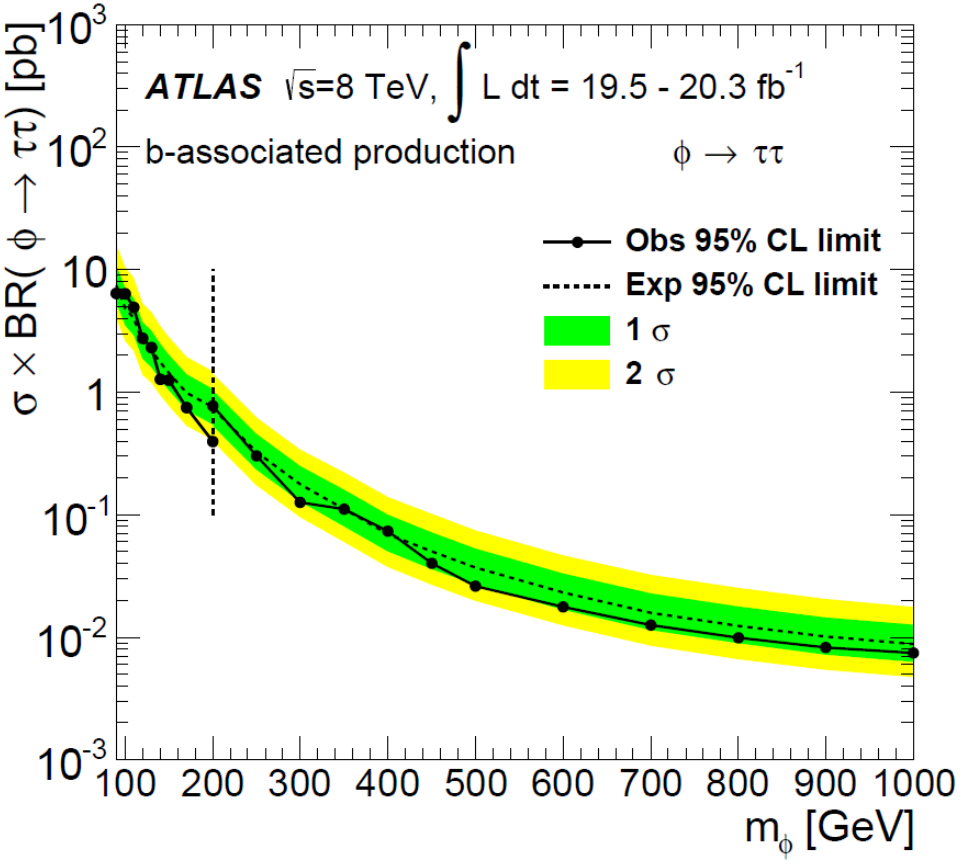

5j exclusive

Sample	2b	3b	4b	3b+4b
4 FS 200 GeV	0.53	0.32	0.03	0.35
5 FS 200 GeV	0.62	0.38	0.04	0.42
rel. difference	16%	20%	21%	20%
4 FS 400 GeV	0.25	0.36	0.04	0.40
5 FS 400 GeV	0.34	0.54	0.07	0.61
rel. difference	37%	53%	48%	53%
4 FS 600 GeV	0.21	0.33	0.03	0.37
5 FS 600 GeV	0.30	0.49	0.05	0.55
rel. difference	41%	48%	67%	50%

5j inclusive

Sample	2b	3b	4b	3b+4b
4 FS 200 GeV	1.33	1.39	0.43	1.82
5 FS 200 GeV	1.20	1.18	0.30	1.48
rel. difference	-10%	-15%	-31%	-19%
4 FS 400 GeV	0.87	2.28	1.10	3.38
5 FS 400 GeV	0.92	2.26	0.87	3.13
rel. difference	6%	-1%	-21%	-8%
4 FS 600 GeV	0.85	2.42	1.23	3.72
5 FS 600 GeV	0.93	2.49	0.99	3.48
rel. difference	9%	3%	-24%	-7%