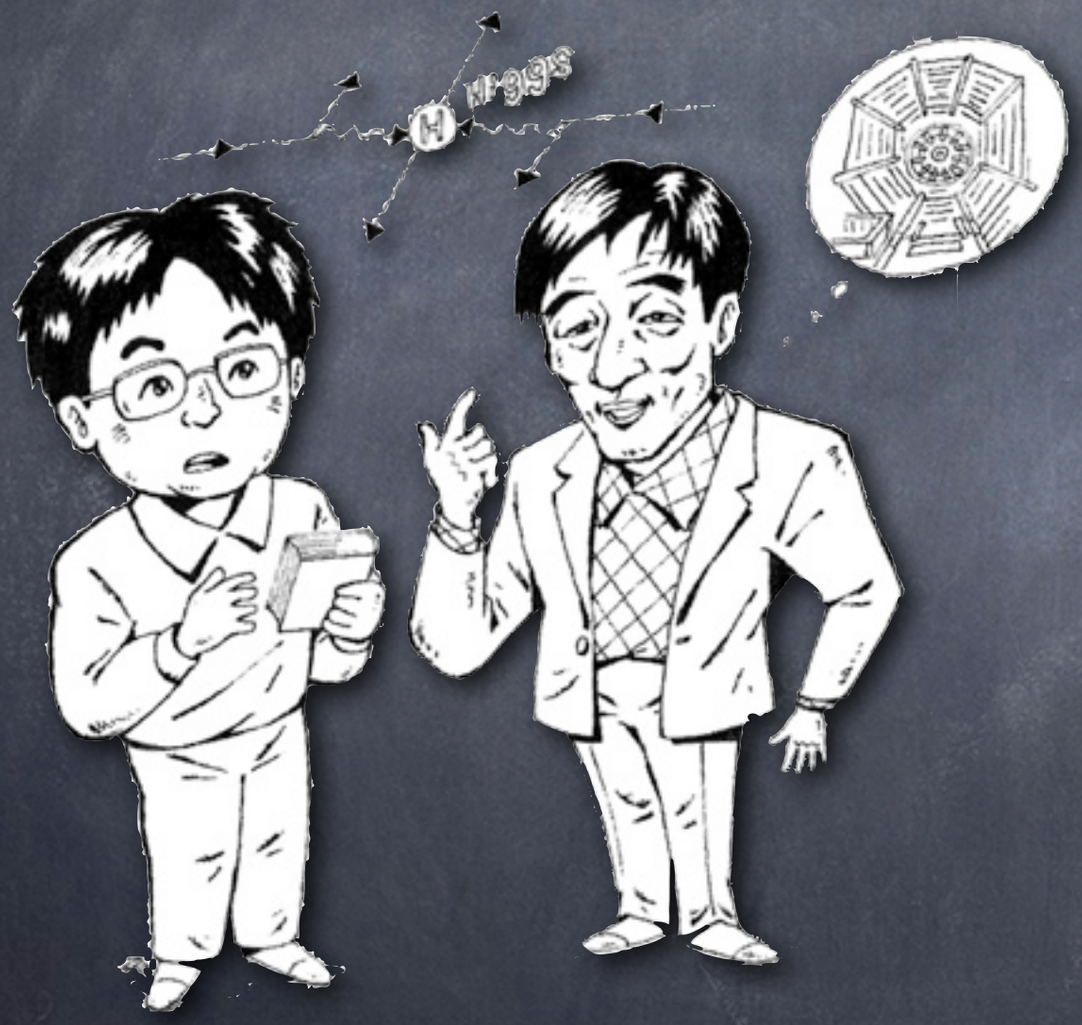
Higgs Cross Sections and Branching Ratios



R. Tanaka, “Comprehensible Higgs”,
Science, Vol.79, No.5, p.488,
Iwanami publishing Co., Japan, May 2009

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LHC Higgs XS WG Workshop
June 12-13, 2014, CERN

Thanks for inputs from previous EXP contacts to LHC Higgs XS WG.

Contents

With focus on recent topics and experiments' needs.

Higgs Physics Theoretical Issues

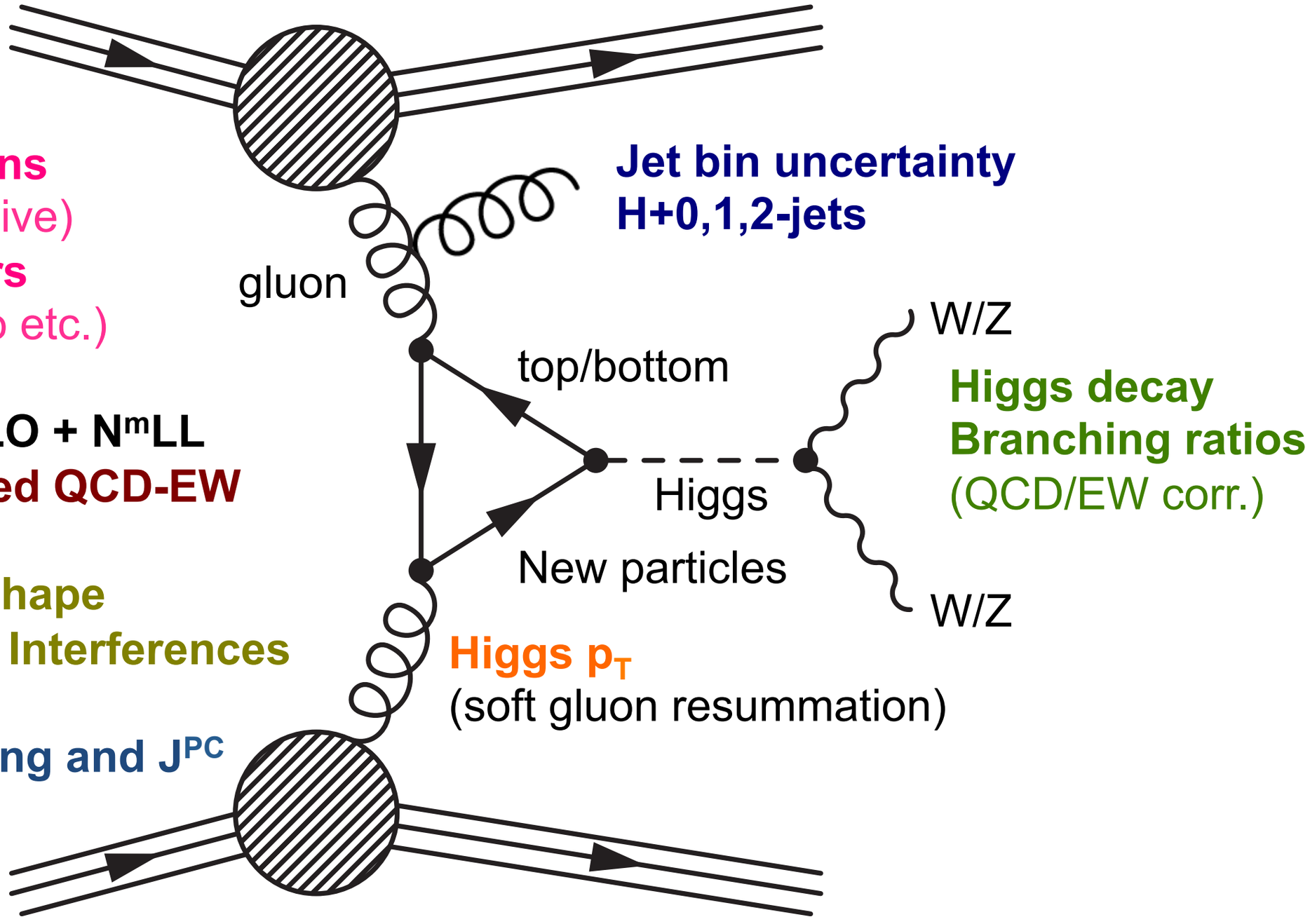
ggF, VBF, WH/ZH, ttH, BSM Higgs

Higgs Cross Sections
(inclusive/exclusive)
Differential K-factors
(effect of jet-veto etc.)

QCD correction $N^kLO + N^mLL$
EW correction, Mixed QCD-EW

Heavy Higgs Line Shape
SM Backgrounds & Interferences

Higgs Mass, Coupling and J^{PC}



Jet bin uncertainty
H+0,1,2-jets

Higgs decay
Branching ratios
(QCD/EW corr.)

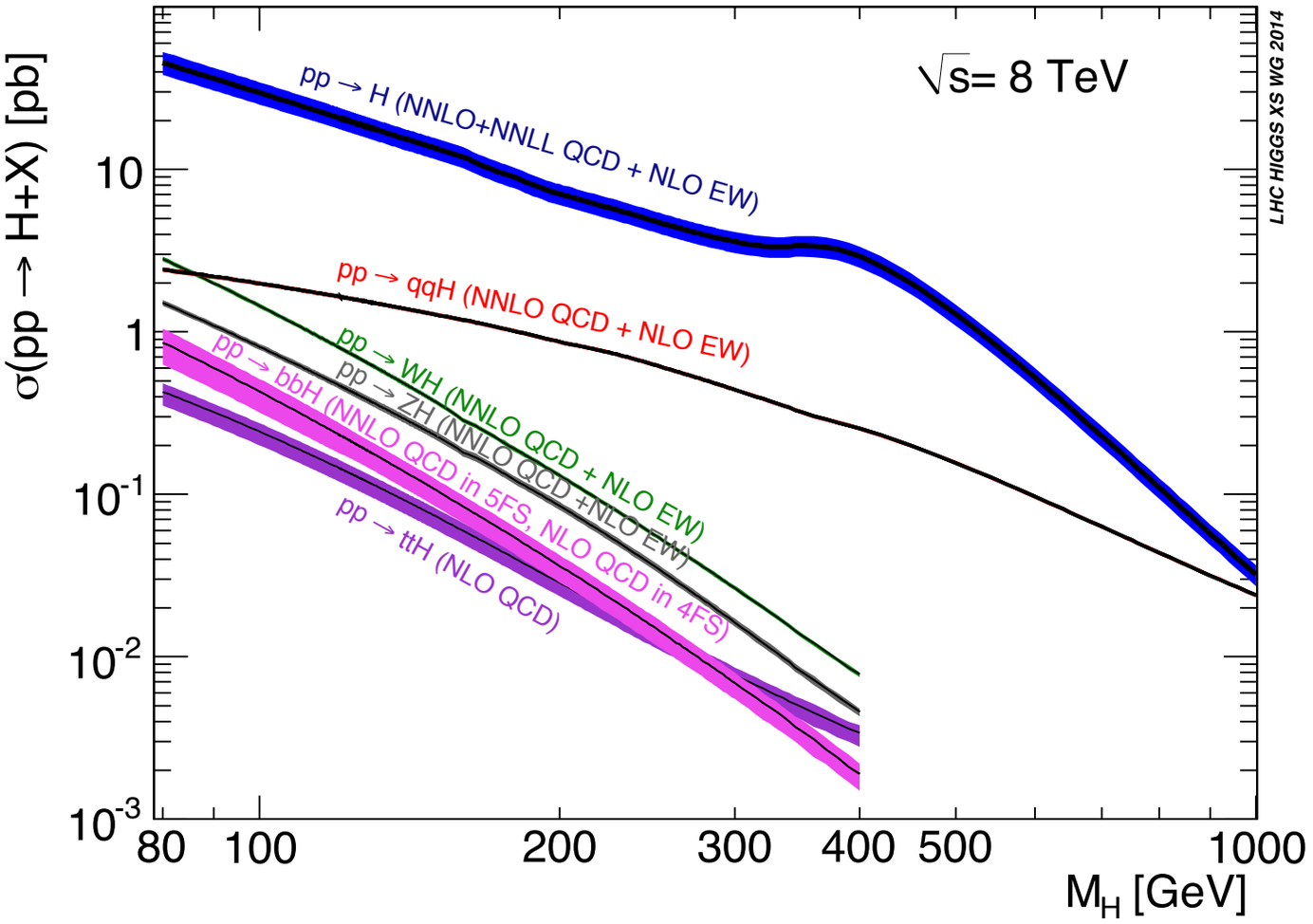
Higgs p_T
(soft gluon resummation)

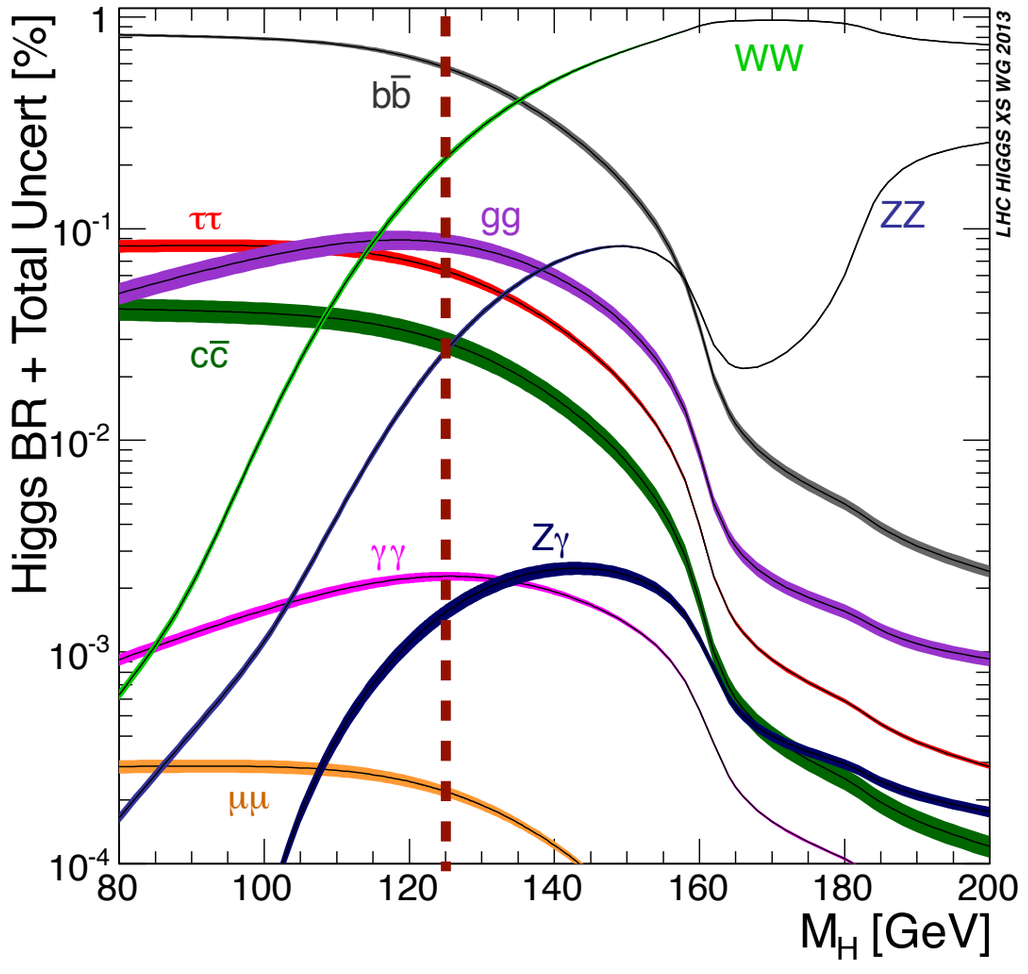
PDF+α_s uncertainties
Renormalization/Factorization scale dependence

1. Higgs Cross Sections and Branching Ratios

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHXSWG

Higgs Cross Sections and Branching Ratios





Higgs mass range and step (new fine scan points in CERN Report 3):

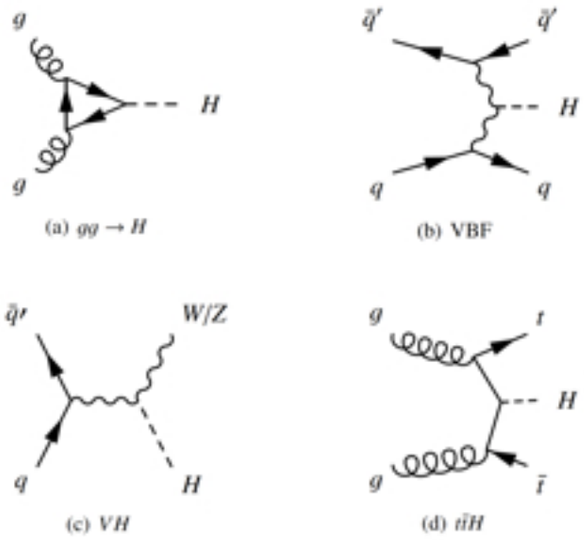
Higgs Mass range	step size	# of points	addendum
[80,110] GeV	1 GeV	31 points	
[110,120] GeV	0.5 GeV	20 points	
[120,130] GeV	0.1 GeV	100 points	
[130,150] GeV	0.5 GeV	40 points	
[150,300] GeV	2 GeV	75 points	+ 165, 175, 185, 195 GeV (4 points)
[300,350] GeV	5 GeV	10 points	
[350,400] GeV	10 GeV	5 points	
[400,1000] GeV	20 GeV	30 points	+ 450, 550, 650, 750, 850, 950 GeV (6 points).

- 321 points for ggF, VBF (M_H=[80,1000]GeV).
- 285 points for WH/ZH, ttH (M_H=[80,400]GeV).

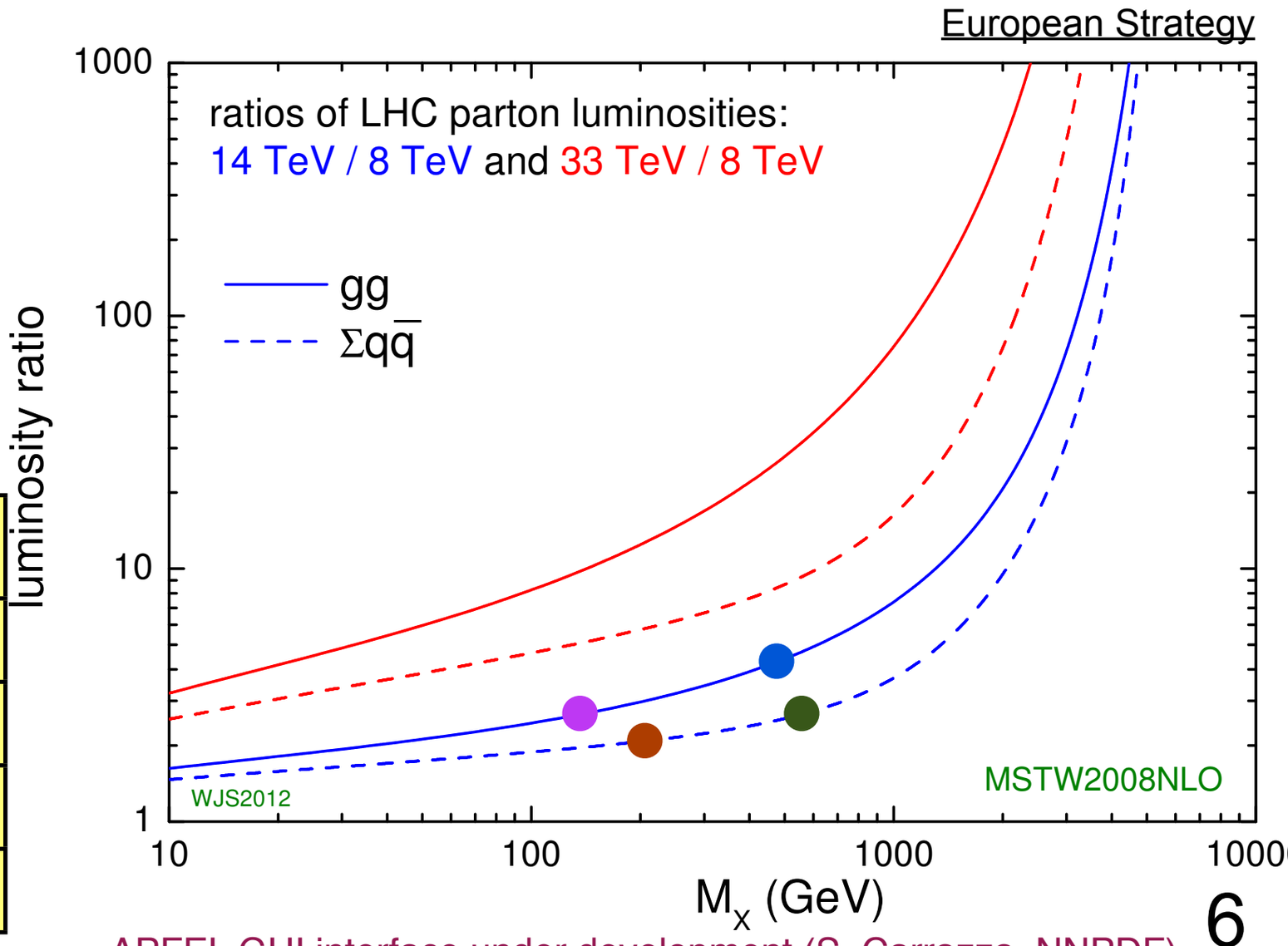
Do we need fine step M_H scan for Higgs XS at 13-14 TeV?

Cross section ratio $\sigma_{14TeV}/\sigma_{8TeV}$

- Frequently-asked-question:
  - Q) Why gains in gg→H and qq→qqH are the same? A) accidental!
  - Q) Why ttH gain is so large? A) phase space opening + large $M_X=2M_t+M_H$ in gg)
- Gains can be estimated via parton-luminosity-ratio if kinematically fully open.



	σ(14TeV)/σ(8TeV)
gg→H	2.6 ($M_X=M_H$)
qq→qqH	2.6 (probes high M_X)
qq→VH	2.1 ($M_X=M_V+M_H$)
gg→ttH	4.7 (phase space+M_{ttH})



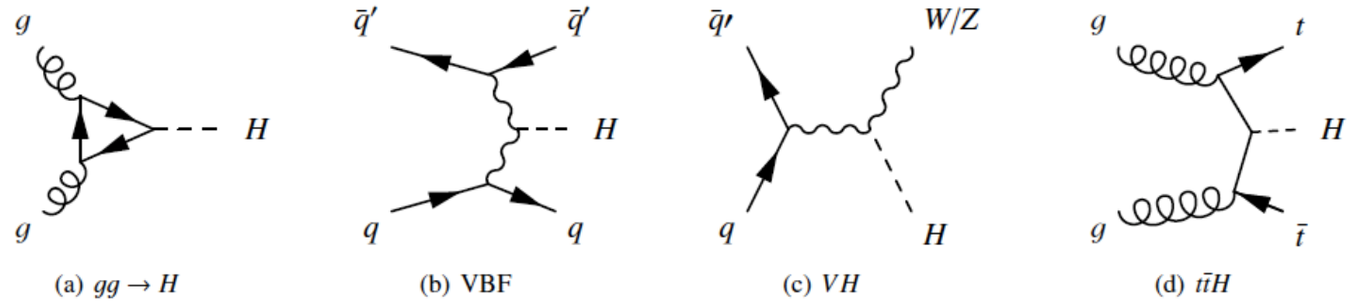
APFEL GUI interface under development (S. Carrazza, NNPDF)

Higgs XS theory uncertainties

N3LO ggF, R.D. Ball et al. +17% in approx.? (NP B874 (2013) 746-772)
New N3LO calculation soon?

M_H=125 GeV

K-factor, QCD scale and PDF uncertainties



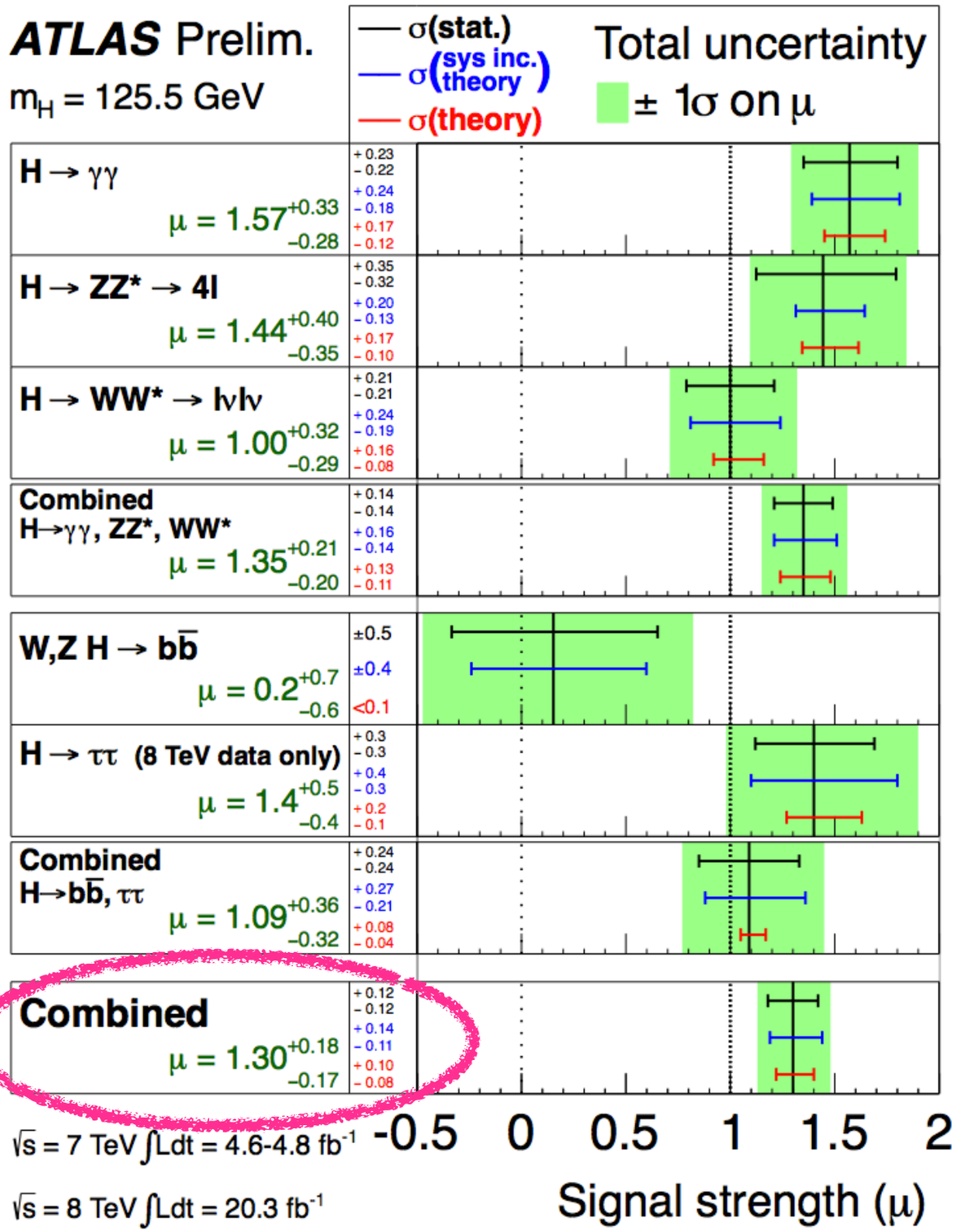
	7 TeV				8 TeV		
	$K_{NNLO/NLO}$ ($K_{NLO/LO}$)	Scale	PDF+α_s	Scale +PDF	Scale	PDF+α_s	Scale +PDF
ggF	+25% (+100%)	+7-8%	±8%	**±15%**	+7-8%	±8%	**±15%**
VBF	<1% (+5-10%)	±1%	±4%	**±5%**	±1%	±4%	**±5%**
WH/ ZH	+2-6% (+30%)	±1%	±4%	**±5%**	±1%	±4%	**±5%**
ttH	- (+5-20%)	+3 -9%	±8%	**+12 -18%**	+4 -9%	±8%	**+12 -17%**

- Renormalization and factorization scale uncertainty study by M. Cacciari et al. work in progress.
- Higher-order calculations, ex. ggF QCD scale: ±8%@NNLO → ±5%@NNNLO in few years ?
- PDF+α_s (PDF4LHC prescription): ±8% → <5% with improvements with LHC data ?
  - jets, top, prompt photons and Z p_T distributions contribute gluon PDF determination.

(but paradoxically, ggF is the best measure to determine gg parton luminosity around M_H=125GeV!)

The signal strength

ATLAS-CONF-2014-009



$$\mu = \frac{\sigma \cdot \mathrm{BR}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$

- Consistent with the SM prediction with precision about 15% level.
- Theory uncertainty (QCD scale ±8%@NNLO and PDF+α_s ±8%) is already comparable to experimental and statistical uncertainties on the combined signal strength!

What is the probability distribution function for the QCD scale uncertainty?

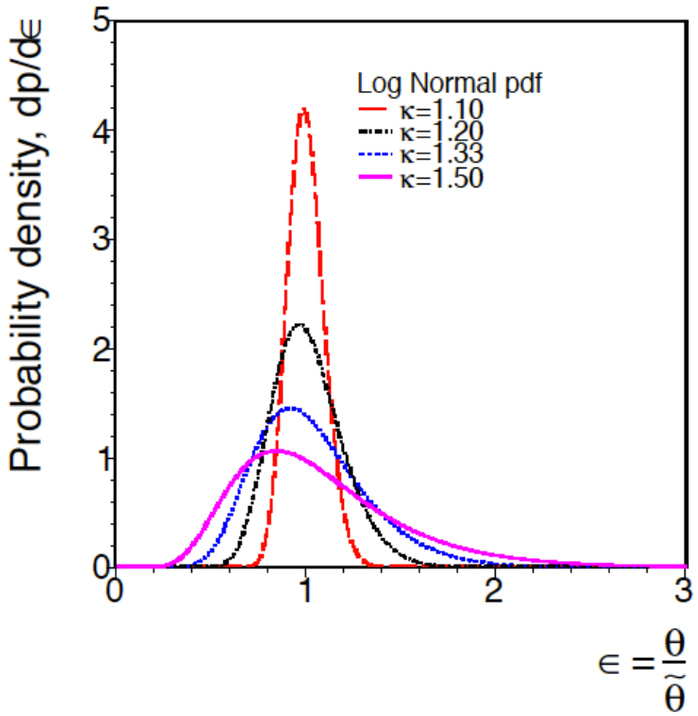
QCD scale uncertainty

- LHC Higgs combination WG's prescription (ATL-PHYS-PUB-2011-011, CMS Note-2011/005)
  - Subdivide nuisance parameters until they become uncorrelated.
  - Take Gaissian/Log-normal for pdf. Practically Gaussian as $\kappa \simeq 1.0$ for scale.
- New method by M. Cacciari and N. Houdeau. JHEP 09 (2011) 039
  - Preserves both characteristics of log-normal (tail) and flat-top.
  - Treats renormalization scale only, factorization scale is work in progress.
  - Questions are flat-top width and tail length.

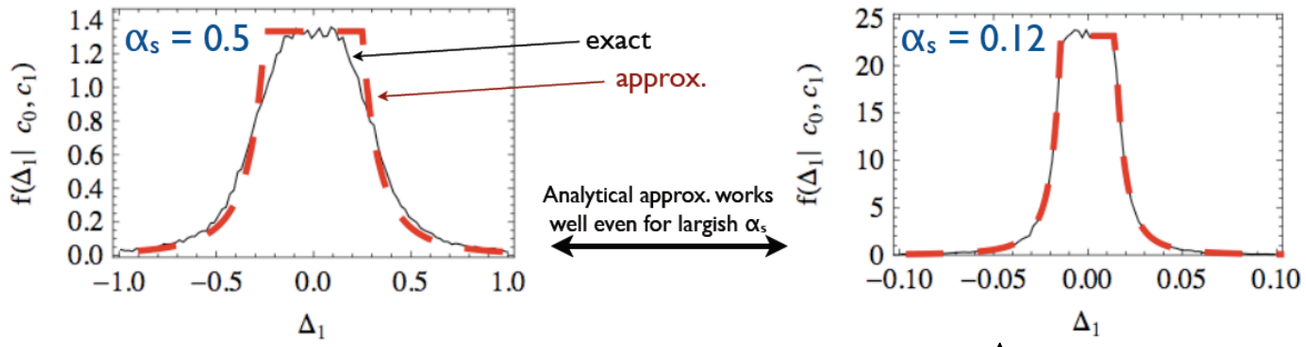
log-Cacciari-Houdeau

Gaussian/log-normal

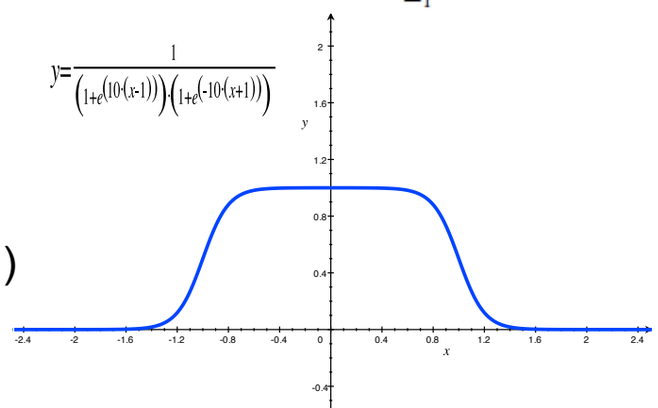
$$\rho(\theta) = \frac{1}{\sqrt{2\pi}\ln(\kappa)} \exp\left(-\frac{(\ln(\theta/\tilde{\theta}))^2}{2(\ln\kappa)^2}\right)\frac{1}{\theta}$$



$$f(\Delta_k|c_0,\ldots,c_k) \simeq \left(\frac{k+1}{k+2}\right)\frac{1}{2\alpha_s^{k+1}\bar{c}_{(k)}}\begin{cases} 1 & \text{if } |\Delta_k| \le \alpha_s^{k+1}\bar{c}_{(k)} \\ \frac{1}{(|\Delta_k|/(\alpha_s^{k+1}\bar{c}_{(k)}))^{k+2}} & \text{if } |\Delta_k| > \alpha_s^{k+1}\bar{c}_{(k)} \end{cases}$$



log-double-Fermi-Dirac to smoothen the edges
(used in ATLAS-CONF-2013-034)



QCD scale uncertainty correlations in qq/gg → VH, VV and H (by educated guess!)

	qq→VH	gg→ZH	qq→VV	gg→VV	gg→H→VV
qq→VH		0	+50%	0	0
gg→ZH	0		0	+50%	+50%
qq→VV	+50%	0		0	0
gg→VV	0	+50%	0		+100%
gg→H→VV	0	+50%	0	+100%	

- Note 1: V=W,Z. And assumes +100% correlation between (qq→WH and ZH), (qq→WW and ZZ), and (gg→WW and ZZ).
- Note 2: +50% correlation among different processes should be reasonable estimate.
- Note 3: no correlations between others: ggF, VBF, VH, ttH, bbH and SM VV ?

PDF+α_S uncertainty correlations between Higgs signal and SM backgrounds

- CERN Report 2, PDF section (Table 10 and 11)

$M_H = 120$ GeV	ggH	VBF	WH	$t\bar{t}H$
ggH	1	−0.6	−0.2	−0.2
VBF	−0.6	1	0.6	−0.4
WH	−0.2	0.6	1	−0.2
$t\bar{t}H$	−0.2	−0.4	−0.2	1
W	−0.2	0.6	0.8	−0.6
WW	−0.4	0.8	1	−0.2
WZ	−0.2	0.4	0.8	−0.4
Wγ	0	0.6	0.8	−0.6
$Wb\bar{b}$	−0.2	0.6	1	−0.2
$t\bar{t}$	0.2	−0.4	−0.4	1
$t\bar{b}$	−0.4	0.6	1	−0.2
$t(\to \bar{b})q$	0.4	0	0	0

	W	WW	WZ	Wγ	$Wb\bar{b}$	$t\bar{t}$	$t\bar{b}$	$t(\to \bar{b})q$
W	1	0.8	0.8	1	0.6	−0.6	0.6	−0.2
WW	0.8	1	0.8	0.8	0.8	−0.4	0.8	0
WZ	0.8	0.8	1	0.8	0.8	−0.4	0.8	0
Wγ	1	0.8	0.8	1	0.6	−0.6	0.8	0
$Wb\bar{b}$	0.6	0.8	0.8	0.6	1	−0.2	0.6	0
$t\bar{t}$	−0.6	−0.4	−0.4	−0.6	−0.2	1	−0.4	0.2
$t\bar{b}$	0.6	0.8	0.8	0.8	0.6	−0.4	1	0.2
$t(\to \bar{b})q$	−0.2	0	0	0	0	0.2	0.2	1

- Current prescription based upon LHC Higgs Combination prescription

  100% correlated PDF+α_s uncertainties for gg-initiated (ggF, ttH, gg->VV) and qq-initiated (VBF, VH, VV) processes.

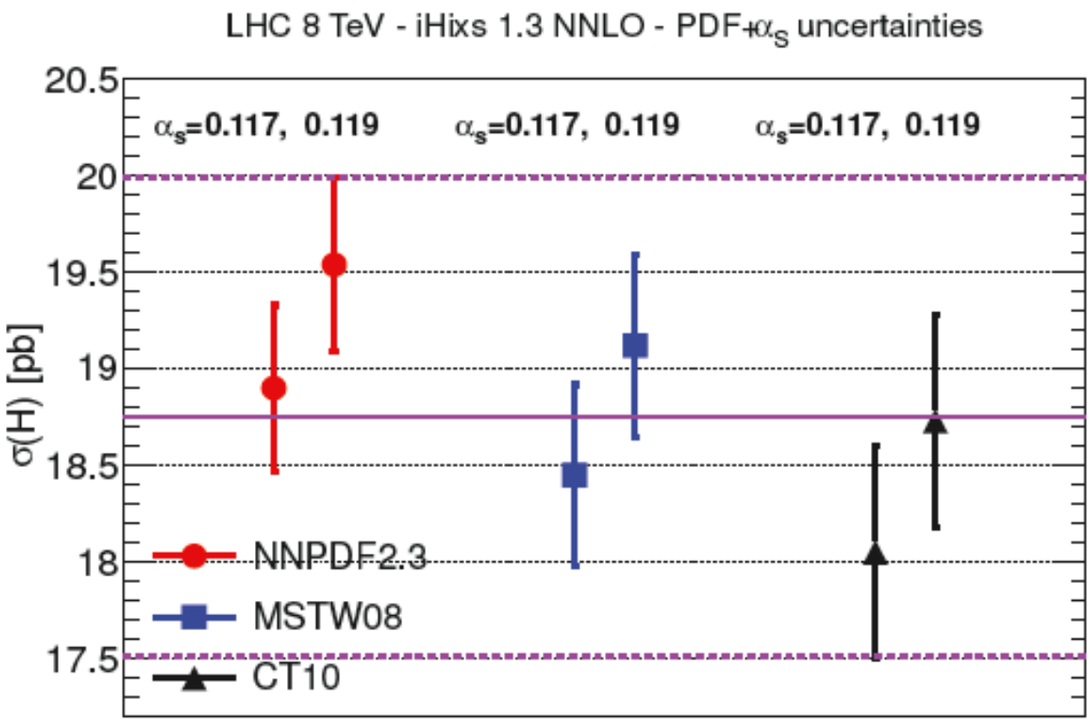
  But we need to take into account PDF uncertainty correlations among Higgs signal and backgrounds.

  Currently discussed in LHC Higgs Combination WG about correlations.

PDF+α_s Uncertainty

- PDF4LHC Prescription (2011)
  - "The PDF4LHC Working Group Interim Recommendations", arXiv:1101.0538 ... envelope of MSTW2008, CTEQ and NNPDF.
- New 2014 NNLO PDF4LHC prescription (using CT10, NNPDF2.3 and MSTW08)
  - Now many PDF sets are at NNLO (CT10, MSTW, NNPDF, ABM11, HERAPDF, ...) and new HERA2 data and also LHC data start to play the role.
  - Prescription can be potentially developed using the meta-PDF technique involving more PDFs. (JHEP 1208 (2012) 052, arXiv:1401.0013)
  - Should α_s be separated out from PDF uncertainty and correlated to that in BR? Perhaps yes.

CERN Report 3, Fig. 59



- Use a common value of α_s of 0.118 with a 68%CL uncertainty of 0.0012.
- Common QCD α_s value and associated uncertainty throughout Higgs XS&BR calculations in LHC Higgs XS WG?

Note: cross section order depends on the process!

Higgs Decay Branching Ratios

- Use HDECAY and Prophecy4f for best estimate.

$$\Gamma_H = \Gamma^{\mathrm{HDECAY}} - \Gamma^{\mathrm{HDECAY}}_{\mathrm{WW}} - \Gamma^{\mathrm{HDECAY}}_{\mathrm{ZZ}} + \Gamma^{\mathrm{Prophecy4f}}_{\mathrm{4f}}$$

- What are the theory (THU) + parametric (PU) uncertainties ?

- Relatively large uncertainties for H→ττ, μμ, γγ, Zγ/WW/ZZ at low M_H.
- Smaller uncertainties relative to scale and PDF+α_s uncertainties in Higgs production.

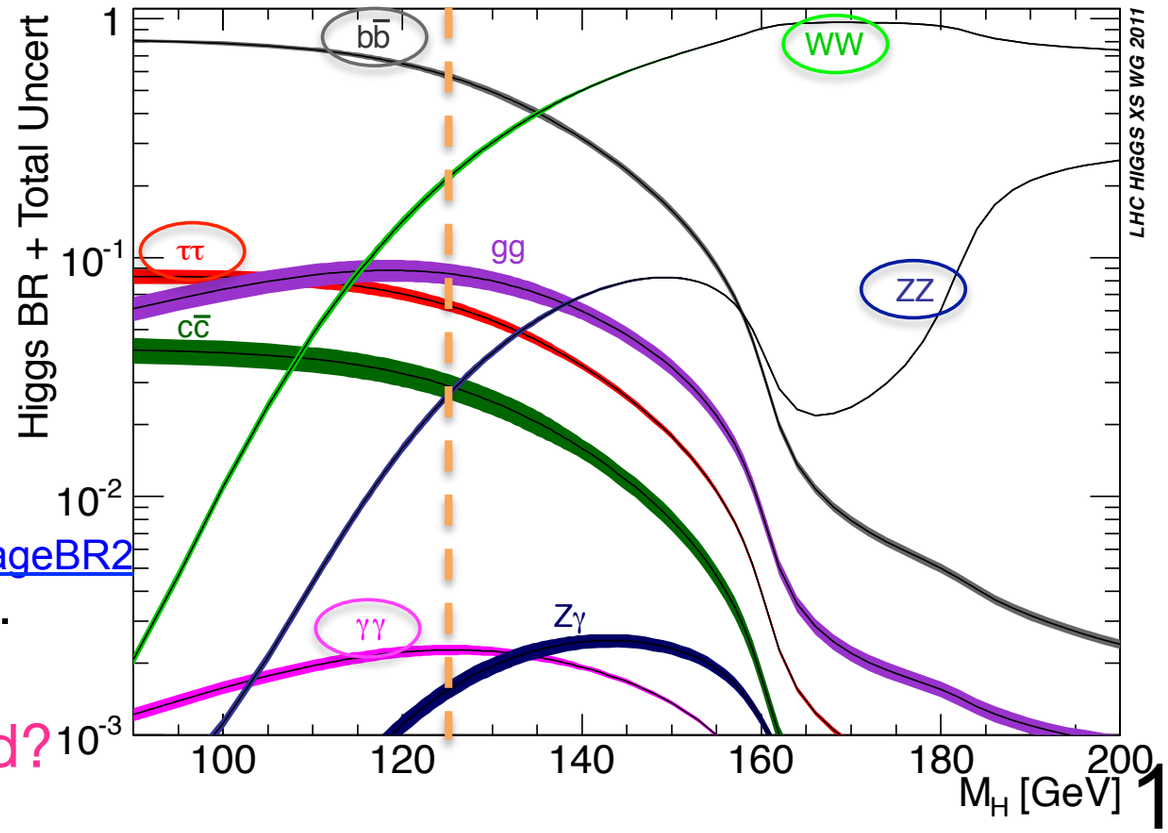
Separation of BR THU and PU are in progress.
Stick to THU+PU **±5-10%** conservative uncertainty.

Updated numbers in CERN Report 2.
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageBR2
Major change was BR(H→ss) due to quark mass definition.

Can THU and PU(α_s, $m_{t,b,c}$, m_H, etc.) be improved?

A. Denner et al., Eur. Phys. J. C (2011) 71

M_H	Decay	THU	PU	Total
120GeV	H→bb	±1.3%	±1.5%	**±2.8%**
	H→ττ	±3.6%	±2.5%	**±6.1%**
	H→μμ	±3.9%	±2.5%	**±6.4%**
	H→γγ	±2.9%	±2.5%	**±5.4%**
	H→Zγ	±6.9%	±2.5%	**±9.4%**
	H→ZZ	±2.2%	±2.5%	**±4.8%**
	H→WW	±2.2%	±2.5%	**±4.8%**



2. Gluon-fusion Process

ggF Wishlists/Questions

- Powheg + MENLOPS would be preferable, but quark mass effects are missing. We would need also EW corrections and CPS scheme implementation for SM-like searches.
- Need to overcome HxBr approximation for proper treatment of offshellness, correction provided as a function of m_{VV}?
- CMS probably going to standard Powheg. Also trying Powheg+MENLOPS (0+1+2 jet NLO?) aMC@NLO (multi-jets up to 3 jets-NLO) need HQ mass implementation. In addition Sherpa.
- Herwig obsolete, aMC@NLO+Pythia8/Herwig++ needs validation work.
- CMS also going to Pythia8 (use common tuning and UE between ATLAS and CMS?) How to evaluate UE uncertainty (eigenvector fit to min-bias observables?) Need tuning Powheg+Pythia8 with hfact (already available at 8 TeV, 13 TeV?) Need to understand differences in Higgs p_T between Powheg+Pythia8 and Powheg +Pythia6.
- Any idea on how we could reduce gg PDF uncertainty using LHC data?
- Can we find measurements able to factorize out the σ_{ggF} uncertainty from the coupling measurement?
- How long we need for full N3LO ggF XS? Will we have also N3LO resummed?

3. Vector-Boson-Fusion and Higgs Associated Production with Gauge Boson

VBF, WH/ZH

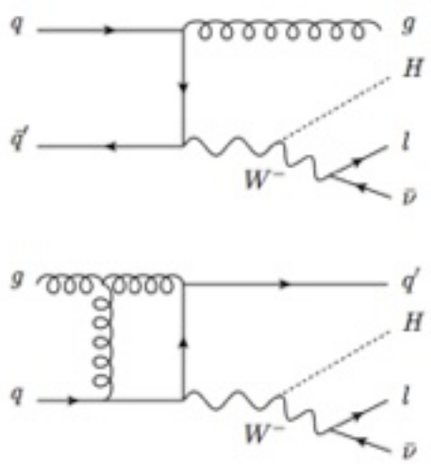
1) VBF - NLO QCD + EW MC (**HAWK**, **VBFNLO**)?

2) HV, HVJ with **POWHEG MiNLO**

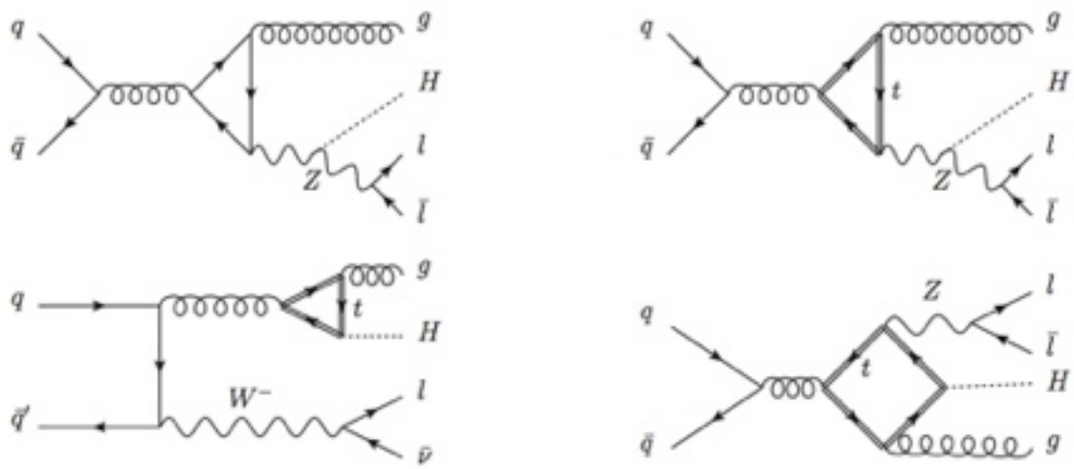
VH(H->bb)

1. QCD NNLO corrections: apply NNLO/NLO weights as function of p_{TW} and NaddJets (0 vs >=1) in CMS.
2. The weights are applied to POWHEG+Herwig++ NLO MC
3. Final state radiation not included by ATLAS/CMS in any way yet.

HVJ production



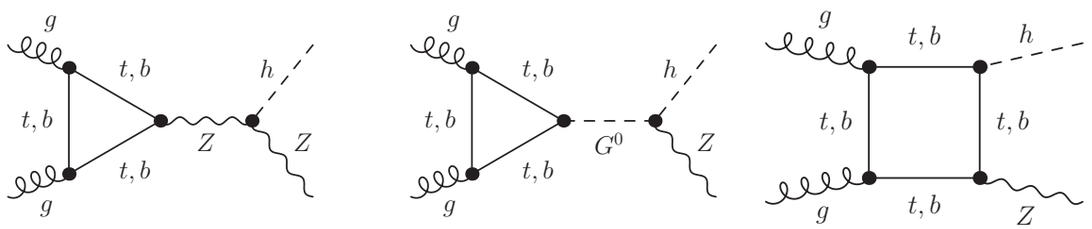
HVJ production



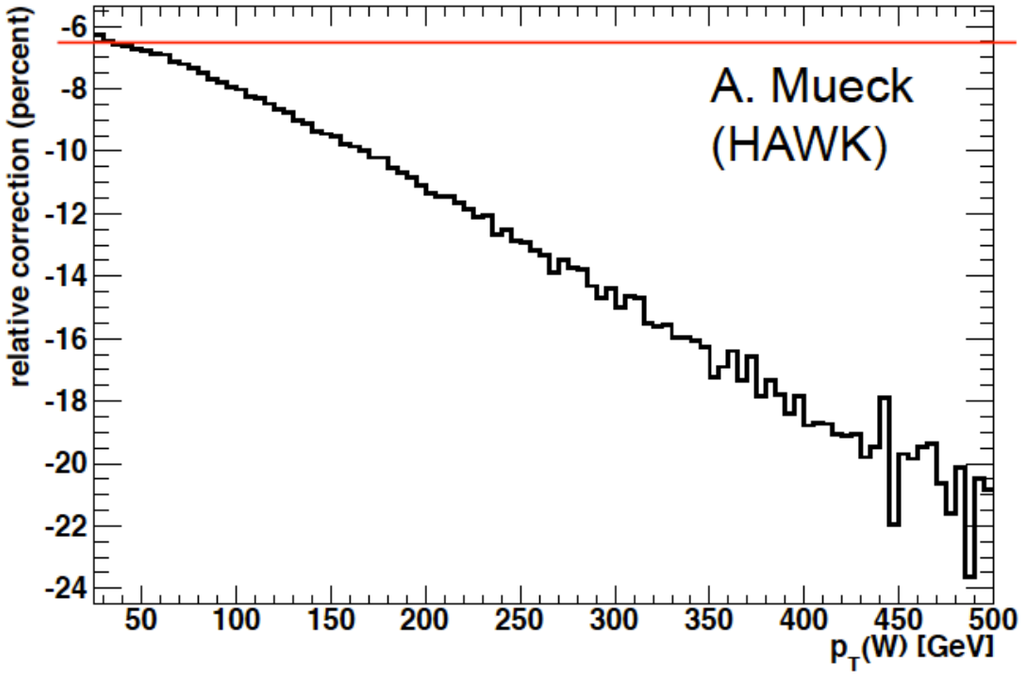
with closed fermion loop

Higgs p_T in VBF and WH/ZH

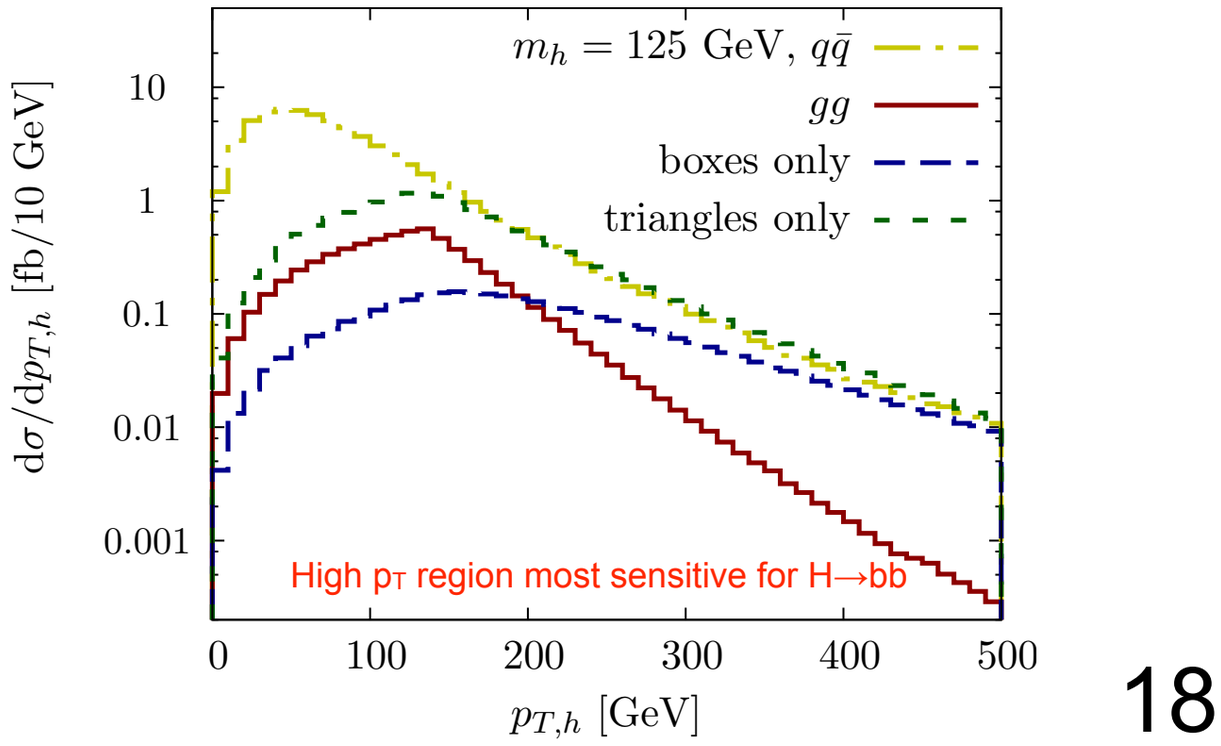
- **NLO EW effect on Higgs p_T in VBF, WH/ZH and dynamical scale issue.**
  - Needs to take into account Higgs p_T dependence of NLO EW radiative correction via MC reweighting (cf. irrelevant in case of ggF).
    - Development of NLO QCD+EW MC?
  - Largely different Higgs p_T in gg→ZH than in qq→ZH. gg→HZ is now available in POWHEG version 2.0.
  - Disentangle gg and qq via p_T binning?



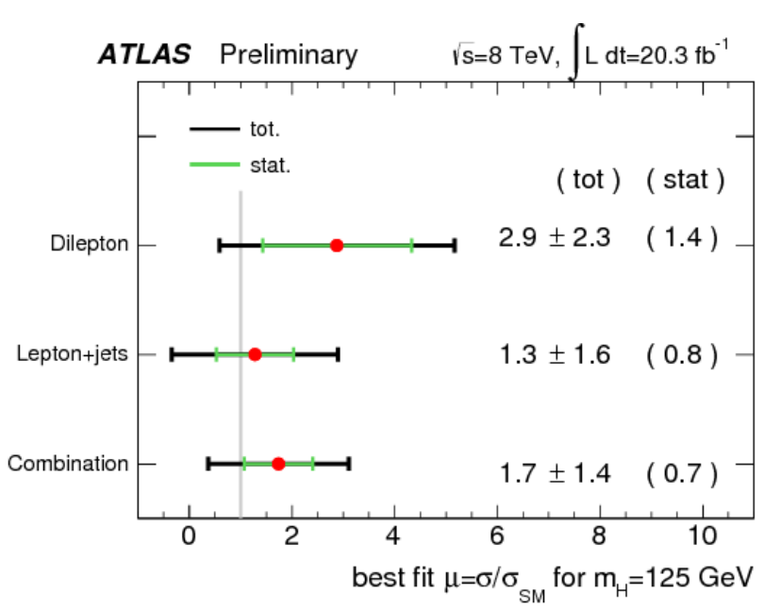
NLO EW corrections inclusive corr.

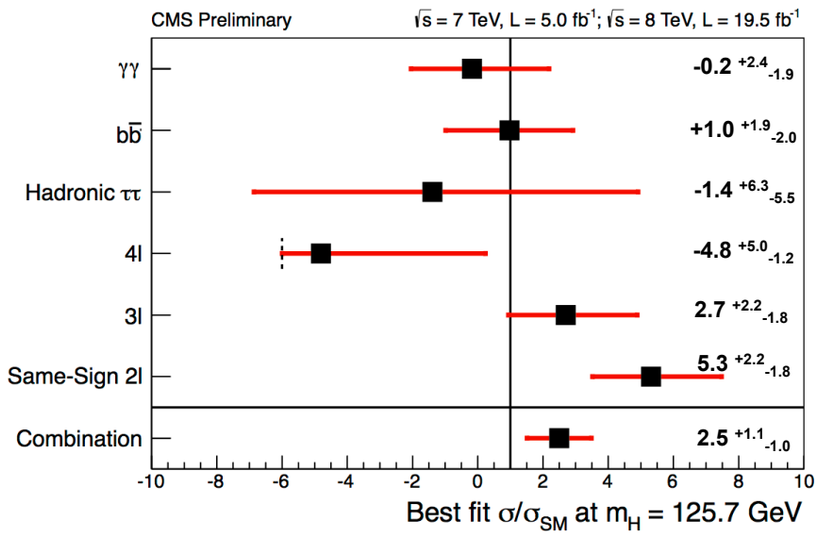


C. Englert et al., PRD 89 (2014) 013013



4. ttH Production





ttH - direct probe of top Yukawa(湯川) coupling

Wishlist in ttH

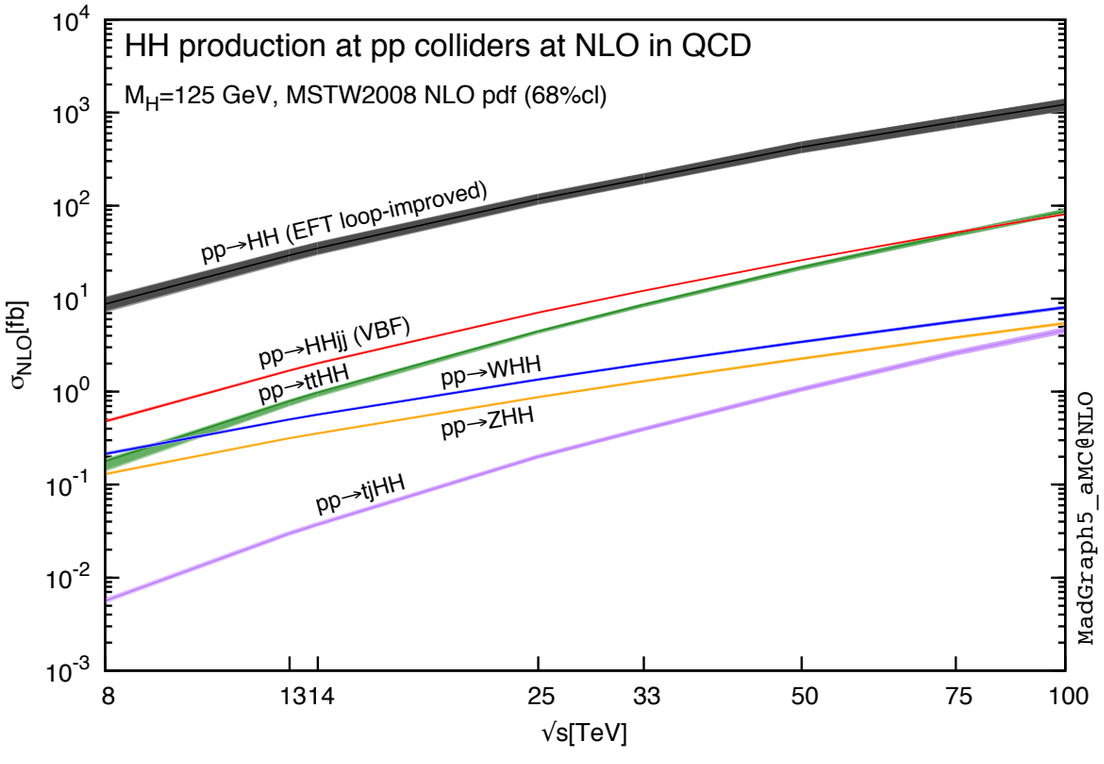
- Event generation
  - Multiple approaches to NLO tt+jets, specifically tt+HF production, interfaced to parton shower MC in an effort to improve modeling and reduce systematics.
  - Need practical ways of generating tt+V+jets with top and V decays at high (1, 2+) multiplicity; if we can do MEPS@NLO even better.
  - Matched NLO generation of signal at least through ttH + 1 jet (boosted ttH).
- Higher order calculations
  - NNLO ttH, ttV inclusive cross sections and/or other ways to reduce cross-section systematic impact on Yukawa coupling measurement.
- Systematics treatment questions
  - How should we correlate systematics between ttV, ttH, tH, tt+jets?
    Is it reasonable to take data-driven corrections to MC from ttbar and apply them to ttV/ttH, or use them as systematics?
  - What are appropriate systematic variations for the heavy flavor fraction of tt+jets, and how can we realize them in generators?

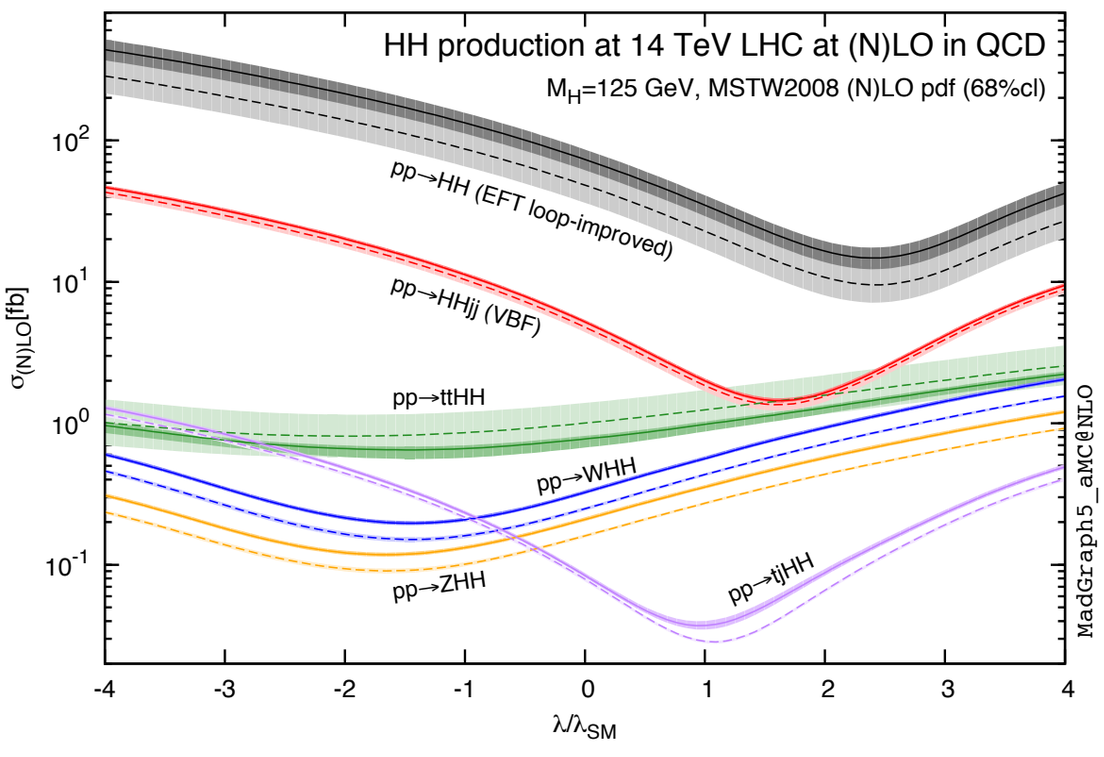
5. Higgs Pair Production

Higgs pair production

- SM gg→HH σ = 33.9 fb (NLO QCD) ➛ 40.2 fb (NNLO QCD) @ 14TeV
  - QCD scale ±20% (NLO) ↘ ±10 %(NNLO), PDF+α_s ±10%, EFT ±10-15%
- SM HH observation in HH→bbγγ, bbττ, WWττ, etc. (difficult challenge in Run-2).
- BSM Higgs in 2HDM, (N)MSSM of heavy Higgs decays (H→hh, $H_3 \to H_1 H_2$, ...).
- SM background study: bbγγ, ccγγ, jjγγ (BlackHat, 2γNNLO, etc.)
- Should new HH subgroup be created in LHC Higgs XS WG in all Higgs XS&BR, Properties and BSM?

R. Frederix et al., PLB 732 (2014) 142

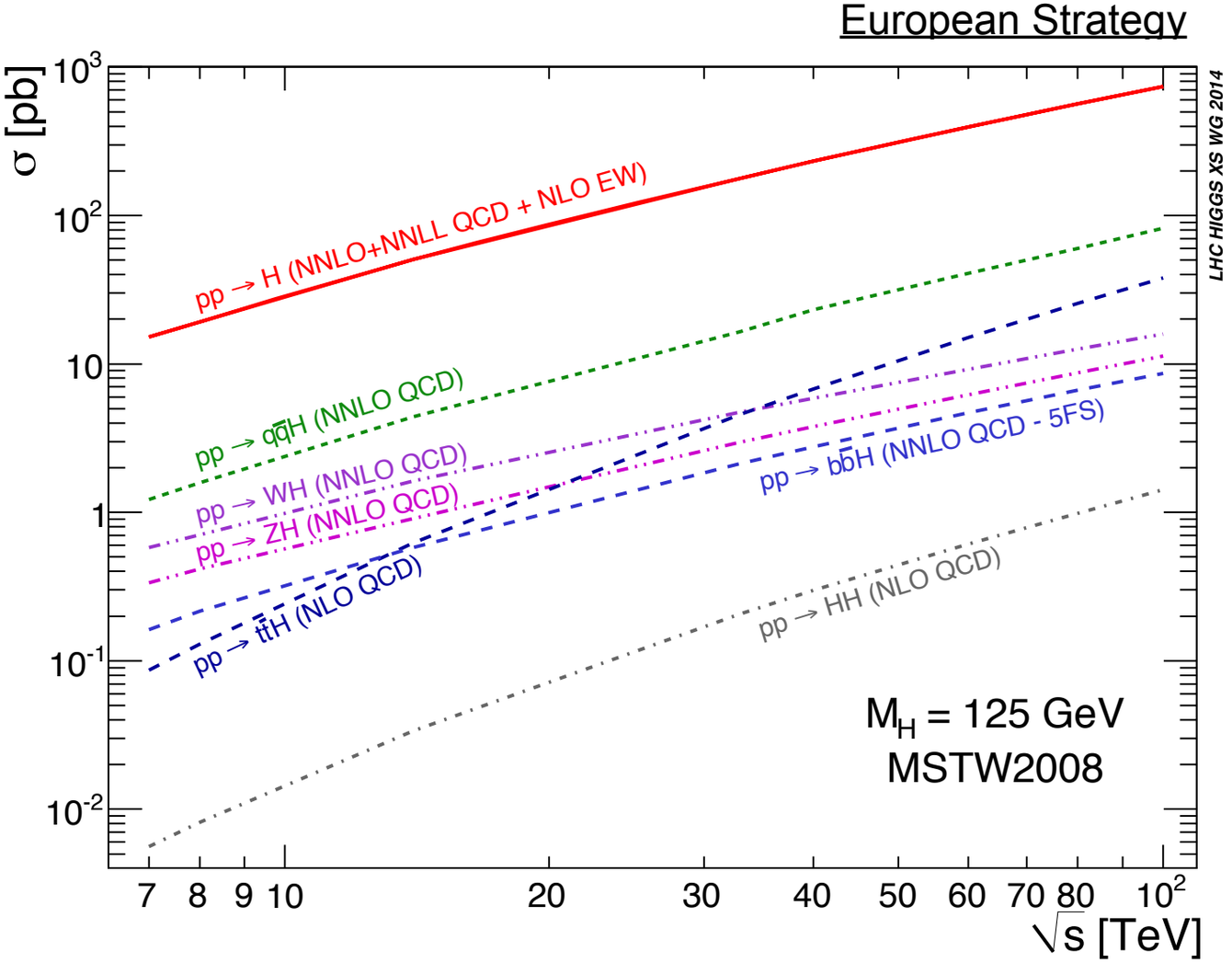




MadGraph5_aMC@NLO

Higgs Cross Sections at √s =13/14 - 100TeV

- Now released (plus parton-luminosity-ratio table)
  - For √s = 13.0, 13.5 and 14.0 TeV (M_H = 125.0, 125.5 and 126.0 GeV),
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CERNYellowReportPageAt1314TeV
- Cross sections at higher centre-of-mass energies (other processes will be added).
  - https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy



We should support FCC (Future Hadron Collider) for Higgs XS&BR.

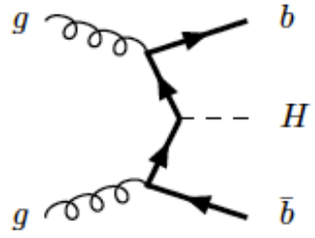
6. Survey All SM Higgs Production and Decay Processes Campaign

bbH - SM bbH cross section is not negligible! (forgotten...)

- SM bbH XS at 7TeV and 8TeV released for M_H = 125.0, 125.5 and 126.0 GeV.
  - 1.1% of ggF at 7-8TeV (ttH 0.6-0.7% of ggF) but ggF scale uncertainty is O(10%).
- Needs bbH (4FS) MC ⇨ Sherpa-MC@NLO, MG5_aMC@NLO ⇨ check acceptance.

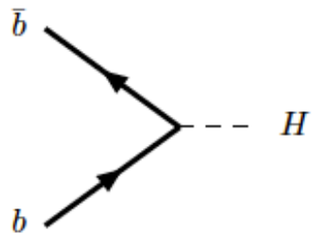
(ii) $b\bar{b}$+Higgs production

4FS



NLO

5FS



NNLO

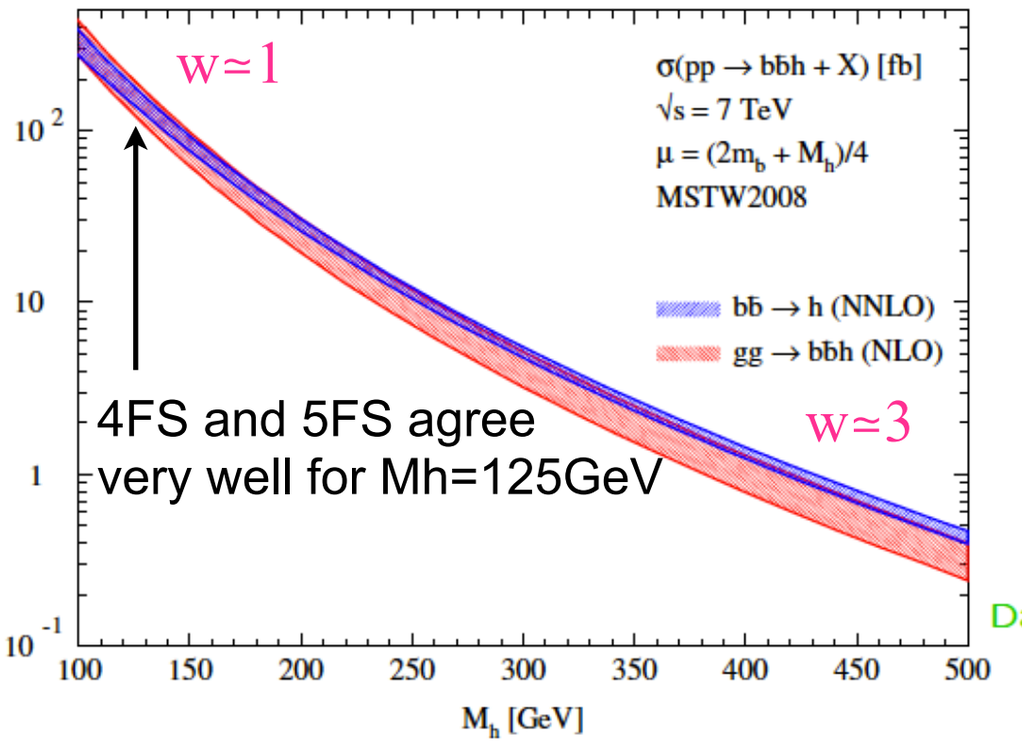
M. Spira

exact $g \to b\bar{b}$ splitting & mass/off-shell effects

no resummation of $\log M_H^2/m_b^2$ terms

massless/on-shell b's, no p_{Tb}

resummation of $\log M_H^2/m_b^2$ terms



Santander matching:

$$\sigma = \frac{\sigma^{4FS} + w\sigma^{5FS}}{1+w}$$

$$w = \log\frac{M_H}{m_b} - 1$$

Harlander, Krämer, Schumacher

Dittmaier, Krämer, S.
Dawson, Jackson, Reina, Wackeroth
Harlander, Kilgore

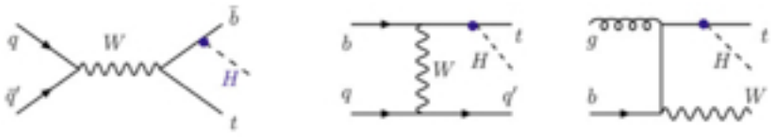
bbH NLO MC in 4FS under validation by MadGraph5_aMC@NLO.

Have we forgotten other process ?

- Abdelhak Djouadi's Anatomy-I, Section 3.5 and 3.6. A. Djouadi, Physics Reports 457 (2008) 1
- Surveyed **[H, qqH, VH]**, **[ttH/bbH/ccH]**, **[tH+V/q]**, **[HH, qqHH, VHH, HHH]**, **[VVH]**, **[qqHV]**.
- Perhaps we are not missing important process, but there are several interesting processes.

- $bq \to tHq'$ (14% of ttH)

  Could resolve degeneracy in $k_F=\pm 1$.

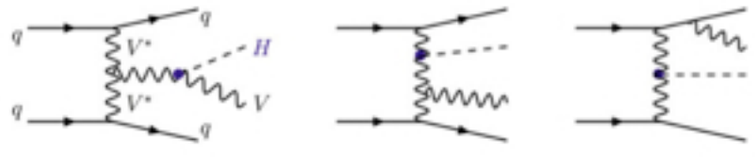


- VBF+γ-tag

- $qq \to HWqq$

  (2% of VBF, 5% of WH)

  interest for HL-LHC to measure Y_b.



Class	14 TeV MH=125GeV			
I	Major production processes at LHC (H, qqH, VH)			
	gg→ggF	60.35	pb	*
	qq→VBF	4.172	pb	*
	qq→WH	1.504	pb	*
	qq→ZH	0.883	pb	*
II	Associated Higgs production with heavy quarks (ffH)			
	gg/qq→bbH	0.8-0.9	pb	A. Djouadi, Phys. Rep. 457 (2008), Fig. 3.30
	gg/qq→ttH	0.611	pb	*
	gg/qq→ccH	O(100fb)		ccH should be about 1/9 of bbH due to Yukawa and PDF
III	Associated Higgs production with a single top quark (TH+V/HF)			
	bq→tHq'	88.2	fb	M. Farina et al. JHEP 05 (2013) 022, Table 2
	bg→WtH	~20	fb	F. Maltoni et al., Phys. Rev. D 64 (2001) 094023, Fig. 4
	qq→btH	~2-3	fb	idem.
IV	Higgs boson pair/triple production (HH, qqHH, VHH, HHH)			
	gg→HH	33.86	fb	*
	qq→HH	< 0.1	fb	D. Dicus, Z. Phys. C 39 (1988) 583, Fig. 2 @17TeV
	gg/qq→ttHH	~1	fb	F. Gianotti et al., Eur. Phys. J. C 39 (2005) 293, Table 7 by C. G. Papadopoulos
	qq→qqHH	1.807	fb	*
	qq→WHH	0.43	fb	*
	qq→ZHH	0.27	fb	*
	gg→HHH	0.044	fb	*
V	Higgs production in association with gauge bosons (VVH)			
	qq→WWH	~8-9	fb	A. Djouadi, Phys. Rep. 457 (2008), Fig. 3.42
	qq→ZZH	~2	fb	pT_γ>10GeV, |y_γ|<2.5
	qq→WZH	~3-4	fb	
	qq→γZH	~3-4	fb	
	qq→γWH	~5	fb	
VI	Higgs production in association with a gauge boson and two jets (HVqq)			
	qq→HWqq	78	fb	D. Rainwater, Phys. Lett. B 503 (2001) 320, Table 1 → 5% of WH !?
	qq→HZqq	-		
	qq→Hγqq	-		
VII	Rare processes			
	qq→Hγ	O(1fb)		A. Djouadi, Phys. Rep. 457 (2008), Section 3.6.3.1 (gg→Hγ forbidden by Furry's theorem)
	t→cH	BR~4E-14		B. Mele, S. Petrarca, A. Soddu, Phys. Lett. B 435 (1998) 401, Table 1
	Diffractive	?		

* https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HiggsEuropeanStrategy

BR and Rare Process&Decay

- Branching ratios
  - Theory and parametric (α_s, $m_{t,b,c}$, m_H, etc.) uncertainty reduction?
- Rare process and decay (Common uncertainty assignment)
  - $qq \to H\gamma$
  - $t \to cH$
  - quarkonia $J/\psi(\Upsilon)+\gamma$
  - $\gamma/W/Z+P$
  - ... etc.

ccH measurement

1. charm tag (difficult at hadron collider)
2. Higgs boson decays to quarkonia

$BR(H \to J/\Psi+\gamma) = 2.5\times10^{-6}$

$BR(H \to \Upsilon+\gamma) = 1.4\times10^{-8}$

➪ ~50 $\mu^+\mu^-\gamma$ events @ 14TeV, 3ab^{-1}

G. Bodwin et al. Phys. Rev. D88 (2013) 053003

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}

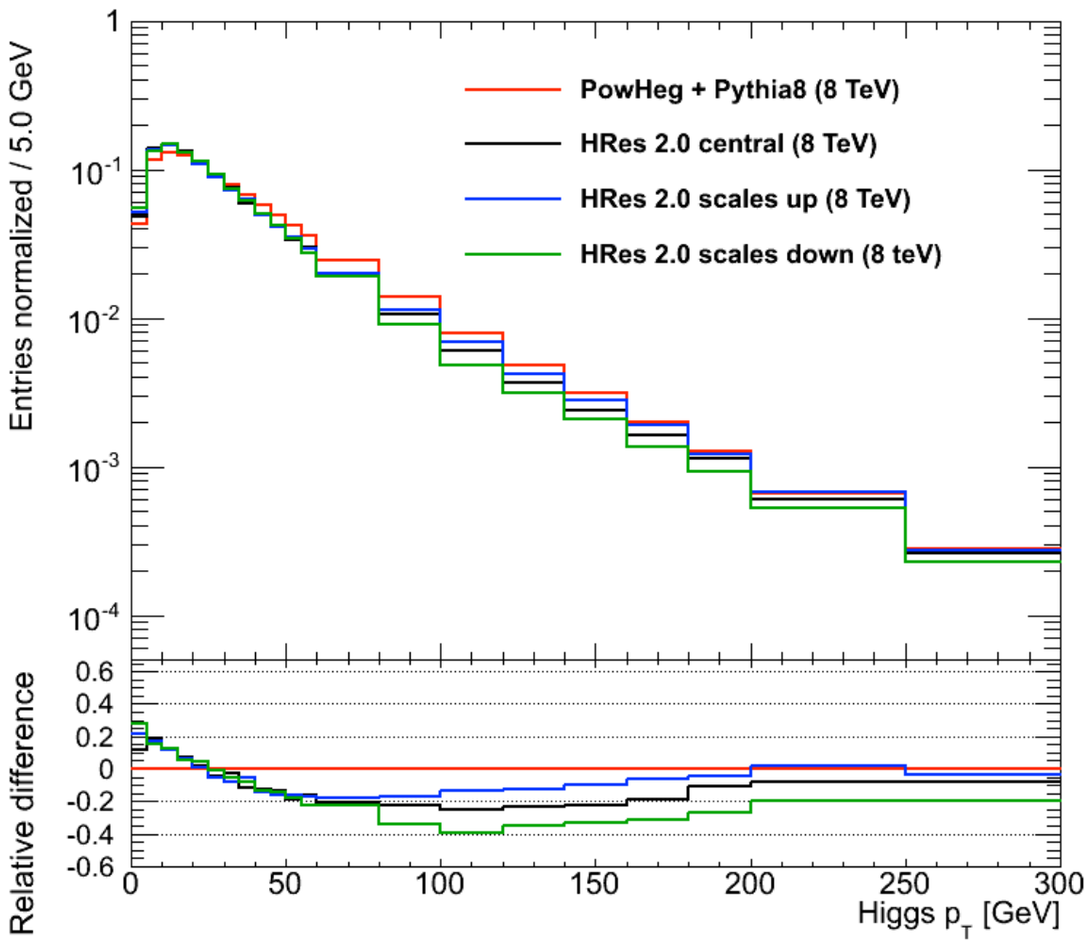
G. Isidori et al., PLB 728 (2014) 131

7. Higgs p_T Distribution in Gluon-Fusion Process

Higgs p_T in ggF

- **Higgs p_T uncertainty in ggF**, Higgs p_T uncertainty assignment ($d\sigma/dp_T$)
- MC reweighting study with HRes in NNLL+NNLO.
  - Decided to survive with reweighting for RUN-1 legacy paper.
  - Use dynamical scale, which is relevant in boosted regime ($p_T > M_H$).
- Needs *hfact* tune in POWHEG.

E. Scifo et al.



- Some interest for BSM Higgs p_T and new physics via $d\sigma/dp_T$.
  - MSSM/2HDM Higgs p_T in POWHEG by A. Vicini et al.
  - bottom quark softens the p_T spectrum compared to top (MSSM already exists).

Higgs p_T in ggF

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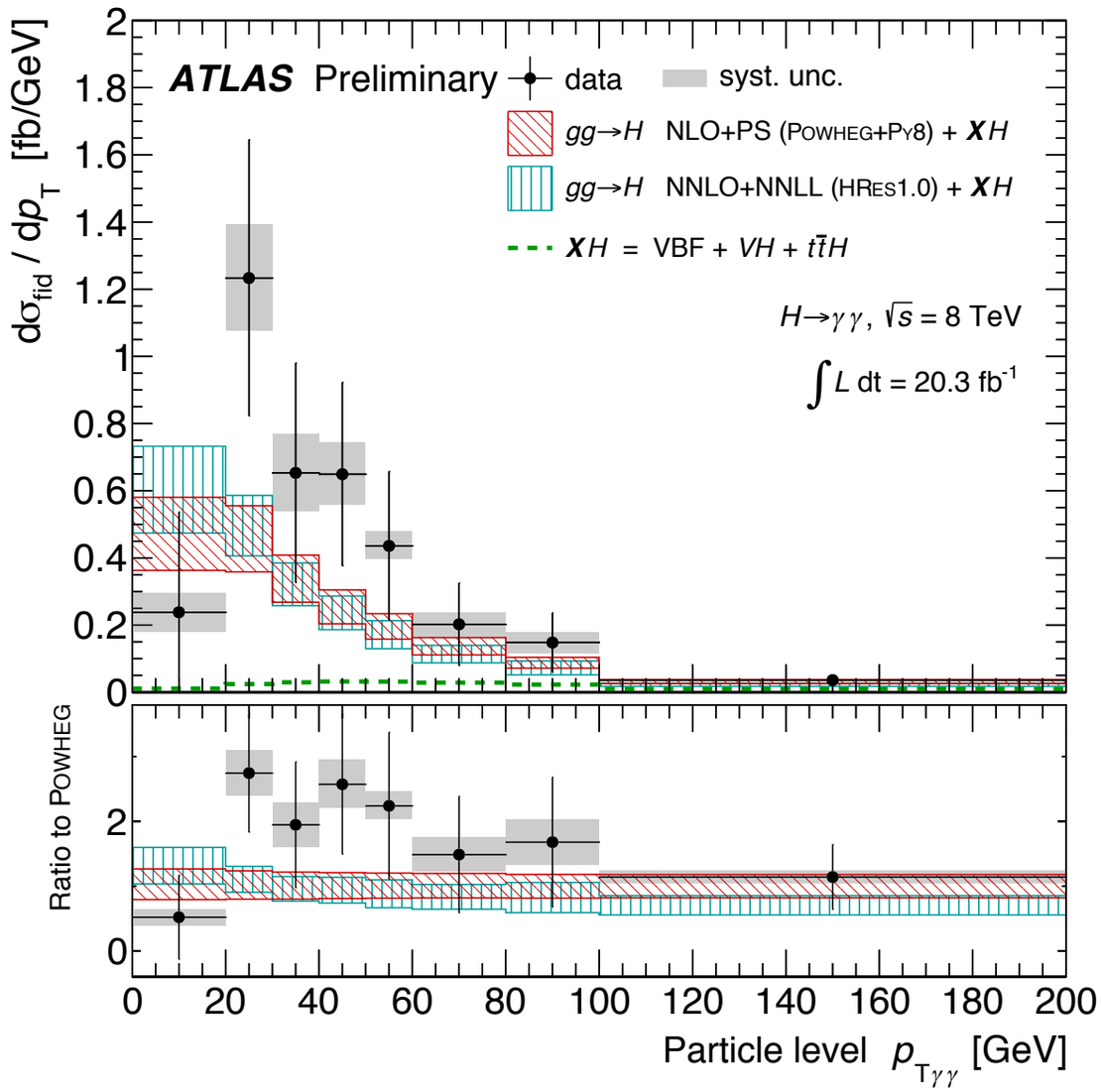

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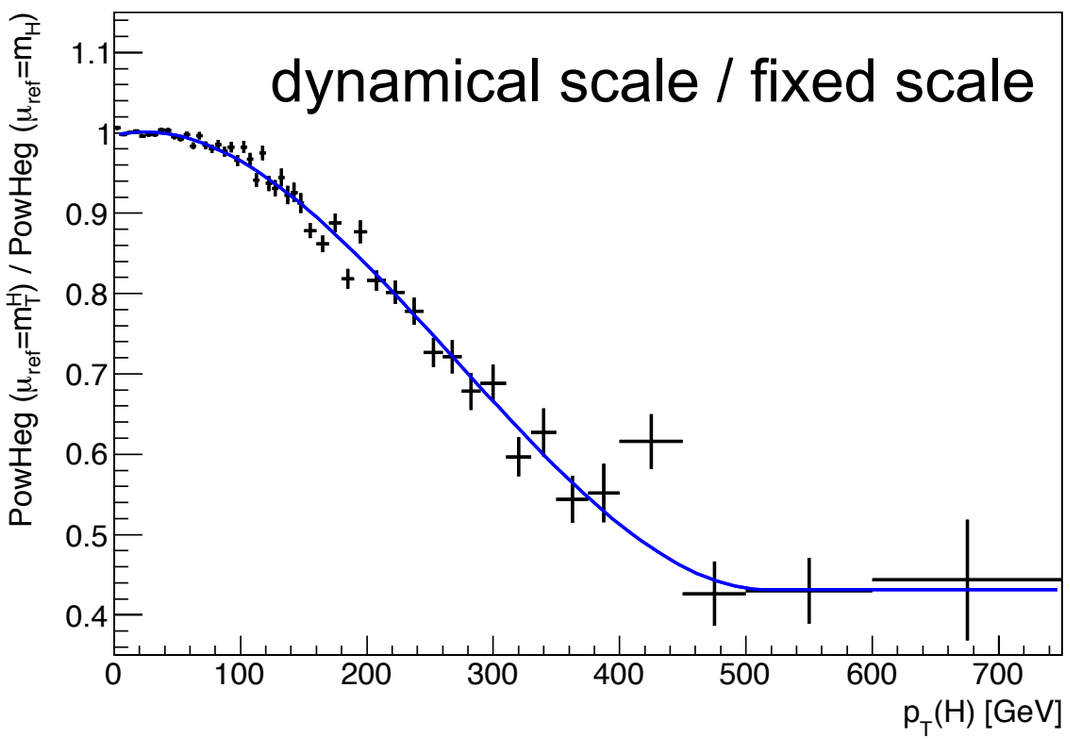
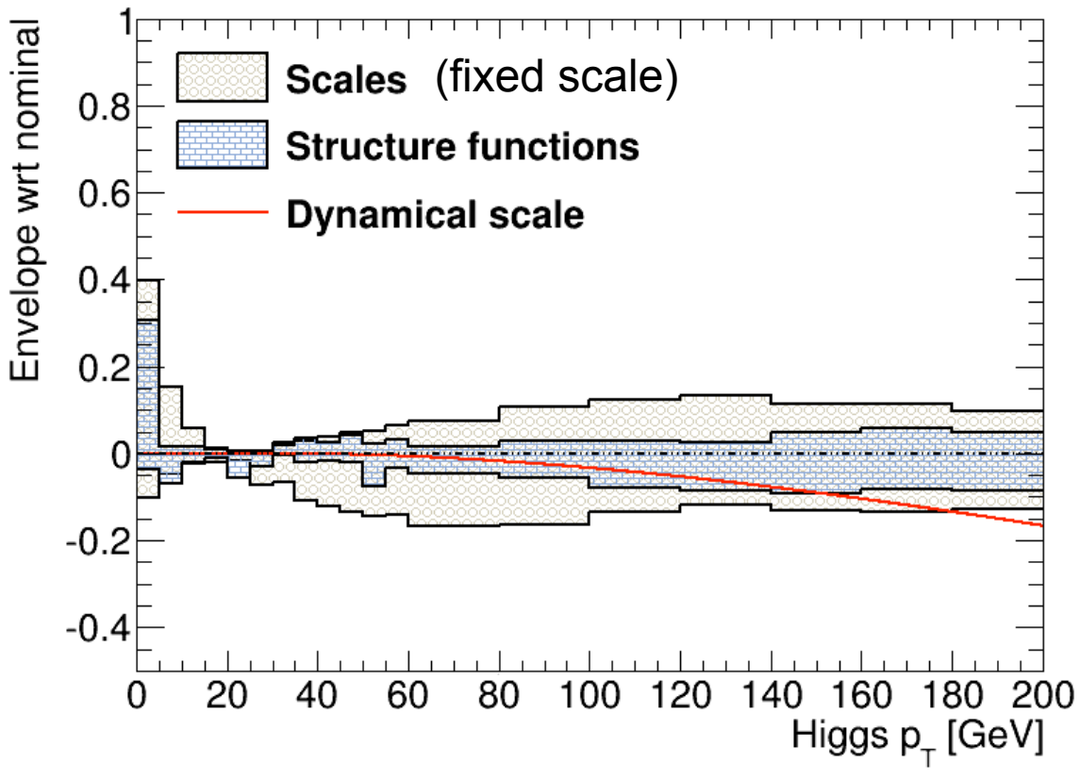
  - bottom quark softens the p_T spectrum compared to top (MSSM already exists).

Dynamical scale

- Dynamical scale is relevant in boosted regime (typically p_T>100GeV or M_H).
  - ex. gg→H with $\mu=\sqrt{p_T^2+M_H^2}$ instead of fixed $\mu=M_H$.
  - Reduces cross section but also changes the shape! Same issue for SM bkg.!
  - Dynamical scale recently implemented in HRes2.1.
  - Dynamical scale effect for VH is <u>relatively small (5%)</u> due to the fact that Higgs is recoiling against V not against jets. How about VBF, SM VV?

<u>Recommends to use dynamical scale for Higgs signal and bkg. when relevant</u>.





8. Jet-bin uncertainty in gluon-fusion process

Jet-bin uncertainty in ggF

1) Stewart&Tackmann prescription ... fixed order calc. Jets meeting on jet-bin in LHCHXSWG

2) Jet Veto Efficiency (JVE-resummed) by Banfi, Salam, et al.

- improvements in 0- and 1-jet bin uncertainty. (Phys. Rev. Lett. 109 (2012) 202001)

3) Updated S&T with 0,1-jet rsummation by Tackmann, Petriello et al. (arXiv:1312.4535)

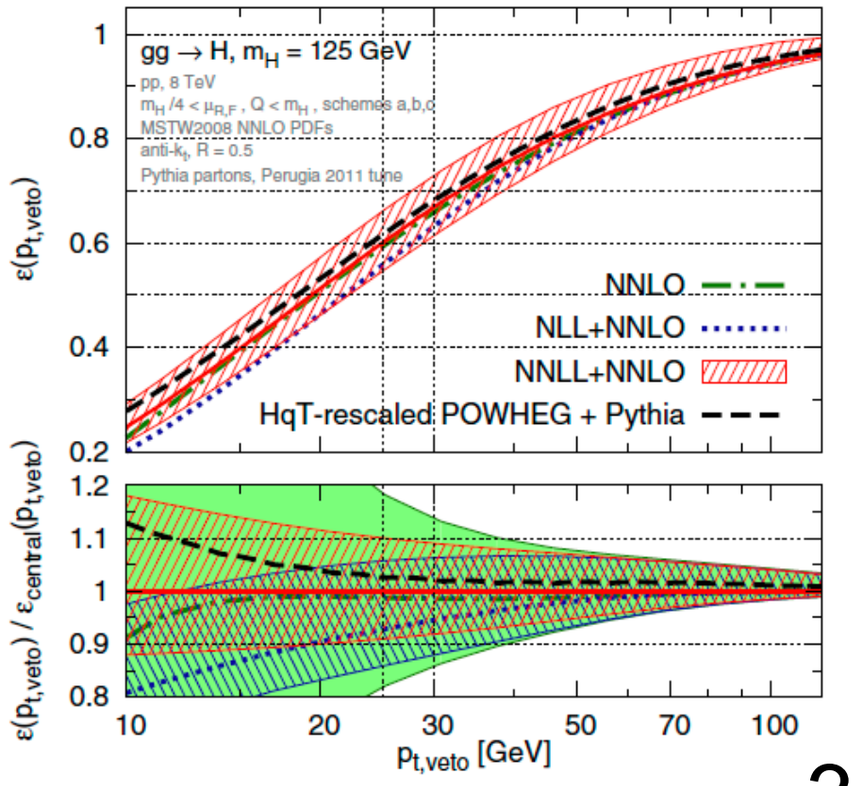
4) Other groups with SCET(soft-collinear effective theory) (M. Neubert et al.)

- JVE-resummed method will affect Δμ and Δσ substantially in exclusive analysis (ex. H→WW) !
- Similar improvements with SCET approach.
- Note that Higgs p_T (p_{Tt}) and jet-bin are correlated.

∵ Higgs p_T is generated by gluon, while Y by PDF.

Improvements with JVE-resumed or SCET approach are highly welcome!

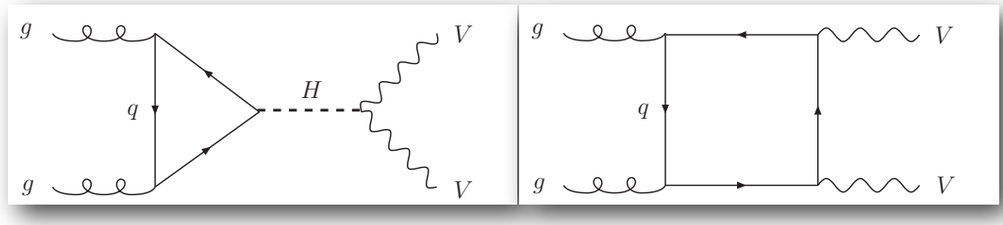
NNLO+NNLL for 0-jet bin uncertainty is ±15%→±9% ! (code JetVHeto)



9. Higgs Interferometry

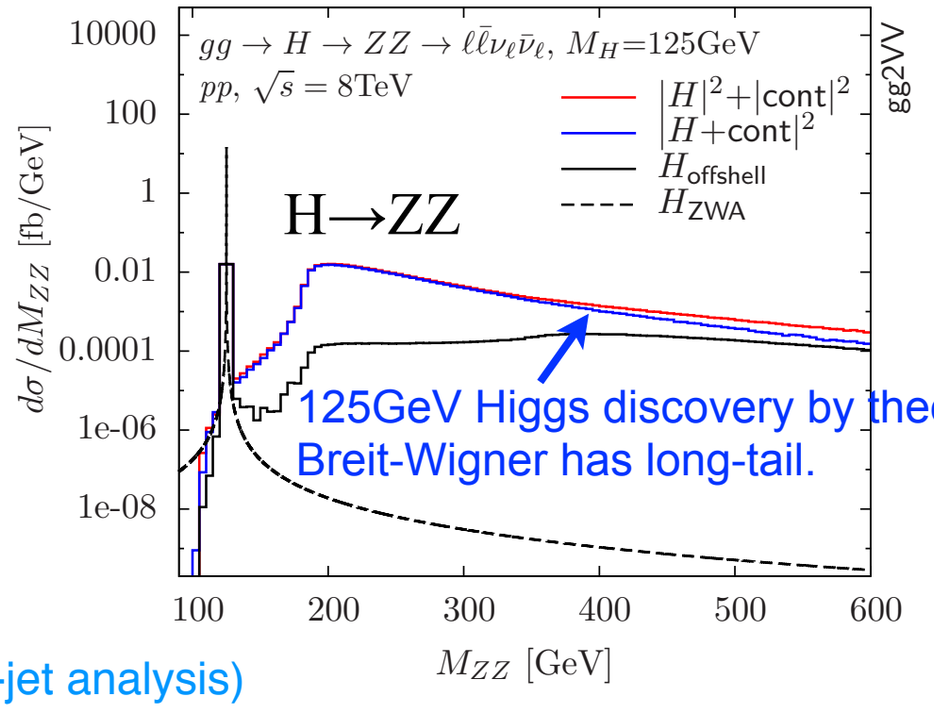
Higgs Interferometry

- Higgs width measurements via Higgs interferometry
- Destructive interference between Higgs signal and gg→VV continuum background.
  - gg→H→γγ (S. Martin, L. Dixon) - mass shift (depends on Higgs p_T) $\Delta M_{\gamma\gamma}$ = -70MeV for SM at NLO
  - gg→H→WW*/ZZ* (N. Kauer, G. Passarino, F. Caola, K. Melnikov) - mass spectrum in high-mass end above $M_{4l} > 2M_{top}$.
    - **Kauer-Passarino-Caola-Melnikov Effect**
  - Tools: gg2VV, MCFM (arXiv:1311.3589, arXiv:1312.1628)
    - MCFM is versatile calc/MC tool.
    - Also will provide MEM tools (qq/gg→VV)



- **Wish list**
  - NLO QCD+EW MC for qq→WW/ZZ
  - NNLO QCD correction in qq→WW/ZZ
    - Exists for onshell ZZ by M. Grazzini.
    - NNLO QCD for WW is missing.
  - NLO QCD MC for gg→WW/ZZ
  - K-factor at NNLO QCD for interference and continuum?
  - Estimate of (NLO QCD)*(NLO EW)? (needed exclusive 1 or 2-jet analysis)
  - VBF ST for gg→(H→)VV+2j and +3j.

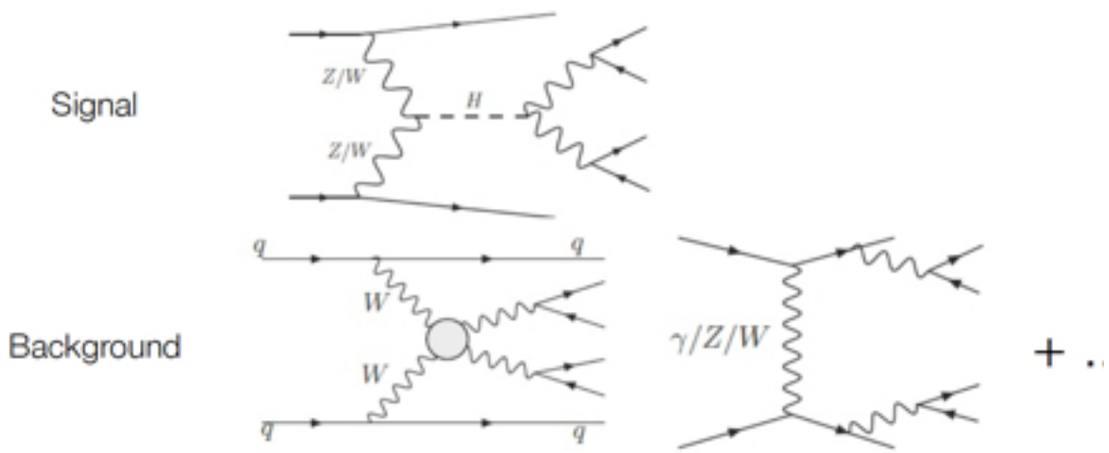
Kauer, Passarino 2012

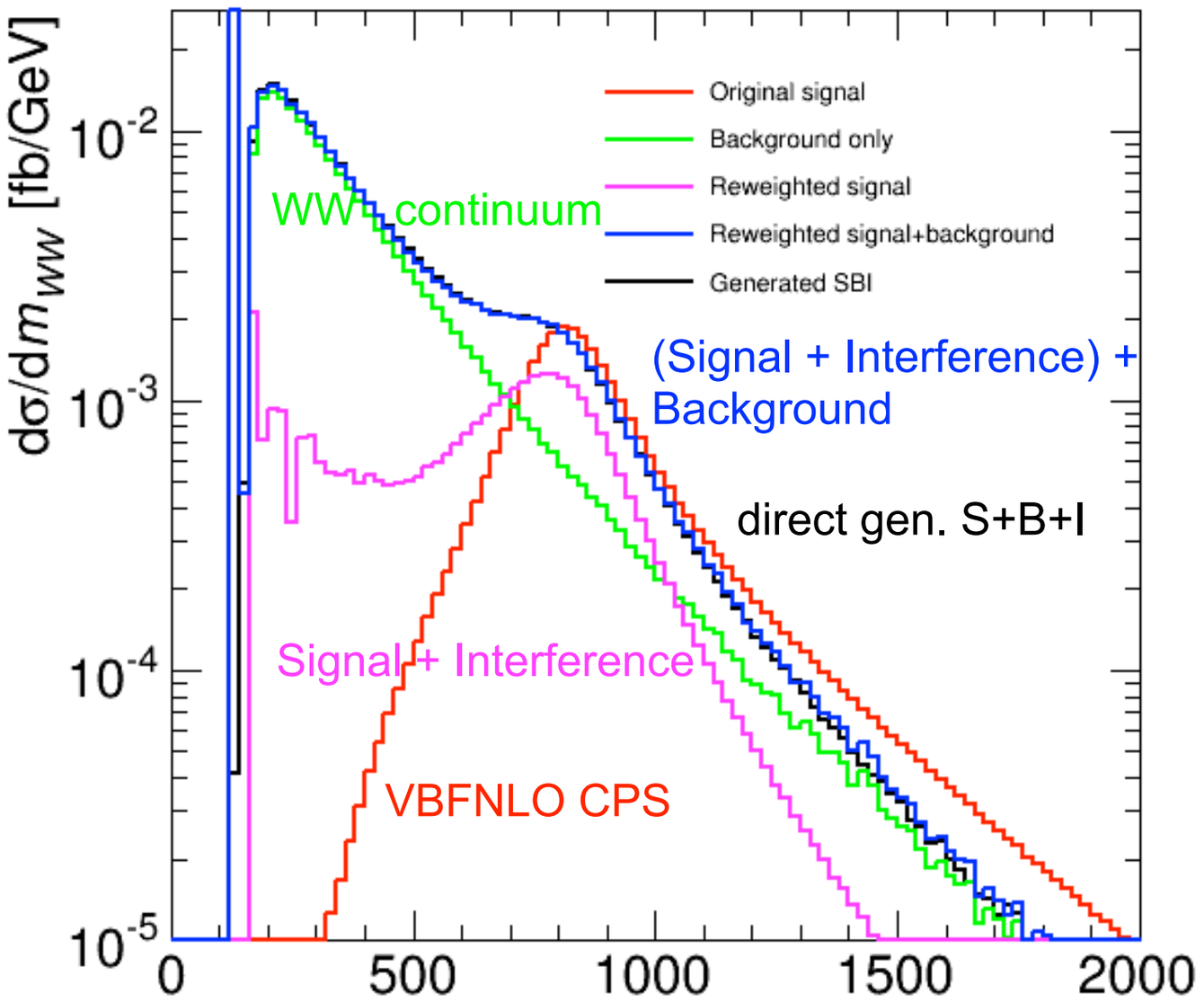


Higgs Interference in VBF

Interference in VBF H→WW/ZZ

- Becomes significant for M_H > 400GeV.
- MadGrapn5, Phantom, VBFNLO, etc.
- Study reweight (S+I)/S.





10. Tools and Monte Carlos

Toward NNLO QCD+NLO EW MC (which does not exist yet!)

gluon-gluon Fusion

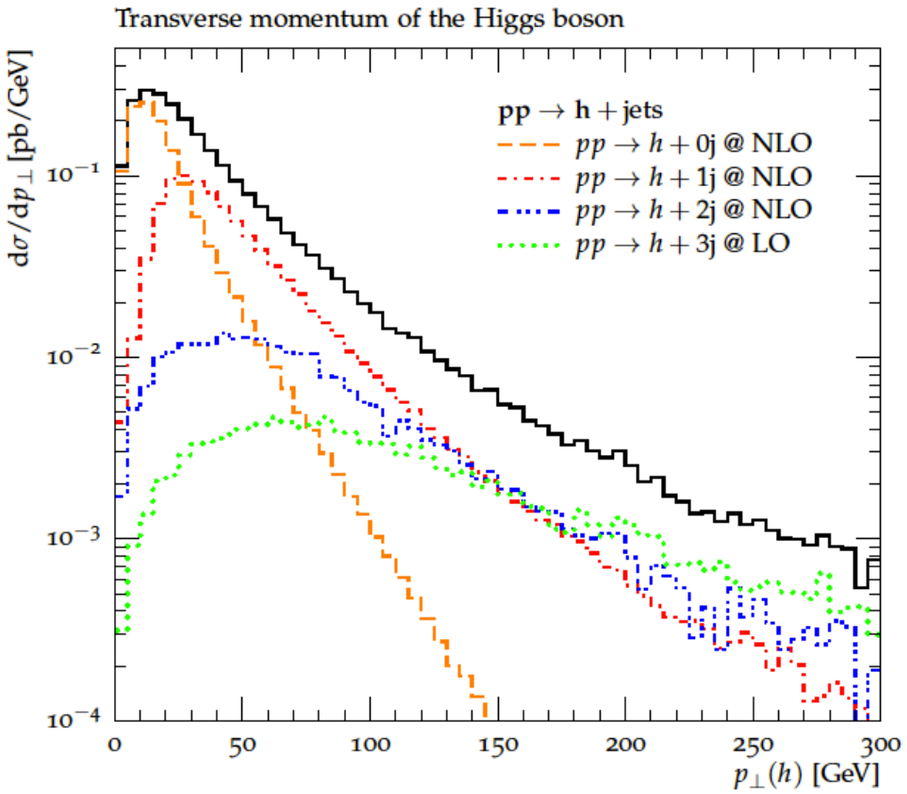
(N)NLO MC - perhaps POWHEG MiNLO remains our default option.

I) **POWHEG MiNLO**: H, HJ, HJJ, attempt for NNLO-PS

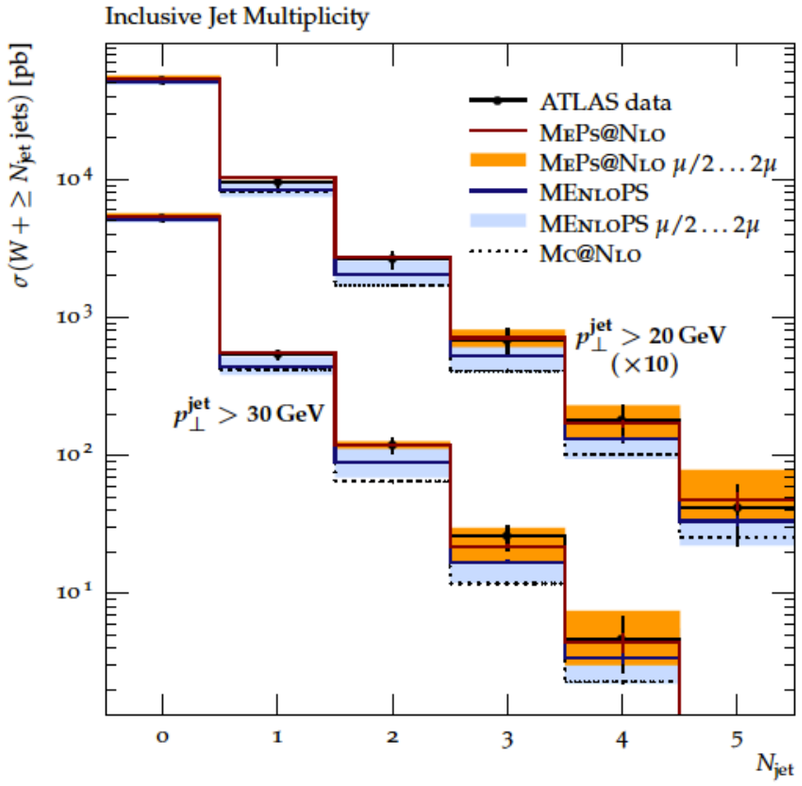
II) **MadGraph5_aMC@NLO**: H+nj → aim HEFT/BSM platform

III) **SHERPA MEPS@NLO**: V/H/VH/WW/tt+jets

IV) MCs like recent **Gosam** H+3J (important for VBF with CJV)



S. Höche et al., JHEP 1304 (2013) 027



Toward NNLO QCD + NLO EW MC

ATLAS and CMS should update Les Houches wishlist for
Higgs signal (H+n-jet, VBF, VH, ttH/bbH/ccH, tHq'/WtH/btH, HH, VVH, HVqq, etc.)
and relevant SM backgrounds (VV+jets, ttbar+HF/V+jets, etc.).

N. Glober,
talk at Exploiting the Higgs breakthrough (Jan.2014)

Draft Les Houches wishlist for Higgs processes

Process	known	desired	details
H	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW finite quark mass effects @ NLO	$d\sigma$ @ NNNLO QCD + NLO EW MC@NNLO finite quark mass effects @ NNLO	H branching ratios and couplings
$H+j$	$d\sigma$ @ NNLO QCD (g only) $d\sigma$ @ NLO EW finite quark mass effects @ LO	$d\sigma$ @ NNLO QCD + NLO EW finite quark mass effects @ NLO	H p_T
$H+2j$	$\sigma_{\rm tot}$(VBF) @ NNLO(DIS) QCD $d\sigma(gg)$ @ NLO QCD $d\sigma$(VBF) @ NLO EW	$d\sigma$ @ NNLO QCD + NLO EW	H couplings
$H+V$	$d\sigma$ @ NNLO QCD $d\sigma$ @ NLO EW	with $H \to b\bar{b}$ @ same accuracy	H couplings
$t\bar{t}H$	$d\sigma$(stable tops) @ NLO QCD	$d\sigma$(top decays) @ NLO QCD + NLO EW	top Yukawa coupling
HH	$d\sigma$ @ LO QCD (full m_t dependence) $d\sigma$ @ NLO QCD (infinite m_t limit)	$d\sigma$ @ NLO QCD (full m_t dependence) $d\sigma$ @ NNLO QCD (infinite m_t limit)	Higgs self coupling

$$(1+\delta^{NLO}_{QCD}+\delta^{NLO}_{EW}) \quad \text{or} \quad (1+\delta^{NLO}_{QCD})\times(1+\delta^{NLO}_{EW})$$

Tools for Higgs Physics

Clickable Link

Cross Section

ggF
HIGLU (NNLO QCD+NLO EW)
iHixs (NNLO QCD+NLO EW)
FeHiPro (NNLO QCD+NLO EW)
HNNLO, HRes (NNLO+NNLL QCD)
SusHi (NNLO QCD)
RGHiggs (NNLO+NNNLL QCD)
ggHiggs (approx. NNNLO QCD)

VBF
VV2H (NLO QCD)
VBFNLO (NLO QCD)
HAWK (NLO QCD+EW)
VBF@NNLO (NNLO QCD)

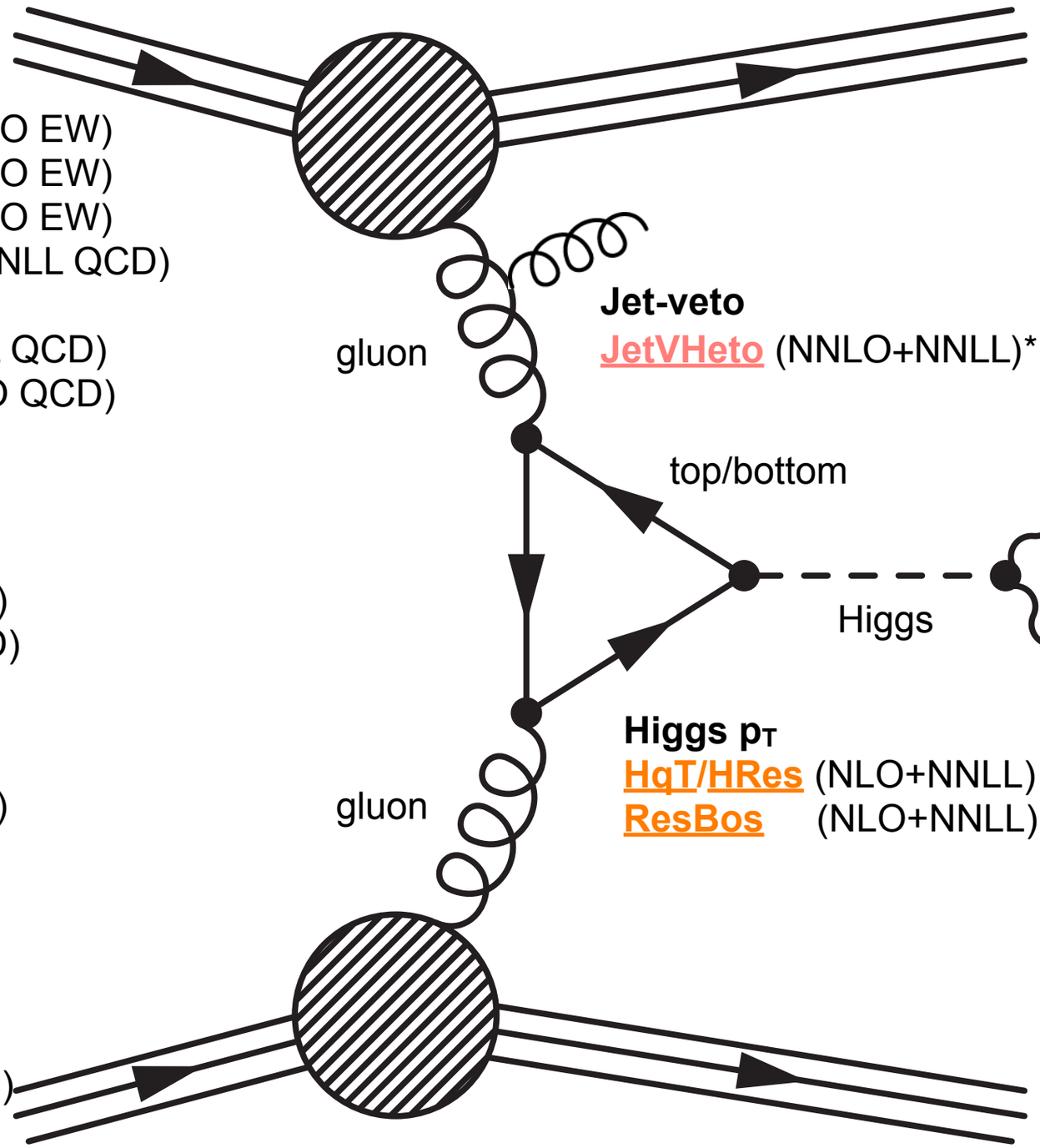
WH/ZH
V2HV (NLO QCD)
HAWK (NLO QCD+EW)
VH@NNLO (NNLO)

ttH
HQQ (LO QCD)

bbH
bbh@NNLO (NNLO QCD)

HH
HPAIR (NLO QCD)

+ private codes.



PDF: MSTW, CTEQ, NNPDF, etc.
LHAPDF, HOPPET, APFEL

NLO MC
POWHEG MiNLO
MadGrapn5_aMC@NLO
SHERPA MEPS@NLO

LO MC
gg2VV

NLO ME
MCFM, MG5_aMC@NLO

Higgs Properties
MELA/JHU, MEKD
MG5_aMC@NLO (HC)
eHDECAY

MSSM/2HDM
FeynHiggs, CPSuperH
SusHi+2HDMC
HIGLU+HDECAY

* NLO+NNLL in differential

Compiled by R. Tanaka, Jan. 2014

Summary of Wishlists

1) ggF - reduction of QCD scale (N3LO) and PDF+α_s uncertainties below 5% possible?
   - probability distribution functions of QCD scale and PDF+α_s uncertainties.
   - improvement in jet-bin uncertainty after S&T to JVE-resummed, SCET approach (0,1-jet incl. calc. 2-jets?).
   - NLO MC in H+n-jets (HJ, HJJ, HJJJ, ...) with finite-quark-mass effect.
2) VBF, WH/ZH
   - (N)NLO QCD + NLO EW MC (currently MC is reweighed for NLO EW with Higgs p_T)
3) ttH/bbH
   - NLO MC developments for ttbar+HF/V+jets.
4) HH
   - NLO MC and relevant backgrounds. Sensitivity in bbbb, bbγγ, etc. BSM scenarios like in 2HDM.
5) BR
   - reduction of THU, PU.
   - correlation handling in different BRs.
6) NLO MC
   - toward NNLO QCD + NLO EW MC?
   - precise predictions for differential distributions like Higgs p_T, new physics effect.
   - improvements in irreducible SM bkg. NLO MC,
     ex. NLO QCD+EW in qq→WW/ZZ, NLO QCD in gg→WW/ZZ (box diagram), NLO ttbar+HF/V+jets.
   - update Les Houches wishlist?
7) MSSM
   - new benchmark and scan in MSSM/2HDM, NMSSM, etc.
   - cover missing cross sections and public tool, ex. charged Higgs XS in MSSM.
8) PDF
   - new PDF4LHC prescription at NNLO PDF, meta-PDF approach.
   - correlation handling in different process (between signal and backgrounds).
9) Tools
   - tool repository? SVN in LHC Higgs XS WG exists.
10) preparing for 13-14TeV run
   - same grid as 7&8TeV for 13-14TeV necessary?
   - “Survey All SM Higgs Production and Decay Processes Campaign”
     → XS&BR calculations with coherent theory uncertainty assignments.