Understanding Higgs Cross Sections at LHC

an overview of ATLAS effort

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(ATLAS Collaboration)

Higgs Physics at the Tevatron and LHC workshop

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Higgs in ATLAS

A signal-like candidate has been seen in ATLAS over huge backgrounds…

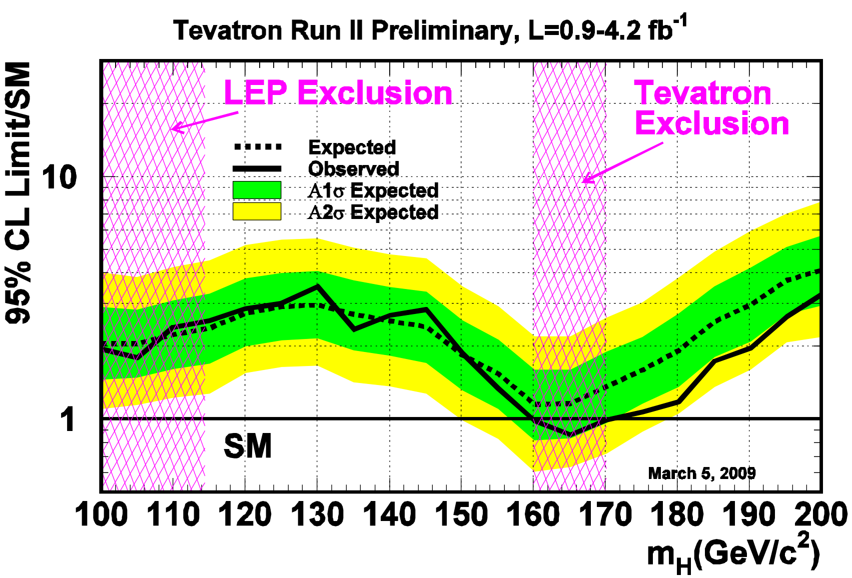
This talk* is about

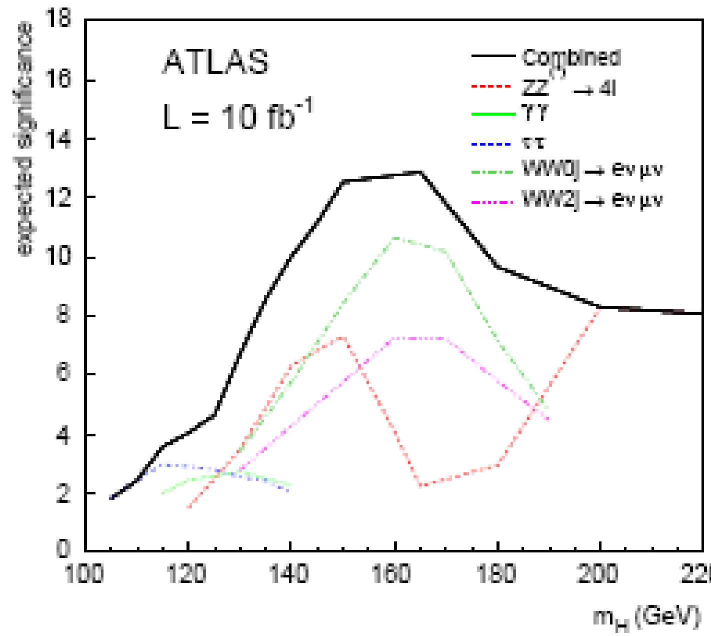
Compiling Higgs production cross sections at LHC

- estimate discovery significances;
- study exclusion potential;

With *real collision* data

- If signal, is it due to Higgs?
- If not, make nice plots like this…





… is not about ATLAS's discovery potential

*views expressed in this presentation are not necessarily shared by ATLAS, but they should be.

ATLAS Effort

- Significant theoretical and phenomenological progress in
  - the calculations of higher order QCD and EW corrections;
  - the constraining of parton distribution functions;

  not an easy task to follow all the latest development for an average analyzer…

- ATLAS Higgs group conveners formed a small group to prepare Higgs cross sections and decay branching ratios in both SM and MSSM for first data analysis
  - survey theoretical calculations/tools and compare their results;
  - recommend a set of Higgs cross sections for the first data analysis;
  - build-up machineries for arbitrary LHC operation energies;

- Working group members:

  N. Andari, A.C. Bourgaux, M. Campanelli, G. Carrillo, M. Escalier, M. Flechl, J. Huston, B. Mellado, J. Qian, D. Rebuzzi, M. Schram, R. Tanaka, T. Vickey, M. Warsinsky, H. Zhang, …

This presentation is largely based on discussions within the working group and with theoretical colleagues that we are working with

Questions from Joey

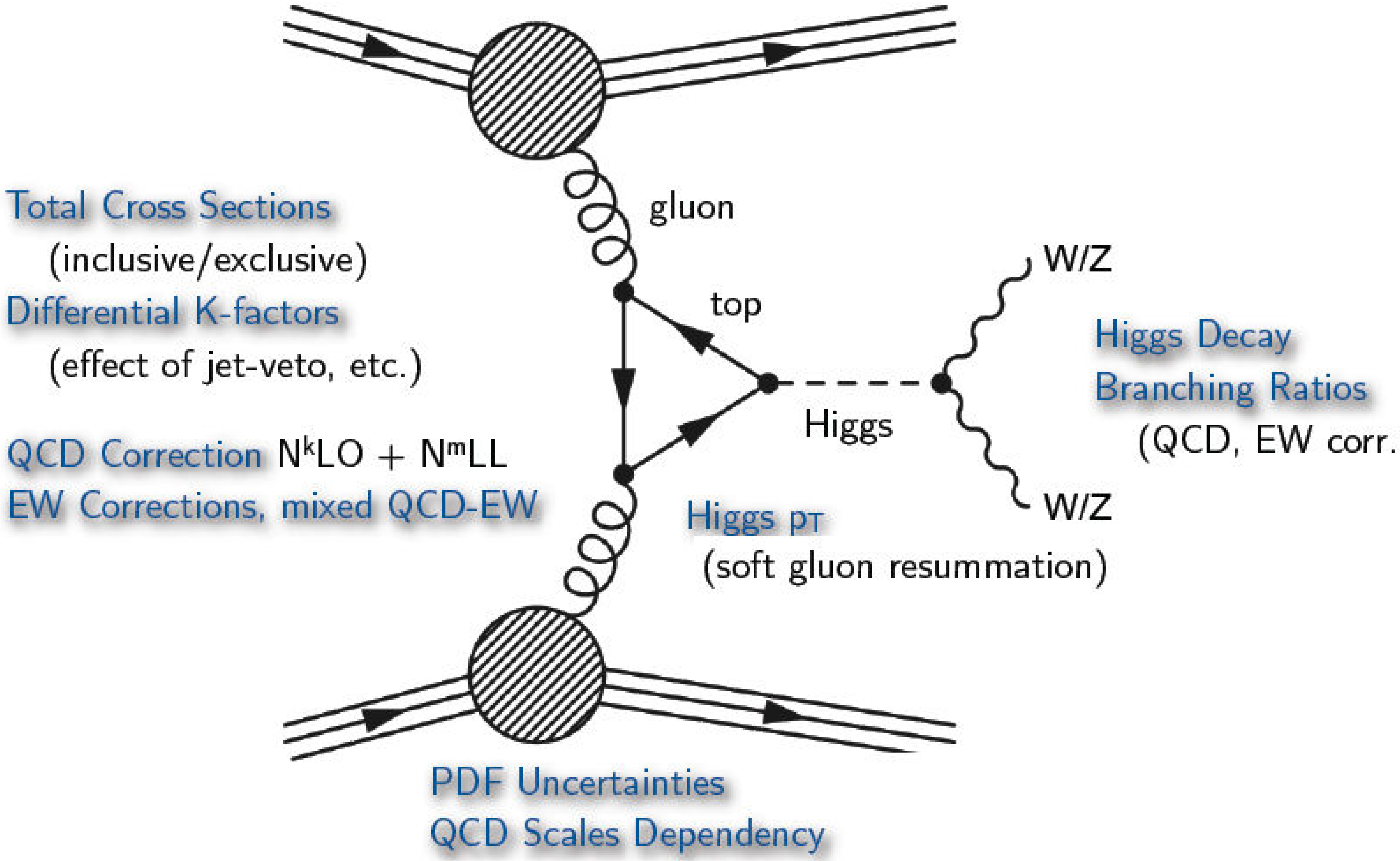
1.a Can we have a dynamic collection of cross sections (detailing methods and parameters used to calculate these cross sections) for all Higgs production processes.

1.b Understanding consistency and best use of predictions at LO, NLO, NNLO, NLO+NLL, NNLO+NNLL

- How consistent are the predictions from CTEQ, MSTW, NNPDF ?
- How to properly include the cross section/PDF uncertainty due to uncertainty on α_s?
- What is the best way of adding PDF and scale uncertainties?
- Should the factorization and renormalization scales be varied separately or together ?
- How to deal with higher order information for differential distributions ?
- Is there a consensus on how to deal with calculations of MSSM Higgs and their uncertainties in 4- and 5-flavor schemes ?

There may not be right answers to some of these questions, but consistent/consensus approaches will be helpful for comparisons and eventual combination of results from different experiments

We are examining…



R. Tanaka, LAL-Orsay and
D. Rebuzzi, Pavia University and INFN

Gluon-Gluon-Fusion

Dominant process at LHC

- exact calculations with full m_t-dependence, available up to NLO;
- in the large m_t limit, available up to NNLO, scaling with
- partial N^{3}LO calculation

$$F_{LO}(m_t) = \frac{\sigma_{LO}(m_t)}{\sigma_{LO}(m_t = \infty)}$$

Tools	QCD Order	Mode	m_t	m_b	EW	Resum
MCFM (Campbell et al.)	NLO	exclusive	∞			
HIGLU(Spira)	NLO	inclusive	exact	$\surd$		
HPro (Anastasiou et al.)	NLO	exclusive	exact	$\surd$		
HNNLO (Grazzini et al.)	NNLO	exclusive	∞			
HggTotal (Anastasiou et al.)	NNLO	exclusive	$\infty + F_{LO}(m_t)$	$\surd$	NLO	
FEHiP (Anastasiou et al.)	NNLO	exclusive	$\infty + F_{LO}(m_t)$			
de Florian, Grazzini	NNLO	inclusive	$\infty + F_{LO}(m_t)$	$\surd$	NLO	$\surd$

Inclusive Calculations

Converging QCD perturbative expansion:

$\sigma(N^kLO) \approx \sigma(LO) \times [\ 1.0\ +\ 0.8\ +\ 0.3\ +\ 0.1\ +\ 0.05\ + \dots\ ]$

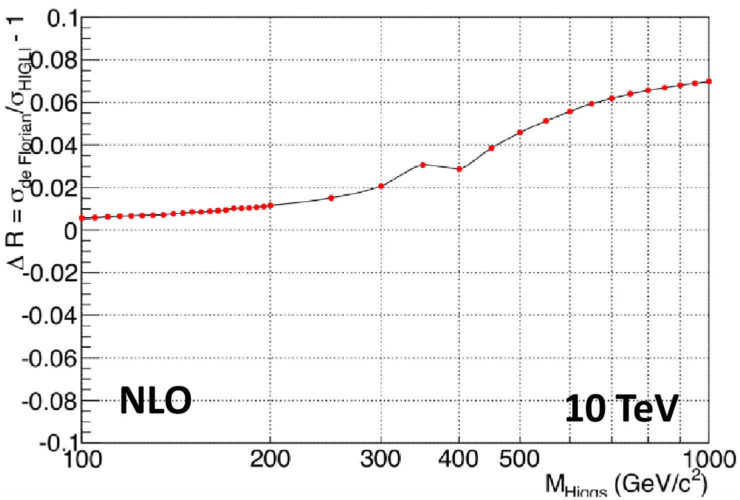
NLO N^2LO N^3LO N^nLL

Relative corrections are weakly dependent on Higgs mass

Additional corrections/issues:

- Electroweak corrections (~±5%),
- bottom quark loop contribution, a reduction of ~8% at low mass;
  a ~2% difference between pole and MSbar mass schemes
- top mass effect, most NLO+ calculations correct m_t effect using $F_{LO}(m_t)$: good at low mass, but ~10% overestimate at high mass
- m_t effect is small at NNLO at low mass (Harlander et al, arXiv:0909.3420)

de Florian/HIGLU - 1

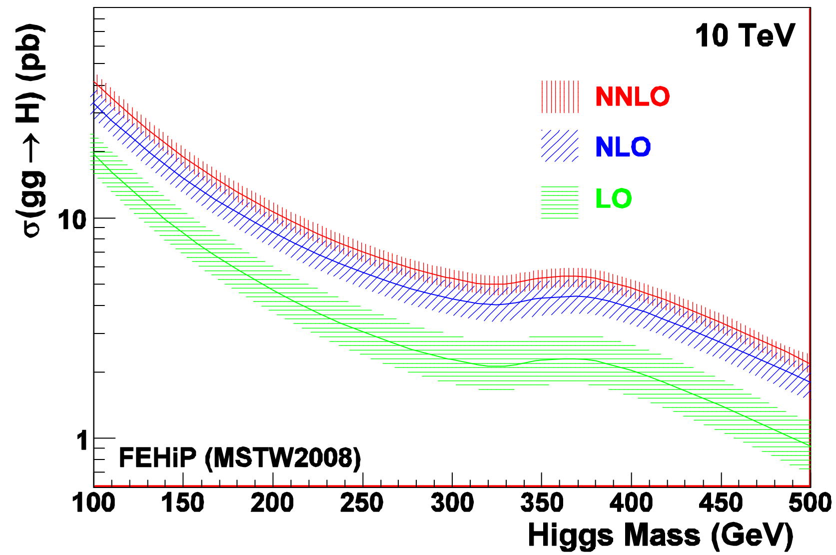


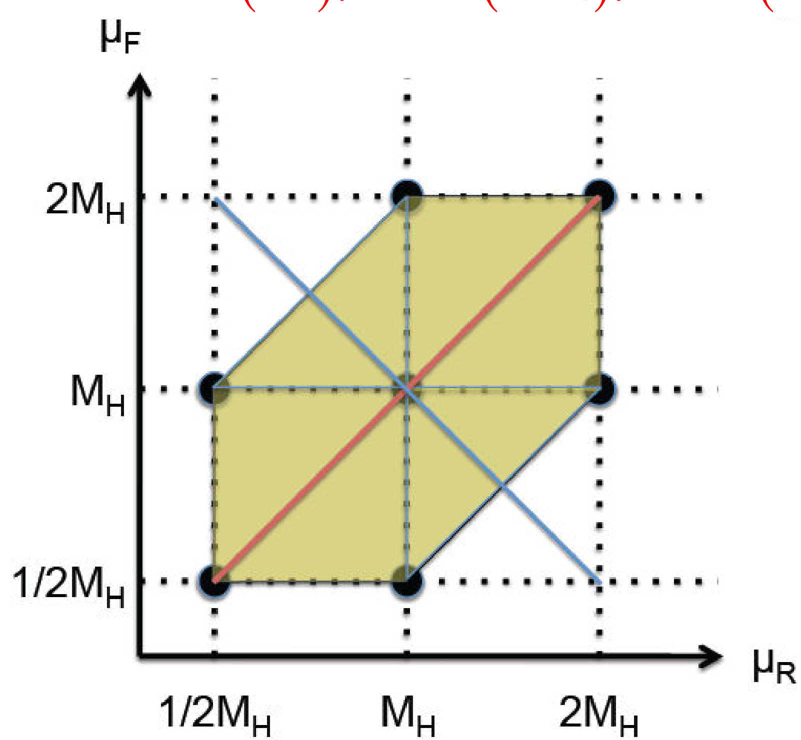
Exact m_t effect is known at NLO now, can we apply NLO m_t correction to the large m_t approximation?

Scale Uncertainties

The cross section suffers large scale dependences, for example, setting $\mu_F=\mu_R$ and varying between [0.5, 2]M_H

$$\frac{\Delta\sigma}{\sigma} \approx \pm 25\%(\text{LO}), \pm 18\%(\text{NLO}), \pm 10\%(\text{NNLO})$$





However, several different approaches in literature

- different choice of the central scale;
- how μ_F and μ_R are varied

Can we reach a consensus ?

- bring people on the same page;
- facilitate comparisons/combinations

PDF and α_s Uncertainties

PDF: Healthy debate on how to estimate its uncertainties

- general agreement on $\Delta\chi^2=1$ is not a sensible option;
- but no agreement on the actual $\Delta\chi^2$ value

($\Delta\chi^2=100$ for CTEQ and $\Delta\chi^2=50$ for MSTW)

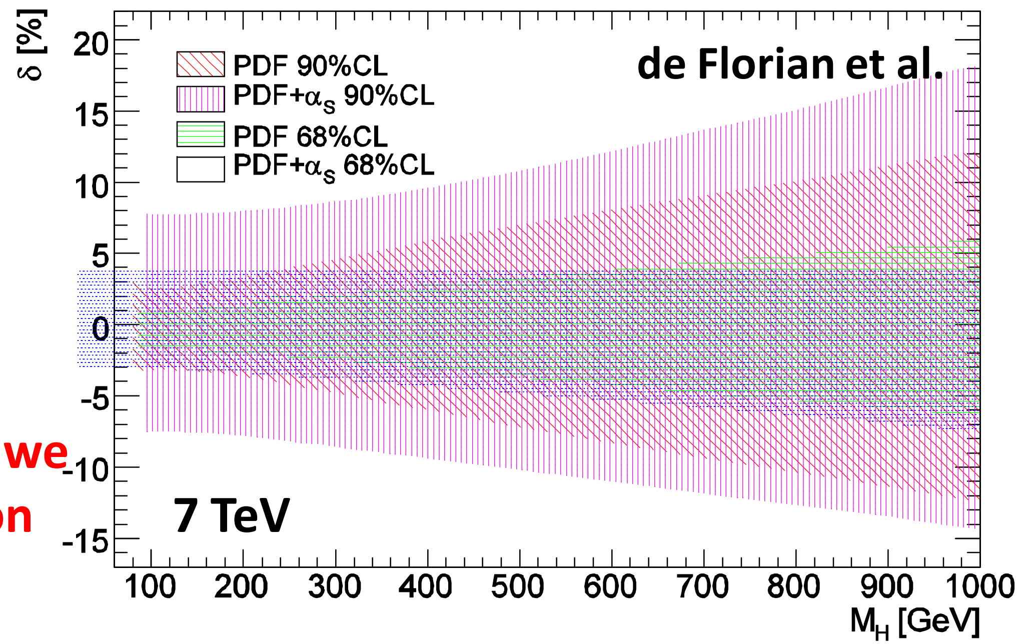
Two different philosophies on α_s:

- CTEQ uses world average $\alpha_s(Mz)=0.118$ at NLO in their fit;
- MSTW determines α_s in their fit: $\alpha_s(Mz)=0.120$ at NLO;

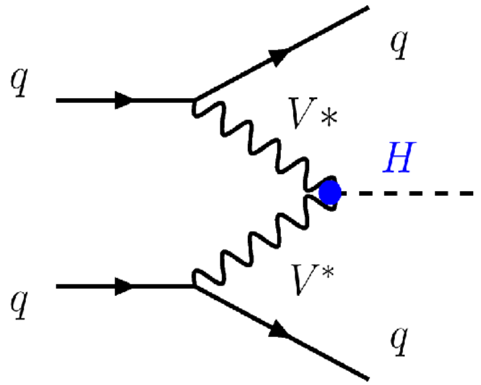
A ~3.5% difference if $\sigma \sim \alpha_s^2$.

Outside the scale-dependence, PDF and α_s are the source of the next largest uncertainty

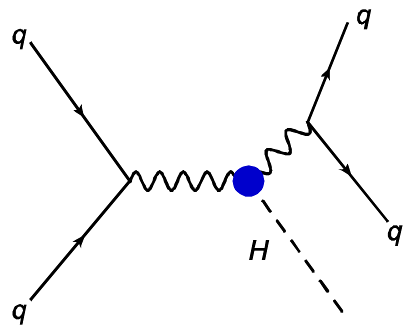
If the PDF folks cannot agree, can we as experimentalists have a common approach on dealing with this ?



Vector Boson Fusion



- The process with the 2nd largest cross section at LHC, unique event topology
- With $H \rightarrow \tau\tau$, important discovery channel for a low mass Higgs (along with $H \rightarrow \gamma\gamma$)
- Also s- and u-channel diagrams, typical tag-jet requirements reduce their contributions

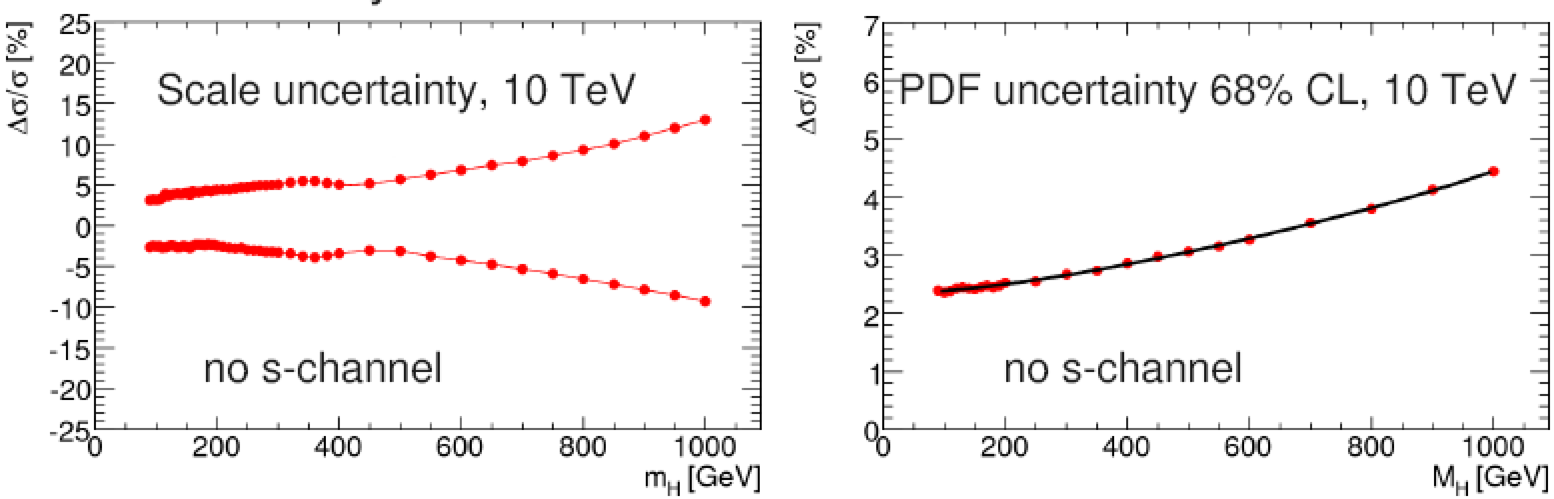


Codes/calculations

- VV2H (Spira):
  NLO QCD, inclusive, t-channel only, no WW/ZZ interference
- VBFNLO: Arnold et al., Comput. Phys. Commun. 180, 1661 (2009)
  NLO QCD, exclusive
- "CDD": Ciccolini, Denner & Dittmaier, arXiv:0710.4749
  - NLO QCD and EW corrections;
  - including t-, s- and u-channel and their interferences

Vector Boson Fusion

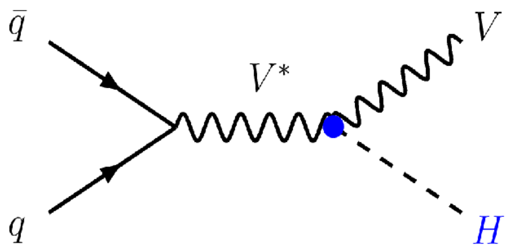
- On the same basis, results from different calculations agree within 1% (Les Houches 2007 report, arXiv:0803.1154);
- NLO corrections are relatively small (~+5% for QCD, ~-5% for EW);
- Relative small scale and PDF uncertainties
  - PDF uncertainty from CTEQ6.6 error sets



(anti)diagonal between [1/4, 4]M_W

All these calculations are done with narrow width approximation, their validity at high mass is not assured…

WH and ZH



- gold at Tevatron, more like brass at LHC though
  boosted Higgs might improve sensitivity
  σ ~ 1 pb for m_H=120 GeV at $\sqrt{s}$=10 TeV
- one of the few channels for potential Yukawa coupling measurements for a low mass Higgs

Calculations up to NNLO in QCD and NLO in EW

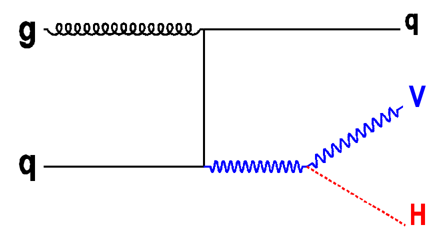
- **NLO calculations**
  - V2HV (Spira): public
  - MCFM (Campbell et al): public
- **NNLO calculations: private**
  - Brein, Djouadi & Harlander, PLB 579, 149 (2004)
  - Ciccolini, Dittmaier & Kramer, PRD68, 073003 (2003)
  - Brein et al., hep-ph/0402003

Cross section numbers are provided by Harlander with the latest PDF (MSTW2008)

WH and ZH

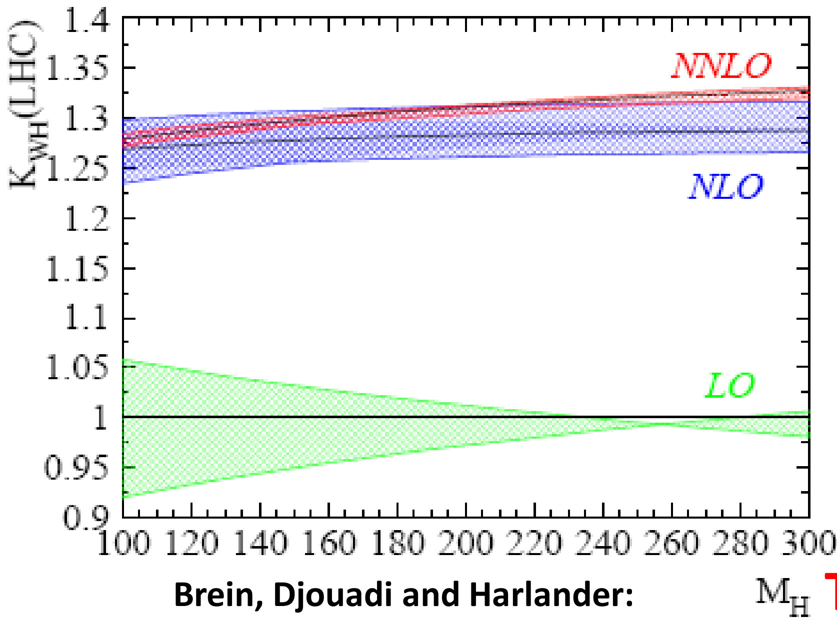
- **NLO QCD corrections increase the cross section by +30%,**
  - new $qg \rightarrow q(W/Z)H$ process

  NLO EW corrections reduce it by up to 7%

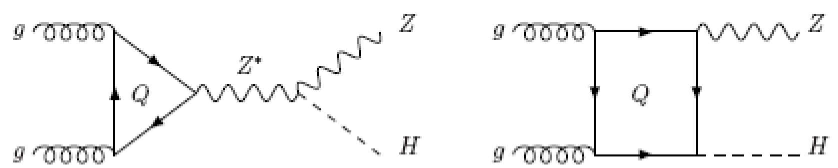


- **NNLO QCD corrections**
  - small increase (~2%) for WH
  - significant increase (~10%) for ZH because of $gg \rightarrow ZH$ contribution

WH scale variation



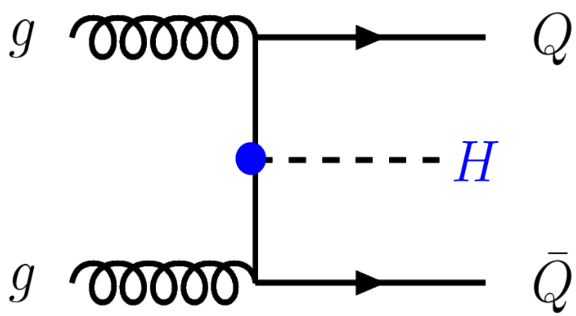
Brein, Djouadi and Harlander: hep-ph/0307206: scale varied one at a time in between $[1/3,3]M_{HV}$



- **scale variation reduces from ~10% at NLO to <3% at NNLO**
- **At NLO, PDF uncertainty ~5%. The uncertainty at NNLO is being evaluated.**

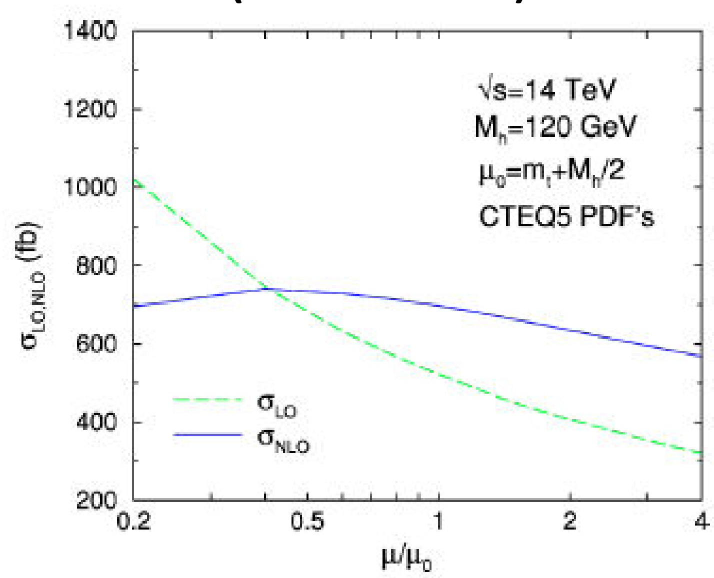
The inclusive cross section is precise enough for any practical purpose

ttH Production



- possibility to measure Htt Yukawa coupling
- σ ~ 0.4 pb for m_H=120 GeV at √s=10 TeV, large background, small S/B ratio

(Dawson et al.)

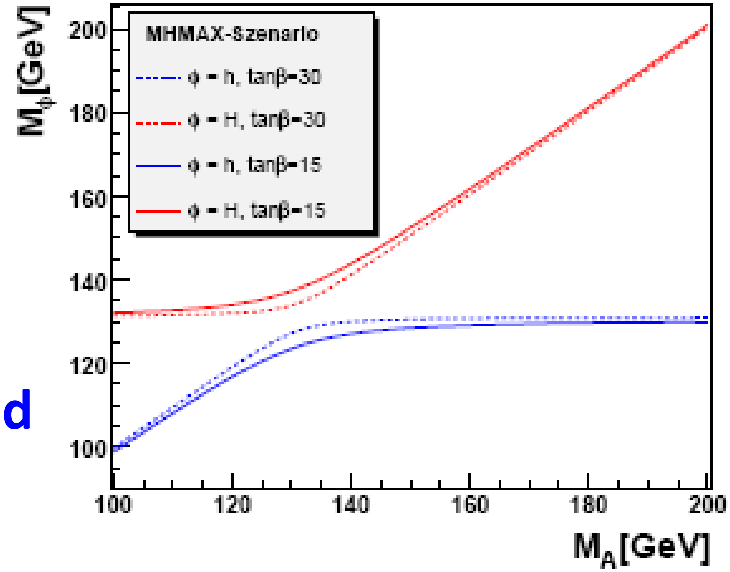


- two independent QCD NLO calculations
  - Dawson et al. PRD68, 034022 (2003)
  - Beenakker et al., Nucl. Phys. B653, 151
  - NLO K-factor: 1.1-1.4 depending on scale
- Codes:
  - Public: HQQ (Spira), but only in LO
  - private NLO available
- Remaining uncertainty
  - ~15% from scale variation
  - ~5% from PDF

Updated NLO numbers from Michael Spira, the real issue is background such as tt+jets…

MSSM Higgs Sector

- **Five Higgs bosons: h^0, H^0, A^0, H^+, H^-**
  Two neutral Higgs bosons are usually degenerate in mass $\Rightarrow \phi$



- **Can be parameterized by two parameters ($\tan\beta$, m_A) in benchmark scenario, assumed mh-max scenario in our study**

- **Enhanced coupling of neutral Higgs to b quark**

$$g_{hbb}^2 + g_{Hbb}^2 + g_{Abb}^2 \approx 2 \times \tan^2\beta \times g_{SM}^2$$

$\Rightarrow$ **new b-associated production $gg \rightarrow \phi bb$, dominant for $\tan\beta > 10$**
$\Rightarrow$ **increased b-loop contribution for $gg \rightarrow \phi$, dominant for $\tan\beta < 10$**

- **Both HDECAY/HIGLU (Spira) and FeynHiggs (Heinemeyer et al) calculate mass spectrum, decay branching ratios and production cross sections.**

MSSM gg→ϕ

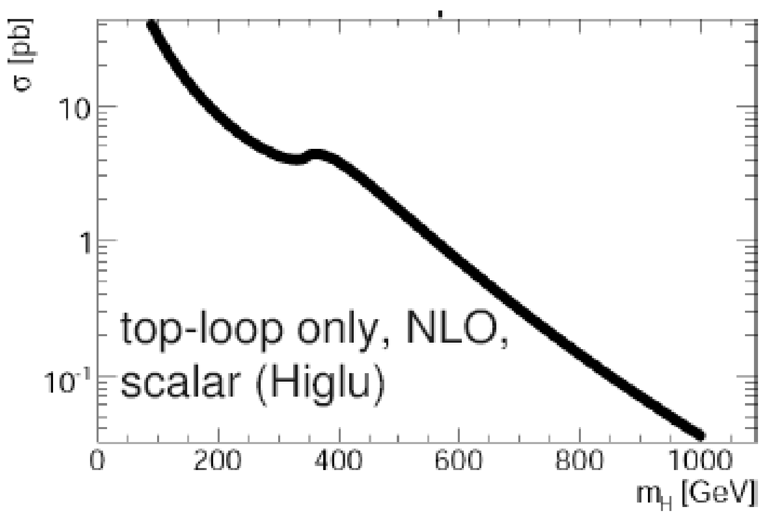
- **Similar to SM gg→H production**
  - modified couplings to top and b quark loops;
  - enhanced b-quark loop contribution at large tanβ

- **Proposal by Spira to reweight SM cross sections with coupling ratios to take advantage of more precise calculations of SM processes**

$$\sigma^{MSSM}_{gg\to\varphi} = g_t^2 \cdot \sigma^{SM}_{tt} + g_t g_b \cdot \sigma^{SM}_{tb} + g_b^2 \cdot \sigma^{SM}_{bb}$$

t-quark loop — **t-b interference** — **b-quark loop**

(only works for scalar, NNLO calculation unavailable for pseduoscalar)



- **Ongoing work**
  - reweighting implementation, comparison with FeynHiggs calculations;
  - understand scale and PDF uncertainties;
  - squark-loop in HIGLU being implemented (Spira)

MSSM $gg \rightarrow \phi bb$

Two schemes for cross section calculations:

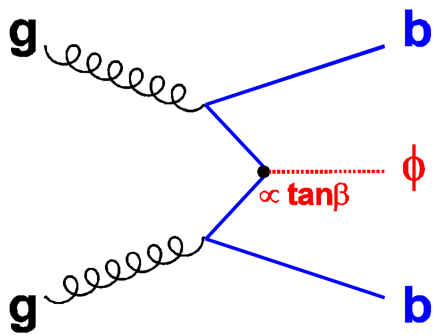
- **4-flavor scheme: $gg \rightarrow bbH$, up to NLO in QCD**

  b-quark from gluon splitting, large log contribution

  Dawson et al., PRD69, 074027 (2004)

  Dittmaier, Kramer & Spira, PRD70, 074010 (2004)

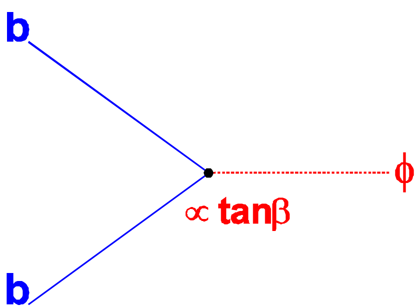
  Private code by Kramer and Spira

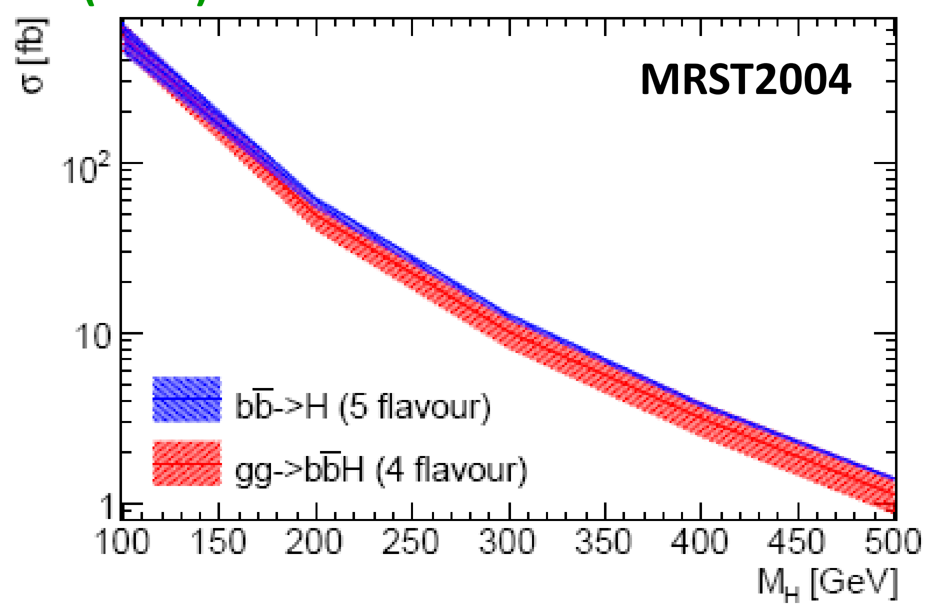


- **5-flavor scheme: $bb \rightarrow H$, up to NNLO in QCD, b-quark from PDF**

  Harlander & Kilgore, PRD 68, 013001 (2003)

  Public code: bbh@nnlo



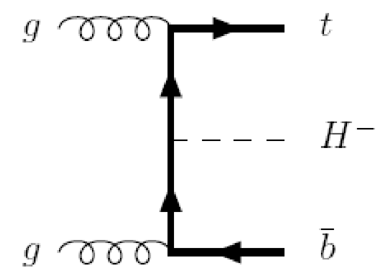


Two calculations differ by ~15%, but agree within uncertainties

MSSM Charged Higgs

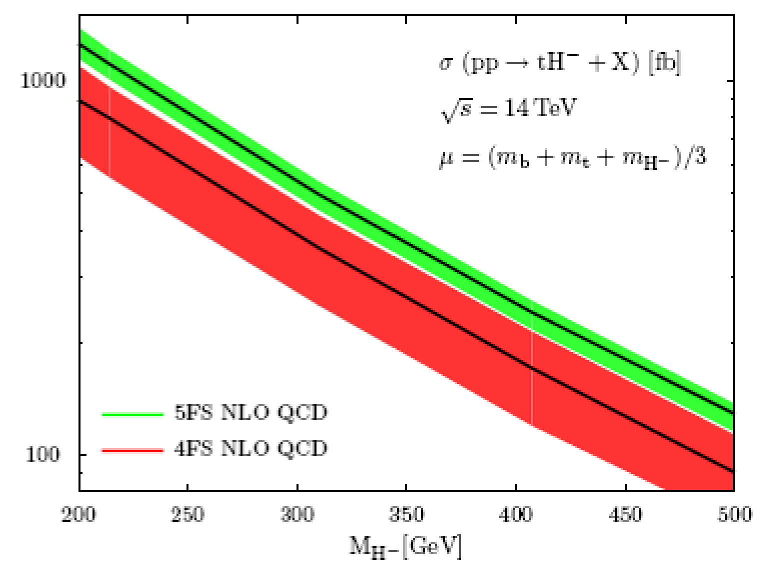
Two main production processes

- top pair production with $t \rightarrow Hb$, dominant for mH<<mt;
- associated production , dominant for heavy Higgs
  $gg \rightarrow tbH^-$ (4-flavor) or $gb \rightarrow tH^-$ (5-flavor)



- **Approximate NNLO σ(tt) calculation**
  Lagernfeld, Moch & Uwer, arXiv:0907.2527
- **Associated production**
  - 5-flavor calculation and semi-private code from T. Plehn
  - 4-flavor calculation from Dittmaier et al. arXiv:0906.2648
- **Br(t→bH) and Br(H→…) from FeynHiggs**

Dittmaier et al



A factor of 1.4 difference!

Uncertainties:

- Scale: ~6% (20%) for light (heavy) Higgs
- PDF: ~5%

Event Kinematics

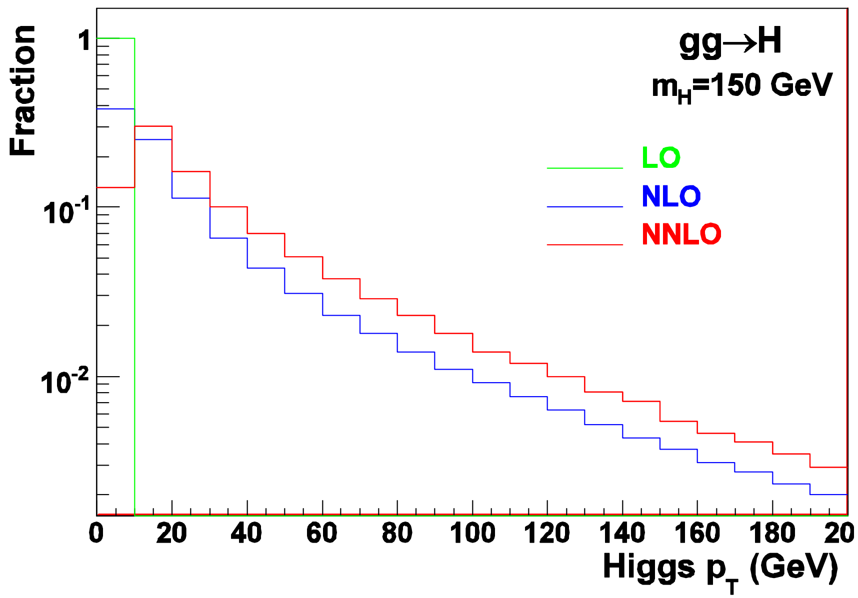
High order corrections can also impact event kinematics. For gg→H

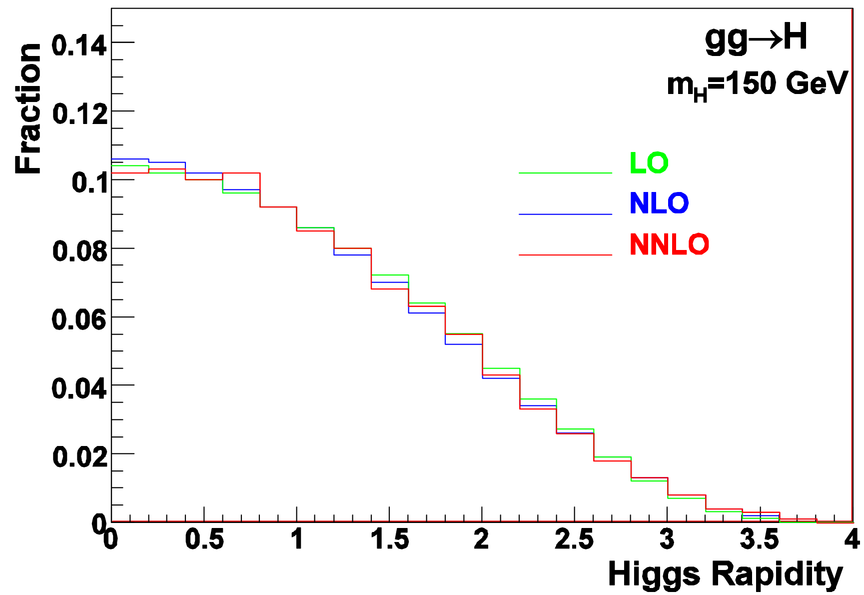
- give Higgs a pT kick and therefore alter pT/η distributions and angular correlations of particles from Higgs decays
- increase jet activity in the event

Higgs decay kinematics depends on its pT and rapidity. Both FEHiP and HNNLO programs calculate differential cross sections

$$\frac{d^2\sigma}{dp_T dy}$$

- significant change in the low pT spectrum (further modified by NNLL)
- negligible change in the rapidity distribution

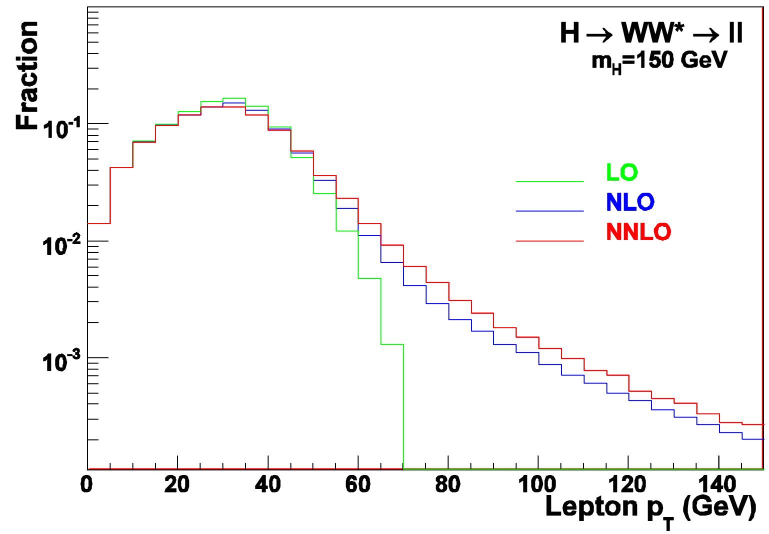


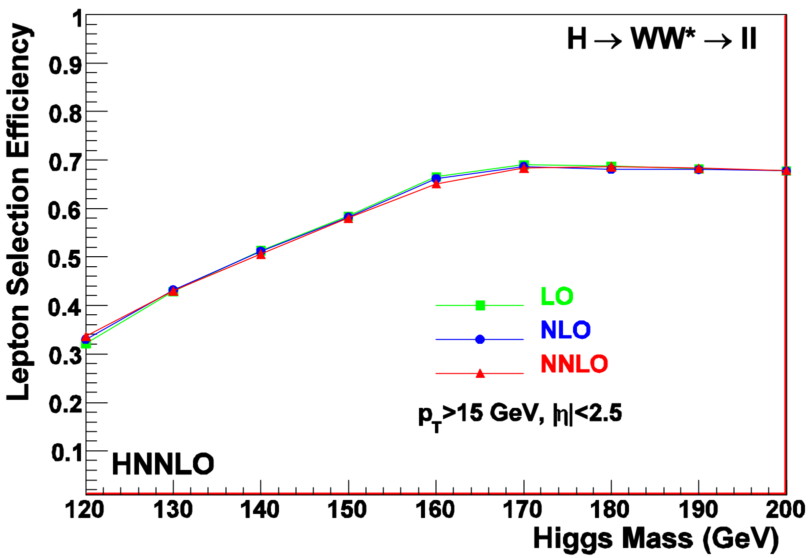


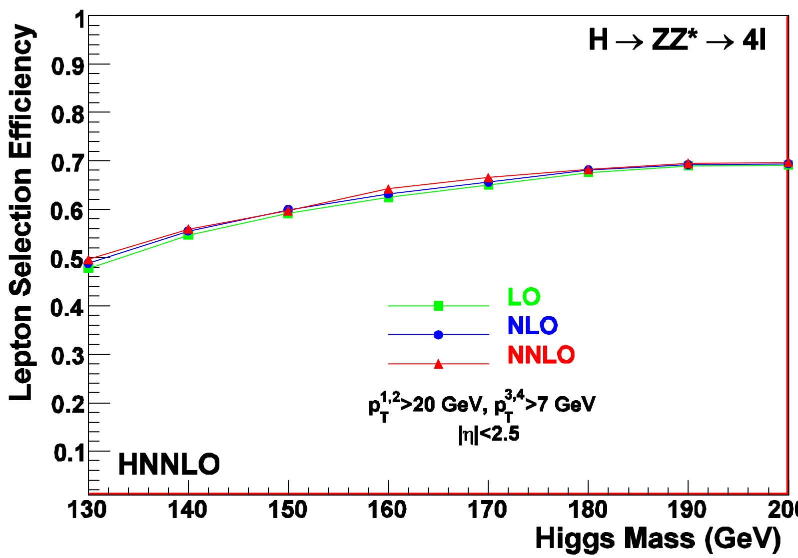
Selection Efficiencies

- Event kinematics change the most from LO to NLO, small change from NLO to NNLO, no significant changes are expected from even higher order corrections

- With mild kinematic cuts, higher order corrections have relatively small effects on selection efficiencies

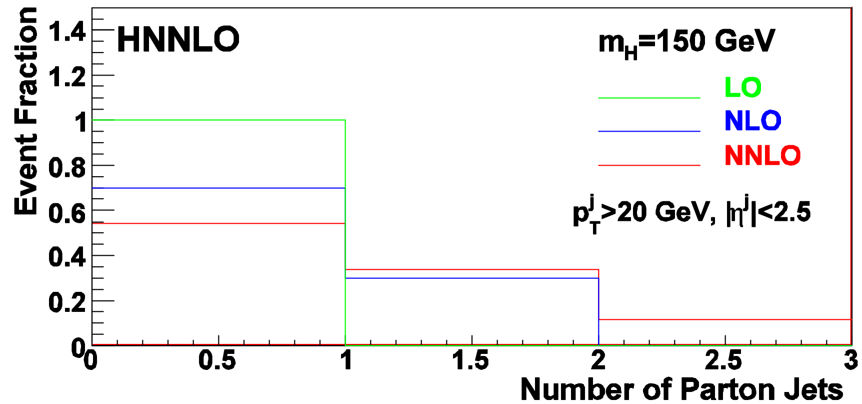






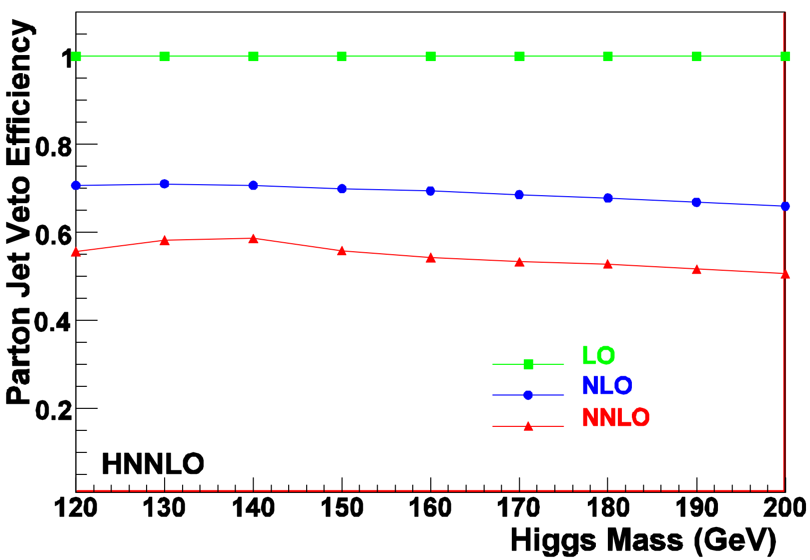
H→WW*→ll: Jet Veto

However…



Event jet activity:

- difficult to model it well in MC;
- strongly impacted by high order corrections;
- significant decrease in jet veto surviving probability at h.o.



The (parton) jet veto kills all the gain from the h.o. corrections!

$$m_H = 150\text{ GeV}: \quad \frac{\sigma_{NNLO} \times \varepsilon_{NNLO}^{Veto}}{\sigma_{NLO} \times \varepsilon_{NLO}^{Veto}} \approx 0.97$$

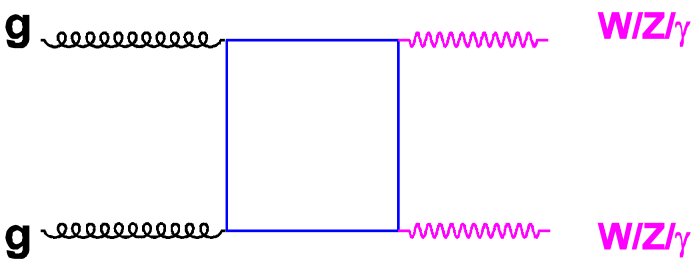
- 1-jet bin has ~30% of the signal, can probably be recovered;
- 2-jet bin has ~10% of the signal, they are probably lost

Effects of soft radiations need to be understood

Comments on Backgrounds

Our work has so far focused on signal processes. For many processes, signal cross section is less an issue compared with that of background process. A few examples…

- **gg→H→VV**
  - How large is the gg→VV NLO correction to the SM VV cross section?
  - Will the correction impact event topology ?



- **VH, ttH**
  - these analyses are overwhelmed by backgrounds, signal cross sections are not real issues. Kinematic regions with highly boosted Higgs will significantly improve S/B, but it places a premium on the understanding of exclusive distributions of both signal and backgrounds.

Help Needed…

- **Make your code public and interface it to LHAPDF !**

  Can experiments agree to quote only published numbers or those from publically available codes?

  - one of the most difficult issues is to deal with private codes and/or calculate with latest PDF…

- **Consensus on scale choices**

  Central scales and ranges for scale variations for individual processes

- **Agreement on procedures for estimating PDF (α_s ?) uncertainties**

  - among PDF communities? Tevatron and LHC communities ?

- **Interface N^kLO calculations with parton shower MC generators, resolve the difference between 4- and 5-flavor calculations of MSSM Higgs**

- **Others…**

  Common SM parameter setup/values, e.g. $m_b(m_b)$ in MSbar vs m_b pole mass; NLO top mass effect for $gg \rightarrow H$; Decay width effect for a heavy Higgs; Interferences between Higgs and SM background diagrams; …

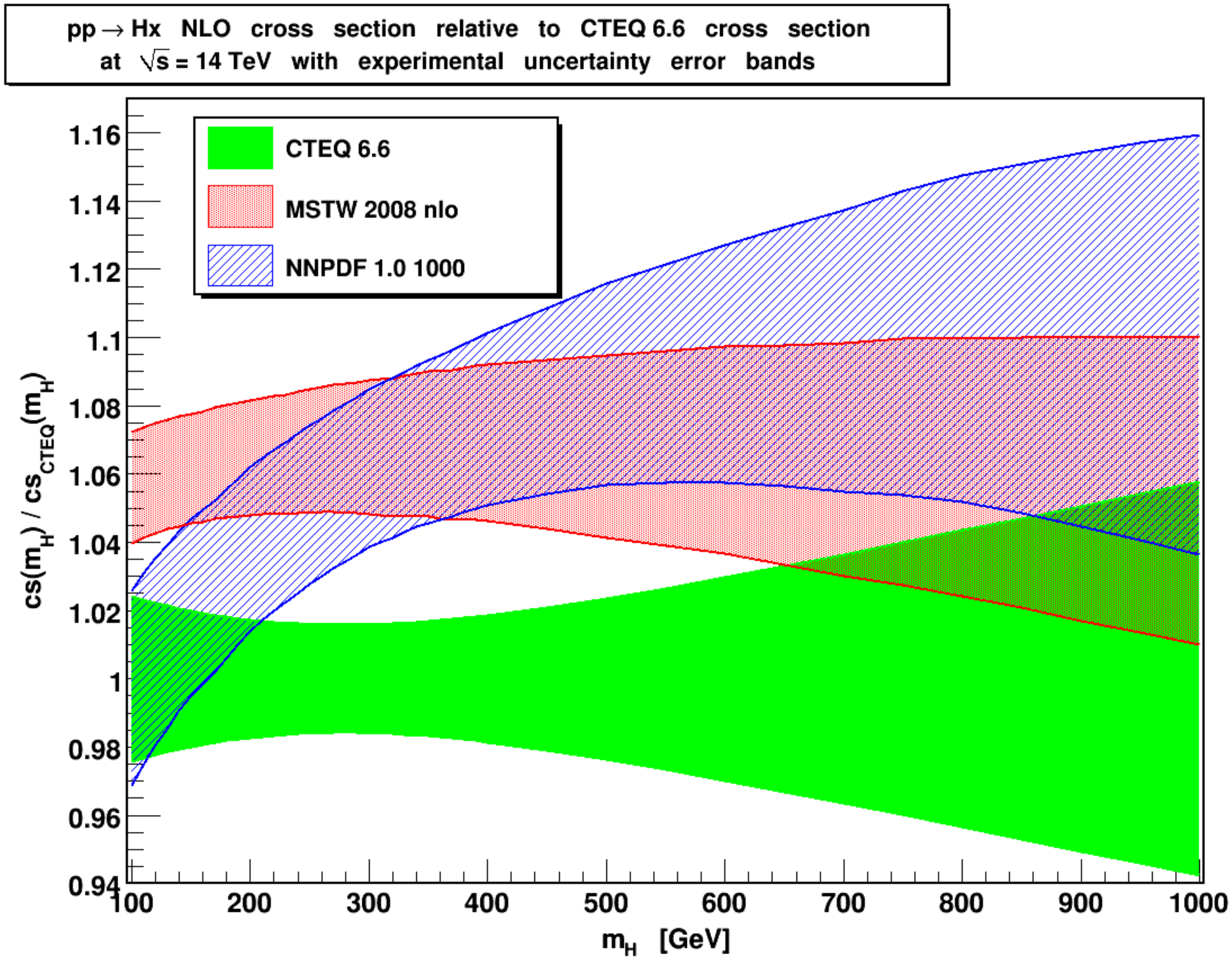
Summary

- An active ATLAS group surveying theoretical calculations/tools, comparing results from different tools and compiling the best estimates of Higgs cross sections;

- Have been actively collaborating with our theoretical colleagues to understand differences and limitations of different calculations; Consensuses on a number of issues among theory and PDF communities will be very helpful;

- Nothing of these is ATLAS specific. A common approach between ATLAS and CMS will be beneficial for potential future combination of results.

ggF PDF



pp → Hx NLO cross section relative to CTEQ 6.6 cross section
at √s = 14 TeV with experimental uncertainty error bands
CTEQ 6.6
MSTW 2008 nlo
NNPDF 1.0 1000
cs(m_H) / cs_CTEQ(m_H)
1.16
1.14
1.12
1.1
1.08
1.06
1.04
1.02
1
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