

Fully differential Higgs boson production and the di-photon signal through NNLO

Frank Petriello

University of Wisconsin-Madison

with Babis Anastasiou, Kirill Melnikov

[hep-ph/0409088](#), [hep-ph/0501130](#)

LoopFest IV

August 2005

Outline

● Introduction

- Higgs at the LHC
- Techniques for real emission corrections at NNLO

● An automated technique for NNLO calculations

- Phase space parameterizations
- Entangled singularities

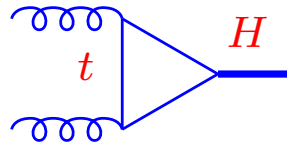
● Phenomenological results for Higgs at NNLO

- Effects of ATLAS, CMS cuts on K -factors
- Comparison of NNLO with MC@NLO
- Higgs coupling extractions

● Conclusions

Higgs signal at higher orders

- Finding the Higgs at the LHC will be an important milestone for the SM
- Dominant production mechanism is $gg \rightarrow H$:



- NLO K -factor is large, $\approx 70\%$; how well does the series converge? (Dawson; Djouadi, Spira, Zerwas)
- Fully inclusive NNLO cross section known (Harlander, Kilgore; Anasasiou, Melnikov; Ravindran, Smith, van Neerven)
 - $K_{NNLO} \approx 2$; residual scale dependence $\approx 20\%$
 - Agrees well with threshold-resummed results (Catani, Grazzini, de Florian)
- Do experimental cuts change conclusions based on inclusive calculation?

Higgs cuts at the LHC

- All Higgs searches at the LHC impose final-state cuts, even primarily inclusive ones
- For $H \rightarrow \gamma\gamma$:
 - $p_T^{(1)} > 25 \text{ GeV}, p_T^{(2)} > 40 \text{ GeV}$
 - $|\eta^{(1,2)}| < 2.5$
 - Isolation cuts: $E_T < 15 \text{ GeV}$ in cone with $R = \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$
- Higgs production dominated by threshold: $E_H \approx m_H, p_T \ll m_H$
- ⇒ don't expect large kinematic shifts at higher orders
- More detailed (5 – 10%) answer requires full NNLO calculation with all cuts included
- Useful testing ground for techniques: scalar production, simple partonic structure, etc.

Real radiation at NNLO

- Current sticking point for $2 \rightarrow 1$ and $2 \rightarrow 2$ processes is real emission corrections
- Fully differential results at NLO typically use dipole subtraction
 - Manual reconstruction of all singular regions
 - Analytic integration of dipoles
- Tough to extend to NNLO, although some success recently (see talks by A. Gehrmann-De Ridder, T. Gehrmann, B. Kilgore)
- Goal: fully automated, numerical method for extracting and cancelling IR singularities
 - For each NNLO component $d\sigma_{VV}, d\sigma_{RV}, d\sigma_{RR}$, obtain an expansion

$$d\sigma_{xy} = \sum_{j=0}^{2(n-2)} \frac{A_j}{\epsilon^j}$$

- A_j are ϵ independent and finite throughout phase space
- ⇒ can handle them numerically
- Cancel poles numerically by combining the $d\sigma_{xy}$

Sketch of the method

• The algorithm:

- Map the integration to the unit hypercube

$$\int d^d p_i \delta(p_{in} - \sum p_i) \delta(p_i^2 - m_i^2) \dots \Rightarrow \int_0^1 dx_i x_i^{a_i \epsilon} (1 - x_i)^{b_i \epsilon}$$

Non-zero a_i, b_i regulate singularities, which appear as $1/x_i, 1/(1 - x_i)$

- Use **sector decomposition** to disentangle overlapping singularities
- Extract singularities using **plus distribution** expansion

$$x^{-1+\epsilon} = \frac{1}{\epsilon} \delta(x) + \left[\frac{1}{x} \right]_+ + \epsilon \left[\frac{\ln(x)}{x} \right]_+ + \dots$$

- All singularities appear as poles in ϵ ; check that they cancel, then discard
- Numerically integrate finite remainder with arbitrary final-state restrictions
- Can do same for Feynman parameters of virtual component (Binoth, Heinrich)

Step 1: Phase space parameterization

- Choosing appropriate phase-space parameterization is crucial for efficiency
- Best to choose different ones for certain classes of diagrams
- **Energy** parameterization:

$$N \int_0^1 d\lambda_1 d\lambda_2 d\lambda_3 d\lambda_4 [\lambda_1(1-\lambda_1)]^{1-2\epsilon} [\lambda_2(1-\lambda_2)]^{-\epsilon} [\lambda_3(1-\lambda_3)]^{-\epsilon} \times [\lambda_4(1-\lambda_4)]^{-\epsilon-1/2} D^{2-d}$$

$$N = \Omega_{d-2} \Omega_{d-3} (1-z)^{3-4\epsilon} / 2^{4+2\epsilon}$$

$$D = 1 - (1-z)\lambda_1 (1 - \vec{n}_1 \cdot \vec{n}_2) / 2$$

$$1 - \vec{n}_1 \cdot \vec{n}_2 = 2 \left[\lambda_2 + \lambda_3 - 2\lambda_2\lambda_3 + 2(1-2\lambda_4) \sqrt{\lambda_2(1-\lambda_2)\lambda_3(1-\lambda_3)} \right]$$

- Guiding principle is the simplicity of the singularity structure

$$s_{13} = -(1-z)\lambda_1(1-\lambda_2), \quad s_{23} = -(1-z)\lambda_1\lambda_2$$

$$s_{14} = -(1-z)(1-\lambda_1)(1-\lambda_3)/D, \quad s_{24} = -(1-z)(1-\lambda_1)\lambda_3/D$$

- For other s_{ij} in denominator, choose a different parameterization

Step 2: Entangled singularities

- Two types of singularities:
 - Factorized: $1/x \Rightarrow$ can directly expand in plus distributions
 - Entangled: $1/(x_1 + x_2) \Rightarrow$ cannot directly expand

- Sector decompose entangled singularities
 - Consider the simple example

$$I = \int_0^1 dx dy \frac{x^\epsilon y^\epsilon}{(x + y)^2}$$

- Divide the integration region by ordering the two variables:

$$I = \int_0^1 dx \int_0^x dy + \int_0^1 dy \int_0^y dx$$

- Singularities factor in each region after the integration region is remapped into $[0, 1]$; consider the $y < x$ region, and set $z = y/x$:

$$I(y < x) = \int_0^1 dx dz \frac{x^{-1+2\epsilon} z^\epsilon}{(1 + z)^2}$$

- Can now expand as before

Advantages

- Very easy to automate entire procedure
- No need to determine physical origin of singular regions (UV, soft, collinear); just search for factorized and entangled forms
- Only integration required is a numerical integration of the finite remainder; divergent parts are found separately as poles in ϵ and discarded
- ⇒ in principle, a solution to extracting and canceling singularities to NⁿLO
- Fully differential results; in principle, can be used to make an event generator
- Method is topological:

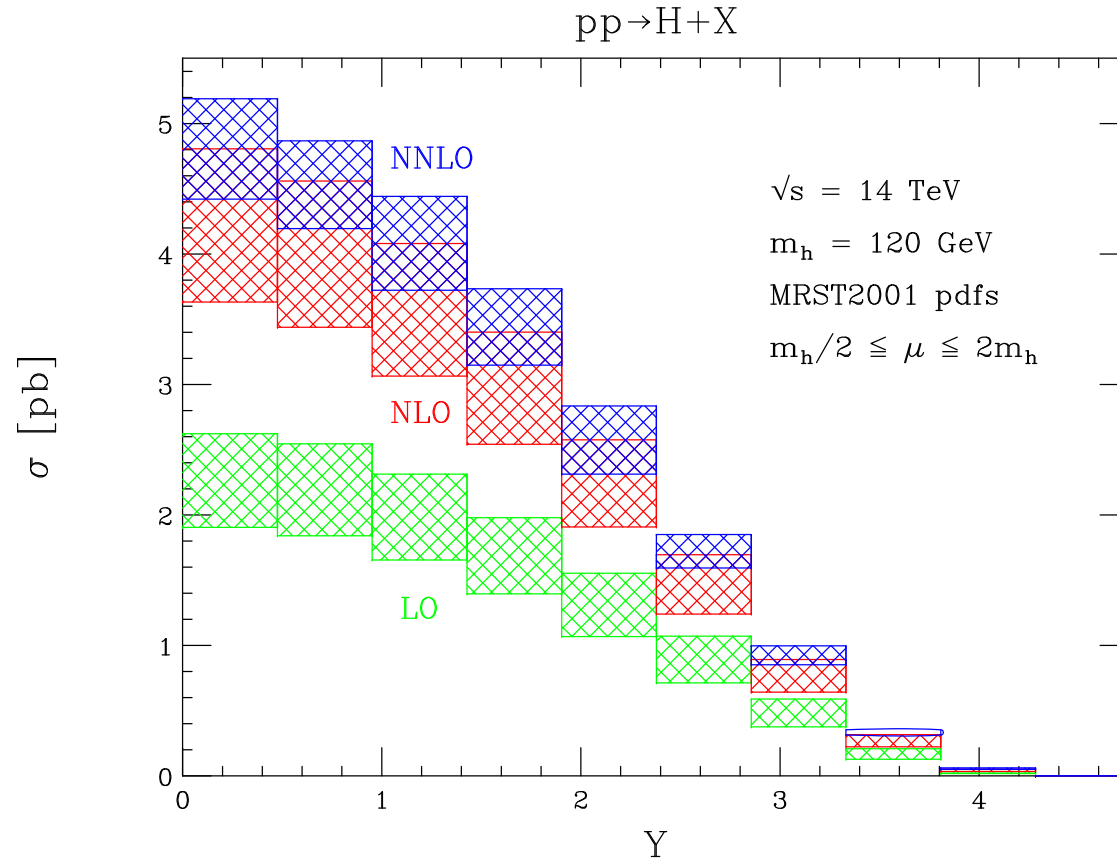
$$|\mathcal{M}|^2 \sim \frac{N(s_{ab}, F_J)}{\prod s_{ij}}$$

- ⇒ algorithm applied only to denominator ⇒ same for all $2 \rightarrow 1$ processes

Summary of results

- Fully differential Higgs production implemented in a FORTRAN code, FEHiP: Fully Exclusive Higgs Production, at
<http://www.phys.hawaii.edu/~kirill/FEHiP.htm>
- Uses VEGAS as implemented in the CUBA library (Hahn)
- Efficiency of code being continually improved
- Currently includes $H \rightarrow \gamma\gamma$ only; more modes to be included in the future
- Allows NNLO study of Higgs signal with *completely* realistic cuts
 - Phenomenological study of K -factors for LHC with all ATLAS, CMS cuts
 - CMS comparison with MC tools PYTHIA, MC@NLO (Dissertori et.al)
 - Calculation of K -factor tables for re-weighting of event generators

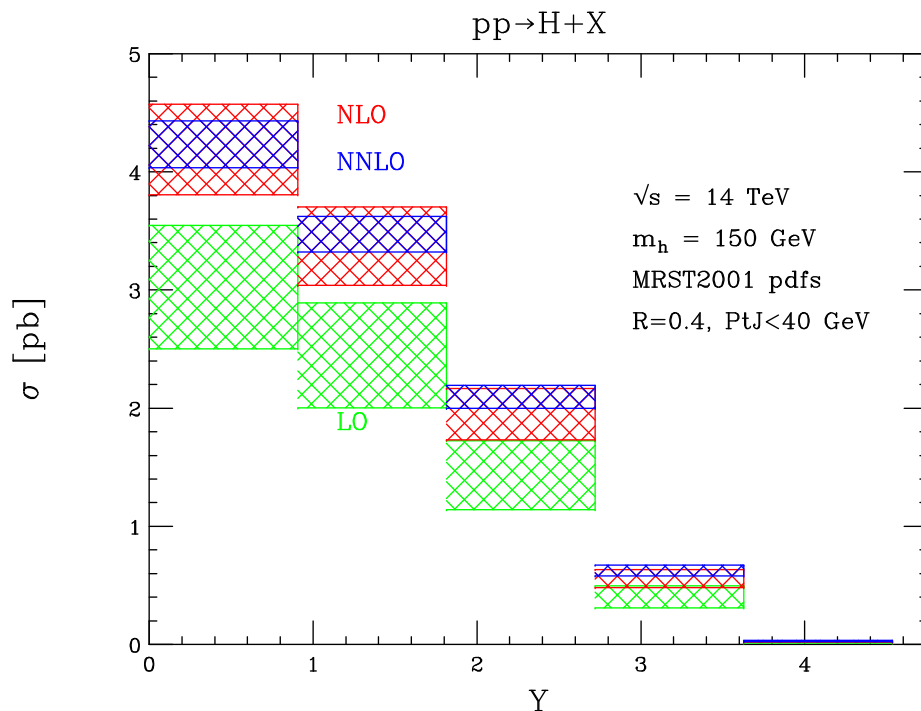
Higgs rapidity distribution



- Scale dependence: 30 – 45% at LO, 25 – 35% at NLO, 15 – 20% at NNLO
- Stabilization of perturbation series at NNLO
- K -factor depends negligibly on rapidity

Jet-vetoed Higgs cross section

- For $H \rightarrow WW$ channel, impose a veto on extra jet activity $\Rightarrow$ suppresses $t\bar{t}$ background

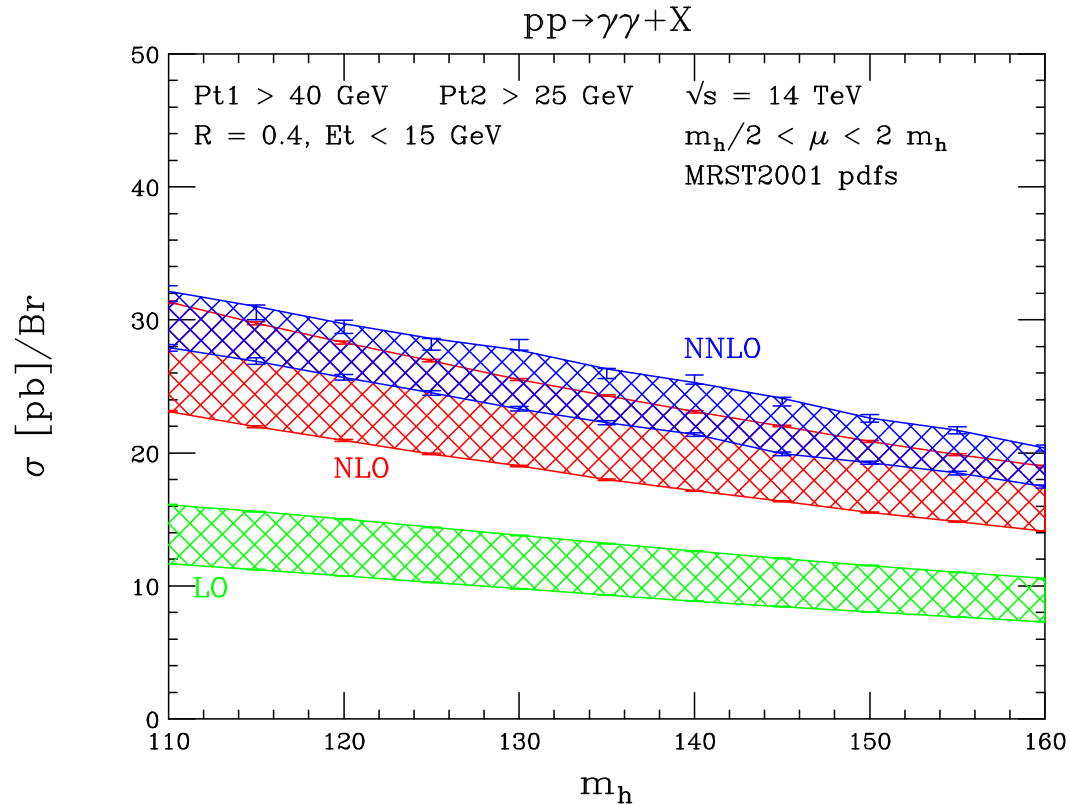


For $\mu = m_h$:

- Inclusive $K^{(2)} = \frac{\sigma_{NNLO}}{\sigma_{NLO}} : 1.18$
- Vetoed $K^{(2)} : 1.04$
- $\langle p_T^{NLO} \rangle = 37.5$ GeV
- $\langle p_T^{NNLO} \rangle = 44.6$ GeV
- More effective veto at NNLO

$\Rightarrow$ inclusive K -factor approximation can be drastically wrong, need calculation to find out!

Di-photon signal at NNLO



• $\sigma_{cut}/\sigma_{inc} \approx 0.55 - 0.70$ for $m_h = 115 - 160$

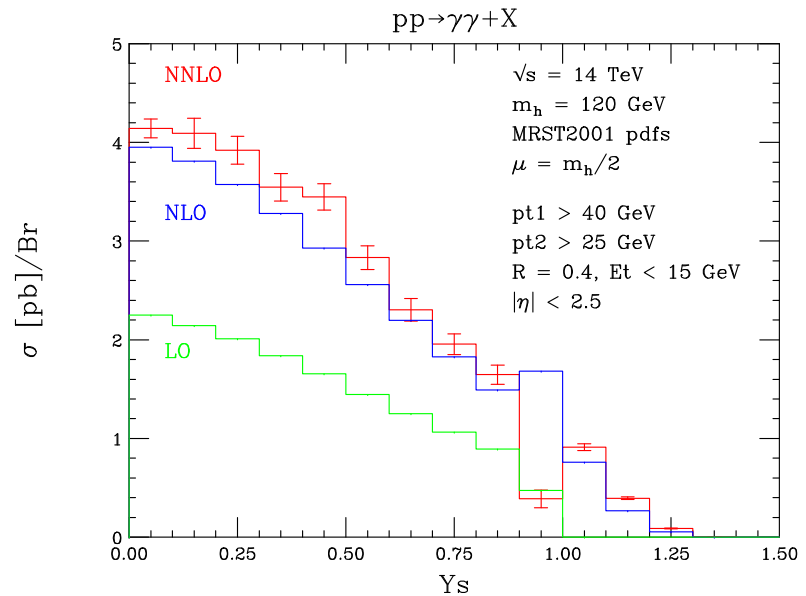
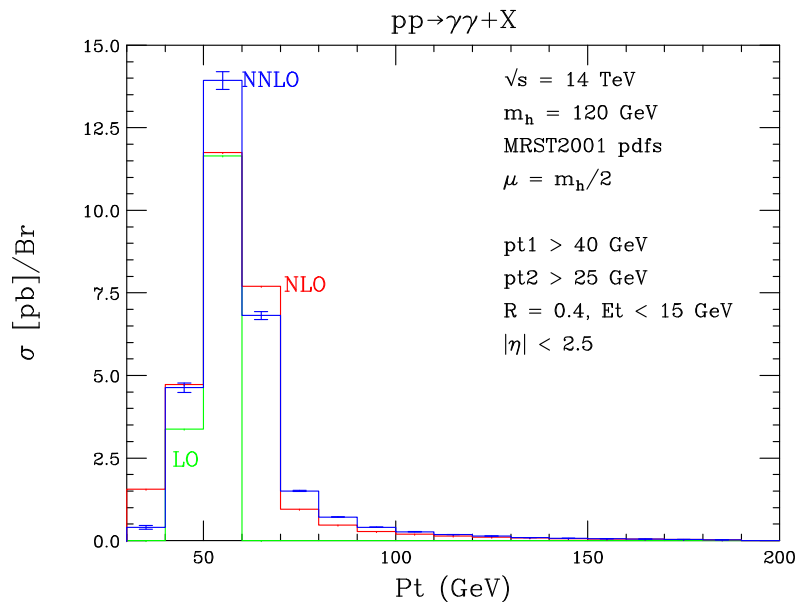
⇒ most of reduction caused by p_T and η cuts; isolation cut is < 5% decrease

• $K_{cut}^{(2)}/K_{inc}^{(2)} \approx 1.02 - 1.08$, with $K^{(2)} = \sigma_{NNLO}/\sigma_{NLO}$

⇒ can we approximate $\sigma_{NNLO}^{cut} \approx \sigma_{NLO}^{cut} K_{inc}^{(2)}$? Yes, with 5% accuracy

Di-photon distributions

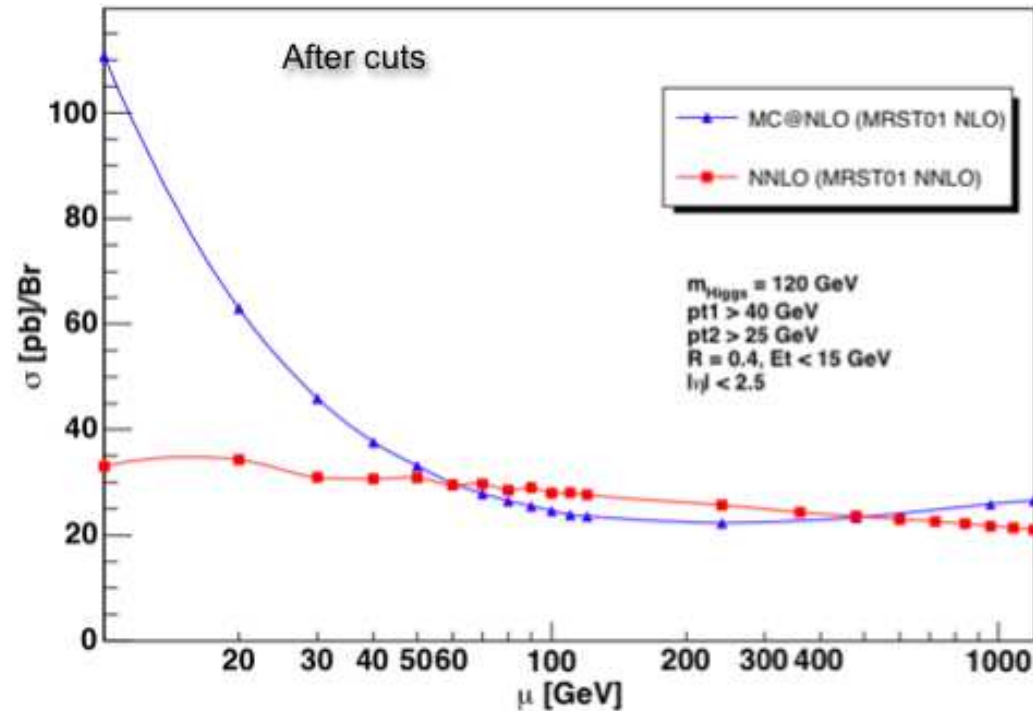
- Photonic η and p_T distributions can be used to discriminate between signal and background



- $p_t = (p_{\perp}^{\gamma,1} + p_{\perp}^{\gamma,2})/2$; $Y_s = |\eta^{\gamma,1} - \eta^{\gamma,2}|/2$
- p_t background distribution has no peak at $m_h/2$
- Y_s background distribution is flat (Bern, Dixon, Schmidt)
- Shapes are stable under perturbative corrections

Comparison with MC@NLO

- Cross sections agree to 5 – 6%, acceptances to 0.5% (Dissertori et. al.)



- Much better control over the theoretical uncertainty!
- To minimize effect of higher order corrections, choose $\mu \sim m_H/2$
- Lower scales make cross section larger; in agreement with threshold resummation

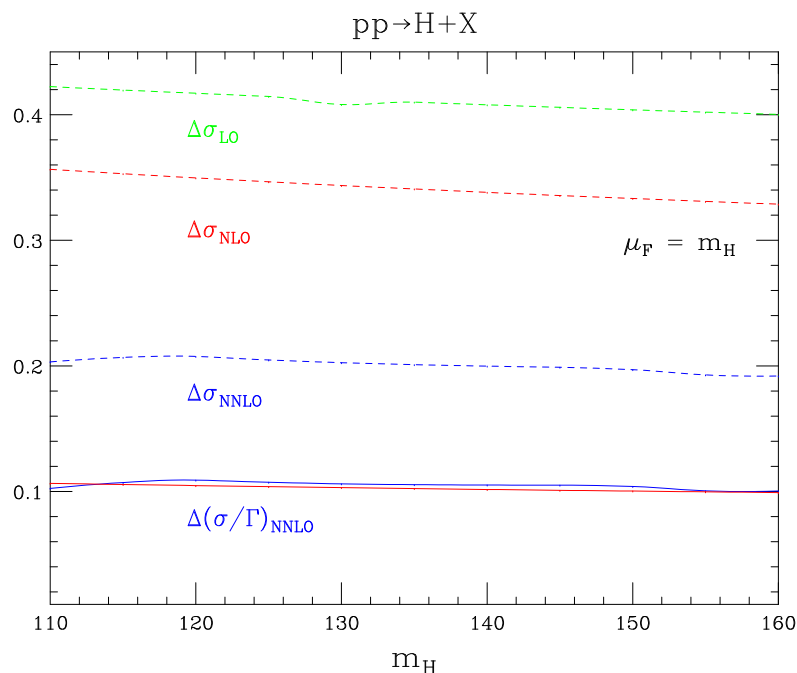
Higgs coupling extractions

- Analyses of Higgs couplings use relation

$$\sigma(H) \times BR(H \rightarrow xx) = \frac{\sigma(H)^{SM}}{\Gamma_p^{SM}} \cdot \frac{\Gamma_p \Gamma_x}{\Gamma}$$

- ⇒ calculate and assign theoretical uncertainty to σ/Γ , extract $\Gamma_p \Gamma_x / \Gamma$

- Current studies assign $\approx 20\%$ theoretical uncertainty to σ/Γ for $gg \rightarrow H$ production mode (Duhrssen et. al.)



- $\Gamma \sim \alpha(\mu_R)^2 C_1(\mu_R)^2 \{1 + \alpha(\mu_R) X_1 + \dots\}$
 $\sigma \sim \alpha(\mu_R)^2 C_1(\mu_R)^2 \{1 + \alpha(\mu_R) Y_1 + \dots\}$
- Corrections to σ, Γ track each other
- ⇒ Large μ_R uncertainty in σ/Γ cancels
- At NNLO, should take $20\% \rightarrow 10\%$ theory error
- Effect on coupling extractions?

Conclusions

- Have presented a new method for real emission contributions at NNLO and beyond
- NNLO Higgs differential cross section is the 1st such result obtained
- Can now provide theoretical predictions with *all* experimental cuts included
- FEHiP is a powerful tool for studying the $H \rightarrow \gamma\gamma$ at the LHC; will be extended to $H \rightarrow WW$, $H \rightarrow ZZ$
 - K -factor dependence on kinematic cuts: can reach 15% or more!
 - Comparisons with other MC tools
 - Accurately quantify and reduce theoretical uncertainties
- Method is applicable to many other processes of interest (see talk by K. Melnikov)