Recent theoretical issues in Higgs production

Frank Petriello

MCTP Spring Symposium on Higgs Physics

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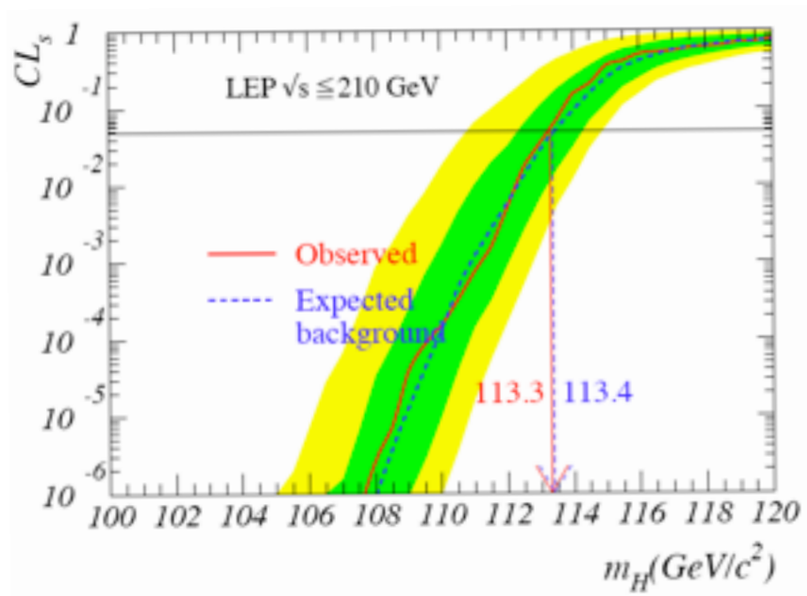
NORTHWESTERN UNIVERSITY

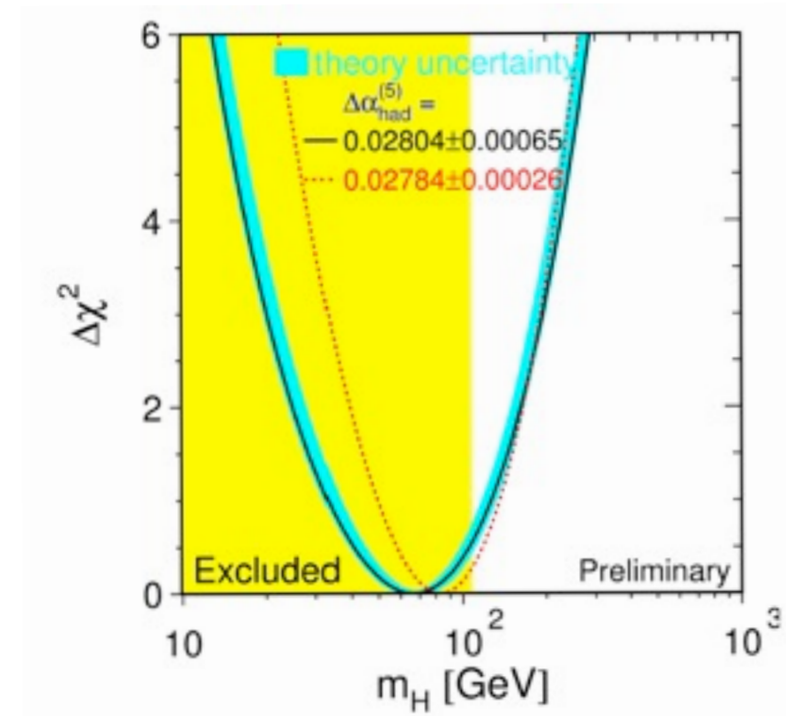
Argonne NATIONAL LABORATORY

The Higgs search from LEP to the LHC

- In early 2000:

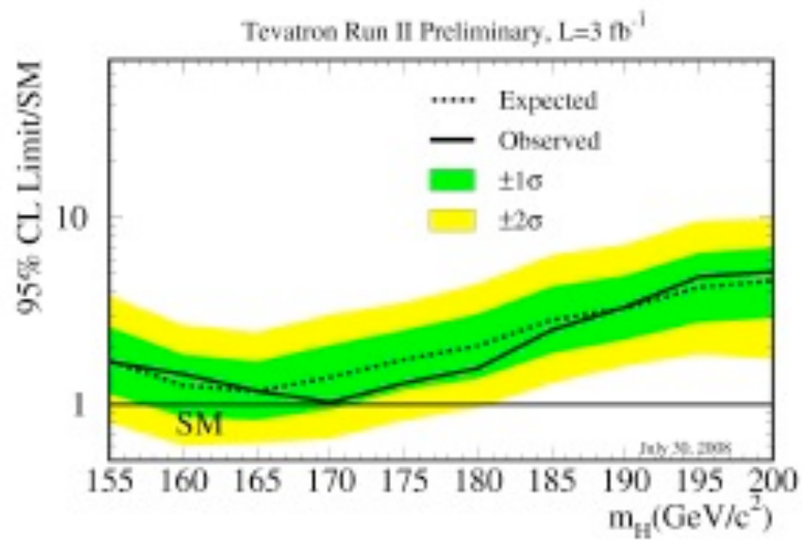


M_H <113.4 GEV EXCLUDED @ 95% CL



M_H<170 GEV @ 95% CL

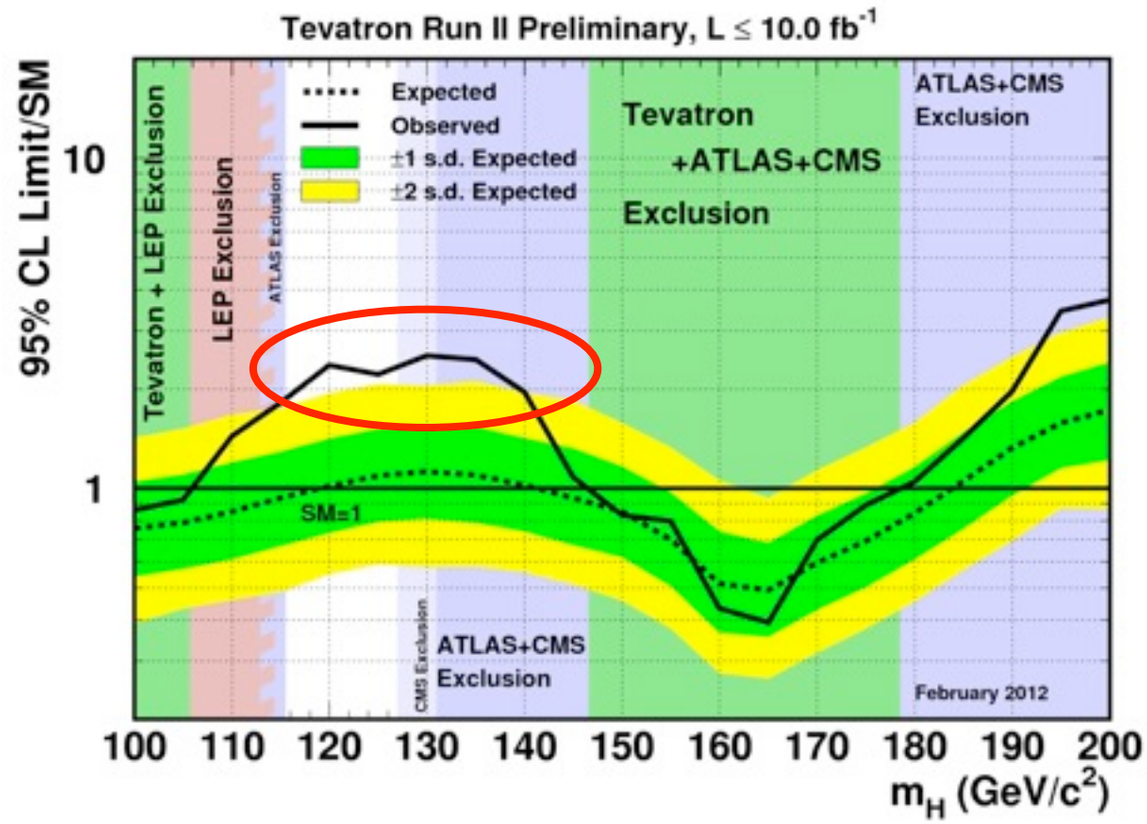
- Fall 2008: first direct exclusion of the SM Higgs from the Tevatron

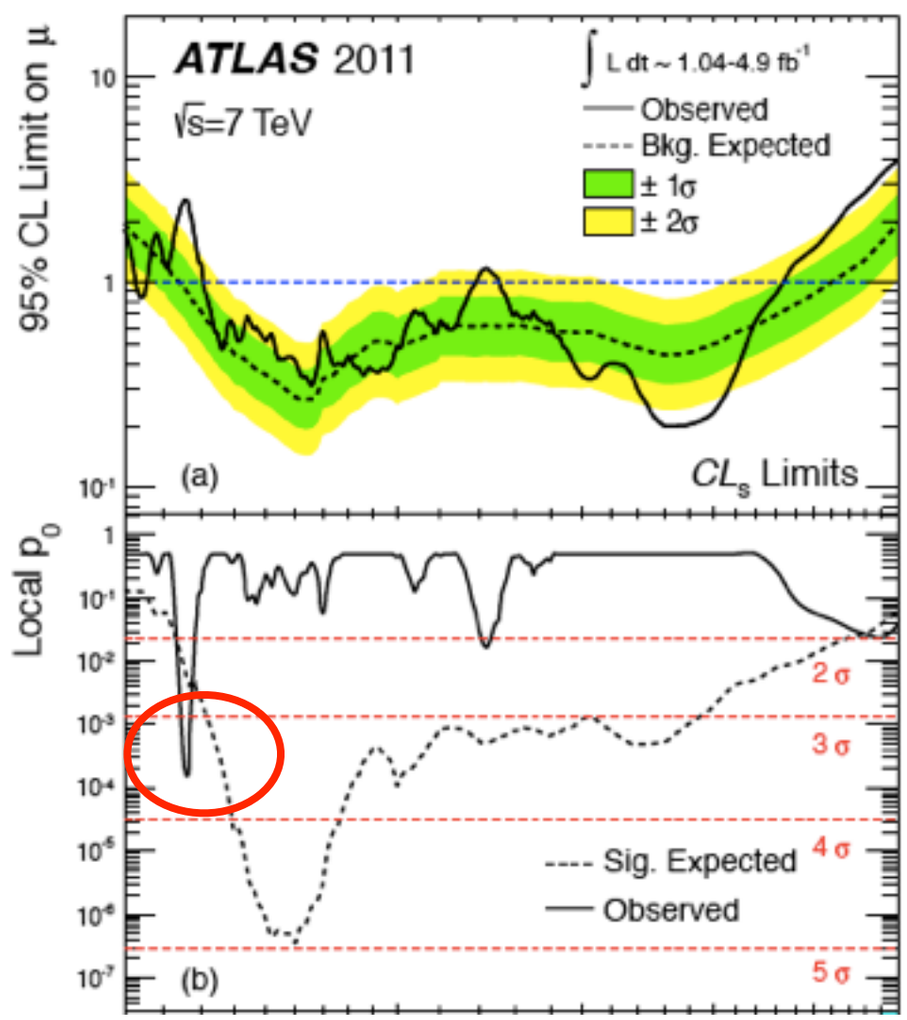


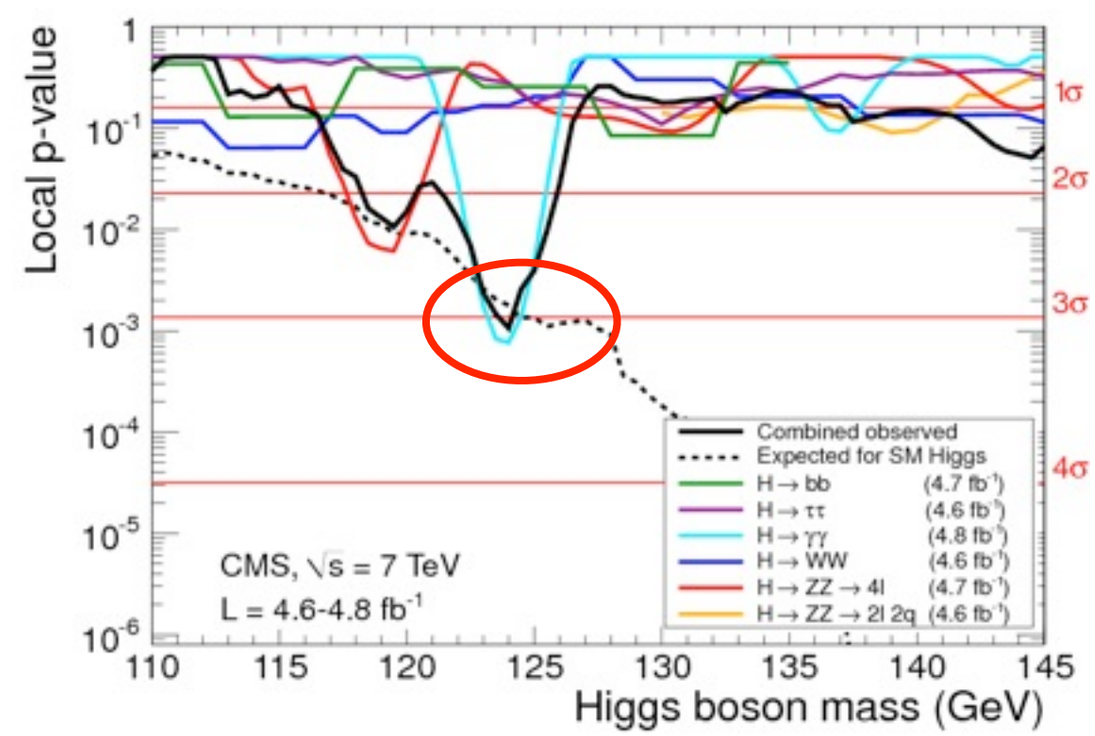
M_H= 170GEV IS EXCLUDED AT 95% CL

The Higgs search today

- Tevatron excess driven by bbar channel
- LHC primarily γγ



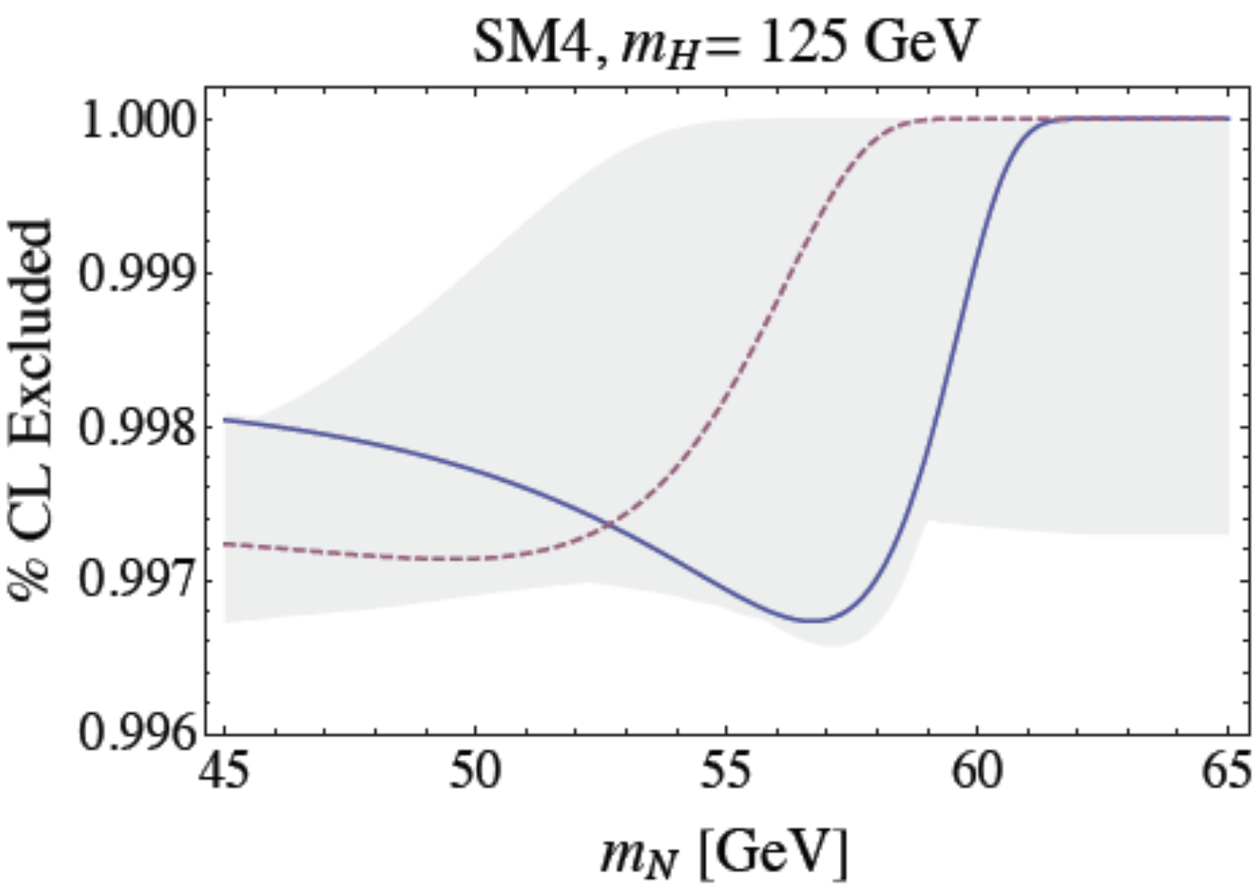




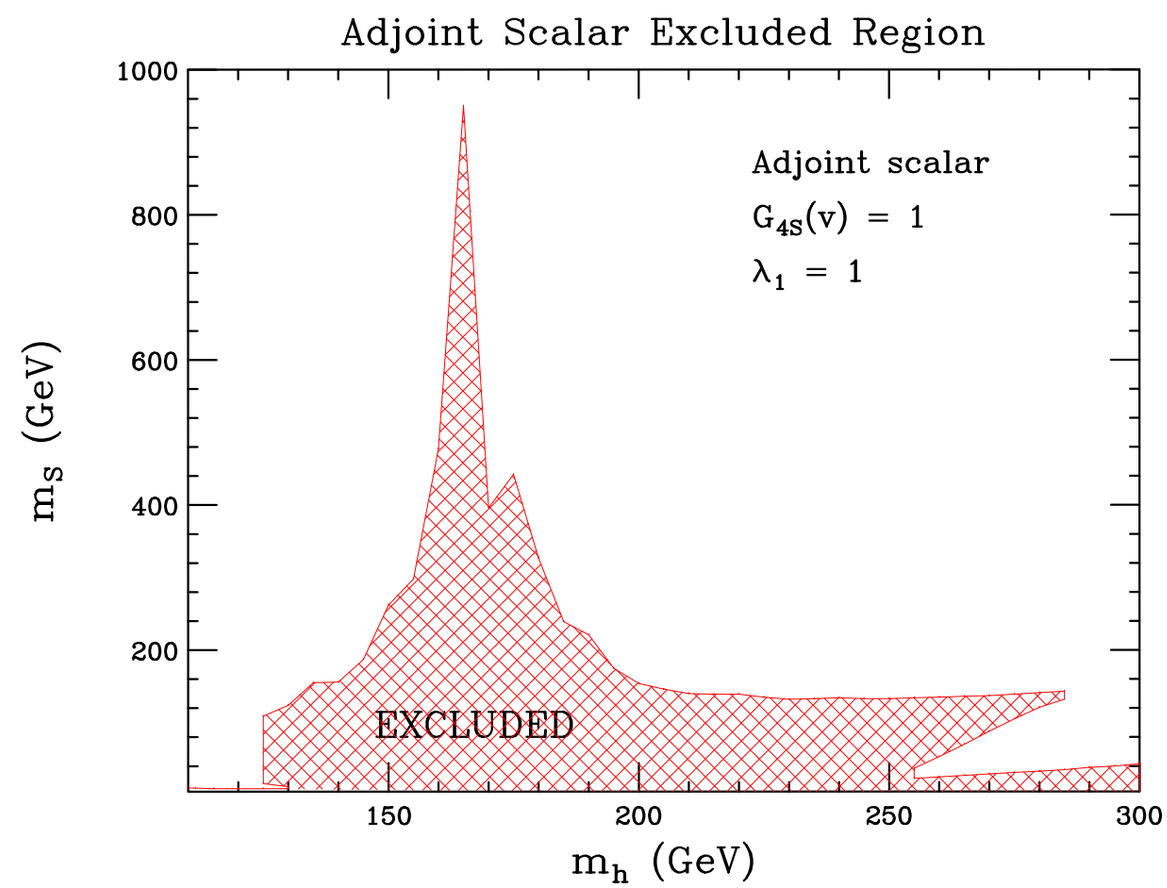
Discovery is the beginning

Narrowing down the possibilities

- Current limits already strongly constrain what SM extensions possible



Kuflik, Nir, Volansky 2012

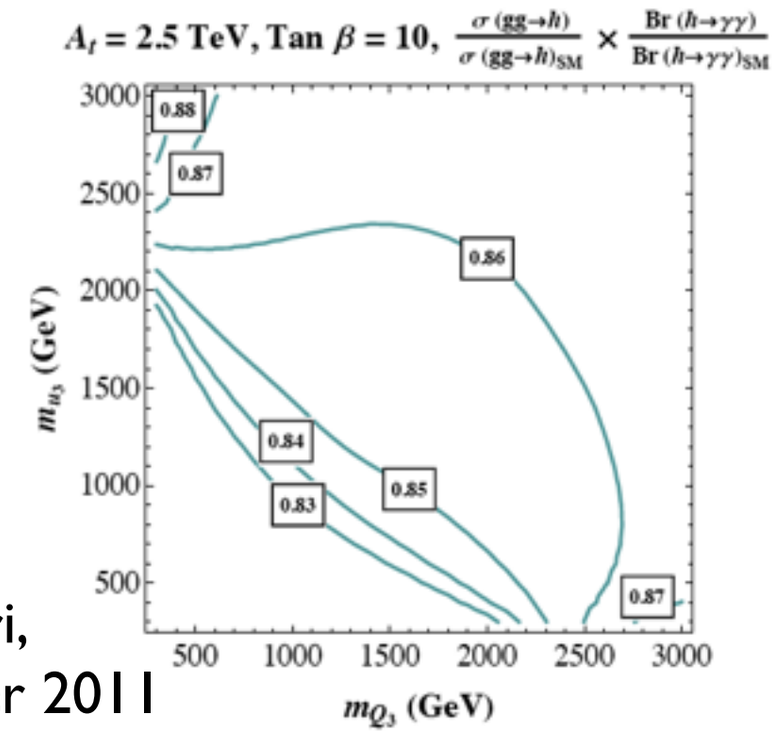


Boughezal 2011

Measuring Higgs properties

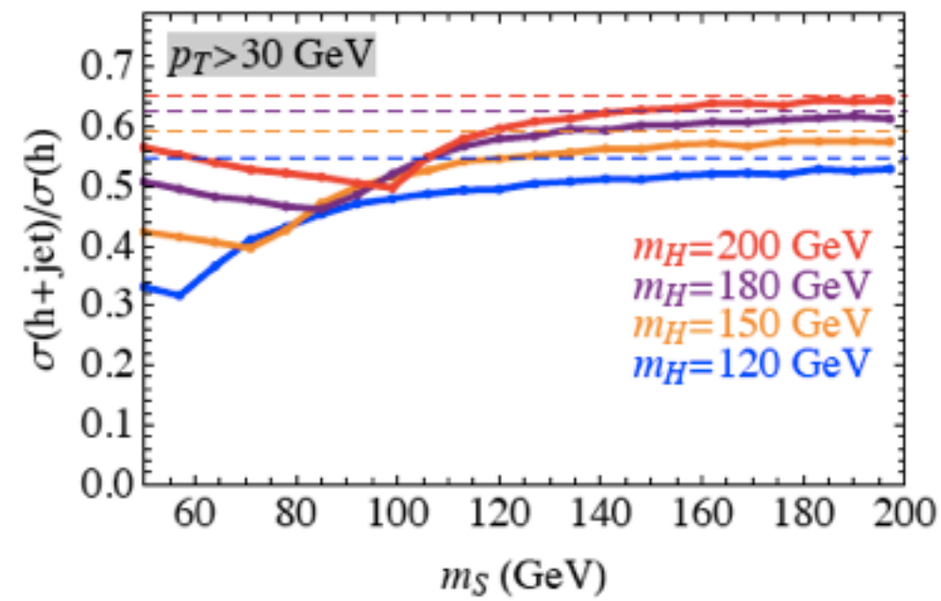
- To pin down the underlying model, what are we interested in measuring?

The rate:



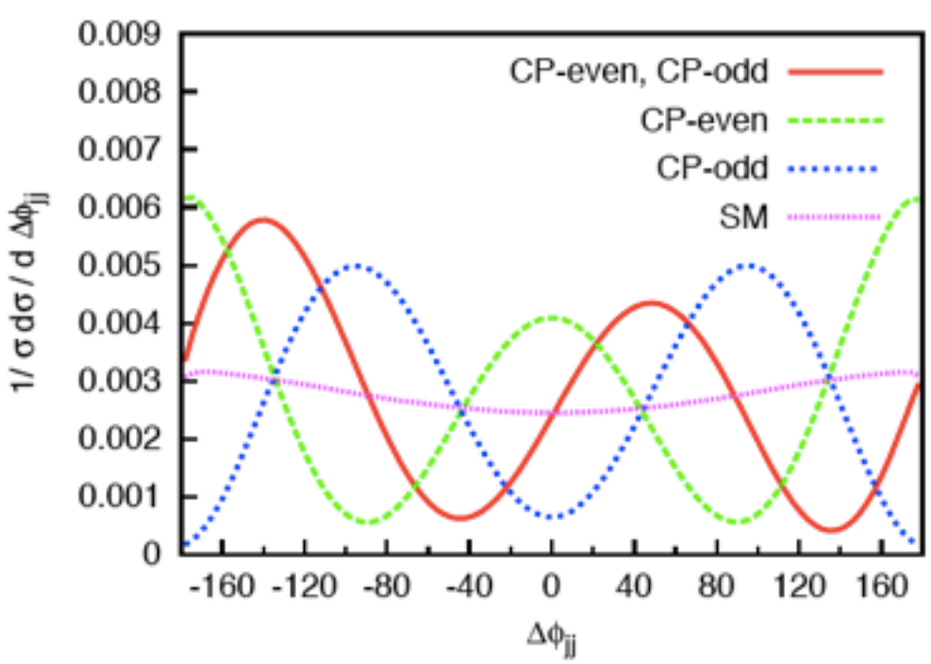
Carena, Gori, Shah, Wagner 2011

pT:



Arnesen, Rothstein, Zupan 2008

$$\mathcal{L} = -\frac{\kappa}{2} v H S^a S^a + \cdots .$$



Angular distributions, of either jets or decay products

Zeppenfeld et al. 2006

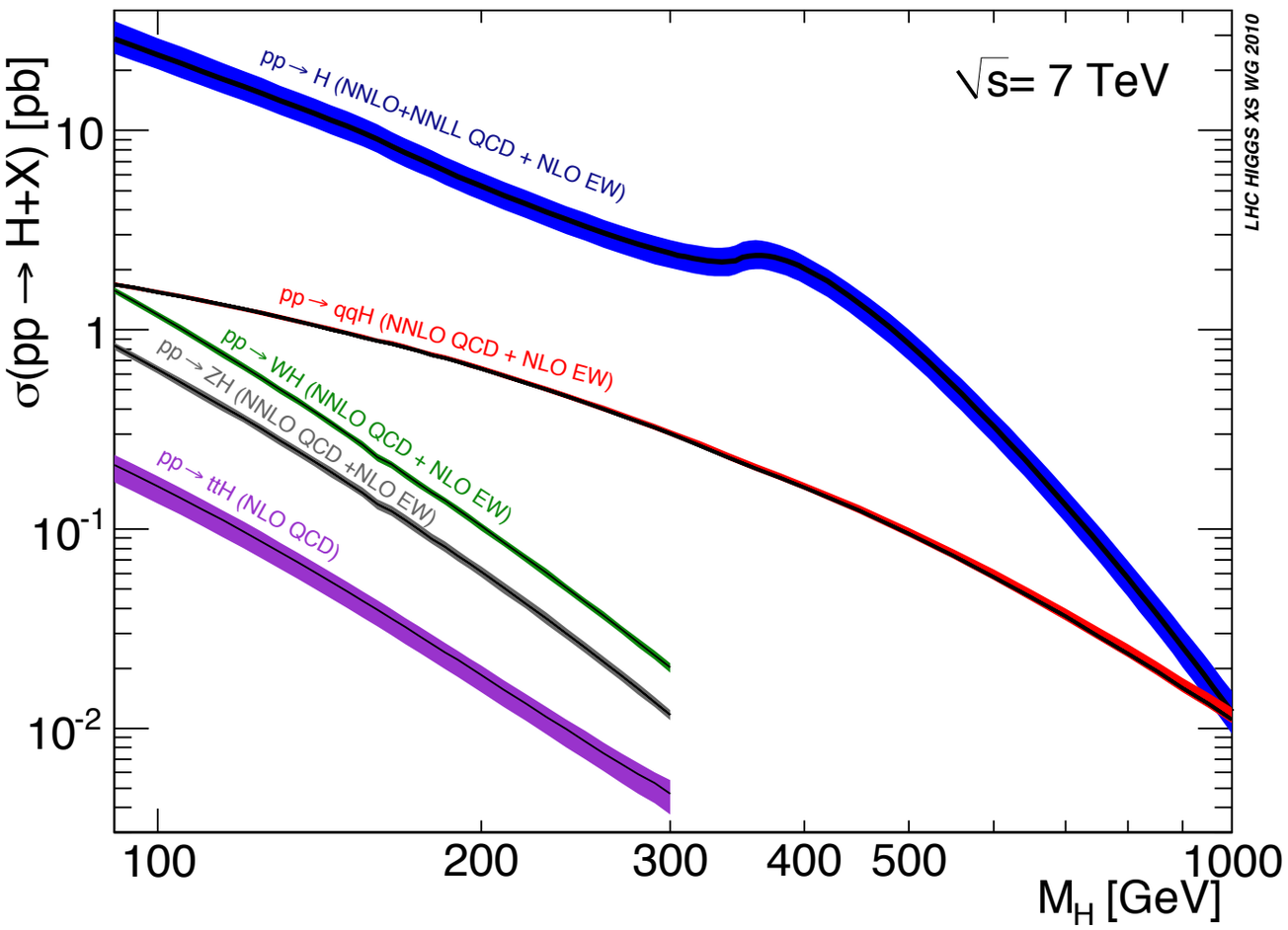
Effects of theory uncertainties

- CMS PAS HIG-11-024: (WW channel) " The overall signal efficiency uncertainty... is dominated by the theoretical uncertainty due to missing higher-order corrections"
- ATLAS CERN-PH-EP-2012-013 (γγ): uncertainties due to QCD scale variation one of the two dominant systematic effects (along with photon reconstruction+ID efficiency)

from G. Rolandi, HCP 2011

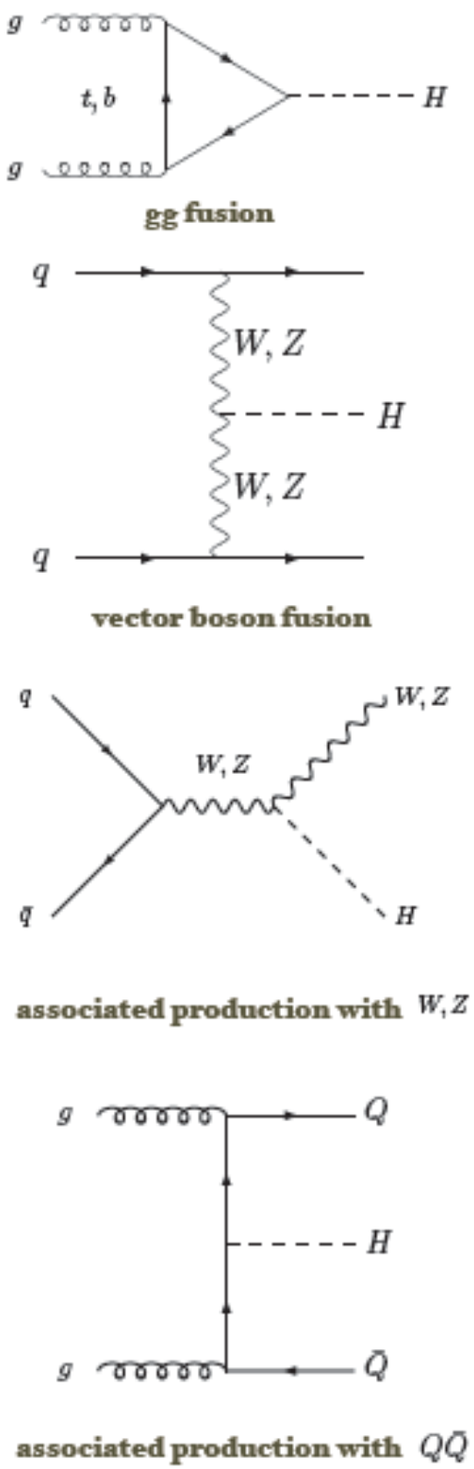
Source	Affected Processes	Typical uncertainty
PDFs+α_s (cross sections)	$gg \to H$, $t\bar{t}H$, $gg \to VV$	$\pm 8\%$
	VBF H, VH, VV@NLO	$\pm 4\%$
Higher-order uncertainties on cross sections	total inclusive $gg \to H$	$^{+12\%}_{-7\%}$
	inclusive "gg" $\to H + \geq 1$ jets	$\pm 20\%$
	inclusive "gg" $\to H + \geq 2$ jets	$\pm 20\%$ (NLO), $\pm 70\%$ (LO)
	VBF H	$\pm 1\%$
	associated VH	$\pm 1\%$
	$t\bar{t}H$	$^{+4\%}_{-10\%}$
	uncertainties specific to high mass Higgs boson, see Section 2.1	$\pm 30\%$
	V	$\pm 1\%$
	VV up to NLO	$\pm 5\%$
	$gg \to VV$	$\pm 30\%$
	$t\bar{t}$, incl. single top productions for simplicity	$\pm 6\%$
acceptance	acceptance for $H \to WW \to \ell\nu\ell\nu$ events	$\pm 2\%$
phenomenology	modelling of underlying event and parton showering	$\pm 10\%$
	fake lepton probability ($W + jets \to \ell\ell^{fake}$)	$\pm 40\%$
luminosities	ATLAS and CMS uncertainties on their luminosity measurements	$\pm 3.7\%$, $\pm 4.5\%$

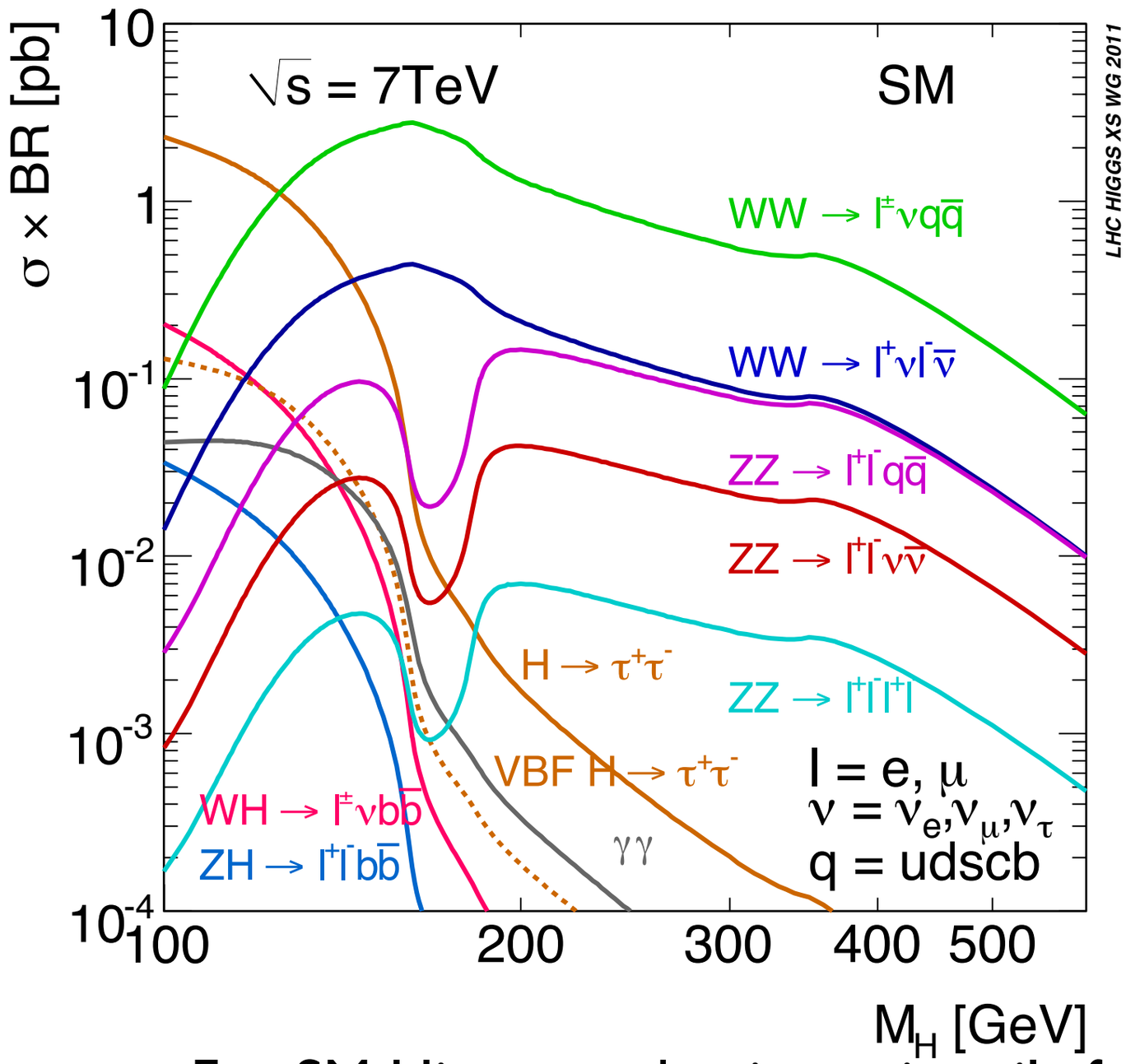
Outline



- Review the theory going into this result and others used in analyses
- Discuss available tools, some of the tricky points in the calculations
- Brief summary of VH, VBF
- Longer discussion of gluon-fusion and its backgrounds; much recent work and still some unresolved issues in this analysis

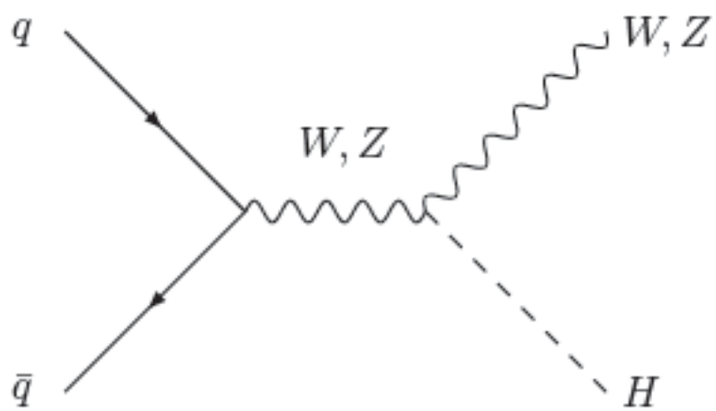
A phenomenological profile





For SM Higgs, production primarily from gg→H, with some contribution from VBF (VH for b Yukawa measurement)

Associated VH production

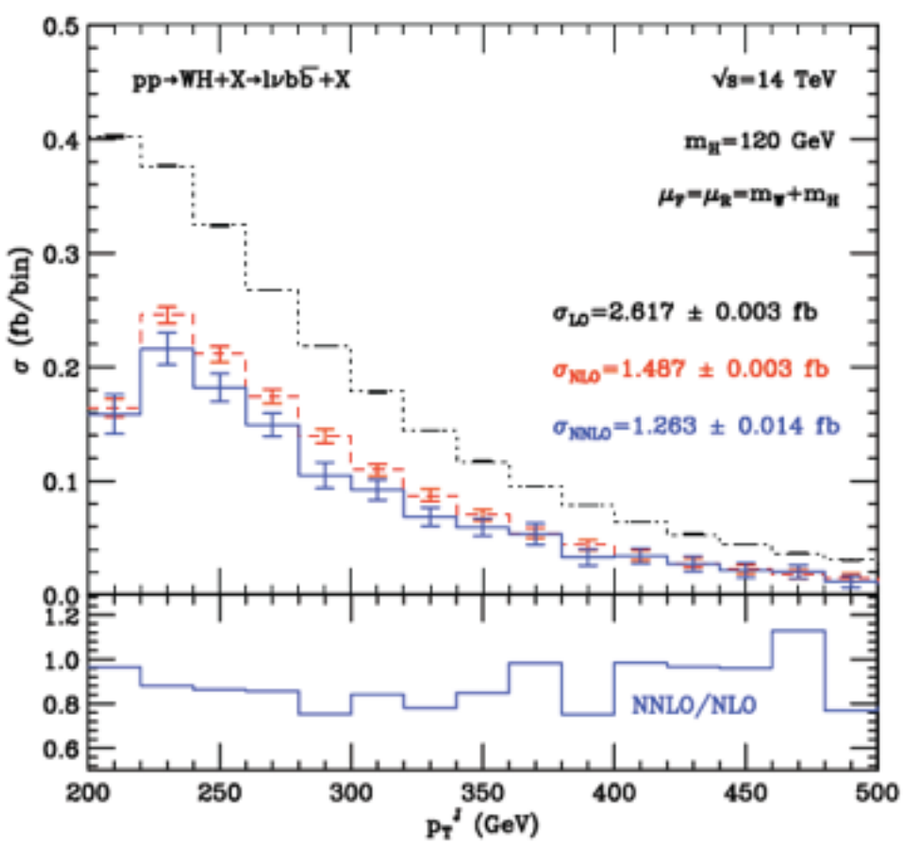


- With bbar decay of Higgs, most important low-mass mode at Tevatron
- At LHC, boosted analysis possible

Butterworth, Davison, Rubin, Salam 2008

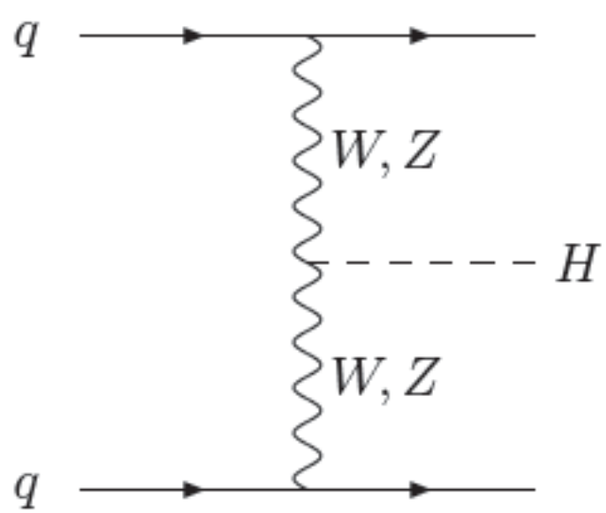
Inclusive NLO QCD: +30% (Han, Wllenbrock 1990), NLO EW: +5-10% (Ciccolini, Dittmaier, Denner 2003)

NNLO QCD: 1-2% in bulk of phase space (Ferrera, Grazzini, Tramontano 2011)



- Original boosted analysis vetoes additional jets to remove ttbar background
- Negative impact on stability of expansion (jet vetoes are theoretically dangerous!)
- Original paper mentions possibility of top-veto instead, likely safer from QCD perspective

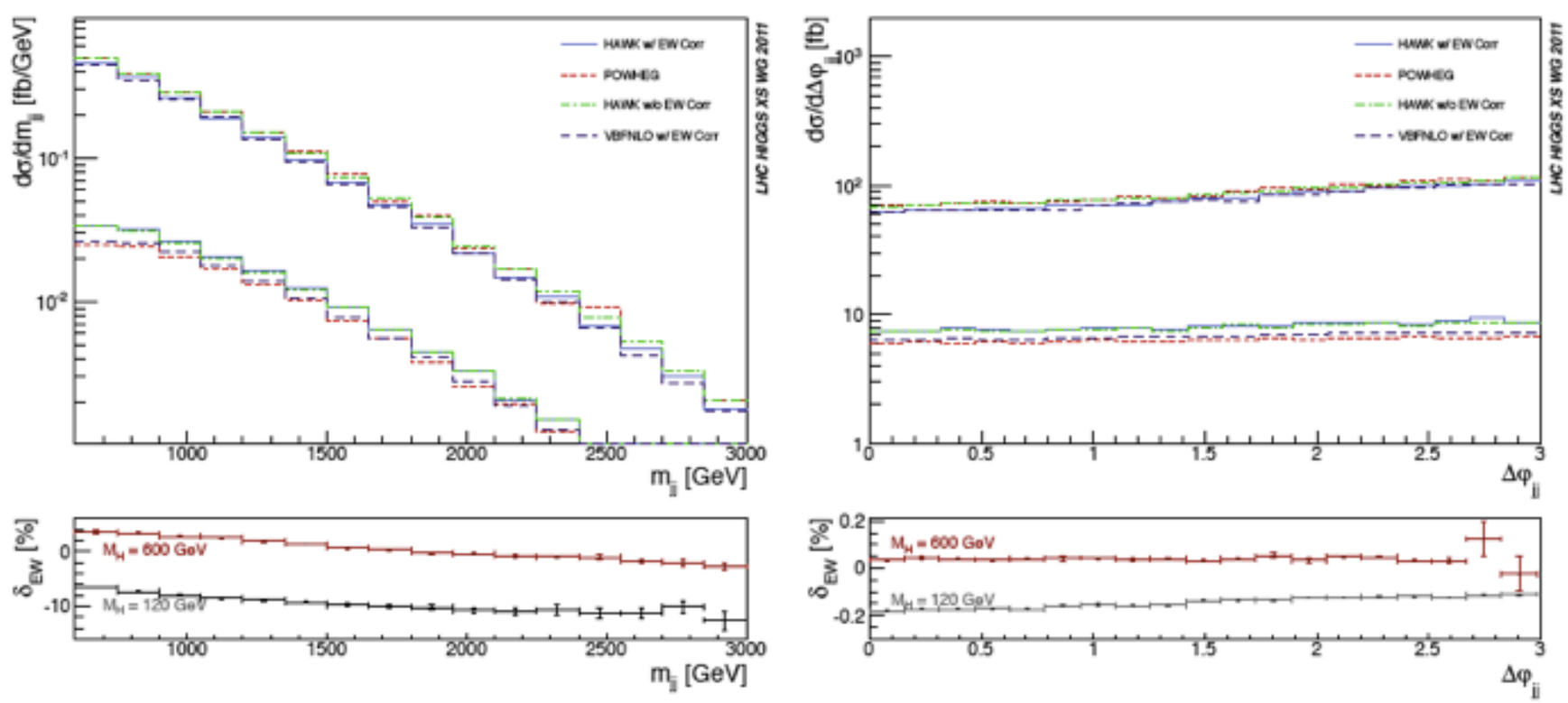
Vector boson fusion



- Important for the low-mass Higgs in both the ττ and γγ modes
- NLO QCD the same as for DIS, increase by 5-10%
- NLO QCD+EW in VBFNLO (Oleari, Zeppenfeld et al., partial EW) and HAWK (Denner, Dittmaier, Mueck, full EW)

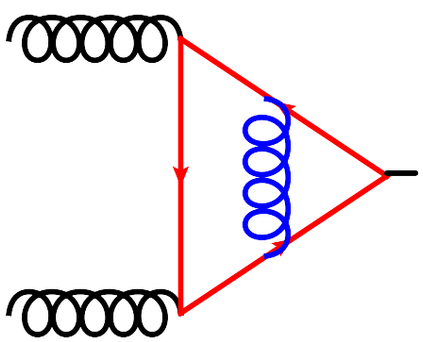
- DIS-like NNLO contributions also calculated, at the percent-level (Bolzoni, Maltoni, Moch, Zaro 2010)

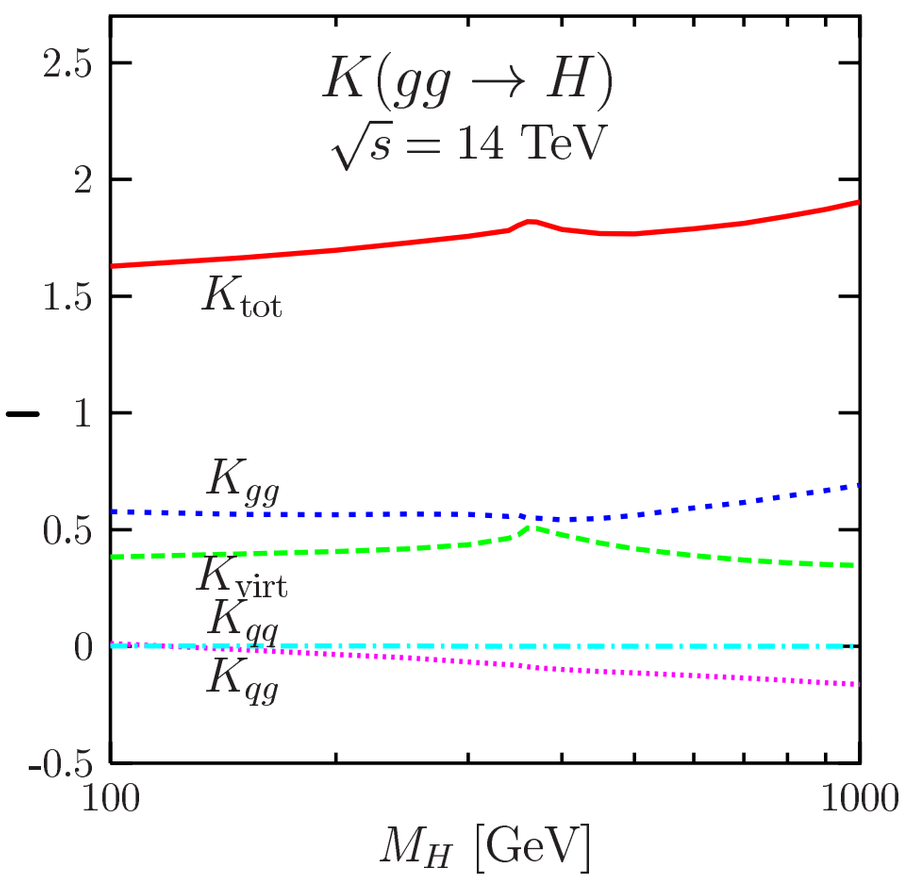
- Important distributions under theoretical control

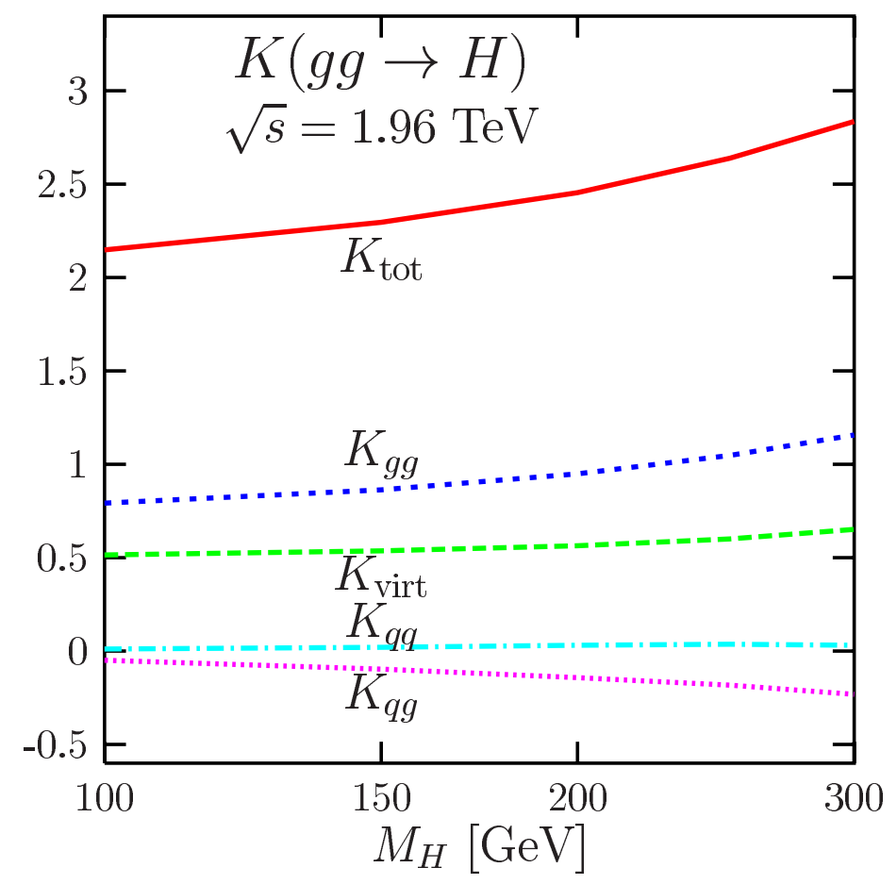


Gluon fusion

- Famously sensitive to large QCD corrections; difficult to calculate to requisite order in perturbation theory. The subject of enormous theoretical effort over the years.

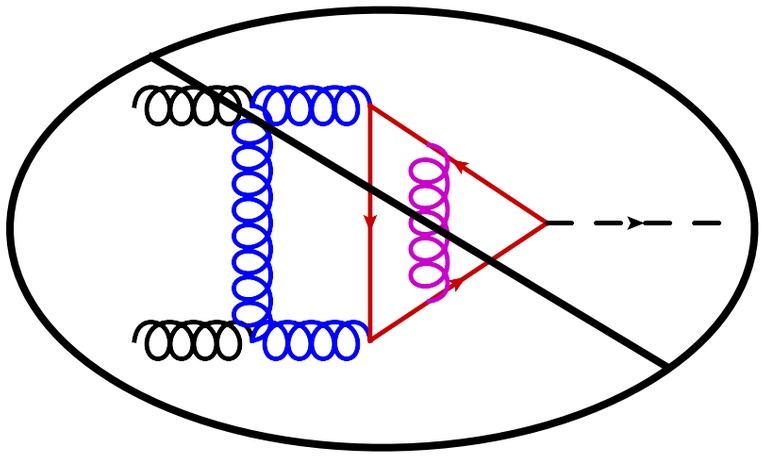






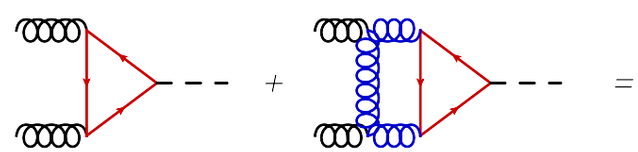
Dawson; Djouadi, Graudenz, Spira, Zerwas, 1991, 1995

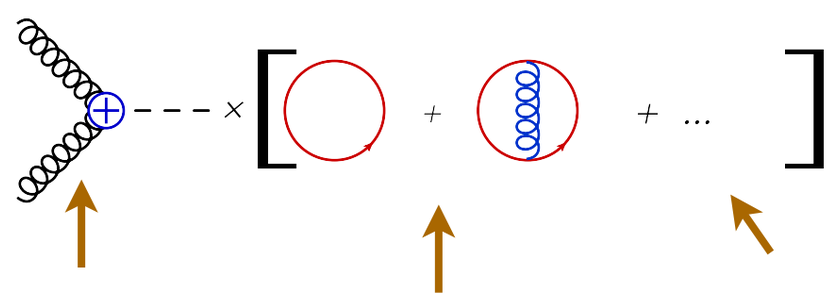
Effective interactions



- Getting the next terms requires new techniques
- *Effective field theory*: exploit heavy mass of virtual particles

Two scales:
M_{Higgs}, m_{top}



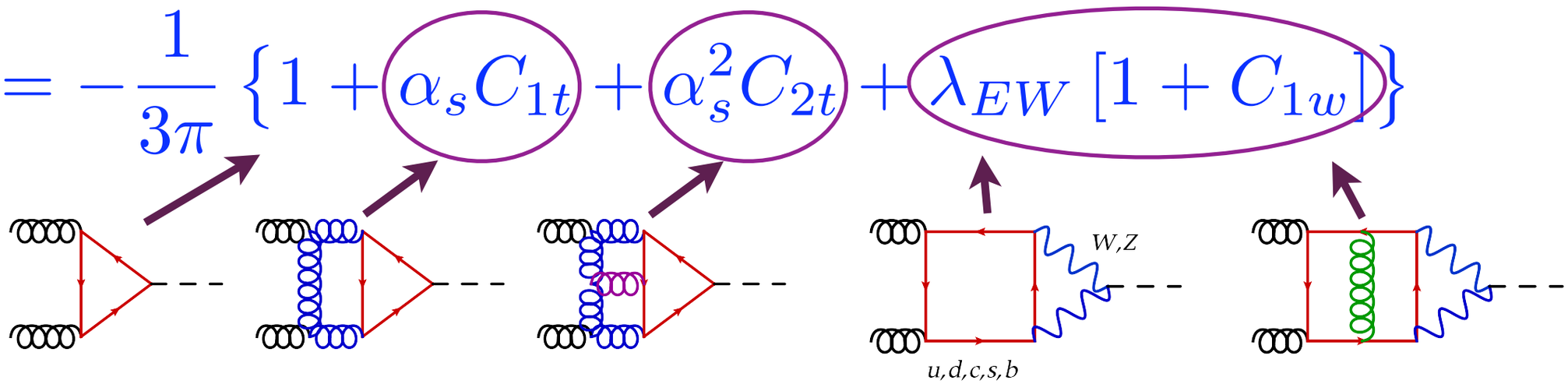


Only M_{Higgs} Only m_{top} $O(M^2_{Higgs}/4m^2_{top})$

$$\mathcal{L}_{eff} = \alpha_s \frac{C_1}{4v} H G^a_{\mu\nu} G^{\mu\nu}_a$$

The Wilson coefficient

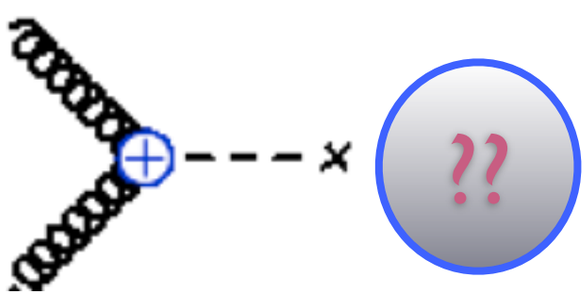
$$C_1 = -\frac{1}{3\pi}\left\{1 + \alpha_s C_{1t} + \alpha_s^2 C_{2t} + \lambda_{EW}\left[1 + C_{1w}\right]\right\}$$



Inami, Kubota, Okada 1982

Chetyrkin, Kniehl, Steinhauser 1997

EW terms: Actis, Passarino, Sturm, Uccirati 2008; Anastasiou, Boughezal, FP 2009



Clear separation of new physics effects into Wilson coefficient, QCD into corrections to the effective vertex

Unreasonably effective EFT

NLO in the EFT:

analytic continuation to time-like form factor

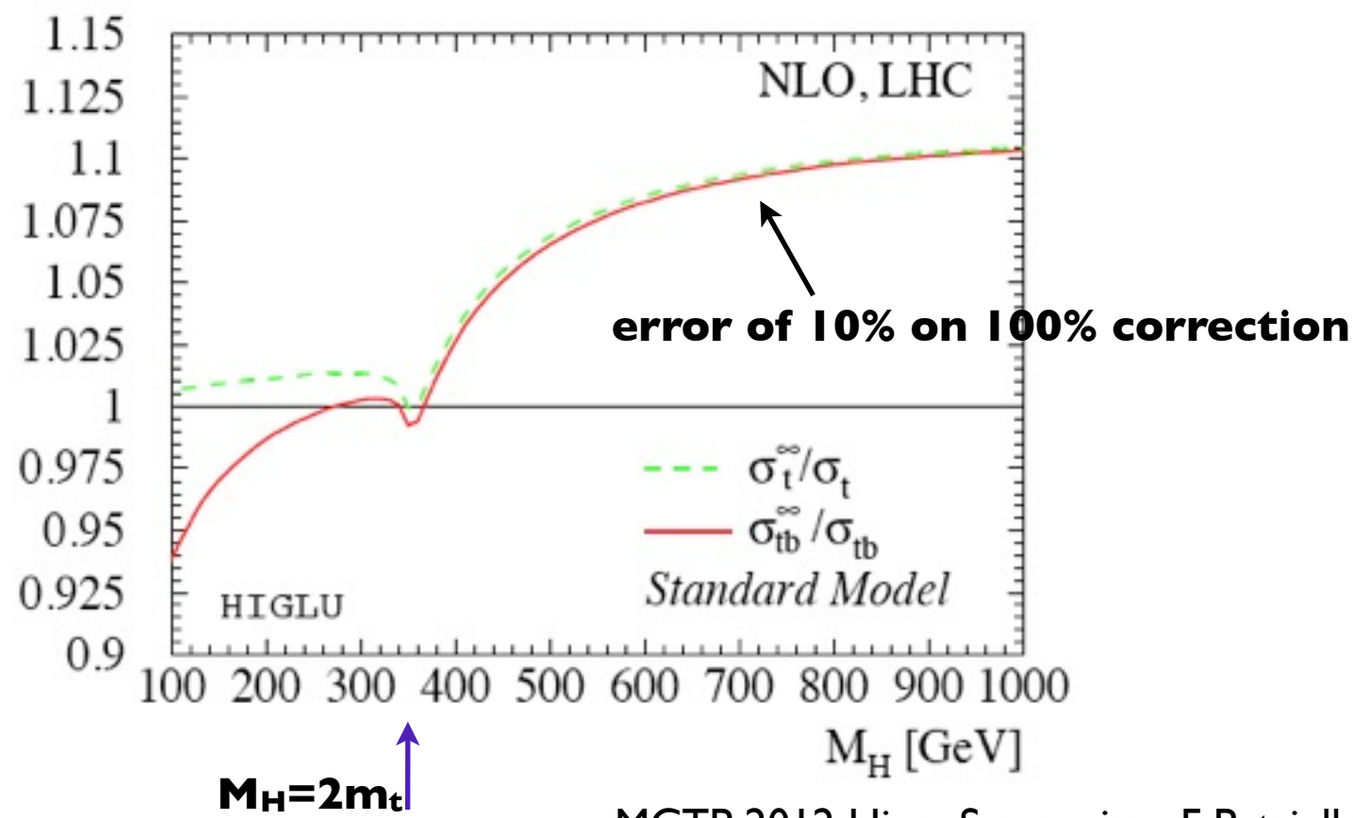
$z=M_H^2/(x_1x_2s)$

$$\Delta\sigma = \sigma_0\frac{\alpha_s}{\pi}\left\{\left(\frac{11}{2}+\pi^2\right)\delta(1-z)+12\left[\frac{\ln(1-z)}{1-z}\right]_+ - 12z(-z+z^2+2)\ln(1-z) -6\frac{(z^2+1-z)^2}{1-z}\ln(z)-\frac{11}{2}(1-z)^3\right\}$$

eikonal emission of soft gluons

Identical factors in full theory with $\sigma_0 \rightarrow \sigma_{LO,\text{ full theory}}$

$$\sigma_{NLO}^{approx} = \left(\frac{\sigma_{NLO}^{EFT}}{\sigma_{LO}^{EFT}}\right)\sigma_{LO}^{QCD}$$

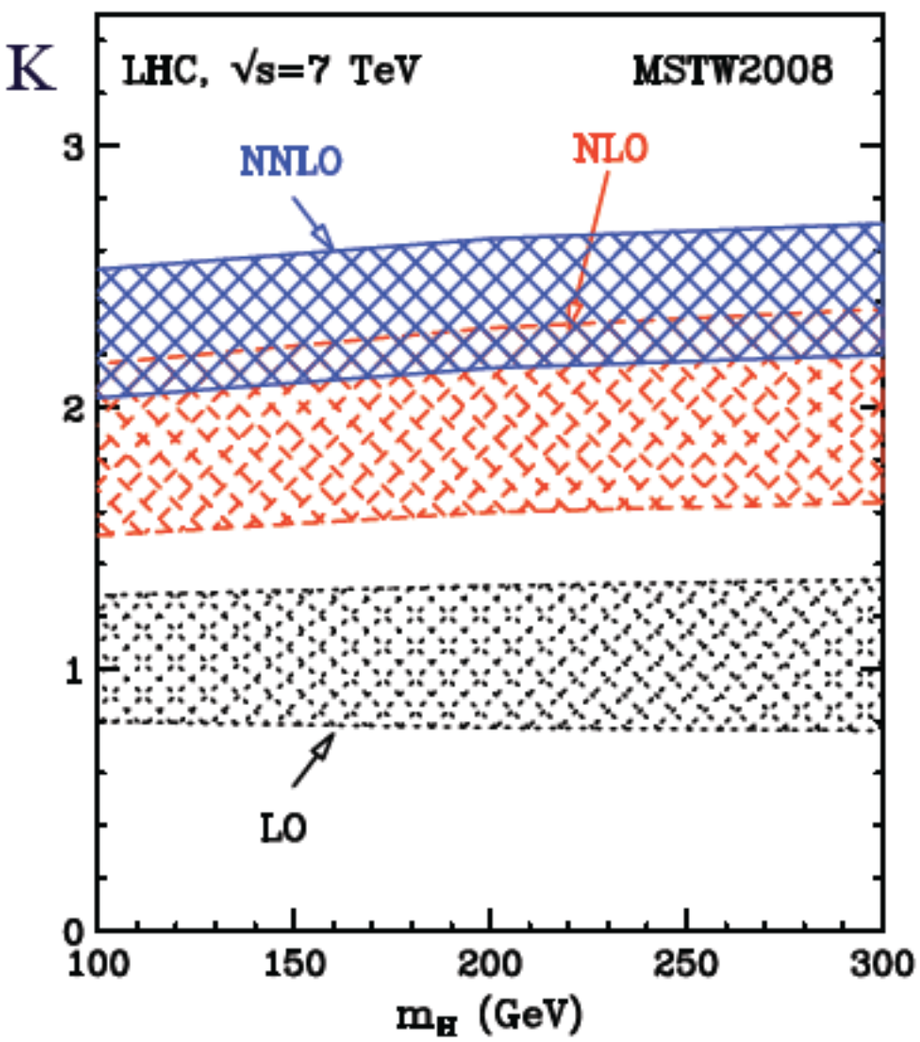


NNLO study of $1/m_t$ suppressed operators, matched to large s-hat limit, large indicates this persists

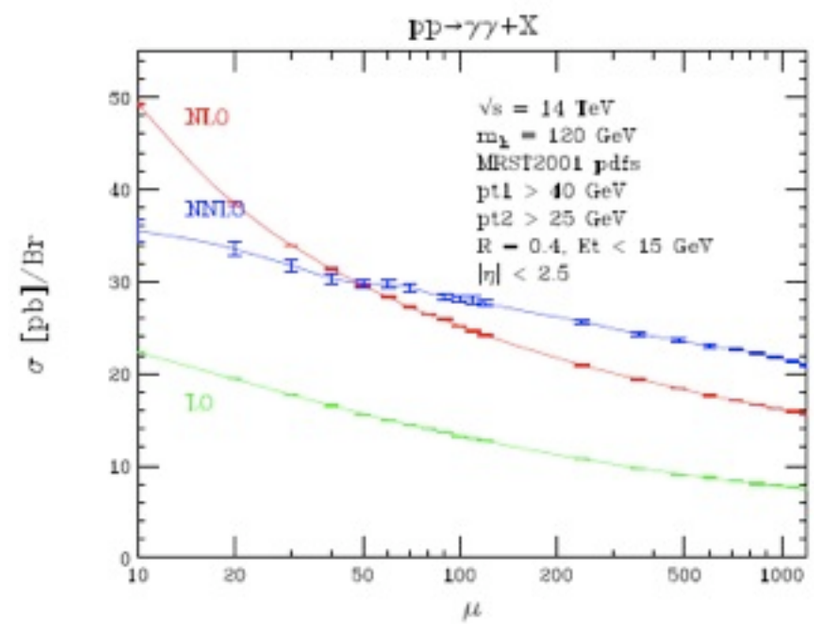
Harlander, Mantler, Marzani, Ozeren; Pak, Rogal, Steinhauser 2009

NNLO in the EFT

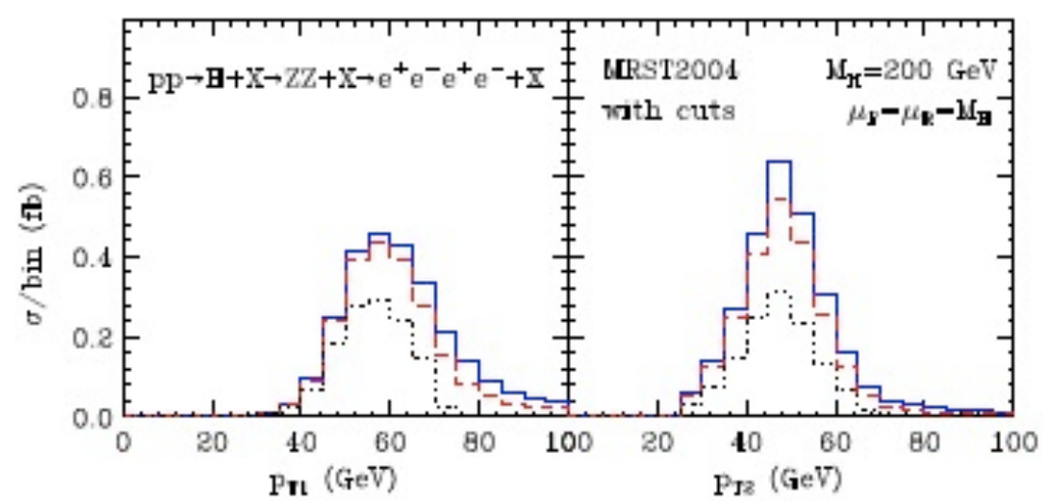
- Success of the EFT over almost entire interesting mass range motivates NNLO calculation



Harlander, Kilgore; Anastasiou, Melnikov; Ravindran, Smith, van Neerven 2002-2003



FEHiP: Anastasiou, Melnikov, FP 2005



HNNLO: Catani, Grazzini 2007-2008

Gluon-fusion: inclusive

Effects of soft-gluon resummation at Next-to-next-to leading logarithmic (NNLL) accuracy (about 6-15%)

S. Catani, D. De Florian, P. Nason, Grazzini (2003)

Partial N^3LO corrections known (considerably reduced scale dependence)

Moch, Vogt (2005)

Two-loop EW corrections are also known (effect is about O(5%))

U. Aglietti et al. (2004)
G. Degrassi, F. Maltoni (2004)
G. Passarino et al. (2008)

Mixed QCD-EW effects evaluated in EFT approach

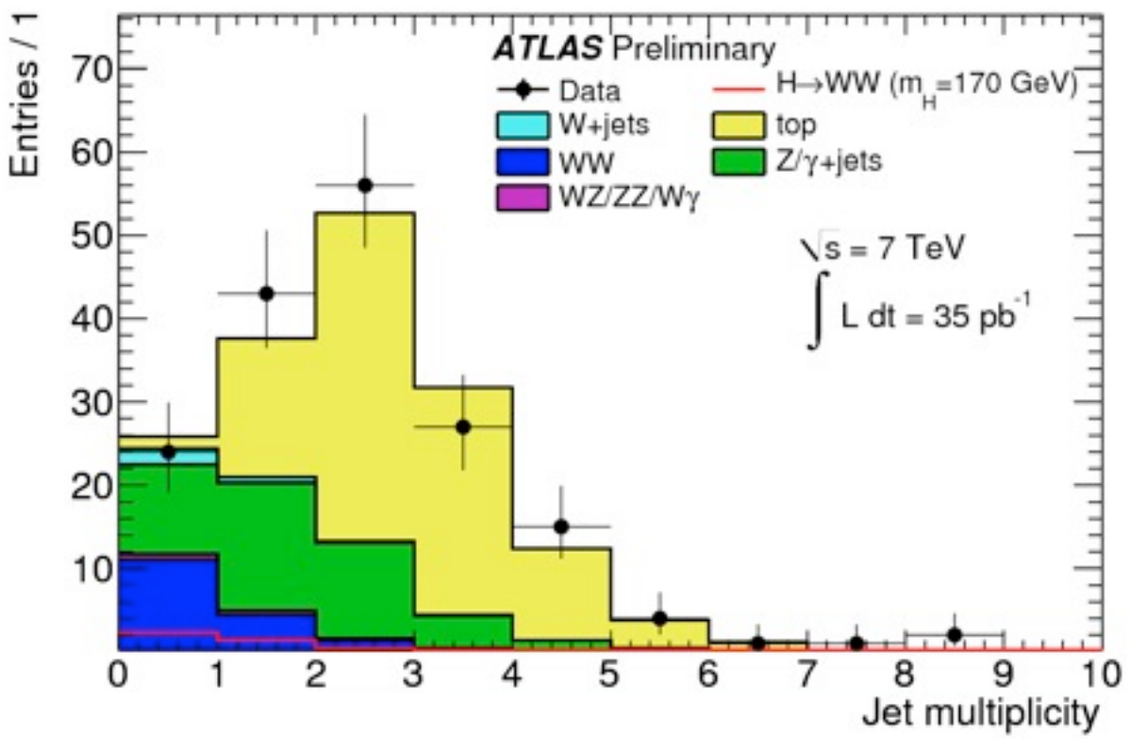
Anastasiou, Boughezal, FP (2008)

→ support "complete factorization": EW correction multiplies the full QCD corrected cross section

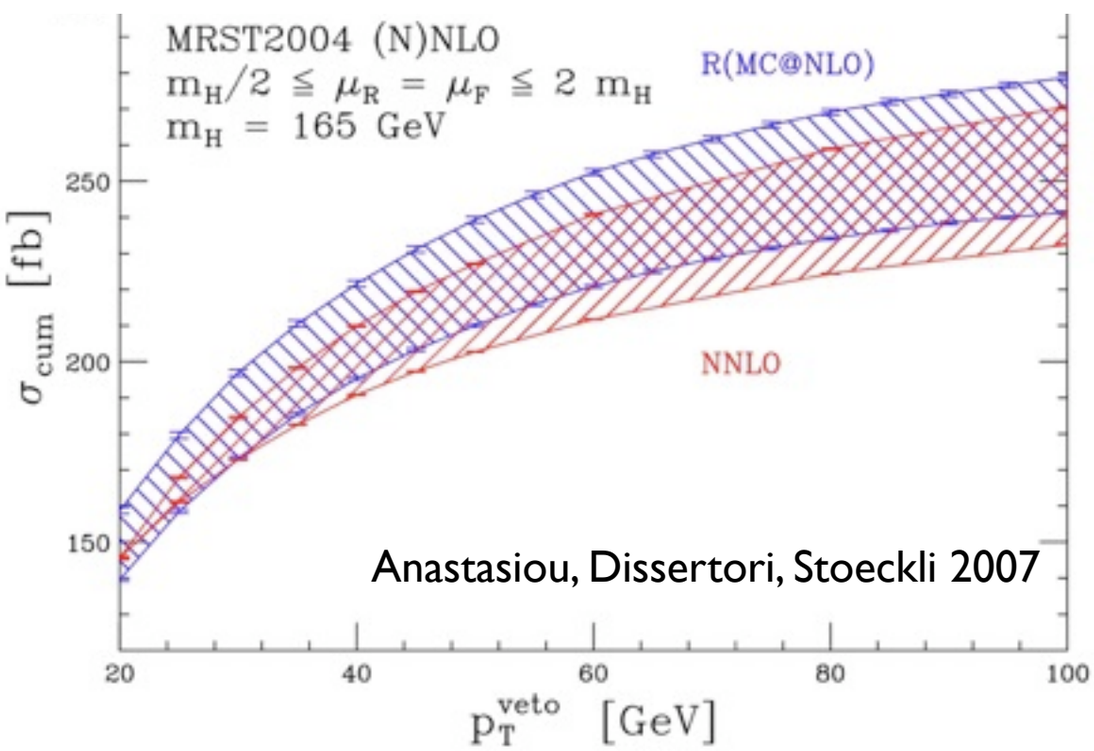
EW effects for real radiation (effect O(1%))

W.Keung, FP, (2009)

The jet-veto in gluon fusion



- Toughest cut from theoretical perspective is the jet veto
- Required in WW channel due to background composition
- 25-30 GeV jet cut envisioned; restriction of radiation leads to large logs



- Inclusive scale variation 10%; with a 25 GeV jet veto, 5-6%!
- Having $\Delta\sigma_{veto} < \Delta\sigma_{tot}$ doesn't seem correct; σ_{veto} has a more complicated structure and a larger expansion parameter, $\alpha_S \ln^2(m_H/p_{T,cut})$ rather than α_S

Cancellations

- Study of cross section structure (Stewart, Tackmann 2011)

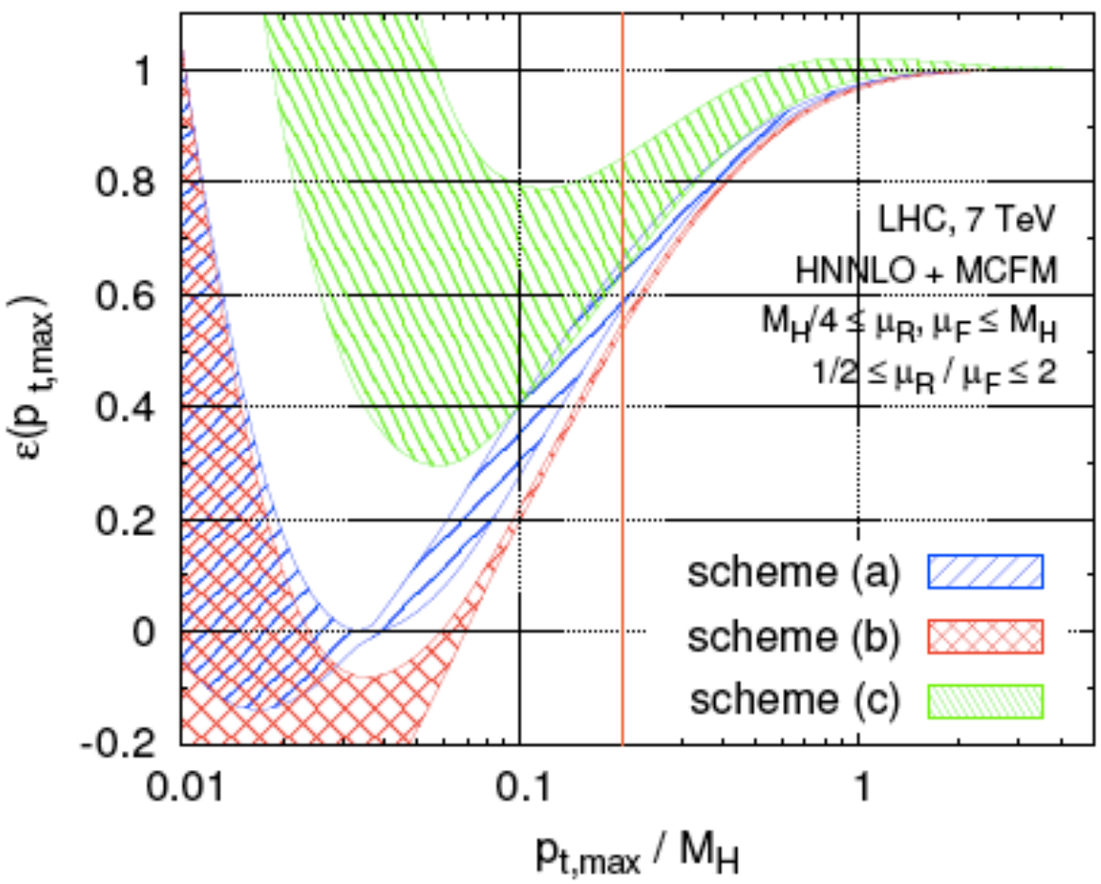
$$\sigma_0(p^{\rm cut}) = \sigma_{\rm total} - \sigma_{\geq 1}(p^{\rm cut})$$
$$\simeq \sigma_B\Big\{\big[1+\alpha_s+\alpha_s^2+\mathcal{O}(\alpha_s^3)\big] - \big[\alpha_s(L^2+L+1)+\alpha_s^2(L^4+L^3+L^2+L+1)+\mathcal{O}(\alpha_s^3 L^6)\big]\Big\}$$

$$\sigma_{\rm total} = (3.32\,{\rm pb})\big[1+9.5\,\alpha_s+35\,\alpha_s^2+\mathcal{O}(\alpha_s^3)\big]\,,$$
$$\sigma_{\geq 1}\big(p_T^{\rm jet}\geq 30\,{\rm GeV}, |\eta^{\rm jet}|\leq 3.0\big) = (3.32\,{\rm pb})\big[4.7\,\alpha_s+26\,\alpha_s^2+\mathcal{O}(\alpha_s^3)\big]\,.$$

- Accidental cancellation between large corrections to total cross section and logarithms, leading to reduced scale error. No reason to persist at higher orders

Explicit demonstration

- Further evidence: three ways of extending the calculation of the 0-jet event fraction that differ by $O(\alpha_S^3)$ w.r.t. leading order



Banfi, Salam, Zanderighi 2012

$$f_0^{(a)}(p_T^{\rm cut}) \equiv \frac{\Sigma^{(0)}(p_T^{\rm cut}) + \Sigma^{(1)}(p_T^{\rm cut}) + \Sigma^{(2)}(p_T^{\rm cut})}{\sigma^{(0)} + \sigma^{(1)} + \sigma^{(2)}}$$

$$f_0^{(b)}(p_T^{\rm cut}) = 1 - \frac{\sigma^{\rm NLO}_{\text{1-jet}}(p_T^{\rm cut})}{\sigma^{(0)} + \sigma^{(1)}} \,.$$

$$f_0^{(c)}(p_T^{\rm cut}) = 1 - \frac{\sigma^{\rm NLO}_{\text{1-jet}}(p_T^{\rm cut})}{\sigma^{(0)}} + \frac{\sigma^{(1)}}{(\sigma^{(0)})^2}\sigma^{\rm LO}_{\text{1-jet}}(p_T^{\rm cut})$$

- Gives results differing from 0.5 to 0.85 for a 30 GeV veto

Error prescription

- A solution using fixed-order results pointed out (Stewart, Tackmann 2011)

- In the limit of $\ln(m_H/p_{T,cut})$ large, σ_{tot} and $\sigma_{\geq 1}$ have independent expansions
- Gives expected result, that $\Delta\sigma_{veto} > \Delta\sigma_{tot}$
- The current prescription used in LHC analyses (phrased in terms of jet fractions)

First consider *inclusive* jet cross sections

$$\sigma_{\rm total},\ \sigma_{\geq 1},\ \sigma_{\geq 2} \quad \Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\rm total} & 0 & 0 \\ 0 & \Delta^2_{\geq 1} & 0 \\ 0 & 0 & \Delta^2_{\geq 2} \end{pmatrix}$$

Transform to *exclusive* jet cross sections

$$\sigma_0 = \sigma_{\rm total} - \sigma_{\geq 1}\,, \qquad \sigma_1 = \sigma_{\geq 1} - \sigma_{\geq 2}\,, \qquad \sigma_{\geq 2}$$

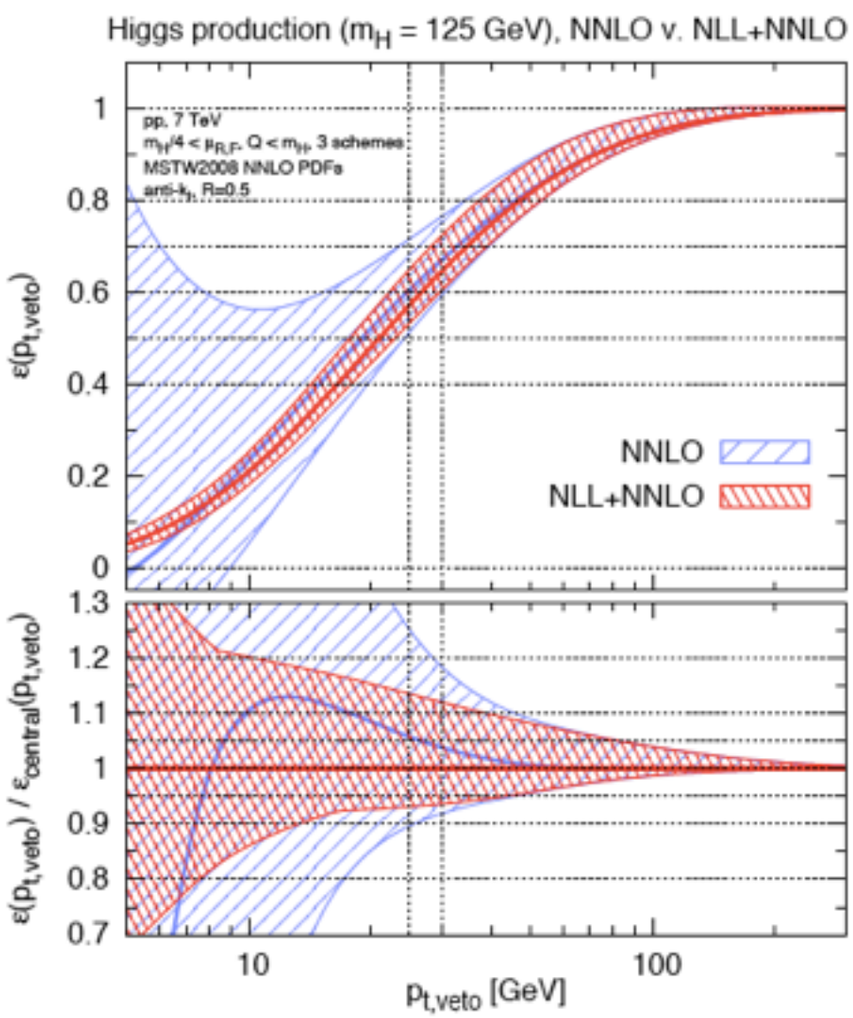
$$\Rightarrow \quad C = \begin{pmatrix} \Delta^2_{\rm total} + \Delta^2_{\geq 1} & -\Delta^2_{\geq 1} & 0 \\ \Delta^2_{\geq 1} & \Delta^2_{\geq 1} + \Delta^2_{\geq 2} & -\Delta^2_{\geq 2} \\ 0 & -\Delta^2_{\geq 1} & \Delta^2_{\geq 2} \end{pmatrix}$$

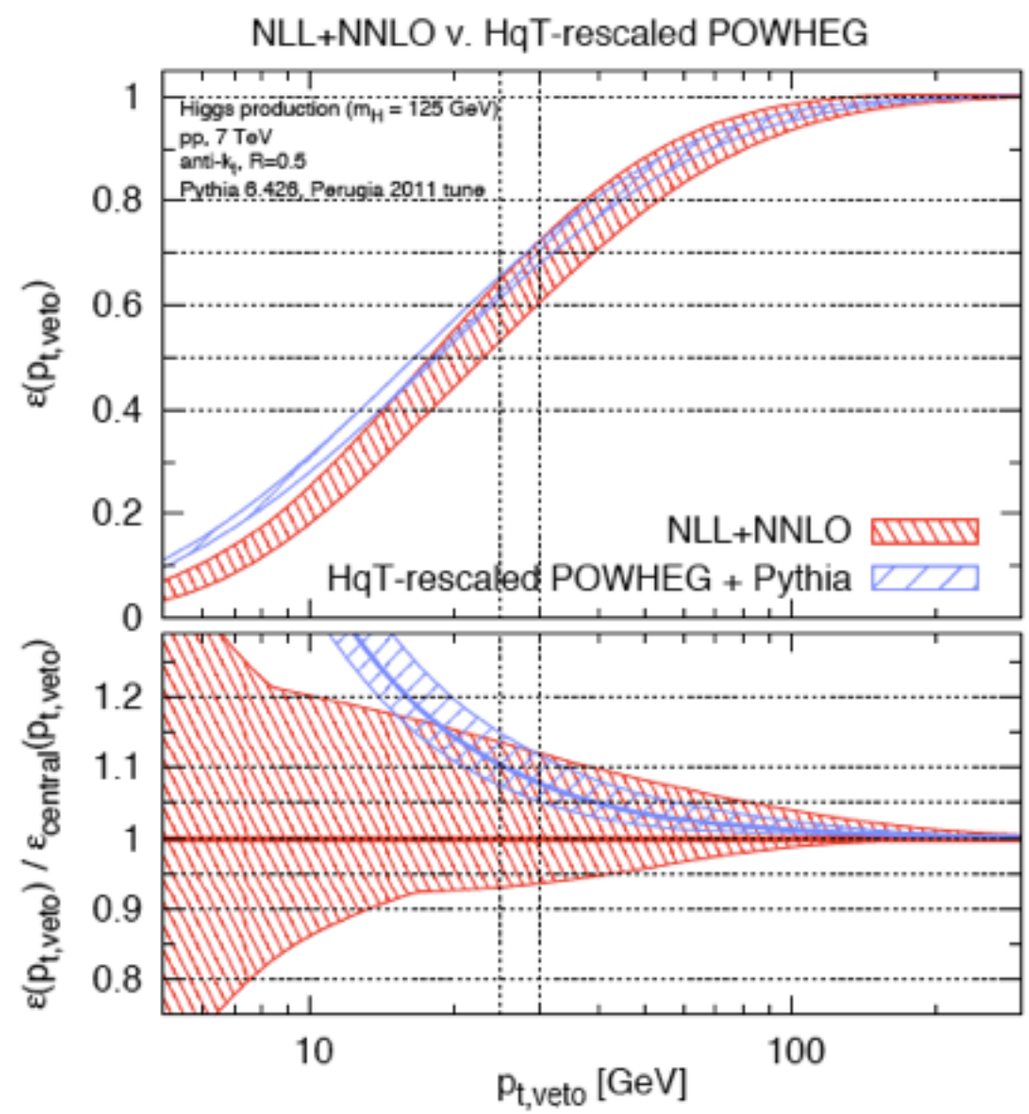
cut	$\frac{\Delta\sigma_{\rm total}}{\sigma_{\rm total}}$	$\frac{\Delta\sigma_{\geq 1}}{\sigma_{\geq 1}}$	$\frac{\Delta\sigma_{\geq 2}}{\sigma_{\geq 2}}$	$\frac{\Delta\sigma_0}{\sigma_0}$	$\frac{\Delta\sigma_1}{\sigma_1}$
$p_T^{\rm cut} = 30\,{\rm GeV},\ \eta^{\rm cut} = 3$	10%	21%	45%	17%	29%

Jet-veto resummed

- Very recent NLL resummation of the jet-vetoed cross section

Banfi, Salam, Zanderighi 2012



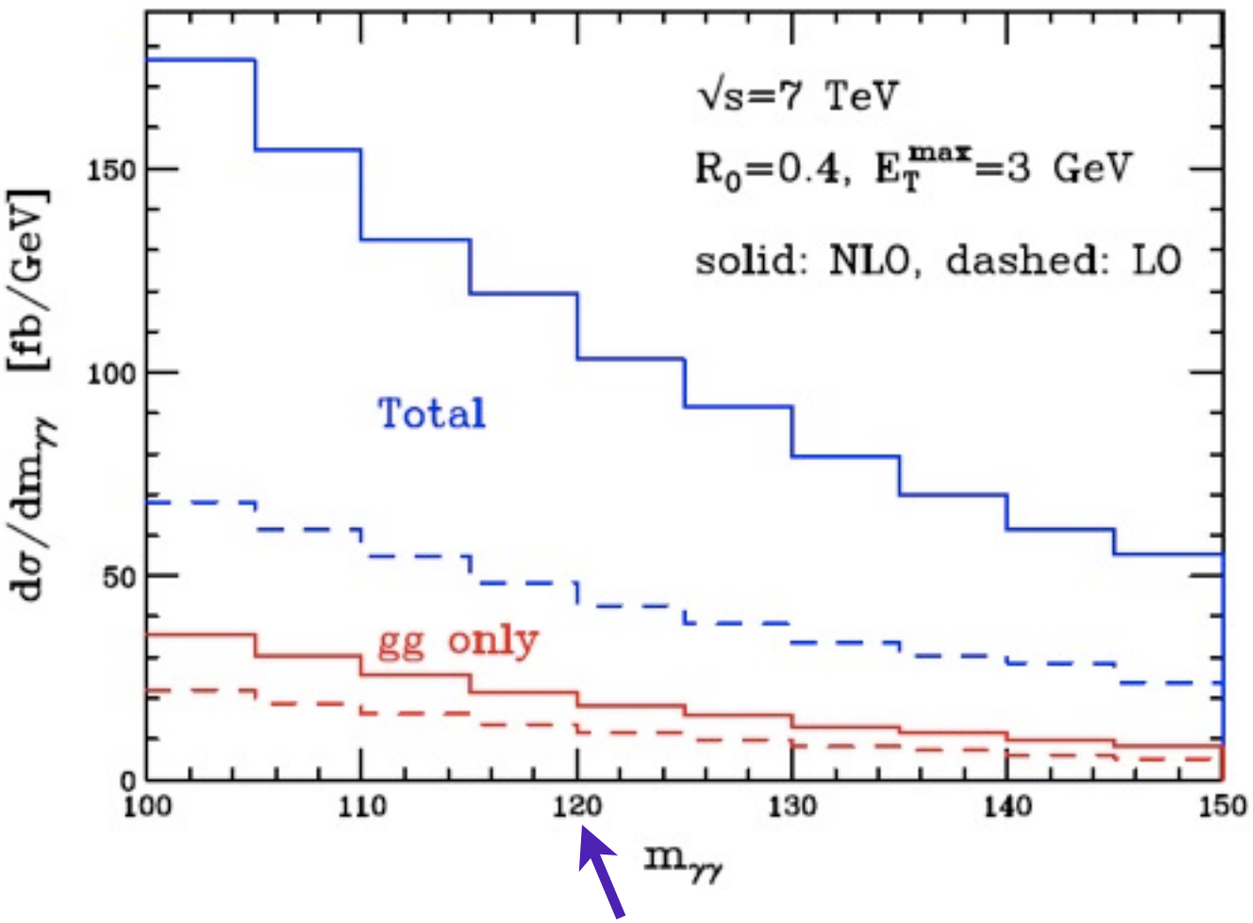


Numbers not much reduced from those estimated using previous prescription (error defined here as envelope of methods a, b, c from before)

Can't use HqT reweighted POWHEG to estimate uncertainty! Central also value off by 10-15%.

Di-photon Higgs background

- Major interest in di-boson production as background to Higgs



$p_T^{\gamma 1} > 40$ GeV , $p_T^{\gamma 2} > 25$ GeV , $|\eta_{\gamma_i}| < 2.5$

from MCFM: Campbell, Ellis, Williams 2011

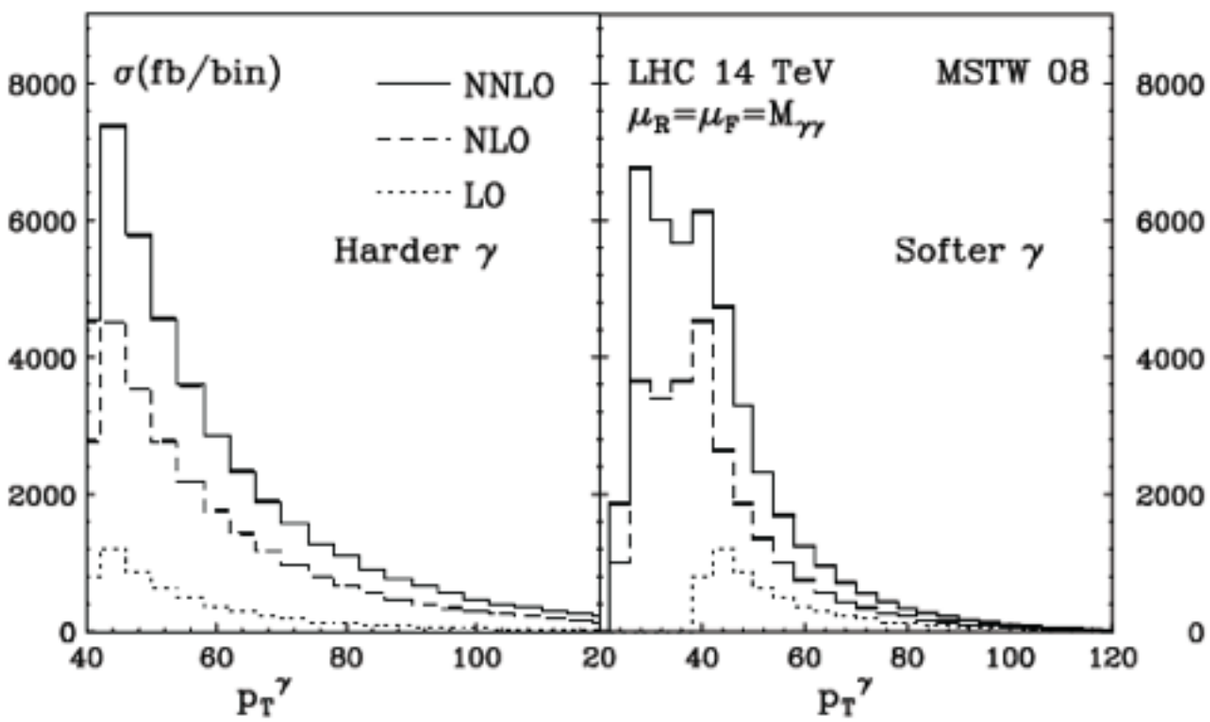
$\sqrt{s}$ [TeV]	$\sigma^{LO}(\gamma\gamma)$ [pb]	$\sigma^{NLO}(\gamma\gamma)$ [pb]
7	35.98(0)	$47.0(1)^{+5\%}_{-6\%}$

$p_T^{\gamma} > 25$ GeV , $|\eta_\gamma| < 5$

- 'Staggered' momentum cuts change K=1.3→3
- At LO, $p_{T1}=p_{T2}$, cut effectively 40 GeV
- Region between 25-40 GeV first opens at NLO, leading to large corrections
- Are the staggered cuts experimentally necessary? They complicate QCD background predictions

Di-photon Higgs background

- Major interest in di-boson production as background to Higgs



- New result at NNLO: an additional 30% increase

Catani, Cieri, de Florian,Ferrera, Grazzini 2011

$\sqrt{s}$ [TeV]	$\sigma^{LO}(\gamma\gamma)$ [pb]	$\sigma^{NLO}(\gamma\gamma)$ [pb]
7	35.98(0)	$47.0(1)^{+5\%}_{-6\%}$

$$p_T^\gamma > 25 \text{ GeV}, \quad |\eta_\gamma| < 5$$

- 'Staggered' momentum cuts change K=1.3→3
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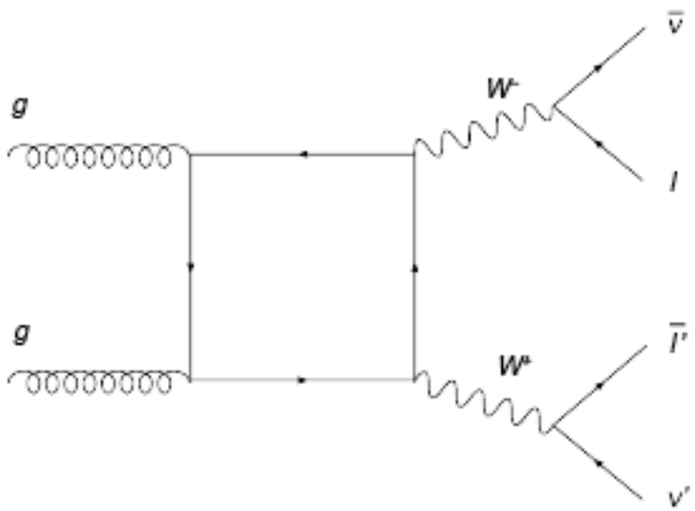
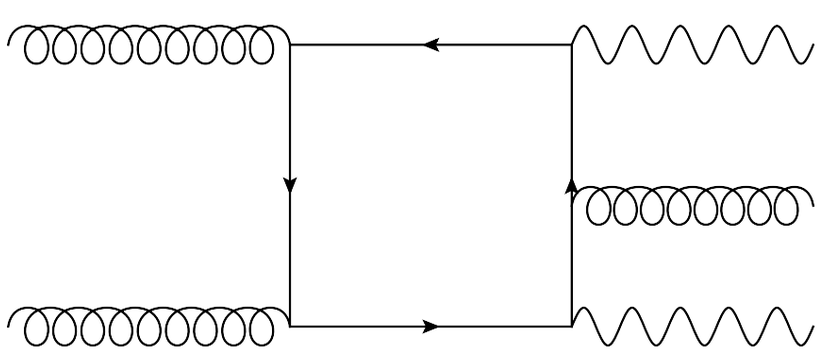
gg→VV(g) background



Binoth, Ciccolini, Kauer, Kraemer 2006

- Formally NNLO, but enhanced by both large gluon luminosity and experimental cuts ($\Delta\varphi_{ll}$ looks like Higgs signal)

$\sigma(pp \to W^*W^* \to \ell\bar{\nu}\bar{\ell'}\nu')$ [fb], LHC					
	gg	$q\bar{q}$		$\frac{\sigma_{\rm NLO}}{\sigma_{\rm LO}}$	$\frac{\sigma_{\rm NLO+gg}}{\sigma_{\rm NLO}}$
		LO	NLO		
σ_{tot}	60.00(1)	875.8(1)	1373(1)	1.57	1.04
σ_{std}	29.798(6)	270.5(1)	491.8(1)	1.82	1.06
σ_{bkg}	1.4153(3)	4.583(2)	4.79(3)	1.05	1.30



- Relevant for the 1-jet bin; not known even at LO!
- Result coming soon... M. Schulze et al.

Conclusions

- We will soon move beyond the discovery stage of the Higgs and begin analyzing the newest discovered particle
- SM predictions for the Higgs are the benchmark against which all other possibilities will be compared.
- After years of work by a large community, predictions under fairly good control
- The few lingering issues occur in the interplay of experimental cuts with QCD... a good idea to discuss the intended cuts with theorists (in general, jet vetoes are bad)
- Many tools exist; recent new ones for both signal and background, and some poised to hit the market soon
- We're prepared for the next stage after discovery!

Jet fractions

- Can be easily translated to be in terms of fractions of events in 0, 1, 2 jet bins

$$\delta(f_0)^2 = \left(\frac{1}{f_0} - 1\right)^2 (\delta^2_{\text{total}} + \delta^2_{\geq 1}) \,,$$

$$\delta(f_1)^2 = \delta^2_{\text{total}} + \left(\frac{1-f_0}{f_1}\right)^2 \delta^2_{\geq 1} + \left(\frac{1-f_0}{f_1} - 1\right)^2 \delta^2_{\geq 2} \,,$$

$$\rho(f_0, \sigma_{\text{total}}) = \left[1 + \frac{\delta^2_{\geq 1}}{\delta^2_{\text{total}}}\right]^{-1/2} \,,$$

$$\rho(f_1, \sigma_{\text{total}}) = -\frac{\delta_{\text{total}}}{\delta(f_1)} \,,$$

$$\rho(f_0, f_1) = -\left(1 + \frac{1-f_0}{f_1}\frac{\delta^2_{\geq 1}}{\delta^2_{\text{total}}}\right)\left(\frac{1}{f_0} - 1\right)\frac{\delta^2_{\text{total}}}{\delta(f_0)\delta(f_1)} \,.$$