Open theoretical issues in Higgs production

Frank Petriello

Confronting Theory with Experiment

November 18, 2011

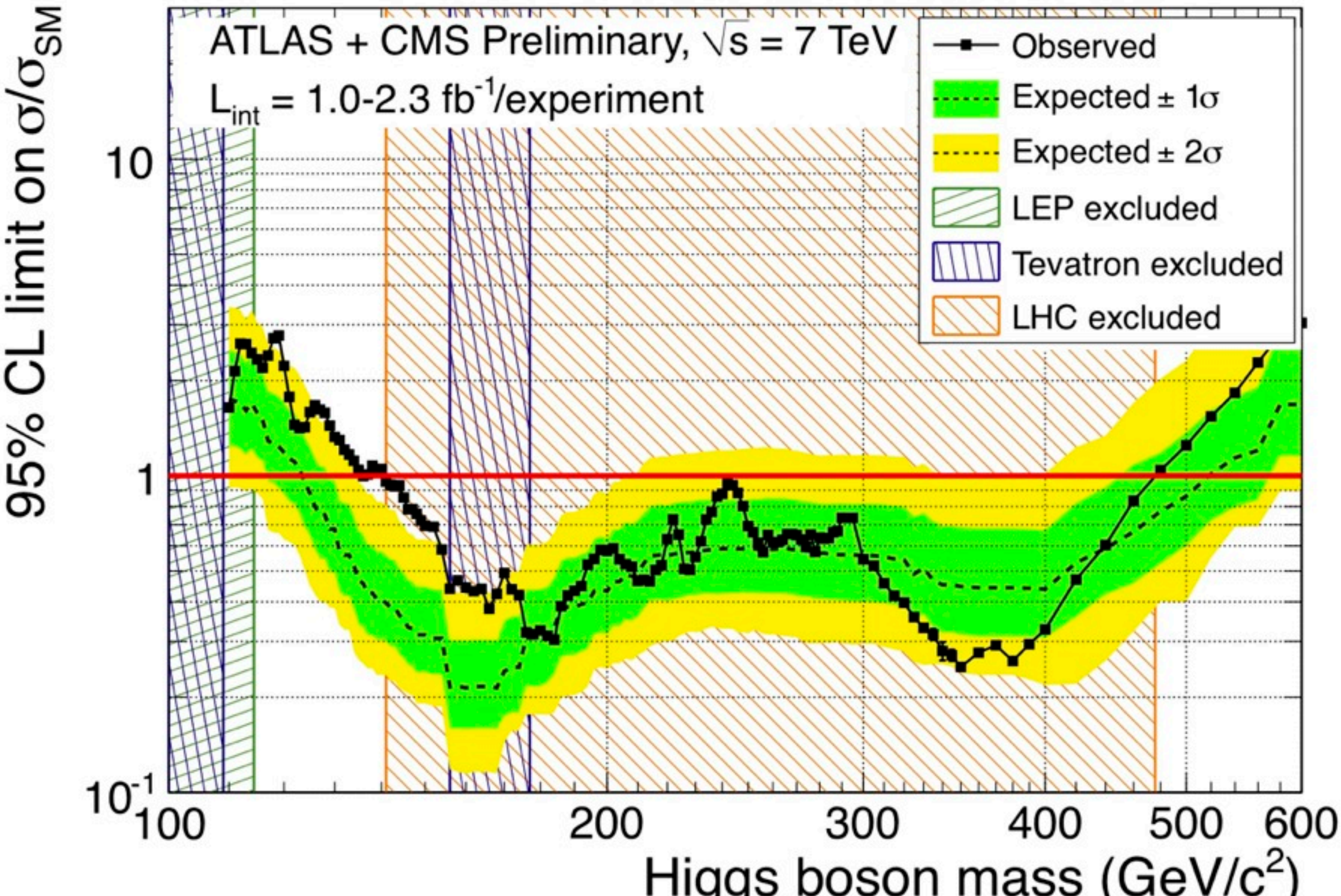
NORTHWESTERN UNIVERSITY

Argonne NATIONAL LABORATORY

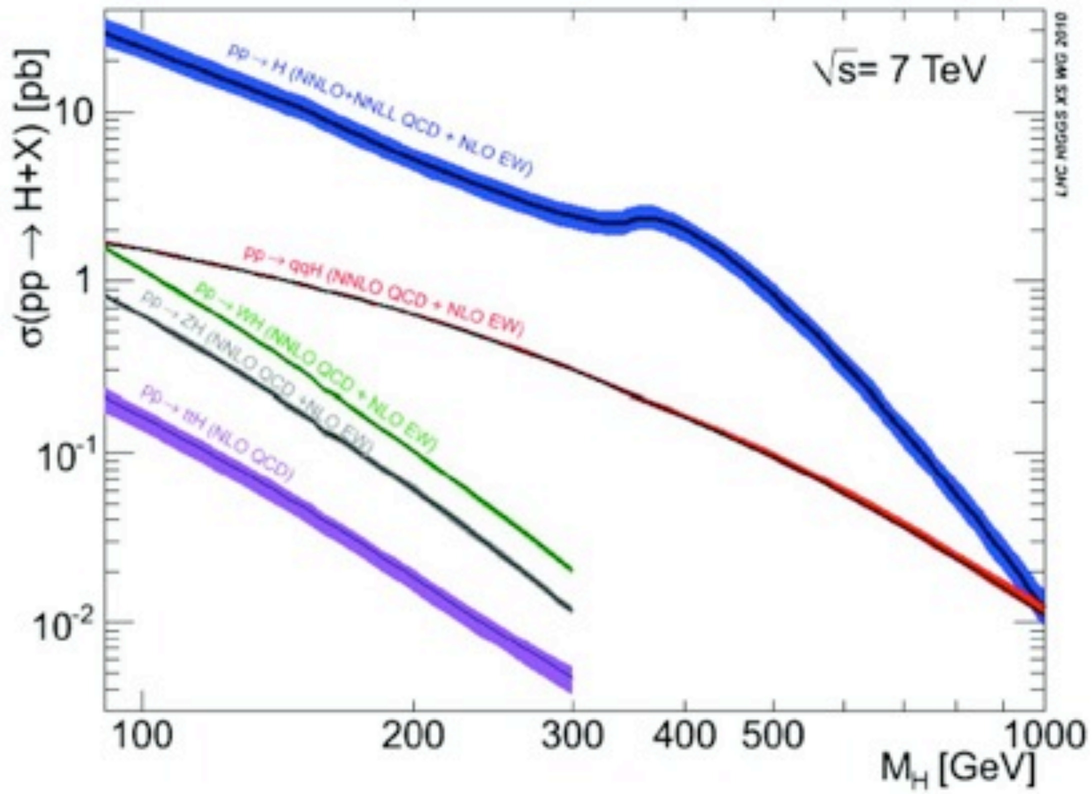
Outline

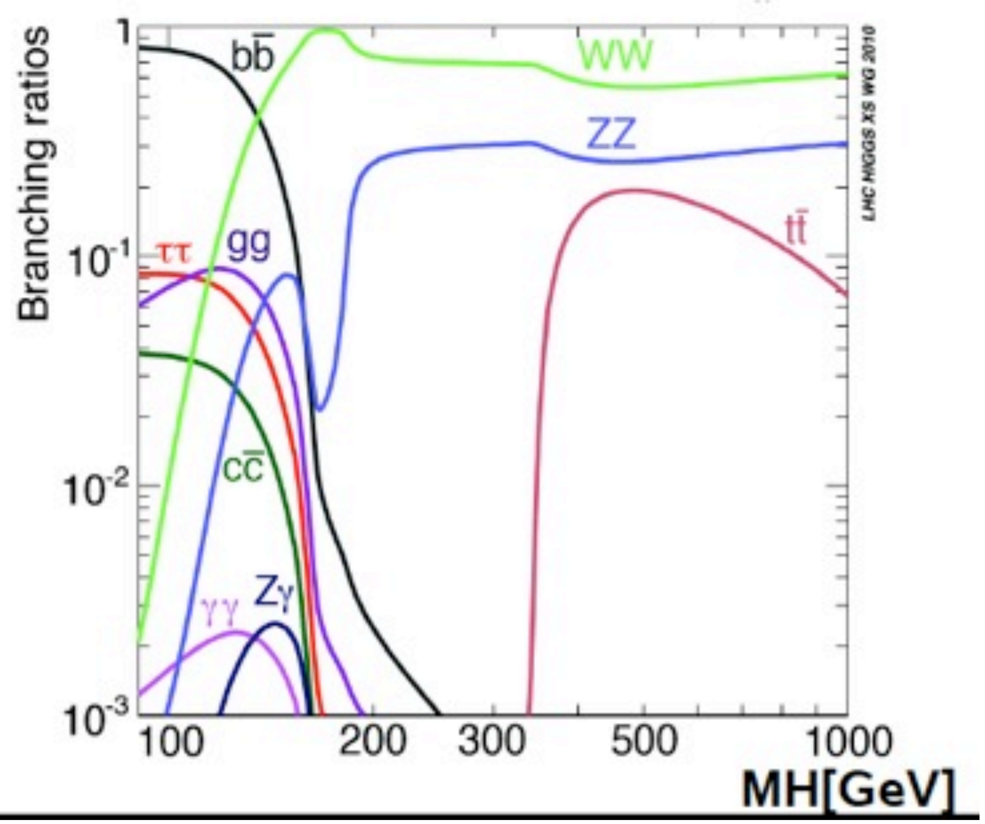
- Focus will be on gluon-fusion production
- Review of theoretical formulation
- Issue #1: PDFs and the strong coupling
- Issue #2: the jet veto

Survey of Higgs results



Phenomenological profile





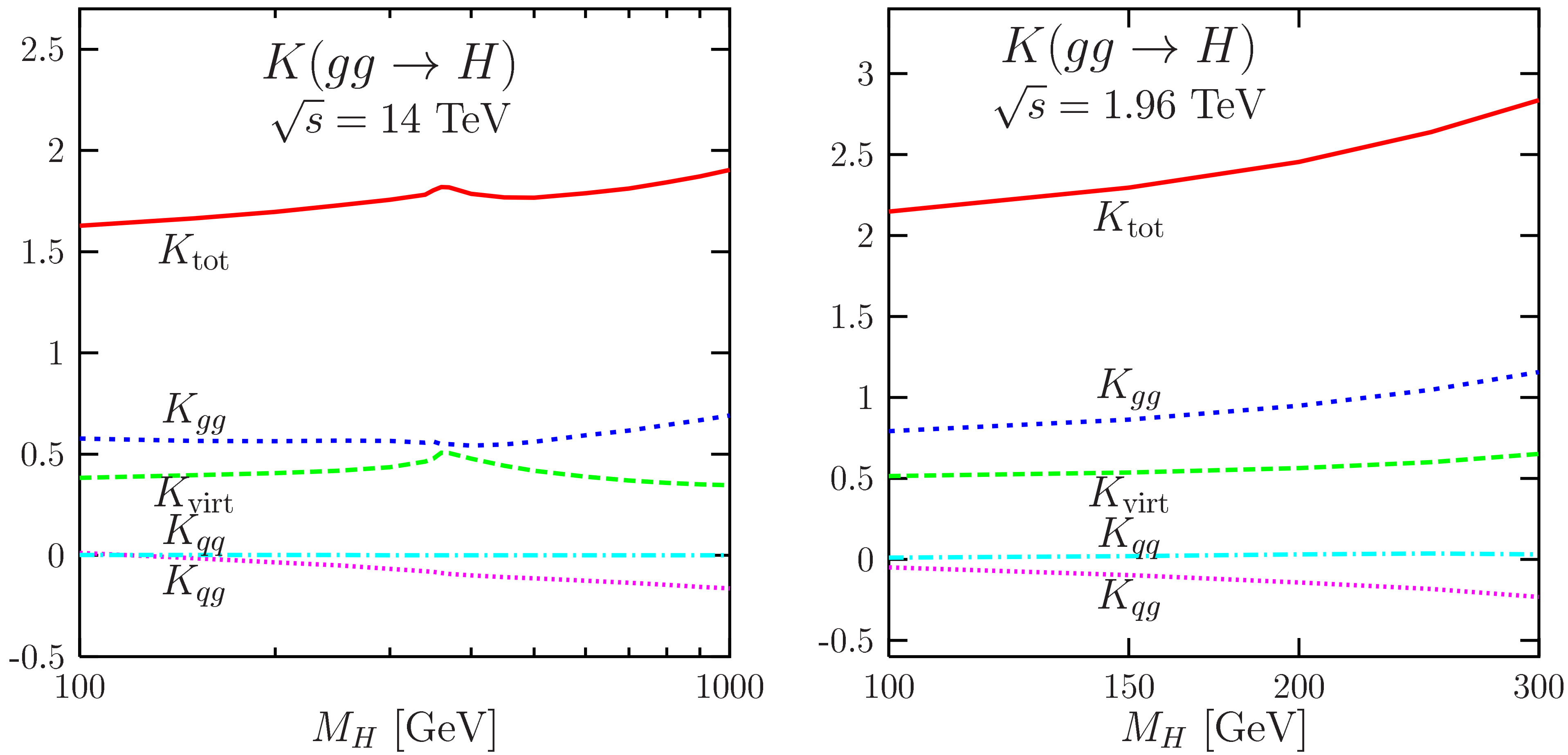
From CMS:

Mode	Mass	L (fb^{-1})	Doc
γγ	110-140	1.1	HIG-11-010
ττ	110-140	1.1	HIG-11-009
ZZ(2ℓ2n)	250-600	1.1	HIG-11-007
ZZ(2ℓ2j)	226-600	1.0	HIG-11-006
ZZ(4ℓ)	110-600	1.1	HIG-11-004
WW(2ℓ2ν)	110-600	1.1	HIG-11-001

- Primary production mode for these channels is gluon fusion; must carefully consider our understanding of this channel

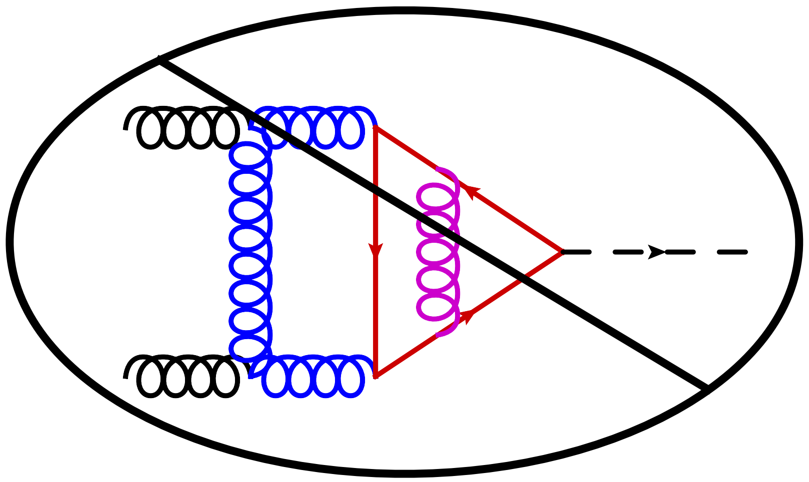
Difficulties

- Famously sensitive to large QCD corrections; difficult to calculate to requisite order in QCD



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

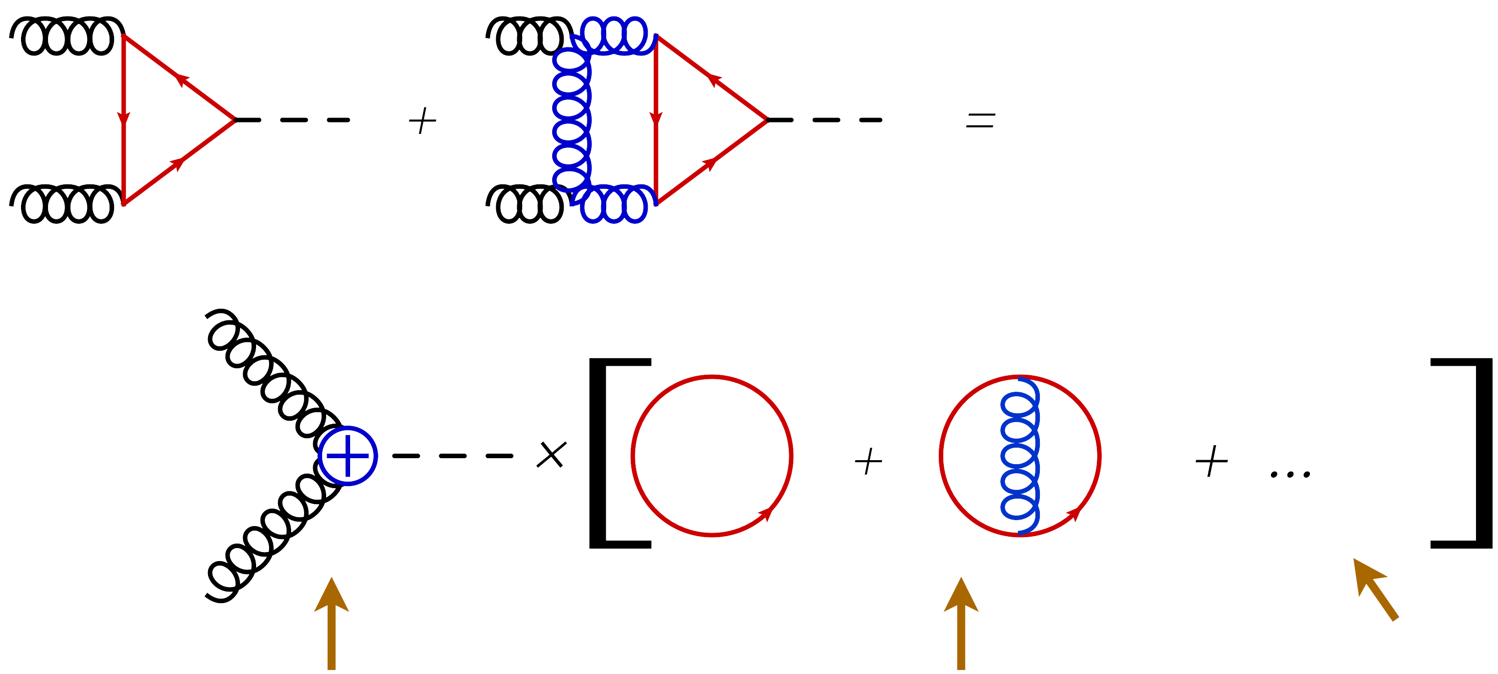
Effective interactions



Getting the next terms requires new techniques

Effective field theory: exploit heavy mass of virtual particles

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



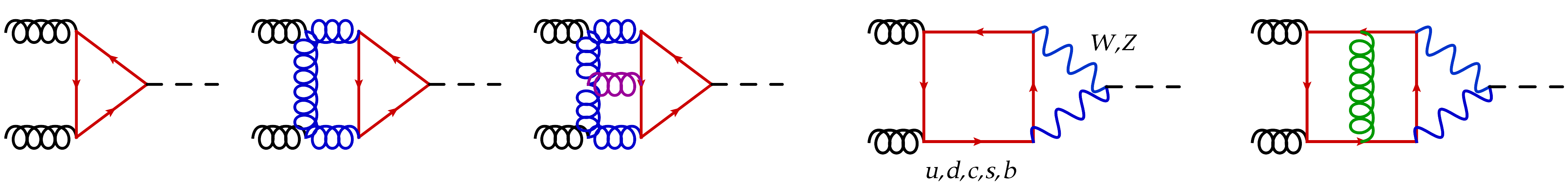
Only M_{Higgs} Only m_{top} $O(M^2_{Higgs}/4m^2_{top})$

The Higgs Lagrangian

Summarized in an "effective Lagrangian" for Higgs-gluon interactions

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

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



Inami, Kubota, Okada 1982

Chetyrkin, Kniehl, Steinhauser 1997

EW terms: Actis et al 2008; Anastasiou, Boughezal, FP 2009

Unreasonably effective EFT

NLO in the EFT:

analytic continuation to time-like form factor

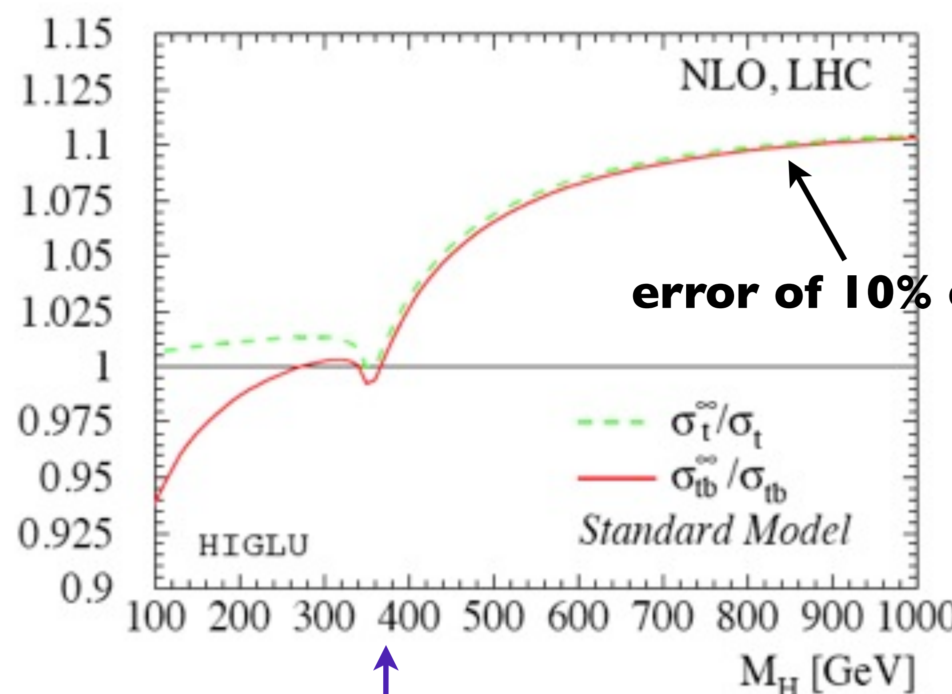
$z=M_H^2/(x_1 x_2 s)$

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

eikonal emission of soft gluons

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

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



error of 10% on 100% correction

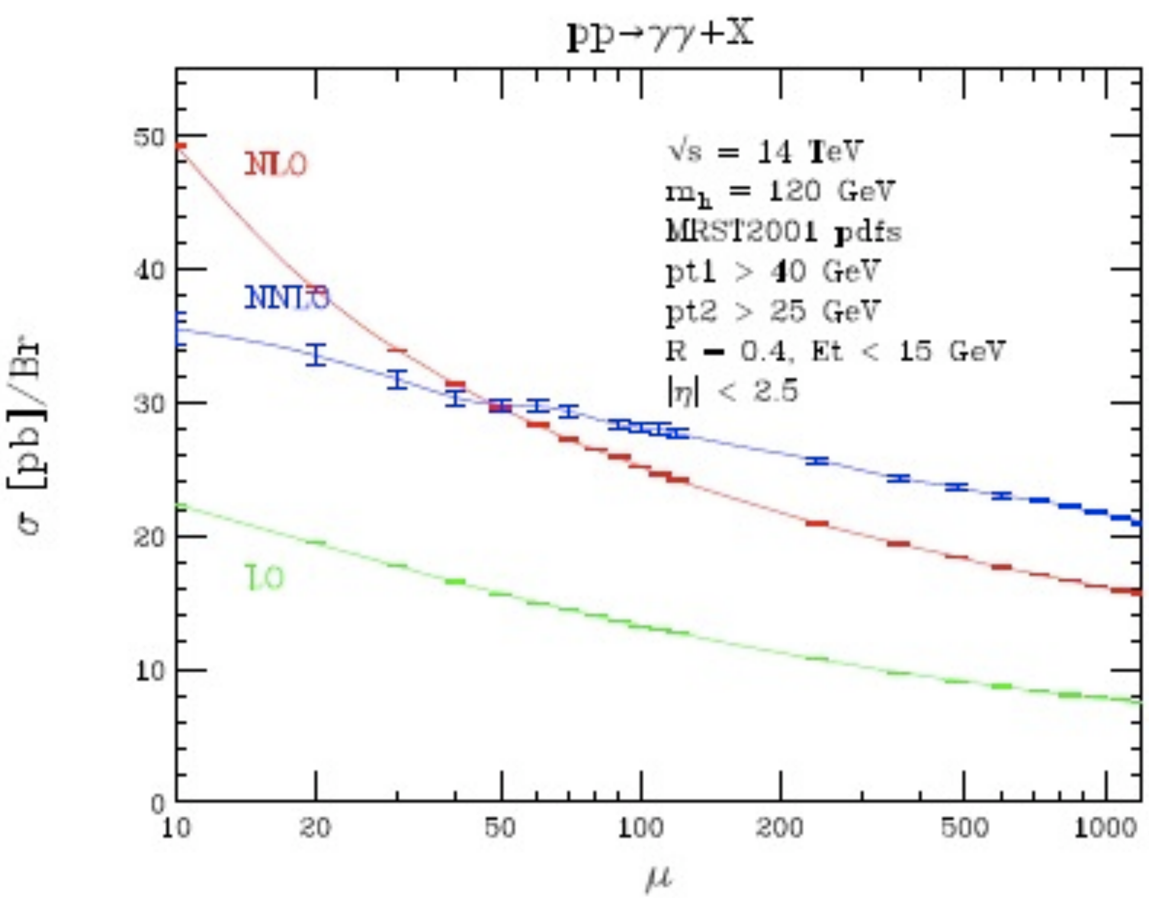
$\mathbf{M_H=2m_t}$

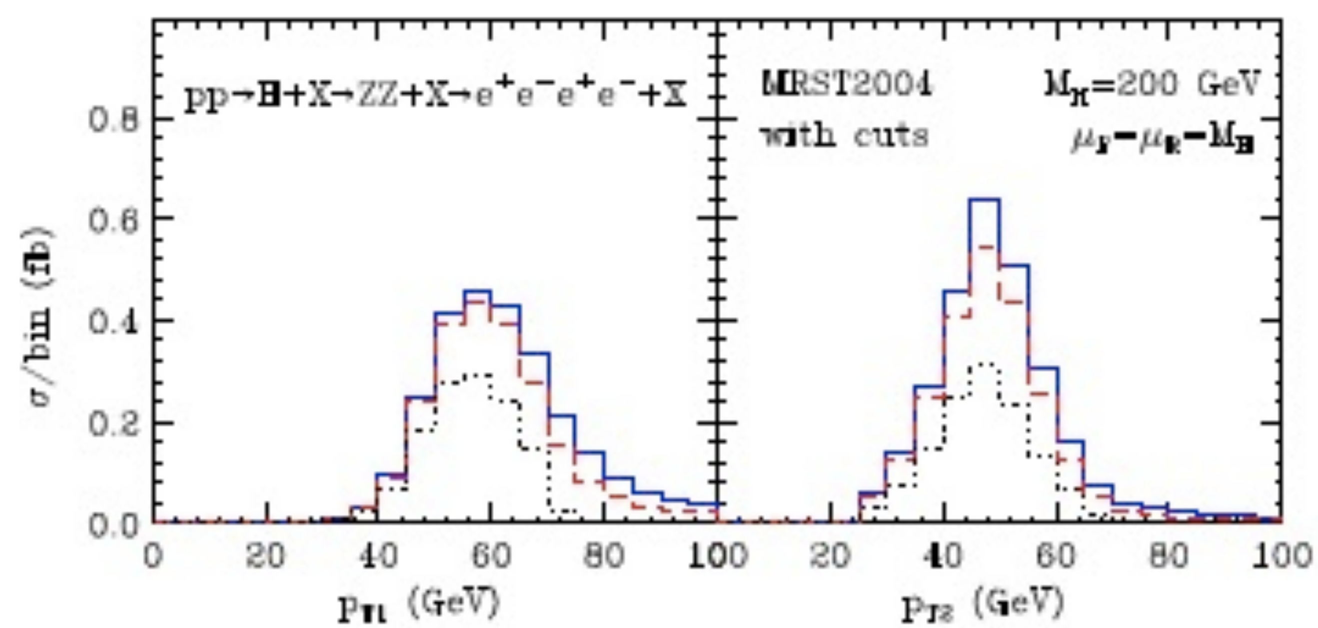
NNLO study of $1/m_t$ suppressed operators, matched to large s-hat limit, large indicates this persists

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

Gluon-fusion: exclusive

- Two fully differential, NNLO tools exist for the study of cuts in Higgs searches
  - FEHIP: based on sector decomposition to handle IR singularities at NNLO Anastasiou, Melnikov, FP 2004-5
  - HNNLO: uses a subtraction method motivated by q_T resummation Catani, Grazzini 2007-8





Ingredients for the prediction

- Differential EFT through NNLO for top quark, normalized to exact LO result (no difference if exact NLO top contribution added) FEHiP: Anastasiou, Melnikov FP 2005; HNNLO: Catani, Grazzini 2007
- For inclusive result, bottom-quark contributions exactly through NLO HIGLU: Spira
- Exact 2-loop electroweak corrections Actis, Passarino, Sturm, Uccirati 2008 together with estimate of QCD corrections Anastasiou, Boughezal FP 2008

Error accounting

- PDFs+strong coupling+scale errors: 15-20%

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

- Use of EFT for top quark: less than 1% for masses less than 350 GeV
- Bottom-quark terms: use of pole, MSbar masses lead to an error estimate of 1-2%
- EW terms: conservatively estimated at 1%

PDF uncertainties

- Higgs cross section very sensitive to gluon distribution and strong coupling; begins at $O(\alpha_S^2)$, and higher order corrections very large...
- Some recent discussions regarding large variation of Higgs cross section with pdf sets

Example: ABM + JR @ Tevatron

ABM vs MSTW at 160 GeV

-30% (>5 sigma)

Cross section in picobarns

M_H (GeV)	ABM10 [8]	ABKM09 [9]	JR [10]	MSTW08 [11]	HERAPDF [12]
100	1.438 ± 0.066	1.380 ± 0.076	1.593 ± 0.091	1.682 ± 0.046	1.417
110	1.051 ± 0.052	1.022 ± 0.061	1.209 ± 0.078	1.265 ± 0.038	1.055
115	0.904 ± 0.047	0.885 ± 0.055	1.060 ± 0.072	1.104 ± 0.034	0.917
120	0.781 ± 0.042	0.770 ± 0.050	0.933 ± 0.067	0.968 ± 0.031	0.800
125	0.677 ± 0.038	0.672 ± 0.045	0.823 ± 0.062	0.851 ± 0.029	0.700
130	0.588 ± 0.034	0.589 ± 0.041	0.729 ± 0.058	0.752 ± 0.026	0.615
135	0.513 ± 0.031	0.518 ± 0.037	0.647 ± 0.054	0.666 ± 0.024	0.541
140	0.449 ± 0.028	0.456 ± 0.034	0.576 ± 0.050	0.591 ± 0.022	0.479
145	0.394 ± 0.025	0.403 ± 0.031	0.514 ± 0.047	0.527 ± 0.020	0.424
150	0.347 ± 0.023	0.358 ± 0.028	0.461 ± 0.044	0.471 ± 0.018	0.377
155	0.306 ± 0.020	0.318 ± 0.026	0.413 ± 0.041	0.421 ± 0.017	0.336
160	0.271 ± 0.019	0.283 ± 0.024	0.371 ± 0.039	0.378 ± 0.016	0.300
165	0.240 ± 0.017	0.253 ± 0.022	0.335 ± 0.036	0.341 ± 0.014	0.269
170	0.213 ± 0.015	0.226 ± 0.020	0.302 ± 0.034	0.307 ± 0.013	0.241
175	0.190 ± 0.014	0.203 ± 0.019	0.274 ± 0.032	0.278 ± 0.012	0.217
180	0.169 ± 0.013	0.182 ± 0.017	0.248 ± 0.030	0.251 ± 0.012	0.195
185	0.151 ± 0.012	0.164 ± 0.016	0.225 ± 0.028	0.228 ± 0.011	0.176
190	0.136 ± 0.011	0.148 ± 0.015	0.205 ± 0.027	0.207 ± 0.010	0.159
200	0.109 ± 0.009	0.121 ± 0.013	0.170 ± 0.024	0.172 ± 0.009	0.131

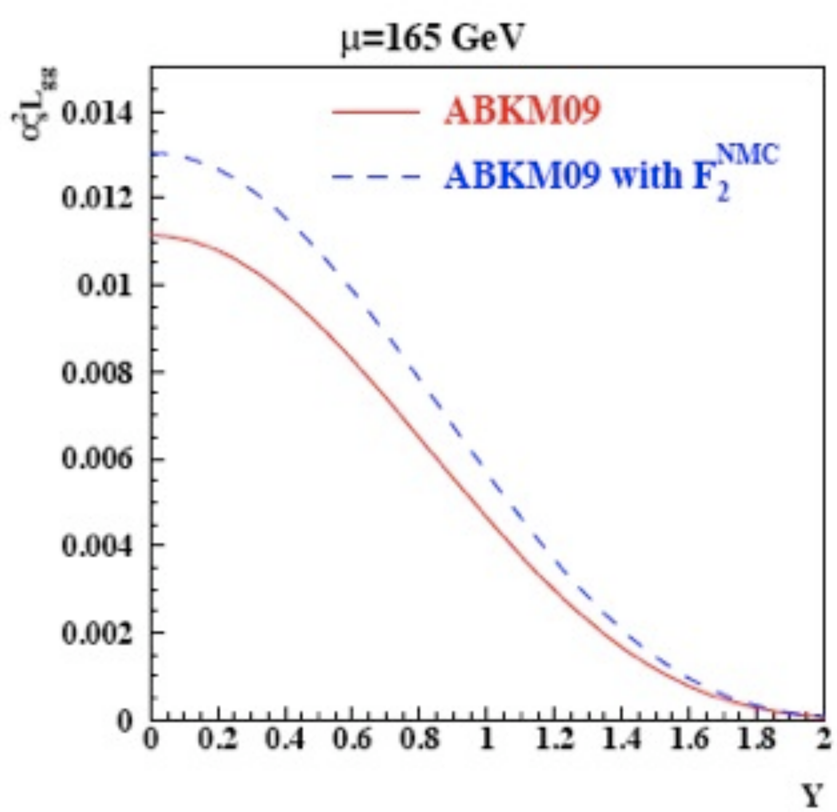
(from D. de Florian)

NMC data and the gluon

- NMC: $Q^2 < 40\ GeV^2$ muon-nucleon scattering

$$\frac{d^2\sigma(x,Q^2)}{dxdQ^2} = \frac{4\pi\alpha^2}{xQ^4}\left\{1-y-xy\frac{M^2}{s}+\left(1-\frac{2m_l^2}{Q^2}\right)\left(1+4x^2\frac{M^2}{Q^2}\right)\frac{y^2}{2(1+R(x,Q^2))}\right\}F_2(x,Q^2)$$

  - NMC gives both $d\sigma$ and F_2; fit to which?
  - F_2 was extracted before QCD corrections to R known
  - MSTW uses F_2; ABKM (lowest σ_H) uses $d\sigma$

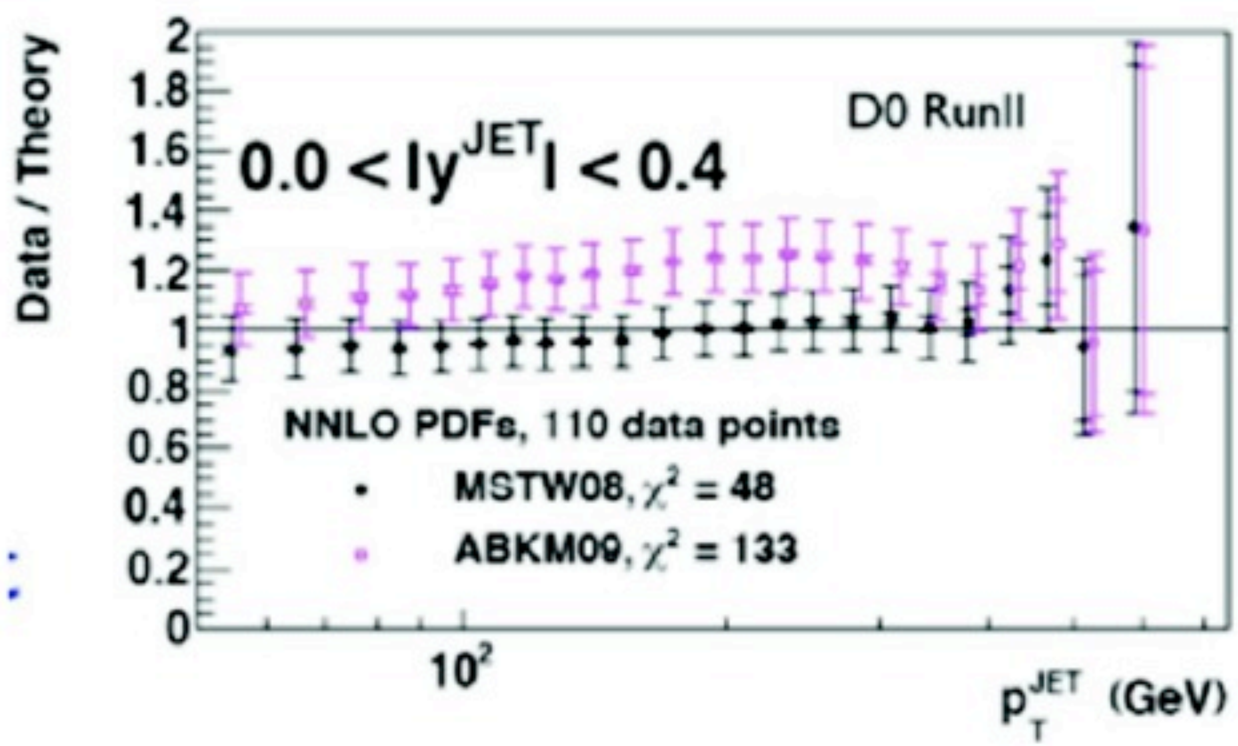


- However, both MSTW and NNPDF find small effects when switching from F_2 to $d\sigma$

Tevatron jet data

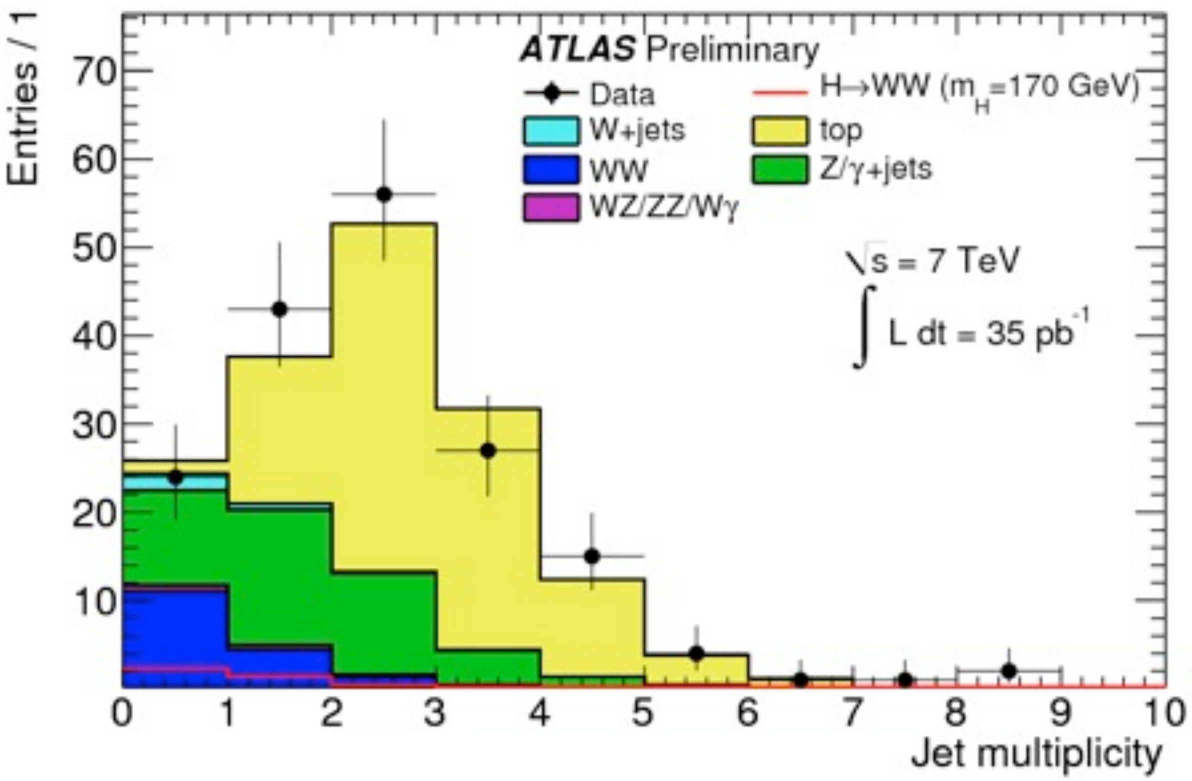
- Interesting exercise by Thorne and Watt (2011)

➡ Check how well PDFs reproduce Tevatron jet data

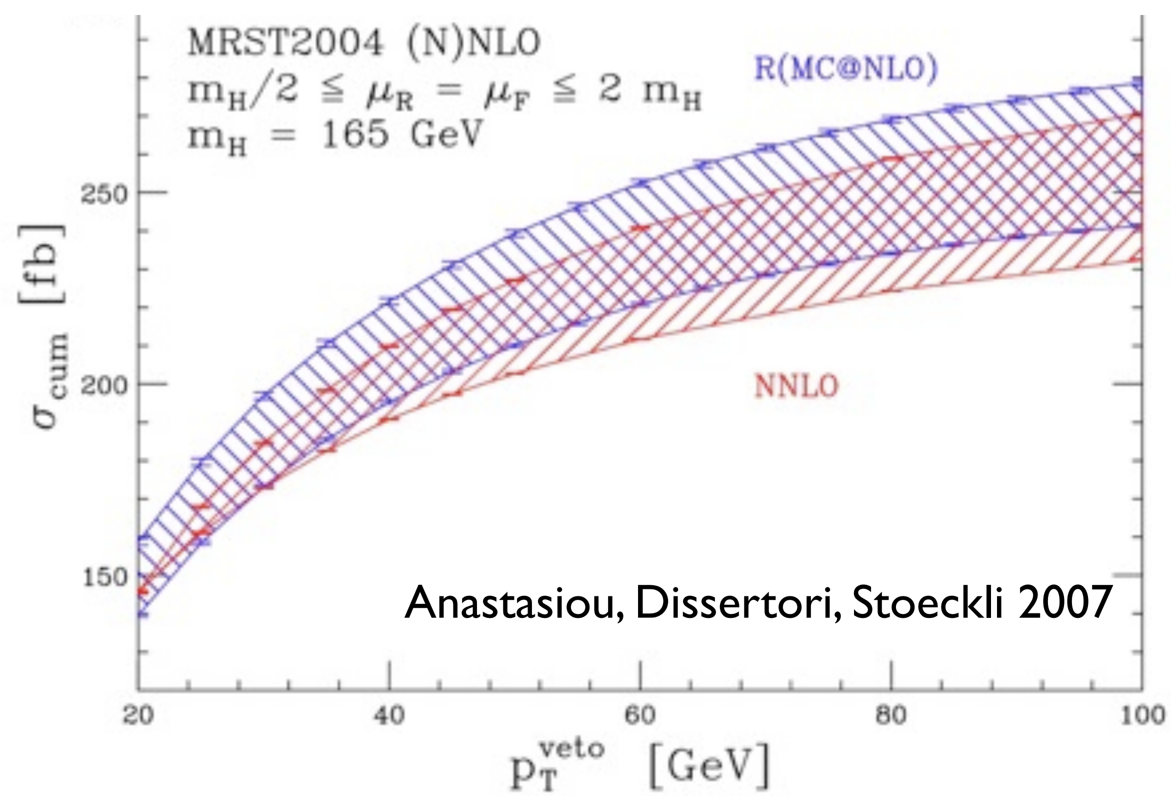


Message from Thorne and Watt: only global analysis provide accurate distributions and uncertainties. No acceptable description of jet data from non-global sets

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



Anastasiou, Dissertori, Stoeckli 2007

- 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 by Stewart, Tackmann

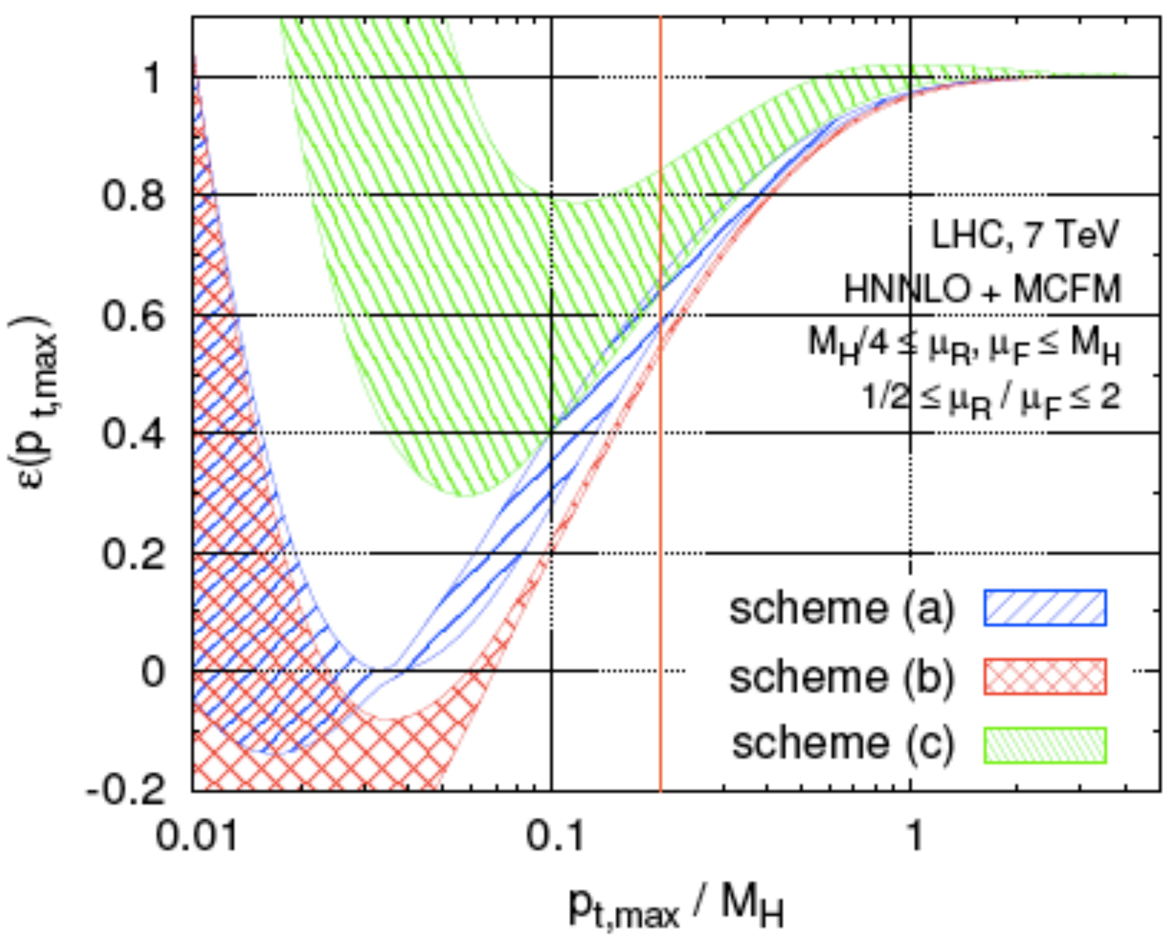
$$\sigma_0(p^{\text{cut}}) = \sigma_{\text{total}} - \sigma_{\geq 1}(p^{\text{cut}})$$
$$\simeq \sigma_B \Big\{ \big[1 + \alpha_s + \alpha_s^2 + \mathcal{O}(\alpha_s^3)\big] - \big[\alpha_s(L^2 + L + 1) + \alpha_s^2(L^4 + L^3 + L^2 + L + 1) + \mathcal{O}(\alpha_s^3 L^6)\big] \Big\}$$

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

- 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, to appear in Yellow Report 2

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

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

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

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

BNL accord

- A solution using fixed-order results pointed out by Tackmann/Stewart

- In the limit of $\ln(m_H/p_{T,cut})$ large, σ_{tot} and $\sigma_{\geq 1}$ have independent expansions
- Gives expected result, that $\Delta\sigma_{veto} > \Delta\sigma_{tot}$
- Agreed to as the procedure for LHC error treatment at 2011 BNL workshop

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 fractions

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

$$
\begin{aligned}
\delta(f_0)^2 &= \left(\frac{1}{f_0} - 1\right)^2 (\delta^2_{\rm total} + \delta^2_{\geq 1}) \,, \\
\delta(f_1)^2 &= \delta^2_{\rm total} + \left(\frac{1-f_0}{f_1}\right)^2 \delta^2_{\geq 1} + \left(\frac{1-f_0}{f_1} - 1\right)^2 \delta^2_{\geq 2} \,, \\
\rho(f_0, \sigma_{\rm total}) &= \left[1 + \frac{\delta^2_{\geq 1}}{\delta^2_{\rm total}}\right]^{-1/2} \,, \\
\rho(f_1, \sigma_{\rm total}) &= -\frac{\delta_{\rm total}}{\delta(f_1)} \,, \\
\rho(f_0, f_1) &= -\left(1 + \frac{1-f_0}{f_1}\frac{\delta^2_{\geq 1}}{\delta^2_{\rm total}}\right)\left(\frac{1}{f_0} - 1\right)\frac{\delta^2_{\rm total}}{\delta(f_0)\delta(f_1)} \,.
\end{aligned}
$$

Conclusions

- Theory for Higgs is under good control; residual errors at the 20% level, all sources (bottom, EW, EFT, PDFs,...) thought through extensively
- Major issue are cuts on phase space. The jet veto is a problem, and the standard scale variation doesn't properly capture higher-order terms in the series.
- Open for discussion!