THEORY SYSTEMATICS FOR GLUON-FUSION HIGGS PRODUCTION

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Higgs Systematics Meeting
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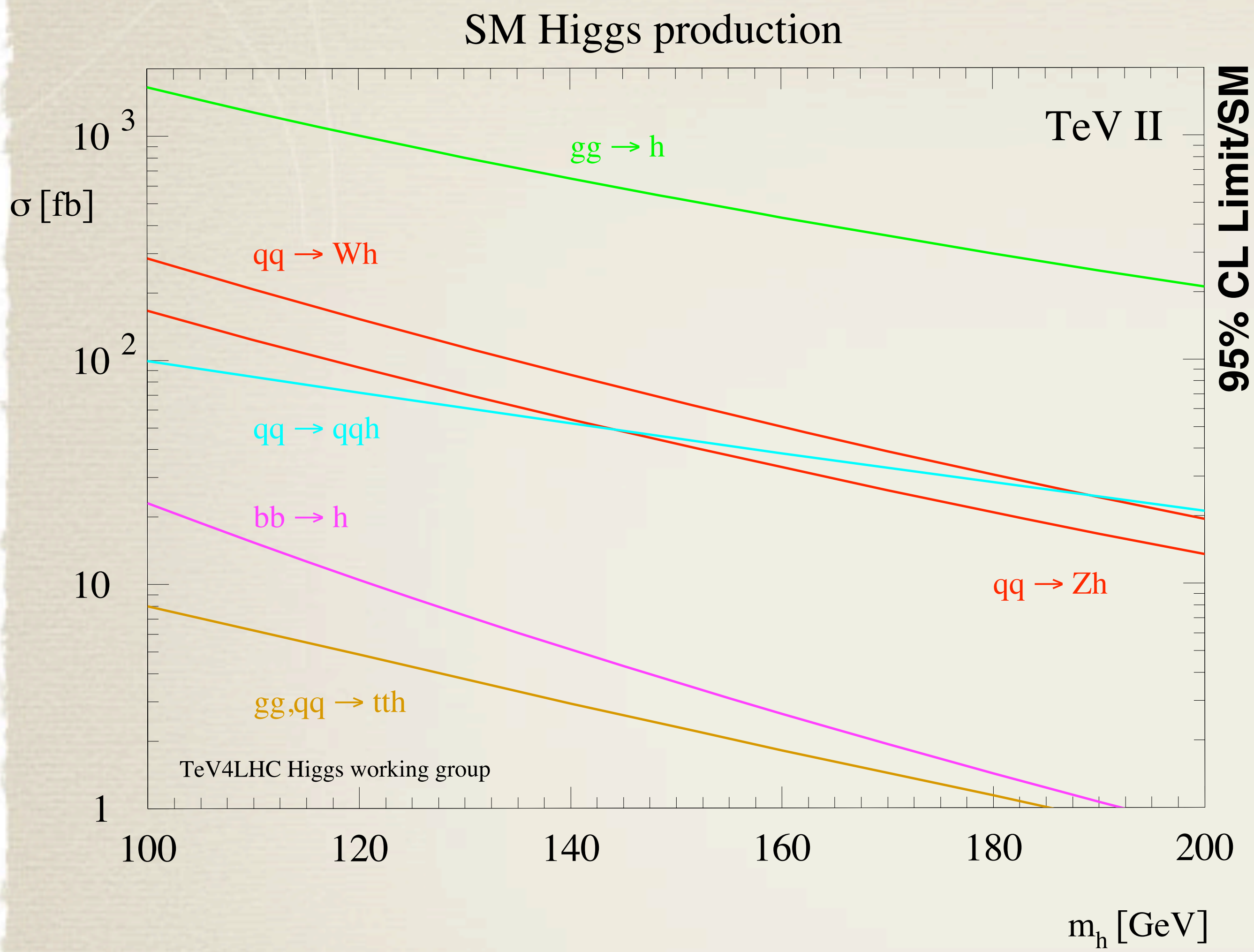
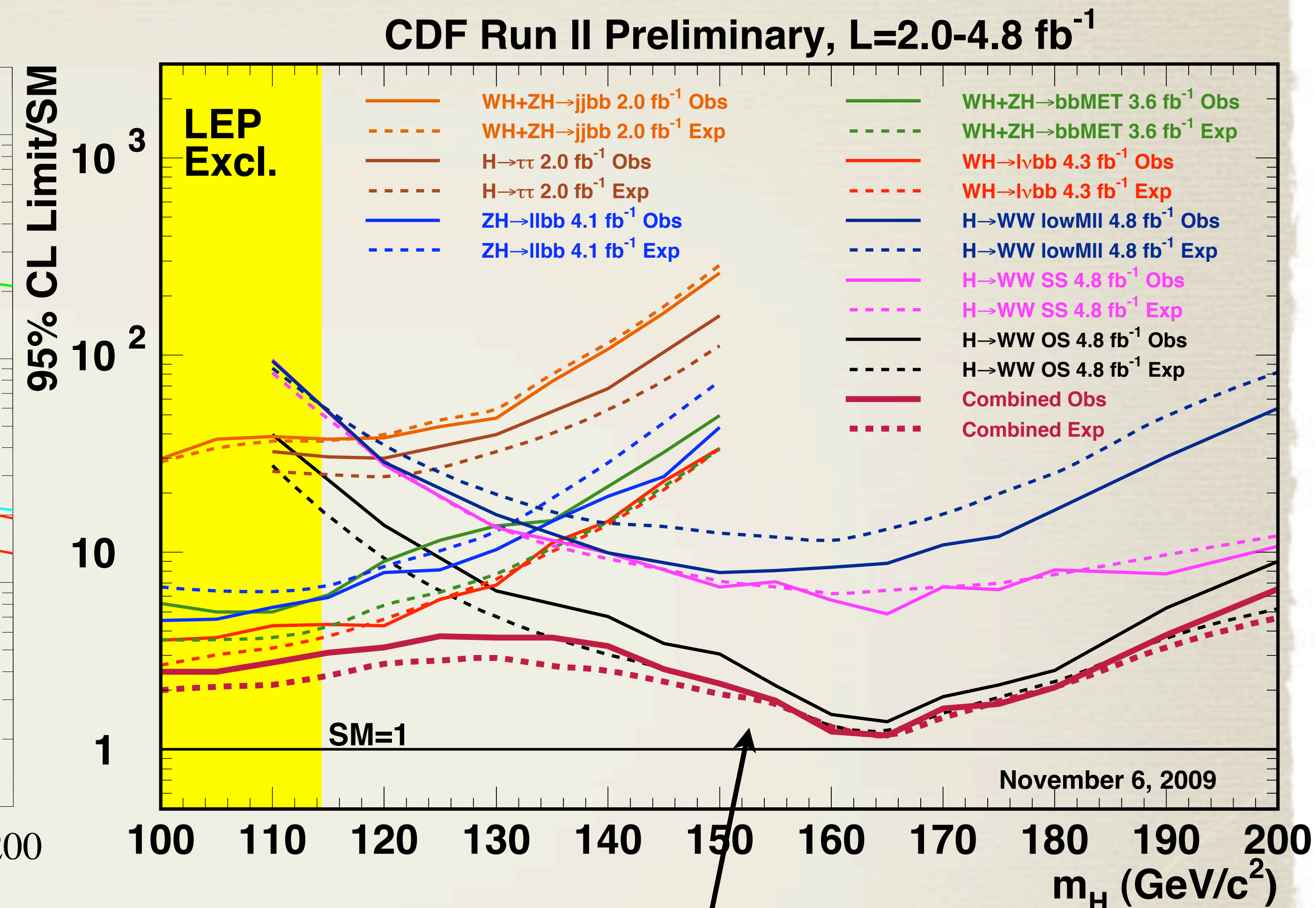
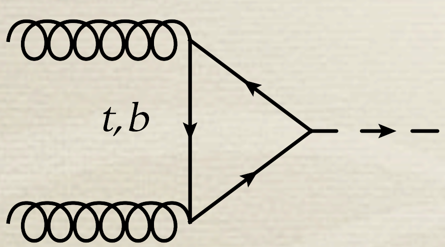
Outline

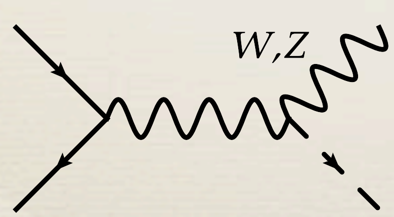
- Framework for gluon-fusion Higgs production
- What went into the theoretical prediction and numbers
- Issues with theory errors; emphasis on those raised by Baglio/Djouadi (BD) arXiv:1003.4266
  - Split into inclusive × acceptance
  - Central-value and scale choices
  - Uncertainties: scale range, EFT usage, EW and bottom quarks
  - PDFs and α_S
- Combining errors

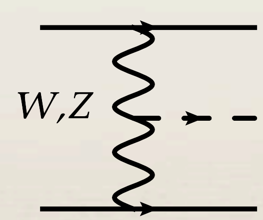
SM Higgs production







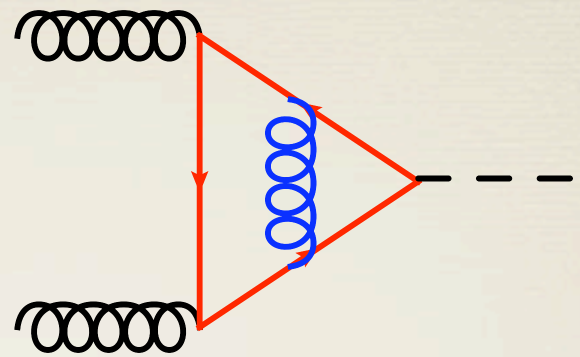


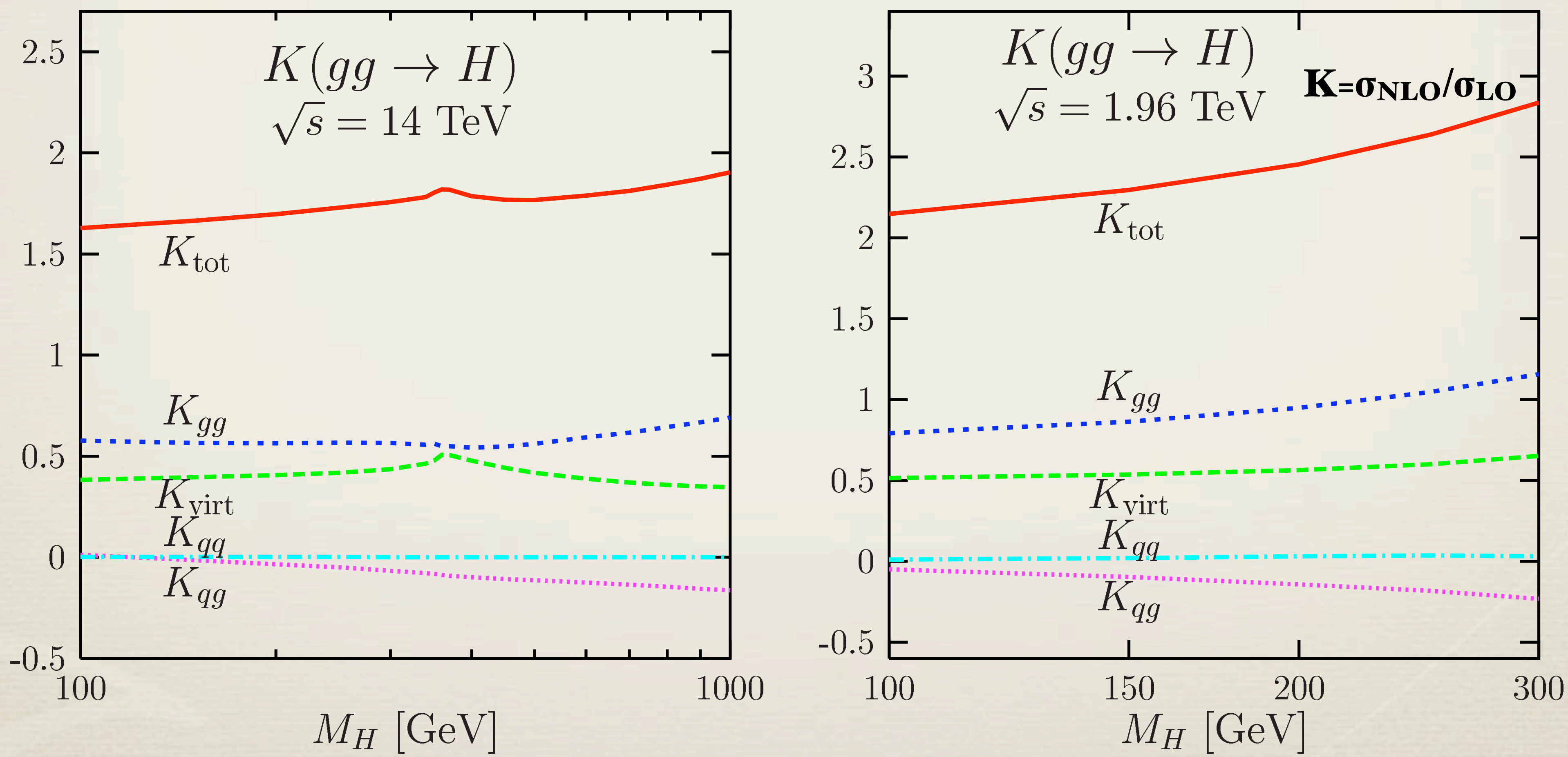


Will focus on
gg→H→WW

Gluon-fusion at NLO

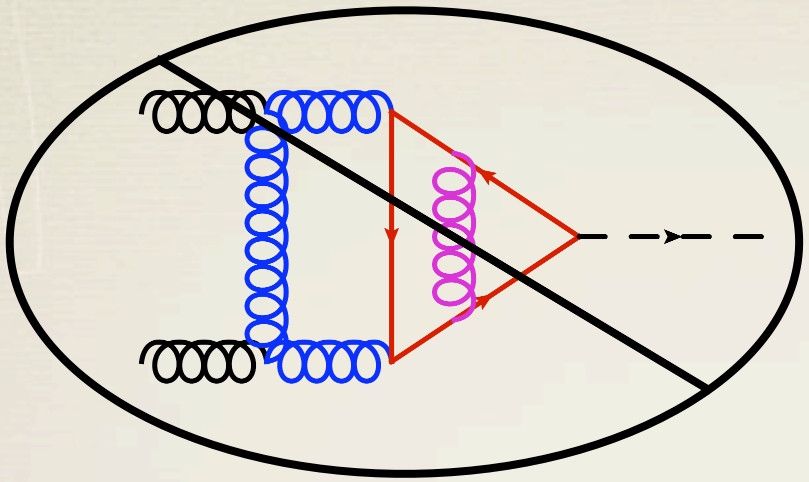
What makes is sensitive to new physics (begins at 1-loop) also makes it tough to calculate...





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

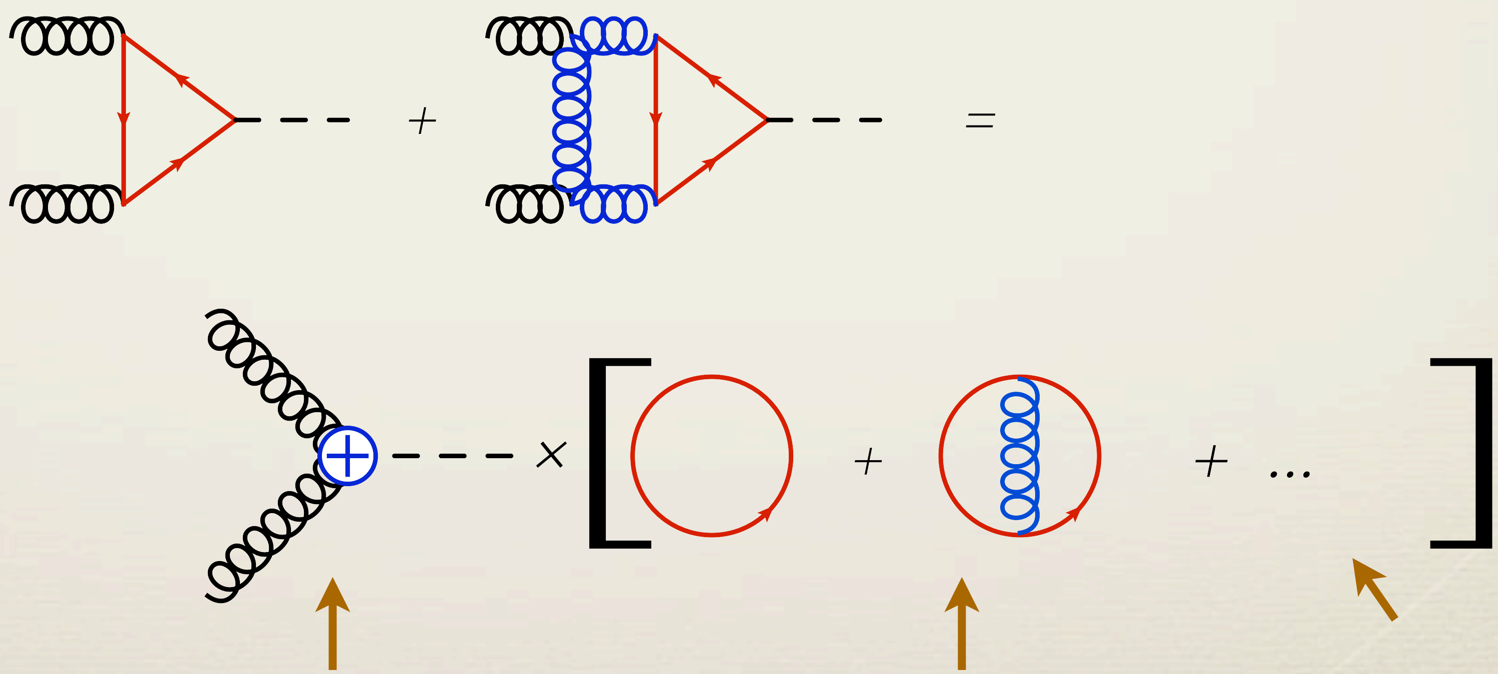
Effective interactions



Getting the next terms requires new techniques

Effective field theory: exploit heavy mass of virtual particles

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



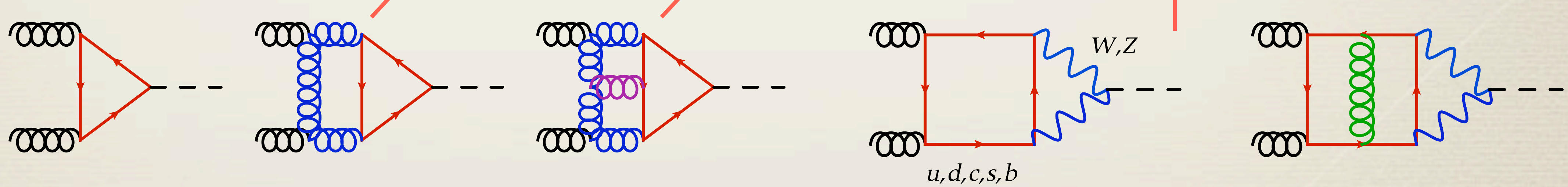
Only M_{Higgs} Only m_{top} $O(M^2_{Higgs}/4m^2_{top})$

The Higgs Lagrangian

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

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

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



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

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

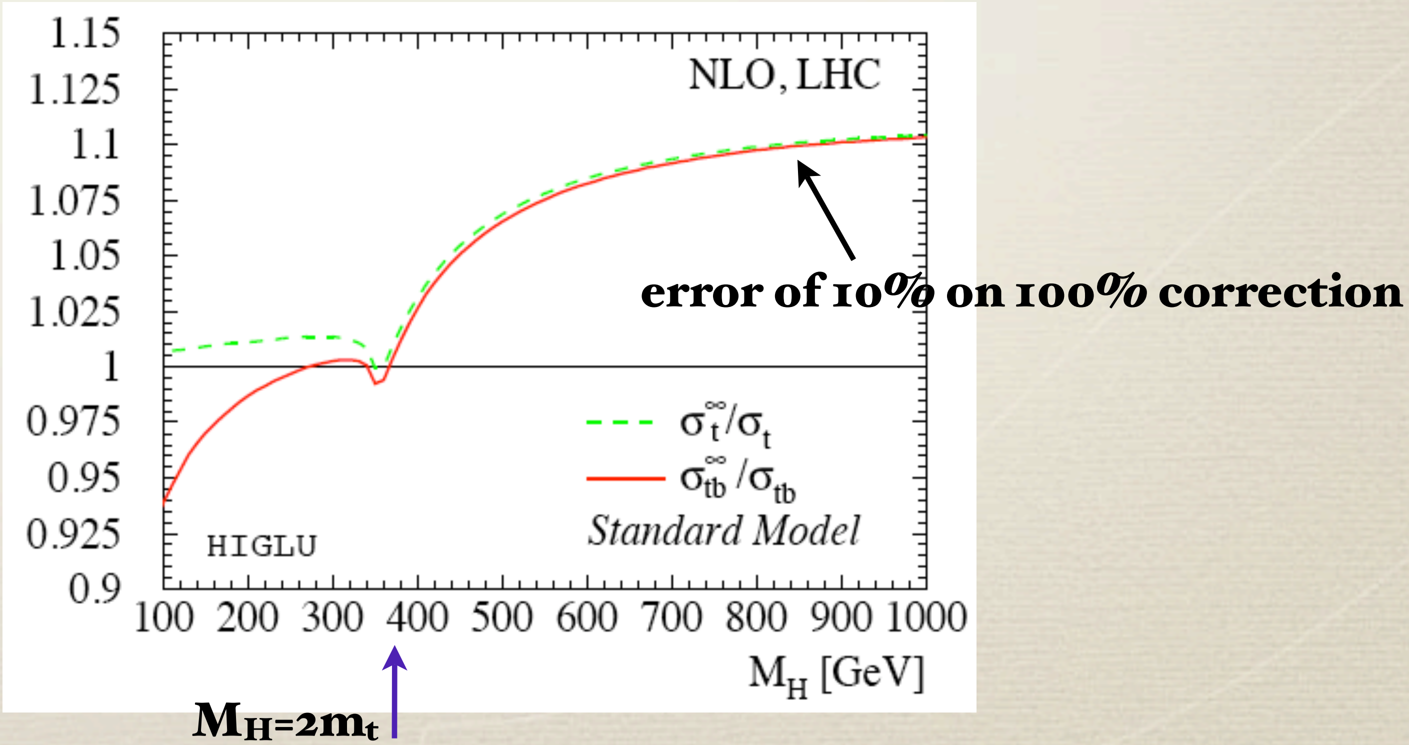
$$\Delta\sigma = \sigma_0 \frac{\alpha_s}{\pi}\left\{\left(\frac{11}{2}+\pi^2\right)\delta(1-z)+12\left[\frac{\ln(1-z)}{1-z}\right]_+ - 12z(-z+z^2+2)\ln(1-z) - 6\frac{(z^2+1-z)^2}{1-z}\ln(z) - \frac{11}{2}(1-z)^3\right\}$$

eikonal emission of soft gluons

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

(Same for EW terms)

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

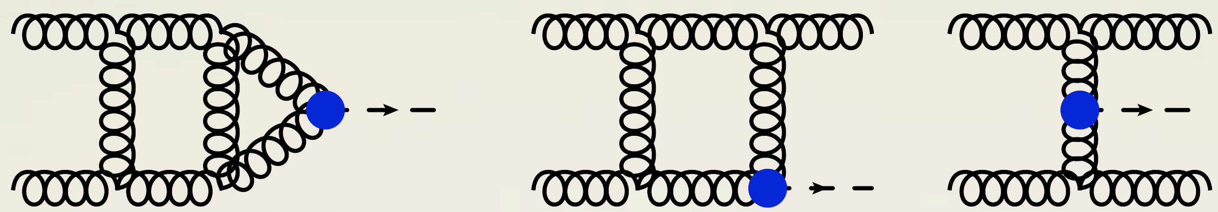


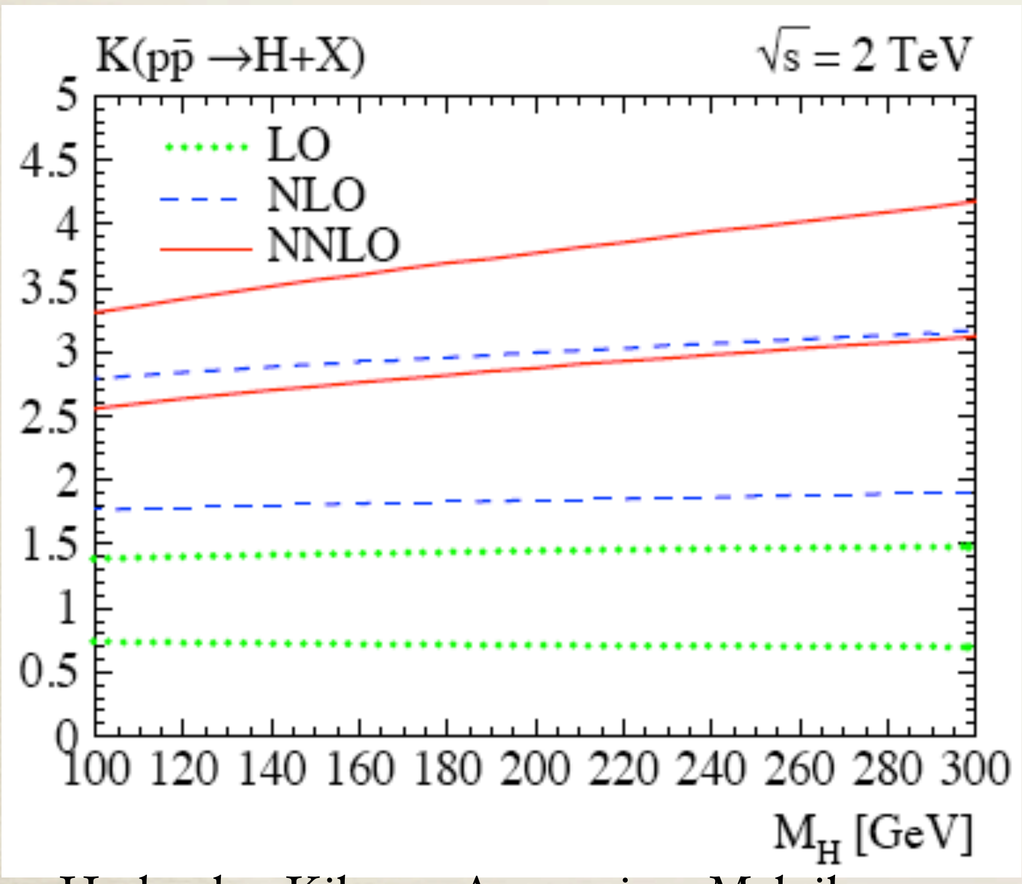
Initial NNLO study of $1/m_t$ suppressed operators indicates this persists

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

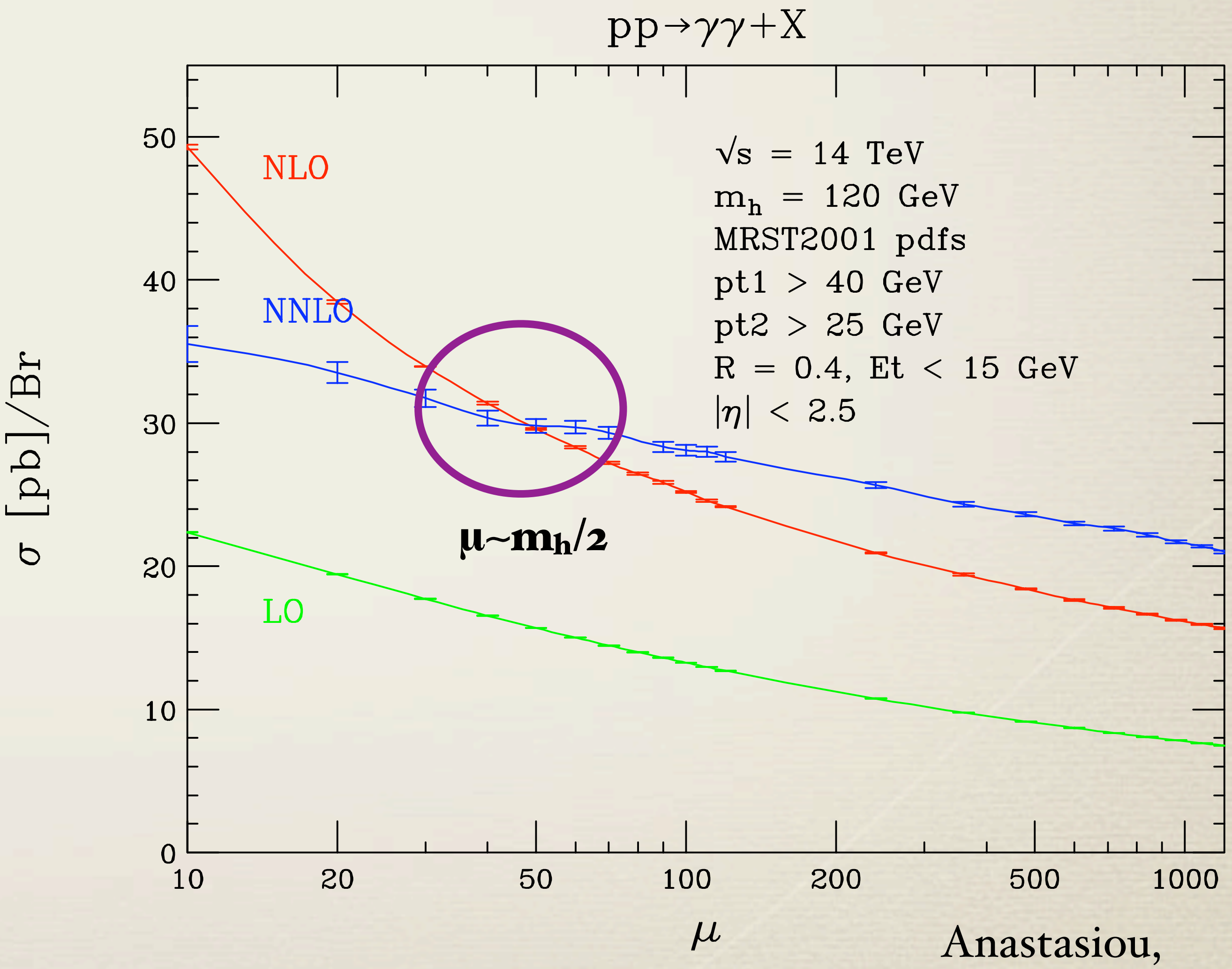
NNLO in the EFT

- Motivates calculation to NNLO in the EFT





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



Anastasiou, Melnikov, FP 2005

K-factor: 2 at LHC, 3.5 at Tevatron

Ingredients for the prediction

$$\sigma_{QCD}^{NNLO} = \sigma^{(0)} G_{ij}(z;\alpha_s) + \sigma_b^{(0)} G_{ij}^{(0)}(z) K_{bb} + \sigma_{t,b}^{(0)} G_{ij}^{(0)}(z) K_{tb}$$

EFT through NNLO for top quark, normalized to exact LO top-mass dependent result (could use exact top-mass result through NLO, no difference)

Bottom-quark pieces with exact mass dependence through NLO (two loops)

$$\sigma_{EW}^{NNLO} = \sigma_{t,lf}^{(0)} \Big\{ G_{ij}^{(0)}(z) \left[1 + a_s(C_{1w} - C_{1q}) + a_s^2 \left(C_{2w} - C_{2q} + C_{1q}(C_{1q} - C_{1w}\right)\right] \\ + a_s G_{ij}^{(1)}(z) \left[1 + a_s(C_{1w} - C_{1q})\right] + a_s^2 G_{ij}^{(2)} \Big\} \quad ,$$

Exact two-loop EW terms from Actis et al. 2009

QCD corrections computed in EFT approach, with previous justification

$$\sigma^{best} = \sigma_{QCD}^{NNLO} + \sigma_{EW}^{NNLO}$$

Tevatron numerics

Anastasiou, Boughezal, FP 0811.3458

110: 1428.28 fb – 11.76%(sc) + 8.79%(sc) – 6.16%(pdf) + 5.75%(pdf) – 10.99%(pdf+as) + 11.46%(pdf+as)

115: 1252.36 fb – 11.77%(sc) + 8.65%(sc) – 6.39%(pdf) + 5.97%(pdf) – 11.14%(pdf+as) + 11.58%(pdf+as)

120: 1102.22 fb – 11.71%(sc) + 8.53%(sc) – 6.62%(pdf) + 6.20%(pdf) – 11.29%(pdf+as) + 11.77%(pdf+as)

125: 973.57 fb – 11.65%(sc) + 8.42%(sc) – 6.85%(pdf) + 6.42%(pdf) – 11.45%(pdf+as) + 12.02%(pdf+as)

130: 863.23 fb – 11.65%(sc) + 8.34%(sc) – 7.08%(pdf) + 6.64%(pdf) – 11.61%(pdf+as) + 12.19%(pdf+as)

135: 767.97 fb – 11.71%(sc) + 8.26%(sc) – 7.31%(pdf) + 6.87%(pdf) – 11.79%(pdf+as) + 12.38%(pdf+as)

140: 685.30 fb – 11.74%(sc) + 8.16%(sc) – 7.53%(pdf) + 7.09%(pdf) – 11.95%(pdf+as) + 12.51%(pdf+as)

145: 613.20 fb – 11.75%(sc) + 8.09%(sc) – 7.76%(pdf) + 7.31%(pdf) – 12.08%(pdf+as) + 12.70%(pdf+as)

150: 549.92 fb – 11.75%(sc) + 8.11%(sc) – 7.99%(pdf) + 7.53%(pdf) – 12.23%(pdf+as) + 12.89%(pdf+as)

155: 494.26 fb – 11.75%(sc) + 8.06%(sc) – 8.22%(pdf) + 7.75%(pdf) – 12.40%(pdf+as) + 13.10%(pdf+as)

160: 442.23 fb – 11.75%(sc) + 8.01%(sc) – 8.45%(pdf) + 7.98%(pdf) – 12.56%(pdf+as) + 13.32%(pdf+as)

165: 388.51 fb – 11.78%(sc) + 8.00%(sc) – 8.68%(pdf) + 8.20%(pdf) – 12.74%(pdf+as) + 13.53%(pdf+as)

170: 347.23 fb – 11.79%(sc) + 8.03%(sc) – 8.90%(pdf) + 8.42%(pdf) – 12.86%(pdf+as) + 13.81%(pdf+as)

175: 312.90 fb – 11.81%(sc) + 8.02%(sc) – 9.13%(pdf) + 8.64%(pdf) – 13.07%(pdf+as) + 14.04%(pdf+as)

180: 282.63 fb – 11.84%(sc) + 8.04%(sc) – 9.35%(pdf) + 8.85%(pdf) – 13.22%(pdf+as) + 14.28%(pdf+as)

185: 253.45 fb – 11.85%(sc) + 8.06%(sc) – 9.57%(pdf) + 9.07%(pdf) – 13.38%(pdf+as) + 14.52%(pdf+as)

190: 228.72 fb – 11.88%(sc) + 8.14%(sc) – 9.79%(pdf) + 9.28%(pdf) – 13.56%(pdf+as) + 14.81%(pdf+as)

195: 207.80 fb – 11.96%(sc) + 8.16%(sc) – 9.99%(pdf) + 9.48%(pdf) – 13.73%(pdf+as) + 15.09%(pdf+as)

200: 189.50 fb – 12.00%(sc) + 8.19%(sc) – 10.21%(pdf) + 9.69%(pdf) – 13.88%(pdf+as) + 15.36%(pdf+as)

$\mathbf{M_H/4 \leq \mu \leq M_H}$

MSTW combined PDF
$+\alpha_S$ uncertainty

Good agreement with resummation results de Florian, Grazzini 0903.2120

Split into inclusive, acceptance

Split of theoretical prediction into inclusive×acceptance

P. 6

An important remark to be made at this stage is that we do not include the soft–gluon resummation contributions which, for the total cross section, have been calculated up to next-to-next-to-leading logarithm (NNLL) approximation and increase the production rate by $\sim$ 10–15% at the Tevatron [17]. We also do not include the additional small contributions of the estimated contribution at N^{3}LO [40] as well as those of soft terms beyond the NNLL approximation [41]. The reason is that these corrections are known only for the inclusive total cross section and not for the cross sections when experimental cuts are incorporated; this is also the case for the differential cross sections [42] and many distributions that are used experimentally, which have been evaluated only at NNLO at

P. 16

the QCD corrections are significantly larger for the total inclusive cross section than for that on which basic selection cuts are applied; see e.g. Ref. [42]. This can be seen from

...

the K–factor for the cross section after cuts is $\sim$ 20–30% smaller than the K–factor for the inclusive total cross section (albeit with a reduced scale dependence). For instance, one has $K^{\rm NNLO}_{\rm cuts} = 2.6$ and $K^{\rm NNLO}_{\rm total} = 3.3$ for $M_H = 160$ GeV and scales set to $\mu_F = \mu_R = M_H$.

Naively, one would expect that this $\sim$ 20–30% reduction of the higher order QCD corrections when selection cuts are applied, if not implemented from the very beginning in the normalisation of the cross section after cuts that is actually used by the experiments (which would then reduce the acceptance of the signal events, defined as $\sigma^{\rm NNLO}_{\rm cuts}/\sigma^{\rm NNLO}_{\rm total}$), to be at least reflected in the scale variation of the inclusive cross section and, thus, accounted for in the theoretical uncertainty. This would be partly the case for scale variation within

Split into inclusive, acceptance

First argument doesn't affect the NNLO fixed-order cross section, for which the differential result is known (FEHiP, HNNLO)

$\sigma_{\rm inc}$ [fb]	LO	NLO	NNLO	$K^{\rm NLO}$	$K^{\rm NNLO}$
$\mu = m_{\rm H}/2$	1.998 ± 0.003	4.288 ± 0.004	5.252 ± 0.016	2.149 ± 0.008	2.629 ± 0.009
$\mu = m_{\rm H}$	1.398 ± 0.001	3.366 ± 0.003	4.630 ± 0.010	2.412 ± 0.002	3.312 ± 0.008
$\mu = 2\,m_{\rm H}$	1.004 ± 0.001	2.661 ± 0.002	4.012 ± 0.007	2.651 ± 0.008	3.996 ± 0.008

Table 1: Inclusive cross sections for $m_{\rm H} = 160\,{\rm GeV}$, at various orders in perturbation theory and for different scale choices. The K-factors are defined in the text; LO=Leading order.

$\sigma_{\rm acc}$ [fb]	LO	NLO	NNLO	$K^{\rm NLO}$	$K^{\rm NNLO}$
$\mu = m_{\rm H}/2$	0.750 ± 0.001	1.410 ± 0.003	1.459 ± 0.003	1.880 ± 0.005	1.915 ± 0.025
$\mu = m_{\rm H}$	0.525 ± 0.001	1.129 ± 0.003	1.383 ± 0.004	2.150 ± 0.007	2.594 ± 0.052
$\mu = 2\,m_{\rm H}$	0.379 ± 0.001	0.903 ± 0.002	1.242 ± 0.001	2.383 ± 0.008	3.261 ± 0.048

Table 3: Accepted cross sections and K-factors after the application of all the selection cuts for $m_{\rm H} = 160\,{\rm GeV}$.

Better convergence of expansion for $\mu = M_H/2$ for both inclusive, after cuts; fixed-order with this scale choice agrees with resummation result⇒okay to use enhancement from soft-gluon resummation

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Anastasiou et al. 0905.3529

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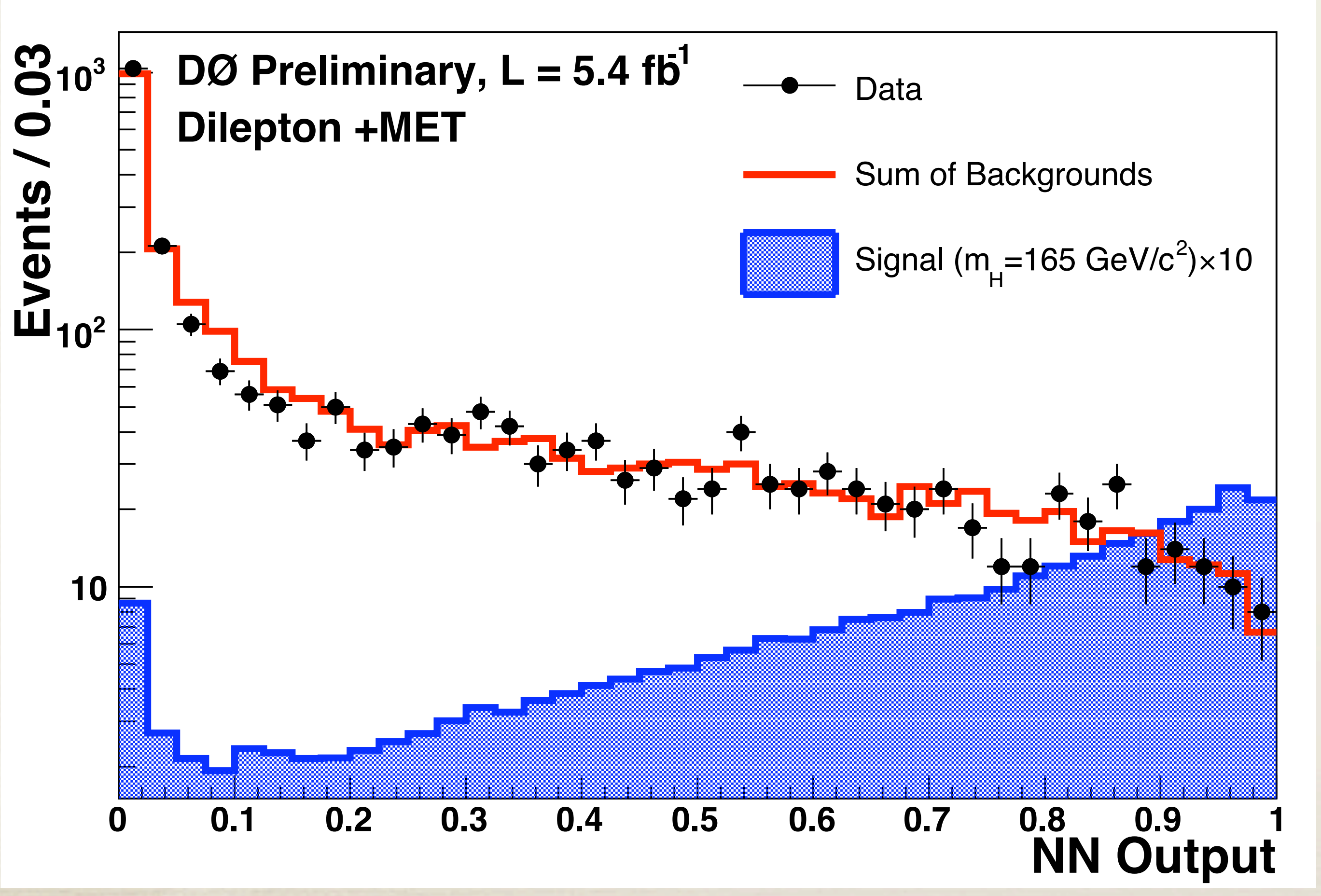
$$\eta_{gg}^{(1)}(x) = \left(\frac{\alpha_s}{\pi}\right)\left\{\left(\frac{11}{2} + 6\zeta_2\right)\delta(1-x) - 6\left[\frac{1}{1-x}\ln\left(\frac{\mu^2}{m_H^2(1-x)^2}\right)\right]_+ + \ldots\right\}$$

In fixed-order, select low μ to minimize large log

Split into inclusive, acceptance

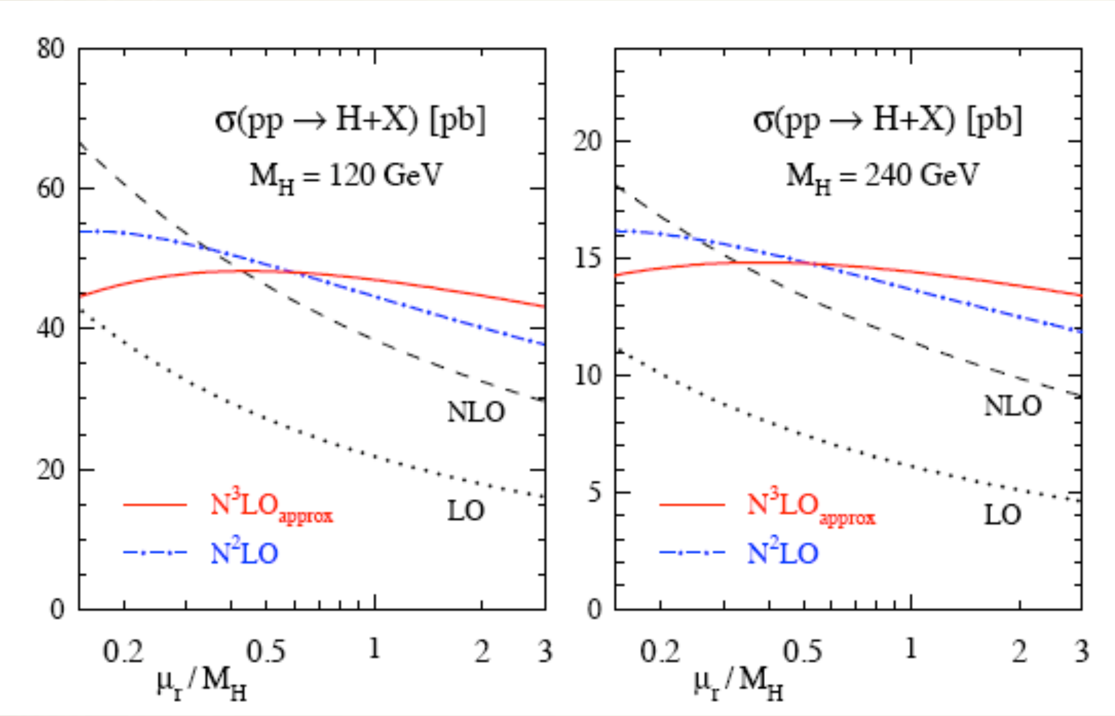
- Presumably, 20-30% decrease from cuts accounted for by reduced acceptance; distributions entering acceptance checked against FEHiP, HNNLO (E. James, CUNY workshop)



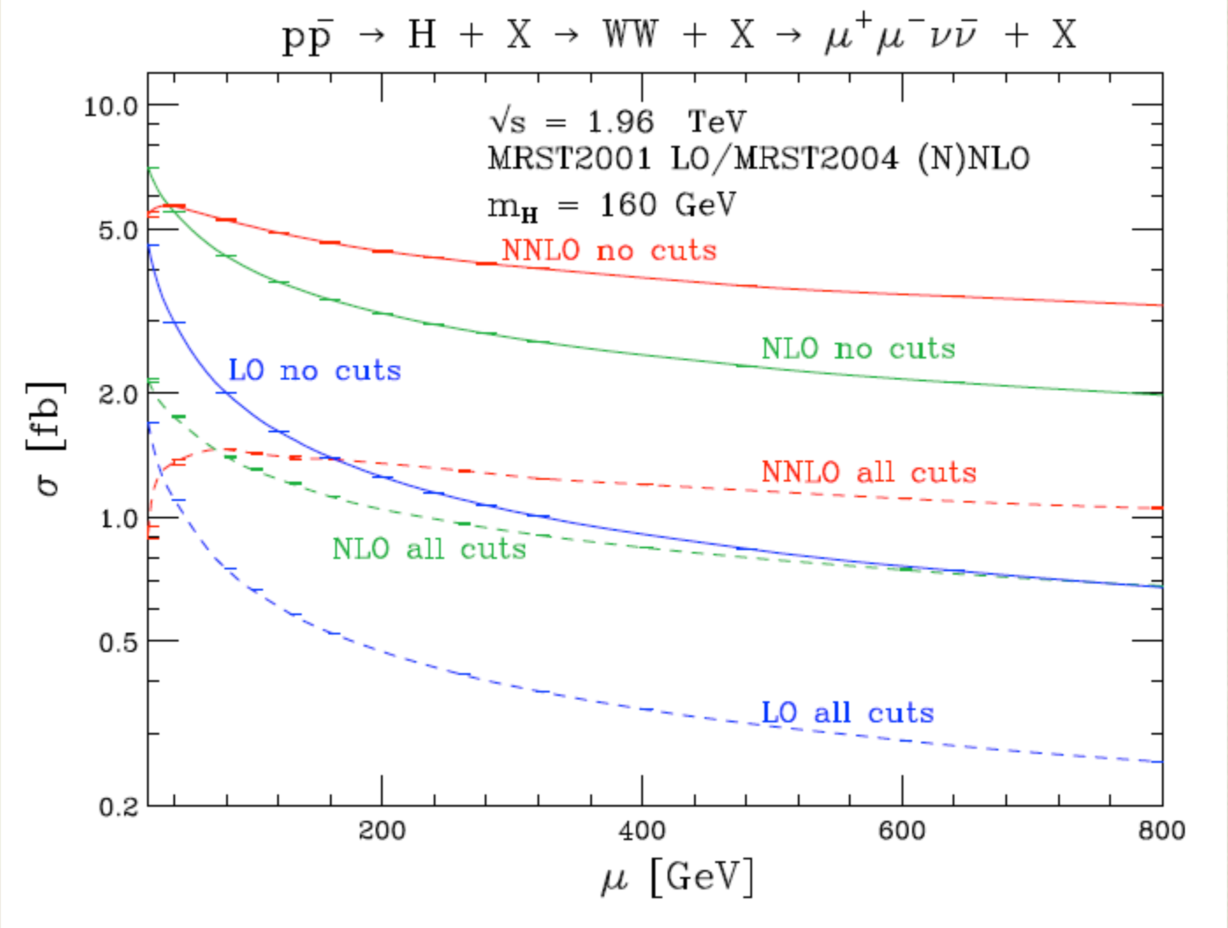
Preliminary result for $gg \to h \to WW$ only exclusion (4th-generation analysis) : turn into cut-based $\Delta\varphi_{ll}$ analysis, compute cross section, errors including cuts directly with NNLO simulation code to check

Central value of prediction

- Choice of the central scale (will address for fixed-order only)



Moch, Vogt 2005 (LHC, but similar for Tevatron)



Anastasiou et al. 0905.3529

Inclusion of partial N3Lo terms, convergence before and after cuts, agreement with resummation result all indicate $\mu \sim M_H/2$

Central value of prediction

- Could even argue that there is an enhancement not included in current predictions

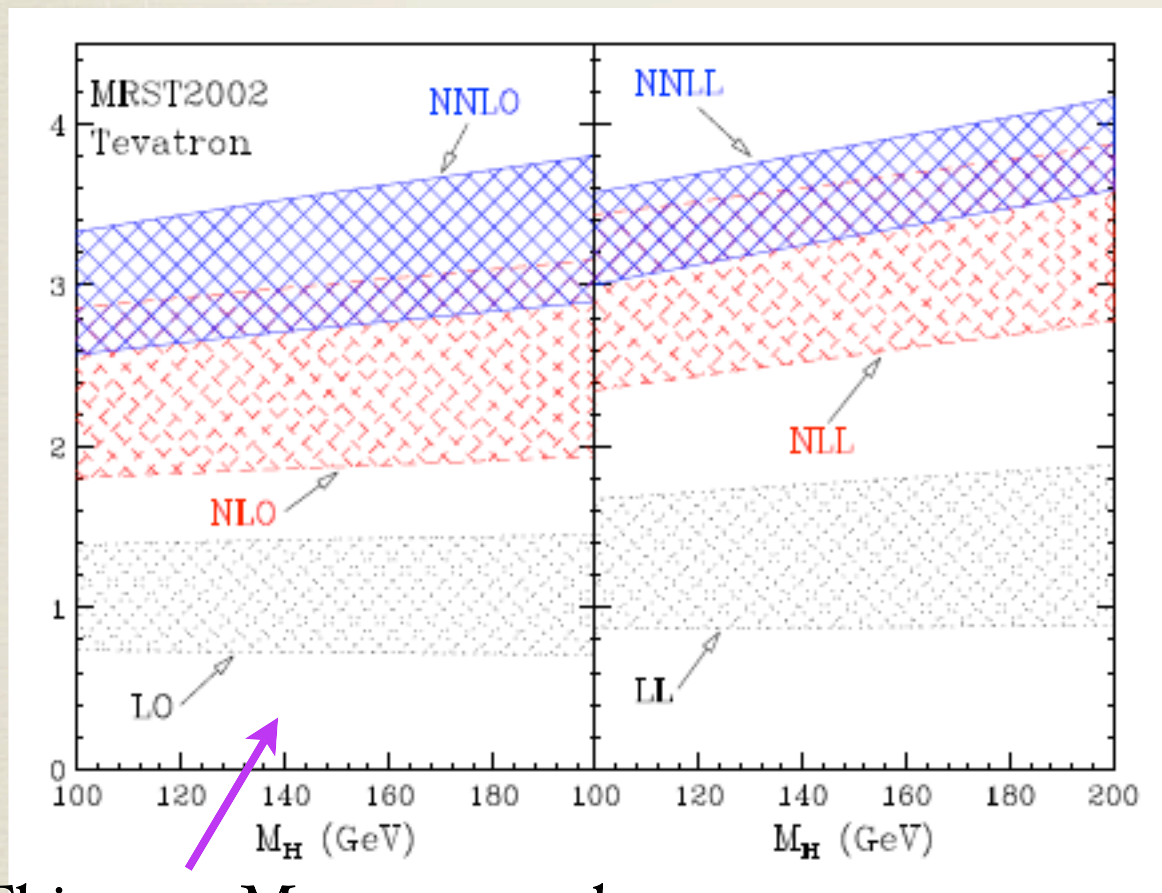
		fixed order	threshold	π^2-enhanced	threshold + π^2
LHC	LO	$15.5^{+2.4+0.4}_{-2.1-0.5}$	$17.8^{+3.3+0.4}_{-2.7-0.6}$	$27.1^{+4.0+0.6}_{-3.8-0.8}$	$31.2^{+5.7+0.8}_{-4.8-1.0}$
	NLO	$35.5^{+5.9+0.8}_{-4.6-1.1}$	$37.7^{+3.6+0.9}_{-1.2-1.2}$	$45.0^{+3.0+1.1}_{-3.3-1.4}$	$46.6^{+2.5+1.1}_{-1.1-1.5}$
	NNLO	$47.6^{+4.5+1.1}_{-4.2-1.5}$	$48.5^{+2.5+1.2}_{-0.5-1.5}$	$51.4^{+1.7+1.2}_{-1.6-1.6}$	$51.4^{+1.4+1.2}_{-0.3-1.6}$
Tevatron	LO	$0.281^{+0.105+0.018}_{-0.071-0.019}$	$0.389^{+0.062+0.023}_{-0.046-0.024}$	$0.491^{+0.180+0.031}_{-0.127-0.033}$	$0.681^{+0.105+0.040}_{-0.080-0.042}$
	NLO	$0.650^{+0.172+0.041}_{-0.131-0.044}$	$0.764^{+0.077+0.045}_{-0.026-0.048}$	$0.855^{+0.125+0.053}_{-0.130-0.056}$	$0.954^{+0.046+0.055}_{-0.022-0.059}$
	NNLO	$0.901^{+0.126+0.056}_{-0.124-0.060}$	$0.961^{+0.048+0.058}_{-0.012-0.062}$	$1.003^{+0.051+0.061}_{-0.074-0.065}$	$1.022^{+0.025+0.061}_{-0.005-0.065}$

Ahrens et al. 0809.4283

Resummation of π^2 coming from time-like production of Higgs; justified within SCET framework, leads to additional +6% correction

Theoretical uncertainties

- Theoretical uncertainties, scale and other



This uses M_H as central value; better with $M_H/2$

Catani et al., 2003

- ☑ Good overlap of NLO, NNLO bands, particularly with resummed result; good agreement with fixed order; NNLO bands with factor of 2 variation contain partial N^3LO result
- ☑ Dominant terms known at higher orders (threshold logs, $C_A\pi^2$)⇒lots of experience with this cross section, no surprises at higher orders (have partial N^3LO results also)
- ☑ Safe to vary by factor of 2 around central value, BD variation by 3 excessively conservative

Roughly ±10% scale uncertainty (see previous table for exact numbers)

Theoretical uncertainties

- Analysis splits into H+0,1,2 jet bins; different uncertainties in each bin

σ [fb]	LO (pdfs, α_s)	NLO (pdfs, α_s)	NNLO (pdfs, α_s)
0-jets	$3.452^{+7\%}_{-10\%}$	$2.883^{+4\%}_{-9\%}$	$2.707^{+5\%}_{-9\%}$
1-jet	$1.752^{+30\%}_{-26\%}$	$1.280^{+24\%}_{-23\%}$	$1.165^{+24\%}_{-22\%}$
$\geq$ 2-jets	$0.336^{+91\%}_{-44\%}$	$0.221^{+81\%}_{-42\%}$	$0.196^{+78\%}_{-41\%}$

Smaller uncertainty than inclusive in dominant 0-jet bin

M_H=160 GeV   Anastasiou et al.0905.3529

New NLO result for 2-jet bin; previous result was LO in this bin Campbell, Ellis, Williams 1001.4495

m_H [GeV]	150	160	165	170	180
Γ_H [GeV]	0.0174	0.0826	0.243	0.376	0.629
σ_{LO} [fb]	$0.329^{+92\%}_{-45\%}$	$0.345^{+92\%}_{-44\%}$	$0.331^{+92\%}_{-44\%}$	$0.305^{+92\%}_{-44\%}$	$0.245^{+91\%}_{-44\%}$
σ_{NLO} [fb]	$0.447^{+37\%}_{-30\%}$	$0.476^{+35\%}_{-31\%}$	$0.458^{+36\%}_{-31\%}$	$0.422^{+41\%}_{-30\%}$	$0.345^{+37\%}_{-31\%}$
Finite m_t correction, R	1.098 ± 0.003	1.113 ± 0.003	1.122 ± 0.004	1.130 ± 0.005	1.149 ± 0.005

Reduction in scale uncertainty yet to be applied in analysis

Theoretical uncertainties

- Use of EFT for top quark: study of $1/m_t$ corrections matched to high energy limit indicates ±1% uncertainty
- Bottom-quark terms: choice of pole, MS mass leads to estimate of ±1% uncertainty
- EW terms: EFT for mixed QCD/EW corrections valid to M_W; for Higgs masses of $M_H \leq 200$ GeV, roughly equivalent to extending top-quark EFT to $M_H = 1$ TeV. This results in error of ±10-15%, estimate same for QCD/EW terms. These reach max of 6% of total cross section ⇒ ±1% conservative estimate of uncertainty

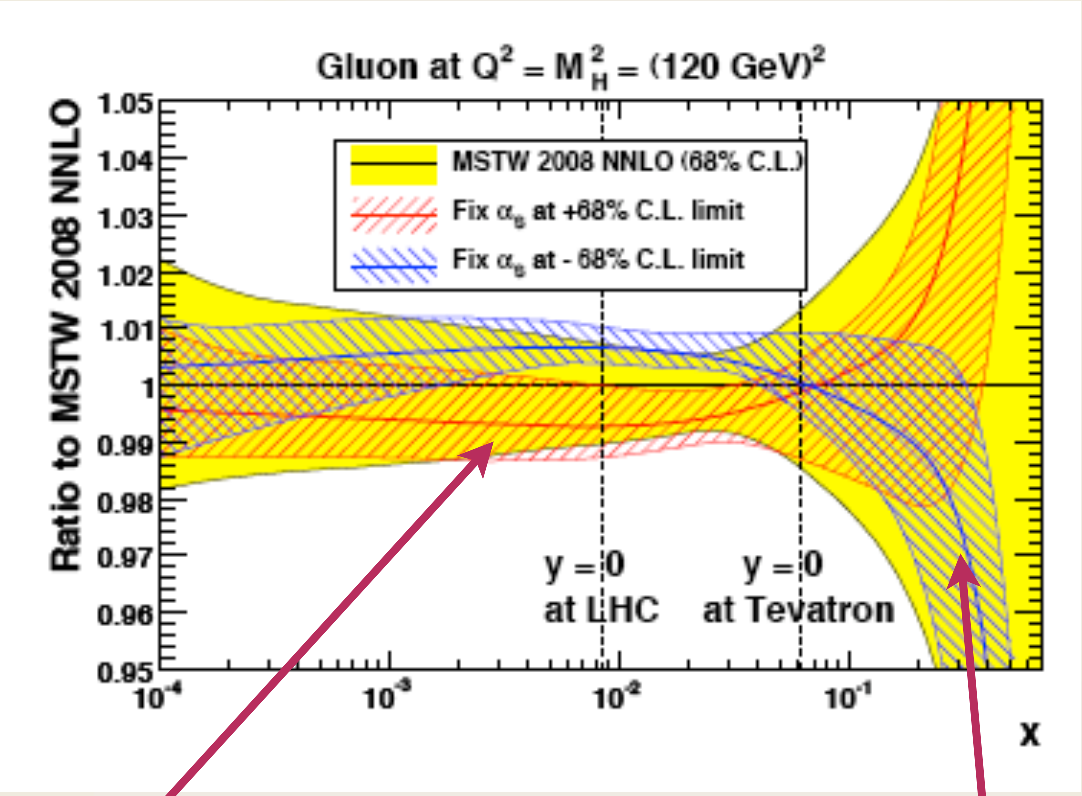
PDF+α_S uncertainties

- Higgs cross section very sensitive to gluon distribution and α_S; begins at α_S^2, and higher-order corrections very large…
- Both groups (Anastasiou, Boughezal, FP; de Florian, Grazzini) use NNLO PDFs
  - Need NNLO DGLAP kernels, otherwise structure of $\ln(\mu_F)$ terms wrong
  - Need to fit using NNLO cross sections, otherwise α_S^2 coefficient functions effectively arbitrary
- Two choices: MSTW; Alekhin, Blumlein, Klein, Moch (ABKM) 0908.2766
- MSTW: DIS, neutrino di-muon, fixed-target DY, Tevatron W/Z, **Tevatron jets**
  - ABKM: DIS, neutrino di-muon, fixed-target DY
- MSTW, ABKM both derive α_S from their fit; other choice, set to world average

PDF+α_S uncertainties

- Important correlations between gluon and α_S that should be considered when obtaining error

MSTW 0905.3531



Anti-correlation at low-x to maintain $dF_2/d\ln(Q^2) \sim \alpha_S \times g$ at HERA

Momentum sum rule gives correlation at high-x

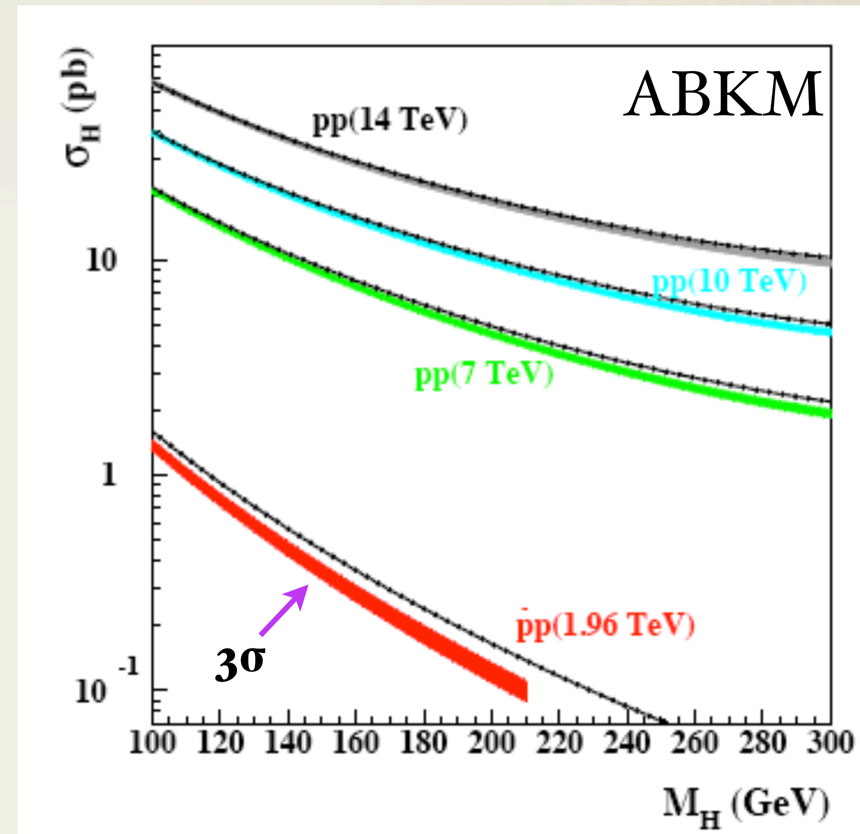
Another interesting feature, seen in Fig. 11(f), is the confirmation of the anticorrelation between the small-x gluon and α_S. This is seen for x between 10^{-4} and 0.1 at $Q^2 = 10^4$ GeV^2, and is a consequence of maintaining the fit quality to the small-x HERA data, i.e. the values of $\partial F_2/\partial \ln Q^2 \sim \alpha_S\, g$. From the momentum sum rule this results in a positive correlation of the high-x gluon and α_S. Note that there is some asymmetry in the deviation. We will return

PDF+α_S uncertainties

- Why do the two fits give such different strong couplings?

	$\alpha_s(M_Z^2)$	
ABKM	0.1135 ± 0.0014	heavy quarks: FFN $N_f = 3$
ABKM	0.1129 ± 0.0014	heavy quarks: BMSN-approach
BBG [42]	$0.1134\ ^{+0.0019}_{-0.0021}$	valence analysis, NNLO
AMP06 [37]	0.1128 ± 0.0015	
JR [52]	0.1124 ± 0.0020	dynamical approach
MSTW [43]	0.1171 ± 0.0014	
BBG [42]	$0.1141\ ^{+0.0020}_{-0.0022}$	valence analysis, N^3LO

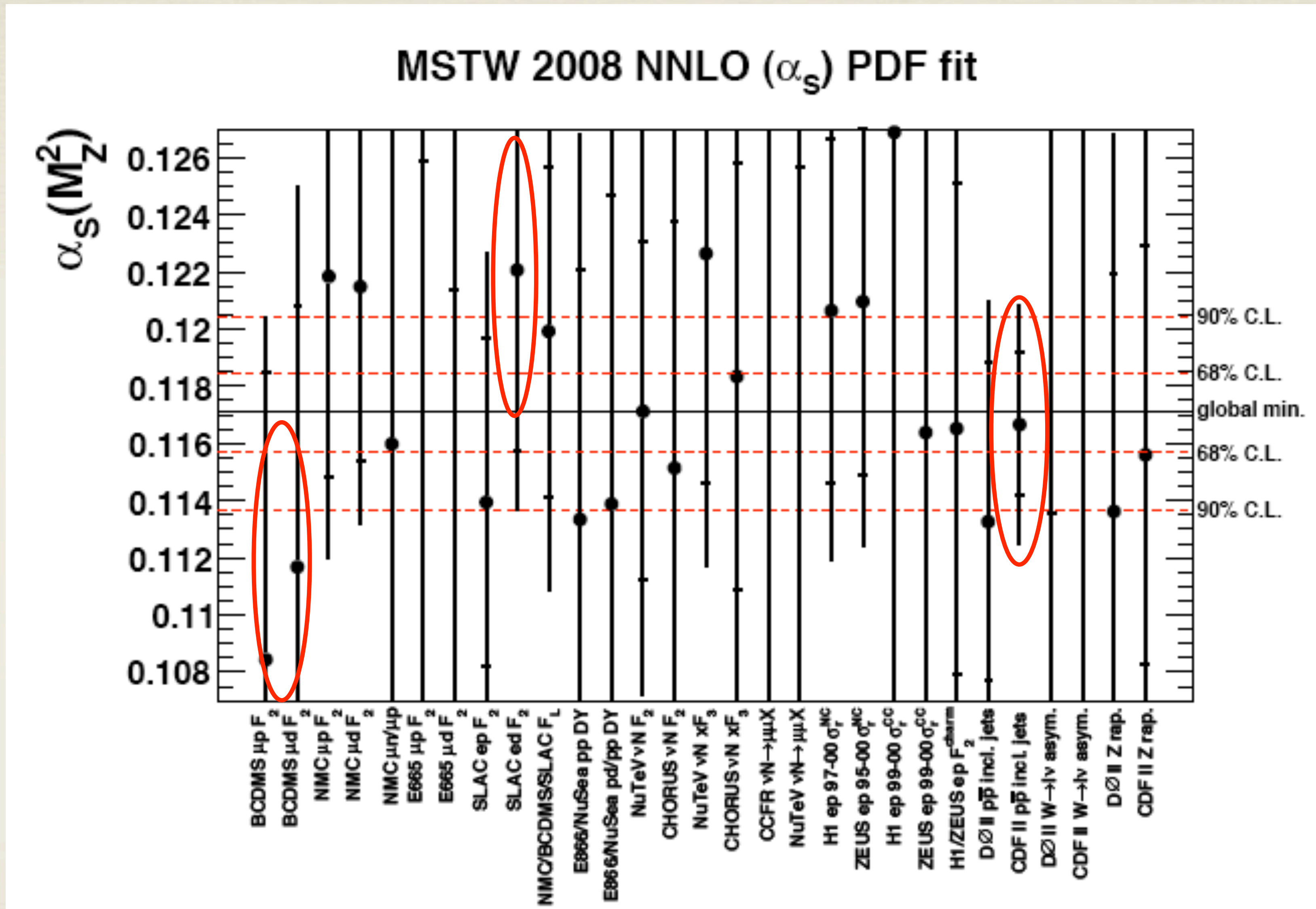
Table 3: Comparison of different measurements of $\alpha_s(M_Z^2)$ at NNLO and higher order.



Additional theoretical uncertainty estimated at ±0.002 (Alekhin, MSTW)

World Average: 0.1184±0.0007
Dissertori et al. e^+e^-: 0.1175±0.002(exp)±0.0015(th)

PDF+α_S uncertainties



In MSTW fit, α_S set by BCDMS μ-p (upper limit), SLAC e-d (lower limit), CDF jets (smallest allowed range of α_S for a single set)

Could missing NNLO corrections to jet production cause this discrepancy?

PDF+α_S uncertainties

- Currently additional theory error on α_S not included; BD suggest including it using fixed-coupling MSTW grids

$$\Delta\sigma^{+}_{\mathrm{PDF}+\alpha_s^{\mathrm{th}}} = \sigma(\alpha_s^0 + \Delta^{\mathrm{th}}\alpha_s, S_0(\alpha_s^0 + \Delta^{\mathrm{th}}\alpha_s)) - \sigma(\alpha_s^0, S_0(\alpha_s^0))$$

$$\Delta\sigma^{-}_{\mathrm{PDF}+\alpha_s^{\mathrm{th}}} = \sigma(\alpha_s^0, S_0(\alpha_s^0)) - \sigma(\alpha_s^0 - \Delta^{\mathrm{th}}\alpha_s, S_0(\alpha_s^0 - \Delta^{\mathrm{th}}\alpha_s))$$

$$\Delta\sigma^{\pm}_{\mathrm{PDF}+\alpha_s^{\mathrm{exp}}+\alpha_s^{\mathrm{th}}} = \left((\Delta\sigma^{\pm}_{\mathrm{PDF}+\alpha_s^{\mathrm{exp}}})^2 + (\Delta\sigma^{\pm}_{\mathrm{PDF}+\alpha_s^{\mathrm{th}}})^2 \right)^{1/2}$$

what was in PDF+α_S errors
shown in earlier table

- Reasonable approach, and it is important to include this error; would like to suggest that this be used to define the uncertainty in future analyses

Combining errors

- Seems reasonable to combine 68% CL PDF errors quadratically with other experimental errors (come from propagation of experimental errors in data sets)
- Would like to see scale errors incorporated as a band for the SM prediction on the exclusion result for at least one plot... difficult since it comes from a combination of many modes
- Could a flat distribution for the scale errors within the quoted band be tried, checked against adding them quadratically? (approach followed in Lafaye et al. 0904.3866)

Summary

- Errors from missing terms in the calculation are:
  ±~10%(scale)±1%(EFT)±1%(bottom) ±1%(EW)
- Disagree with BD choice of central value in the fixed-order result, and also their range of scale variation ⇒ we know a lot about what higher-order terms appear in the cross section!
- Some updates to the 2-jet scale variation used by Tevatron
- Discrepancies in α_S values between MSTW, ABKM; as a first way to increase associated error in analysis, incorporate α_S theory error following BD approach
- Would like to see checks of the split into inclusive×acceptance, error combination