THE STRONG COUPLING AND LHC CROSS SECTIONS

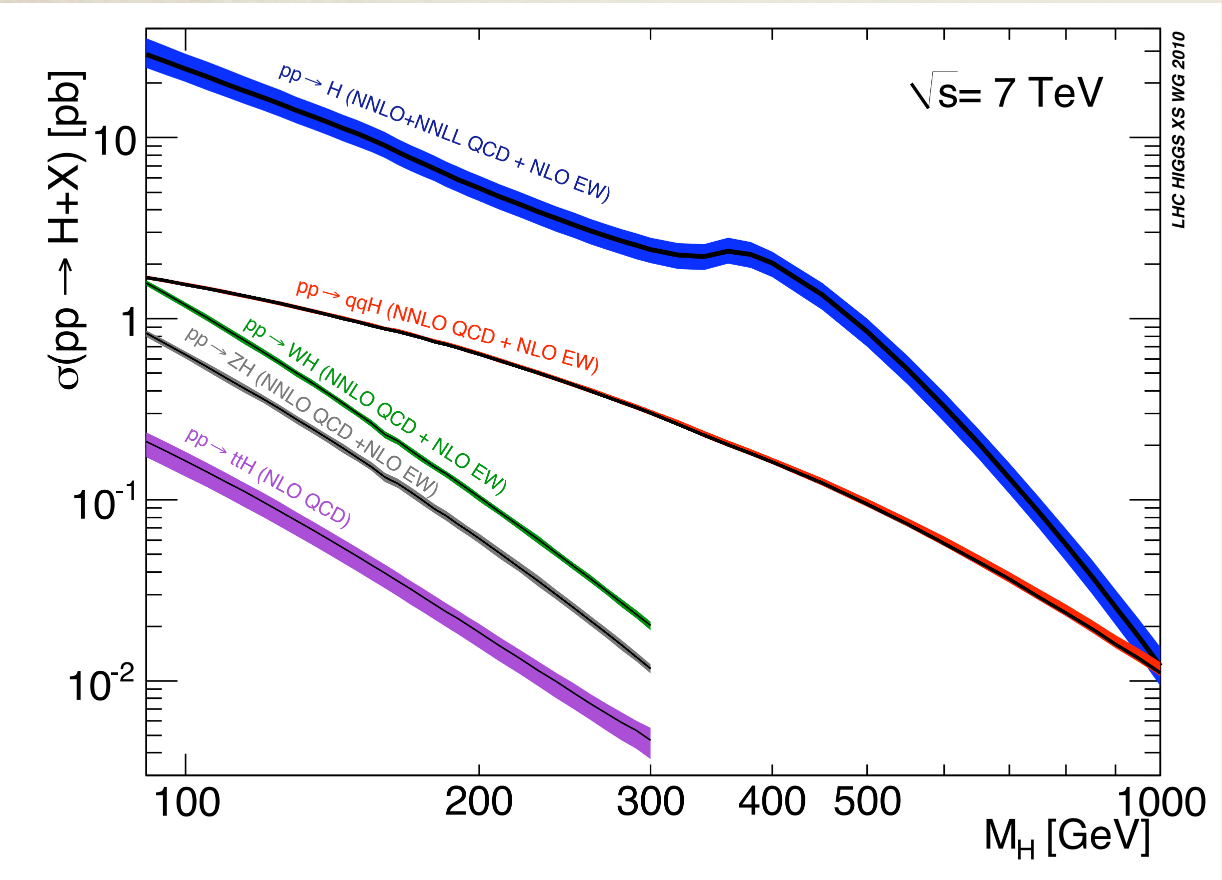
Frank Petriello
Argonne National Laboratory
and
Northwestern University

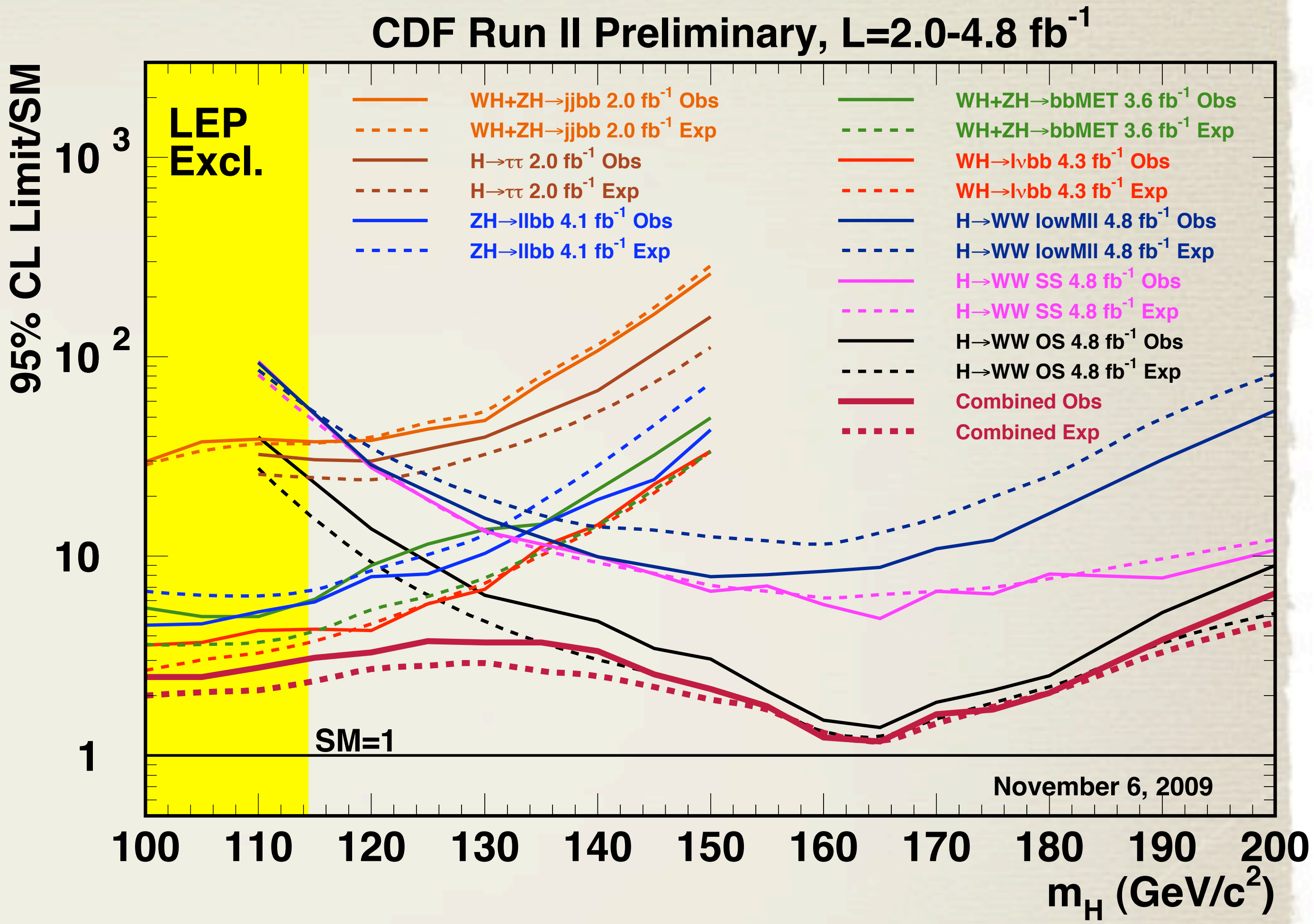
Workshop on Precision Measurements of α_S
February 11, 2011

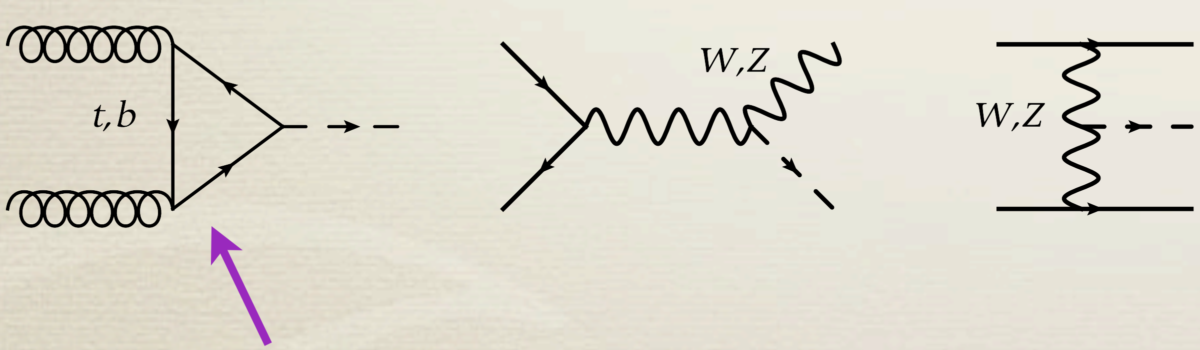
Outline

- Focus of talk: ‘customer feeback,’ what uncertainties are induced by α_S on benchmark LHC cross sections? How, and which, α_S uncertainties should be propagated through predictions?
- Emphasis on Higgs production; lively debate within community over both Tevatron results and LHC predictions
- Some further discussion of W/Z (+jets), top production

SM Higgs production





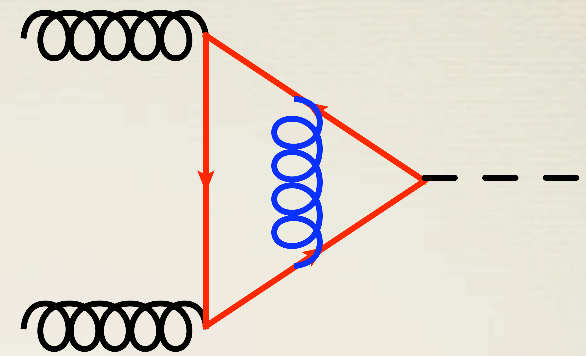


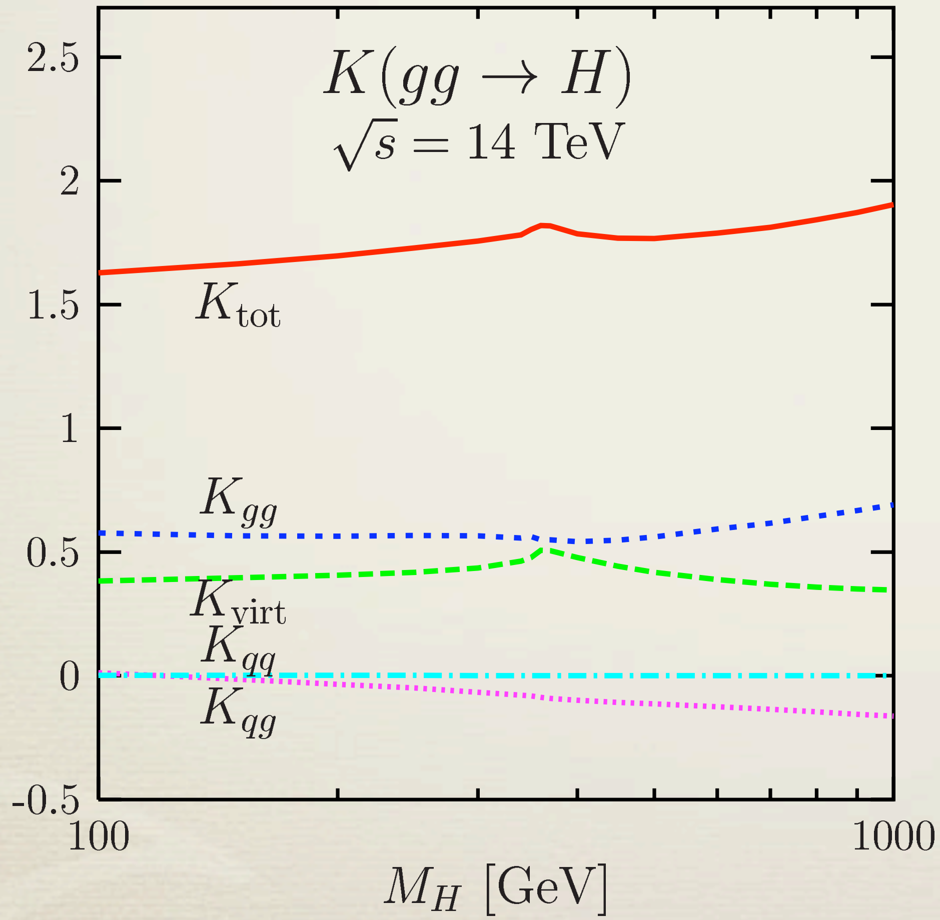
and possibly t', b', S^a, ...

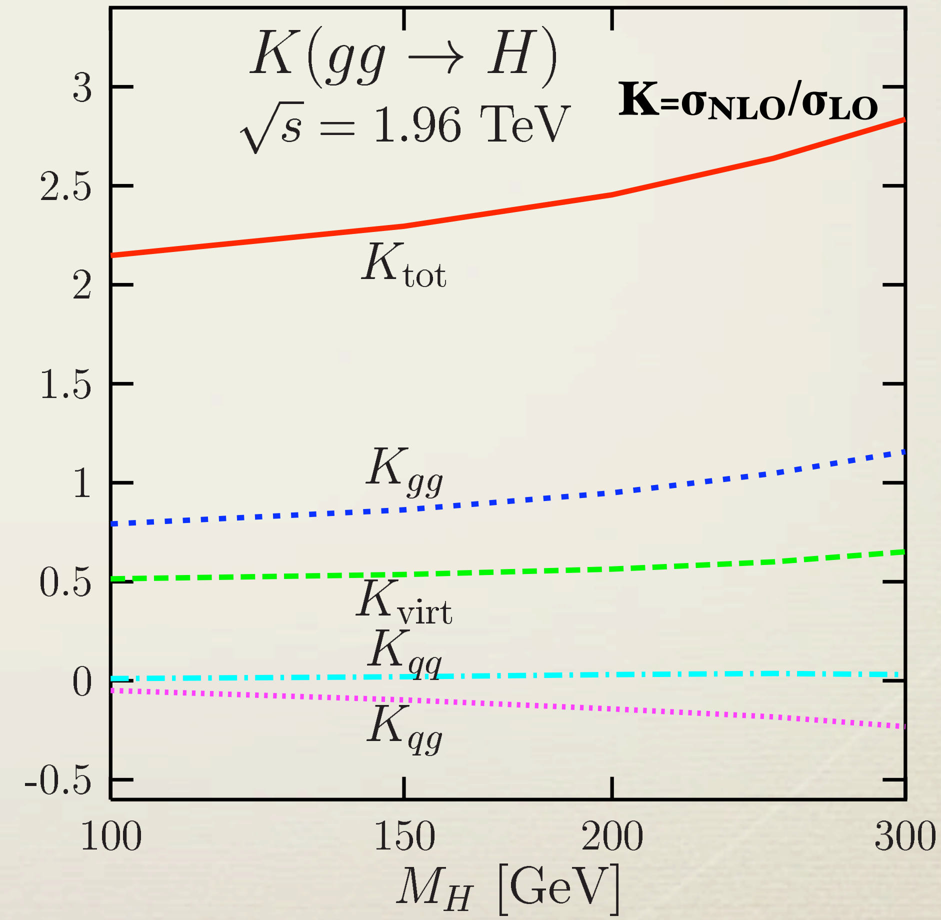
Dominant production mode is gg→h at both Tevatron, LHC

Gluon-fusion at NLO

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

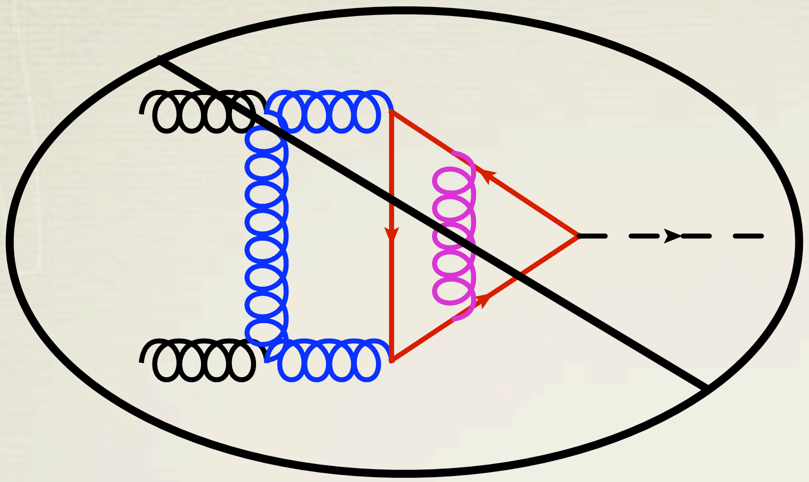






Dawson; Djouadi, Graudenz, Spira, Zerwas, 1991, 1995

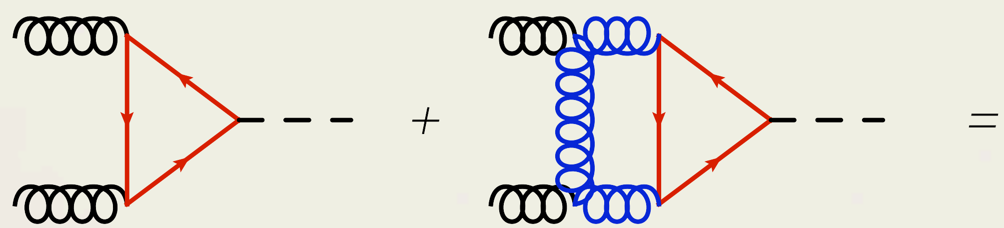
Effective interactions

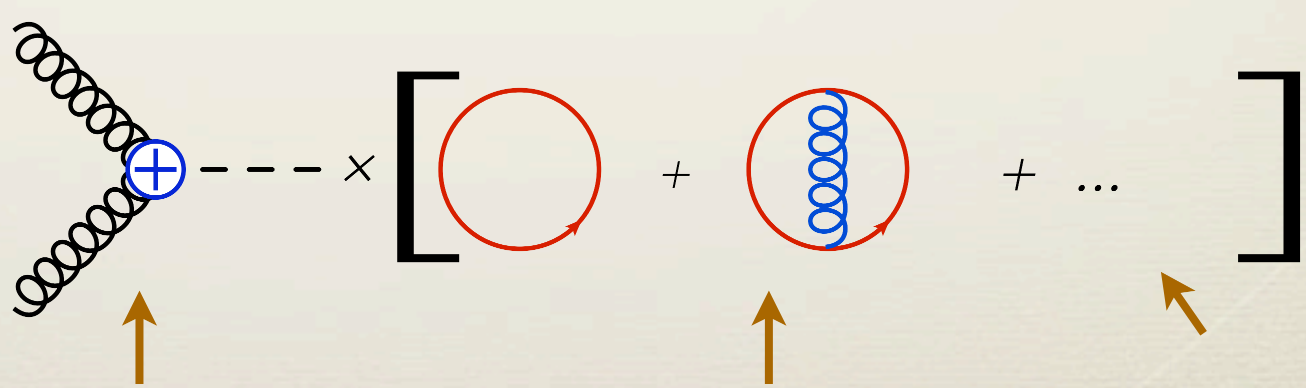


Getting the next terms requires new techniques

Effective field theory: exploit heavy mass of virtual particles

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





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

Ingredients for the prediction

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

Exact NLO top-mass dependent result + NNLO correction in the EFT Harlander, Kilgore; Anastasiou, Melnikov; Ravindran et al. 2002-2003

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

- Subleading $1/m_t$ corrections 0.5% for $M_H < 300$ GeV
  Harlander et al.; Pak, Rogal, Steinhauser 2009-2010
- Soft gluon resummation through NNLL Catani et al. 2003 and N^3LL Moch, Vogt 2005
- Two-loop EW corrections (5% increase for $M_H \approx 160$ GeV)
  Uglietti et al.; Degrassi, Maltoni; Actis et al. 2004-2008
- Mixed QCD-EW (few percent) Anastasiou, Boughezal, FP 2008
- EW effects on real radiation (1% effect) Keung, FP 2009

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

PDF+α_S error definitions

- Tevatron: MSTW 90% grids using recommended prescription (as of ICHEP 2010)

$$(\Delta F_{\mathrm{PDF}+\alpha_S})_+ = \max_{\alpha_S}\left(\{F^{\alpha_S}(S_0) + (\Delta F^{\alpha_S}_{\mathrm{PDF}})_+\}\right) - F^{\alpha_S^0}(S_0)$$

$$(\Delta F_{\mathrm{PDF}+\alpha_S})_- = F^{\alpha_S^0}(S_0) - \min_{\alpha_S}\left(\{F^{\alpha_S}(S_0) - (\Delta F^{\alpha_S}_{\mathrm{PDF}})_-\}\right)$$

- LHC follows the PDF4LHC recommendation: First compute MSTW 68% PDF+α_S errors at NNLO. Then take envelope of CTEQ, MSTW, NNPDF errors at NLO divided by MSTW error at NLO. Multiply NNLO error by this ratio, which is roughly 2.

Numerical results

Example Tevatron results: Anastasiou, Boughezal, FP; de Florian, Grazzini 2009

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)

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)

LHC predictions: LHC Higgs cross section working group 2010-2011

M_{H}[GeV]	σ[pb]	Scale [%]	PDF+α_s [%]	PDF4LHC [%]
115	18.12	+7.4 −8.0	+4.0 −3.0	+7.7 −7.0
120	16.63	+7.2 −7.9	+4.0 −3.0	+7.6 −7.0
155	9.80	+6.5 −7.3	+3.9 −3.1	+7.5 −7.5
160	9.08	+6.4 −7.2	+3.9 −3.1	+7.5 −7.6
290	2.55	+5.8 −6.1	+4.2 −3.7	+8.0 −8.3
300	2.42	+5.8 −6.0	+4.2 −3.8	+8.0 −8.3

- Scale error: $M_H/4 \le \mu_{R,F} \le M_H$, central choice $\mu = M_H/2$, restriction $1/2 < \mu_R/\mu_F < 2$
- Other theory errors (EW, EFT) at the percent level

Already the dominant error are the PDF+α_S errors

Extreme sensitivity

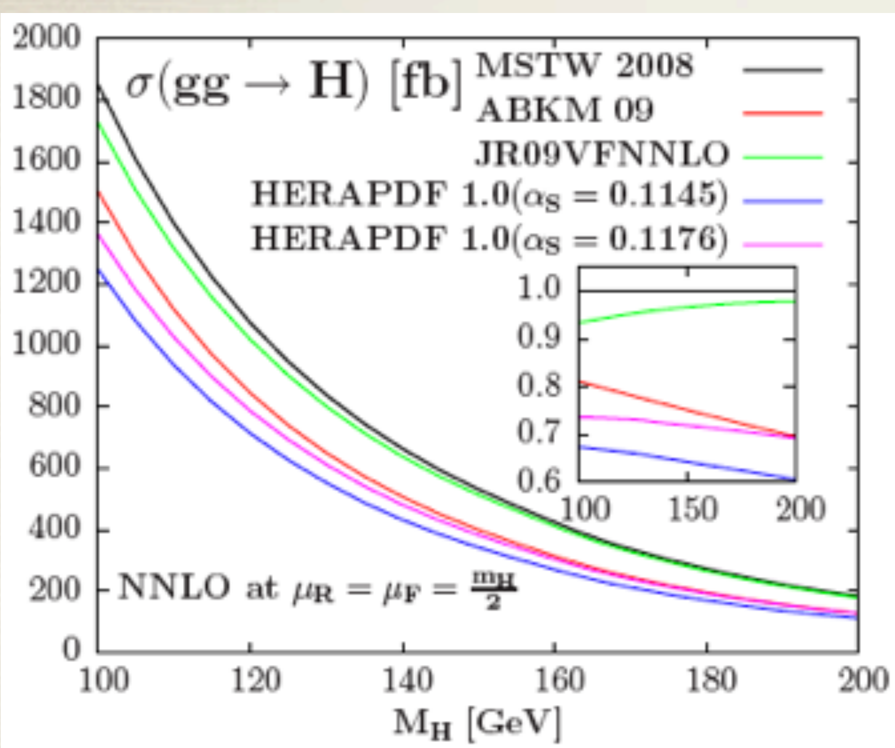
- Sensitivity of gg→H to gluon PDF, α_S:

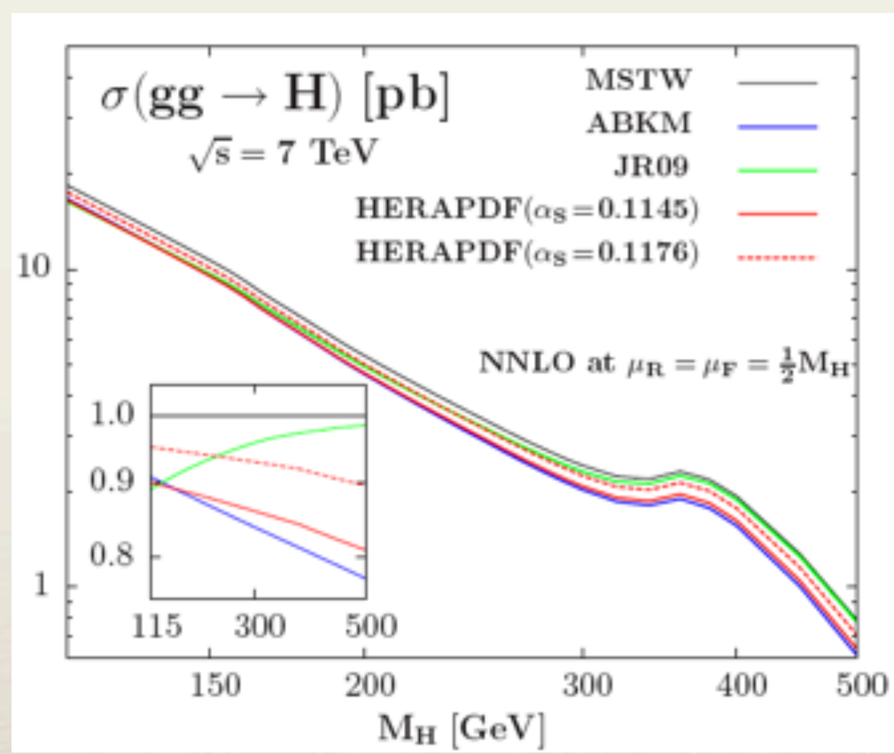
$$\text{Tevatron:}\quad \sigma \sim \alpha_S^3 \times [f_g(0.075)]^2$$

$$\text{LHC:}\quad \sigma \sim \alpha_S^{2.5} \times [f_g(0.02)]^2$$

because of large higher-order corrections

MSTW coupling: NNLO: $\alpha_S(M_Z^2) = 0.1171 \ {}^{+0.0014}_{-0.0014}$ (68% C.L.) ${}^{+0.0034}_{-0.0034}$ (90% C.L.)





10-15% (LHC) or 20-40% (TeV) differences from sets with lower α_S

from Baglio, Djouadi et al. 2009-2011

Additional α_S uncertainty

- Do the current uncertainties used properly account for this spread observed between the different sets?
- Low Higgs predictions (ABKM, HERAPDF with α_S=0.1145) tend to have low strong coupling constants

Process	Q [GeV]	$\alpha_s(Q)$	$\alpha_s(M_{Z^0})$	excl. mean $\alpha_s(M_{Z^0})$	std. dev.
τ-decays	1.78	0.330 ± 0.014	0.1197 ± 0.0016	0.11818 ± 0.00070	0.9
DIS $[F_2]$	2 - 170	–	0.1142 ± 0.0023	0.11876 ± 0.00123	1.7
DIS [e-p $\rightarrow$ jets]	6 - 100	–	0.1198 ± 0.0032	0.11836 ± 0.00069	0.4
$Q\overline{Q}$ states	7.5	0.1923 ± 0.0024	0.1183 ± 0.0008	0.11862 ± 0.00114	0.2
Υ decays	9.46	$0.184^{+0.015}_{-0.014}$	$0.119^{+0.006}_{-0.005}$	0.11841 ± 0.00070	0.1
e^+e^- [jets & shps]	14 - 44	–	0.1172 ± 0.0051	0.11844 ± 0.00076	0.2
e^+e^- [ew prec. data]	91.2	0.1193 ± 0.0028	0.1193 ± 0.0028	0.11837 ± 0.00076	0.3
e^+e^- [jets & shps]	91 - 208	–	0.1224 ± 0.0039	0.11831 ± 0.00091	1.0

(Bethke, arXiv:0908.1135)

	$\alpha_s(M_Z^2)$	
BBG (2006)	$0.1134 \begin{array}{l} +0.0019 \\ -0.0021 \end{array}$	valence analysis, NNLO
ABKM	0.1135 ± 0.0014	HQ: FFS $N_f = 3$
ABKM	0.1129 ± 0.0014	HQ: BSMN-approach
JR (2008)	0.1124 ± 0.0020	dynamical approach
MSTW (2008)	0.1171 ± 0.0014	
HERAPDF (2010)	0.1145	(combined H1/ZEUS data, prelimiary)
ABM (2010)	0.1147 ± 0.0012	(FFN, combined H1/ZEUS data in)
A.Hoang et al.	$0.1135 \pm 0.0011 \pm 0.0006$	e^+e^- thrust
BBG (2006)	$0.1141 \begin{array}{l} +0.0020 \\ -0.0022 \end{array}$	valence analysis, N^3LO
WA (2009)	0.1184 ± 0.0007	

Blümlein, Munich 2011

Given large spread of values and σ sensitivity, do current prescriptions account for uncertainty?

Theory α_S uncertainty

- Currently, an additional theory error on α_S not included; one suggestion for including it in cross section predictions:

Baglio, Djouadi 2009

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

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

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

what was in PDF+α_S errors
shown in earlier table

What $\Delta^{\mathrm{th}}\alpha_S$ be taken? ±0.002 as suggested in MSTW?

W/Z production

- Important for calibration, backgrounds; potential eventual use as a few percent-level partonic luminosity monitor
  Dittmar, Pauss Zurcher 1997
- Comparison of pp→(Z,γ*)→ll with different sets at NNLO using FEWZ: Melnikov, FP 2006; Gavin et al. 2010; see also Alekhin et al. 2011

$$\text{MSTW:}\quad \sigma_{inc} = 963.7^{+4.9}_{-6.8}(\text{scale})^{+16.7}_{-15.2}(\text{PDF})^{+24.3}_{-17.9}(\text{PDF}+\alpha_S)\ (\text{pb})$$

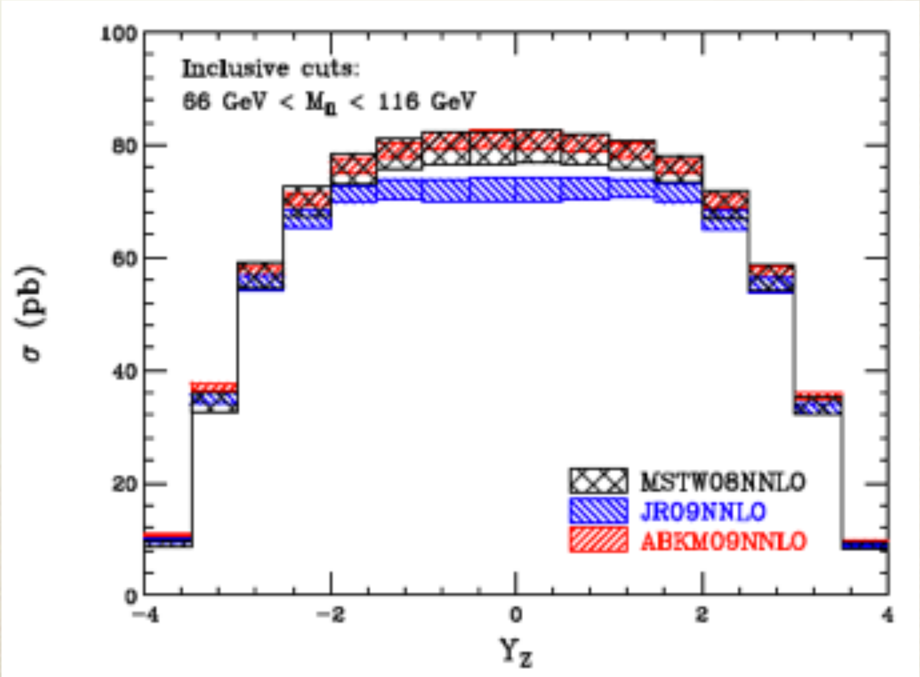
$$\text{ABKM:}\quad \sigma_{inc} = 980.5^{+15.6}_{-15.6}(\text{PDF}+\alpha_S)$$

$$\text{JR:}\quad \sigma_{inc} = 907.3^{+17.9}_{-20.3}(\text{PDF}+\alpha_S)$$

$$\text{ATLAS:}\quad \sigma_{inc} = 830^{+70}_{-70}(\text{stat.})^{+60}_{-60}(\text{syst.}) \pm 90(\text{lumi.})\ \text{pb};$$

$$\text{CMS:}\quad \sigma_{inc} = 882^{+77}_{-73}(\text{stat.})^{+42}_{-36}(\text{syst.}) \pm 97(\text{lumi.})\ \text{pb}.$$

- Scale errors negligible; dominant uncertainty from PDFs
- MSTW errors seem to indicate little direct sensitivity to α_S (increase of <1% when adding its uncertainty to PDF one)
- Small impact of α_S remains true for most distributions: lepton η, Z rapidity, ...

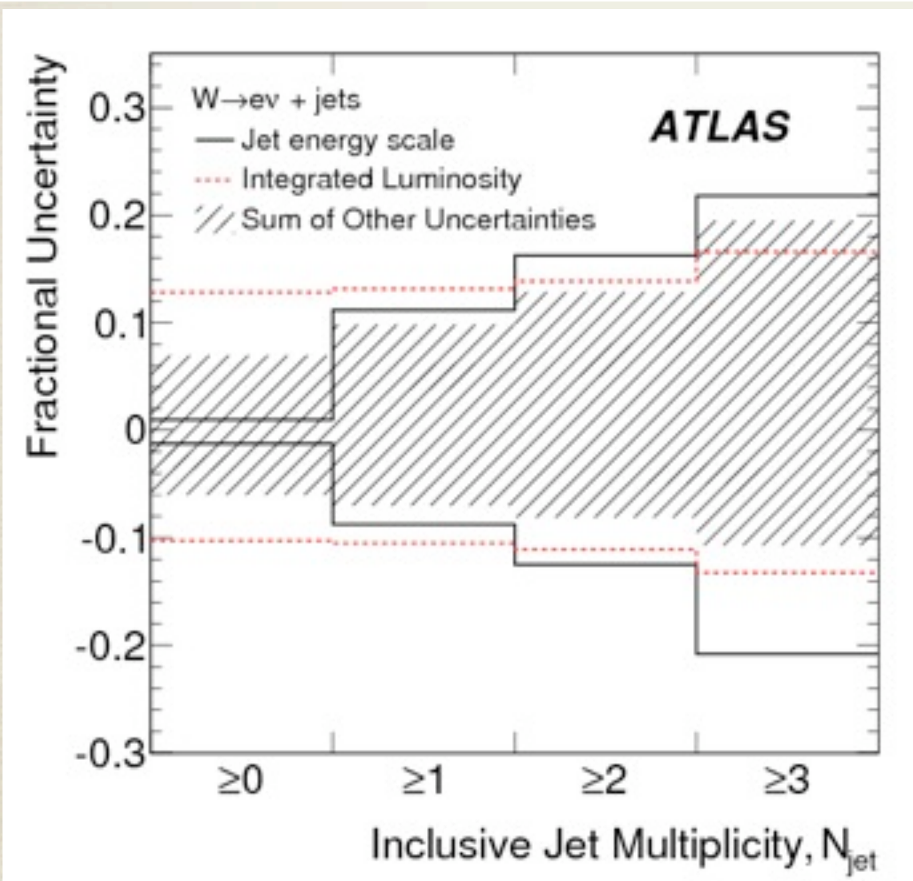


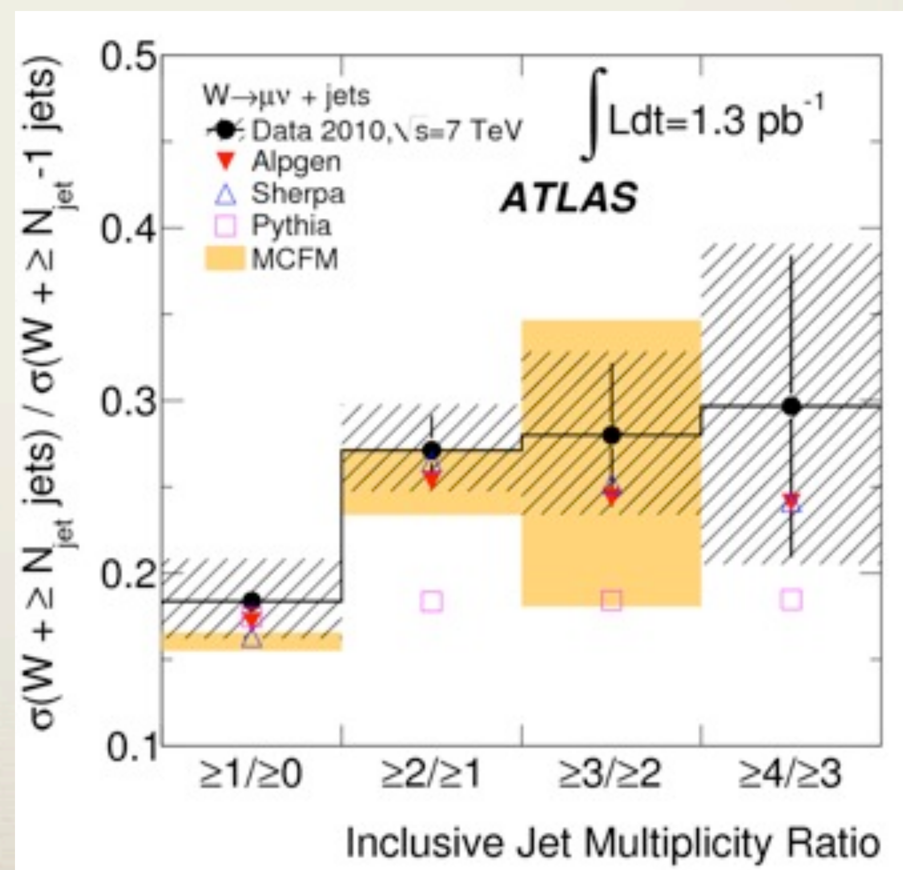
W/Z+jet(s)

- W/Z+n jet production proportional to α_S^n; can constraints on coupling be derived from these data sets?
  - From running MSTW 68% CL with FEWZ:
    Z+1 jet: ±1.2% (PDF); ±2.5% (PDF+α_S)
    Z+2 jets: ±0.6% (PDF); ±2.6% (PDF+α_S)

⇒ at least currently, JES and other systematics too large

NNLO: $\alpha_S(M_Z^2) = 0.1171 \ {}^{+0.0014}_{-0.0014}$ (68% C.L.) ${}^{+0.0034}_{-0.0034}$ (90% C.L.)

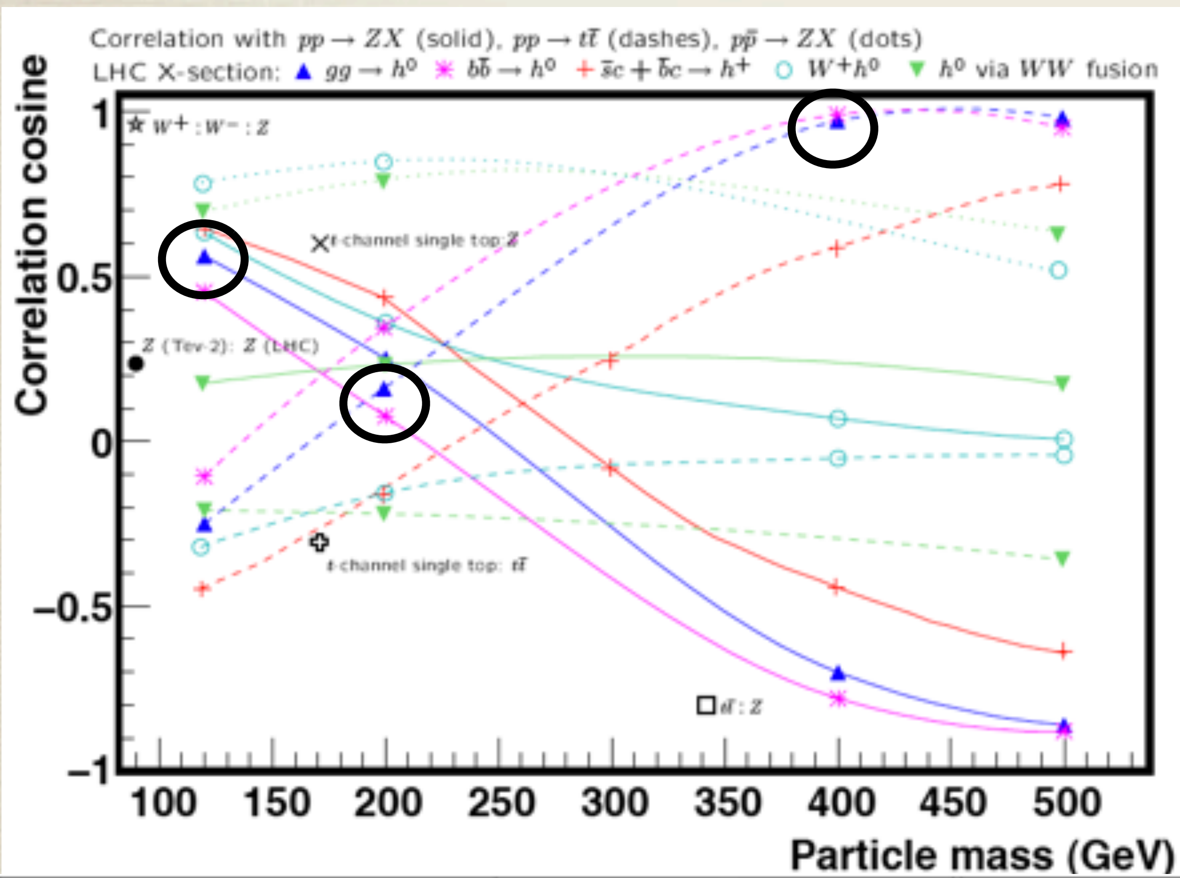




⇒JES is dominant

Top production

- Dominant partonic production has $\sigma \sim \alpha_S^2 \times f_g^2$; strong correlation with Higgs expected; ratio should lead to error cancellation



- Only correlation with Higgs at higher masses due to different contributing x_{BJ}
- Interestingly, correlation between Higgs and Z at low M_H

		$p\bar{p} \to TX$ ($\sqrt{s} = 1.96$ TeV)			$pp \to TX$ ($\sqrt{s} = 14$ TeV)		
Final state	Parameter	$\mu = m_t/2$	$\mu = m_t$	$\mu = 2\,m_t$	$\mu = m_t/2$	$\mu = m_t$	$\mu = 2\,m_t$
$T = t\bar{t}$	A [pb]	7.546	7.197	6.412	951.2	857.9	761.6
	B [pb·GeV^{-1}]	-0.237	-0.225	-0.201	-26.12	-23.43	-20.81
	C [pb·GeV^{-2}]	0.0041	0.0039	0.0034	0.41	0.37	0.33
	$\Delta_\mu(m_t = 171)$	+5%	reference	−11%	+11%	reference	−11%
	$\Delta_{PDF}(m_t = 171)$	$^{+8.4}_{-6.4}$ **(7.4)%**			$^{+3.3}_{-3.2}$ (3.3)%		

CTEQ 2008

- Will need NNLO tt cross section for α_S constraint at LHC

Conclusions

- Significant effect of the strong coupling on the Higgs search at the Tevatron and the LHC; are the errors properly accounted for in current analysis?
- Should an additional theory uncertainty be added to the current error mix?
- W/Z benchmarks relatively insensitive to α_S; perhaps constraints from V+jet(s) when JES and other systematics are tamed
- A complete NNLO result for tt is needed to exploit this channel's potential to normalize heavy Higgs cross sections and to extract α_S