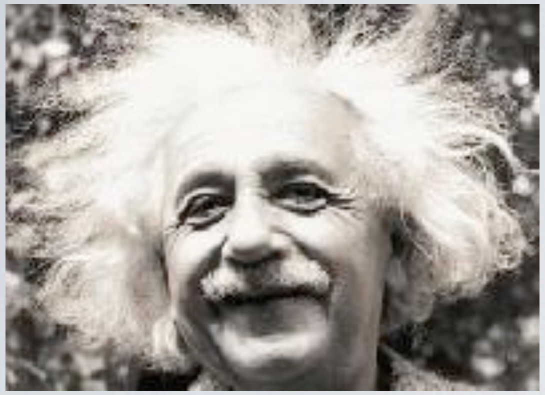
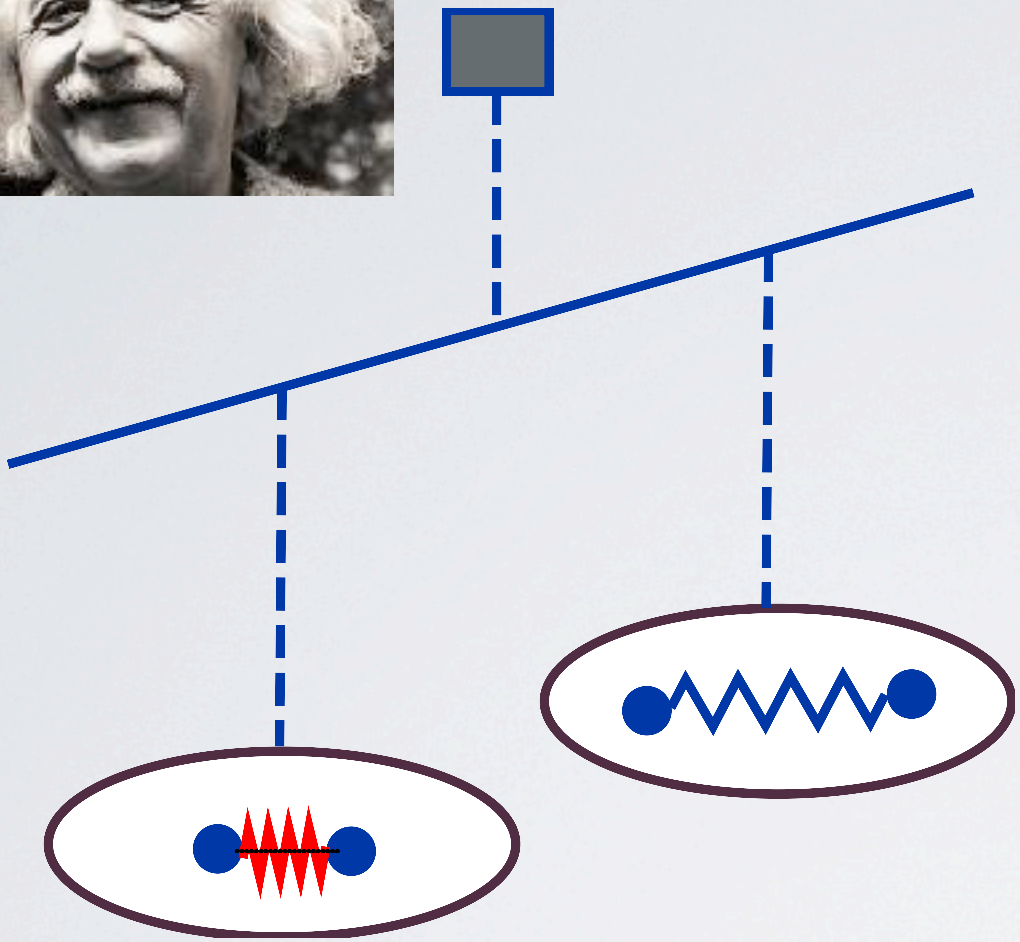
HIGGS PRODUCTION RATES AT THE TEVATRON AND THE LHC

Babis Anastasiou
Stephan Buehler
Franz Herzog
Achilleas Lazopoulos

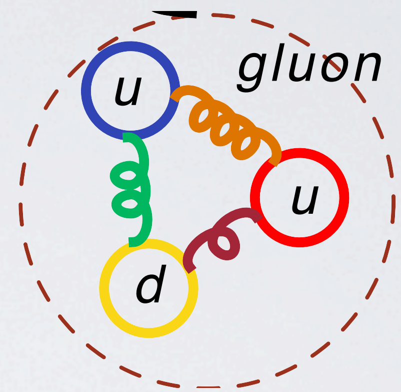
Recontres de Moriond 2011



$$Mass = \frac{Energy}{c^2}$$

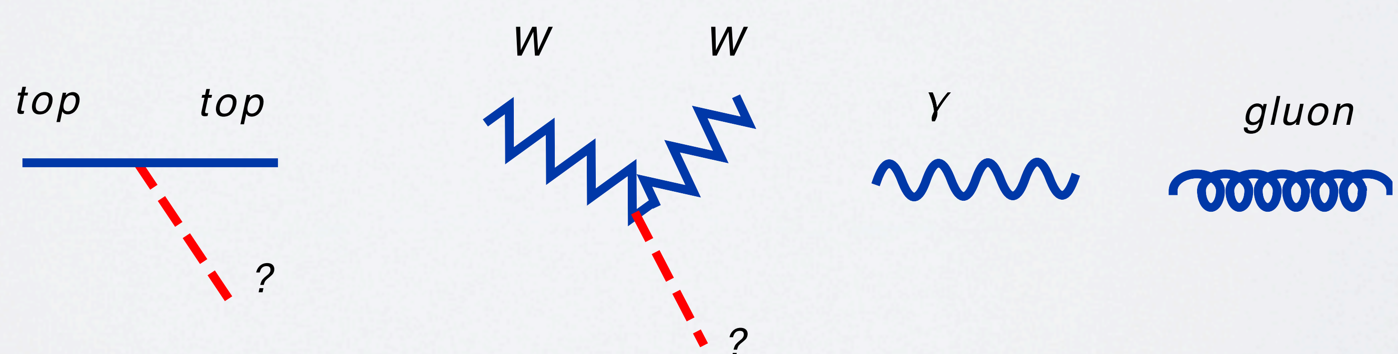


$$\text{Gluon Interactions} \approx 99\%\, m_{proton}$$

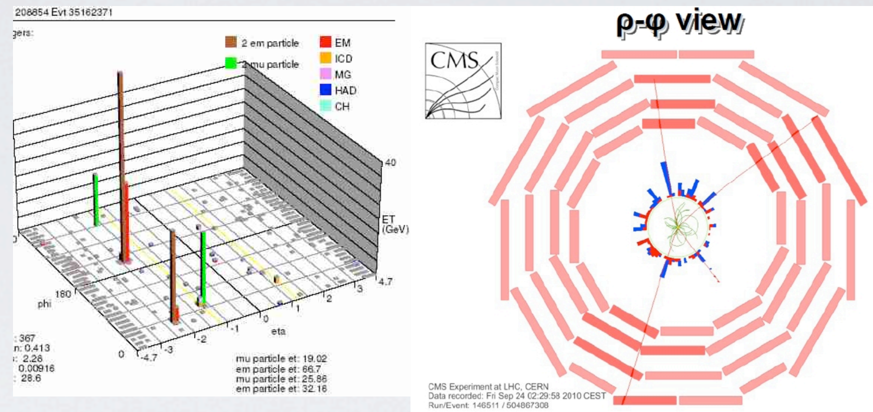


$$2m_{up} + m_{down} \approx 1\%\, m_{proton}$$

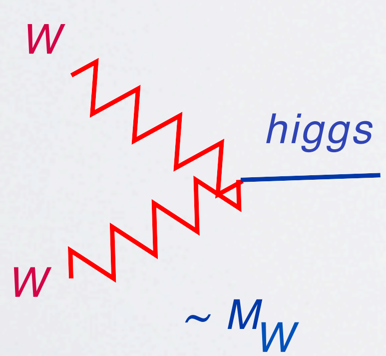
WHAT IS THE MASS OF ELEMENTARY PARTICLES?

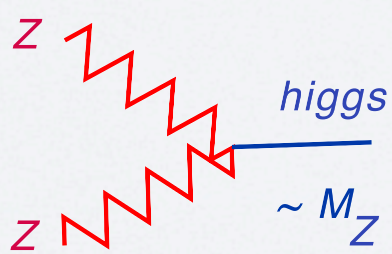


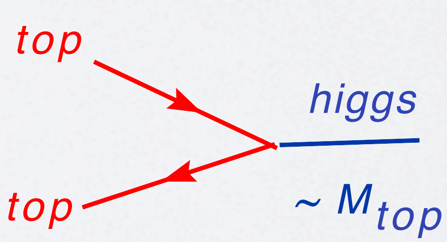
SOON TO VERIFY

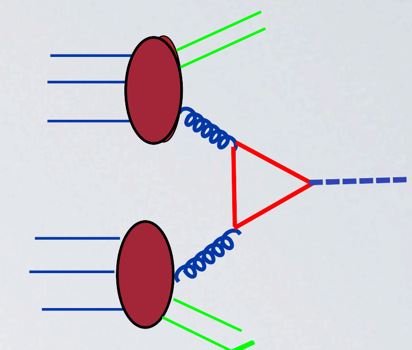


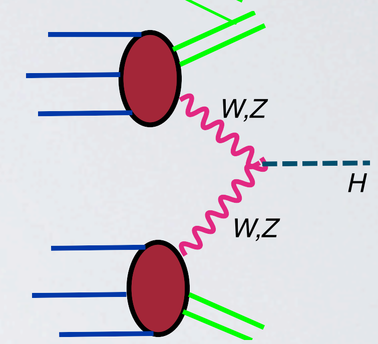
- Gluon fusion
- Electroweak gauge boson decay
- Electroweak gauge boson fusion
- Quark fusion

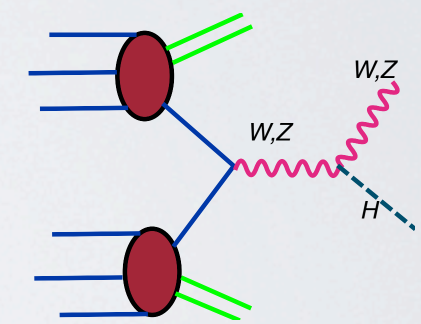


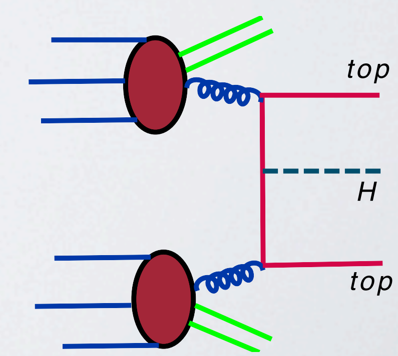










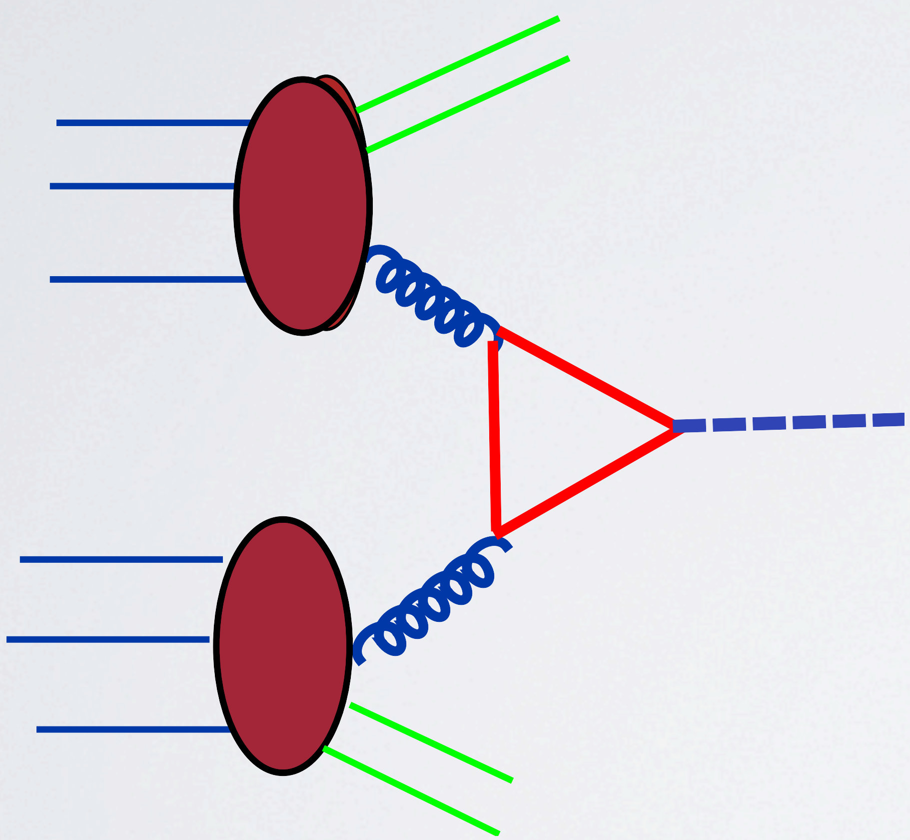


SOURCES OF UNCERTAINTY

$$\sigma = \sum_{ij} f_i(x_1) \otimes f_j(x_2) \otimes \sigma_{ij}(\mathcal{L}, E, M_H, \alpha_s, \alpha, M_t, M_b, M_w, M_z, \ldots, \text{“cuts''})$$

- Higher order perturbative corrections (Th)
- Parton densities (Exp + Th)
- Coupling and mass parameters (Exp + Th)
- Model (Th)
- Infrared behavior of cross-sections with colliding energy (Th)
- Infrared behavior of cross-sections with cuts (Exp+Th)

THE GLUON FUSION CROSS-SECTION



- LO, NLO, NNLO QCD
- Re-summing threshold logarithms and π^2
- Gluon density and strong coupling uncertainty
- ``Heavy'' top-quark approximation
- Electroweak corrections
- Trifles such as finite Higgs width, combining with branching ratios, …
- Experimental cuts
- Physics beyond the Standard Model

NLO QCD CORRECTIONS

cross-section for gluon fusion via a heavy (top) quark:

$$\sigma \sim \mathcal{L}_{gg}(\mu) \times \left(\frac{\alpha_s(\mu)}{\pi}\right)^2$$

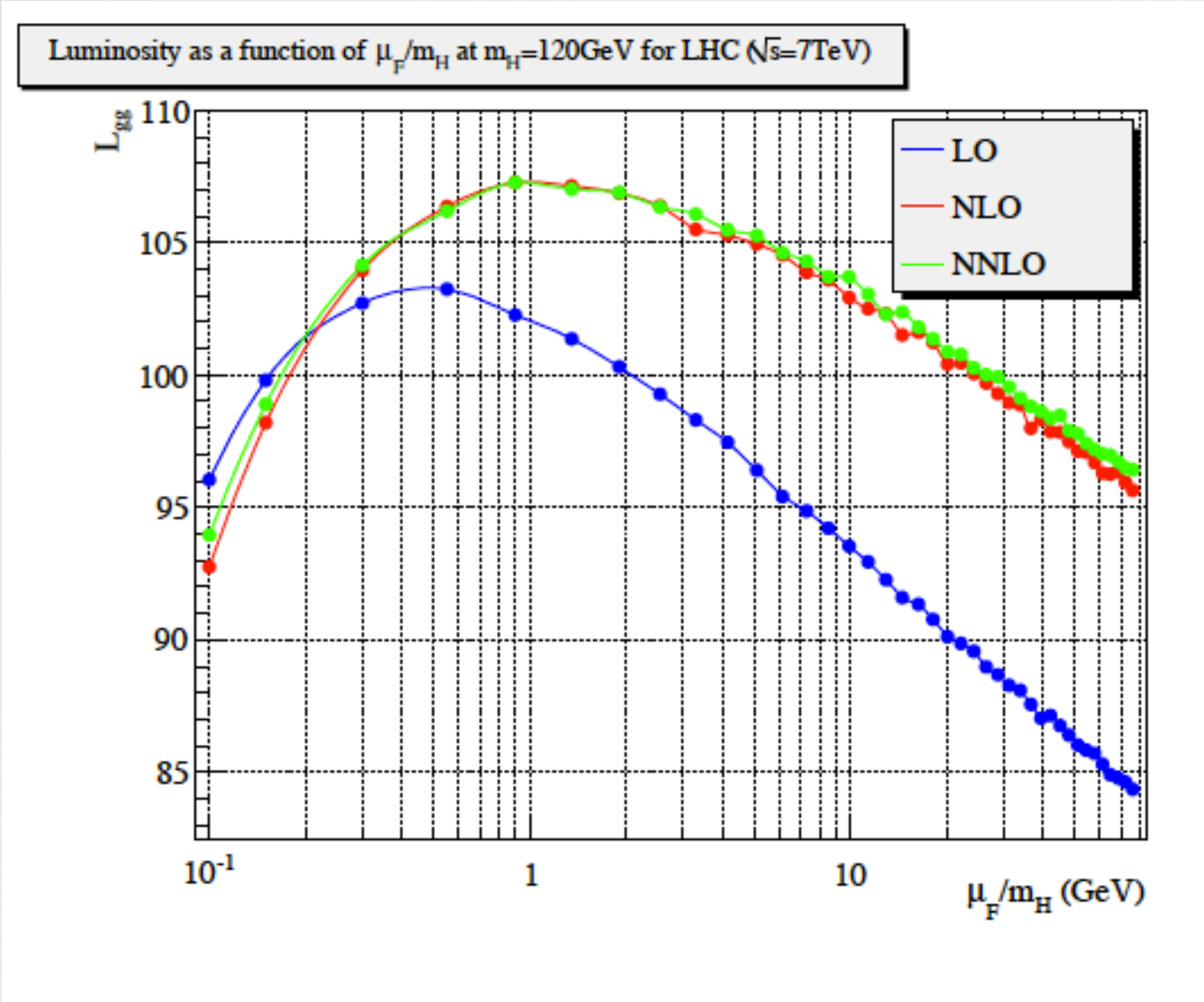
$$\left\{1 + \frac{\alpha_s(\mu)}{\pi}\left[N_c \frac{\pi^2}{3} + \frac{11}{2}\right] + 2\log\left(\frac{\mu^2}{p_T^2}\right) N_c \mathrm{Coll}\left(\frac{p_t^2}{M_h^2}\right) + \mathrm{Reg}\left(\frac{p_t^2}{M_h^2}, \theta\right)\right\}$$

Soft real and virtual corrections $\pi^2, \log\left(\frac{\mu^2}{p_T^2}\right)$

$\frac{11}{2} = 2\,C_1$ Wilson coefficient of Heavy Quark Effective Theory (~ UV nature)

$\mathrm{Reg}\left(\frac{p_t^2}{M_h^2}, \theta\right) \to 0,$ hard, vanishes in $p_t, \theta, \pi - \theta \to 0$

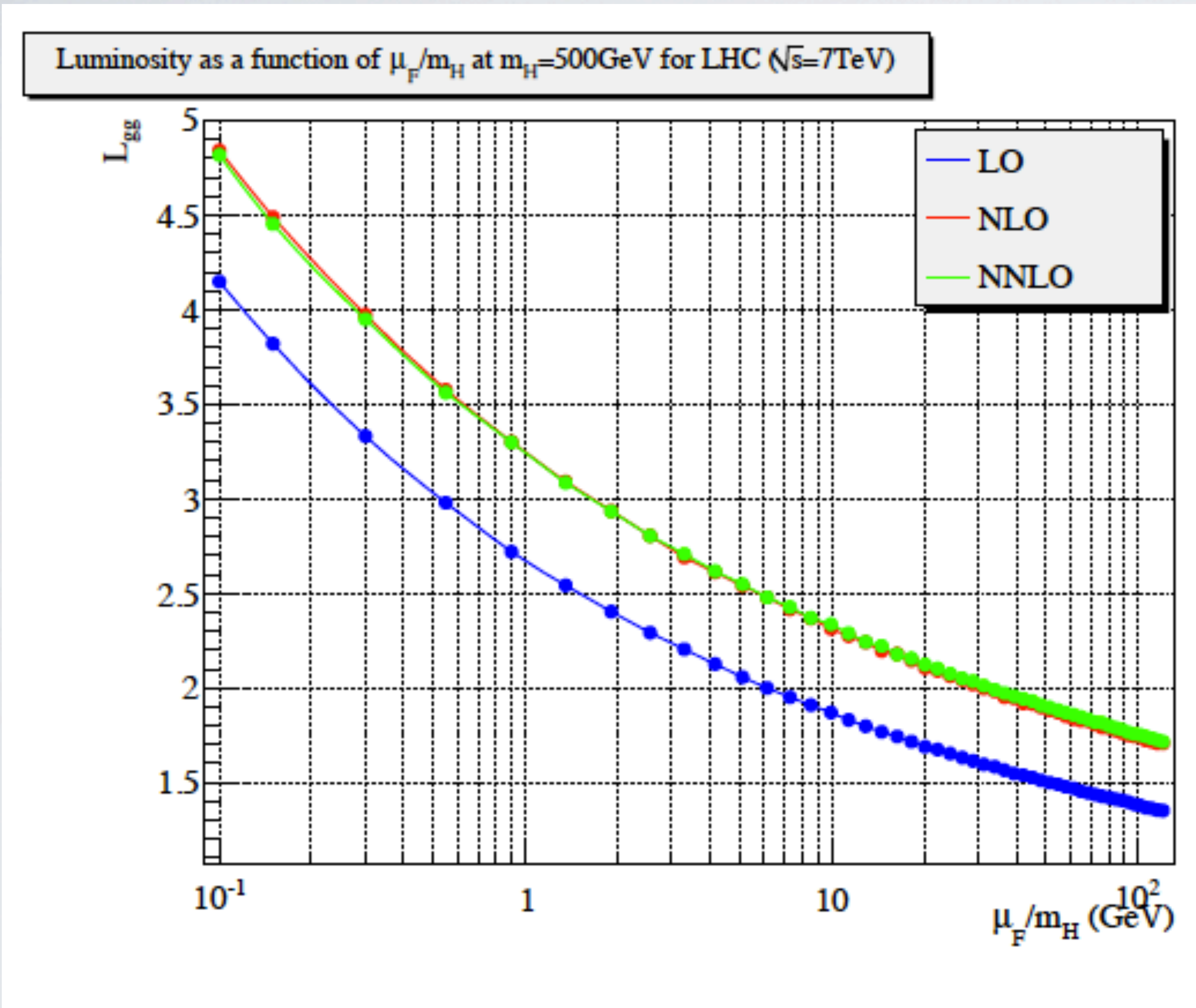
GLUON-GLUON LUMINOSITY



Lgg(Mh=120GeV, LHC7, MSTW08)

- Very stable from NLO to NNLO
- Within 5% from LO for a light Higgs boson at the LHC for reasonable factorization scales.
- ~ 20% higher than LO for large factorization scales

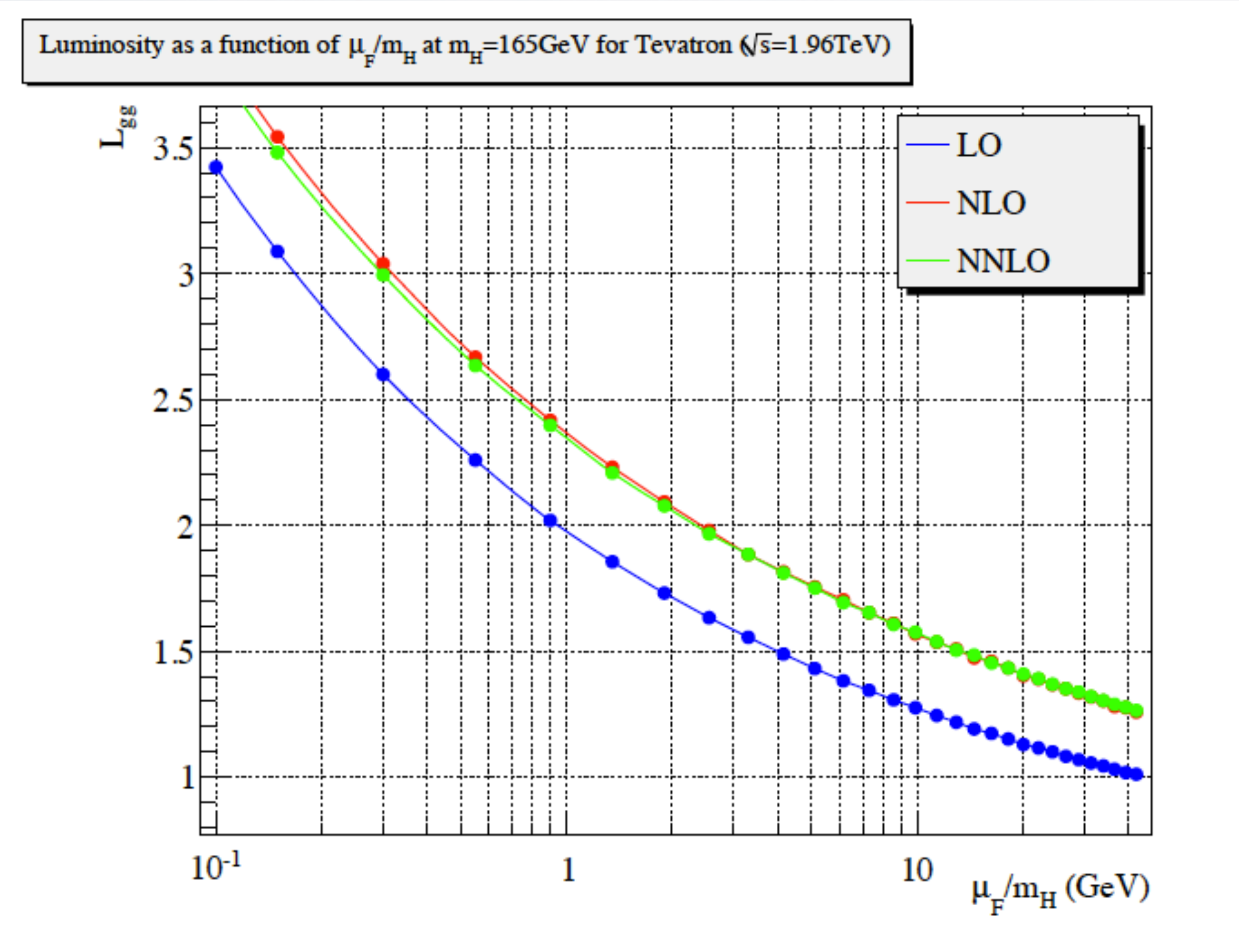
GLUON-GLUON LUMINOSITY



Lgg(Mh=500GeV, LHC7, MSTW08)

- Very stable from NLO to NNLO
- Within 15-20% from LO for a heavy Higgs boson at the LHC.

GLUON-GLUON LUMINOSITY



- Very stable from NLO to NNLO
- Within 15-20% from LO for a light Higgs boson at the TEVATRON.

Lgg(Mh=165GeV, TEVATRON, MSTW08)

LARGE K-FACTORS

$$\frac{\text{NLO}}{\text{LO}} \sim (80\% - 105\%)\left\{1 + 4\%\left[\underset{\pi^2}{9.876} + 5.5\right] + \ldots\right\}$$

NLO/LO gluons and alpha_s

Wilson coefficient

Bound to have a large K-factor of at least 1.5-1.6 due to pi's and the Wilson coefficient

Milder K-factor if gluon fusion is mediated through a light quark (bottom) as, for example, in large tan(beta) MSSM.

Two-loop bottom amplitude.

$$\frac{\text{NLO}}{\text{LO}} \sim (80\% - 105\%)\left\{1 + 4\%\left[\underset{\pi^2}{9.876} + 0.9053\right] + \ldots\right\}$$

LARGE K-FACTORS (II)

$$\frac{\mathrm{NLO}}{\mathrm{LO}} \sim (80\% - 105\%) \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \left[\ldots + 6 \log\left(\frac{\mu^2}{p_T^2}\right) + \ldots \right] \right\}$$

NLO/LO gluons
and alpha_s

- Logarithmic enhancement at small transverse momentum
- Integrable: reliable perturbative expansion for inclusive cross-sections.
- The mu scale is arbitrary, but no need to be senseless.
- Choices very different than pt spoil the perturbative expansion.

$$M_H = 165\,\mathrm{GeV}\ \mathrm{@TEVATRON} \rightsquigarrow < p_t > \sim 25\,\mathrm{GeV}$$

$$\left\{ 1 + 4\% \left[9.876 \ + \ 5.5 \ + \mathcal{O}(20.) \right] + \ldots \right\} \mu = M_h$$

$$\frac{\mathrm{NLO}}{\mathrm{LO}} \sim (80\% - 105\%)$$

π^2 Wilson coefficient Pt-Log

NLO/LO gluons
and alpha_s

$$\left\{ 1 + 4\% \left[9.876 \ + \ 5.5 \ + \mathcal{O}(6.) \right] + \ldots \right\} \mu = \frac{M_h}{4}$$

LARGE K-FACTORS (II)

$$\frac{\text{NLO}}{\text{LO}} \sim (80\% - 105\%) \left\{ 1 + \frac{\alpha_s(\mu)}{\pi} \left[\ldots + 6 \log\left(\frac{\mu^2}{p_T^2}\right) + \ldots \right] \right\}$$

NLO/LO gluons and alpha_s

- Logarithmic enhancement at small transverse momentum
- Integrable: reliable perturbative expansion for inclusive cross-sections.
- The mu scale is arbitrary, but no need to be senseless.
- Choices very different than pt spoil the perturbative expansion.

$$M_H = 120\,\text{GeV @LHC7} \rightsquigarrow < p_t > \sim 35\,\text{GeV}$$

$$\left\{ 1 + 4\% \left[9.876 + 5.5 + \mathcal{O}(15.) \right] + \ldots \right\} \quad \mu = M_h$$

$$\frac{\text{NLO}}{\text{LO}} \sim (80\% - 105\%)$$

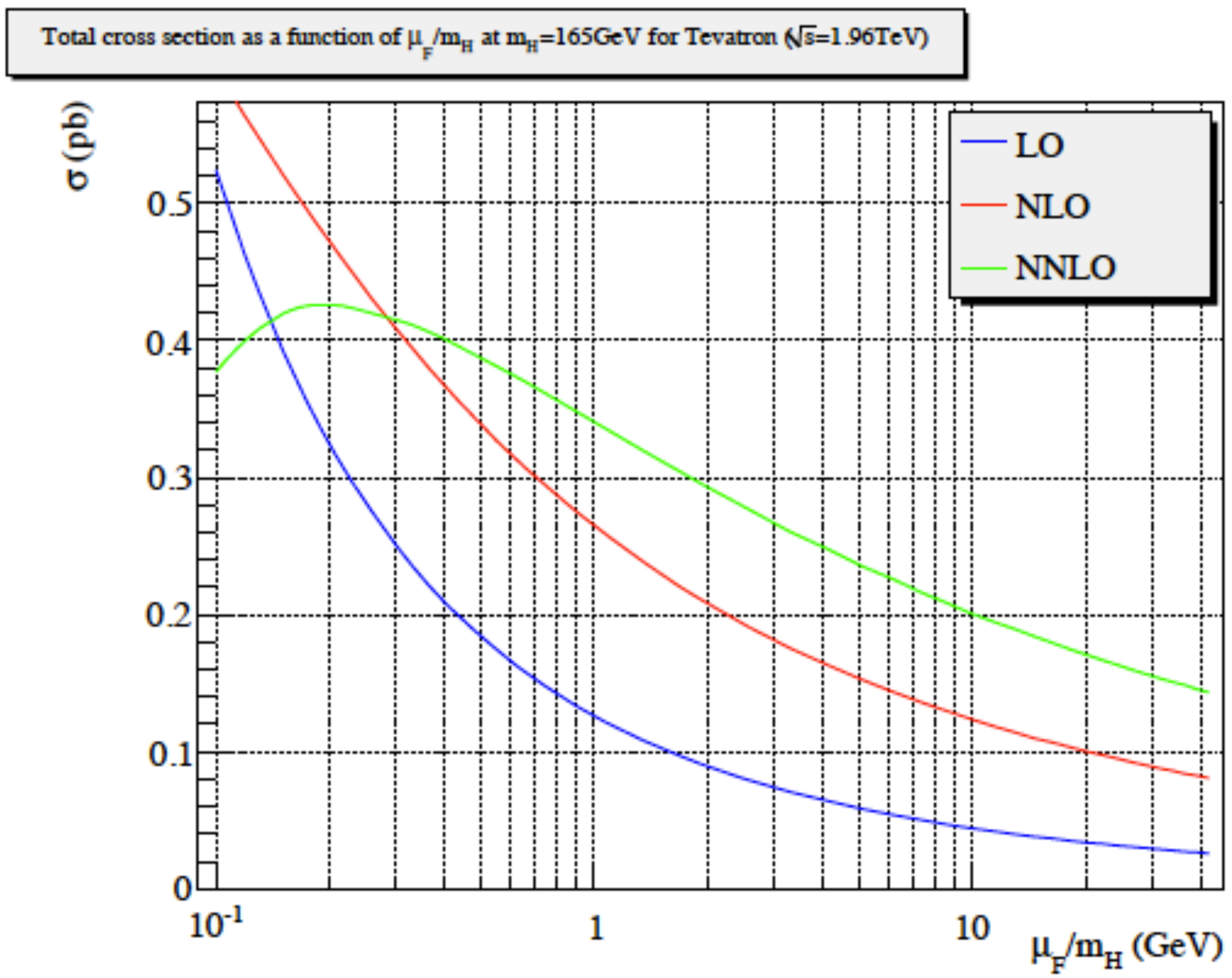
π^2 — *Wilson coefficient* — *Pt-Log*

NLO/LO gluons and alpha_s

$$\left\{ 1 + 4\% \left[9.876 + 5.5 + \mathcal{O}(1.) \right] + \ldots \right\} \quad \mu = \frac{M_h}{4}$$

GLUON FUSION CROSS-SECTION

scale variation

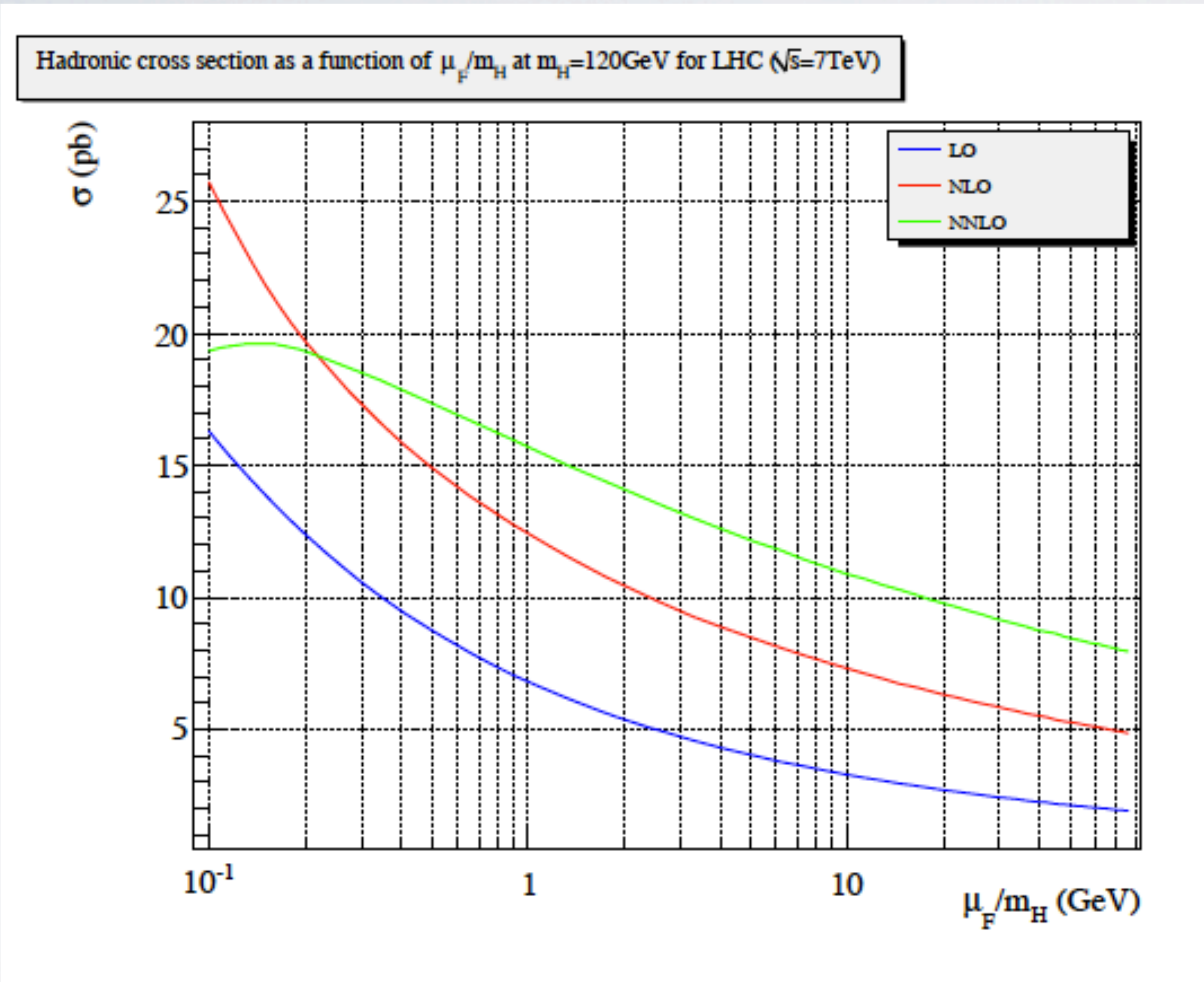


TEVATRON $M_H = 165\text{GeV}$

- Known through NNLO in fixed order perturbation theory
- ``Large'' NLO perturbative corrections.
- Smaller but significant NNLO corrections.
- Small scale variation at NNLO

GLUON FUSION CROSS-SECTION

scale variation



LHC7 $M_H = 120\text{GeV}$

- Known through NNLO in fixed order perturbation theory
- ``Large'' NLO perturbative corrections.
- Smaller but significant NNLO corrections.
- Small scale variation at NNLO

PERTURBATIVE CONVERGENCE?

- Three main worries from the NLO calculation:
  - Large NLO Wilson coefficient ~15-20%
  - Pi^2 = 2 x Nc x (Pi^2/6) term ~ 30-40%
  - Large logs (2 x Nc x Log(pt^2/mu^2)) of transverse momentum (sensitive to mu) ~1% - 80%

- Comforting that the NNLO corrections are mild. The Wilson coefficient has a regular perturbative expansion.

At NNLO:

Wilson coefficient

$$C \sim 1 + (4\%) \cdot 5.5 + (4\%)^2 \cdot 10.$$

Chetyrkin, Kniehl, Steinhauser

PERTURBATIVE CONVERGENCE?

- Half of Pi^2 belongs to a different Wilson coefficient when matching to SCET. It ``exponentiates''. We are left to explain with the other half, which is not as much of a concern.

At NNLO and beyond:

Ahrens, Becher, Neubert

$$1 + \frac{\alpha_s}{\pi} \cdot (\pi^2) + \ldots \sim e^{\frac{\alpha_s}{\pi} \cdot \left(\frac{\pi^2}{2}\right)} \left(1 + \frac{\alpha_s}{\pi}\left[\frac{\pi^2}{2}\right] \ldots\right)$$

- Logs due to soft radiation exponentiate and can be resummed with NNLL accuracy at all orders.

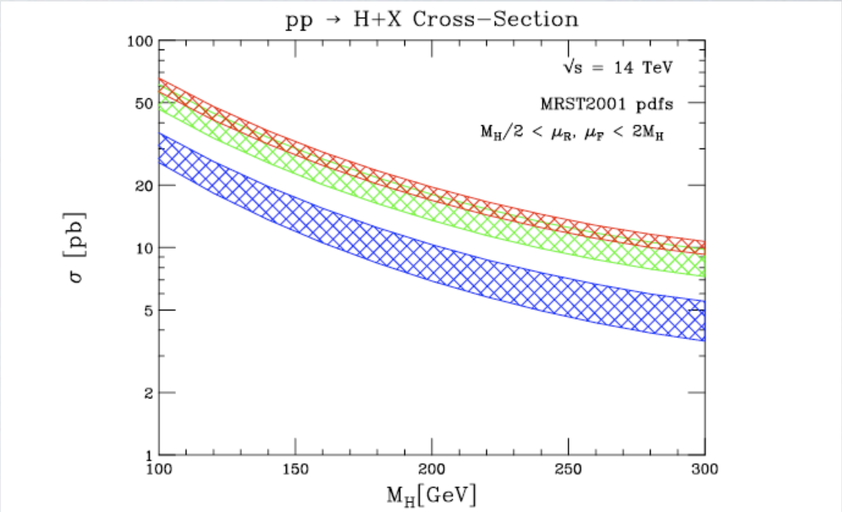
Catani, de Florian, Grazzini

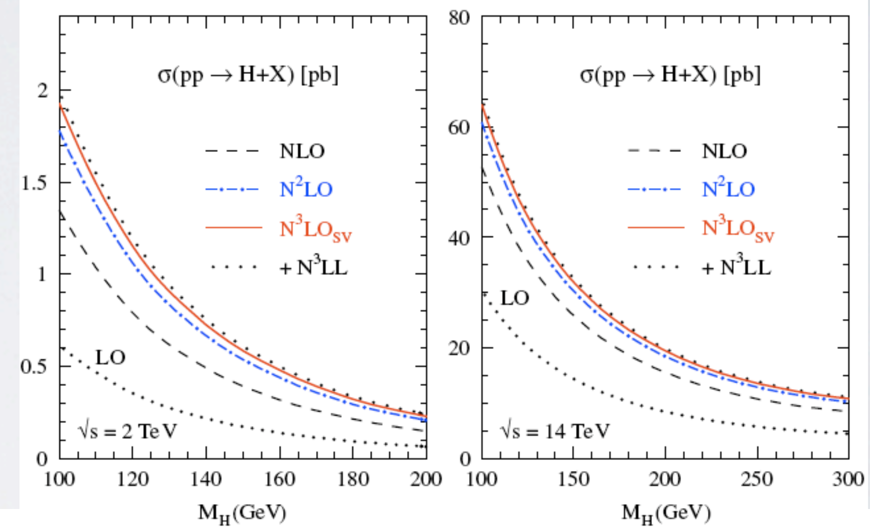
- Yield small corrections beyond NNLO which are negligible for natural scale choices close to $\mu \sim < p_t >$

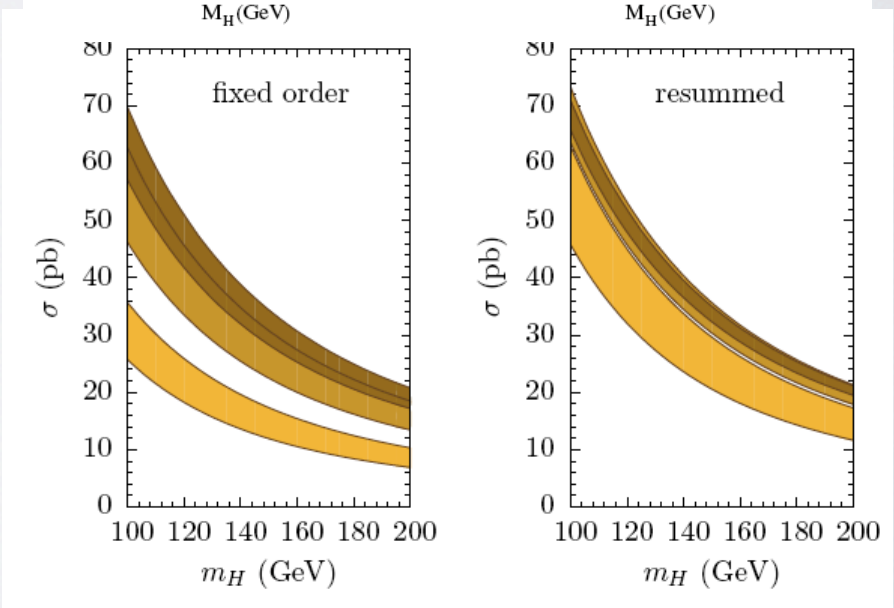
Ahrens, Becher, Neubert

EXHAUSTIVE STUDIES OF LARGE AND SMALL EFFECTS

- Total cross-section at NLO
  (Dawson; Spira, Djouadi, Graudenz, Zerwas; ...)
- Total cross-section at NNLO (Harlander,Kilgore; CA,Melnikov; Ravindran, Smith, van Neerven,...)
- Threshold resummation
  (Catani, de Florian, Grazzini, Nason; Moch, Vogt; Laanen, Magnea; Kulesza, Sterman; Idilbi, Xi, Ma, Juan; Ravindran; Ahrens, Becher, Neubert)
- Tranverse momentum resummation (Bozzi, Catani, de Florian, Grazzini)

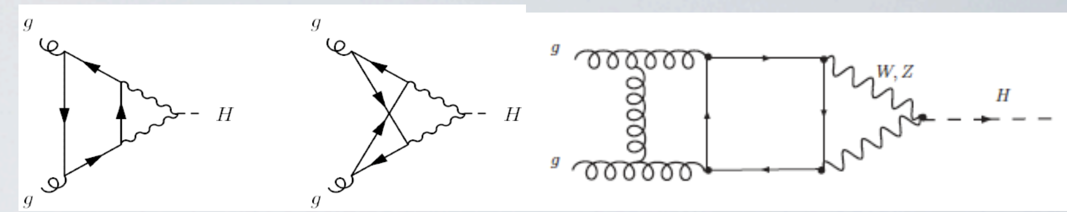




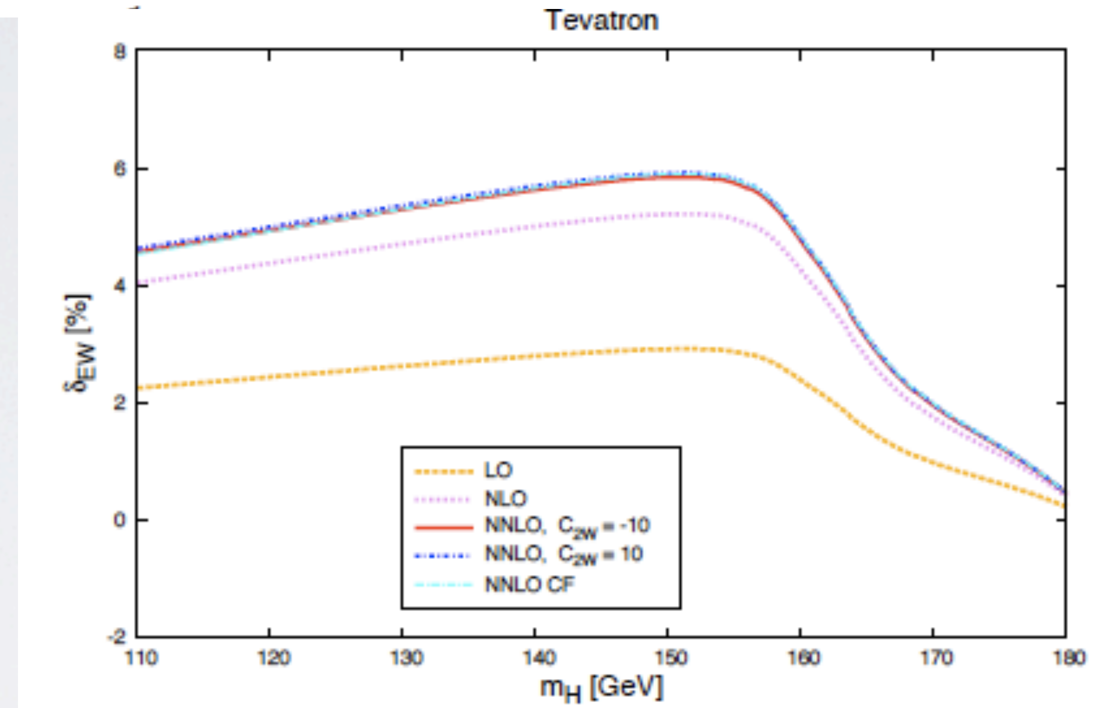


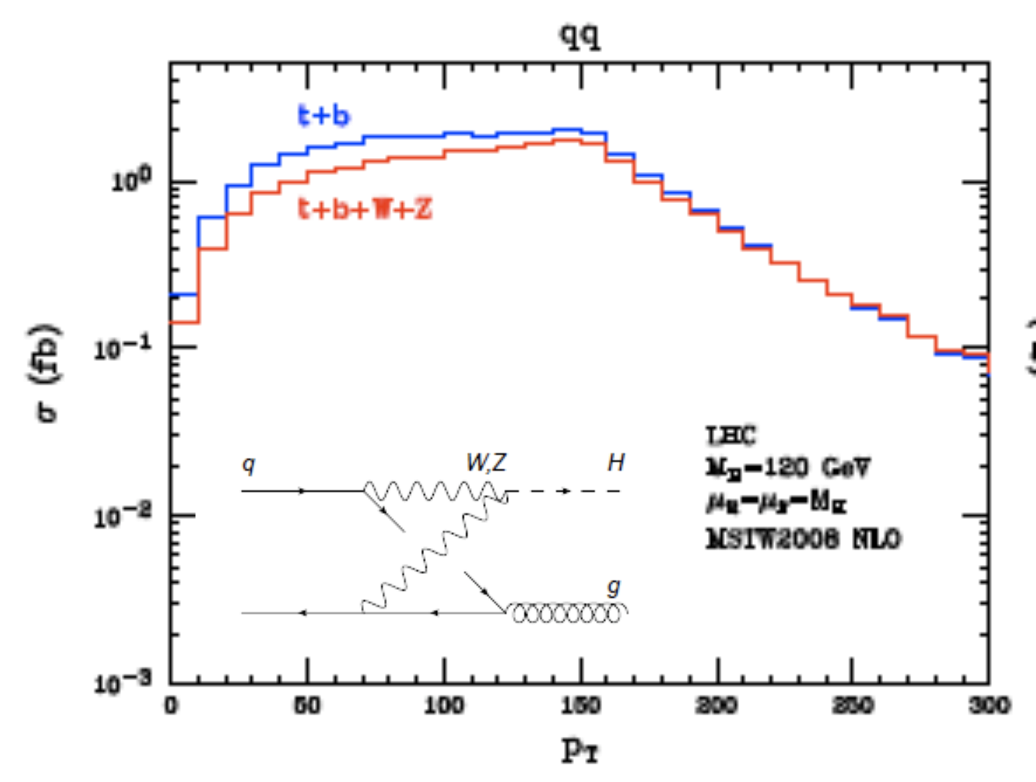
GLUON FUSION EWK

- Two-loop light fermion amplitude (Aglietti,Bonziani, Degrassi, Vicini)
- Full two-loop EWK amplitude (Actis, Passarino, Sturm, Uccirati)
- Three-loop mixed QCD and EWK (CA,Boughezal,Petriello)
- One-loop EWK, with Pt > 0 (Keung, Petriello)



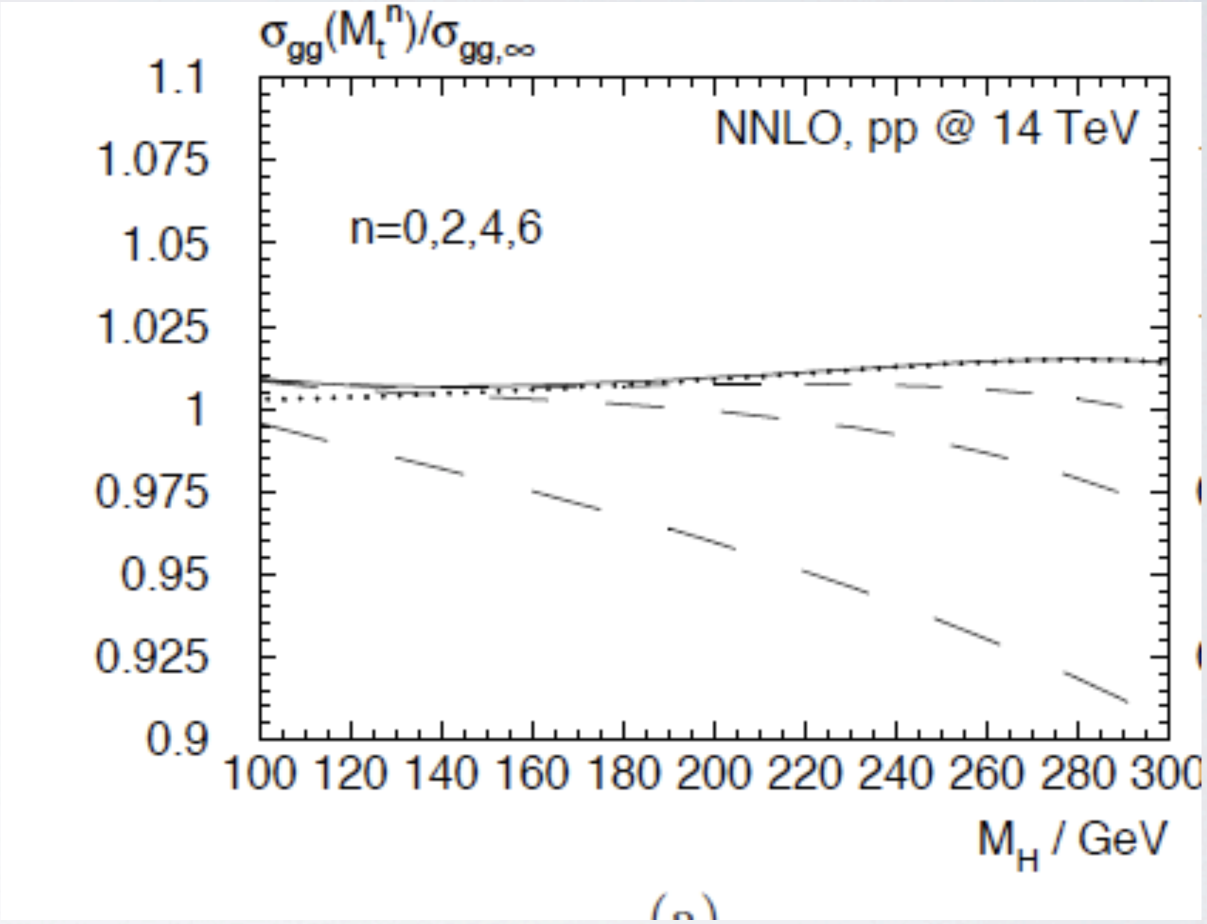
$$C_1 = -\frac{1}{3\pi}\left\{1 + \lambda_{EW}\left[1 + a_s C_{1w} + a_s^2 C_{2w}\right] + a_s C_{1q} + a_s^2\right.$$





HEAVY TOP QUARK EXPANSION

- Beyond the leading term (Chetyrkin, Kniehl, Steinhuser; Kraemer, Laenen, Spira) in the heavy quark-mass expansion at NNLO (Harlander, Mantler, Ozeren; Pak,Rogal,Steinhauser)

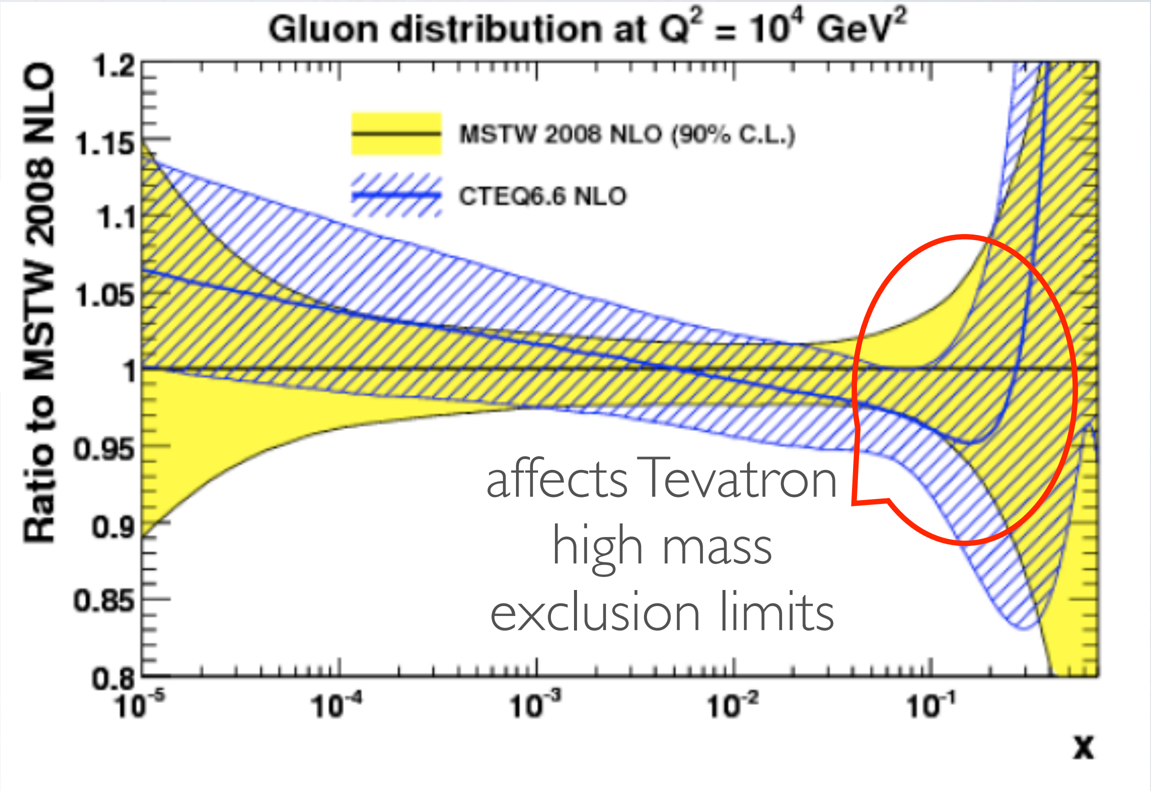


- High energy limit (Marzani,Ball,del Duca, Forte, Vicini)

PARTON DENSITIES

- PDF uncertainties have surprised us at times!

MRST 2001	MRST 2004	MRST 2006	MSTW 2008
0.3833	0.3988	0.3943	0.3444



- estimate of alpha_s uncertainty
  (Martin,Stirling,Thorne, Watt)

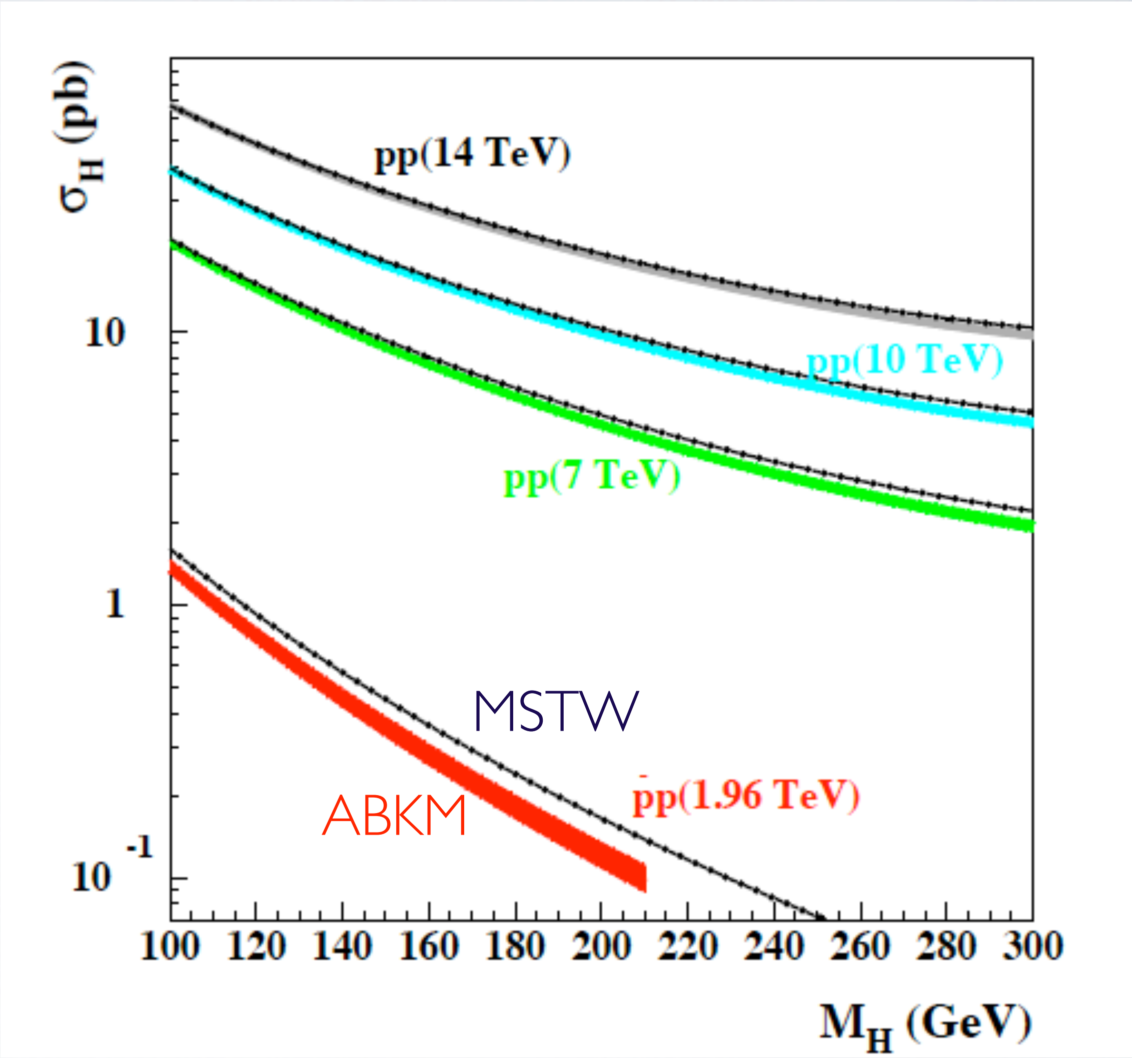
- comparable or bigger uncertainty than scale choice

$$389.0\,\text{fb}\,^{+8.1\%}_{-11.7\%}\,(\text{scale})\,^{+13.6\%}_{-12.0\%}\,(\alpha_s + \text{pdf})^{90\%\text{CL}}$$

@ TEVATRON MHIGGS = 165 GEV

PDF DIFFERENCES

- Three NNLO pdf sets: Martin,Striling,Thorne,Watt (MSTW) Alekhin,Bluemlein,Klein,Moch (ABKM) Jimenez,Reya (JR)
- Important differences on gluon density and alpha_s beyond estimated uncertainties which affect Higgs cross-sections, especially @ Tevatron
- No compelling reason to choose one set over the others.
- MSTW includes Tevatron jet data, and their alpha_s is very close to world average
- Need to check compatibility of all pdf sets with observables sensitive to high-x at NNLO. Jets and tops at LHC7 will be soon of help.



MODEL DEPENDENCE OF CROSS-SECTIONS AND THEIR UNCERTAINTY

- Higgs sector is unexplored territory with particle experimentation.
- It is the most popular theoretical portal to BSM physics. Higgs cross-sections depend on the model. Can we read out BSM Higgs boson cross-sections from Standard Model results?
- In many cases yes, due to identical initial and final state, and the uniformity of field theory perturbative techniques.
- Nevertheless, the Standard Model is the simplest scenario.
- Obtaining precise Higgs cross-sections beyond the SM is a generally more intricate or difficult task. Let us see two simple examples.

GLUON FUSION WITH NON-FIXED BOTTOM YUKAWA COUPLING

- This process receives contribution from both top-quark and bottom-quark loops.
- Top-quark amplitudes are known to NNLO, using effective theory.
- Bottom-quark amplitudes are less precise, and only known to NLO.
- Bottom loops are luckily suppressed in the Standard Model.
- In models with non-fixed bottom Yukawa coupling they may become sizable.

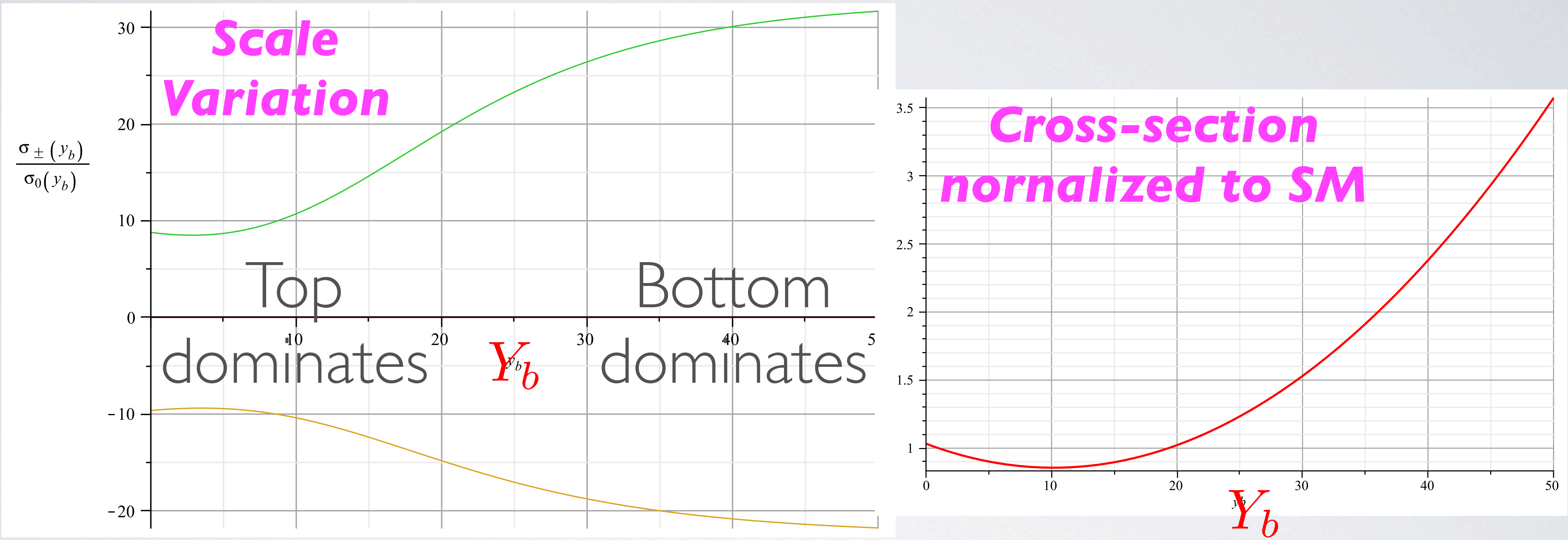
$$\mathcal{M} = Y_t \cdot \mathcal{M}_t^{(NNLO)} + Y_b \cdot \mathcal{M}_b^{(NLO)}$$

precise, dominates in the SM

less precise, suppressed in the SM

not necessarily suppressed in th SM

BOTTOM DOMINANCE OF UNCERTAINTY



Such differences in the uncertainty should be accounted for in placing exclusion limits on Higgs bosons of models with enhanced bottom Yukawa coupling

GLUON FUSION IN MODELS WITH NEW HEAVY PARTICLES

$$\mathcal{M}_Q = C_Q M_{global}$$

- Amplitudes factorize in terms of a universal HQET amplitude and a Wilson coefficient depends on the model and the new heavy particles.
- QCD corrections are very much like in the SM.
- Care is needed for some important details, beyond the effective theory approach, which matter at the 10% level collectively in the SM.

EXAMPLE: FOURTH SM-LIKE QUARK GENERATION

$$\mathcal{M}_{\rm 4gen} = C_{t+B+T} M_{global}$$

$$@NLO: \quad C_{t+T+B} = 3C_t \to \left.\frac{\sigma_{4gen}}{\sigma_{SM}}\right|_{NLO,eff} = 9$$

- It is a poor approximation to scale up the SM cross-section by a factor 9.
- Finite heavy quark mass effects cannot be neglected at LO.
- bottom amplitudes and electroweak corrections do not scale by a factor of 3.
- Different NNLO Wilson coefficient: $@NNLO: \quad C_{t+T+B} \neq C_t + C_T + C_B$

Higgs.All.Inclusive.Rates

CA, S. Buehler, F. Herzog, A. Lazopoulos

- A program to compute the total cross-section for Higgs boson production in a generalized SM with additional heavy quarks and arbitrary.
- Can be used for SM, SM with additional generations, composite Higgs models, etc
- Exact QCD calculation through NLO. Effective theory at NNLO
- All NNLO pdf sets and error estimation. LHAPDF
- SM Electroweak corrections
- Finite width effects, interfaced to HDECAY
- Gluon fusion and bottom fusion cross-sections
- *Beta version in the material of this presentation*

GLUON FUSION CROSS-SECTION IN SM4GEN WITH H.A.I.R

MSTW2008

$$M_H = 110\text{GeV} \qquad \sigma = 183.4\,\text{pb}\,{}^{+9\%}_{-10\%}(\text{scale})^{+8\%}_{-8\%}(\alpha_s + \text{pdf})^{90\%\text{cl}}$$

$$M_H = 165\text{GeV} \qquad \sigma = 74.22\,\text{pb}\,{}^{+8\%}_{-9\%}(\text{scale})^{+8\%}_{-8\%}(\alpha_s + \text{pdf})^{90\%\text{cl}}$$

$$M_H = 200\text{GeV} \qquad \sigma = 46.31\,\text{pb}\,{}^{+7\%}_{-9\%}(\text{scale})^{+8\%}_{-8\%}(\alpha_s + \text{pdf})^{90\%\text{cl}}$$

LHC 7TeV

Predictions of equal precision as the Standard Model cross-section.

CONCLUSIONS

- No time to discuss other channels and their uncertainties. Usually less complicated higher order effects.
- Precision of Higgs production rates is impressive, and at the 10-15% level. After a lot of hard work and numerous contributions from independent and different approaches.
- Have learnt to live with large K-factors, with a good understanding of their analytic structure.
- Progress in improving theory predictions must continue on various levels (pdfs,higher orders, new models)