Higgs production via gluon fusion

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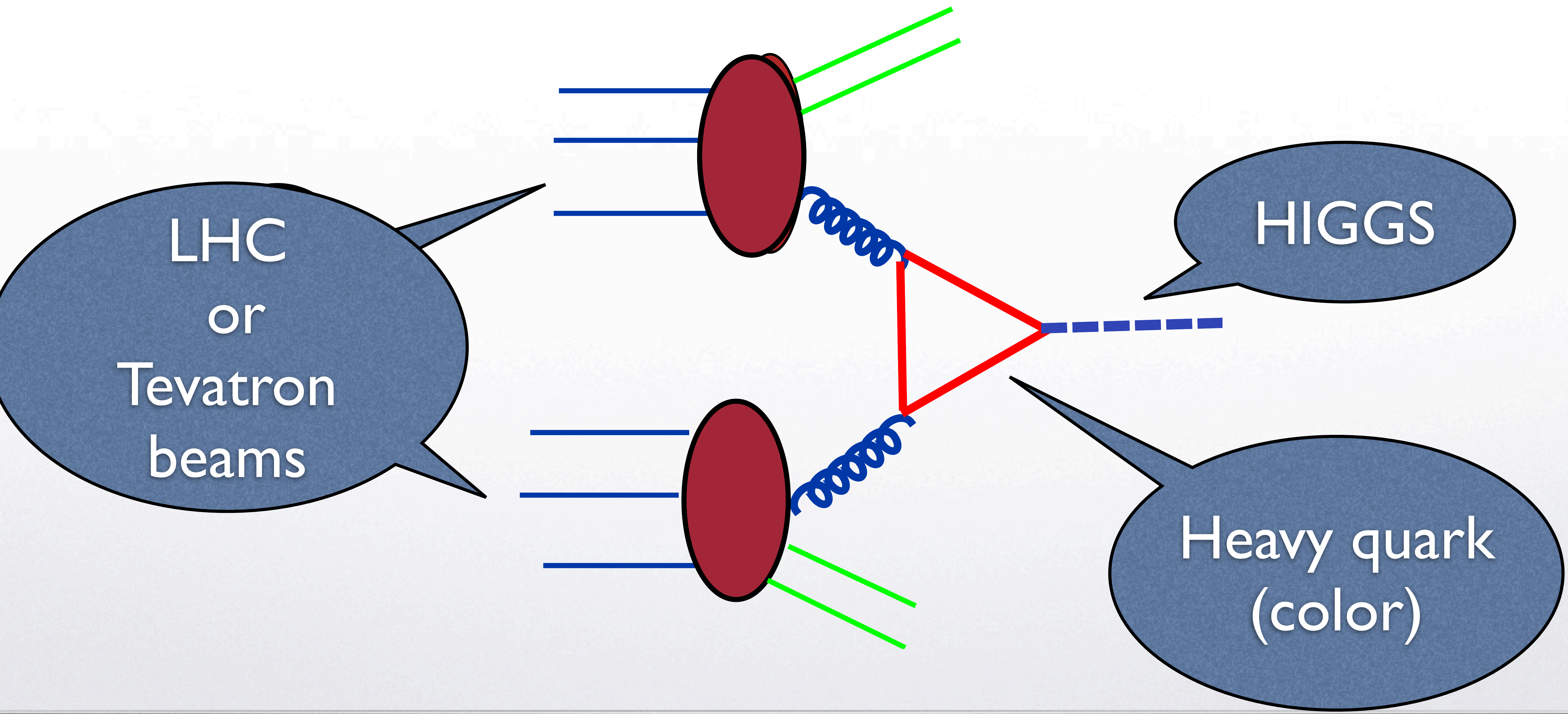
Higgs Hunting, Paris, July 2010

in collaboration with A. Lazopoulos

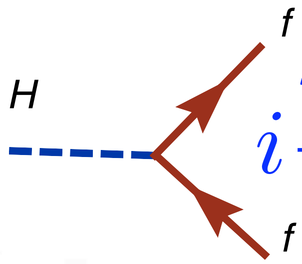
- Introduction
- QCD
- HQET and EWK
- New physics
- Experimental vs Theoretical Observables
- The ultimate precision

- *How many perturbative orders?*
- *What scale?*
- *What parton distribution functions?*
- *What strong coupling value?*
- *The importance of top-quark loops?*
- *Bottom quark loops?*
- *Bottom quarks as initial state?*
- *Are new physics and QCD factorized?*
- *Are event generators reliable in estimating the ratio of measured Higgs signals vs the total?*

The gluon fusion process

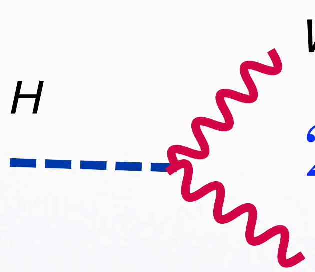


The end of a Higgs boson



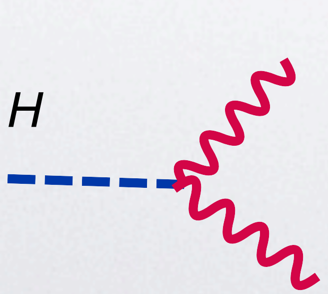
$$i\frac{m_f}{v}\delta_{ij}$$

$$\Gamma\left(H \to f\bar{f}\right) = \frac{M_H}{8\pi}\left(\frac{M_f}{v}\right)^2 N_c \left(1 - \frac{4M_f^2}{M_H^2}\right)^{\frac{3}{2}}$$



$$2i\frac{M_W^2}{v}g_{\mu\nu}$$

$$\Gamma\left(H \to WW\right) = \frac{M_H}{16\pi}\left(\frac{M_H}{v}\right)^2 \left(1 - \frac{4M_W^2}{M_H^2}\right)^{\frac{1}{2}} \times \left[1 - 4\left(\frac{M_W^2}{M_H^2}\right) + 12\left(\frac{M_W^2}{M_H^2}\right)^2\right]$$



$$2i\frac{M_Z^2}{2v}g_{\mu\nu}$$

$$\Gamma\left(H \to ZZ\right) = \frac{M_H}{32\pi}\left(\frac{M_H}{v}\right)^2 \left(1 - \frac{4M_Z^2}{M_H^2}\right)^{\frac{1}{2}} \times \left[1 - 4\left(\frac{M_Z^2}{M_H^2}\right) + 12\left(\frac{M_Z^2}{M_H^2}\right)^2\right]$$

Two photon decay

(Light Higgs)

$$N_c Q_t^2 (4/3) \qquad (-7)$$

Small decay width

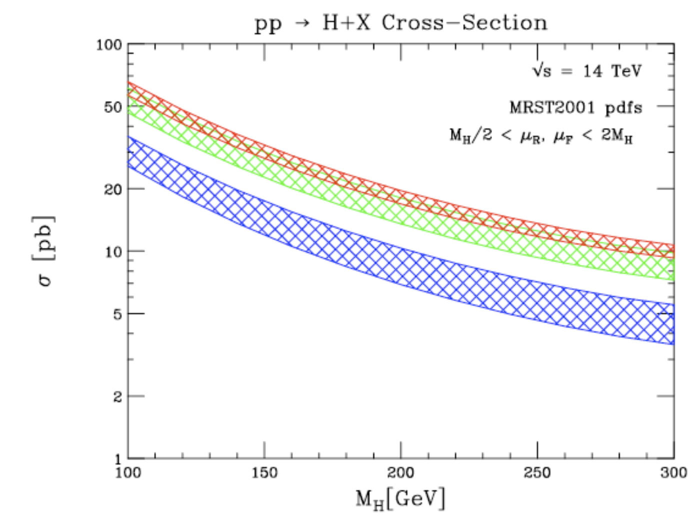
Probes the electroweak content of the vacuum. Sensitive to new heavy gauge bosons.

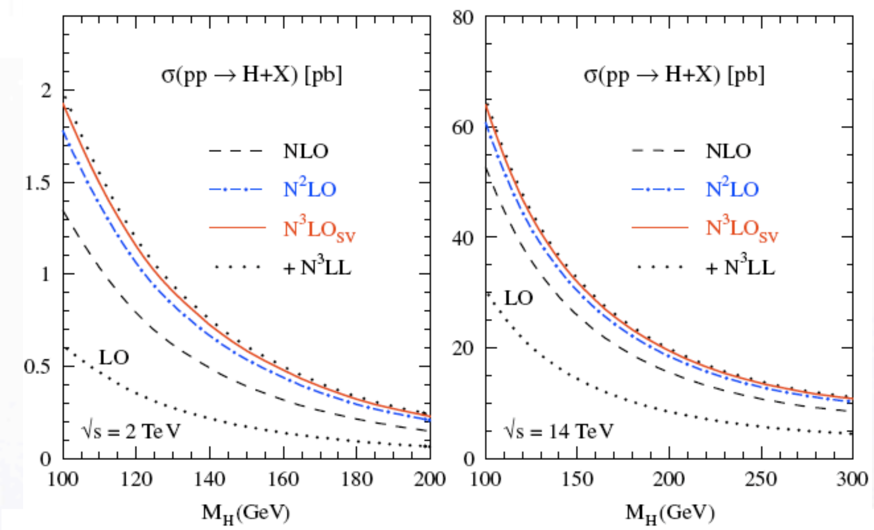
A field theory laboratory

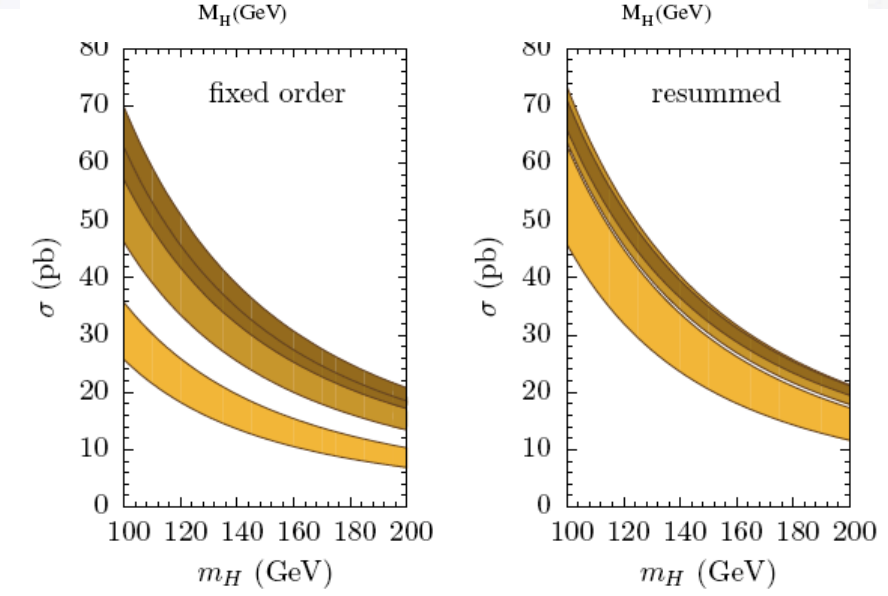
- Simple colorless final state, fixed order QCD perturbative calculations at LO, NLO, NNLO,...
- Diverse energy scales (twice-quark mass, Higgs mass, Higgs recoil energy)
- HQET effective theory, factorization, resummation

Gluon fusion QCD

- 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)

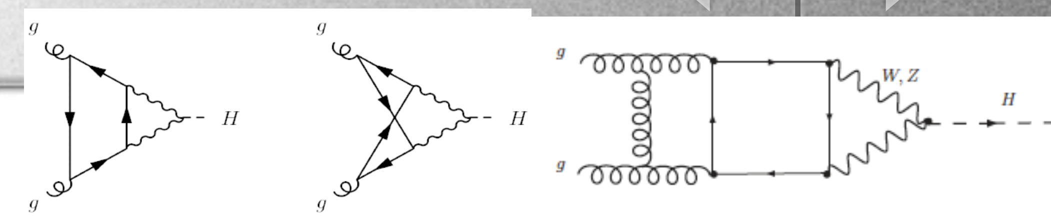




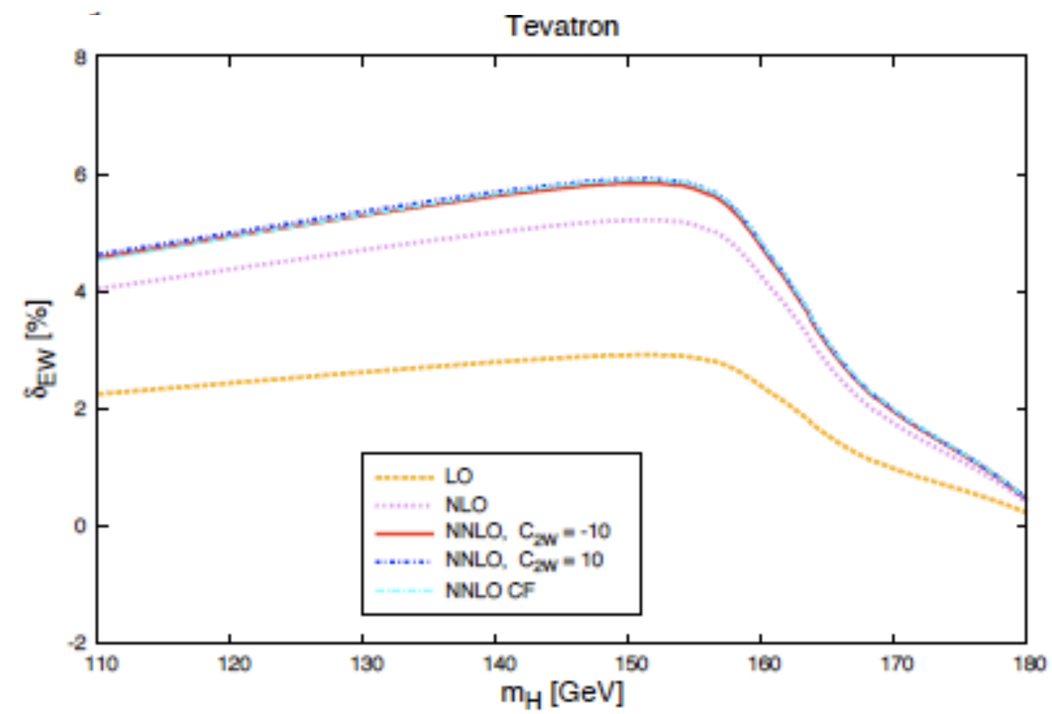


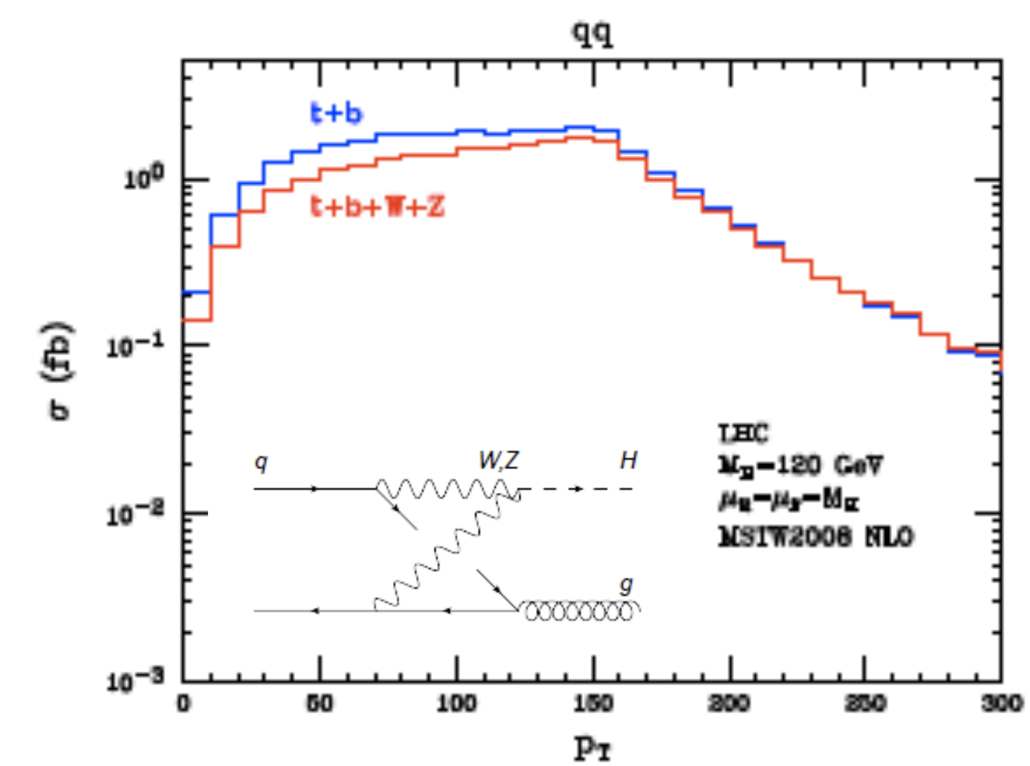
Gluon fusion EWK

- 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)



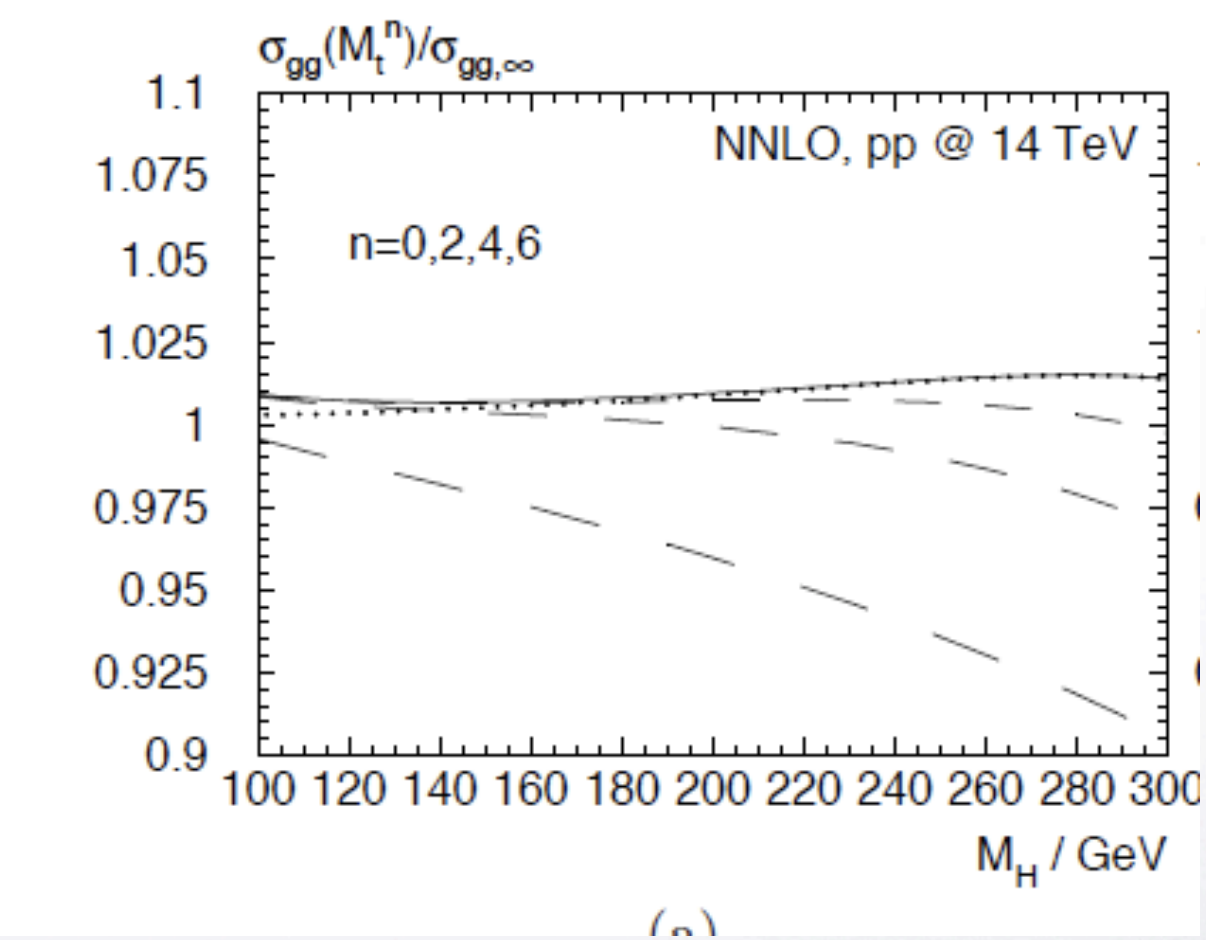
$$C_1 = -\frac{1}{3\pi}\left\{1+\lambda_{EW}\left[1+a_sC_{1w}+a_s^2C_{2w}\right]+a_sC_{1q}+a_s^2\right.$$





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)

Differential NNLO

- Fully Exclusive Higgs Production

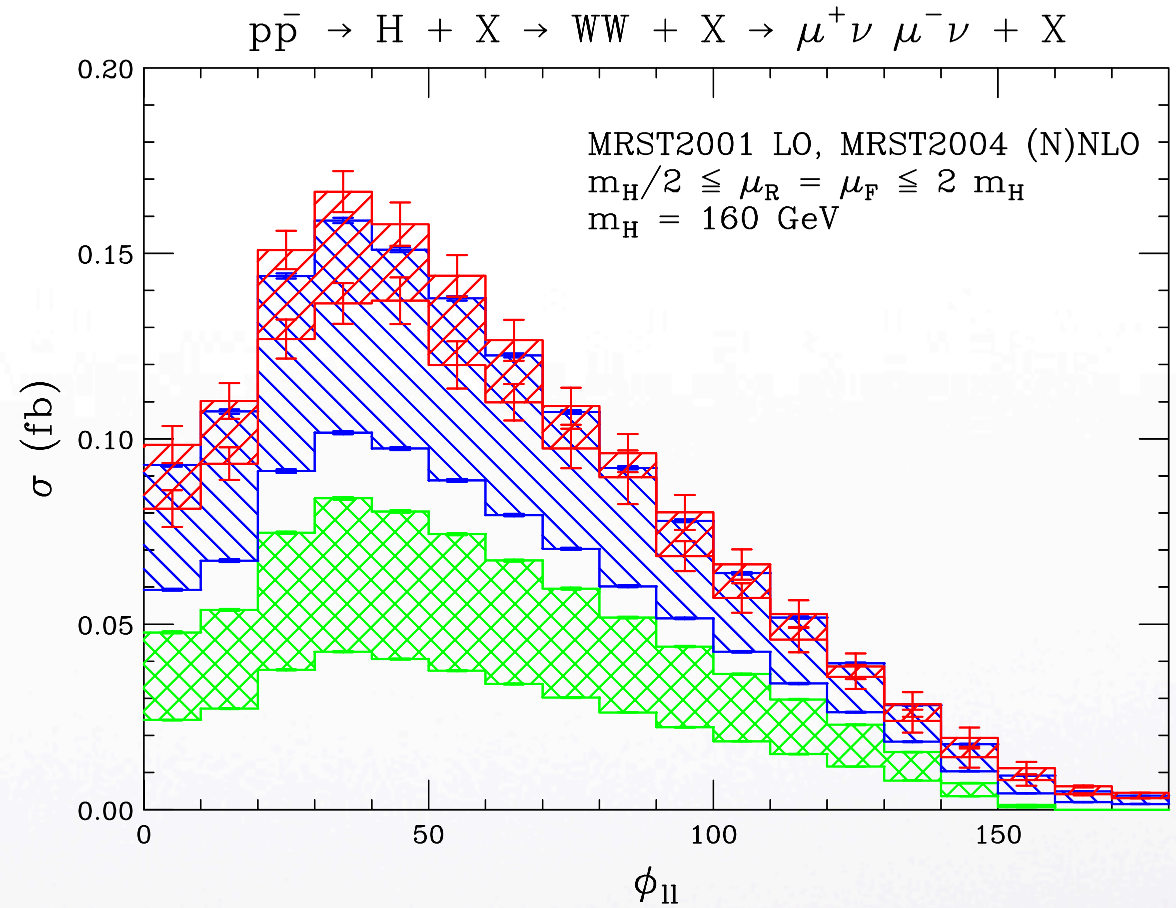
  (CA,Melnikov,Petriello;
  CA, Dissertori, Stoeckli)

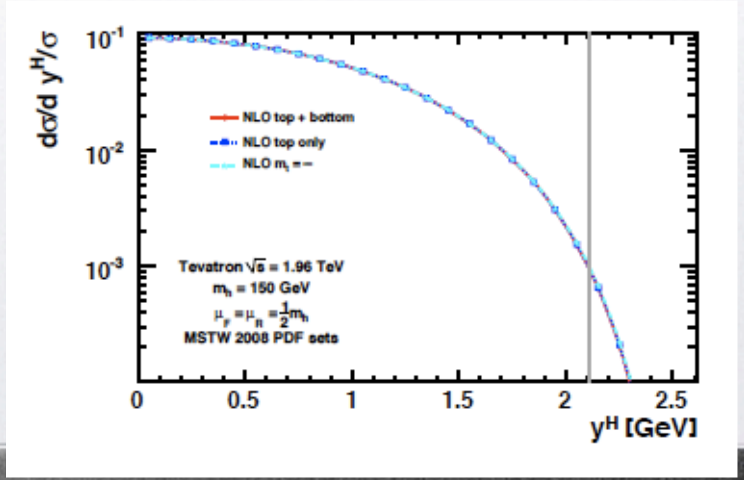
- HNNLO method

  (Catani,Grazzini; Grazzini)

- Fully differential NLO cross-section with exact mass quark effects

  (CA,Bucherer, Kunszt)





In summary

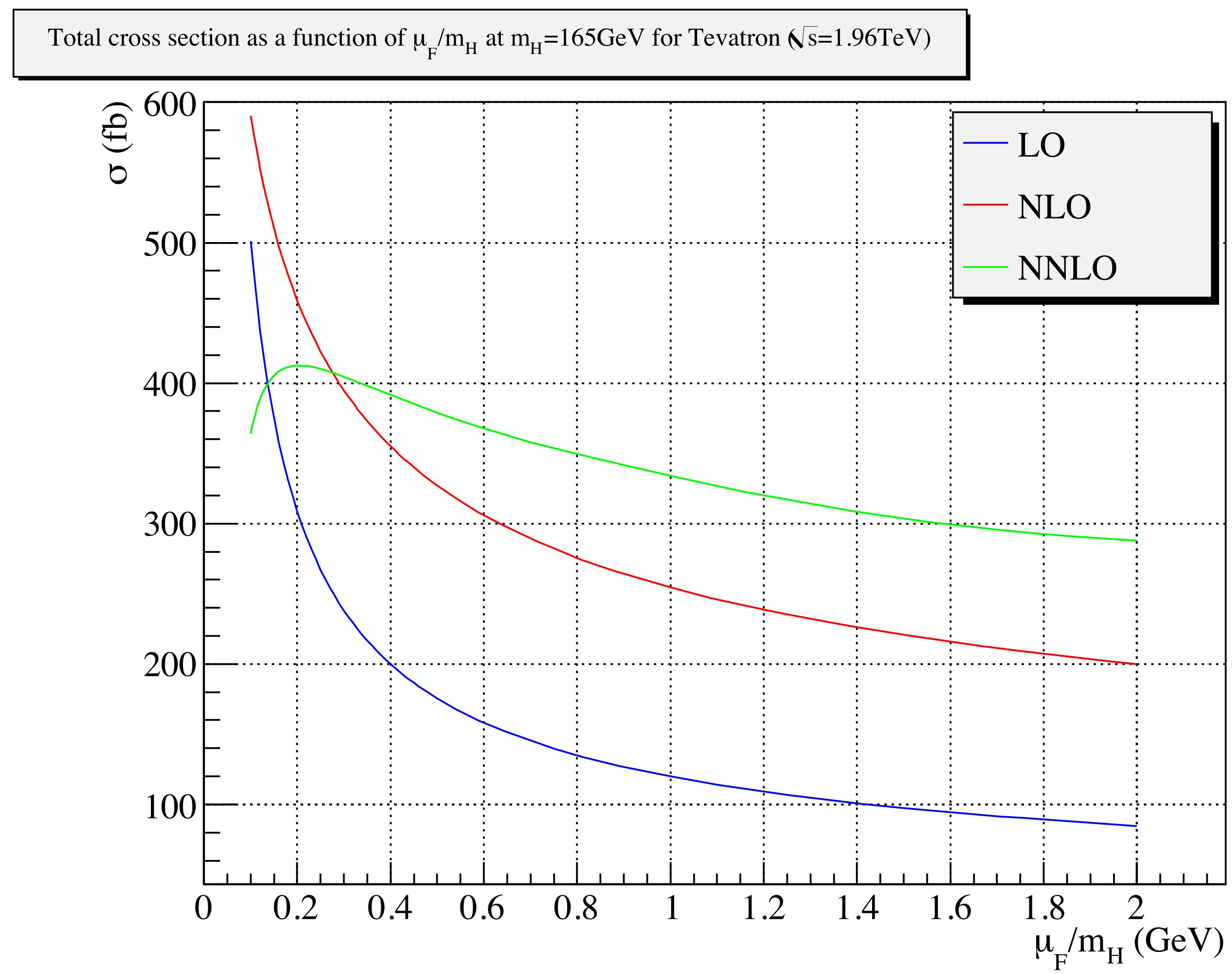
- Full NLO QCD (very sizable)
- Full NNLO HQET (less sizable)
- Glimpses at NNNLO and all-orders in HQET with resummation methods (generally small)
- Electroweak corrections (quite small)
- *ALL indispensable in order to trust the error estimates on our predictions for the number of Higgs boson signals that may be detected at the LHC and Tevatron.*

A manual to reliable precision for all inclusive and differential gluon fusion cross-sections

- Compute through NNLO QCD
- Choose a renomalization/factorization scale which captures the physics of the process
- Include parton densities through the same order and take into account their uncertainties
- Include exact quark mass effects through NLO
- Include known electroweak corrections (in complex mass scheme)

What scale?

- An almost philosophical question without "theory data"
- Large scales ~ (2 Mhiggs) fail to capture higher order effects for the total cross-section @ Tevatron
- Small scales ~ (Mhiggs/2) are much better

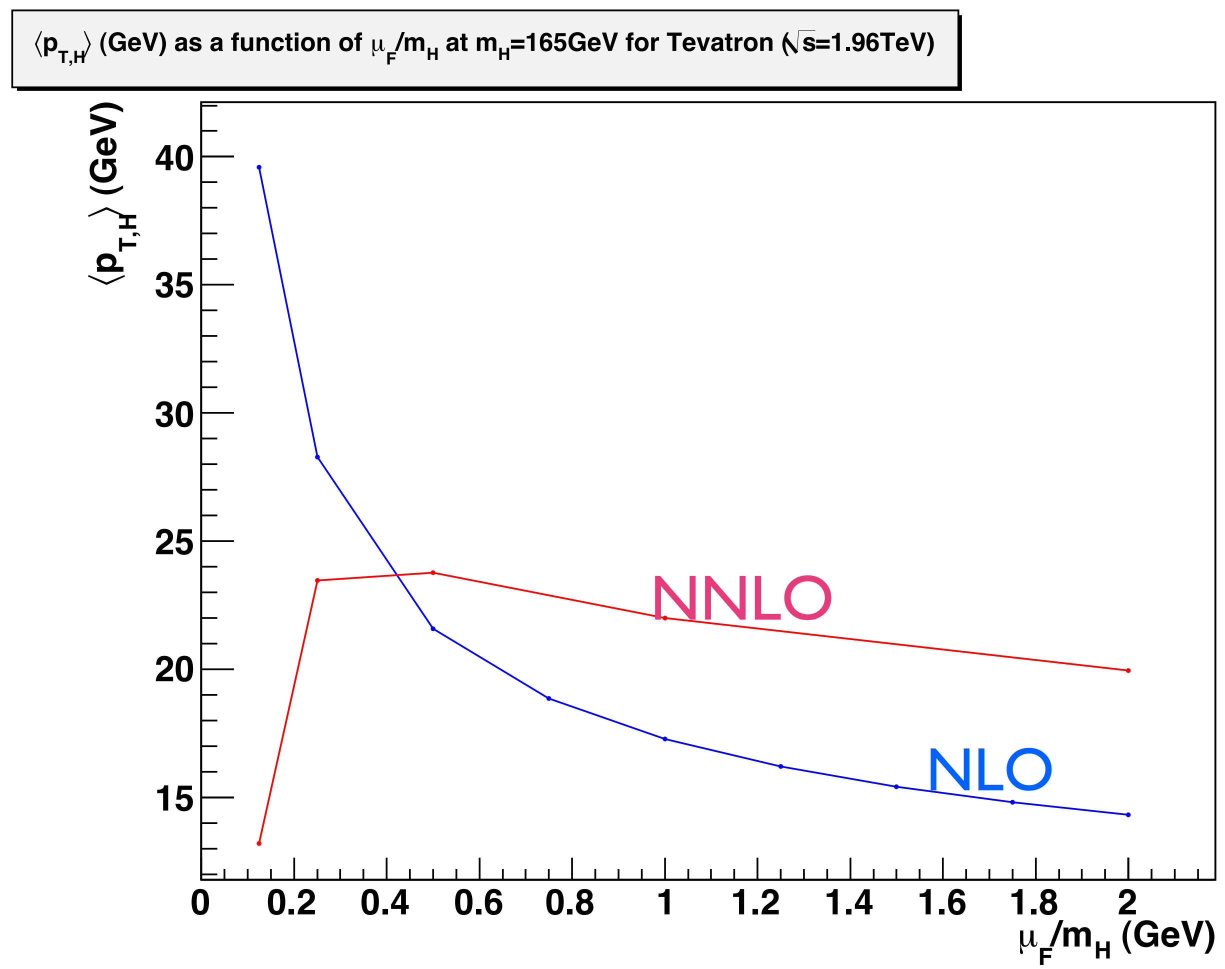


Total cross-section @ Tevatron

Mhiggs = 165 GeV

What scale?

- Average transverse momentum is zero at LO.
- Large scales ~ (2 Mhiggs) fail to capture higher order effects for <Pt> @ Tevatron
- Small scales ~ (Mhiggs/2) are much better



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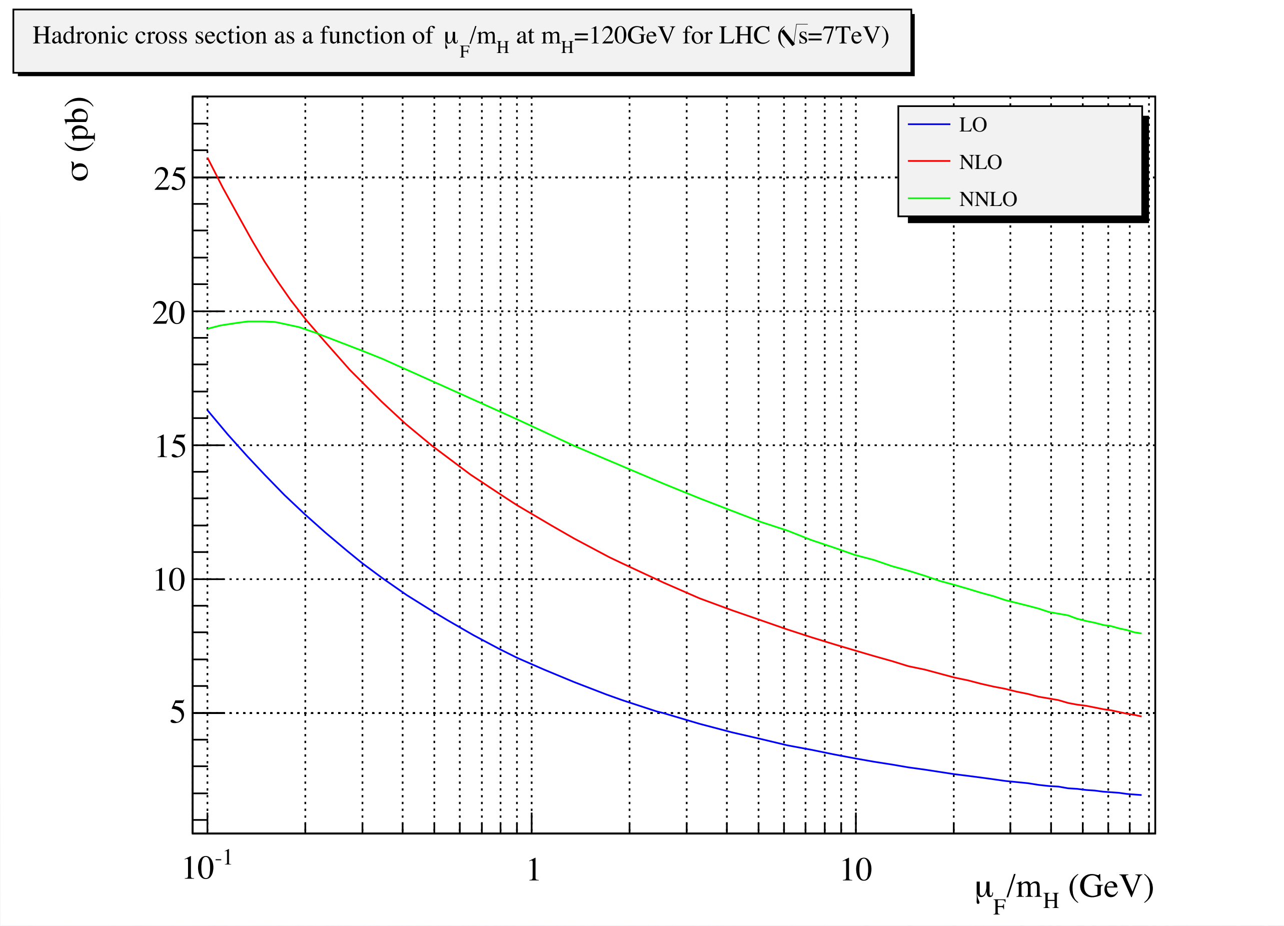
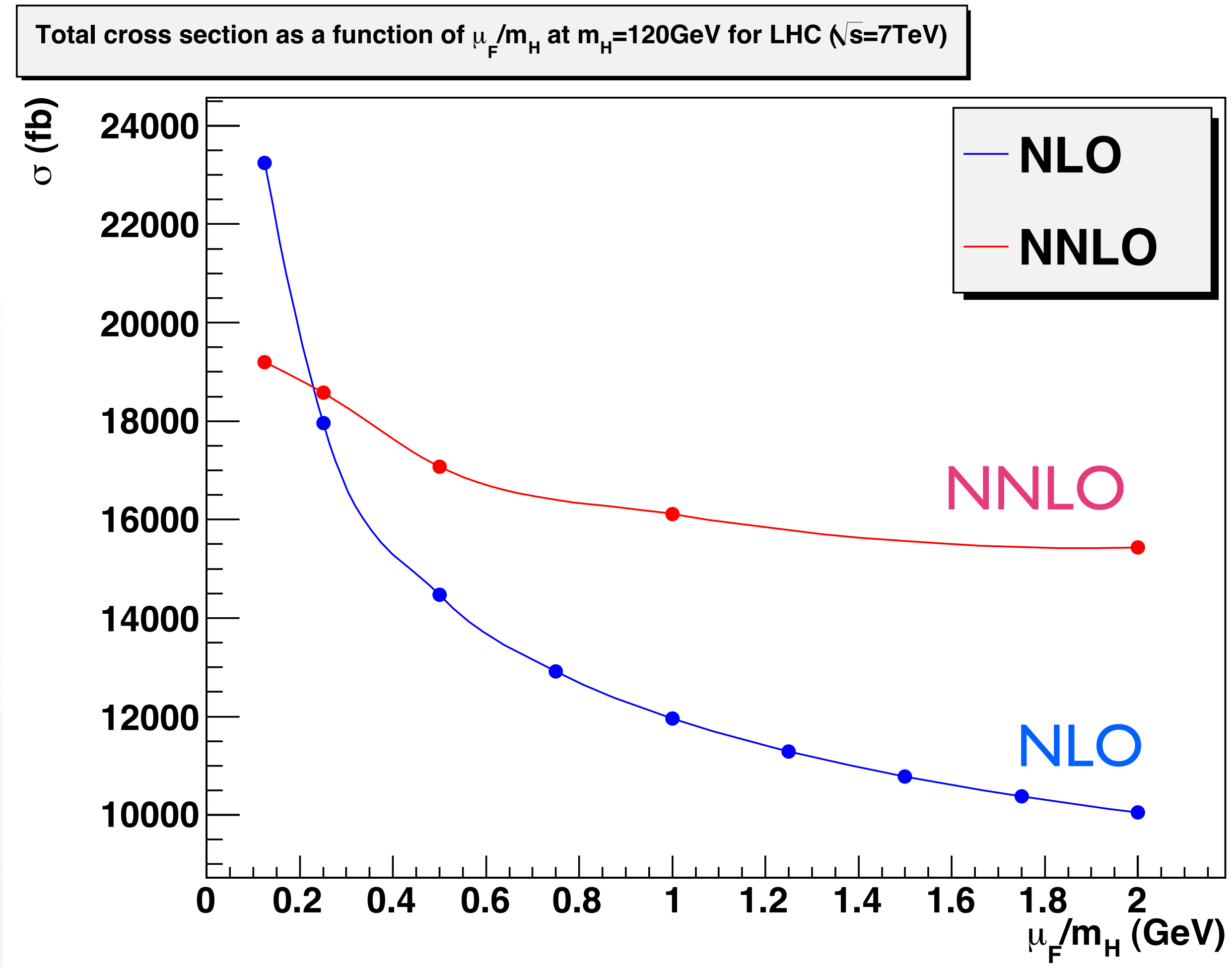


Total cross-section @ LHC 7 TeV

Mhiggs = 120 GeV

What scale?

- Average transverse momentum is zero at LO.
- Large scales ~ (2 Mhiggs) fail to capture higher order effects for <Pt> @ LHC
- Small scales ~ (Mhiggs/2) are much better



Average pt @ LHC 7 TeV

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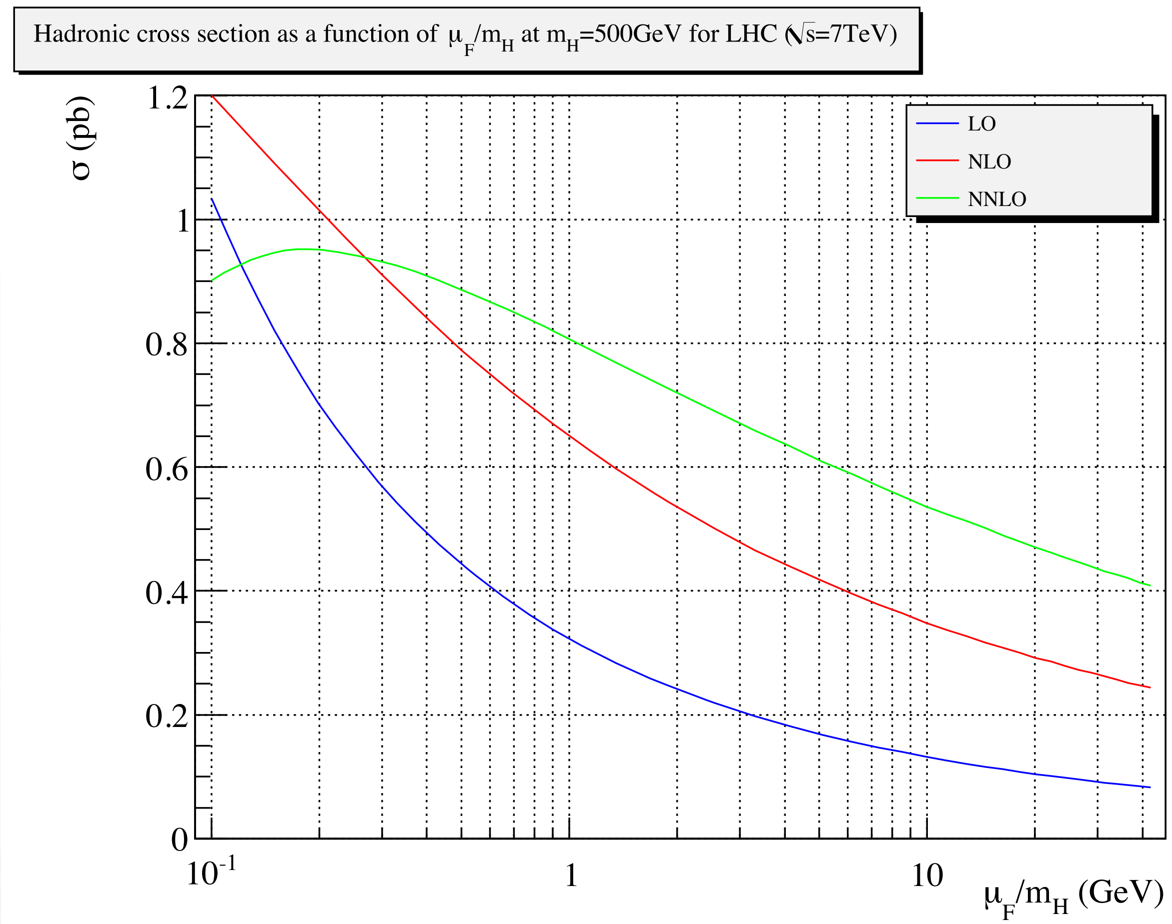
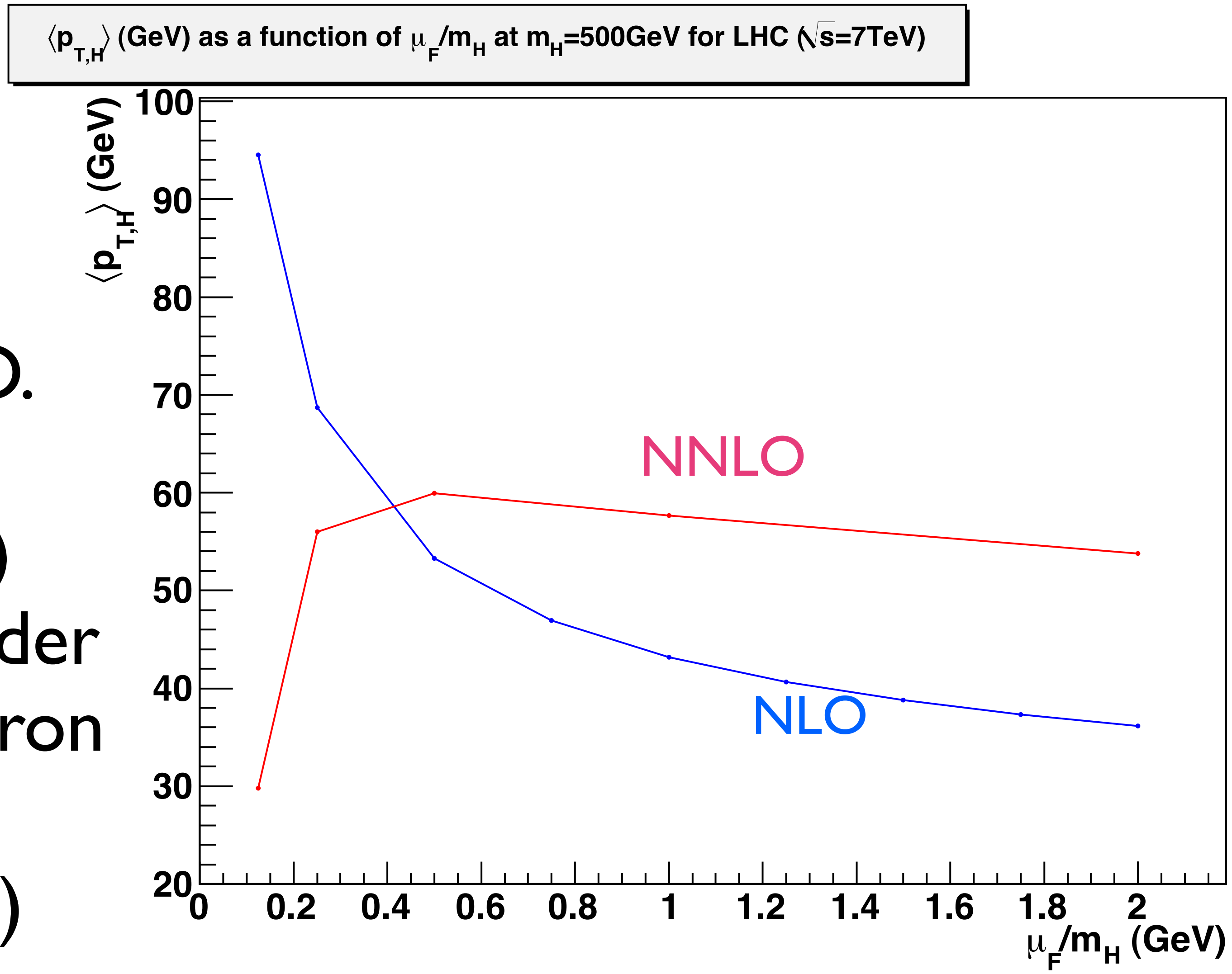


Total cross-section @ LHC 7 TeV

Mhiggs = 500 GeV

What scale?

- Average transverse momentum is zero at LO.
- Large scales ~ (2 Mhiggs) fail to capture higher order effects for <Pt> @ Tevatron
- Small scales ~ (Mhiggs/2) are much better



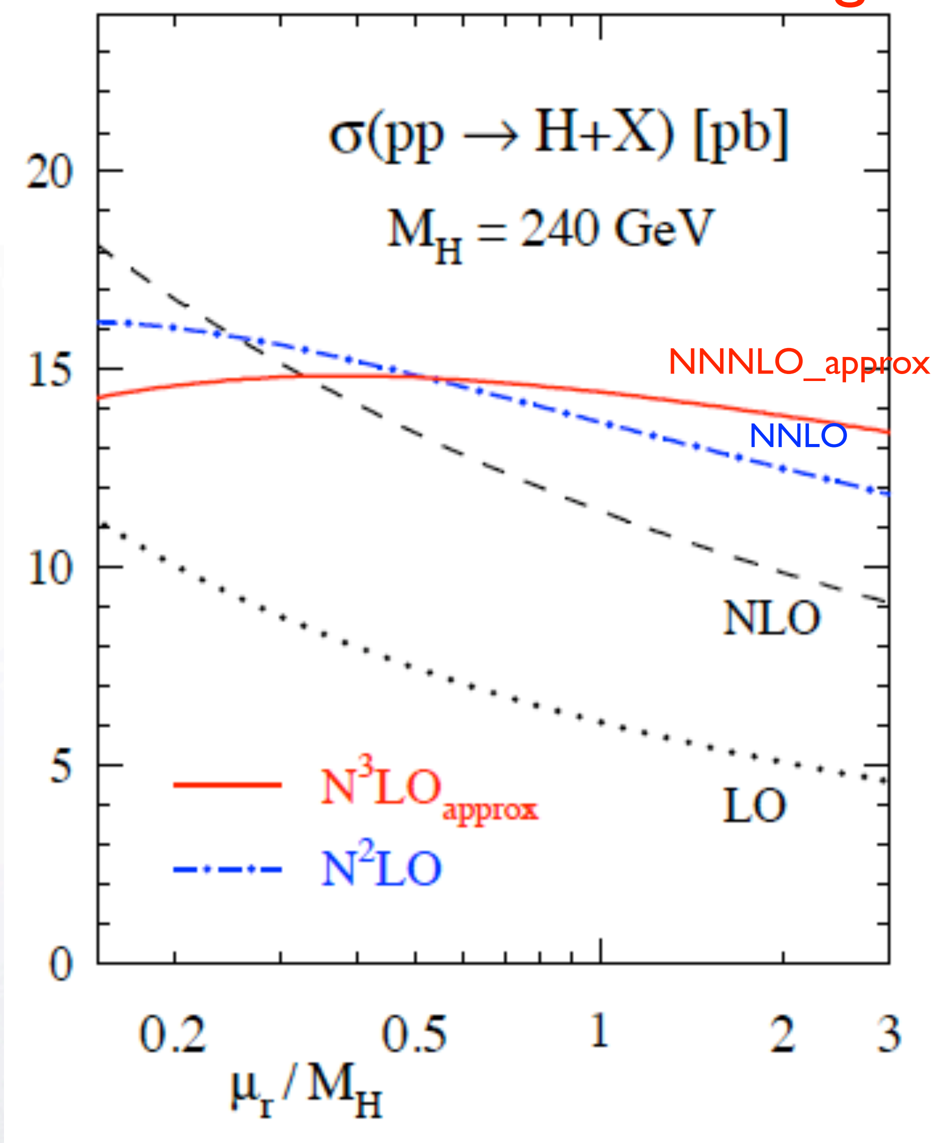
Average pt @ LHC 7 TeV

Mhiggs = 500 GeV

Missing higher orders?

- A small scale leads to a faster convergence from NLO to NNLO.
- Are we missing even higher order effects
- A lot is known from threshold resummation methods.
- Small mu scales are safe!

Moch and Vogt



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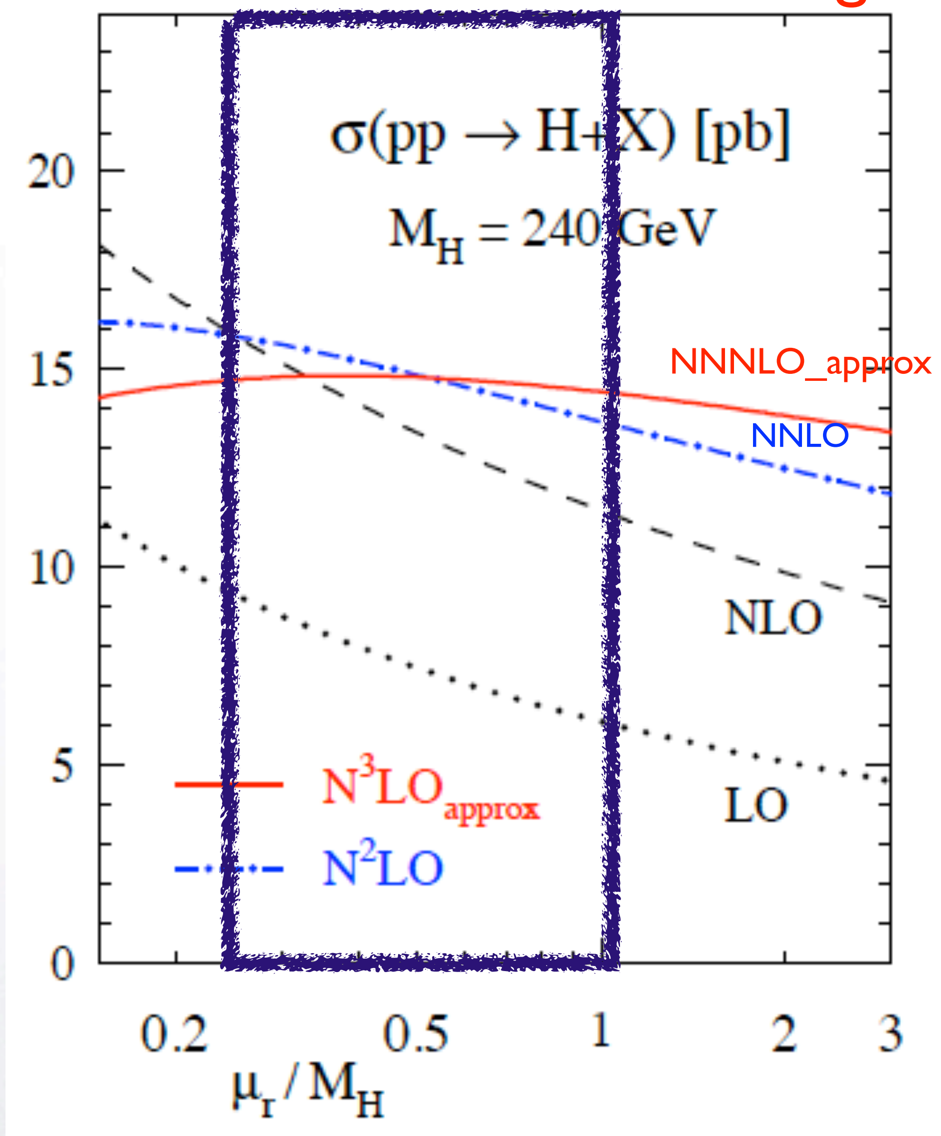
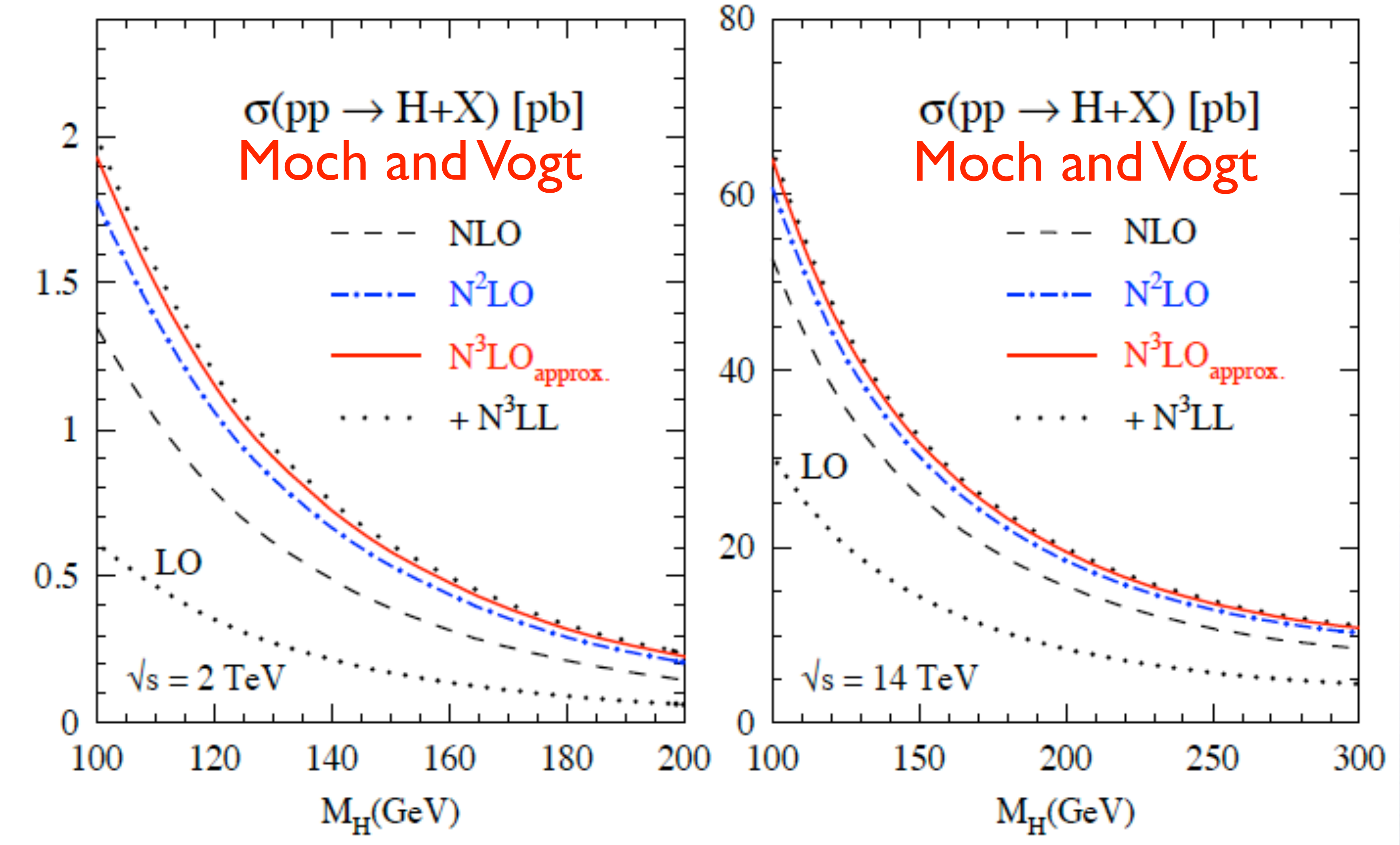


Missing higher orders?



NNLO seems to be a conservative estimate of the cross-section

Is threshold dominant?

$$\sigma = \int dx_1 dx_2 f_1(x_1) f_2(x_2) \hat{\sigma}\left(z = \frac{m_h^2}{\hat{s}}\right)$$

σ [pb]	$\delta(1-z)$	$\left[\frac{\log^n(1-z)}{1-z}\right]_+$	Regular
LO@NNLO	14.87	0	0
NLO@NNLO	8.07	5.06	5.91
NNLO@NNLO	1.55	2.84	6.81

LHC 14 TeV

Mhiggs = 120 GeV

mu = 120 GeV

No suppression from NLO to NNLO

Closer look on logarithmically enhanced terms:

σ [pb]	n=3	n=2	n=1	n=0
LO@NNLO	0	0	0	0
NLO@NNLO	0	0	5.06	0
NNLO@NNLO	6.19	0.67	-0.47	-3.53

No suppression of subleading logs

Is threshold dominant?

$$\sigma = \int dx_1 dx_2 f_1(x_1) f_2(x_2) z \left(\frac{\hat{\sigma}\left(z = \frac{m_h^2}{\hat{s}}\right)}{z} \right)$$

σ [pb]	$\delta(1-z)$	$\left[\frac{\log^n(1-z)}{1-z}\right]_+$	Regular
LO@NNLO	14.87	0	0
NLO@NNLO	8.07	10.04	0.92
NNLO@NNLO	1.55	8.48	1.17

Many equivalent definitions of threshold logs: can reduce the "regular part"

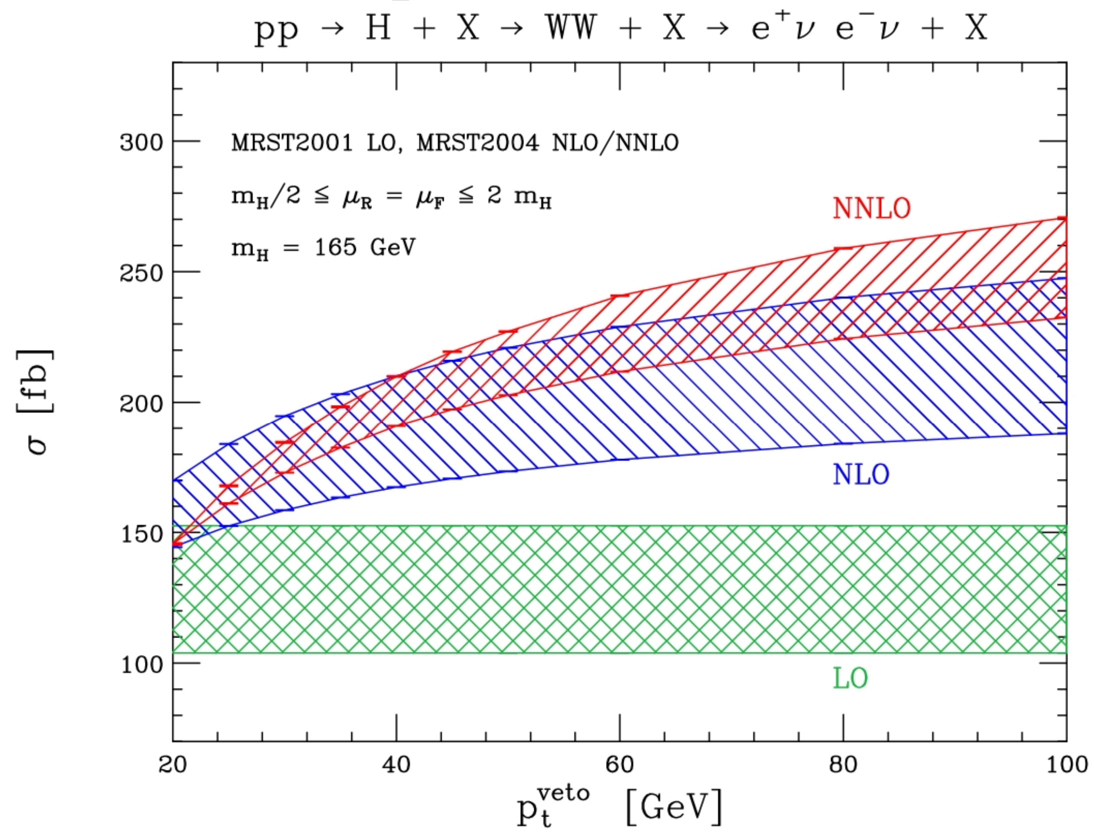
Closer look on logarithmically enhanced terms:

σ [pb]	n=3	n=2	n=1	n=0
LO@NNLO	0	0	0	0
NLO@NNLO	0	0	10.04	0
NNLO@NNLO	13.81	1.43	-0.93	-5.83

Same observations on threshold dominance and convergence

The Higgs+1-jet subprocess

- If threshold logs are not the full reason for the large K-factors, then what?
- Their magnitude depends strongly on a jet-veto.
- Higgs+1-jet subprocess is important.
- Interesting to see the application of the ideas on large K-factors by Rubin, Salam, Sapeta on Higgs production



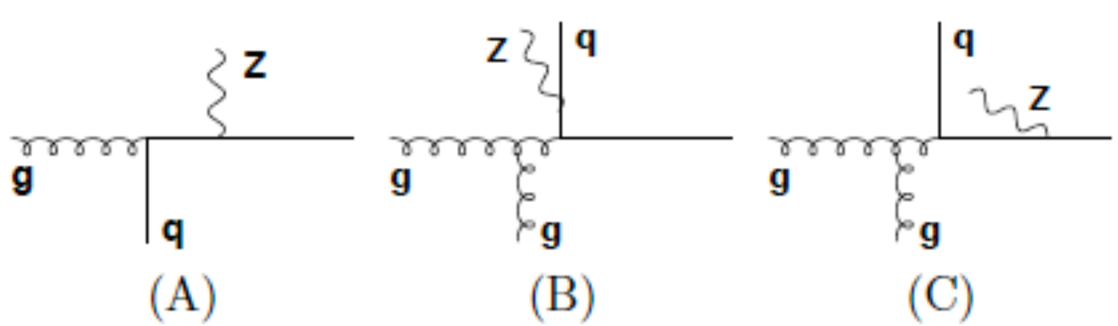
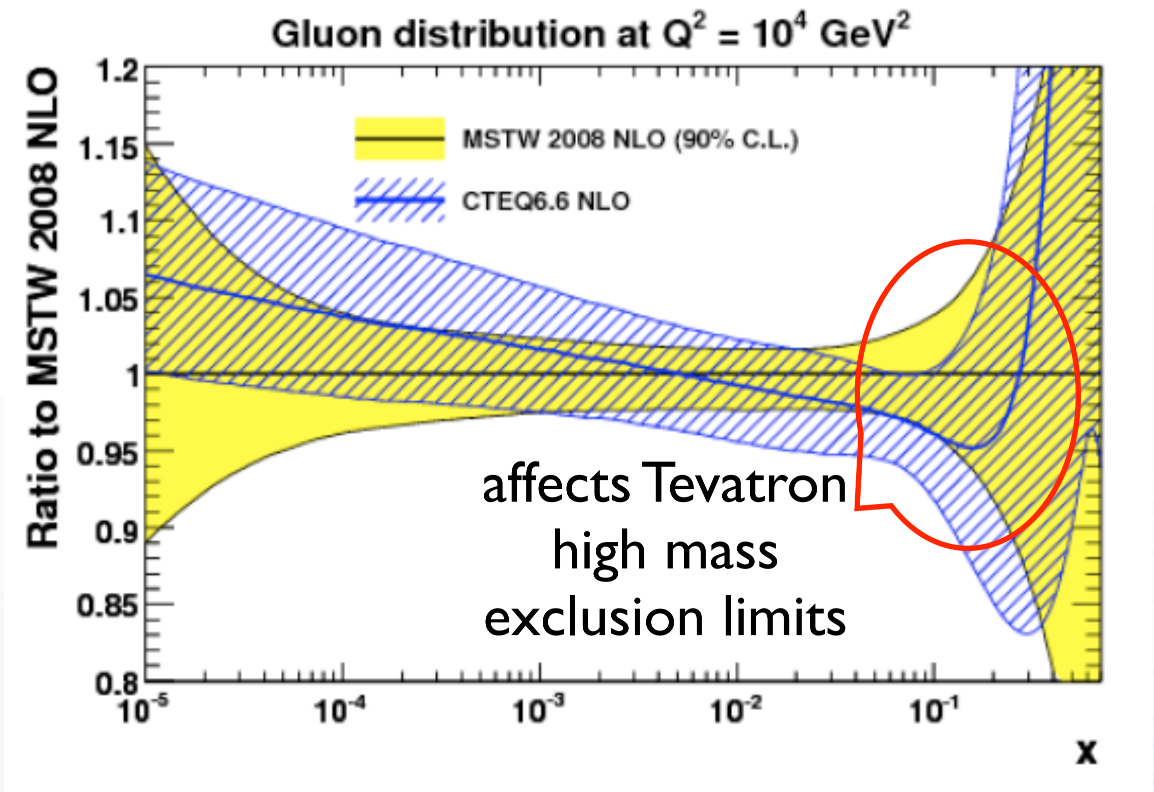


Figure 2: A) a LO contribution to Z+jet production; B) and C) two contributions that are NLO corrections to Z+jet observables but whose topology is that of a dijet event with additional radiation of a soft or collinear Z-boson either from a final-state quark (B) or an initial-state one (C).

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)

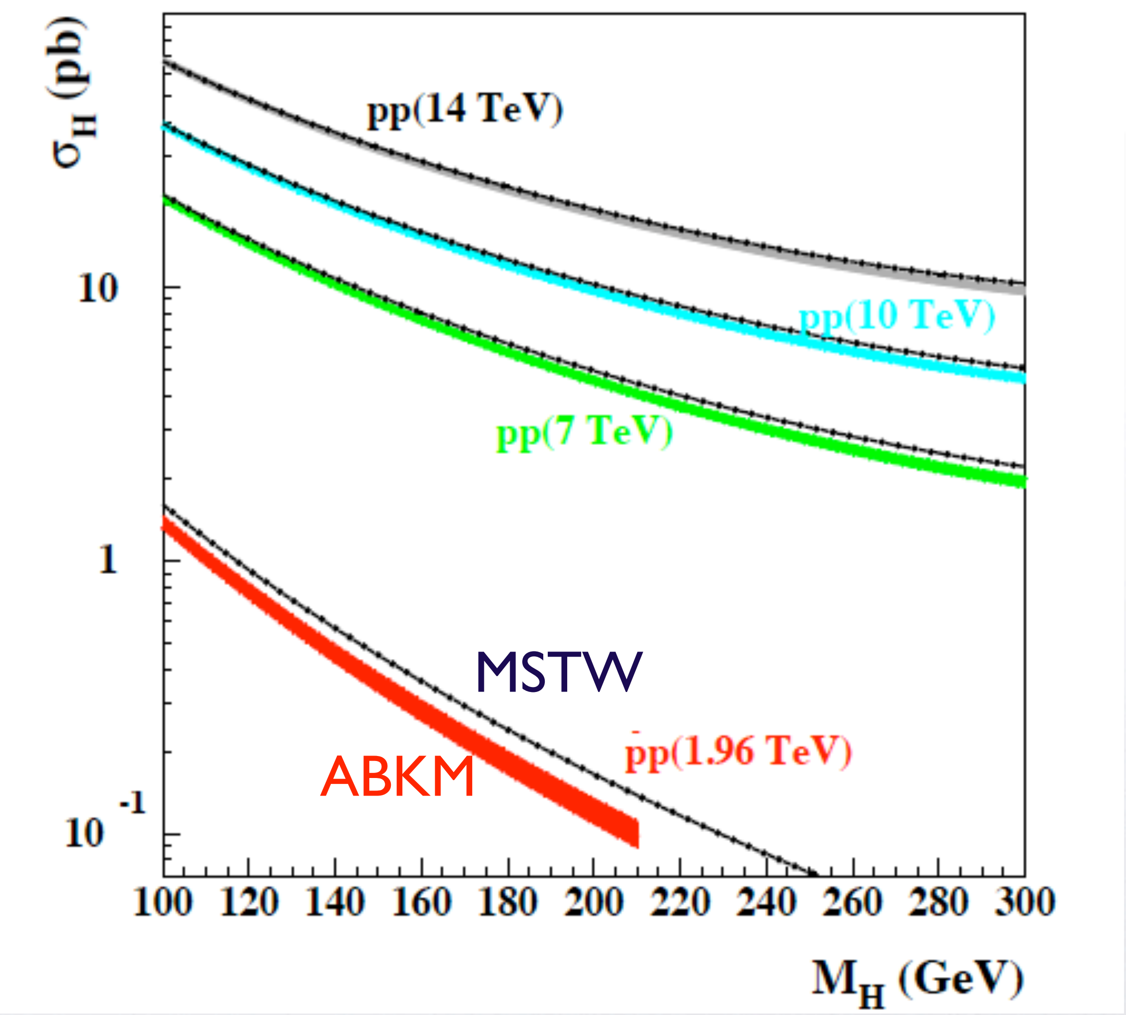
- comparable or bigger uncertainty than scale choice

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

@ TEVATRON   MHIGGS = 165 GEV

PDF set differences

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



Precision of HQET

- At LO and NLO in the strong coupling expansion, we can compute total and fully differential (HPro) cross-sections in the full SM theory.
- We only need to employ HQET for the NNLO coefficient, which amounts to about 20% of the total.
- A “mistake” of 10% due to finite top and bottom mass effects at NNLO gives a very forgiving error of less than 2% for the full LO+NLO+NNLO.

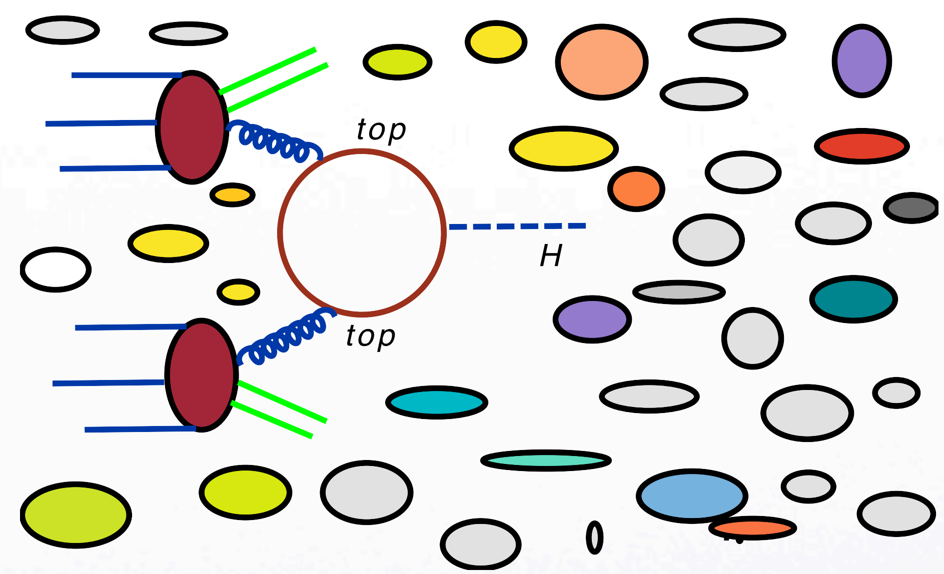
Combining theory uncertainties

- PDF uncertainties have or are made to have a statistical interpretation *(Gaussian priors/ combination in quadrature)*

- Other theory uncertainties parameterize the ignorance of theorists, reflecting a safe interval of cross-section estimates which should contain a hypothetical perfect (all orders) theoretical calculation *(flat priors / linear combination)*

"New" Higgs Physics

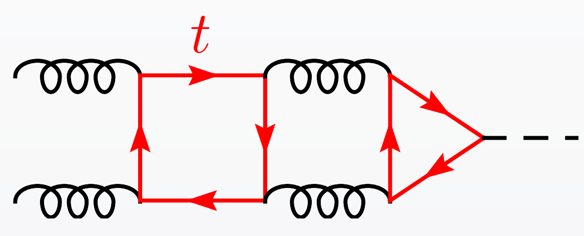
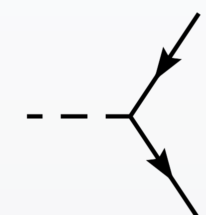
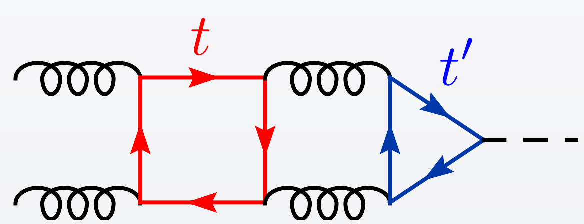
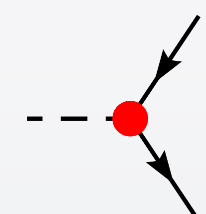
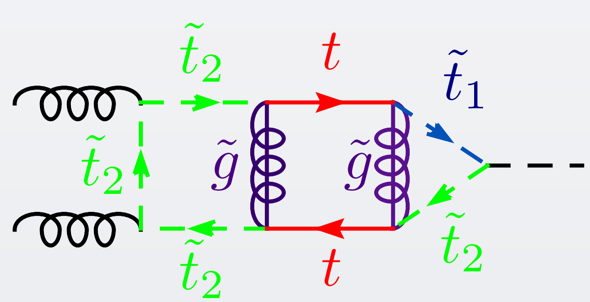
- In the standard model, the higgs mass is the only missing parameter to describe all LHC phenomena
- But Higgs physics is new physics!
- Standard Model is likely to fail in describing Higgs cross-sections in the presence of relatively light new states (eg. Low, Rattazzi, Vichi; Falkowski; Barbieri, Rychkov; Kitano, Nomura; Dermisek, Low;...)
- Higgs cross-sections will be precision tests to be passed by any successful theory of LHC phenomena



Beyond the Standard

- Can we derive a mass exclusion limit for a BSM scalar Higgs from a SM analysis?
- Very often yes, if qcd corrections and shapes of signal discriminants are model independent.
- If we can compute the gluon fusion cross-section in BSM as accurately as in the SM.

... Many possibilities!

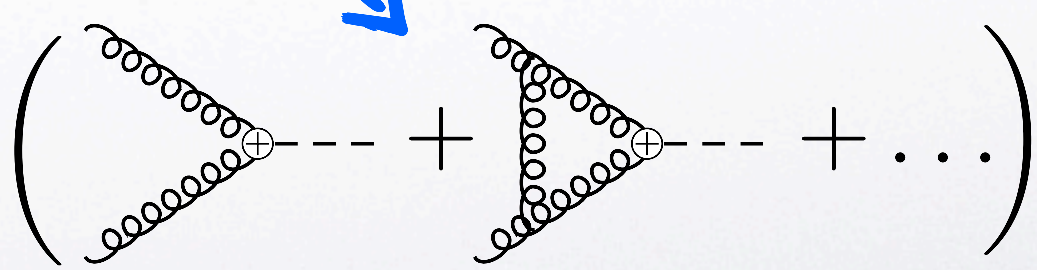
particles in different representations of the Lorentz group	particles of different mass in the loops	particles in different colour representations	different structure of the Higgs couplig
quarks		singlets, triplets, octets	 $\sim \bar{\psi}\psi$
squarks		fundamental, adjoint	 $\sim \bar{\psi}\gamma_5\psi$
Majorana fermions		⋮	⋮
⋮	⋮		

Separating new physics

- Experiments (LEP, Tevatron, ..) indicate that new particles must be heavy, while the Higgs is light
- this allows for an effective-theory approach:

$$\mathcal{L}_{eff} = -\frac{\alpha_S}{4v} C \, H G^a_{\mu\nu} G^{a\mu\nu}$$

$$\left(C_0 + \left(\frac{\alpha_s}{\pi}\right) C_1 + \left(\frac{\alpha_s}{\pi}\right)^2 C_2 + \ldots \right)$$



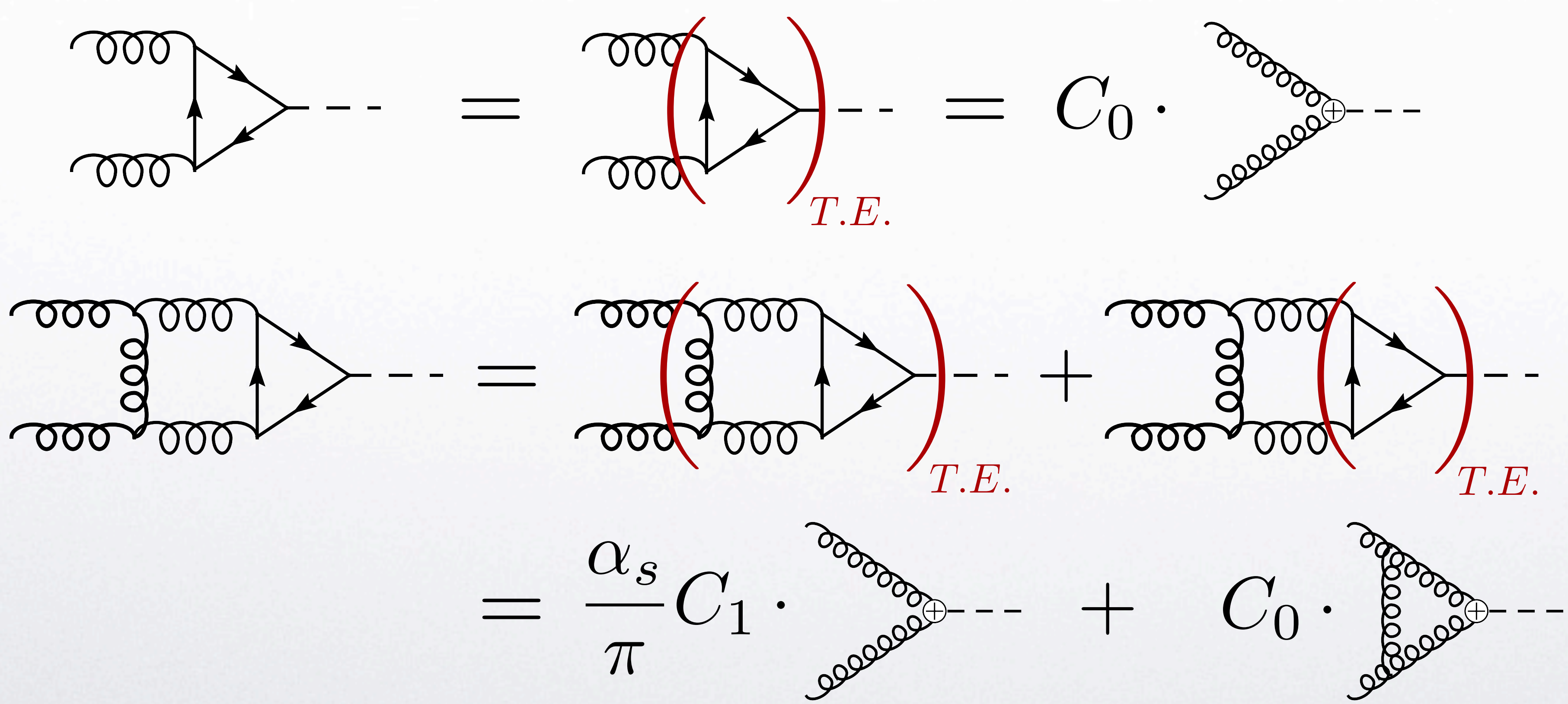
depends on the specific model

QCD only!

factorization of QCD and NP effects

Matching calculations through NNLO

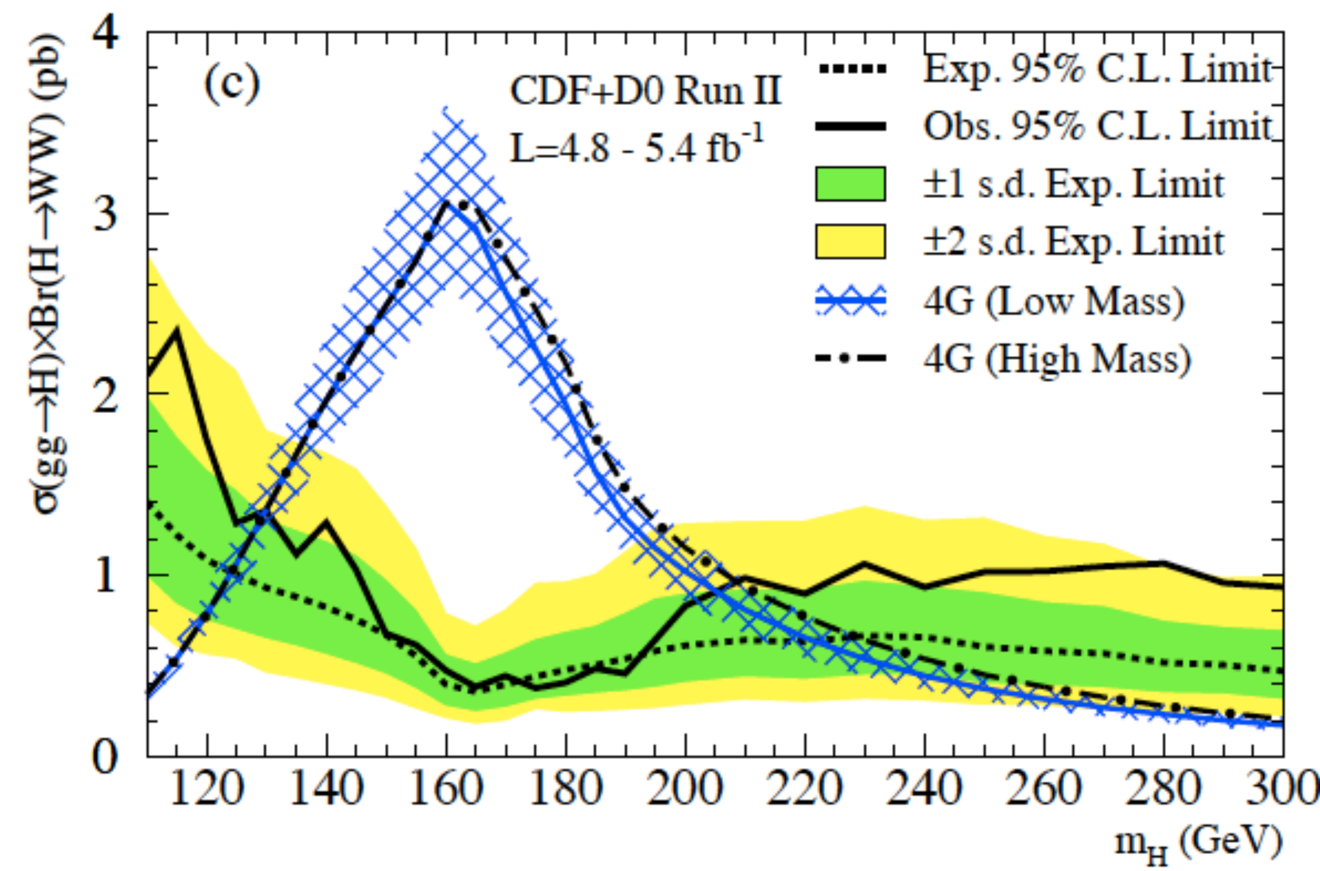
Expansion by subgraphs (Chetyrkin; Gorishny; V.A. Smirnov)
+ small momentum expansion (Fleischer, Tarasov):



...

Testing BSM via gluon fusion

- BSM predictions for the gluon fusion cross-section at NNLO can be tested
- 4th generation (CA, Boughezal, Furlan), studied at Tevatron.
- color octets (Boughezal, Petriello)



Future challenge:
models with significant Higgs coupling to light fermions

Theory vs Experimental Signals

- The experimental searches aim to measure Higgs signals to a region of phase-space which is not a necessarily democratic representation of the total cross-section.
- Do we trust experimental efficiencies of parton-shower Monte-Carlo's?
- How do we quantify the precision on their predicted efficiencies?
- Can we assign the precision of the NNLO, resummed NNLL, NNNLO approx, etc total cross-section to the "targeted signal cross-section" (eg, most significant bins of a neural network on a likelihood analysis)?

Example from CDF

- Break up total NNLO cross-section into 0,1, and 2 jet bins (Pt,jet = 20 gev). The theory precision degrades from the 0-jet to the 1-jet and the 2-jet bin.

$$\frac{\Delta N_{\rm inc}(\text{scale})}{N_{\rm inc}} = 66.5\% \cdot \begin{pmatrix} +5\% \\ -9\% \end{pmatrix} + 28.6\% \cdot \begin{pmatrix} +24\% \\ -22\% \end{pmatrix} + 4.9\% \cdot \begin{pmatrix} +78\% \\ -41\% \end{pmatrix} = \begin{pmatrix} +14.0\% \\ -14.3\% \end{pmatrix}$$

- Apply slightly different e.g. lepton selections in the various jet-bins, which are more severe in the 0-jet bin.

$$\frac{\Delta N_{\rm signal}(\text{scale})}{N_{\rm signal}} = 60\% \cdot \begin{pmatrix} +5\% \\ -9\% \end{pmatrix} + 29\% \cdot \begin{pmatrix} +24\% \\ -22\% \end{pmatrix} + 11\% \cdot \begin{pmatrix} +78\% \\ -41\% \end{pmatrix} = \begin{pmatrix} +18.5\% \\ -16.3\% \end{pmatrix}$$

- Theory uncertainty for the accepted signal events is different than for the total number before cuts.

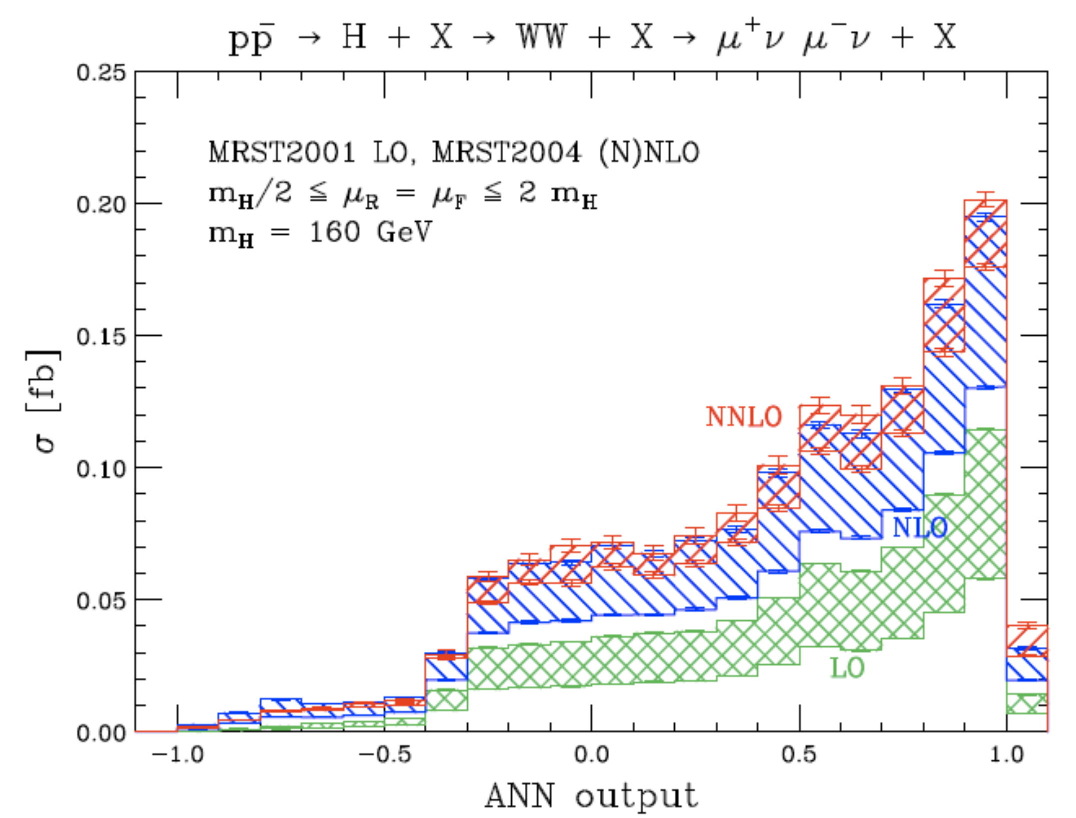
(CA,Dissertori,Grazzini, Stoeckli,Webber)

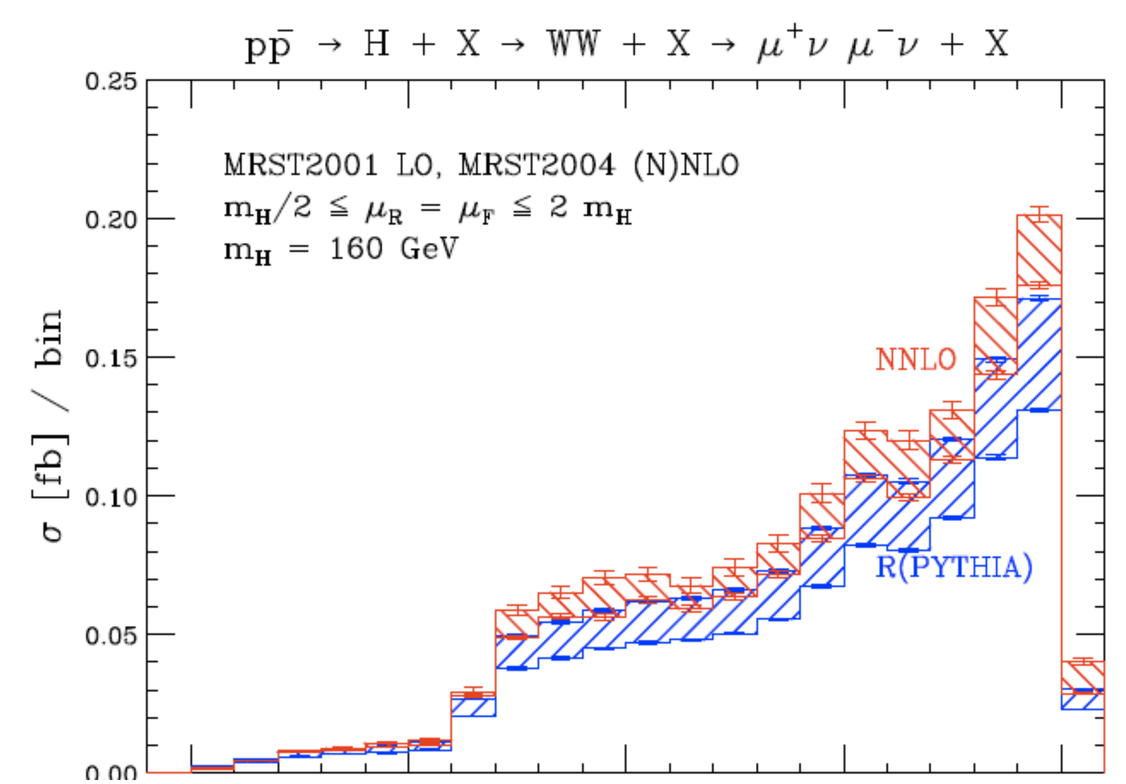
Differential Theory

- Lesson: check theory uncertainty on the kinematic bins which drive exclusion

- An NNLO computation of a neural net is as simple as for a rapidity distribution.
  (CA,Dissertori,Grazzini,Stoeckli,Webber)

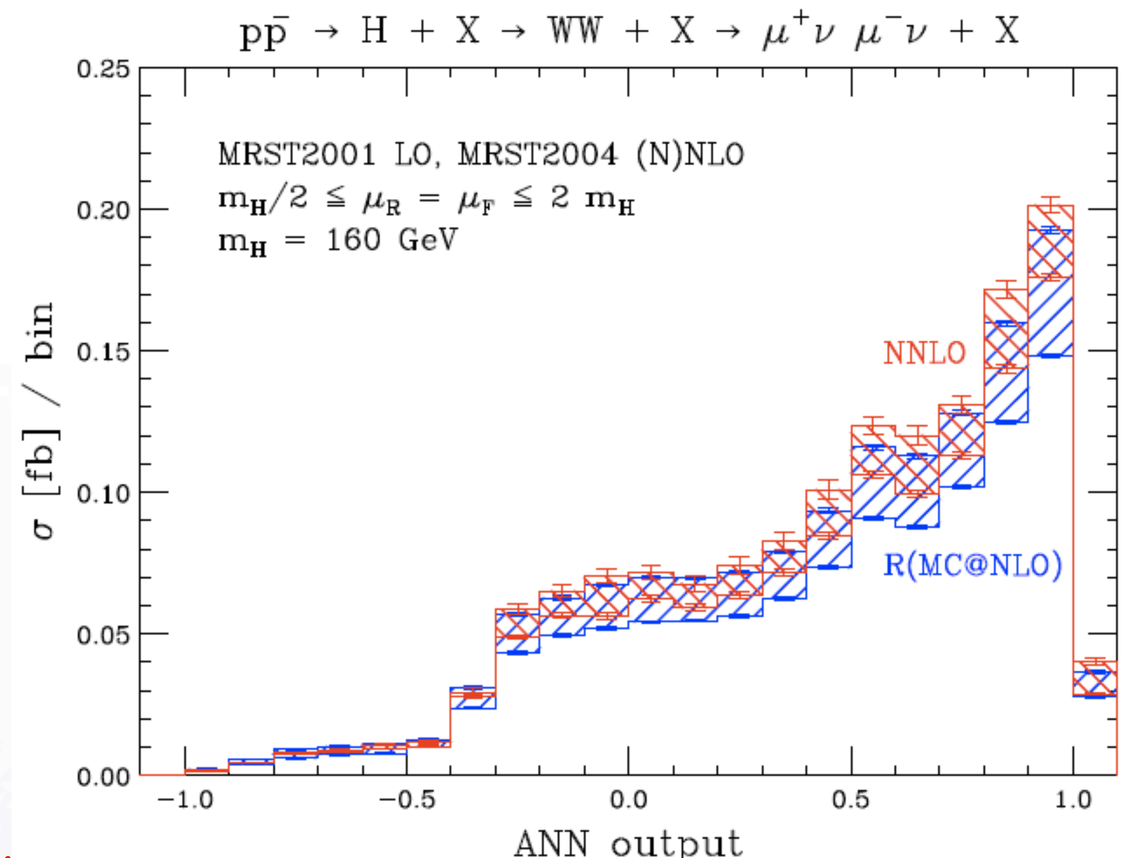
- Highly recommended for the low statistics CDF, D0 and first LHC analyses.





Generators differ!

- Pythia has a smaller jet-veto and isolation acceptance than HERWIG and MC@NLO
- HERWIG and MC@NLO closer to NNLO



(CA,Dissertori,Grazzini, Stoeckli,Webber)

$\sigma_{acc}/\sigma_{incl}$	Trigger	+ Jet-Veto	+ Isolation	All Cuts
NNLO ($\mu = m_H/2$)	44.7%	39.4% (88.1%)	36.8% (93.4%)	27.8% (75.5%)
NNLO ($\mu = 2\ m_H$)	44.9%	41.8% (93.1%)	40.7% (97.4%)	31.0% (76.2%)
MC@NLO ($\mu = m_H/2$)	44.4%	38.1% (85.8%)	35.3% (92.5%)	26.5% (75.2%)
MC@NLO ($\mu = 2\ m_H$)	44.8%	38.8% (86.7%)	35.9% (92.5%)	27.0% (75.2%)
HERWIG	46.7%	40.8% (87.4%)	37.8% (92.7%)	28.6% (75.7%)
PYTHIA	46.6%	37.9% (81.3%)	32.2% (85.0%)	24.4% (75.8%)

- *How many perturbative orders?*
- *What scale?*
- *What parton distribution functions?*
- *What strong coupling value?*
- *The importance of finite mass in top-quark and bottom quark loops?*
- *Are new physics and QCD factorized?*
- *Are event generators reliable in estimating the ratio of measured Higgs signals vs the total?*
- *What is the ultimate precision?*
- *Room for improvements?*

FUTURE

COULD NOT LOOK ANY ROSIER