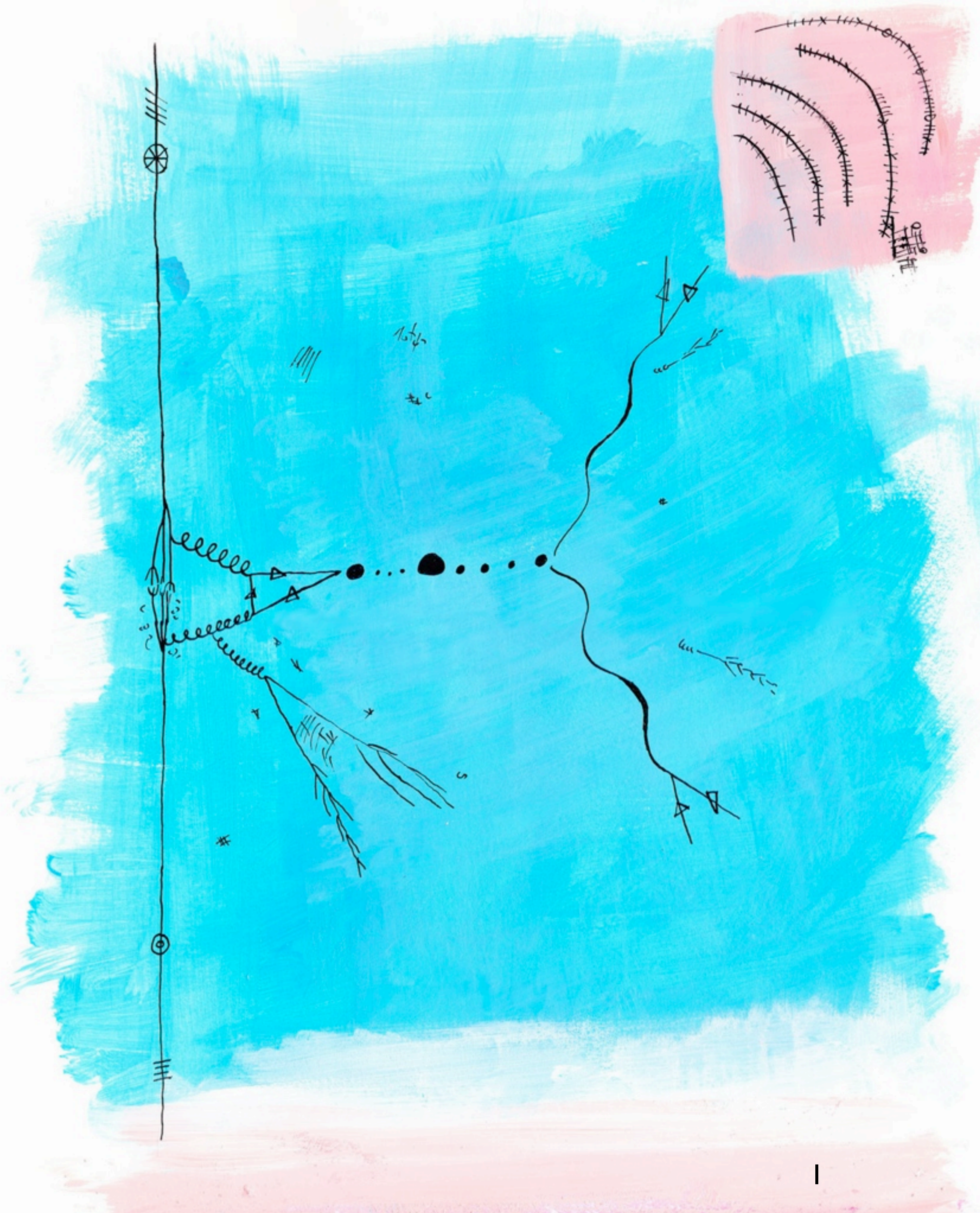


Higgs

in gluon fusion and other NNLO stories

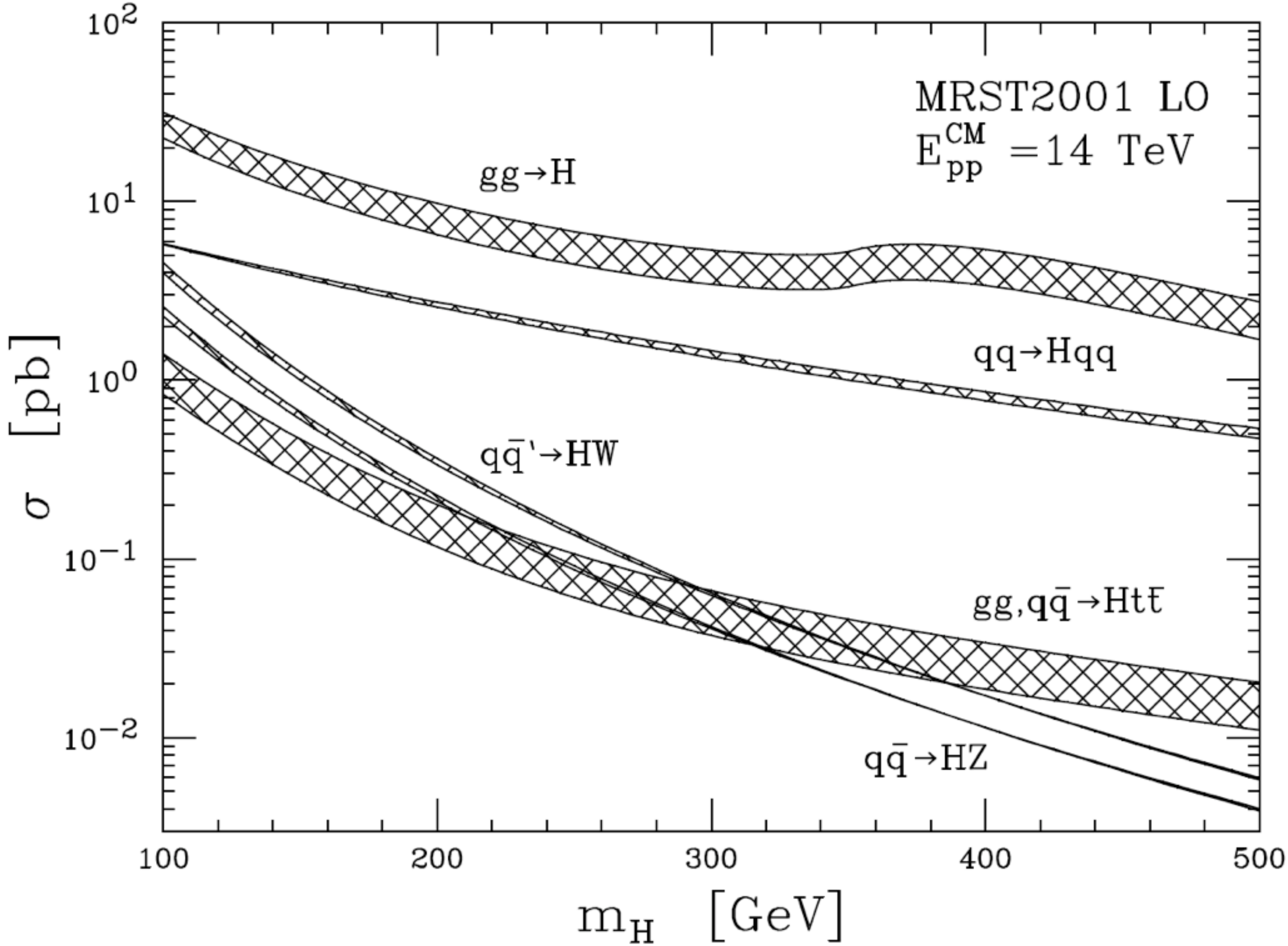
by A. Lazopoulos

ETH ZURICH

15 september 2010

HP^2.3rd

Gluon fusion is the largest Higgs production mode at the LHC



Total cross section @ NLO
Dawson | Spira, Djouadi, Graudenz, Zerwas

Total Cross section @ NNLO
Harlander, Kilgore | Anastasiou, 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

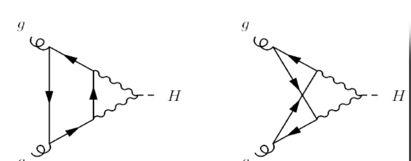
Pt resummation
Bozzi, Catani, de Florian, Grazzini

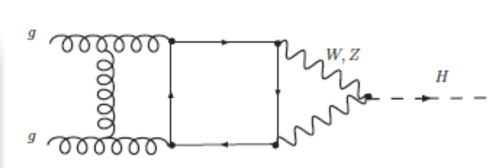
Two-loop Light fermions EW
Aglietti, Bonziani, Degrassi, Vicini

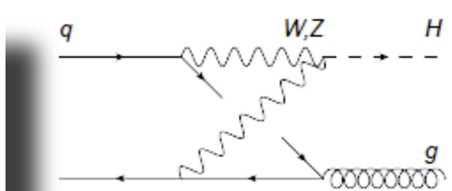
Two-loop EW
Actis, Passarino, Sturm, Ucciratti

Three-loop mixed qcd and ewk
(Anastasiou, Boughezal, Petriello)

One-loop ewk, Pt > 0
Keung, Petriello





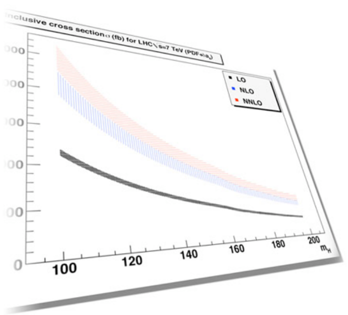


HNNLO

FeHiP / FeHiPro

FeHiPro: next version

- FeHiPro is undergoing some major renovations. New version out soon.



- ZZ decay to leptons included
- Finite Higgs width effects included
- Flexible python interface for arbitrary cuts and histograms, mass scans, PDF and scale uncertainties etc.
- BSM physics with FeHiPro (see talk by E.Furlan)

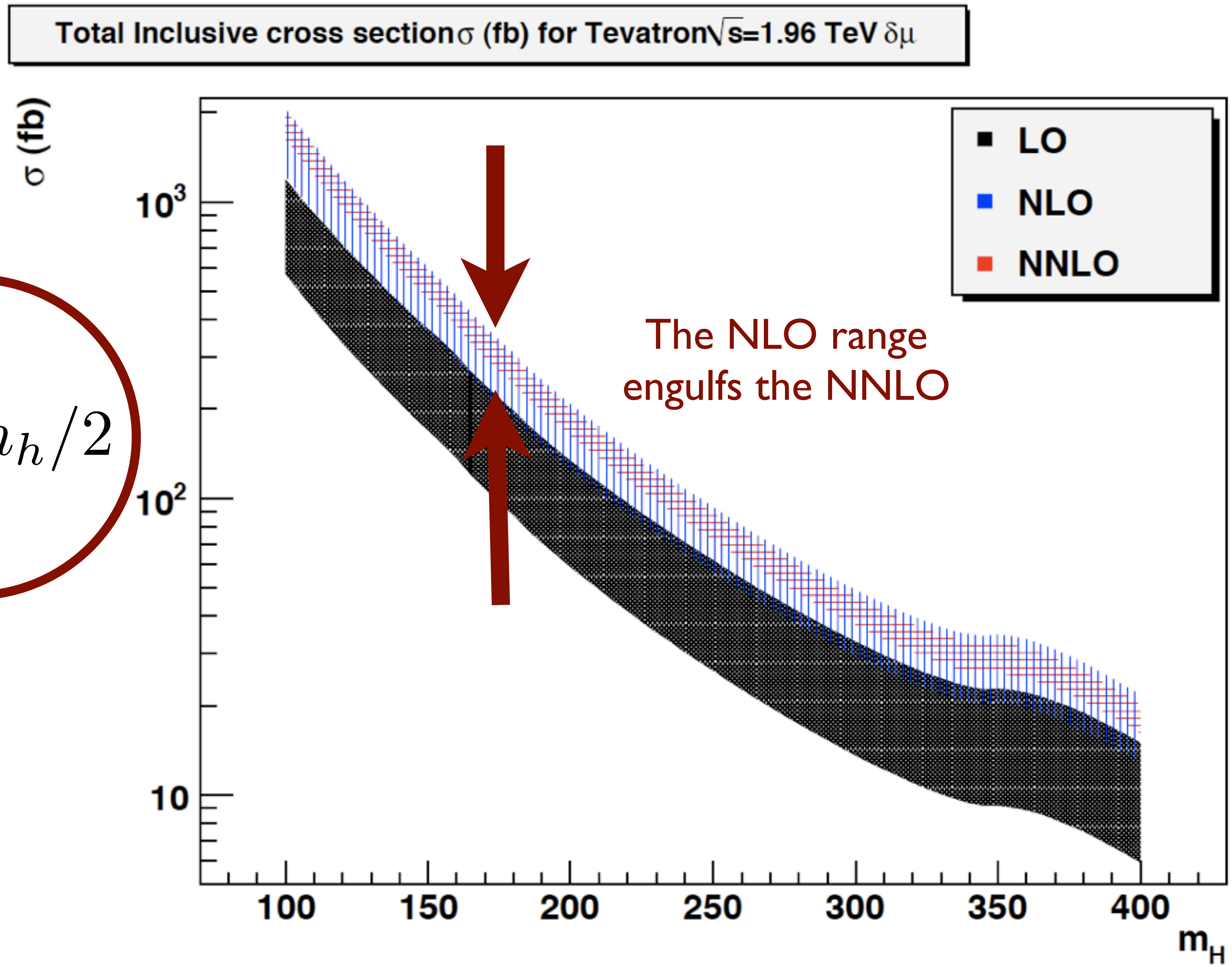
Total and differential cross section

- use NNLO computation
- choose scales such that the physics is captured ($\mu_0 = m_h/2$)

Structure of logs
SCET studies
Perturbative convergence

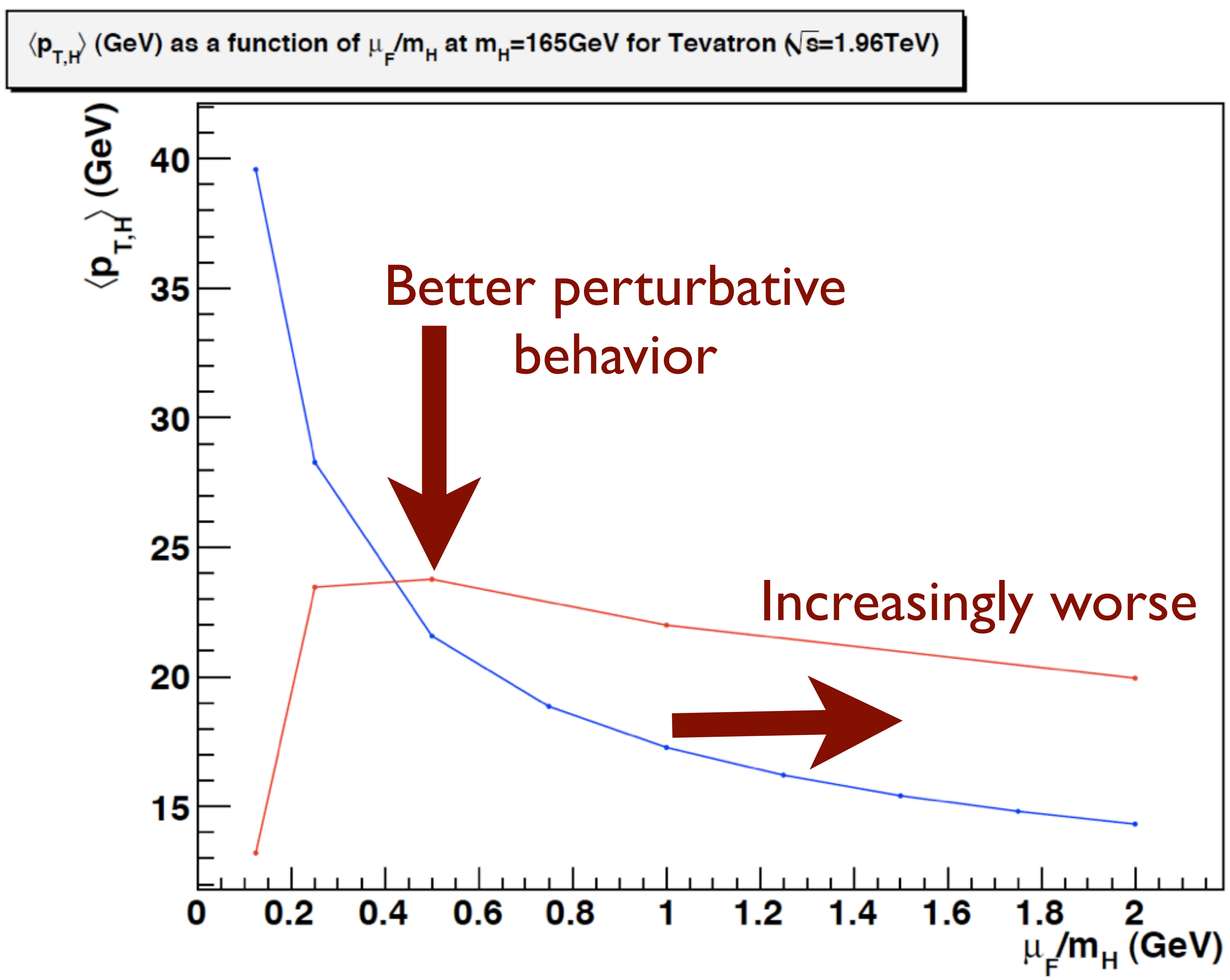
- Include PDFs at NNLO
- Exact quark mass effects at NLO
- Include known e/w corrections
- Supply PDF error (including a_s)

What scale ?

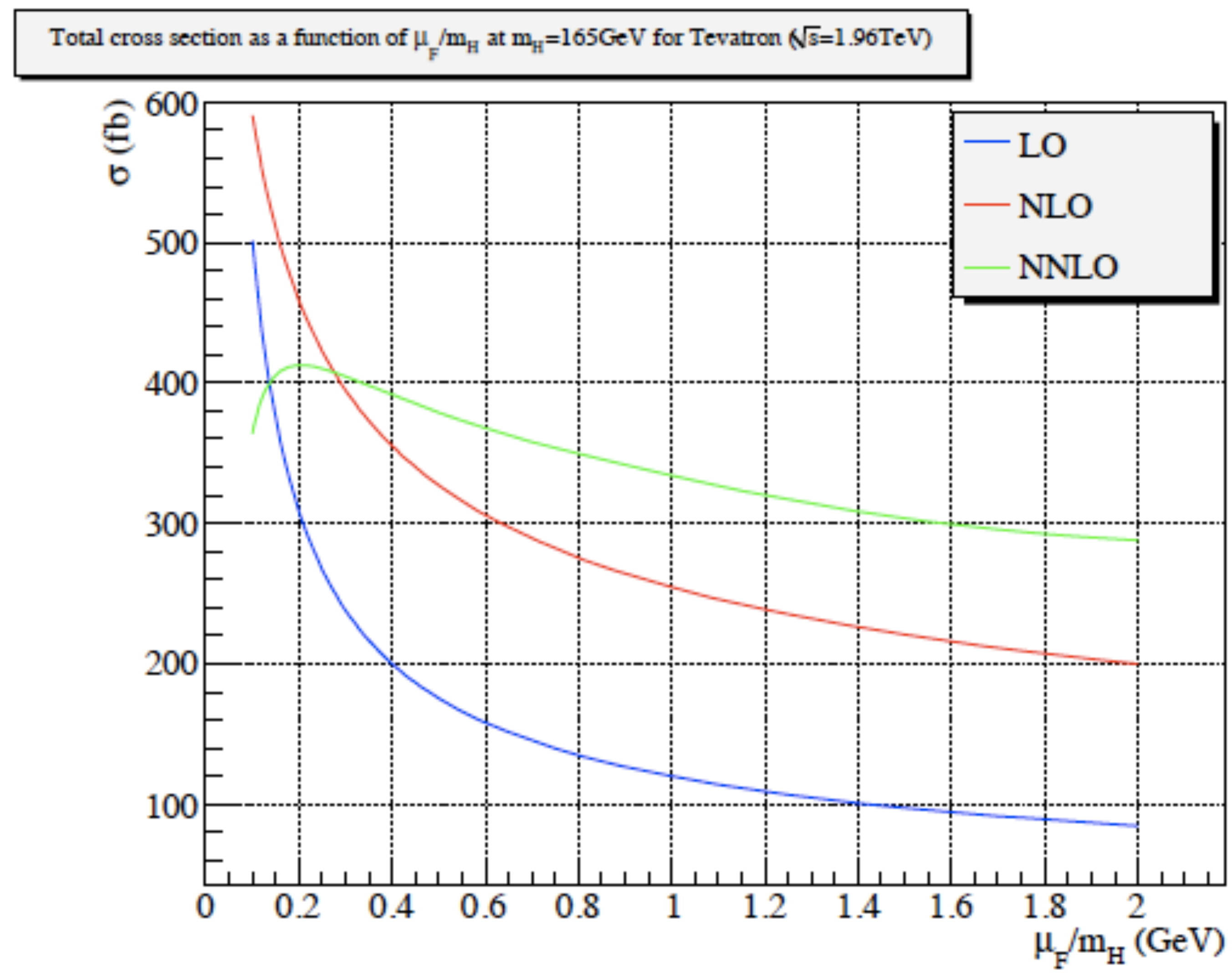


$$\mu = m_h/2$$

What scale?

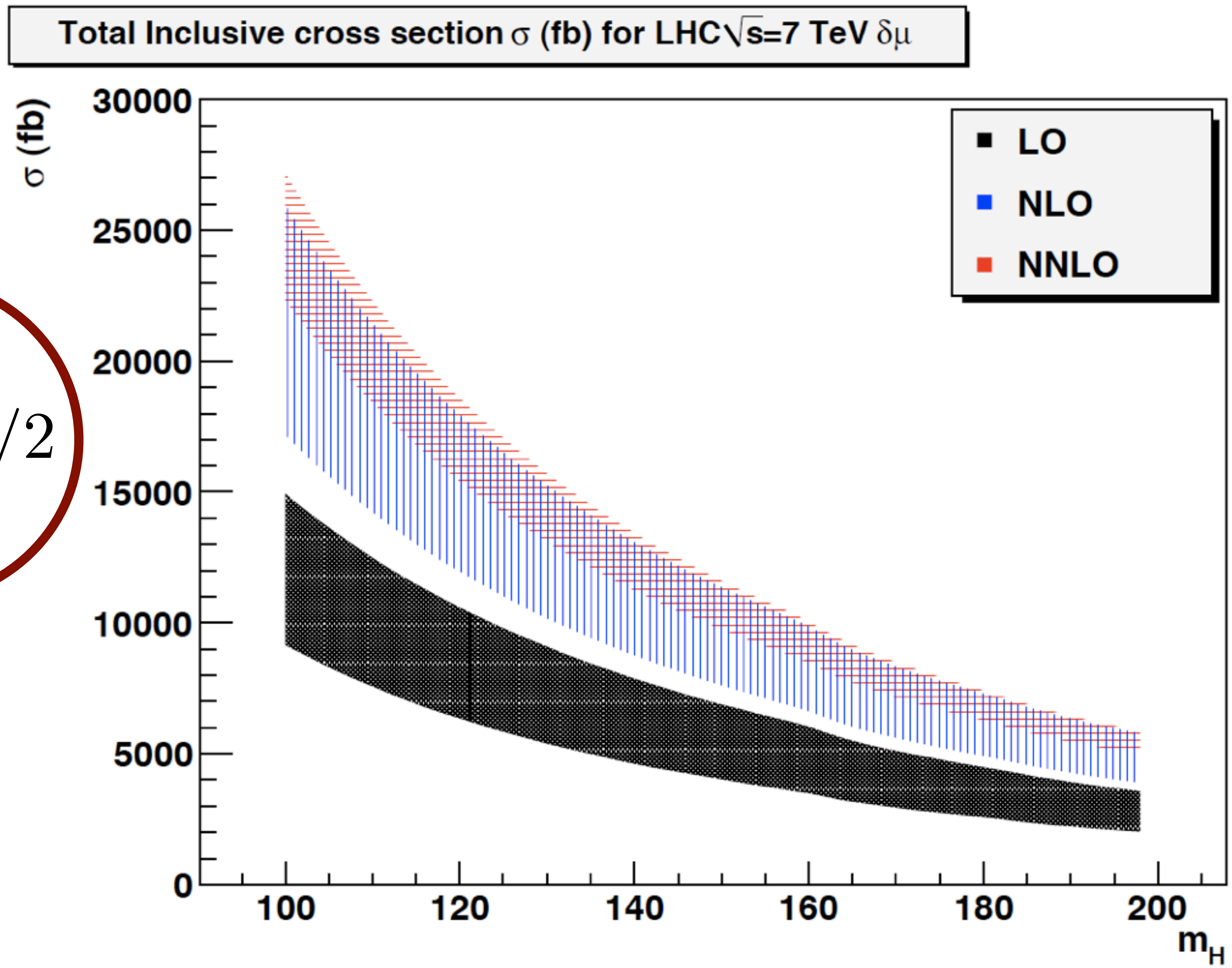


⟨p_{T,H}⟩ (GeV) as a function of μ_F/m_H at m_H=165GeV for Tevatron (√s=1.96TeV)
⟨p_{T,H}⟩ (GeV)
40
35
30
25
20
15
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
μ_F/m_H (GeV)
Better perturbative behavior
Increasingly worse



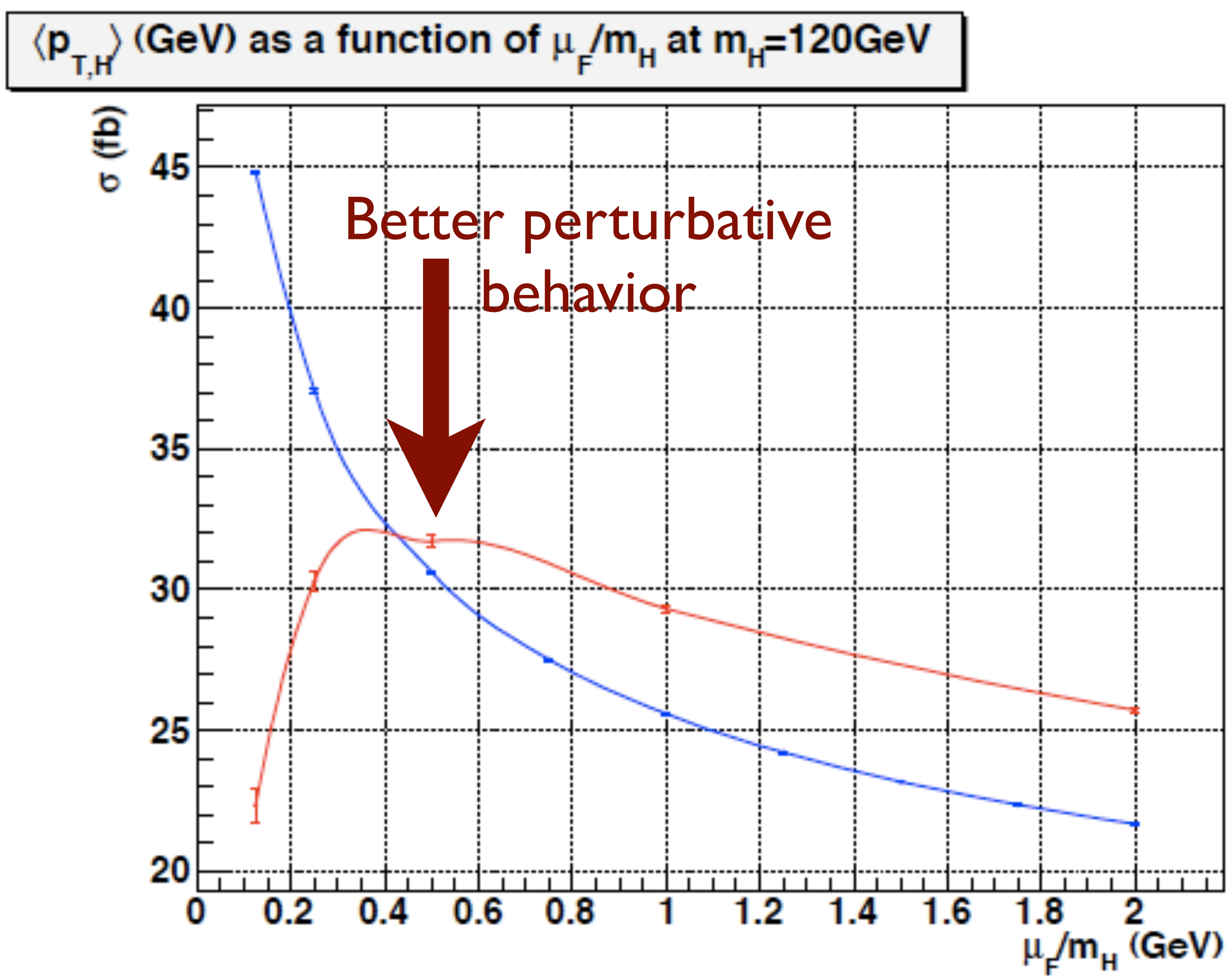
Total cross section as a function of μ_F/m_H at m_H=165GeV for Tevatron (√s=1.96TeV)
σ (fb)
600
500
400
300
200
100
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
μ_F/m_H (GeV)
LO
NLO
NNLO

What scale?

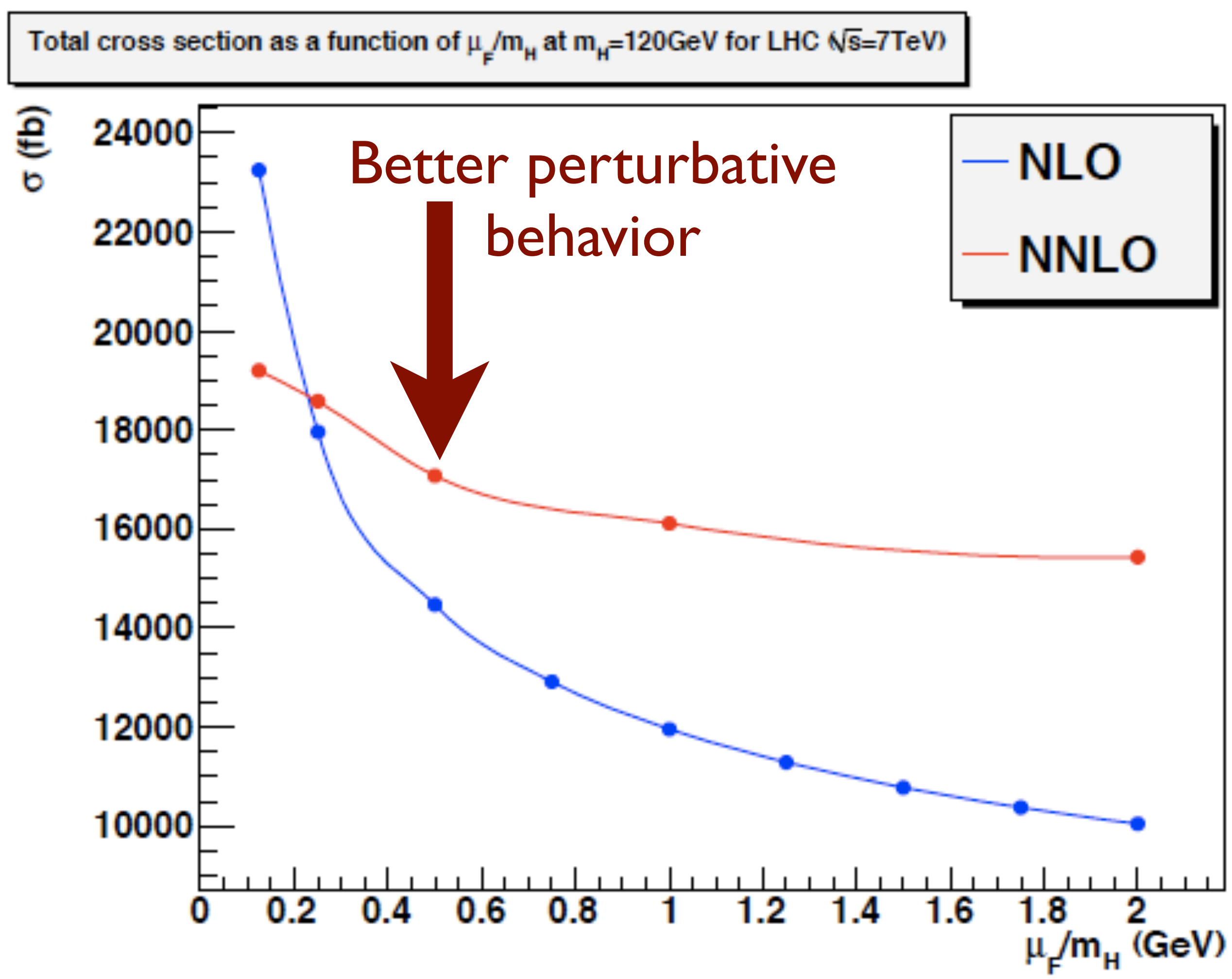


$$\mu = m_h/2$$

What scale?

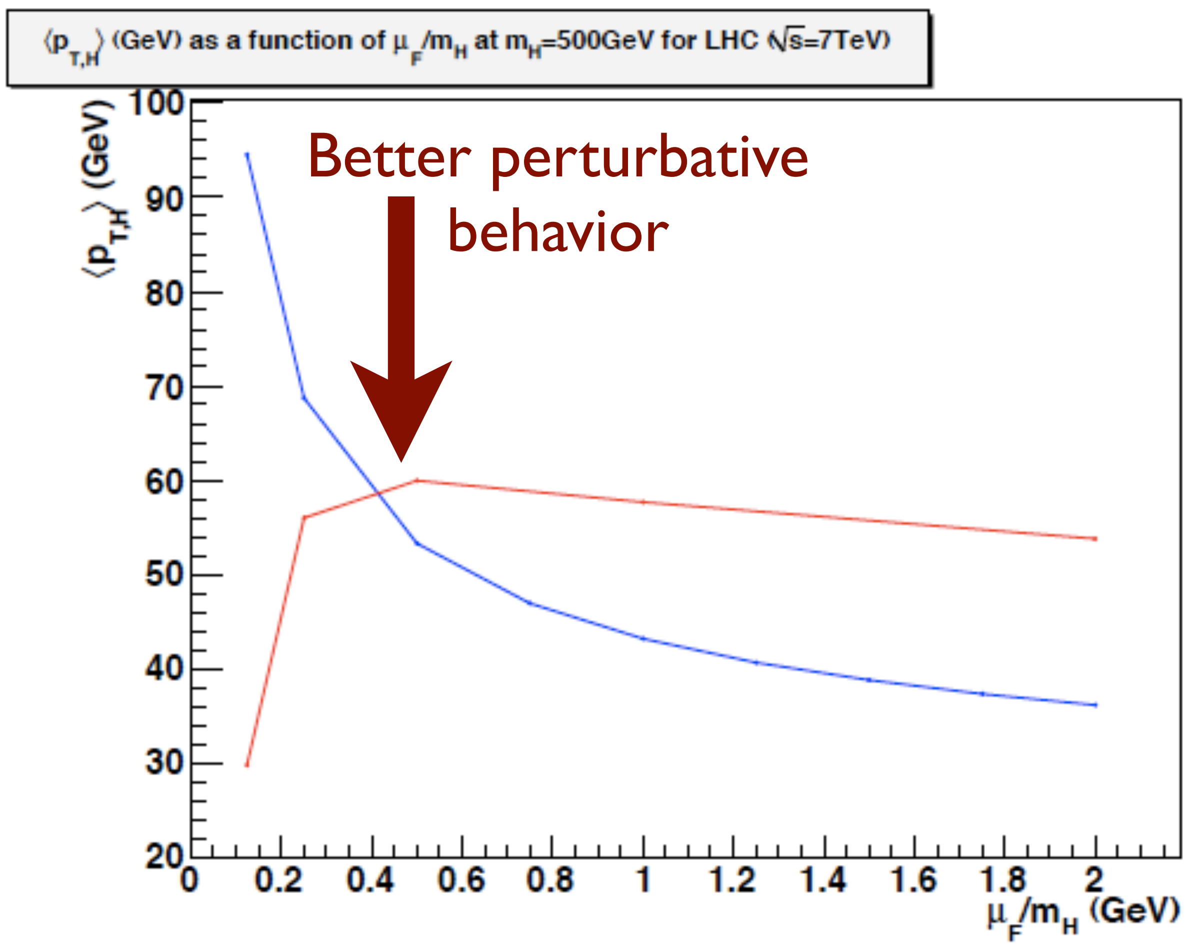


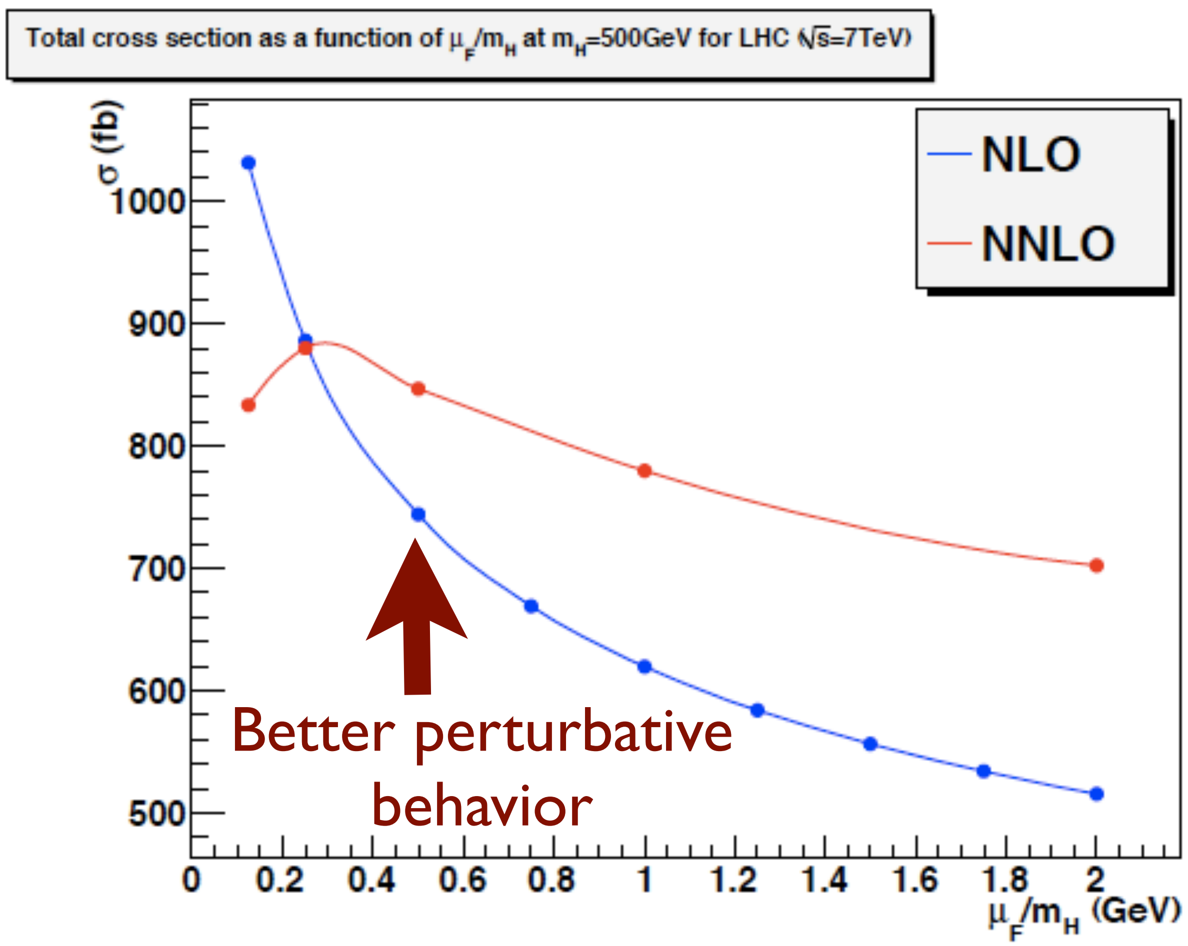
$\langle p_{T,H} \rangle$ (GeV) as a function of μ_F/m_H at m_H=120GeV
σ (fb)
45
40
35
30
25
20
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
μ_F/m_H (GeV)
Better perturbative behavior

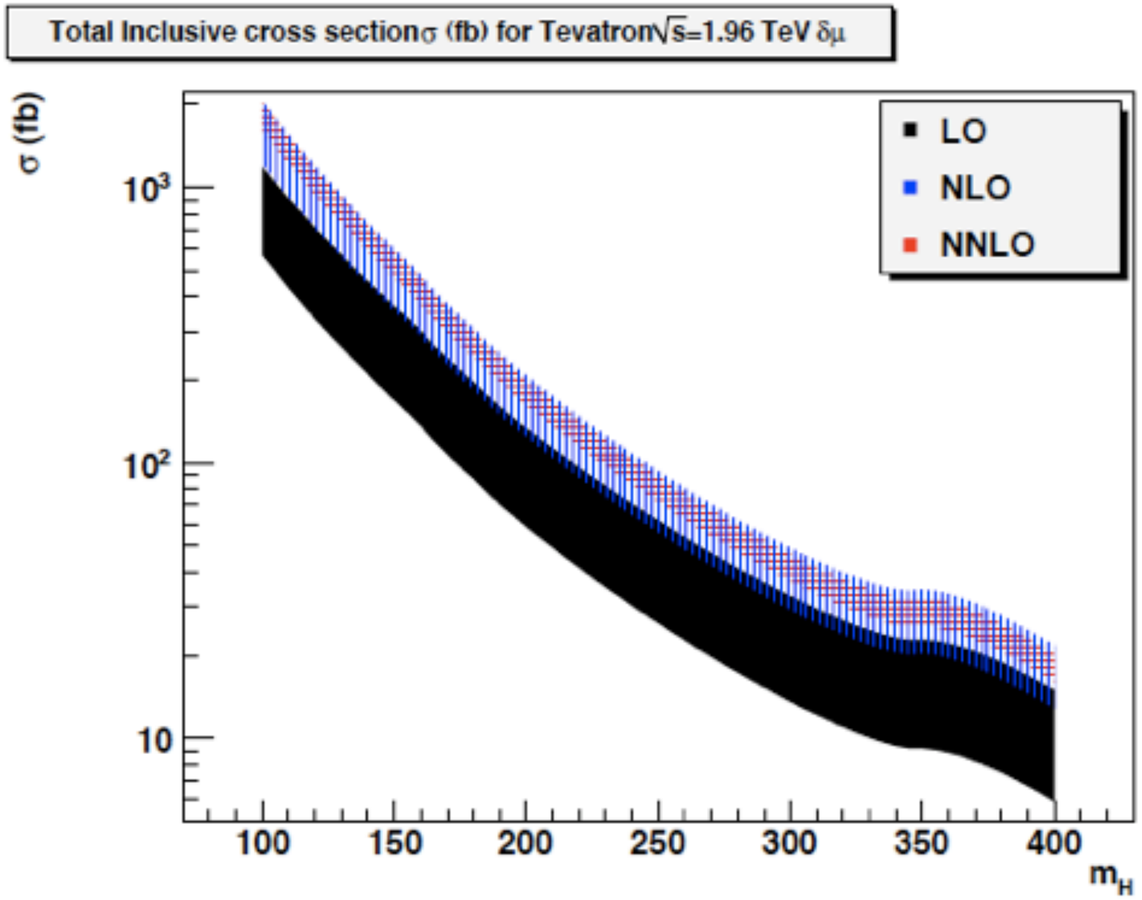


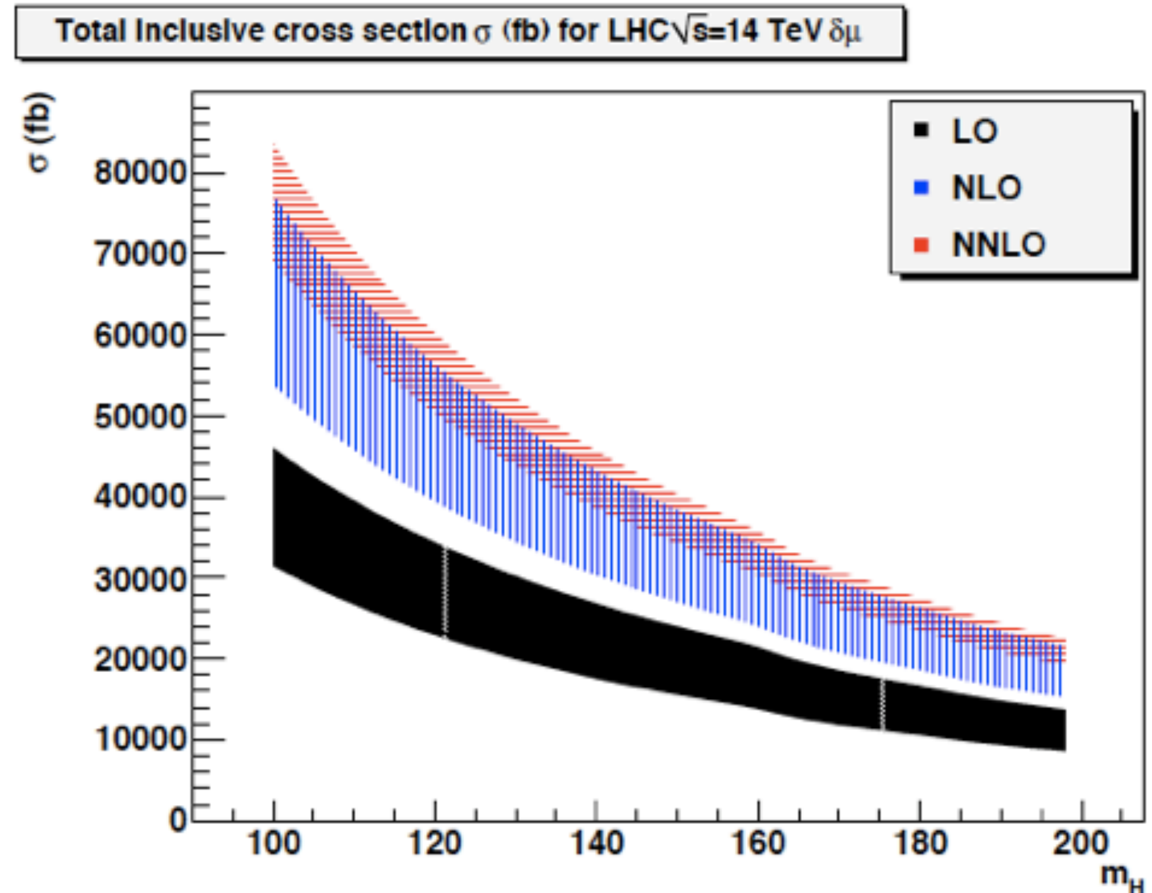
Total cross section as a function of μ_F/m_H at m_H=120GeV for LHC ($\sqrt{s}$=7TeV)
σ (fb)
24000
22000
20000
18000
16000
14000
12000
10000
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
μ_F/m_H (GeV)
NLO
NNLO
Better perturbative behavior

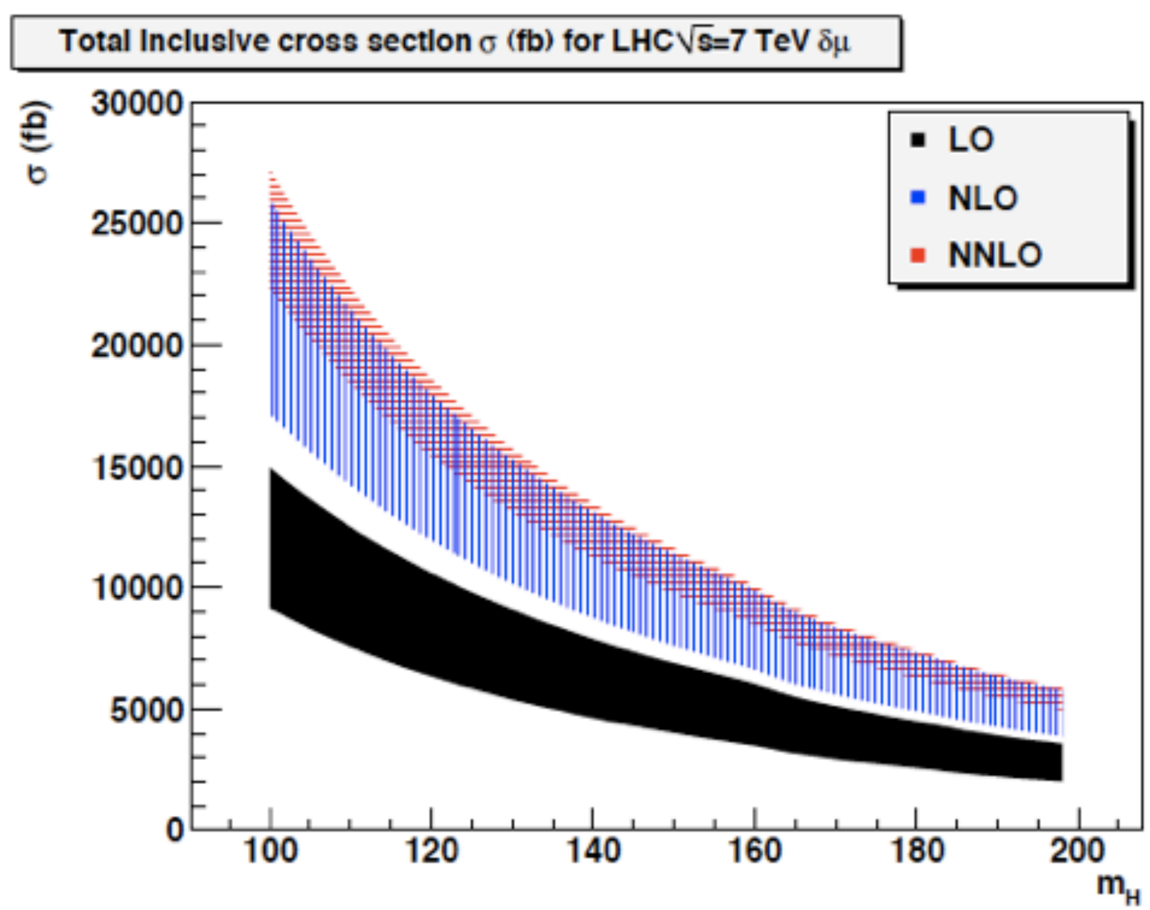
What scale?


⟨p_T,H⟩ (GeV) as a function of μ_F/m_H at m_H=500GeV for LHC √s=7TeV)
⟨p_T,H⟩ (GeV)
μ_F/m_H (GeV)
Better perturbative behavior


Total cross section as a function of μ_F/m_H at m_H=500GeV for LHC √s=7TeV)
σ (fb)
μ_F/m_H (GeV)
NLO
NNLO
Better perturbative behavior


Total Inclusive cross section σ (fb) for Tevatron √s=1.96 TeV δμ
σ (fb)
LO
NLO
NNLO
m_H


Total Inclusive cross section σ (fb) for LHC √s=14 TeV δμ
σ (fb)
LO
NLO
NNLO
m_H


Total Inclusive cross section σ (fb) for LHC √s=7 TeV δμ
σ (fb)
LO
NLO
NNLO
m_H

Scale and PDF uncertainty correlations

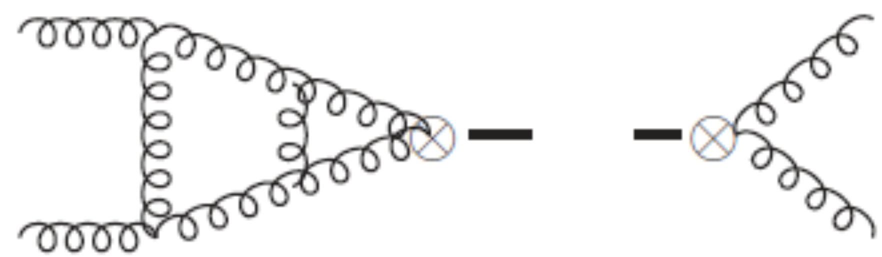
- Is the PDF error correlated with the choice of scale?
- Calculate PDF uncertainty with scales $[\mu = m_h/4, m_h]$
- Over a large mass range, for the Tevatron, the relative scale uncertainty $\frac{d\sigma(pdf,\mu)}{\sigma(pdf,\mu)}$ is constant to 0.3%

And now for something completely different: towards better NNLO calculations

In collaboration with C. Anastasiou and F. Herzog

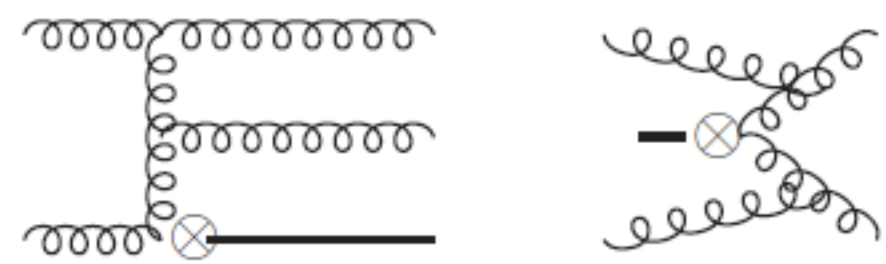
NNLO is different than NLO

Double virtual



entangled singularities

Double real



The entangled singularities

$$I = \int_0^1 dx_1 dx_2 \frac{1}{(x_1 + c x_2)^{2-\epsilon}} \qquad c > 0$$

$x_1 > x_2$

$x_2 > x_1$

$x_2 \longrightarrow x_2 x_1$ (linear trsansformations) $x_1 \longrightarrow x_1 x_2$

$$I_1 = \int_0^1 \frac{dx_1 dx_2}{x_1^{1-\epsilon}} \frac{1}{(1 + c x_2)^{2-\epsilon}} \qquad I_2 = \int_0^1 \frac{dx_1 dx_2}{x_2^{1-\epsilon}} \frac{1}{(x_1 + c)^{2-\epsilon}}$$

Disentangling them

$$x_2 = \frac{x_1 x_2'}{x_1 + (1 - x_2')}$$

$$\downarrow$$

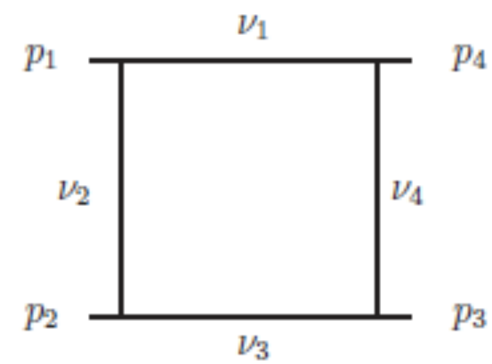
non-linear transformation preserves the integration region

$$I_1 = \int_0^1 \frac{dx_1 dx_2}{\underline{x_1^{1-\epsilon}}} \boxed{\frac{(1+x_1)(1-x_2+x_1)^\epsilon}{(1-x_2+x_1+cx_2)^{2-\epsilon}}}$$

FINITE

Ready for plus-distribution expansion $x^{-1+\epsilon} = \frac{\delta(x)}{\epsilon} + \sum_{n=0}^{\infty} \frac{\epsilon^n}{n!} \left[\frac{\ln^n(x)}{x}\right]_+$

The one loop box



$$I = \int_0^1 dx_1 \ldots dx_4 \delta\left(1 - x_1 - \ldots - x_4\right) f(x_1, \ldots, x_4)$$

$$f(x_1, \ldots, x_4) \equiv \frac{\Gamma(2+\epsilon)}{\left[-s x_1 x_3 - t x_2 x_4 - i0\right]^{2+\epsilon}}.$$

$$I = 2\,\Gamma(2+\epsilon) \int_0^1 dy_1 dy_2 dy_3 \left(1 + y_1 + y_2 + y_3\right)^{2\epsilon}$$
$$\times \left\{\left[-s y_1 - t y_2 y_3\right]^{-2-\epsilon} + \left[-t y_1 - s y_2 y_3\right]^{-2-\epsilon}\right\}$$

The one loop box

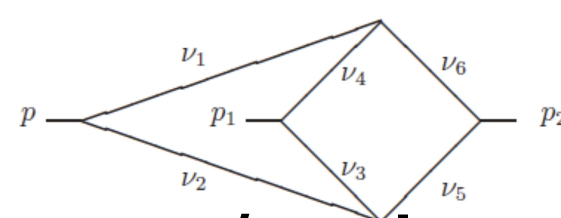
$$y_1 \to \frac{y_1 y_2 y_3}{1 - y_1 + y_2 y_3}$$

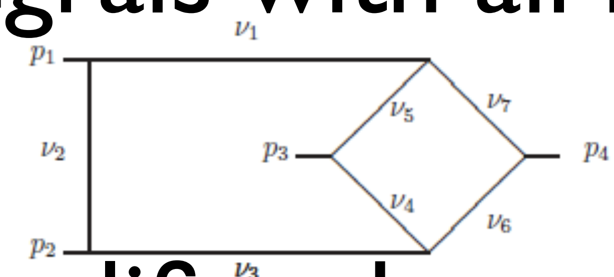
$$I = 2\,\Gamma(2+\epsilon)\int_0^1 dy_1 dy_2 dy_3 \boxed{(y_2 y_3)^{-1-\epsilon}} (1 - y_1 + y_2 y_3)^{-\epsilon}\left[y_1 y_2 y_3 + (1 + y_2 + y_3)(1 - y_1 + y_2 y_3)\right]^{2\epsilon}$$
$$\times \left\{\left[-s y_1 - t(1-y_1) - t y_2 y_3\right]^{-2-\epsilon} + \left[-t y_1 - s(1-y_1) - s y_2 y_3\right]^{-2-\epsilon}\right\} \qquad (4.15)$$

Singularities extracted!

The most complicated cases at 2-loops

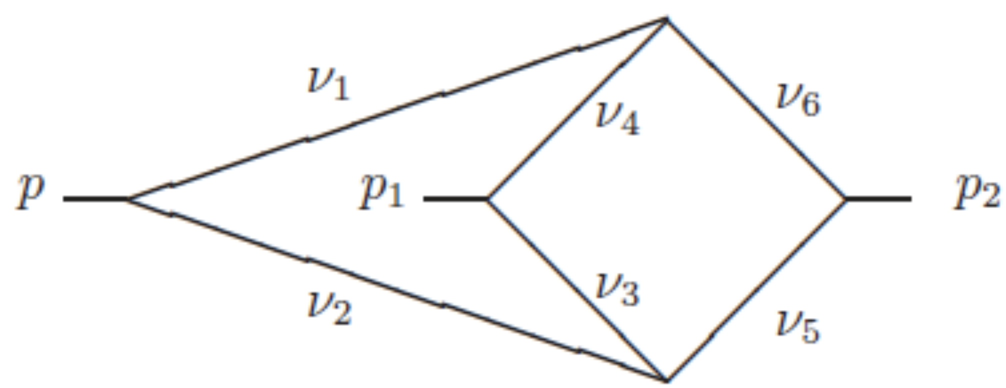
- Massless non-planar integrals with all legs on-shell





- Adding masses/scales simplifies the singularity structure.
- Threshold singularities that appear can be treated numerically with contour deformation.

The two loop Xtriangle



$$Xtri = 4^{2+2\epsilon} \int_0^1 dx_1 dx_2 dz dy dx \frac{z y^{1+\epsilon}(1-y)^{-1-\epsilon}(1-z)^{-1-\epsilon}}{[x(1-x) + yz(x-x_1)(x-x_2)]^{2+2\epsilon}}$$

$\downarrow$

Complicated singularity structure $x, y, z \to 0, 1$ etc.

Unavoidable split in 4 integrals to remove singularities at 1

The Xtriangle resolved

$$Xtri_{11} = 2^{6+9\epsilon} \int_0^1 dx_1 dx_2 dz dy dx \frac{z y^{1+\epsilon}(2-y)^{-1-\epsilon}(2-z)^{-1-\epsilon}}{[4x(2-x)+yz(2x_1-x)(2x_2-x)]^{2+2\epsilon}}$$

$$x \to \frac{xyzx_1x_2}{1-x+yzx_1x_2} \longrightarrow$$

Trivial numerical evaluation
Number of integrals reduced by a factor of 16 with respect to sector decomposition

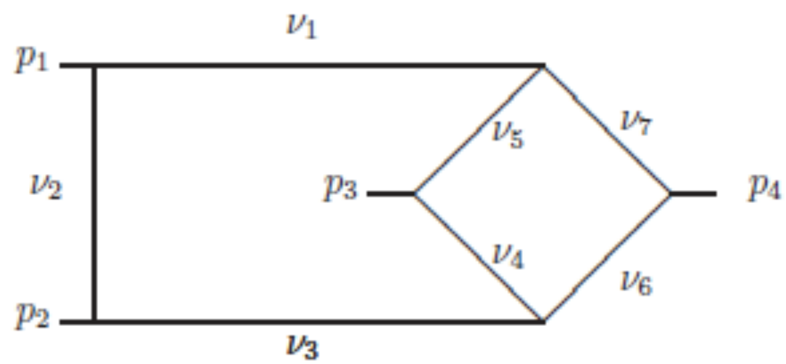
Identical procedure for the other integrals

$$Xtri_{12} = 2^{6+9\epsilon} \int_0^1 dx_1 dx_2 dz dy dx \frac{(2-z) y^{1+\epsilon}(2-y)^{-1-\epsilon} z^{-1-\epsilon}}{[4x(2-x)+y(2-z)(2x_1-x)(2x_2-x)]^{2+2\epsilon}} \quad (6.$$

$$Xtri_{21} = 2^{6+9\epsilon} \int_0^1 dx_1 dx_2 dz dy dx \frac{z (2-y)^{1+\epsilon} y^{-1-\epsilon}(2-z)^{-1-\epsilon}}{[4x(2-x)+(2-y)z(2x_1-x)(2x_2-x)]^{2+2\epsilon}} \quad (6.$$

$$Xtri_{22} = 2^{6+9\epsilon} \int_0^1 dx_1 dx_2 dz dy dx \frac{(2-z)(2-y)^{1+\epsilon} y^{-1-\epsilon} z^{-1-\epsilon}}{[4x(2-x)+(2-y)(2-z)(2x_1-x)(2x_2-x)]^{2+2\epsilon}}$$

The Xbox and alikes



Same type of singularities

$$X_{box} = \Gamma(3+2\epsilon)(-s)^{-3-2\epsilon} \int \frac{dy\ dz\ dx_2\ dx_4\ [dx_{567}] \quad y^{1+\epsilon} z(1-y)^{-1-\epsilon}(1-z)^{-1-\epsilon}}{[x_5 x_6 + zy(x_6 - x_2)(x_6 + x_7 - x_4) + zy(x_4 - x_2) x_7\ t/s]^{3+2\epsilon}}$$

The number of integrals is reduced by a factor of 20 in comparison to sector decomposition.

Extending to double real

- We pursue an identical approach for the double real.
- The standard approach used in Fehip is sector decomposition and results in many sectors.
- The number of integrals is greatly reduced with our non-linear mappings.

Overview

Higgs in gluon fusion

- Developing the next version of FeHiPro for NNLO predictions of Higgs production at the fully differential level.
- Perturbative evidence that the correct central scale should be chosen at values lower than m_h
- Studies of average pT also suggests low central scale
- Studies of PDF and scale uncertainties show little correlation

Towards new NNLO

- New approach to disentangling singularities for NNLO double virtual and double real amplitudes.
- It avoids the proliferation of integrals.
- Very promising first results in the most difficult 2-loop cases.
- Similar treatment for the double real.
- Great optimism for better differential NNLO calculations.

What scale?

Tevatron

68% CL

$m_H(GeV)$	$\sigma(fb)$	$\delta^+_{PDF+a_s}(\%)$	$\delta^-_{PDF+a_s}(\%)$	$\delta\mu^+(\%)$	$\delta\mu^-(\%)$
100	1851.39	5.40	4.75	9.55	12.22
105	1605.82	5.47	4.84	9.37	12.16
150	536.96	6.28	5.70	8.37	11.90
155	482.56	6.38	5.80	8.30	11.88
160	431.60	6.49	5.90	8.21	11.87
165	379.16	6.60	6.01	8.18	11.88
170	338.92	6.71	6.11	8.17	11.90
175	305.40	6.81	6.21	8.13	11.91
180	275.91	6.93	6.31	8.11	11.92