Finite fermion mass effects in Higgs boson production beyond NLO

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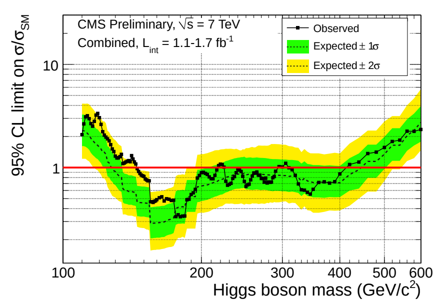
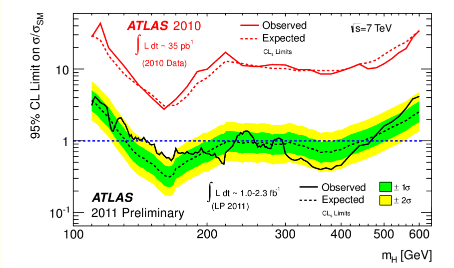
A Firts glimpse of the Tera Scale, BNL, October 19th, 2011

Exclusion plots from the LHC: heavy Higgs almost excluded

SM Higgs already excluded in the range $200 < m_h < 400$ GeV





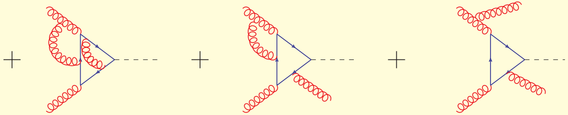
Very soon we can have stronger statements for heavy Higgs (Discovery / exclusion on the full $m_h > 200$ GeV range)

Amazing Experimental Results

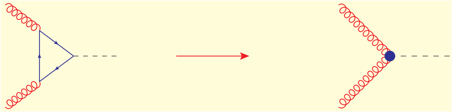
The theory beyond exclusion plots: $m_t/m_h \to \infty$

Main theoretical ingredient: NNLO QCD

- Full result: very hard to compute



- Actual computations: "heavy top approximation", i.e. $m_t/m_h \to \infty$

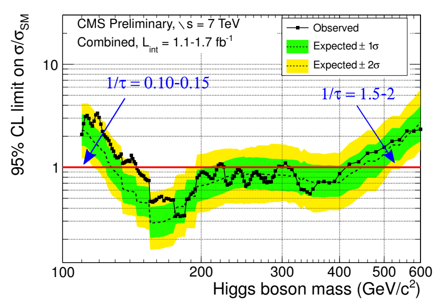


Only the leading term in a m_h/m_t expansion is retained

How can this possibly work for a heavy Higgs?

$m_t/m_h \to \infty$: almost never true

Effective parameter: $\tau \equiv 4m_t^2/m_H^2$. (Heavy top limit: $1/\tau \to 0$)



- Potentially large corrections even for small m_h
- Non convergent expansion beyond the top threshold
- Always miss $t-b$ interference effects ($\sim 5\%$ in the SM)

Why are the exclusion plots valid?

Should we go ahead and compute the full NNLO?

NLO: finite mass effects don't show up

A posteriori lessons from NLO:

THE HEAVY TOP THEORY WORKS (ALMOST TOO) WELL

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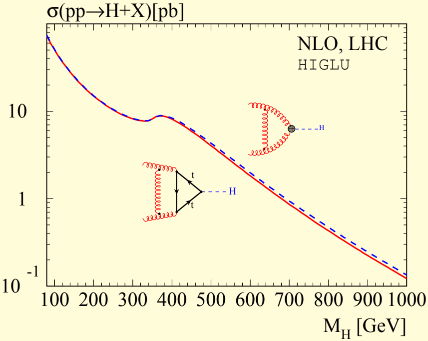


$$\sigma \equiv \sigma_{LO}(m_t) \times \left(\frac{\sigma_{NLO}}{\sigma_{LO}}\right)_{m_t/m_h \to \infty}$$

$\sim$ 5% accuracy at $m_h = 1$ TeV

CAN WE UNDERSTAND THIS?

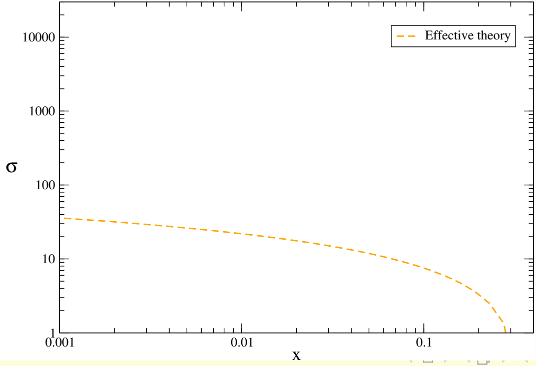
Accidental cancellation or physical origin? ($\longrightarrow$ NNLO)

Taylor expansion in m_h/m_t does not converge

Taylor expand in $1/\tau$: is this well-behaved? (Dawson, Kauffman, 93)

$$\hat{\sigma}(\hat{s}, m_t^2, m_H^2) = \sum_k \left(\frac{1}{\tau}\right)^k c_k(x), \qquad x = \frac{m_H^2}{\hat{s}}, \quad \tau = \frac{4m_t^2}{m_H^2}$$

At NLO:



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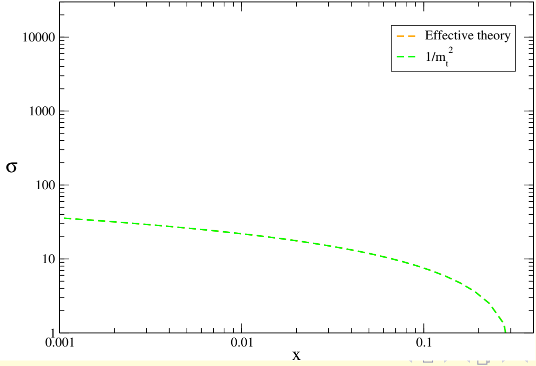

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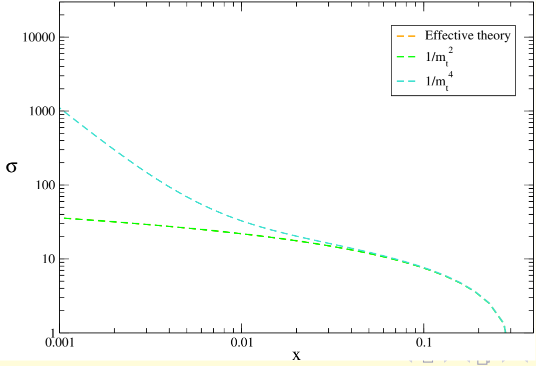

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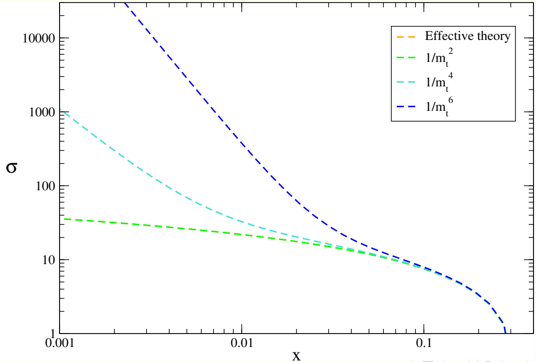

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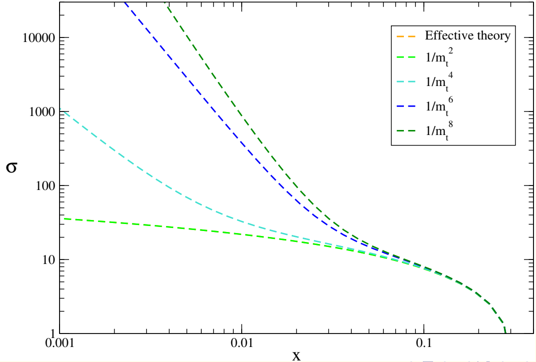

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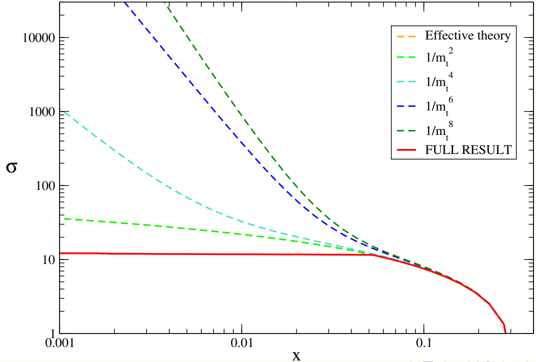

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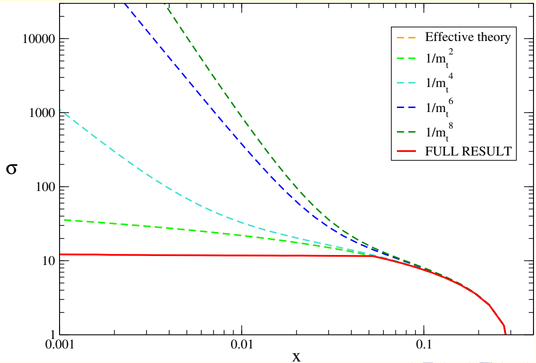
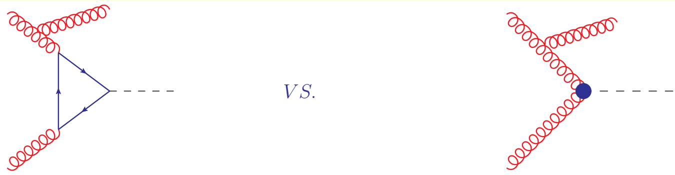
Completely wrong small-x behavior!



At small-x the top quark is never a heavy d.o.f.

$x = \frac{m_H^2}{\hat{s}}$, i.e. small-$x \longleftrightarrow$ large $\hat{s}$



High-energy (i.e. small-x) gluon can resolve the top loop $\longrightarrow$

Hard QCD gluons, and not the top quark, are the heavy d.o.f.!

At small-x the $m_t \to \infty$ approximation is bound to fail $\longrightarrow$

We can probe leading finite mass effects with **high energy gluons**

Small-$x \longleftrightarrow$ handle on the $m_t \to \infty$ approximation

QCD at small-x: fully under control and much easier

Separation between d.o.f. (gluons are heavy): $\longrightarrow$ **factorization**

High-energy gluon emission is universal and can be described within the framework of k_t factorization:

- Fully inclusive: Catani, Ciafaloni, Hautmann (1991)
- Differential (rapidity) distributions: FC, Forte, Marzani (2010)

Within this framework computations are **much easier**

- Singularity structure is universal and known at all orders
- Computations can be done numerically

For the Higgs:

Computing the full NNLO at small-x is possible

Leading small-x terms can be computed to all orders

The recipe for a reliable NNLO: matching

Two extreme situations:

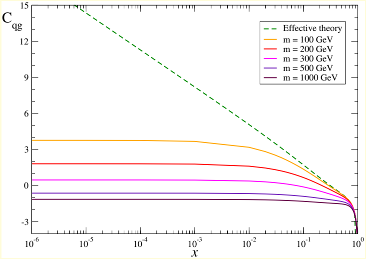
- large-x: top is effectively heavy and we can safely integrate it out $\longrightarrow$ available (rescaled) NNLO computations are fine
- small-x : gluons are the heavy d.o.f. $\longrightarrow$ we know the right answer from the high-energy effective theory

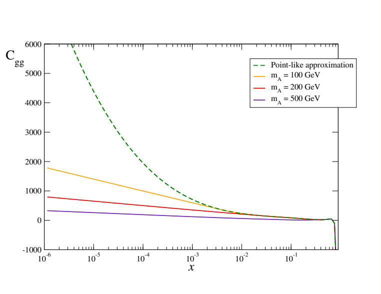
To obtain a fully reliable NNLO prediction:

Match these two limits

- Simple match, vary matching point to study uncertainties
  - Scalar Higgs, fully inclusive: Marzani et al (08)
  - Scalar/pseudoscalar, distributions: FC, Marzani (11)
- Match small-x with a m_H/m_t expansion
  - Scalar, fully inclusive: Harlander et al, (09-10)
  - Pseudoscalar, fully inclusive: Pak et al, (11)

Inclusive results: finite m_t effects are always negligible





Fully inclusive production (no cuts):

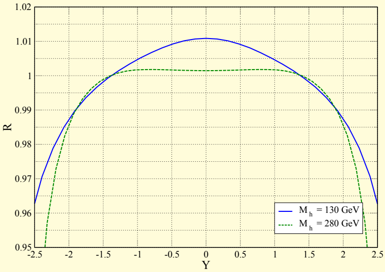
- for low mass, finite mass effects are $< 1\%$
- up to 1 TeV: never above few percent
- For pseudoscalar Higgs: larger corrections, but still $\leq 5\%$

$b - t$ interference effects:

- At LO: $\mathcal{O}(10\%) \rightarrow$ large!
- Still under control if full NLO is used!

Shapes analysis: a $K-$factor description is fine

$$K = \left(\frac{1}{\sigma_{NLO}}\frac{d\sigma_{NLO}}{dY}\right)_{m_t\to\infty} \Bigg/ \left(\frac{1}{\sigma_{NLO}}\frac{d\sigma_{NLO}}{dY}\right)$$



- $\sqrt{S} = 7$ TeV
- $\mu_R = \mu_F = m_H$
- NNPDF2.0 central set

Quantitative results:

- NLO: up to 5% (✓ Anastasiou et al, 09)
- NNLO: at most 2%
- Perturbatively stable result

Lower effect on shape for higher mass

$K-$factor description is OK (NNLO)

Recap: theoretical framework

Finite fermion mass effects are under control

- The origin of (large) finite mass effects is now fully understood: high-energy gluons resolve the fermion loop
- Small-x QCD is a easy and effective way to assess them
  - Fully inclusive since a long time
  - Now also differential distributions

Leading finite mass effects:

- match exact small-x results with available NNLO
- sensistivity to matching procedure / point very small
  - Simple matching $\sim$ matching to a m_H/m_t expansion
- Results are perturbatively stable (i.e. beyond NNLO)
- Can be computed for any Higgs-like theory via small-x EFT
- Up to now: results exist for SM Higgs and pseudoscalar Higgs
- Interference effects easily taken into account

Conclusions: LHC phenomenology

Higgs boson searches at the LHC

- Although parametrically large, finite m_t effects can be systematically neglected
- Rescaling with full NLO is a good enough approximation
- Shapes are only slightly affected
- Beyond NLO, $t - b$ interference plays no significant role
- Similar results also hold for pseudoscalar Higgs

The theoretical input for SM Higgs searches is perfectly fine

Rescaled NNLO is fully reliable up to very large Higgs masses