# (Some) New stuff for top-pair production at Hadron Colliders

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# We care about the top quark !

- Discovered 1996 at the Tevatron
- Very heavy: $m_{top} \approx 172$ GeV
  - ➔ 35 times heavier than the next quark - the bottom

The importance of top physics at LHC can be gauged by the number of recent review articles:

- R. Kehoe at al. (hep-ex/0712…)
- T. Han (hep-ph/0803…)
- W. Bernreuther (hep-ph/0805…)

- LHC: a new era in top physics
  - Huge statistics – a top pair produced each second (top factory ☺),
  - $\sigma_{top}$ measured within 9%. Can we do better?
  - Current NLO theory uncertainty ??? ~ 15%. Not good enough!

# The Top Quark: applications

- Complete our understanding of SM
- EWSB: top has large mass and Yukawa coupling: preferred role of the top?
- Background for Higgs ($H \to WW$)

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- Searches for New Physics:
  - Heavy vector bosons or resonances ($Z' \to$ tt-bar, $W' \to t\, b$),
  - Charged Higgs ➔ likely SUSY: $t \to b+H^+$ ; $H^+ \to t+b$

- Most recently:

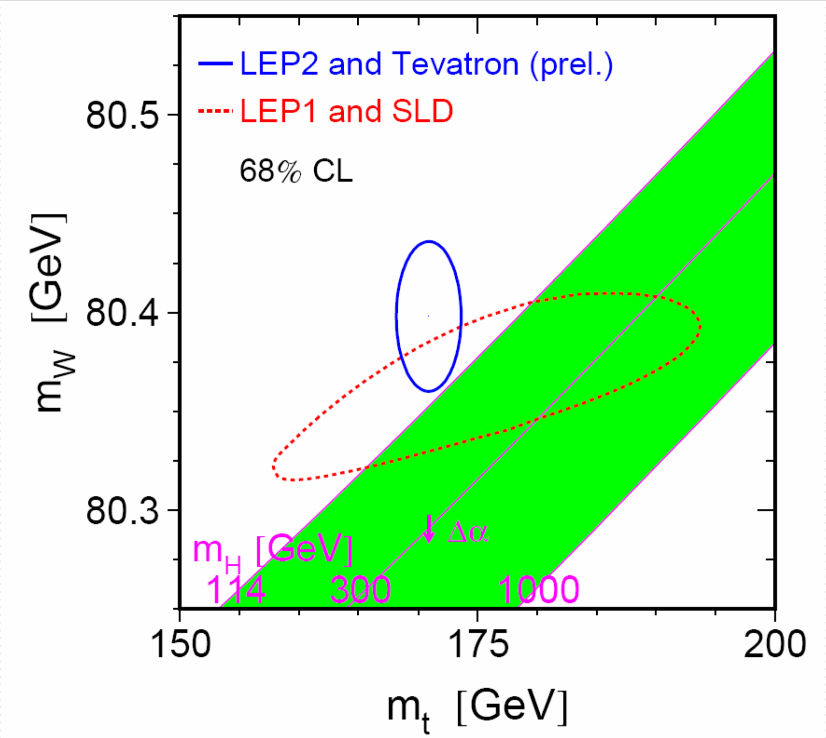
  tt-bar cross-section “promoted” to standard candle (CTEQ 2008)

Achieving (two loop) precision here is crucial.

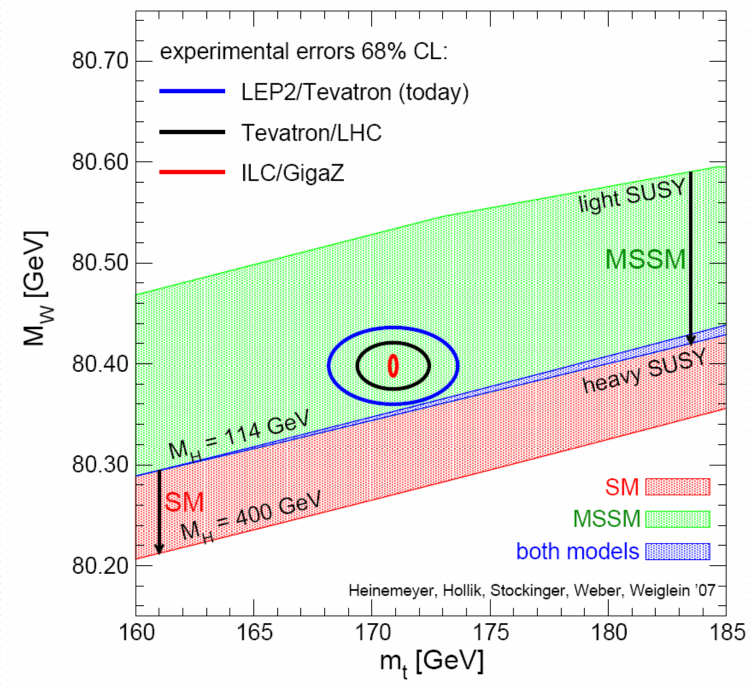
# Top mass - precise measurement needed !

Best (and only) measurement from the Tevatron ( $\Delta m_{top}$ = 2.1 GeV)

- ✓ Do we understand well enough the mass that we measure?
- ✓ New options at LHC (due to the large statistics),
- ✓ Determination from $\sigma_{TOT}$(tt-bar)




*arXiv:0712.2733[hep-ex]*




Heinemeyer et al, hep-ph/0604147

# What is known in top-production? All NLO QCD corrections:

- ✓ Fully inclusive and one particle inclusive cross-section

  Nason, Dawson, Ellis (1989)
  Beenakker at al (1990)

- ✓ Fully differential production

  Mangano, Nason, Ridolfi (1992)

- ✓ Spin correlations

  Bernreuther et al (2004)

Beyond fixed order: soft gluon resummations:

- NLL in $\alpha_S{}^n \ln^m(\beta)$ for the total inclusive cross-section

  Bonchani, Catani, Nason, Mangano, Trentadue, (mid 1990’s)

- NLL for the differental cross-section

  Kidonakis, Sterman, Laenen (mid 1990’s)

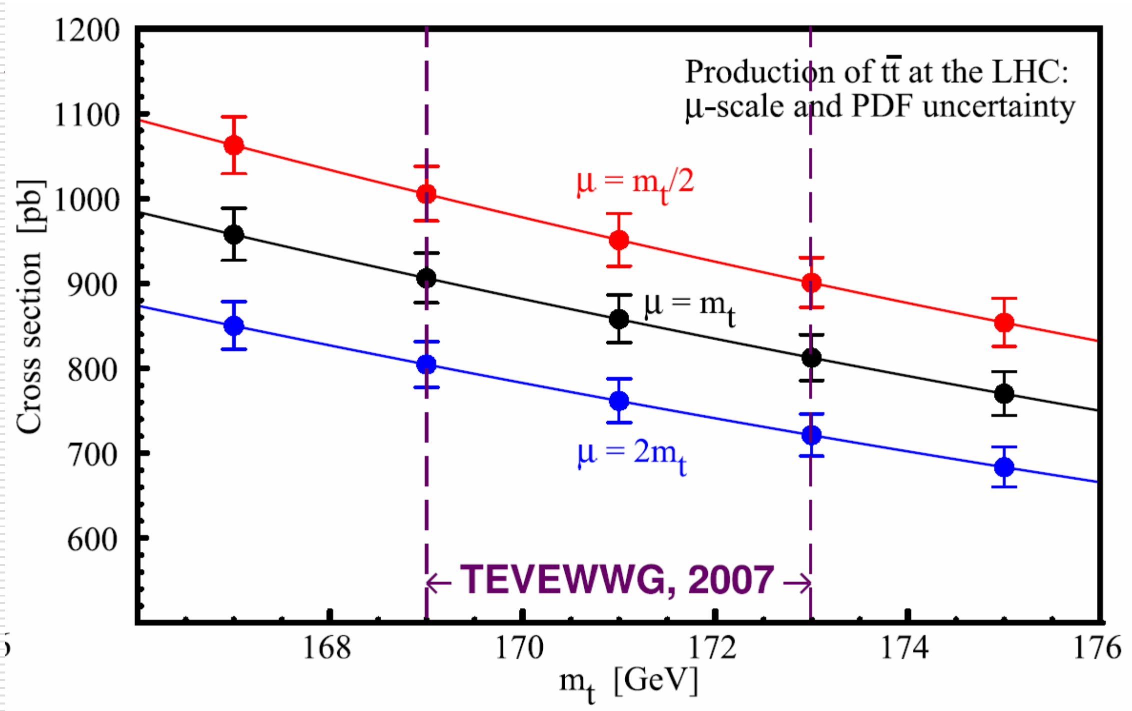
- Work beyond NLL for total inclusive cross-section

  Moch, Uwer (2008)

# Highlights from the known results:

✓ Large NLO corrections (typically 30-50%)

✓ Scale uncertainty – in the 15% range.




✓ Soft-gluon effects reduce somewhat scale uncertainty!

✓ For not too strong cuts, the NLO effect is on normalization, not shapes !

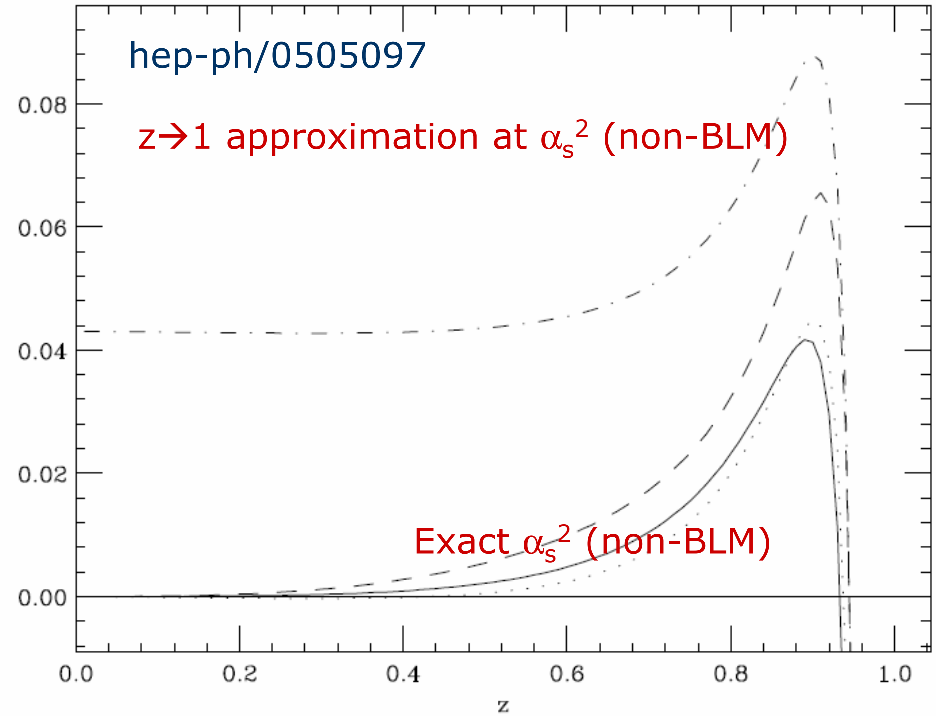
# Our motivation

- Understanding true scale uncertainty requires full NNLO calculation !
- The appropriate observable is the total inclusive cross-section.
- Soft-gluon effects should be treated very carefully! Their importance not well understood:
- Attempts have been made to get some NNLO terms by truncating all-order results.
  - is this a systematic approximation?

$$\sigma(\mu) \sim e^{\int_{\mu}\cdots}$$

In general, this is a poor approximation to fixed order calculations:

Example: the photon spectrum in $B \to s + \gamma$:




- ✓ A reasonable approximation only at very large $z \to 1$
- ✓ Does not work for the whole spectrum.

# Our goal: to develop a working approach to NNLO

- For top at hadron colliders, especially at LHC, the full mass dependence is required.

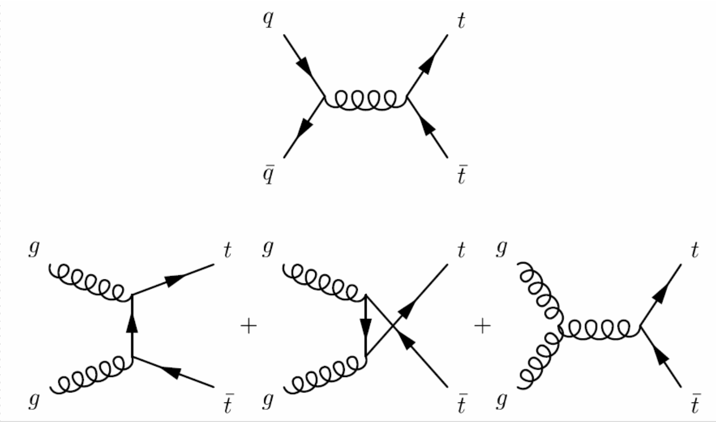
- the idea is to calculate directly the total cross-section
- Integrate real and/or virtual at the same time
- use IBP

Anastasiou, Melnikov (2002)

What are the subtle points?

- Large number of diagrams.
  This is a truly 3-loop problem with masses

- Very complex IBP reduction




- there is more (next page ☺ )

❖ Particularly unpleasant feature: complex analytical structures!

Even at LO things like β start to appear: $$\beta = \sqrt{1-\frac{4m^2}{s}}$$

➢ evaluating integrals or solving differential equations in such functions is a nightmare (perhaps not feasible).

Our "fix" is:

- identify the possible singularities. There are 3 of them:
  - ✓ $m^2 \to 0$ (physical endpoint singularity),
  - ✓ $4m^2=s$ (physical endpoint singularity – partonic threshold),
  - ✓ $|m| \to \infty$ (unphysical singularity).
- change variables to map them to x=(-1,0,1) $$\frac{m^2}{s} = \frac{x}{(1+x)^2} \qquad x = \frac{1-\sqrt{1-4\frac{m^2}{s}}}{1+\sqrt{1-4\frac{m^2}{s}}}$$
- The resulting equation is of well known – Riemann – type.
  In fact, one expects HPL's only.

# How far have we got?

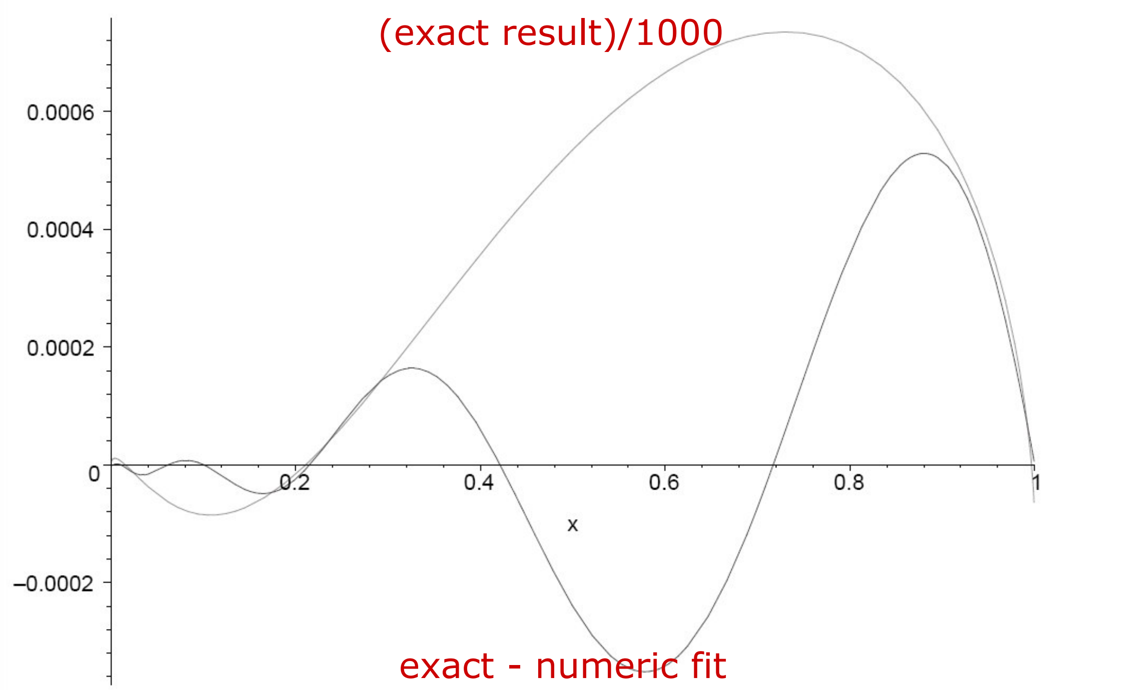
The NLO corrections are evaluated analytically (should have them out very soon):

- ✓ qq → tt reaction is complete,
- ✓ qg → tt complete,
- ✓ gg → tt – finalizing.

The result for the

qq→ tt

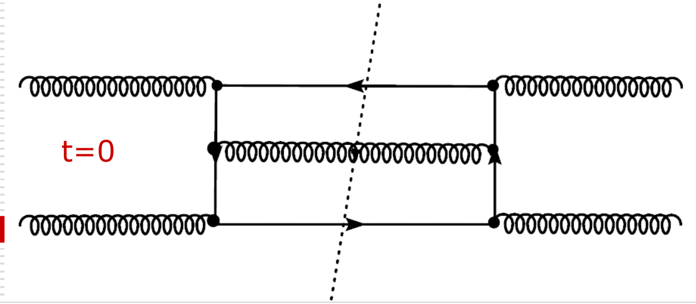
reaction:



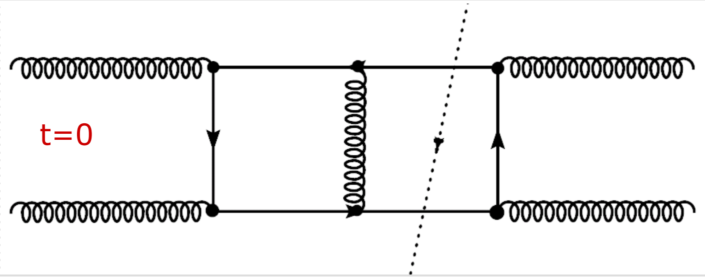

From Nason, Dawson, Ellis ('89)

# How far have we got?

Here are few sample diagrams that we had to deal with at NLO:




+ crossed




+ crossed

- Note: these are 2 loop (cut) boxes with masses. Never studied before.
- One day might become a good testing ground for unitarity methods at 2 loops with masses ☺

# Interesting observations

- ✓ The whole problem is mapped into 37 master integrals (real+virtual),
- ✓ We observe unexpected thing:
  - ➢ few of the most complicated integrals (cross-box like) have additional singularities ("pseudothresholds"),

- ❖ Their presence is expected in scattering amplitudes; but we have here a physical cross-section.
- ❖ We see them as additional singularities in the differential equations of the master integrals in the following points.

$m^2 = s$; $m^2 = -s$; $m^2 = -1/4s$ ; $m^2 = -1/16s$
(in addition to $m^2=1/4s$ and $m^2=0$).

- ❖ They are outside the physical region, so no numerical problems,
- ❖ The problem is technical: for few masters we have differential equations with more than 3 singularities. So no HPL solutions.

# Interesting observations

- These poles do not appear to be a big problem at NLO.

  In practice they lead to integrals like:

$$\int_x^1 dz \frac{\ln^2(z)}{(1+z+z^2)}$$

Such integrals are trivial to evaluate *numerically*.

- Unlike other (simpler) known examples,

  these contributions do not appear to cancel in the final cross-section.

# Summary

- The top physics program at LHC requires NNLO corrections to production cross-section.

- I have presented a program capable of tackling the calculation of the NNLO cross-section (thus avoiding the problem M. Grazzini mentioned in his talk ☺ )

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- The NLO qq and qg contributions are completed analytically (new). The NLO gg reaction is almost done.

- Interesting feature: the NLO gg→tt cross-section has “pseudo-thresholds”.

- It does not appear they cancel.

- Analytic NLO results are useful to extract constants needed in threshold resummation

- Many technical points I did not discuss,

- The approach is very promising ☺