Review of Top Quark Physics: Theory

Fabio Maltoni

Center for Cosmology, Particle Physics and Phenomenology (CP3)
Universitè catholique de Louvain, Belgium

THE HOTTEST NEWS IN TOP PHYSICS

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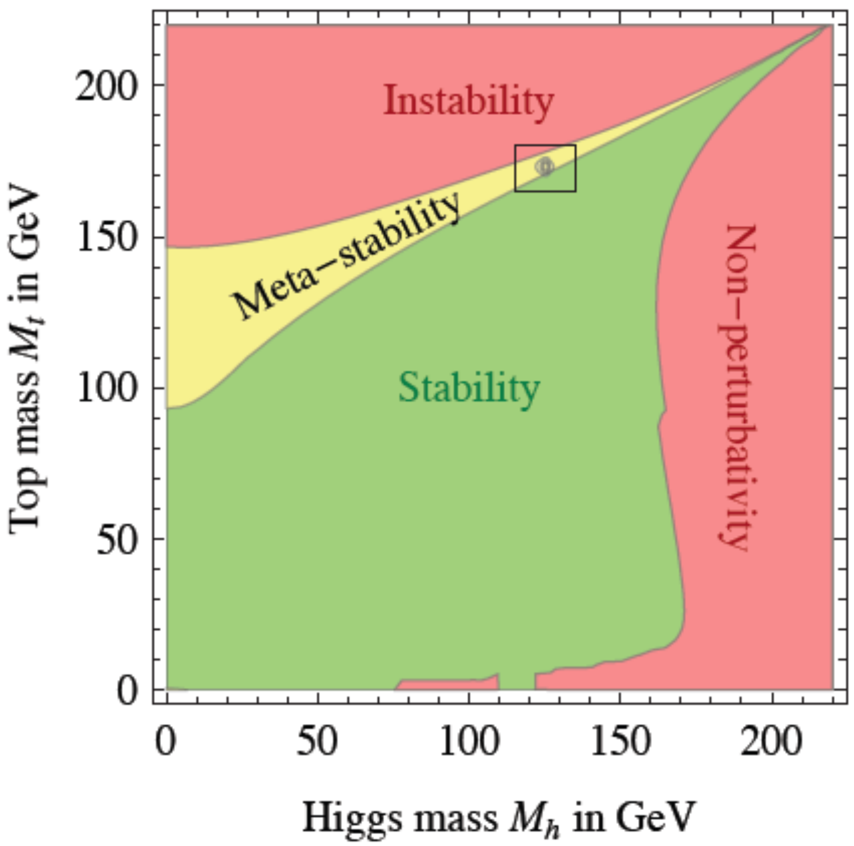
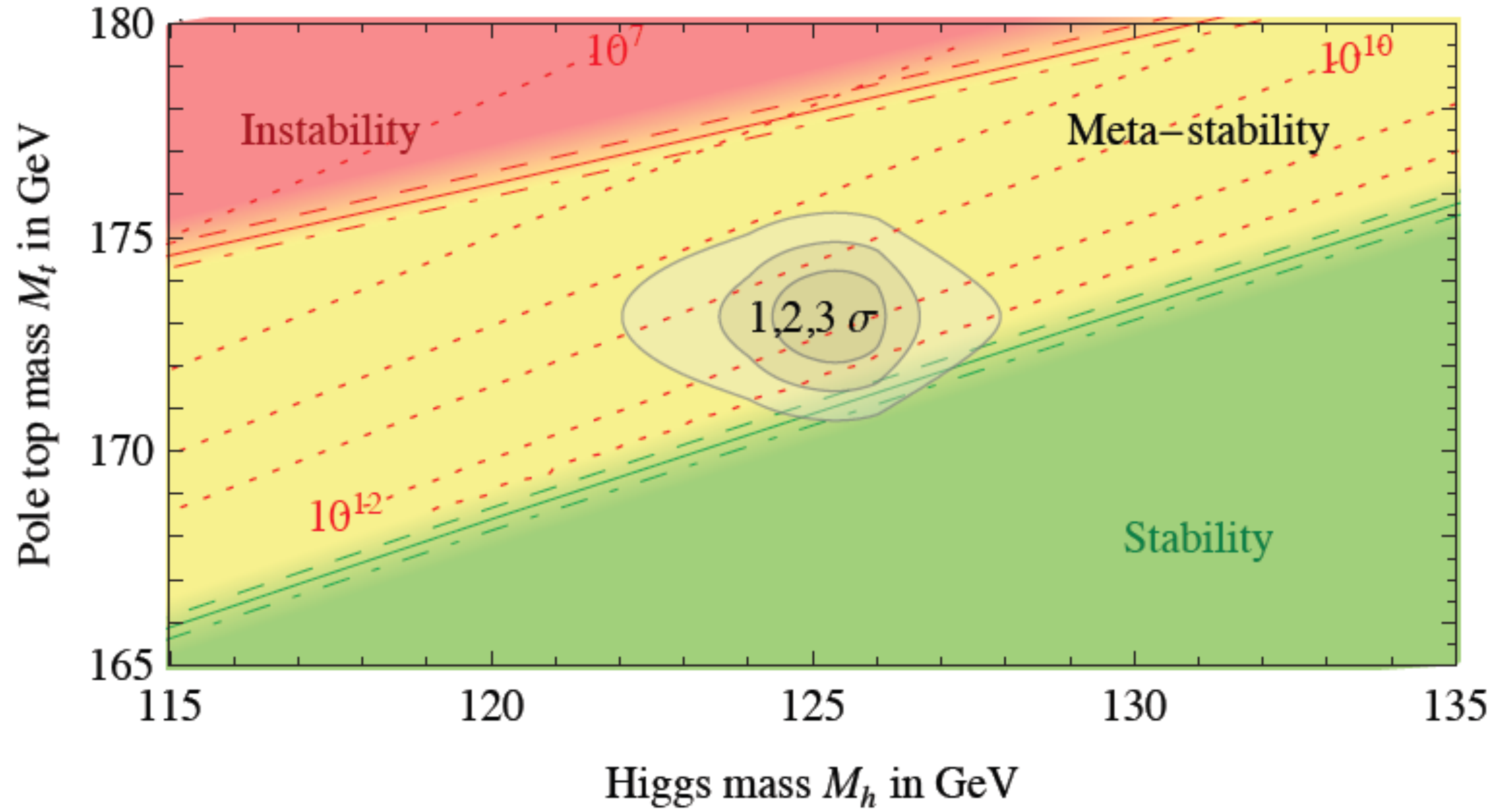
The fate of the Universe depends on 1GeV in m_{top}

Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice, Isidori, Strumia '12





$$\lambda_{\rm eff}(h) = e^{4\Gamma(h)}\left\{\lambda(h) + \frac{1}{(4\pi)^2}\sum_p N_p\kappa_p^2(r_p - C_p) + \frac{1}{(4\pi)^4}y_t^4\left[8g_s^2(3r_t^2 - 8r_t + 9) - \frac{3}{2}y_t^2\left(3r_t^2 - 16r_t + 23 + \frac{\pi^2}{3}\right)\right]\right\}$$

$$y_t(M_t) = 0.93587 + 0.00557\left(\frac{M_t}{\rm GeV} - 173.15\right)\ldots \pm 0.00200_{\rm th}$$

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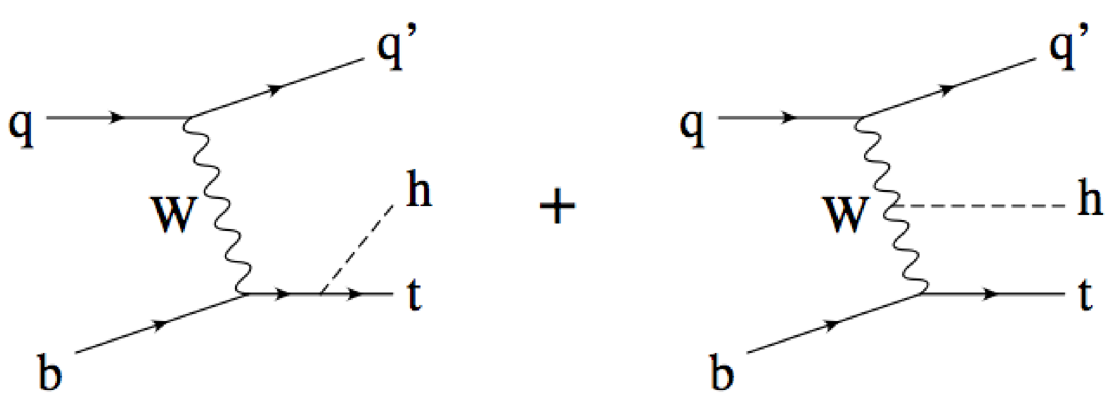
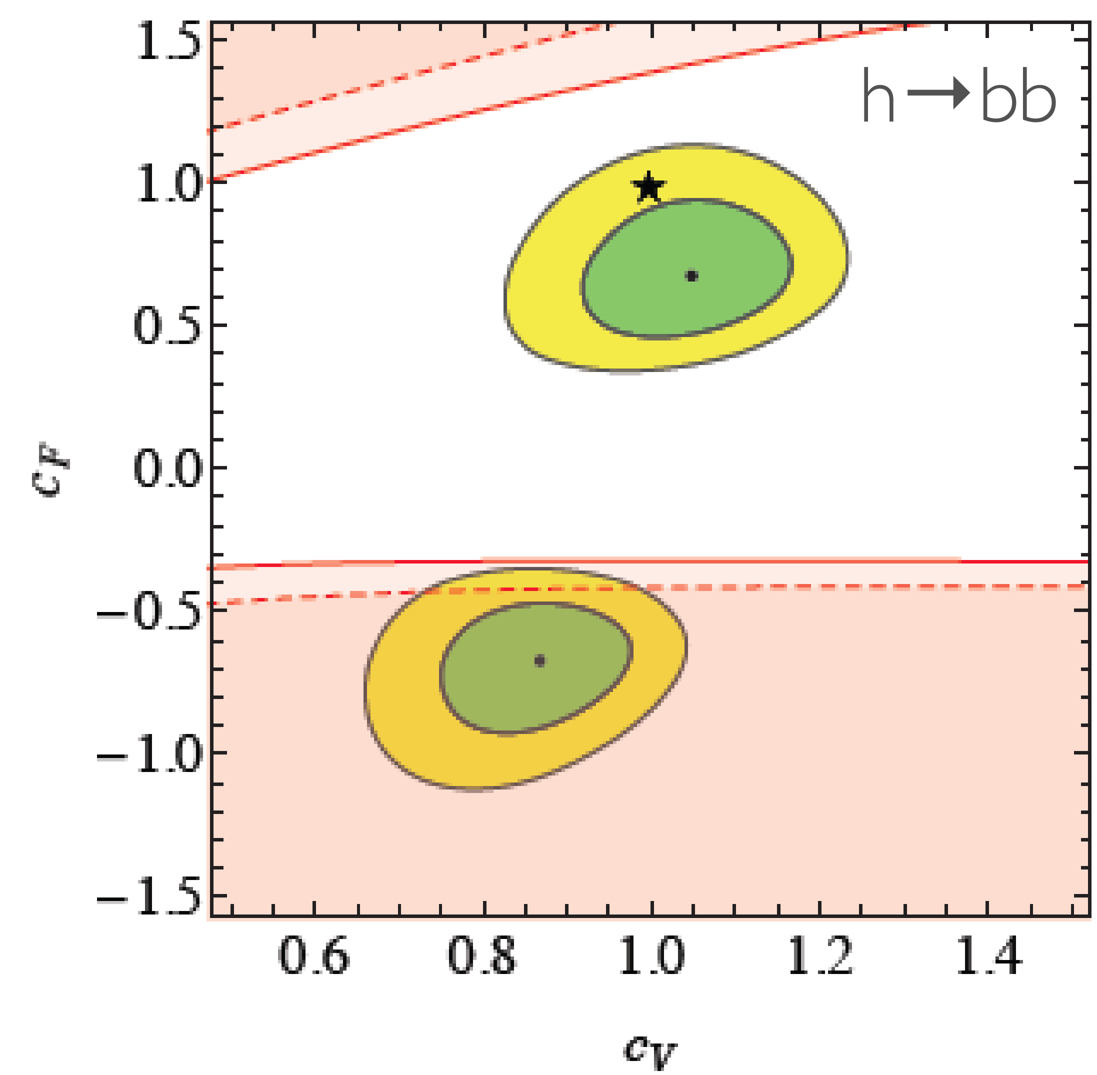
Sign of the Yukawa coupling enters in the destructive interference between W and top loops in $h \to \gamma\gamma$. Another process exists with a similar behaviour:



aMC@NLO	$\sigma^{NLO}(pp \to thj)$ [fb] $c_F = 1$	$c_F = -1$
8 TeV	$18.28^{+0.42}_{-0.38}$	$233.8^{+4.6}_{-0.}$
14 TeV	$88.2^{+1.7}_{-0.}$	982^{+28}_{-0}



Farina et al. 2012

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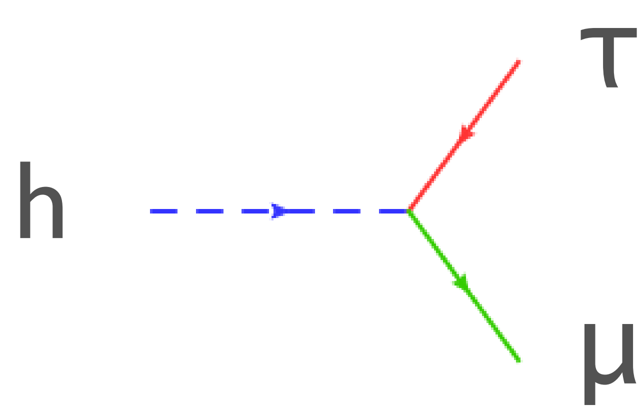
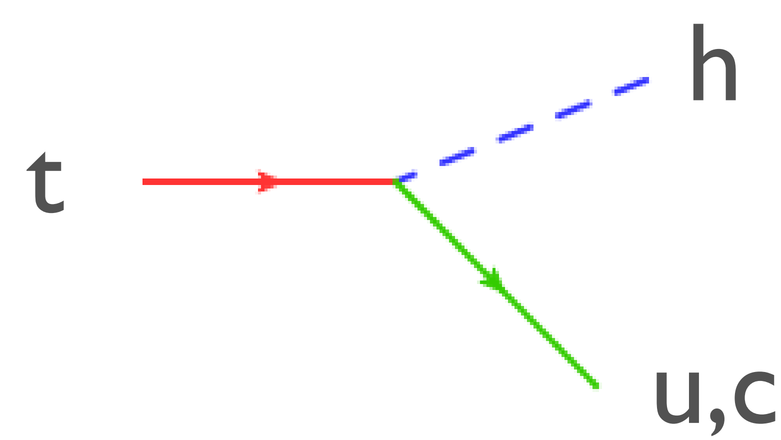
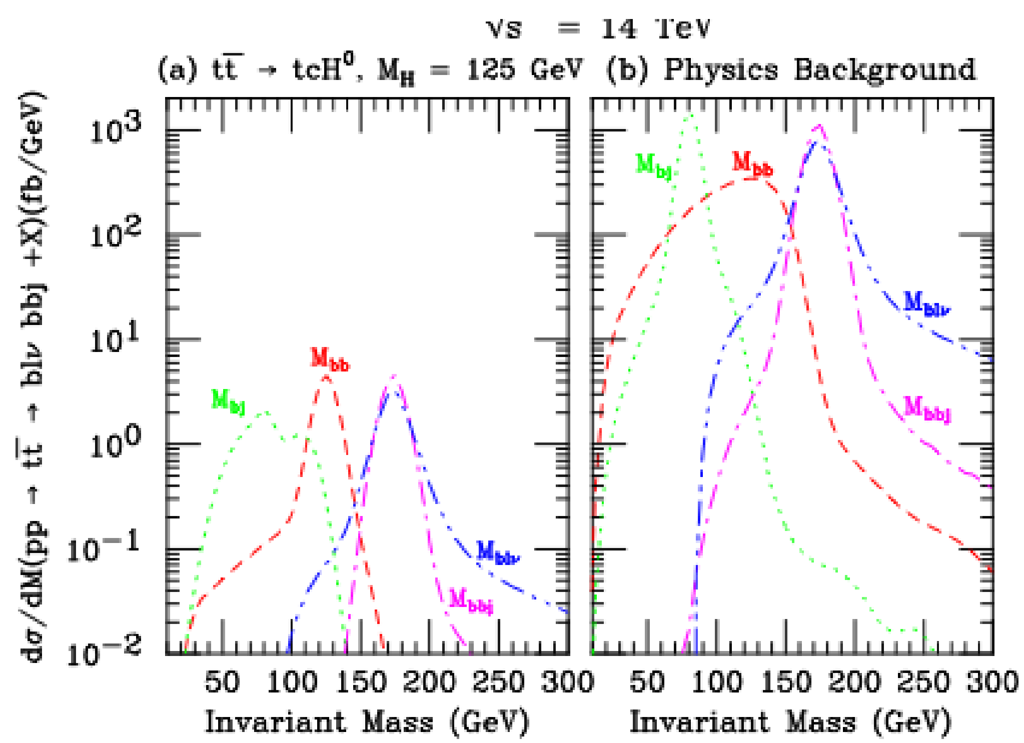
The study of FC Higgs couplings will bring new information:





Model	$R_{\tau^+\tau^-}$	$X_{\mu^+\mu^-}/(m_\mu^2/m_\tau^2)$	$X_{\mu\tau}$
SM	1	1	0
NFC	$(V_{h\ell}^* v/v_\ell)^2$	1	0
MSSM	$(\sin\alpha/\cos\beta)^2$	1	0
MFV	$1+2av^2/\Lambda^2$	$1-4bm_\tau^2/\Lambda^2$	0
FN	$1+\mathcal{O}(v^2/\Lambda^2)$	$1+\mathcal{O}(v^2/\Lambda^2)$	$\mathcal{O}(\|U_{23}\|^2 v^4/\Lambda^4)$
GL	9	25/9	$\mathcal{O}(X_{\mu^+\mu^-})$

Deri et al. 2012



Kao et al. 2012

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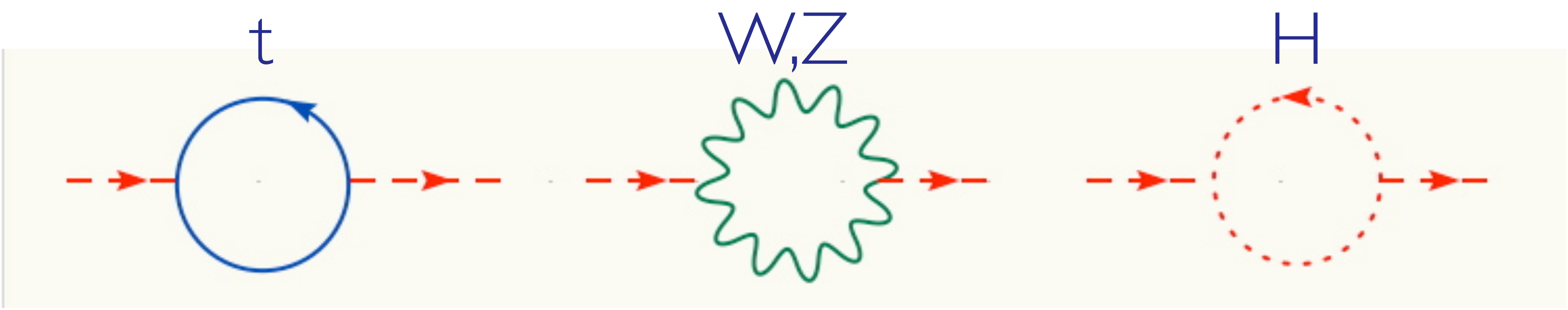
The top quark dramatically affects the stability of the Higgs mass.
Consider the SM as an effective field theory valid up to scale Λ:



$$m_H^2 = m_{H0}^2 \quad - \frac{3}{8\pi^2} y_t \Lambda^2 \quad + \frac{1}{16\pi^2} g^2 \Lambda^2 \quad + \frac{1}{16\pi^2} \lambda^2 \Lambda^2$$

Putting numbers, I have:

$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right] \left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

TOP IN THE HIGGS ERA

$m_h^2 \sim (125\text{ GeV})^2$

$$(125\,\mathrm{GeV})^2 = m^2_{H0} + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

Definition of naturalness: less than 90% cancellation:

$$\Lambda_t < 3\,\mathrm{TeV} \qquad \Lambda_t < 9\,\mathrm{TeV} \qquad \Lambda_t < 12\,\mathrm{TeV}$$

One can actually prove that this case in model independent way, i.e. that the scale associated with top mass generation is very close to that of EWSB.

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Many BSM models point to the top:

SUSY → top ⇒ EWSB, stop are light

Little Higgs → vectorial top partners

Strong Dynamics → ETC, colorons, ...4t interactions

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Little Higgs → vectorial top partners

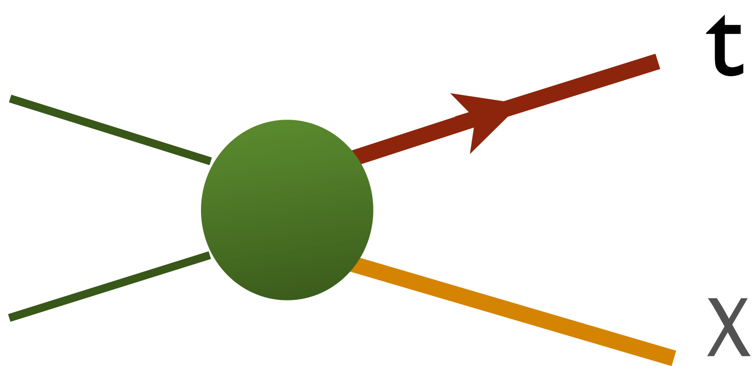
Strong Dynamics → ETC, colorons, ...4t interactions

In a more model-independent way:

Higher dimensional operators involving top *[Willenbrock and Zhang 2011, Aguilar-Saavedra 2011]* are not very much constrained from low energy data. Room for NP in top couplings strengths and structure.

TOP IN THE HIGGS ERA

Many exotic signatures **still worth** to be explored:



monotops
[Andrea et al. 2011]

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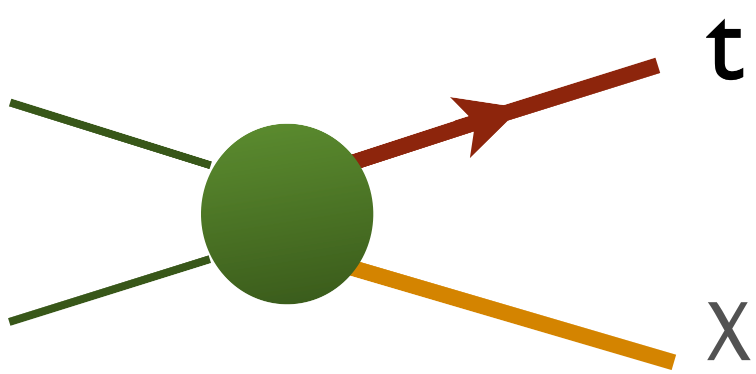

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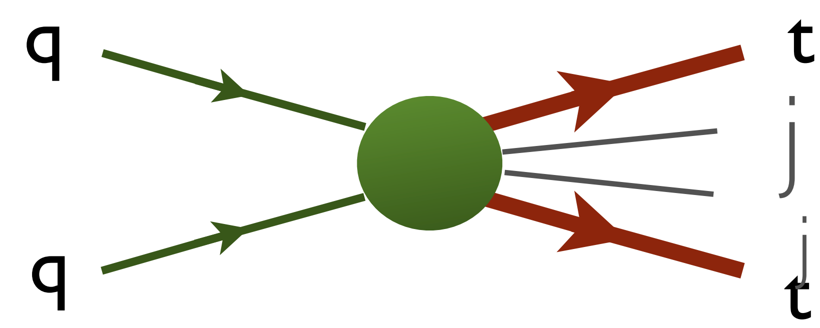

tt ($\bar{t}\bar{t}$) (+ jets)

[Aguilar-Saavedra, 2011, Degrande et al. 2011, Kraml et al. 2006, Durieux et al. 2012,2013]

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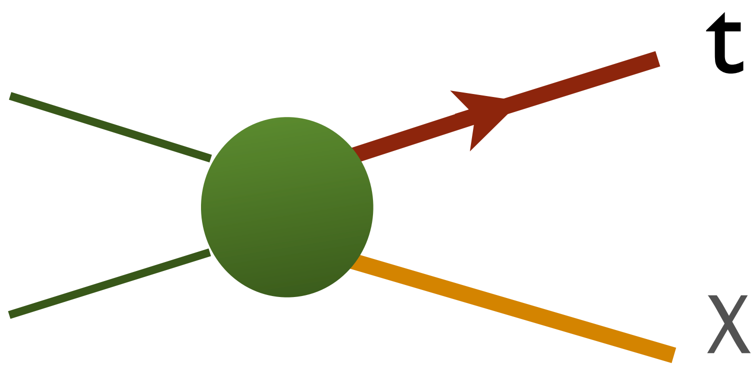

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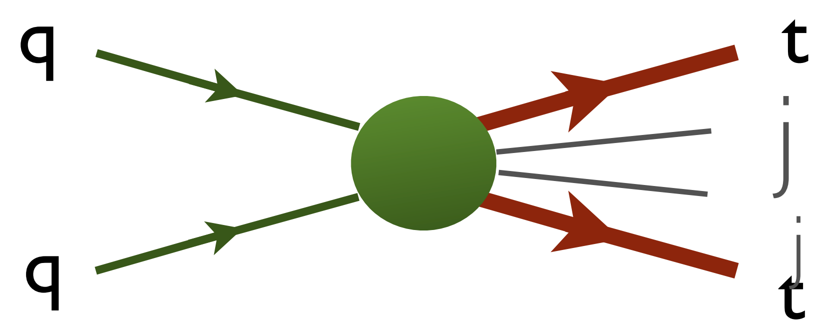

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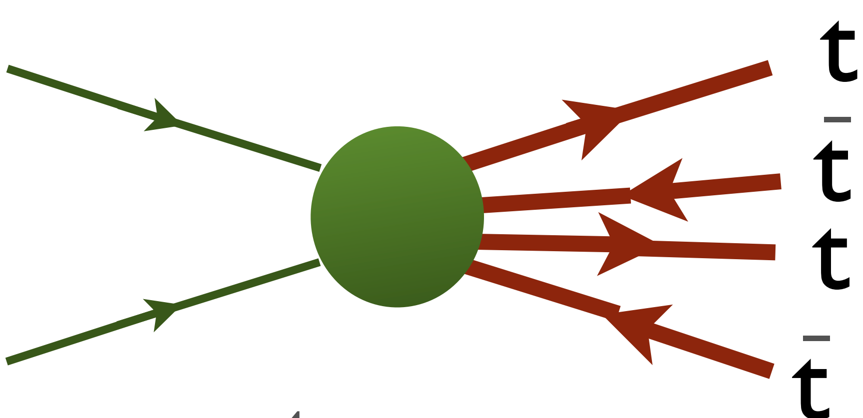

4 tops

[Tait et al, 2008, Gregoire et al,, 2011, Servant et al. , Cacciapaglio et al. 2011, Degrande, ...]

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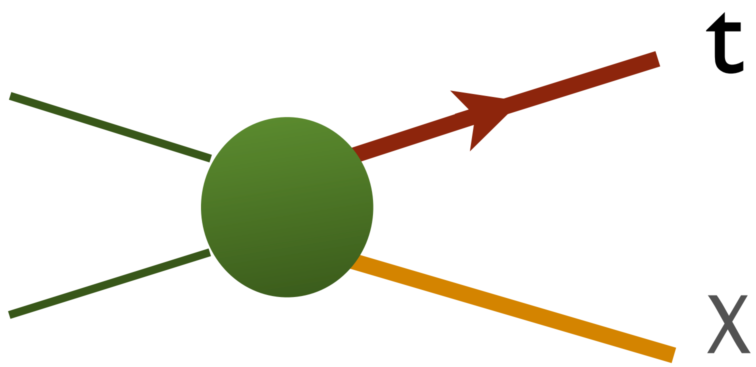

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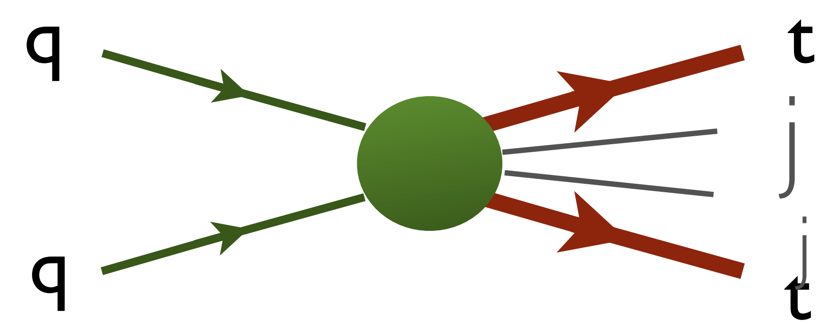

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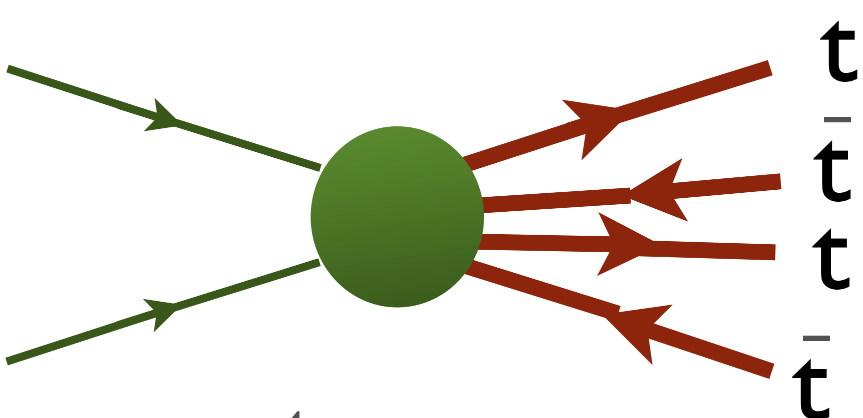

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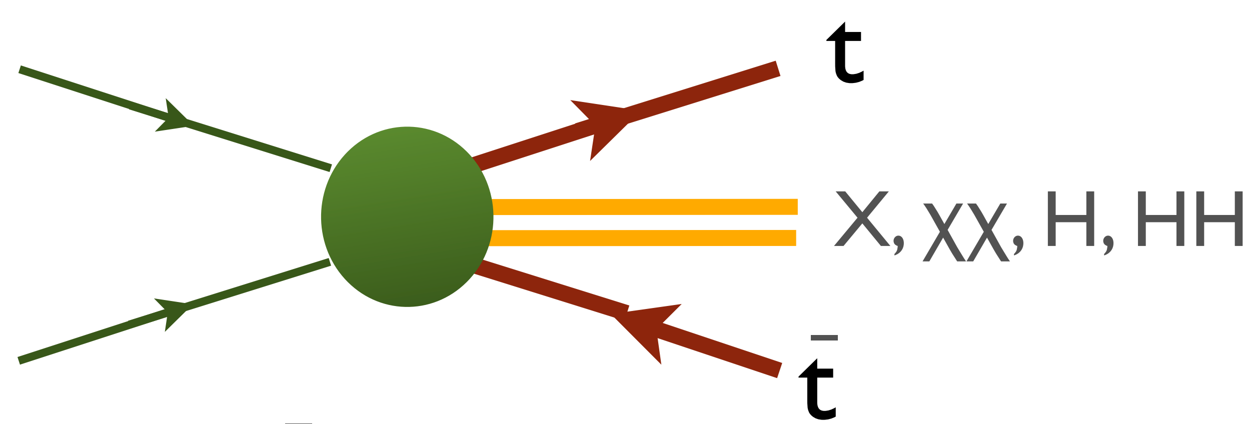

$t\bar{t}$ + $\not{E}_T$, H,...

[Many.....Lin et al 2013.]

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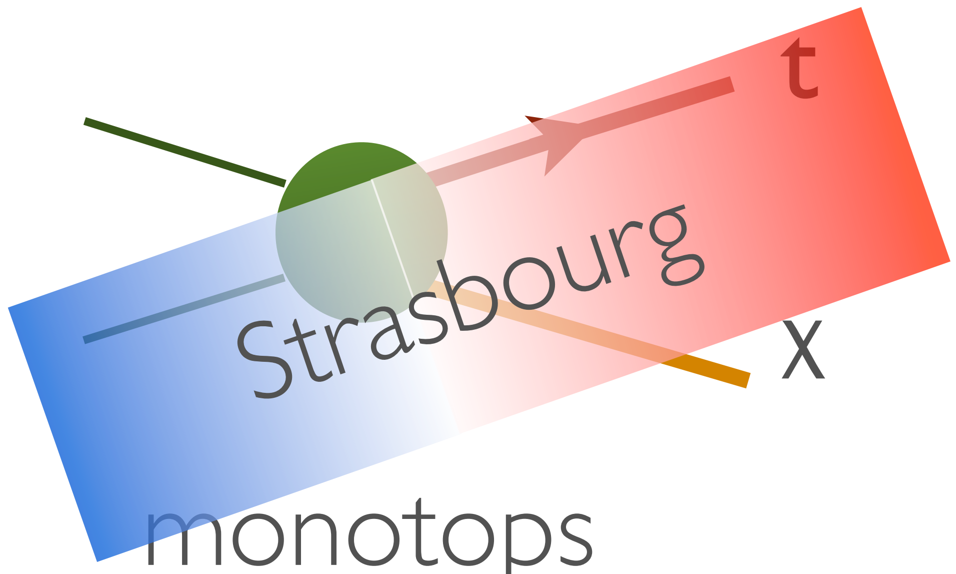

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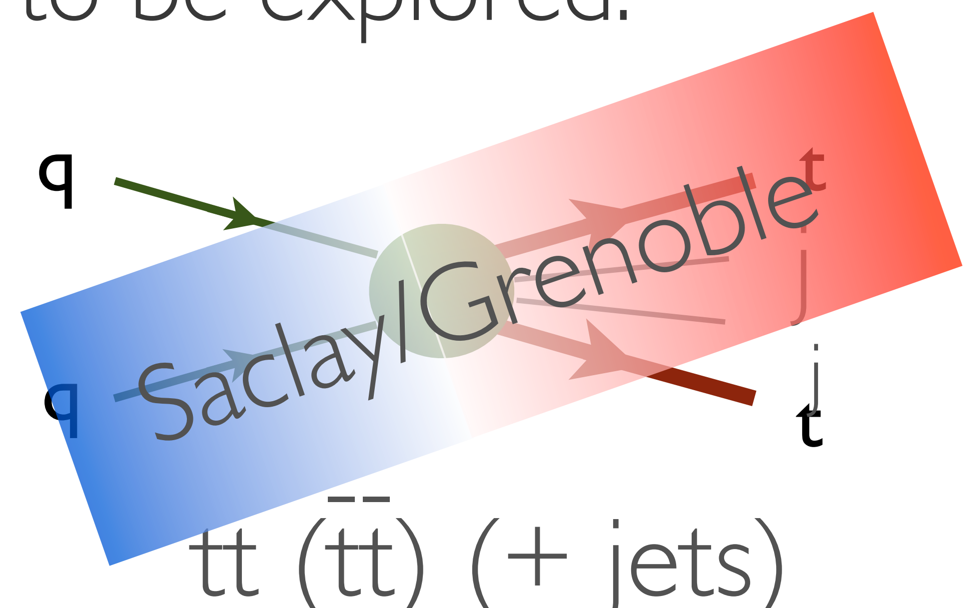

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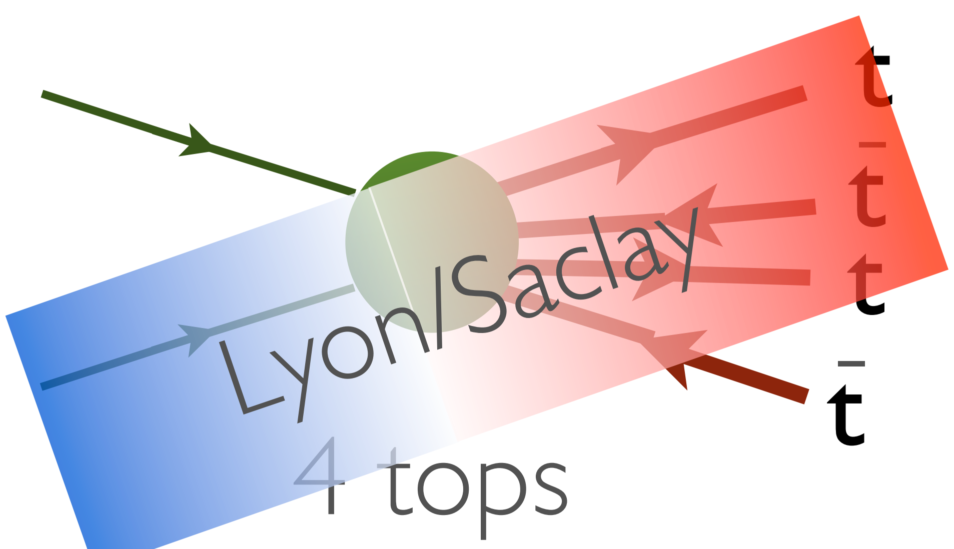

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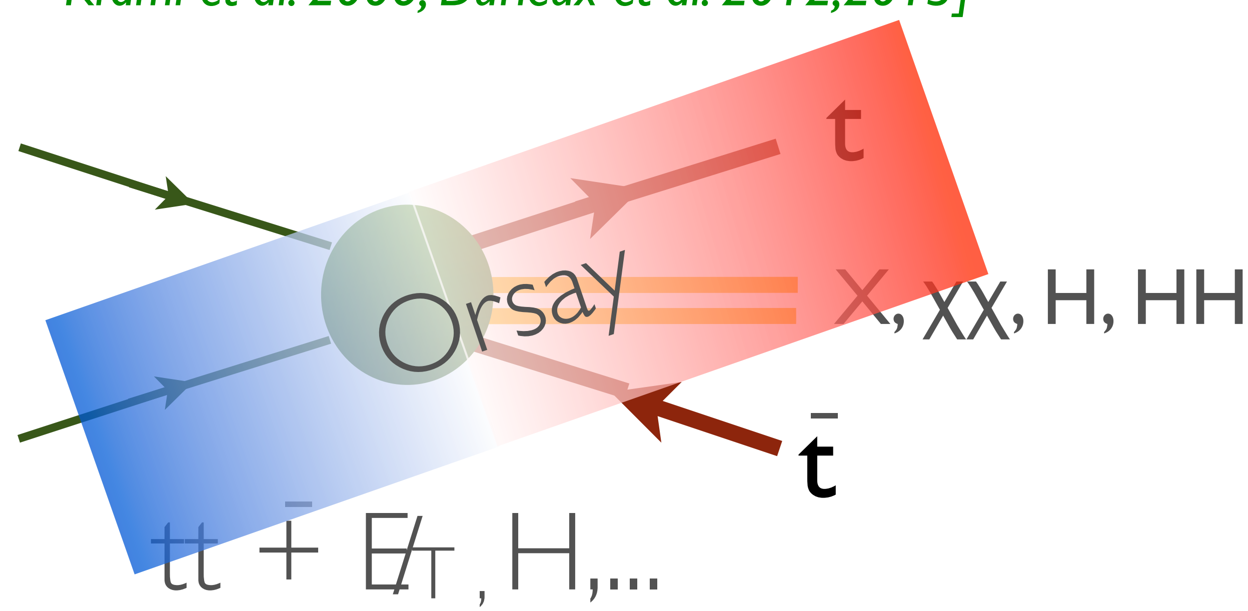

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- Strategies for top mass measurements
- Automatic MC event generators at the NLO

SIGMA(T TBAR) AT NNLO

A long history...

- Early NLO QCD results (inclusive, semi-inclusive)

  Nason, Dawson, Ellis '88
  Beenakker et al '89

- First fully differential NLO

  Mangano, Nason, Ridolfi' 92

- 1990's: the rise of the soft gluon resummation at NLL

  Catani, Mangano, Nason, Trentadue '96
  Kidonakis, Sterman '97
  Bonciani, Catani, Mangano, Nason `98

- NNLL resummation developed (and approximate NNLO approaches)

  Beneke, Falgari, Schwinn '09
  Czakon, Mitov, Sterman `09
  Beneke, Czakon, Falgari, Mitov, Schwinn `09
  Ahrens, Ferroglia, Neubert, Pecjak, Yang `10-`11

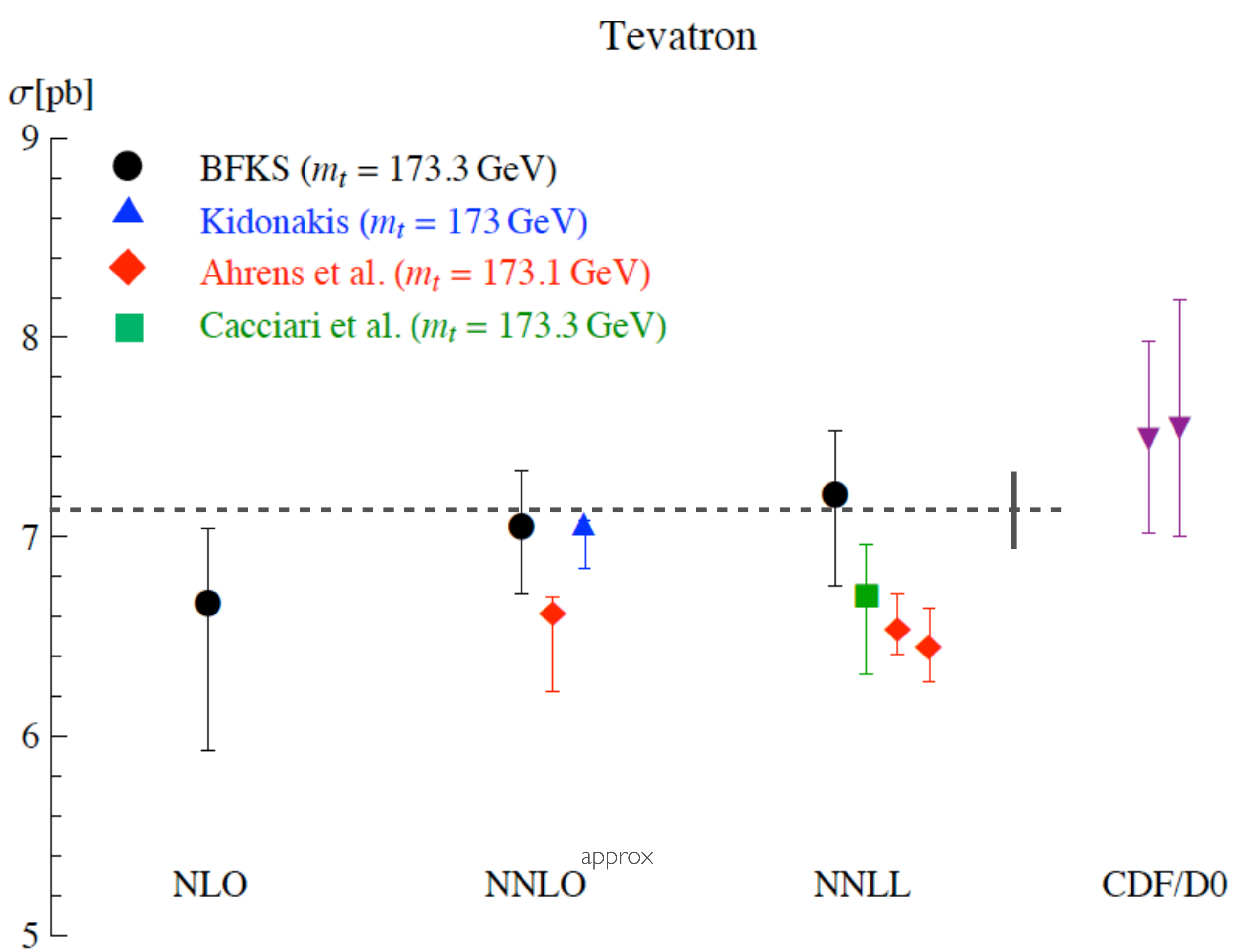
- Electroweak effects at NLO known (small ~ 1.5%)

  Beenakker, Denner, Hollik, Mertig, Sack, Wackeroth `93
  Hollik, Kollar `07
  Kuhn, Scharf, Uwer '07

AlexandreMitov®

SIGMA(T TBAR) AT NNLO

- Until one month ago σ(t tbar) analyzed exclusively in approximate NNLO QCD



Beneke, Falgari, Klein, Schwinn `11

Beneke, Falgari, Klein,Schwinn `09-`11
Ahrens, Ferroglia, Neubert, Pecjak,Yang `10-`11
Kidonakis `03-`11
Aliev, Lacker, Langenfeld, Moch, Uwer,Wiedermann '10
Cacciari, Czakon, Mangano, Mitov, Nason '11

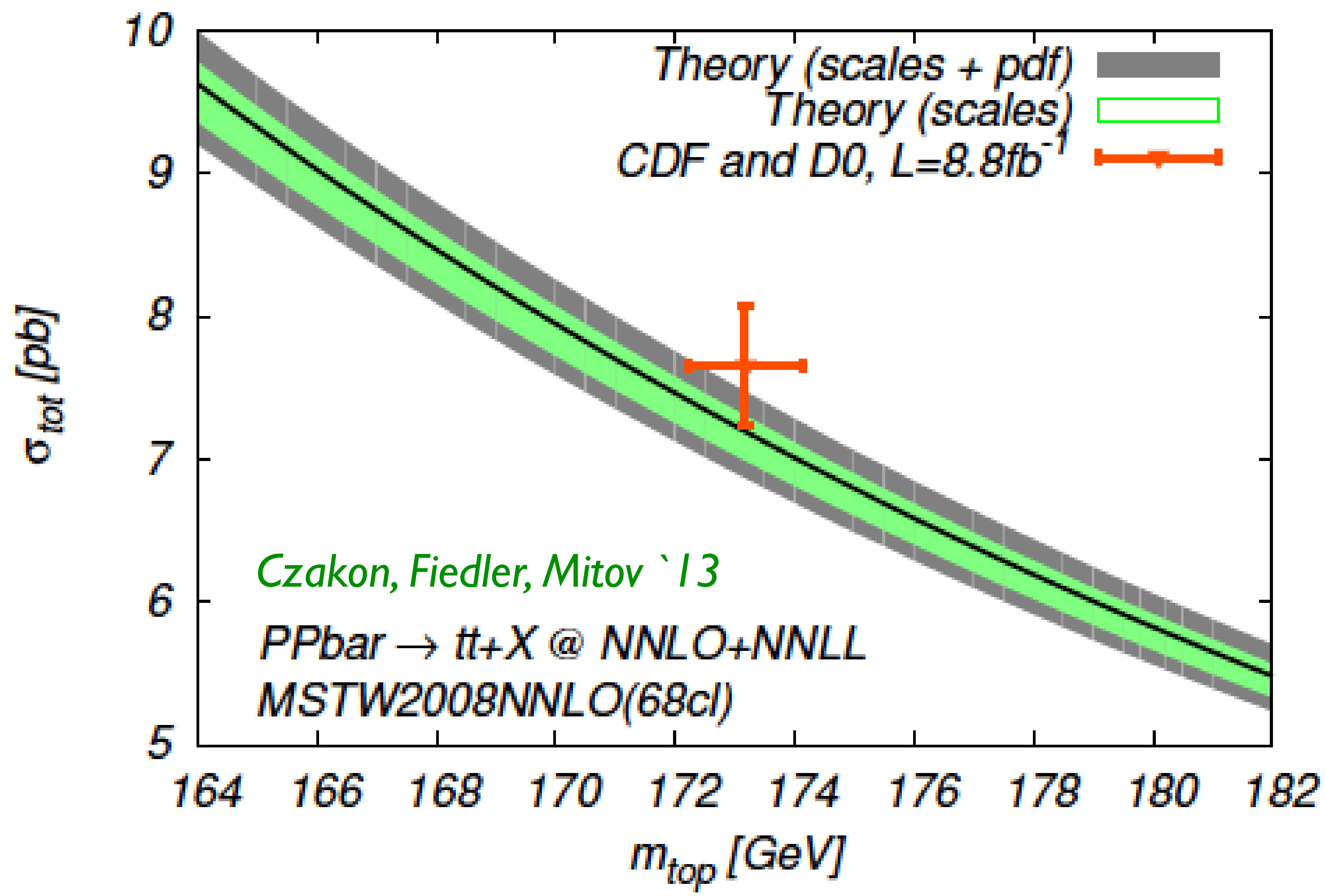
SIGMA(T TBAR) AT NNLO

Monumental MILESTONE in perturbative QCD:

- First ever hadron collider calculation at NNLO with more than 2 colored partons.
- First ever NNLO hadron collider calculation with massive fermions.

  - Published qQ → tt +X
    Bärnreuther, Czakon, Mitov `12
  - Published all fermionic reactions (qq,qq',qQ')
    Czakon, Mitov `12
  - Published gq
    Czakon, Mitov `12
  - Published gg
    Czakon, Fiedler, Mitov `13

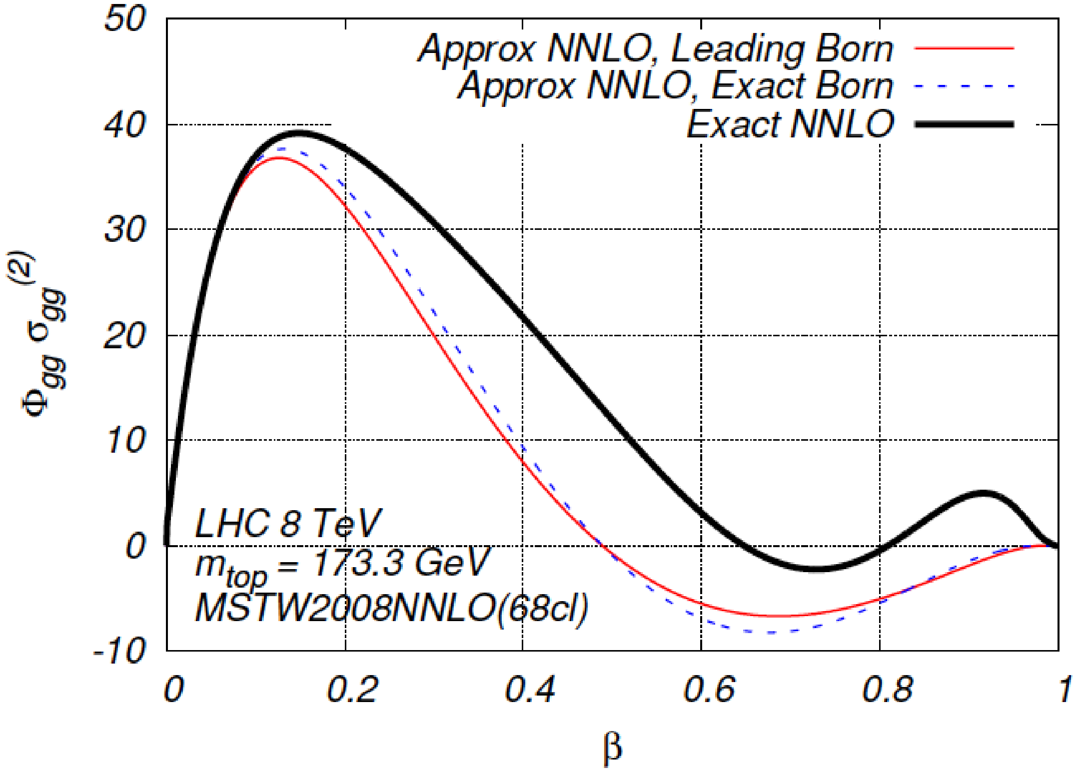
SIGMA(T TBAR) AT NNLO+NNLL



- Two loop hard matching coefficient extracted and included
- Very week dependence on unknown parameters (sub 1%): gg NNLO, A, etc.
- ~ 50% scales reduction compared to the NLO+NNLL analysis of

SIGMA(T TBAR) AT NNLO+NNLL

Czakon, Fiedler, Mitov `13



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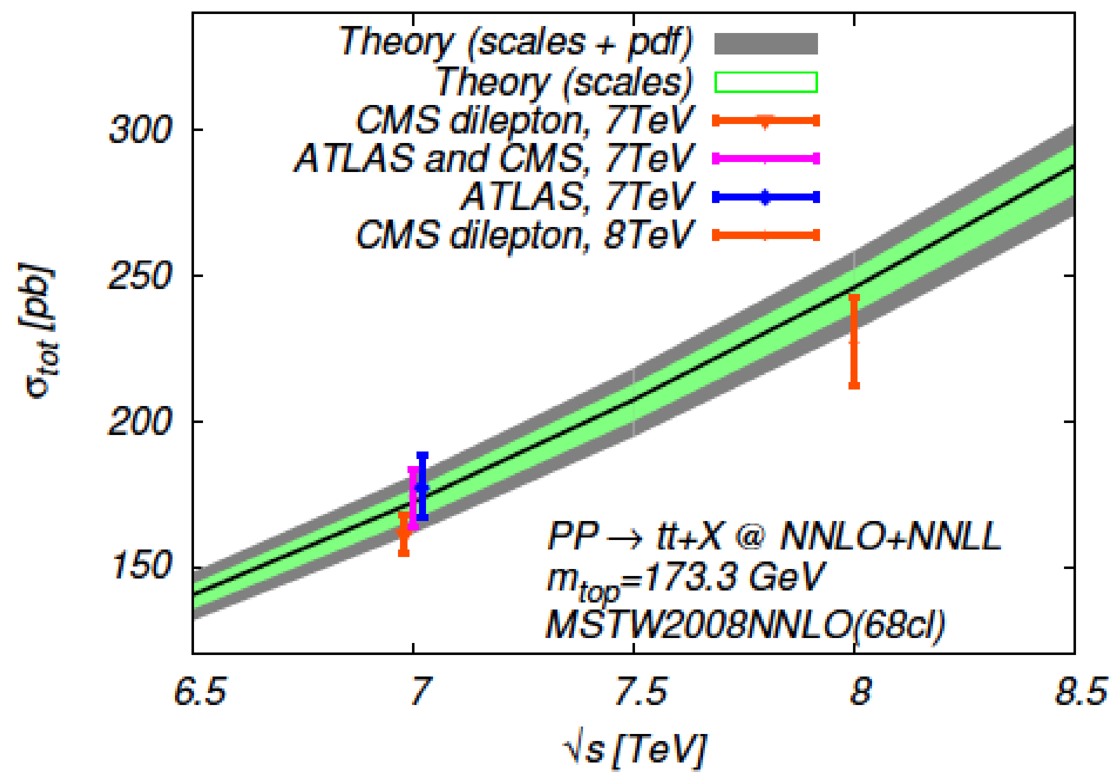
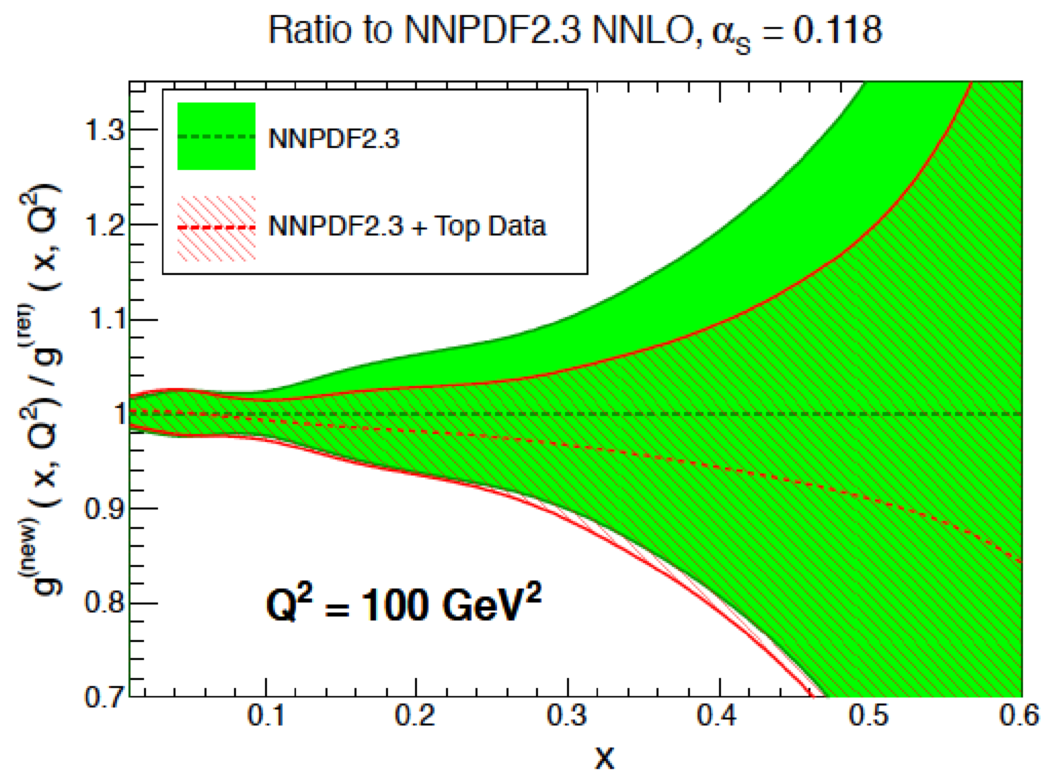


Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$	$+16.2(1.7\%)$ $-17.8(1.9\%)$

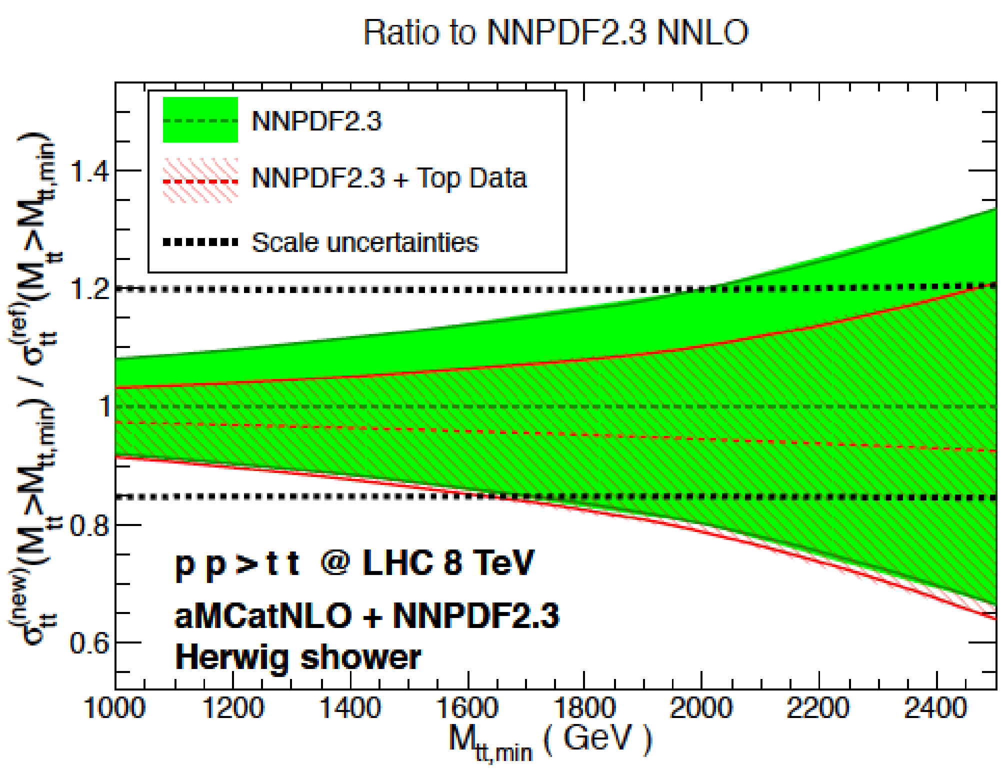
- Theoretical and exp uncertainties comparable now.
- Finally, we can learn how good/bad previous approximations were!

SIGMA(T TBAR) AT NNLO+NNLL

First applications: improve the gluon at large x with LHC data.



Czakon, Mangano, Mitov, Rojo `13



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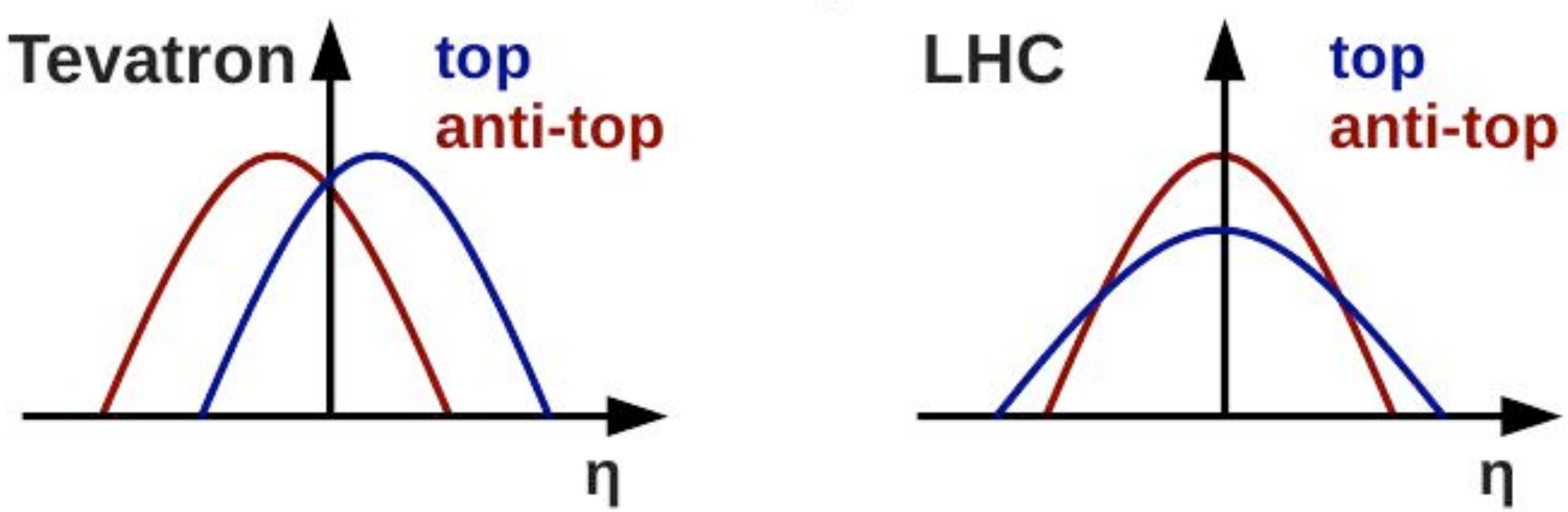
TTBAR ASYMMETRY

$$A_{CC}^{t\bar{t}} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$$

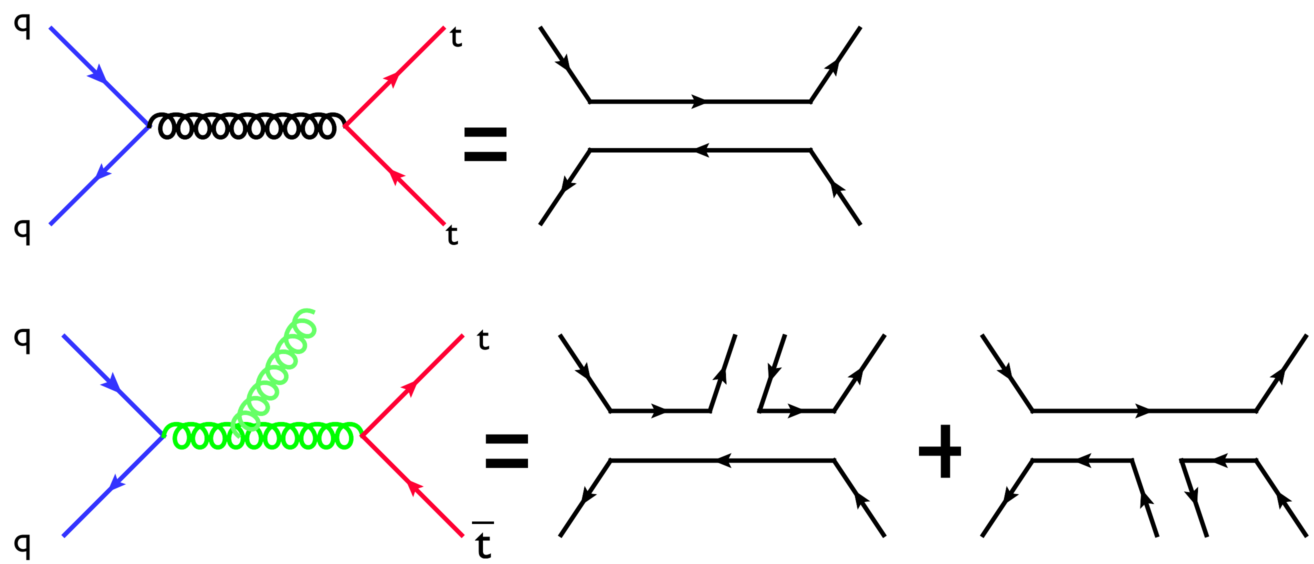


$$\Delta y^{\mathrm{TEV}} = y_t - y_{\bar{t}} \qquad \Delta y^{\mathrm{LHC}} = |y_t| - |y_{\bar{t}}|$$

Other definitions are used: lab frame at Tevatron, central charge *[Antunano, et al,]* and one-side asymmetries *[Wang et al. 2010]* at the LHC which depend on a cut. A_{CC} at the LHC has been introduced by CMS (in terms of pseudo-rapidity). LHCB does not need any special definition *[Kagan et al.]*

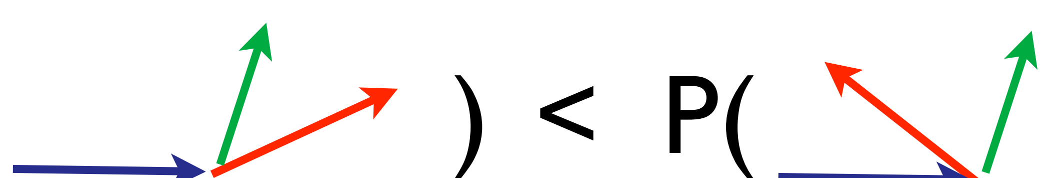
TTBAR ASYMMETRY

Intuitive picture:



In the soft limit $$|A_{soft}|^2 \simeq |A_{born}|^2 \left(\frac{q \cdot t}{q \cdot k \; t \cdot k} + \frac{\bar{q} \cdot \bar{t}}{\bar{q} \cdot k \; \bar{t} \cdot k} \right)$$

The probability to emit a gluon is larger the more the top is accelerated (like in QED) and therefore going backwards, so the contribution to the A_{FB} asymmetry is negative

P() $<$ P( )

The virtuals have to cancel the soft divergences of the reals and therefore the contribution is of the opposite sign.

At the end the asymmetry is positive due to the very LARGE virtual contribution.

TTBAR ASYMMETRY

$$A_{CC}^{t\bar{t}} = \frac{A\alpha_S^3 + B\alpha_S^4 + \ldots}{C\alpha_S^2 + D\alpha_S^3 + \ldots}$$

Observable only
known only at the leading order!

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1. Approx NNLO results indicate no major changes *[Almeida et al; 2010 Ahrens et al. 2010;Antunano et al 2010.]*
2. Studies on ttj indicate that the nature of the asymmetry is twofold and no genuinely new contributions should arise at higher order. *[Melnikov & Schulze, 2010]*
3. EW corrections are small *[Kuhn & Pagani 2011]*

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t tbar jj : LO <0
Virtuals always dominate : what about the two-loop contributions? to be seen...

TTBAR ASYMMETRY

$$A_{CC}^{t\bar{t}} = \frac{A\alpha_S^3 + B\alpha_S^4 + \ldots}{C\alpha_S^2 + D\alpha_S^3 + \ldots}$$

Observable only
known only at the leading order!

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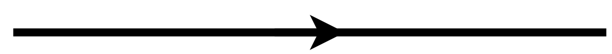
The α_S^4 (NLO) calculation for the A(ttbar) will give the final answer!

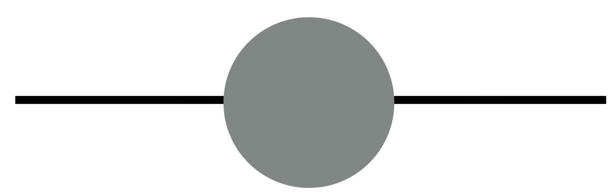
THE TOP MASS

The top mass is so precisely measured (mt=173.3 ± 0.7 GeV) that we have to worry about its definition.

Leading order: 

$$\frac{1}{\not{p} - m}$$

(pole) mass = ***m***

Higher orders: 

$$\frac{1}{\not{p} - m_R - \Sigma(\not{p})}$$

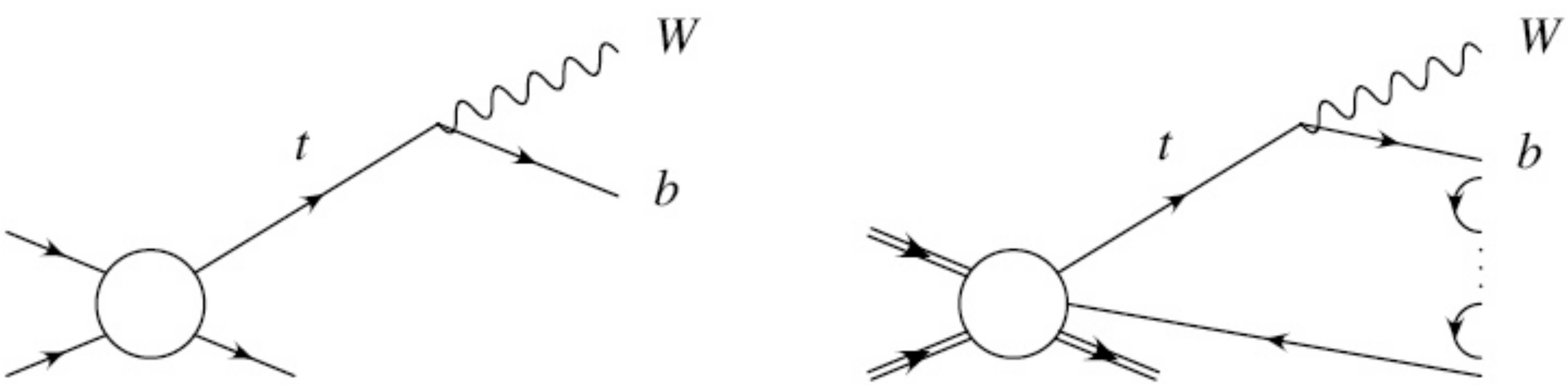
m_R = renor. mass

(At least) two possible renormalisation schemes: MSbar and on-shell, leading to to different mass definitions.

The MSbar mass is a fully perturbative object, not sensitive to long-distance dynamics. It can be determined as precisely as the perturbative calculation allows. The mass is thought as any other parameter in the Lagrangian. It is the same as the Yukawa coupling. For example, it could be extracted from a cross section measurement (see later).

THE TOP MASS

The pole mass would be more physical (pole = propagation of particle, though a quark doesn't usually really propagate -- hadronisation!) but is affected by long-distance effects: it can never be determined with accuracy better than Λ_{QCD}.



The pole mass is closer to what we measure at colliders through invariant mass of the top decay products. The ambiguities in that case are explicitly seen in the modeling of extra radiation, the color connect effects and hadronization.

The two masses can be related perturbatively (modulo non-perturbative corrections!!):

$$m_{pole} = \overline{m}(\overline{m}) \left(1 + \frac{4}{3}\frac{\overline{\alpha}_s(\overline{m})}{\pi} + 8.28 \left(\frac{\overline{\alpha}_s(\overline{m})}{\pi}\right)^2 + \cdots \right) + O(\Lambda_{\rm QCD})$$

THE TOP MASS

Several strategies for top mass measurement:

1. Template and MEM methods. Still LO in their essence, yet calibrated to NLO MC simulations. MC mass is closely related to the pole mass (=suffers of the same NP uncertainties)

   ➡Improvements: MEM automated in MG5 *[Artoisenet et al. 2010]*

   ➡First steps towards NLO *[Campbell et al. 2012]*

2. Alternative more exclusive final state observables, such as the m(J/psi, lepton) *[Kharchilava '99 Chierici, Dierlamm CMS NOTE 2006/058]*

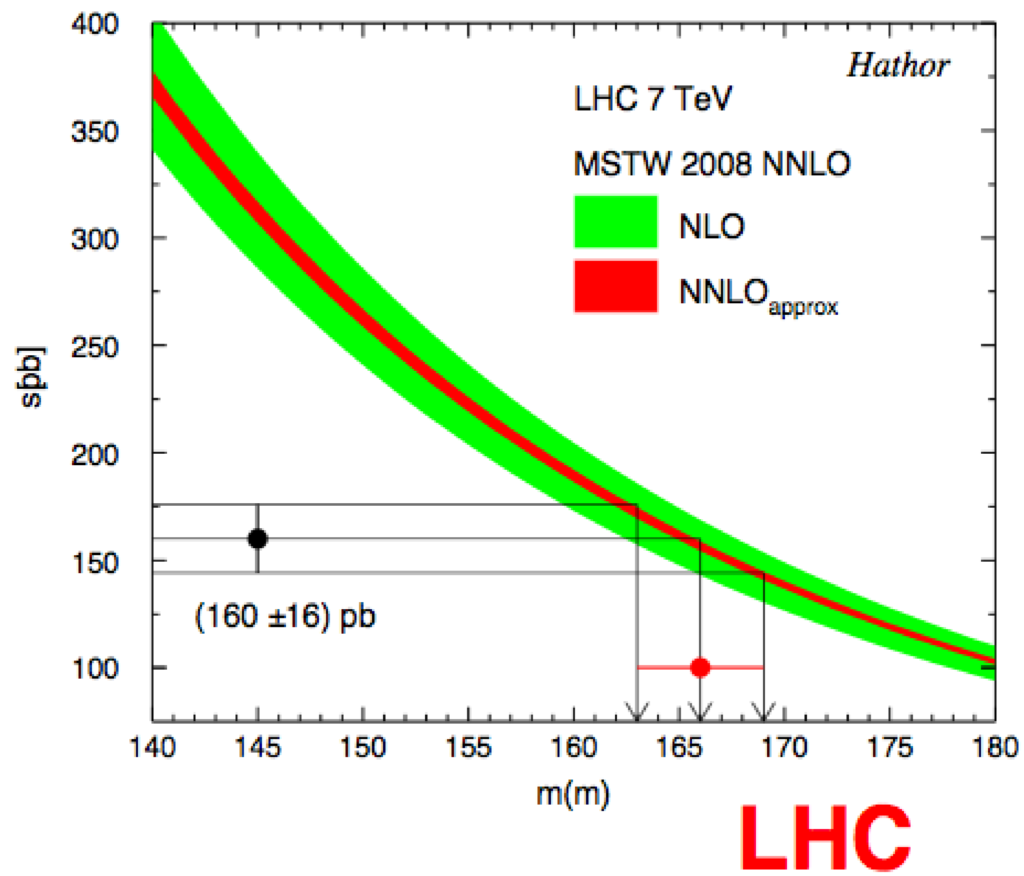
   ➡Statistically limited

THE TOP MASS

Several strategies for top mass measurement:

3. Extraction of m^{MSbar} from the cross section

[Langenfeld, Moch, Uwer `09, Beneke, Falgari, Klein, Schwinn `11 Ahrens, Ferroglia, Neubert, Pecjak, Yang `11]



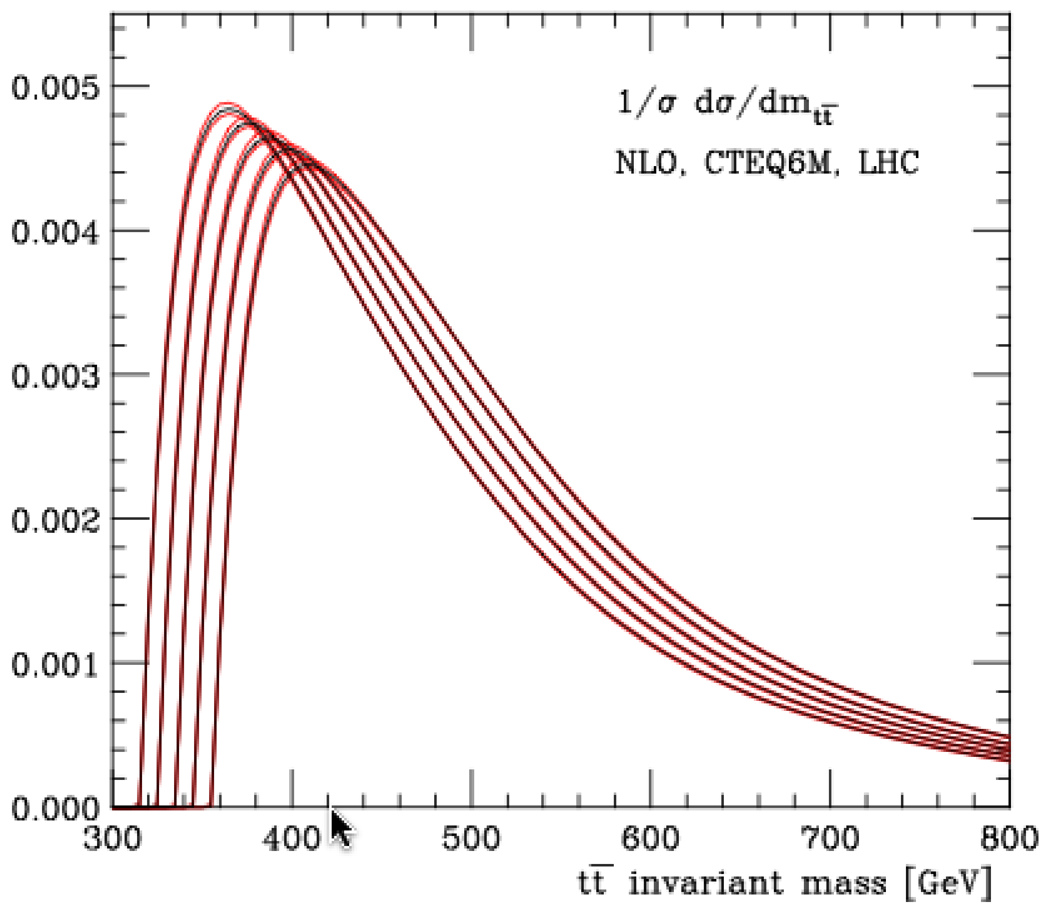
- Not competitive right now due uncertainties in the cross section measurement, to the slope and the TH uncertainty band.
- $\Delta m/m \sim 3\%$

THE TOP MASS

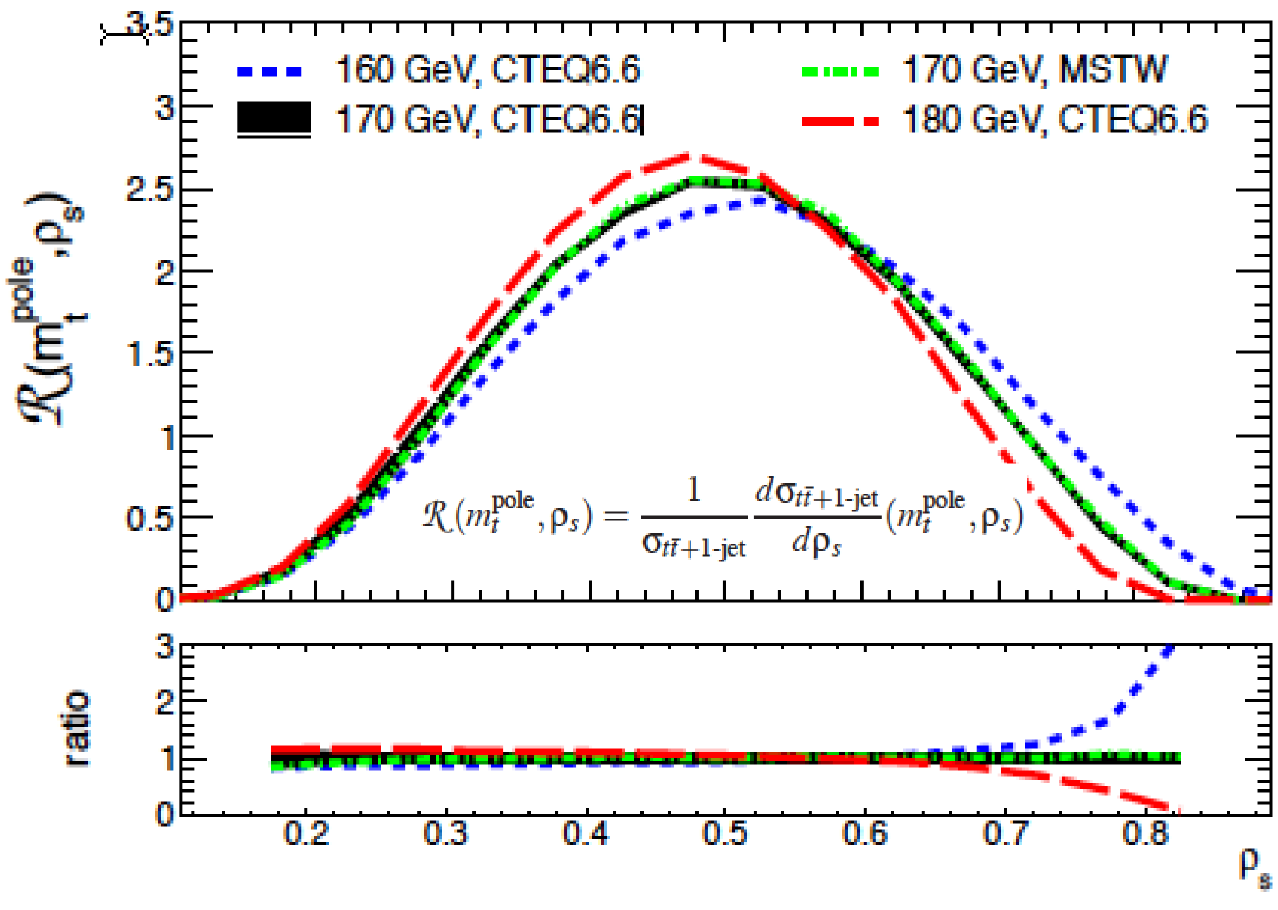
Several strategies for top mass measurement:

4. Extraction of m_{top} from distributions:

Frederix, FM 2009

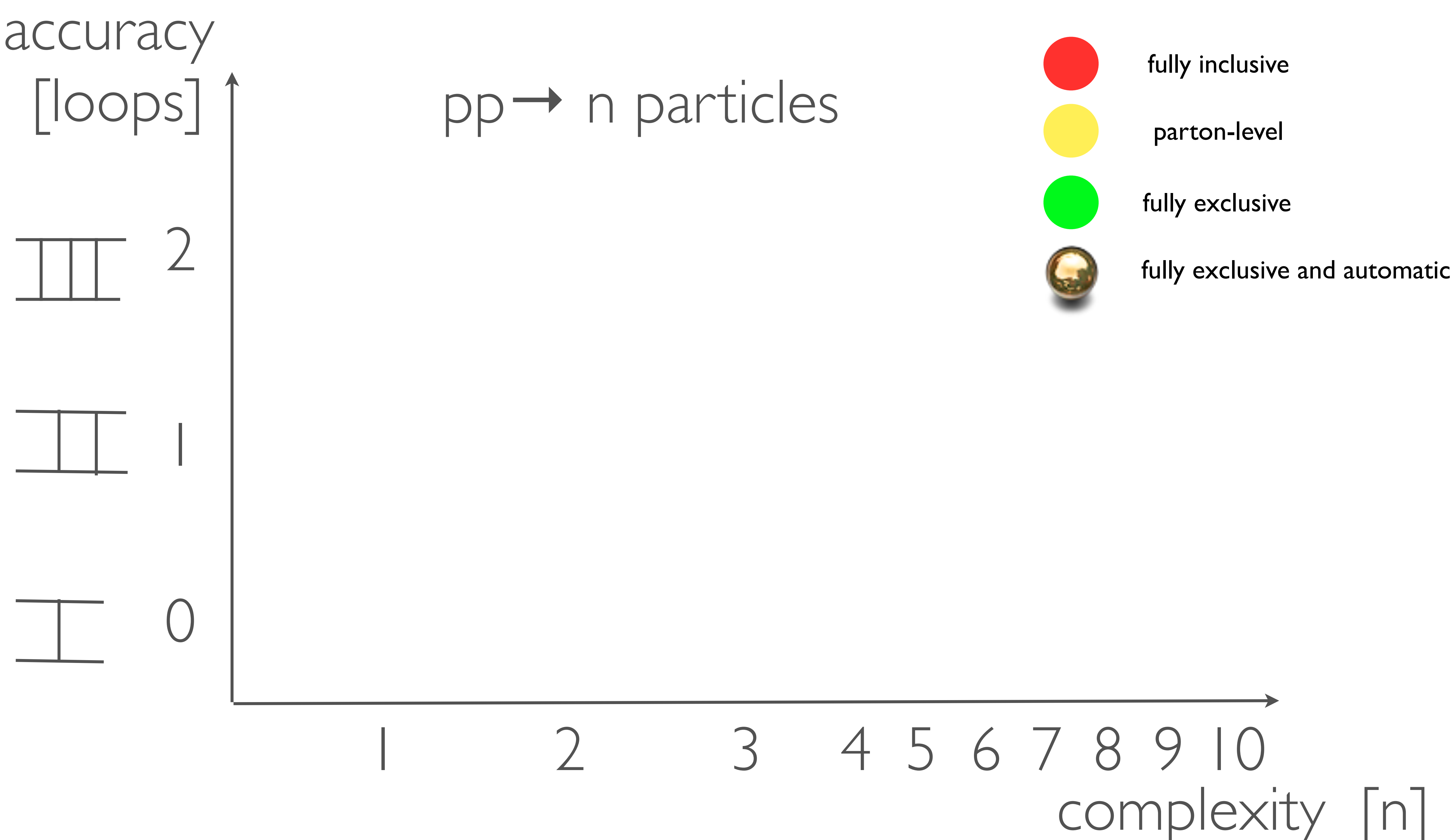


Alioli et al. 2013



Difficult roads, yet worth to be explored!

AUTOMATIC MC'S AT NLO



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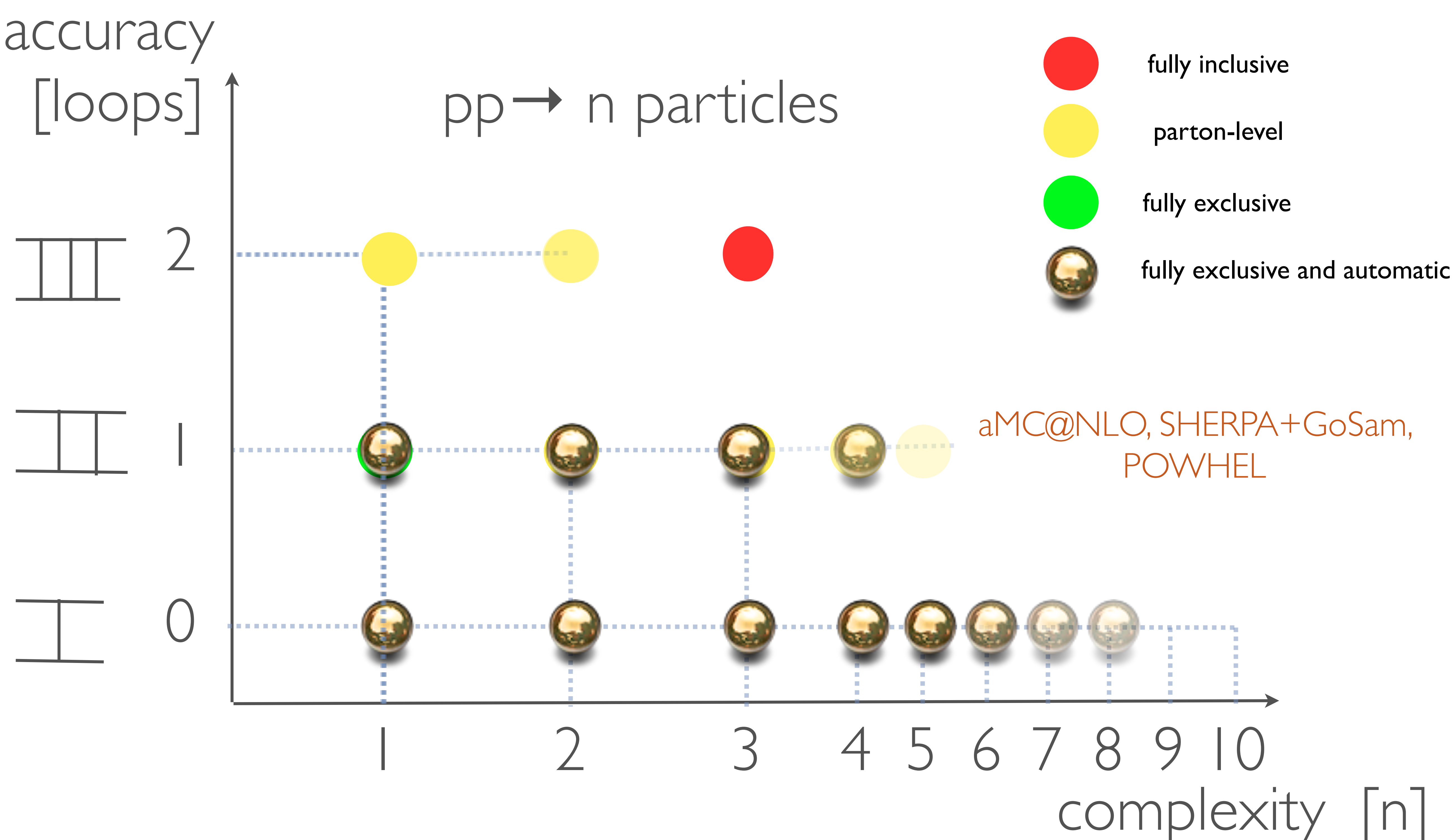

(SEMI) AUTOMATIC MC'S AT NLO

Processes involving tops can be simulated at the NLO+PS level, via:

- POWHEG-Box (public) library : tt, tj (4F and 5F),tb, tW
- POWHEL (not public) : ttj, ttbb, ttZ, ttH
- Sherpa + external loop codes (to be public): tt
- aMC@NLO (public): process directly generated by the user.

AUTOMATIC MC'S AT NLO

Suppose now you are interested in studying Higgs production in association with t tbar :

```
./bin/mg5
> generate p p > t t~ h [QCD]
> output tth
> launch
```

or with single top (both t and t~):

```
./bin/mg5
> define tx = t t~
> generate p p > tx h j[QCD]
> output thj
> launch
```

AUTOMATIC MC'S AT NLO

The range of SM processes that can be generated **aMC@NLO** (SM plus weak BSM) is only limited by computing power. It encompasses and goes beyond the current MCFM and POWHEG-Box libraries.

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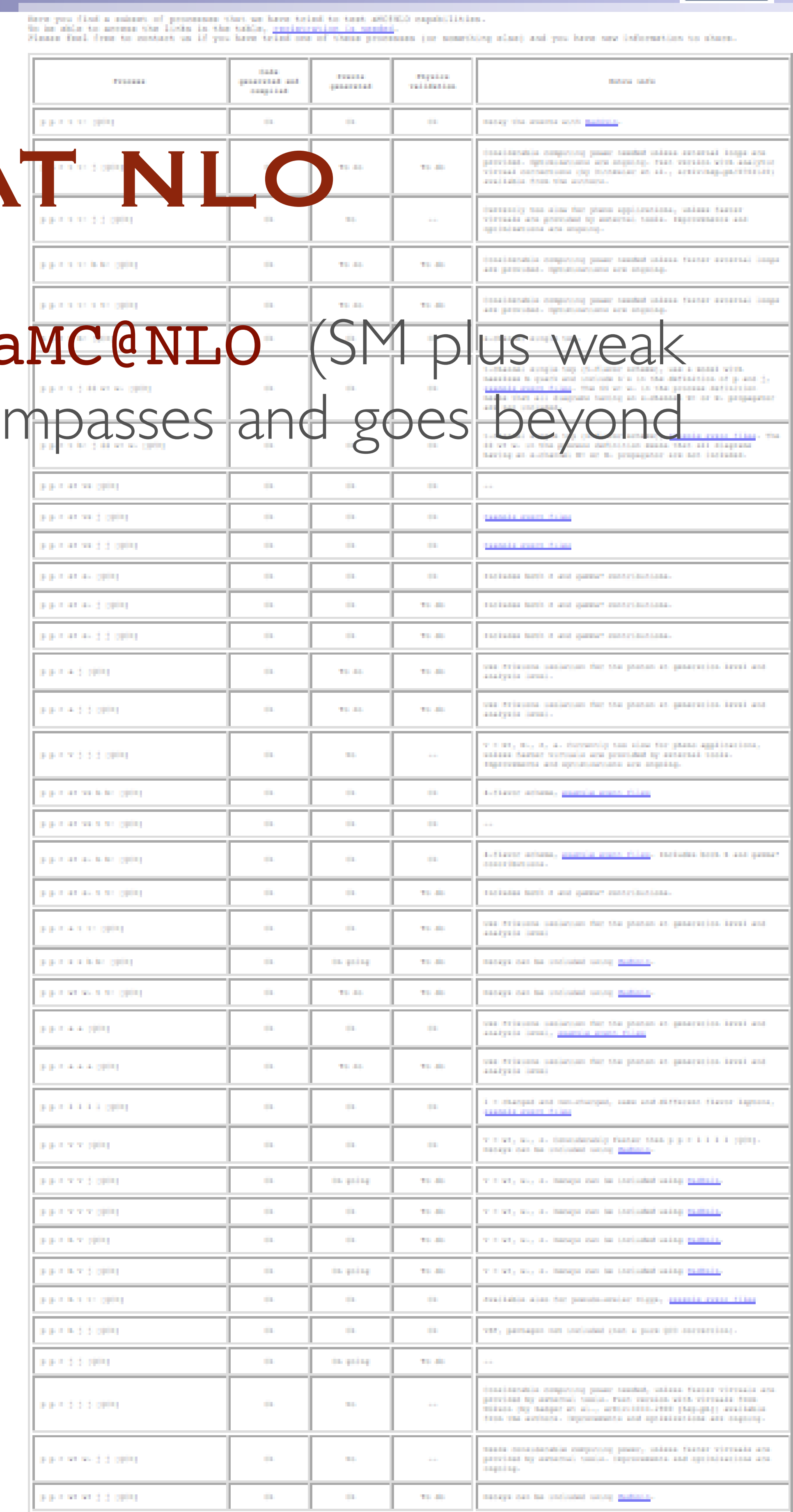

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Examples in the SM:

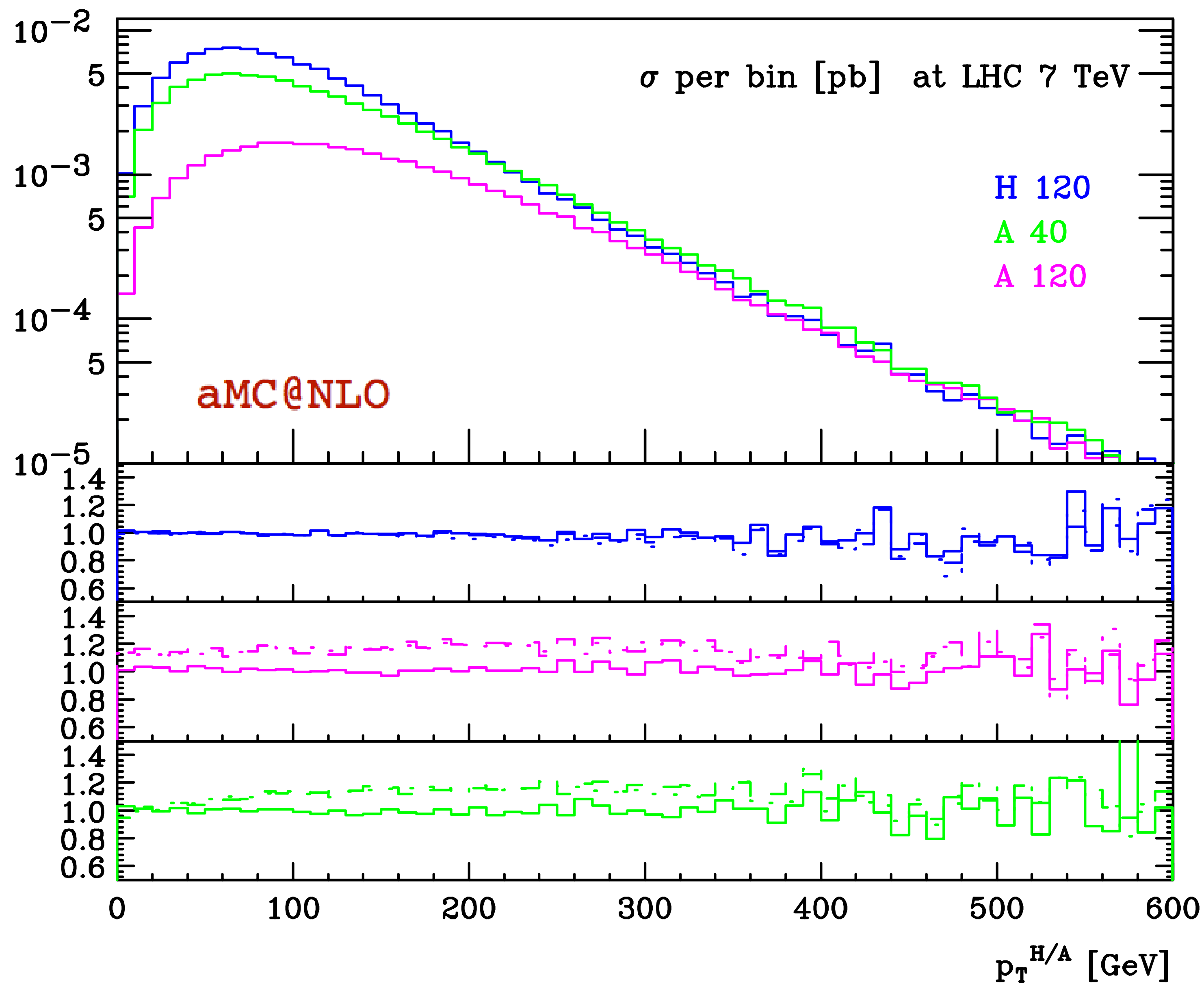
- t tbar : pp→tt, pp→ttj
- single top : pp→tj (4 and 5F), pp→tW, pp→tb
- resonant + non-resonant : pp→(Wb)(Wb), pp→ (Wb)j (being validated)
- Higgs associated : pp→tth, pp→thj
- Vector boson associated : pp→ttγ, pp→ttW, pp→ttZ, pp→tZj
- Heavy quark associated : pp→tttt, pp→ttbb

AUTOMATIC MC'S AT NLO

For H, NLO results known (but no public code available) for scalar Higgs since some time. No results for pseudoscalar A known.

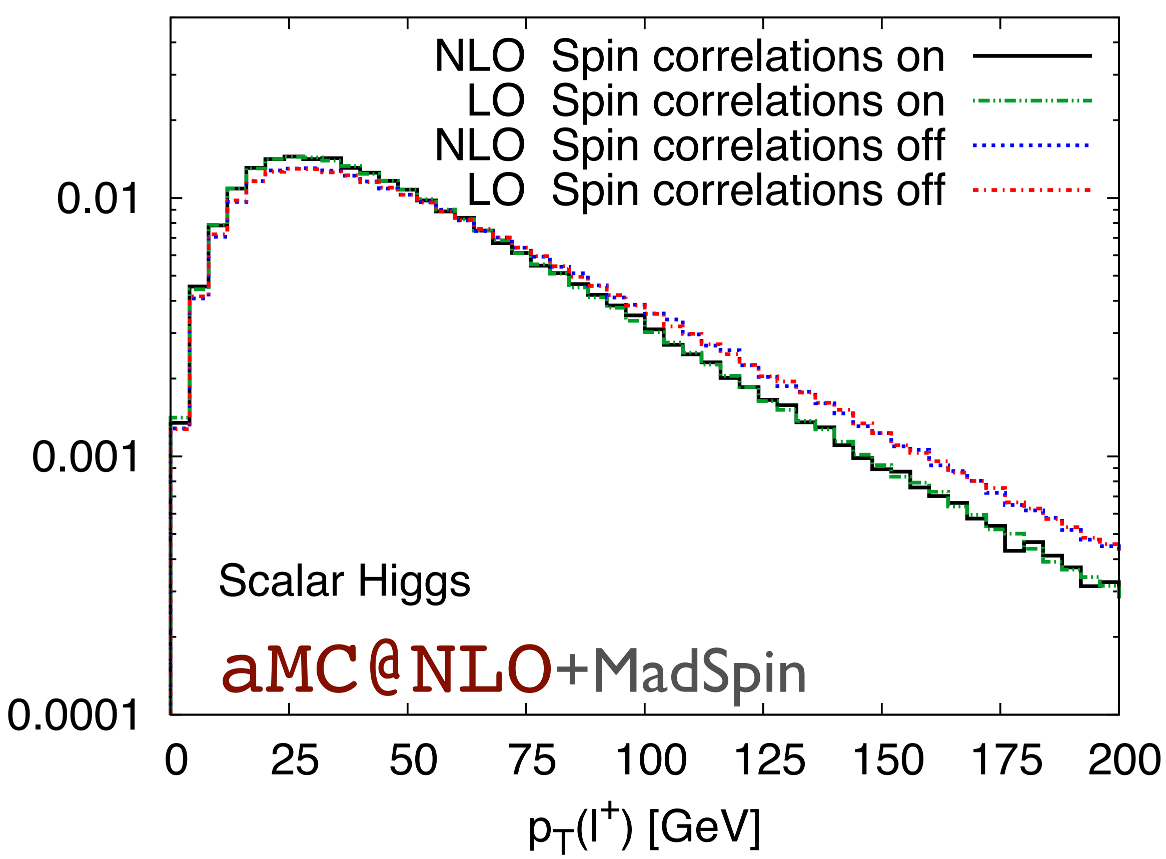
First fully automatic results for both H and A *[aMC@NLO:1104.5613].*

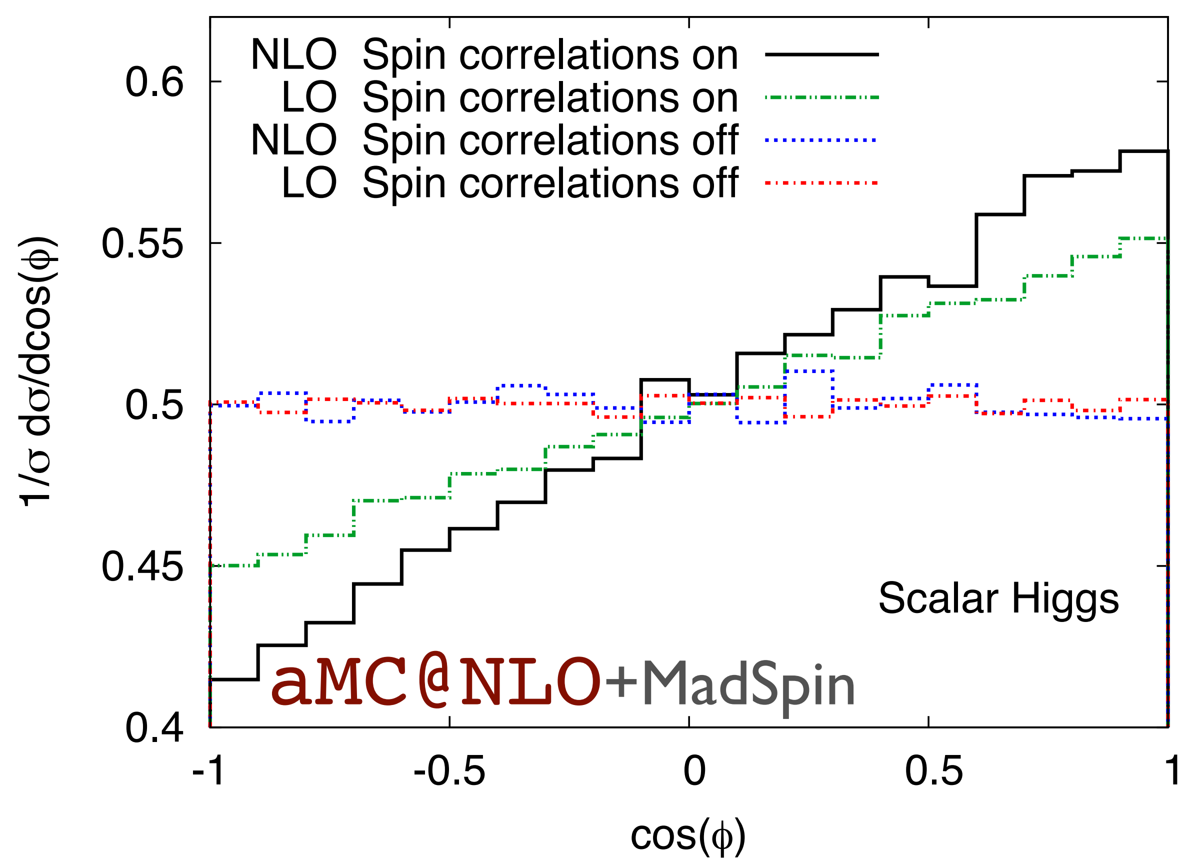
Mild corrections to the shapes for m_h=120 GeV. p_T pseudoscalar is harder. At high p_T (boosted Higgs) the three curves are equal in shape and normalization.



AUTOMATIC MC'S AT NLO

Inclusion of spin correlations in top decays, can now be done via post-processing of NLO event samples out in the Les Houches format with top on shell.





For example, in tth, the effects of the spin correlations on the pt shape of the charged lepton is more important than that of NLO QCD corrections!

AUTOMATIC MC'S AT NLO

[Frederix, Frixione, 1209.6215]

- aMC@NLO samples for S+0j, S+1j, S+2j, S+...j consistently without double counting (where S can be a Higgs, a ttbar pair, a W-boson, etc.)

Use techniques from CKKW/MLM and multi-scale improved fixed order NLO or "MINLO" *[Hamilton, Nason & Zanderighi, 2012]* to define **exclusive event samples** for S+0j, S+1j, etc.

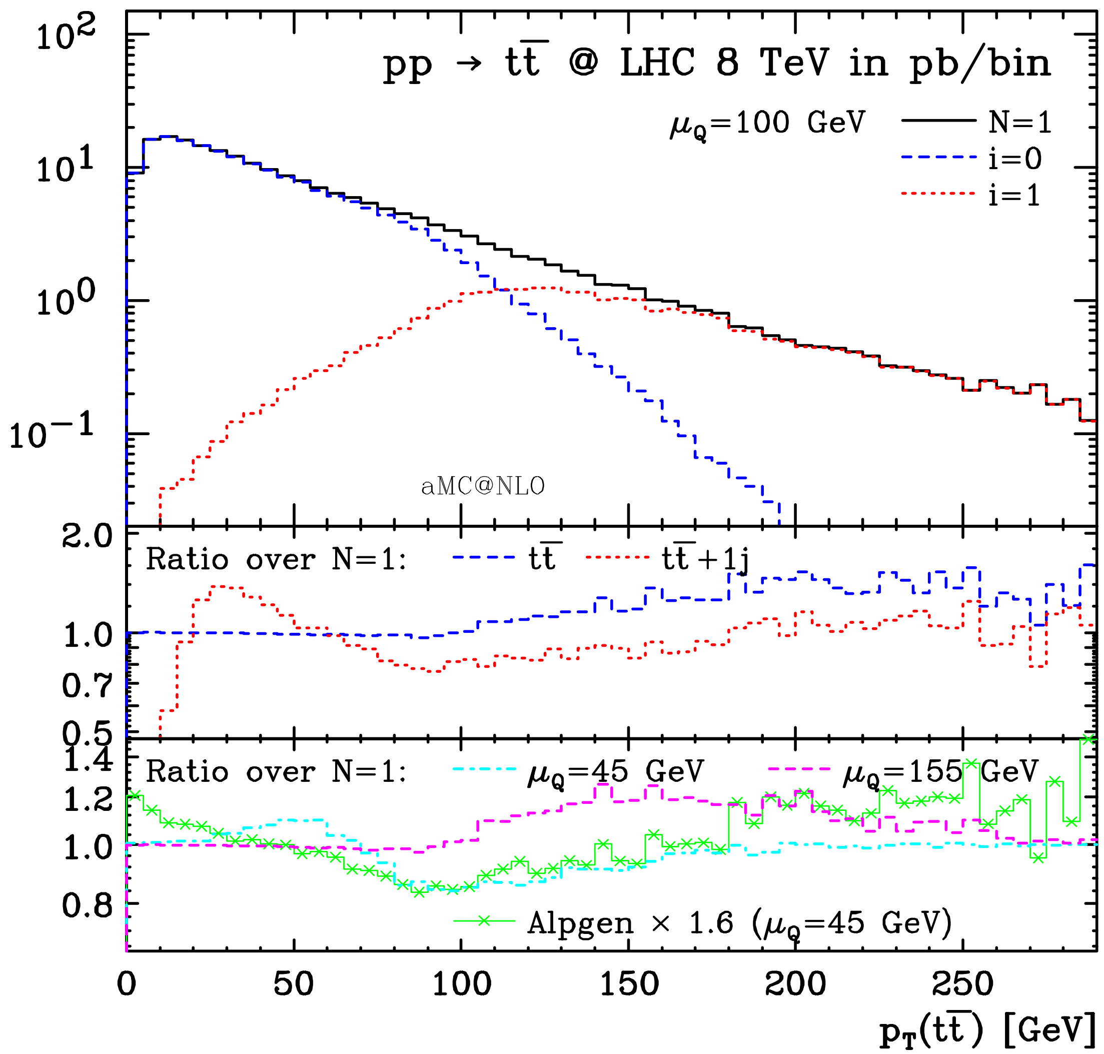
  - In such a way that the exclusive samples can simply be combined to one big event sample

- Special care needed for the highest multiplicity sample

AUTOMATIC MC'S AT NLO

[Frederix, Frixione, 1209.6215]

FXFX MERGING IN aMC@NLO



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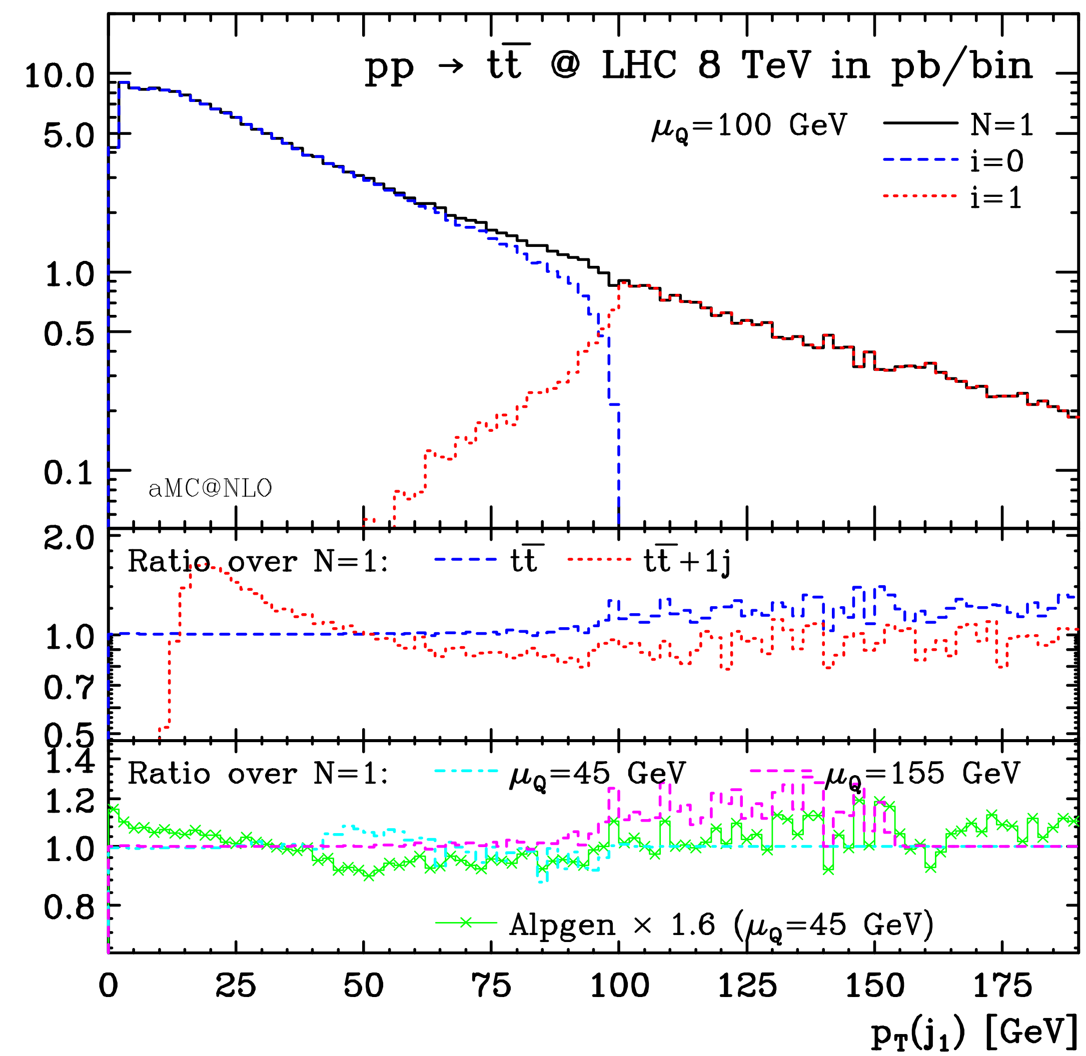

- Transverse momentum of the ttbar pair and of the 1st jet.
- Agreement with ttbar+0j at MC@NLO and ttbar+1j at MC@NLO in their respective regions of phase-space; Smooth matching in between; Small dependence on matching scale

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