2nd Taipei School on

FeynRules-MadGraph for LHC Physics

9/4-8, 2013, National Taiwan Normal University, Taipei

Top Quark Theory

in the Higgs era

Fabio Maltoni

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

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Degrassi, et al. '12

Click on the references for more info

THE HOTTEST NEWS IN TOP PHYSICS

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- A new **force** has been discovered, the first ever seen* not related to a gauge symmetry.

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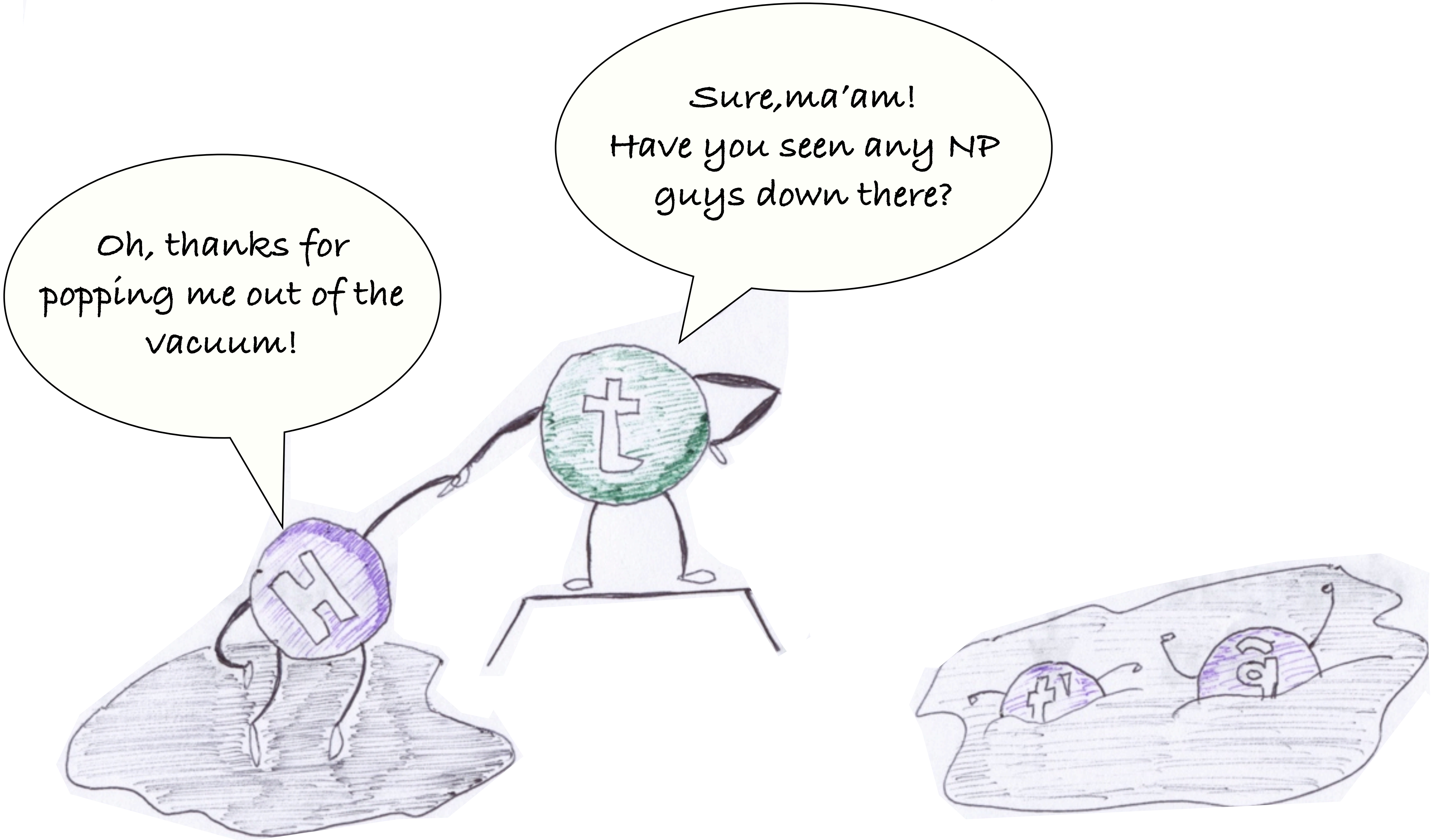
THE HOTTEST NEWS IN TOP PHYSICS

- A new **force** has been discovered, the first ever seen* not related to a gauge symmetry.
- Its **mediator** looks a lot like the SM scalar

*fundamental, ie with elementary mediators.

THE HOTTEST NEWS IN TOP PHYSICS



TOP IN THE HIGGS ERA

Is this good or bad news (for top physics) ?

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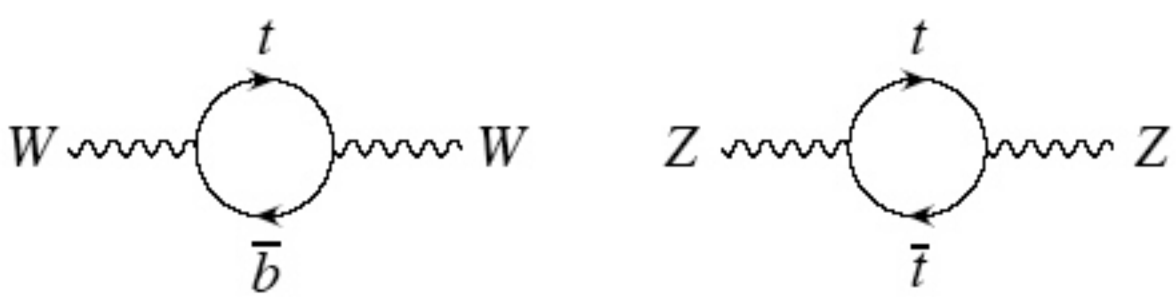
☺ Renewed interest and strong motivation for **precision measurements** in top physics, first of all the top mass.

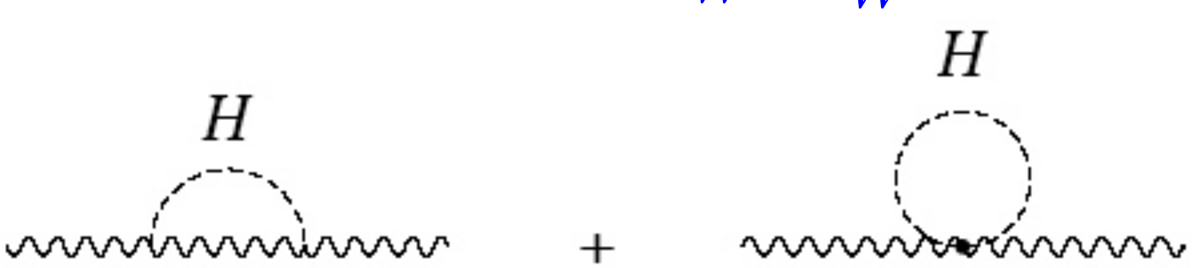
PRECISION MEASUREMENTS

Indirect evidence for the existence of particles not yet detected can be inferred from quantum corrections. At tree level mW=mZ cos θW. At one loop:

$$m_W^2\left(1-\frac{m_W^2}{m_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

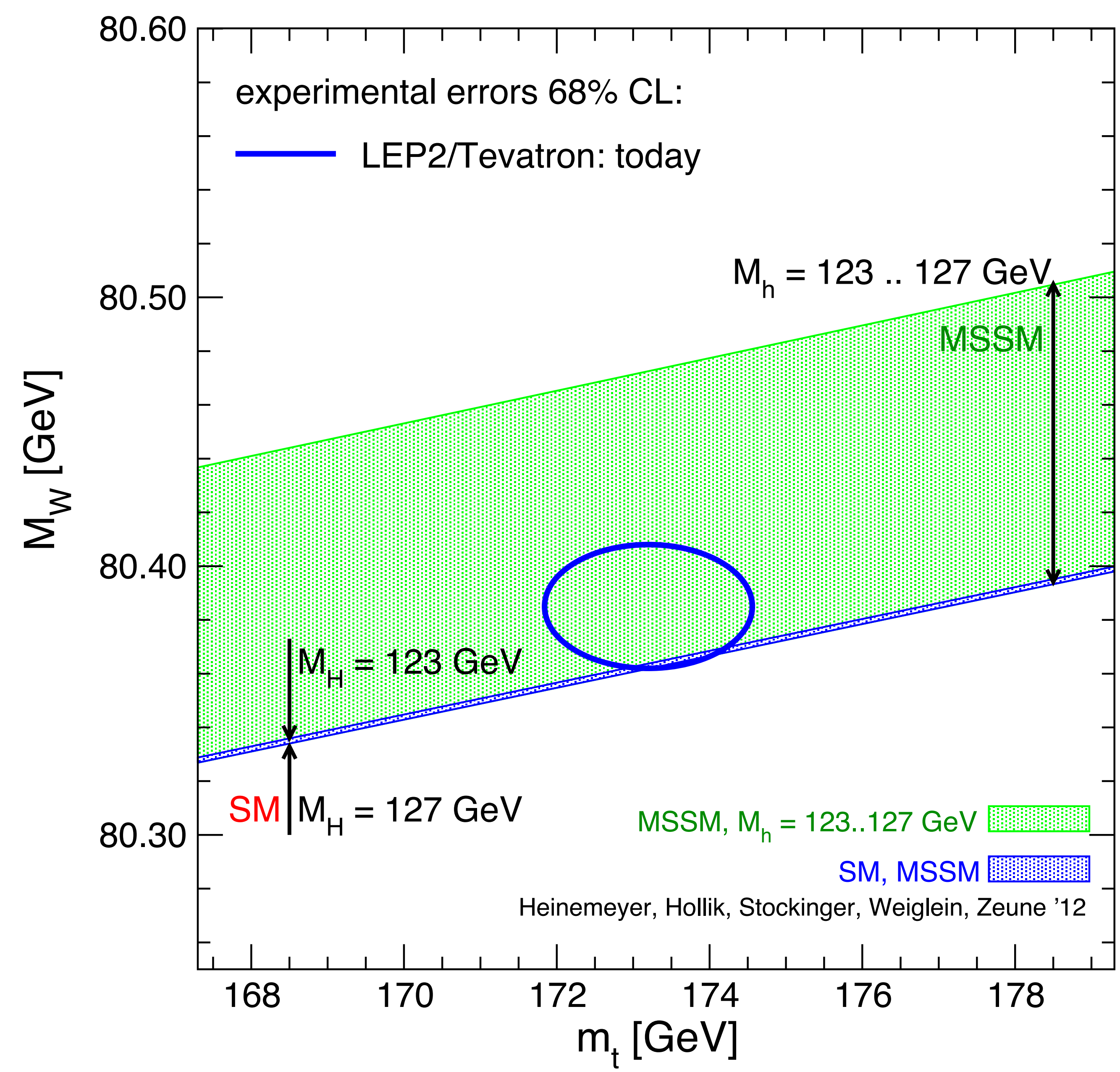


$$\Delta r_{\rm top}=-\frac{3\alpha}{16\pi}\frac{\cos^2\theta_W}{\sin^4\theta_W}\frac{m_t^2}{m_W^2}$$



$$\Delta r_{\rm Higgs}=+\frac{11\alpha}{48\pi\sin^2\theta_W}\log\frac{m_H^2}{m_W^2}$$

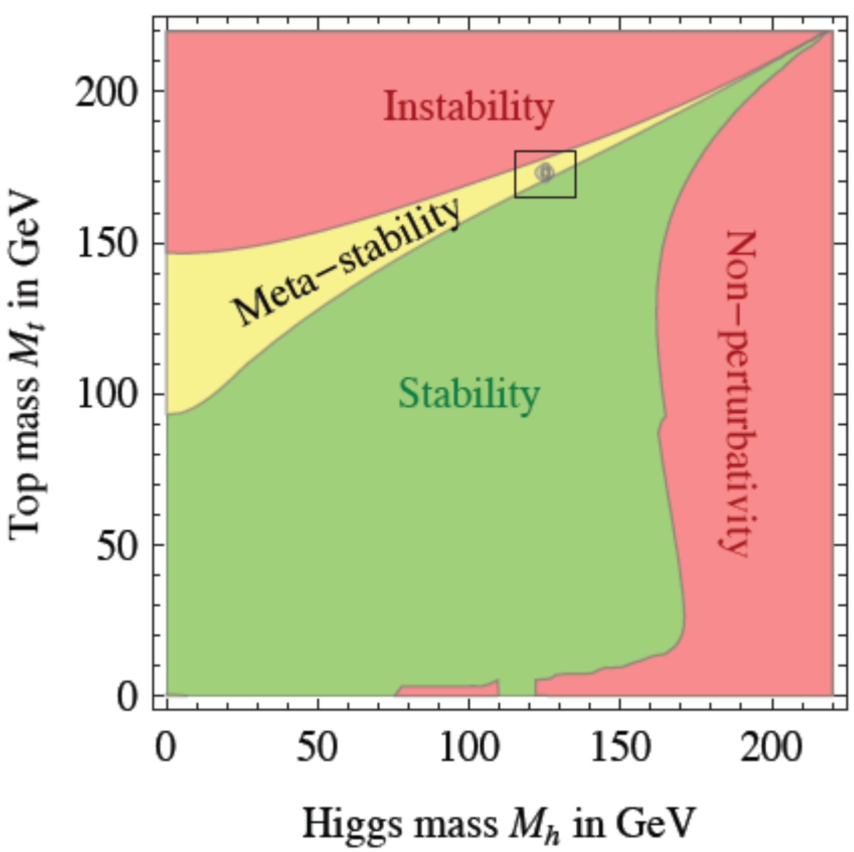
Heinemeyer et al. '12

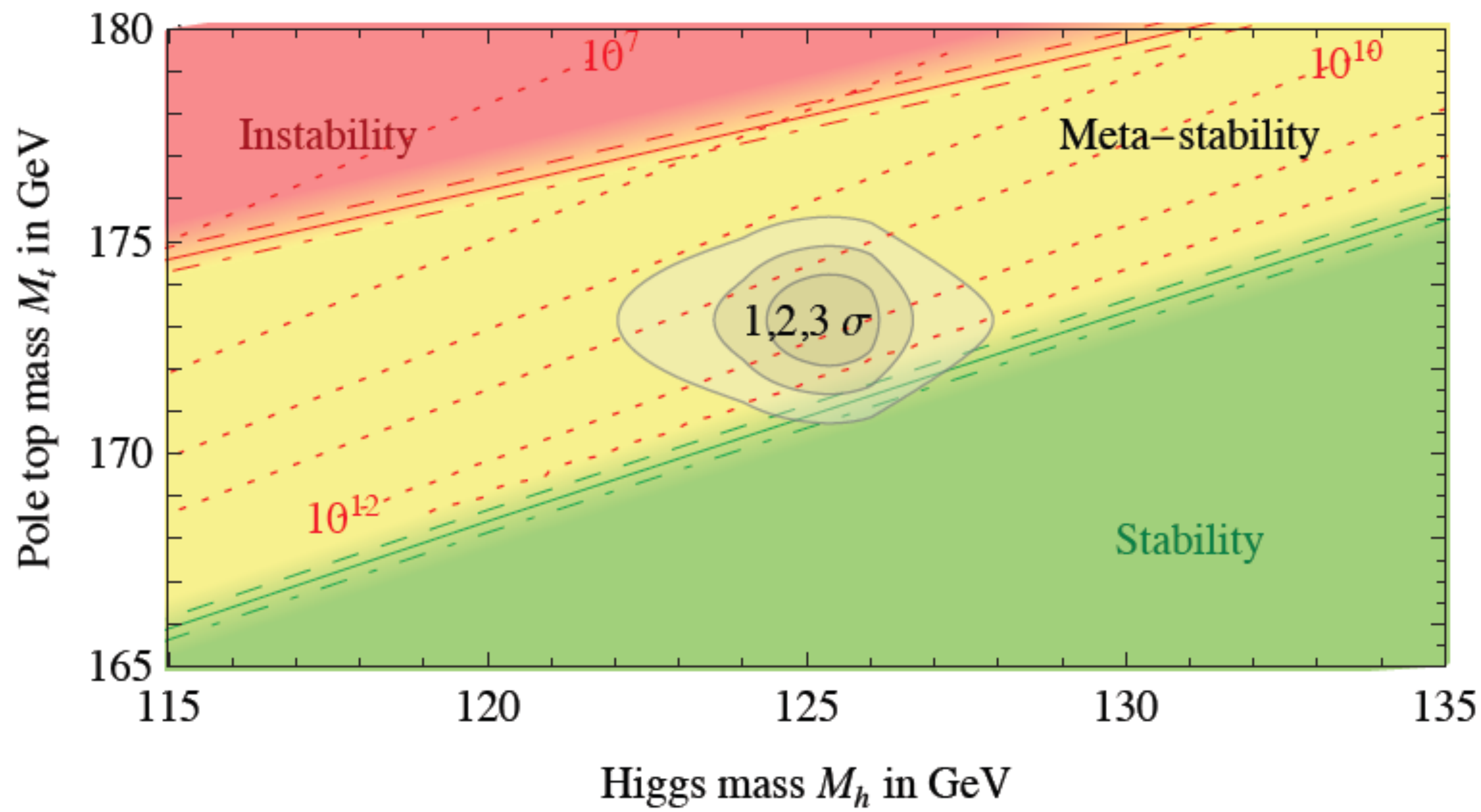


PRECISION MEASUREMENTS

The fate of the Universe depends on 1GeV in m_t

Degrassi, et al. '12

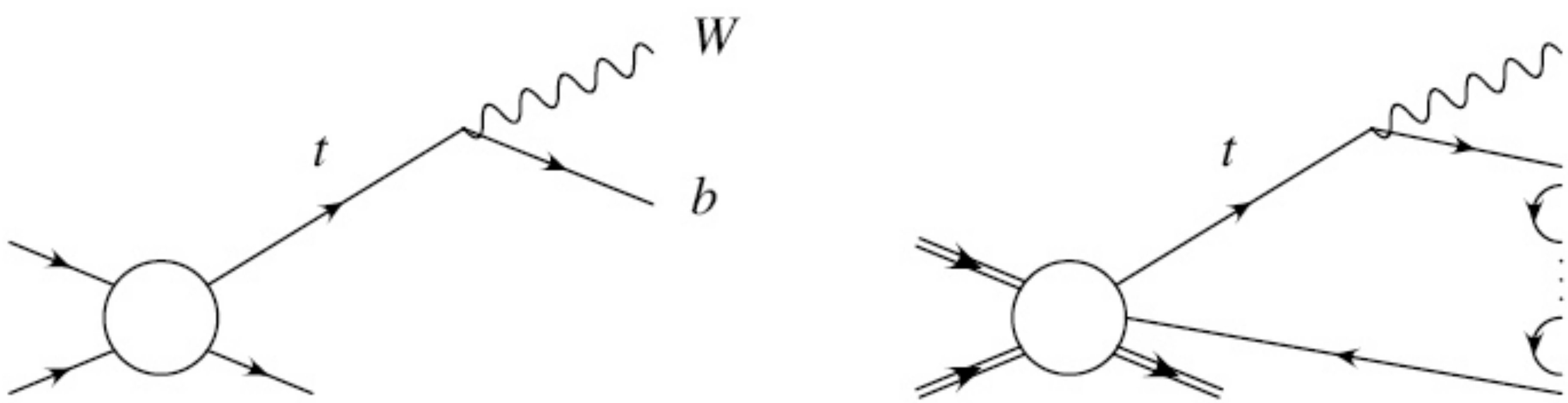




$$y_t(M_t) = 0.93587 + 0.00557\left(\frac{M_t}{\text{GeV}} - 173.15\right)\ldots \pm 0.00200_{\text{th}}$$

THE TOP MASS

The pole mass corresponds to our physical intuition of a stable particle (pole = propagation of particle, though a quark doesn't usually really propagate -- hadronisation!) however, it can never be determined with accuracy better than Λ_{QCD}.



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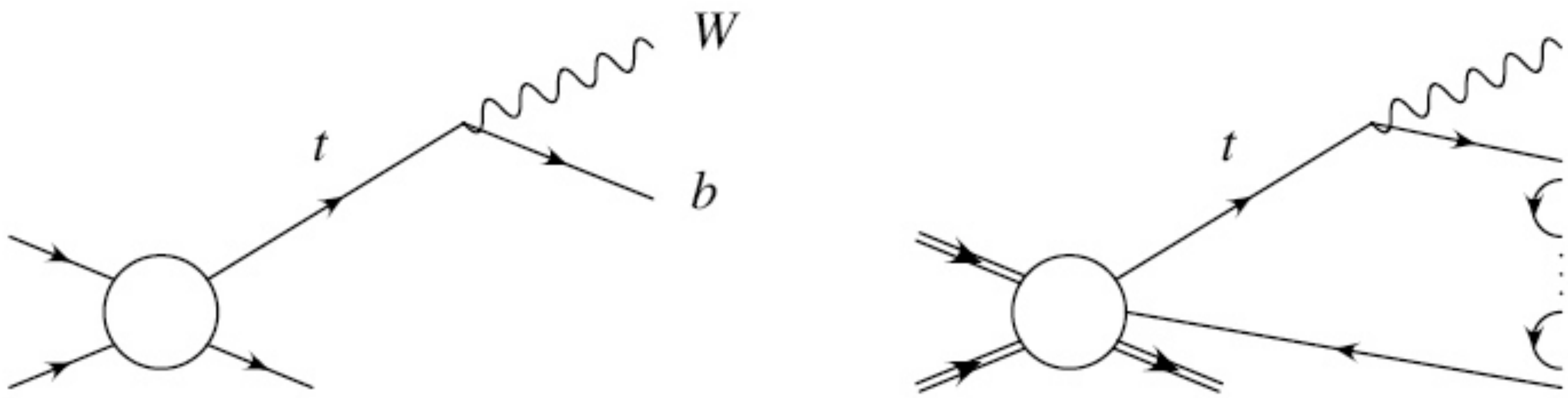

The pole mass is closer to what we measure at colliders through invariant mass of the top decay products. The ambiguities in that case are explicitly seen in the modeling of extra radiation, the color connect effects and hadronization.

It can be connected to a short distance mass perturbatively (modulo non-perturbative corrections!!):

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

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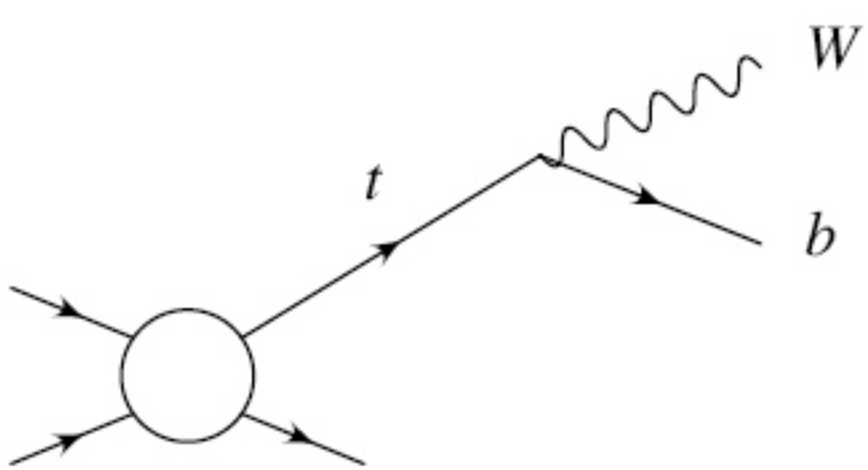

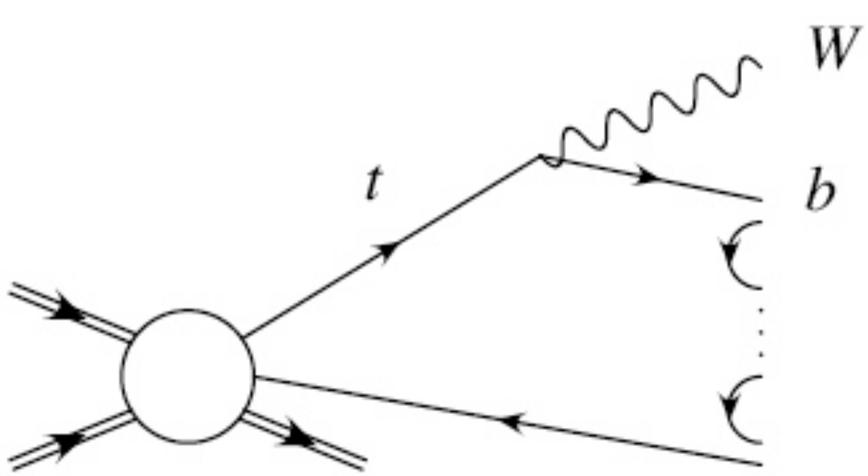

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1. Template and Matrix Element Methods. Still LO in their essence, yet calibrated to NLO MC simulations. MC mass is closely related to the pole mass (=suffers of the same NP uncertainties). MEM: automation [Artoisenet et al. 2010] and first steps towards NLO [Campbell et al. 2012]

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

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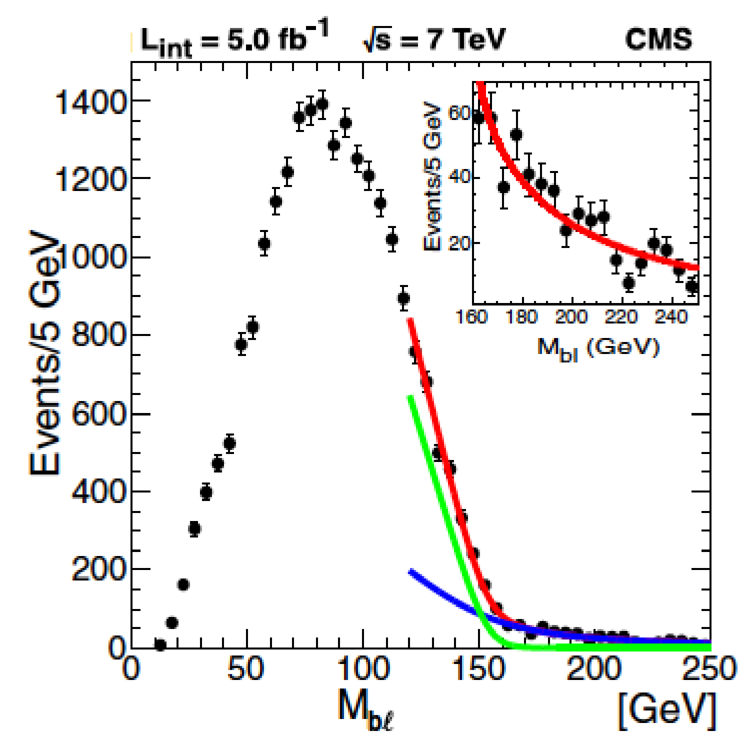
3. End point method [CMS, 2013] : m_{T2}, simple and resilient.

$$M_{b\ell}^{\max} = \sqrt{m_b^2 + \left(1 - \frac{m_\nu^2}{M_W^2}\right)\left(E_W^* + p^*\right)\left(E_b^* + p^*\right)}$$

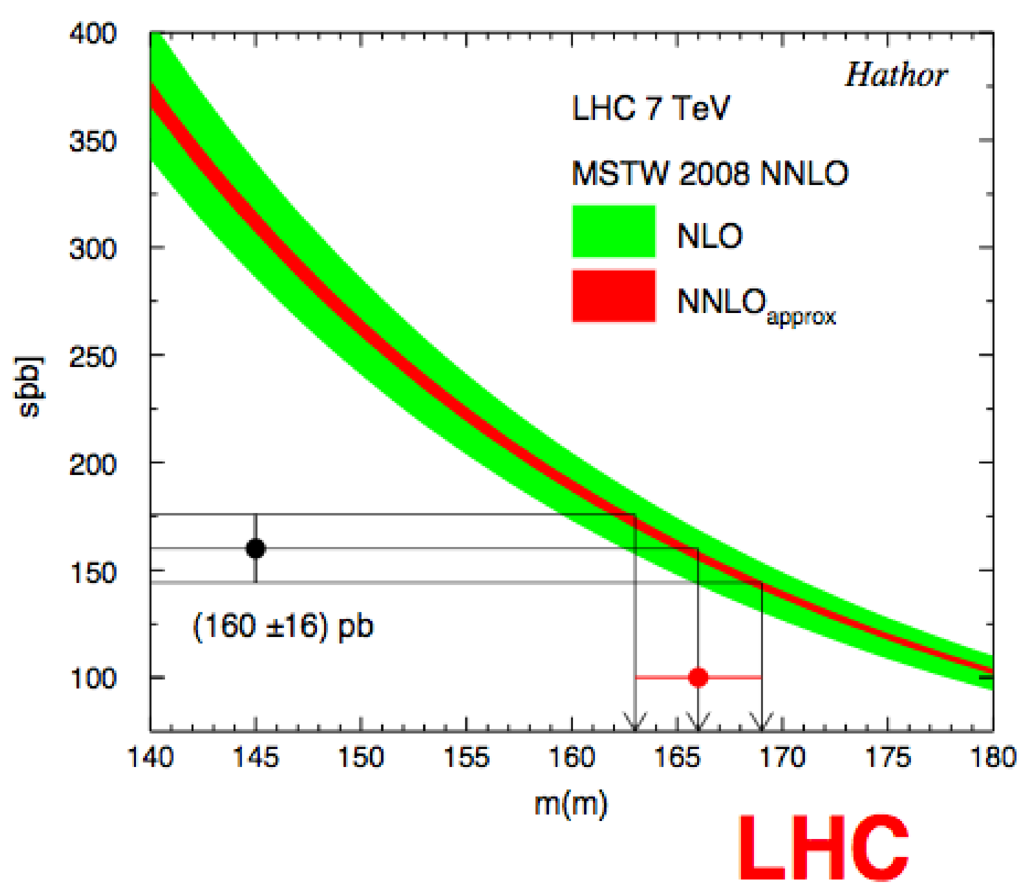


THE TOP MASS

Several strategies for top mass measurement:

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

[Langenfeld, Moch, Uwer 2009, 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.
- $\Delta m/m \sim 3\%$

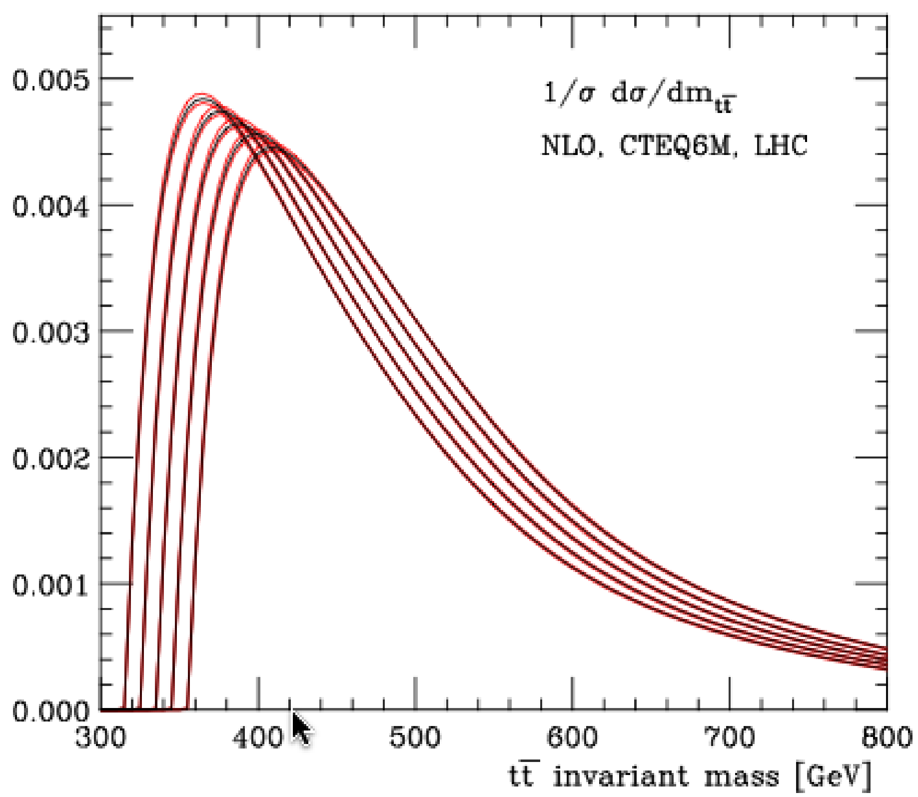
Sunday 8 September 2013

THE TOP MASS

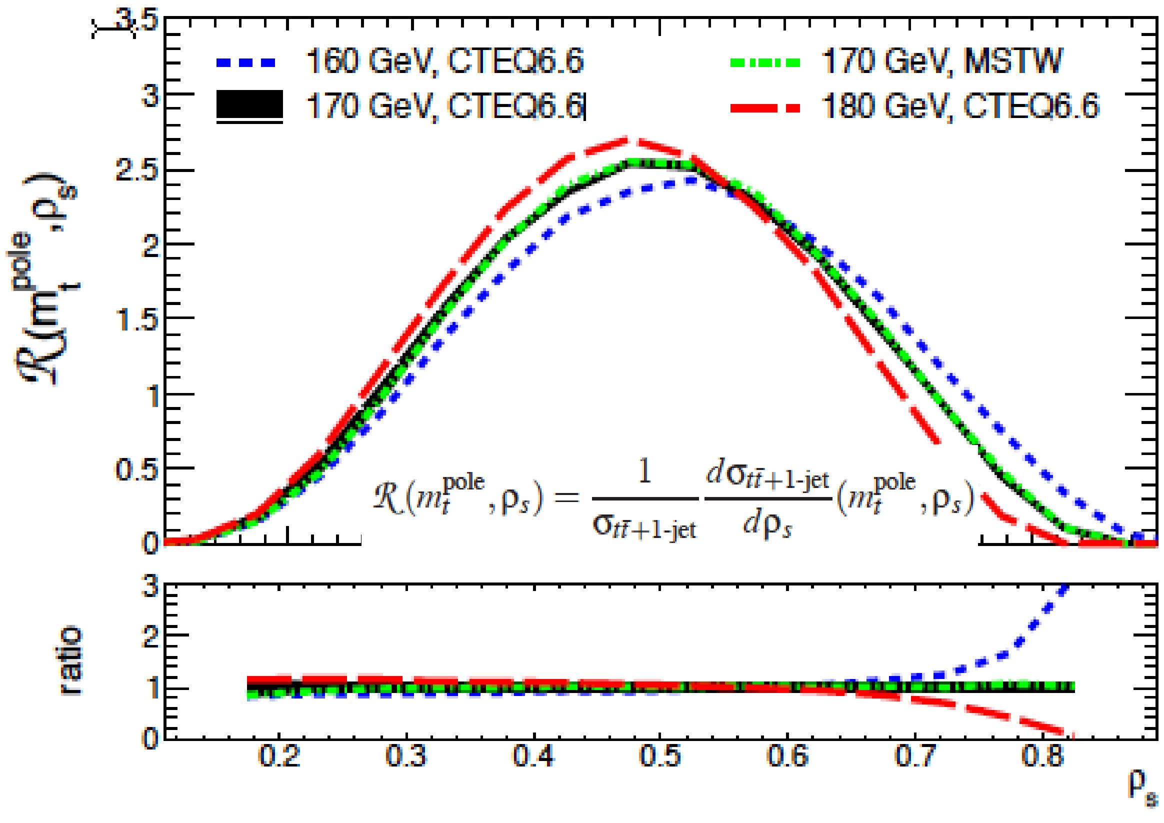
Several strategies for top mass measurement:

4. Extraction of m_{top} from distributions:

[Frederix, FM 2009]



[Alioli et al. 2013]



Difficult roads, yet worth to be explored! Boosted states and single-top production could also be used to independently assess the impact of non-perturbative corrections.

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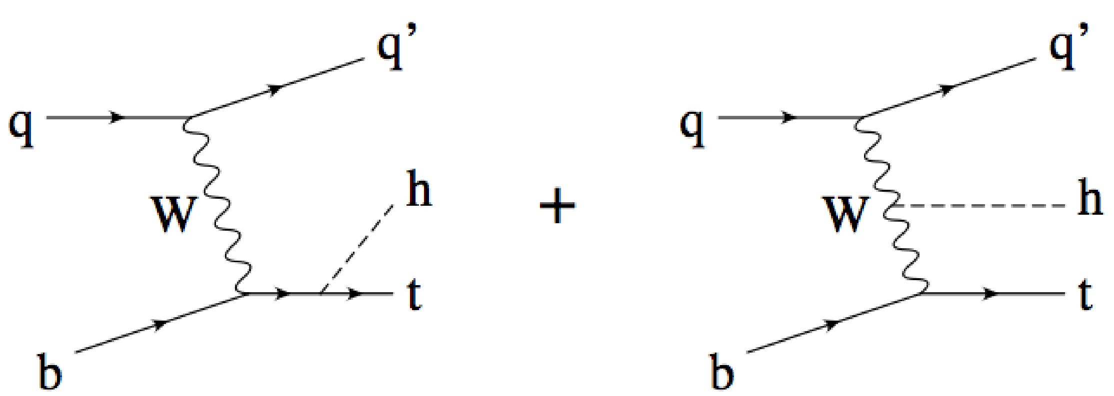
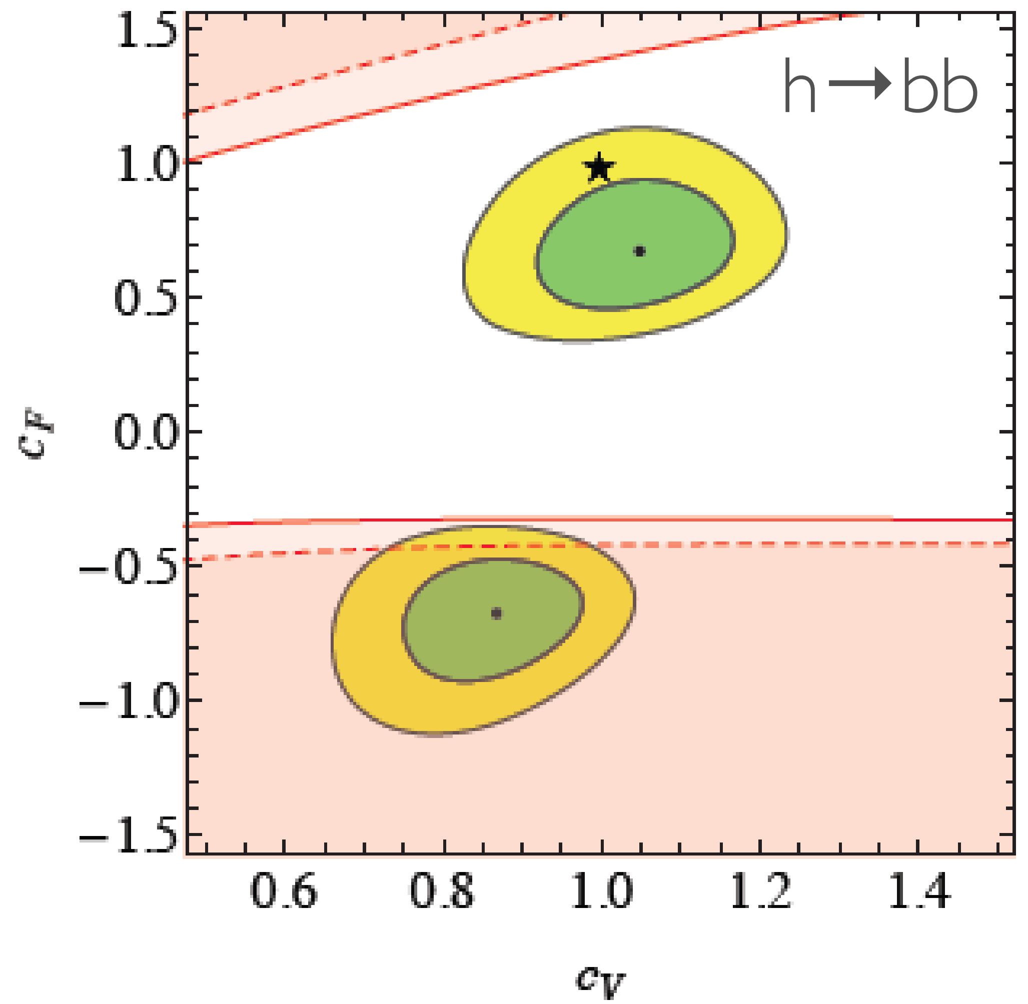
TOP-HIGGS INTERACTIONS

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	$\sigma^{\rm NLO}(pp \to thj)$ [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}

[Biswas et al. 2012, Farina et al. 2012]



TOP-HIGGS INTERACTIONS

Effective lagrangian approach

$$\mathcal{L} = \mathcal{L}^{SM} + \sum \frac{c_i}{\Lambda^2}\mathcal{O}_i + O\left(\frac{1}{\Lambda^4}\right)$$

In general dimension 6 ops 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.

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$$\mathcal{O}_{hg} = \left(\bar{Q}_L H\right)\sigma^{\mu\nu}T^a t_R G^a_{\mu\nu},$$

$$\mathcal{O}_{Hy} = H^\dagger H \left(H\bar{Q}_L\right) t_R$$

$$\mathcal{O}_{Ht} = H^\dagger D_\mu H \bar{t}_R \gamma^\mu t_R\,,$$
$$\mathcal{O}_{HQ} = H^\dagger D_\mu H \bar{Q}_L \gamma^\mu Q_L$$
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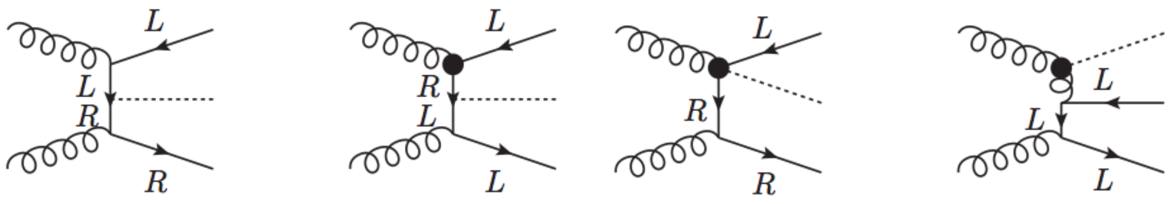

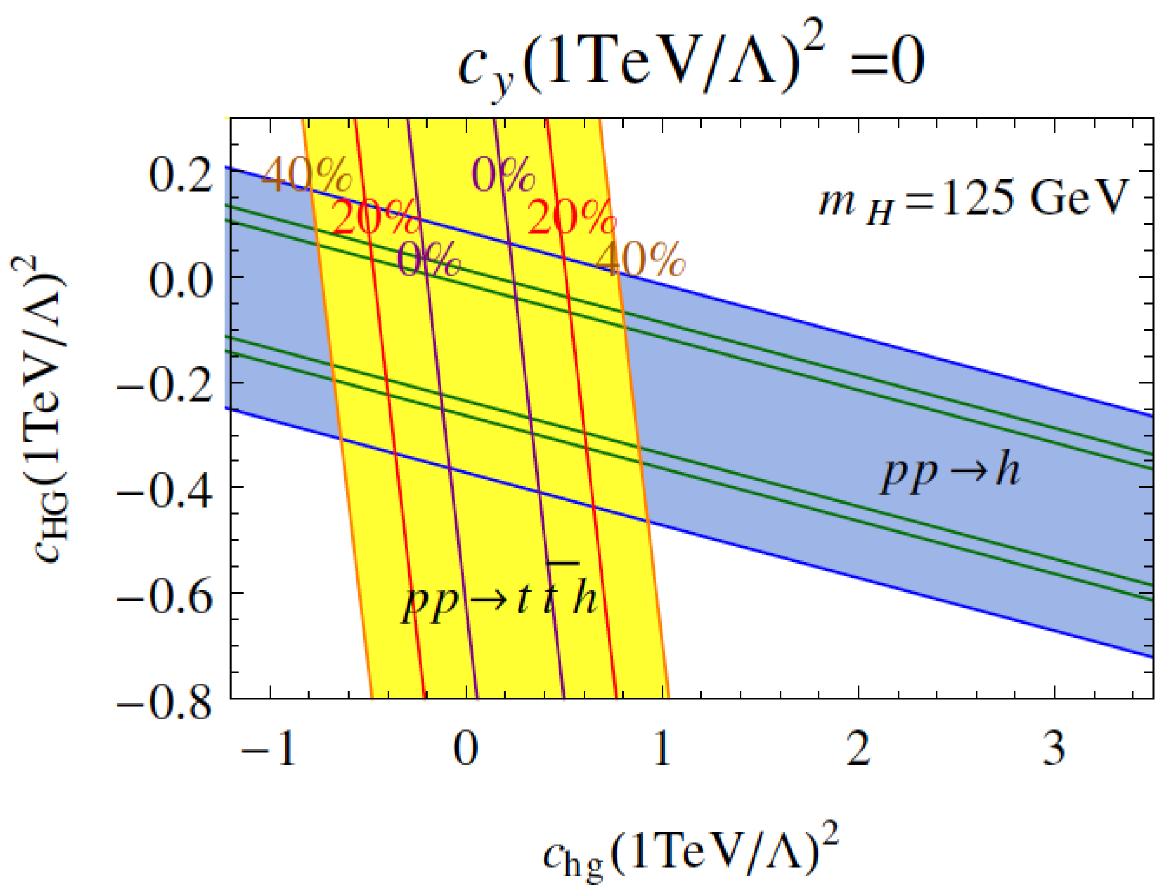

[Degrande et al. 2012]

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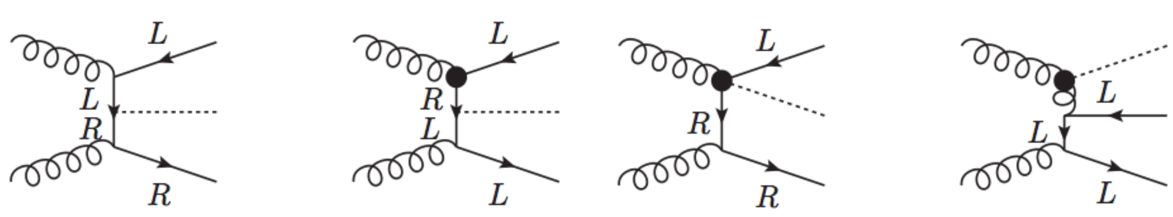

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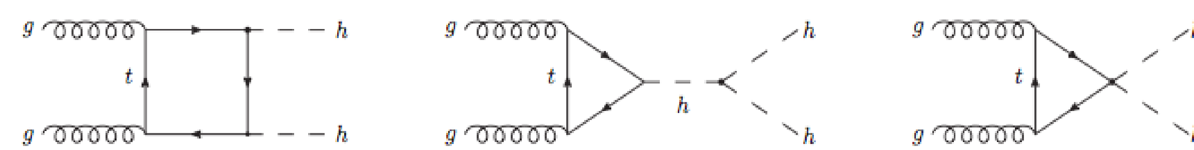

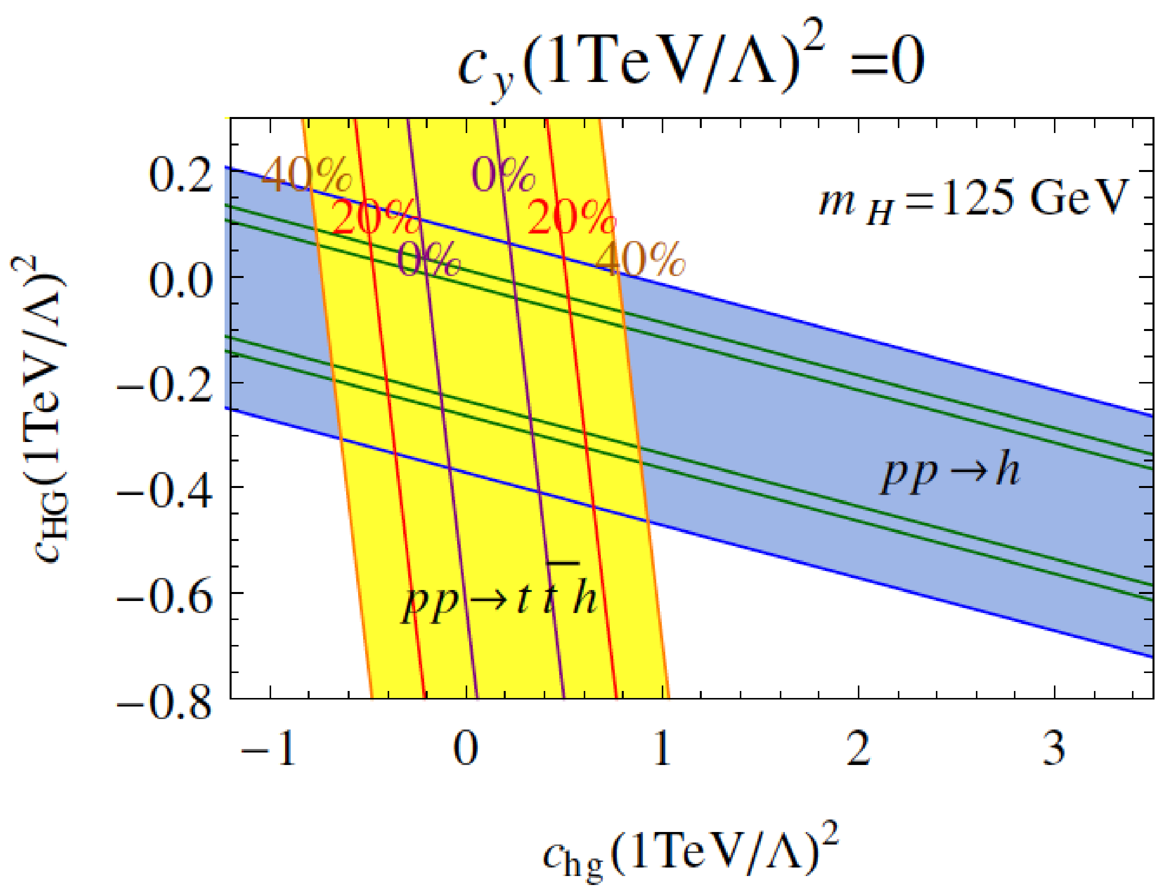

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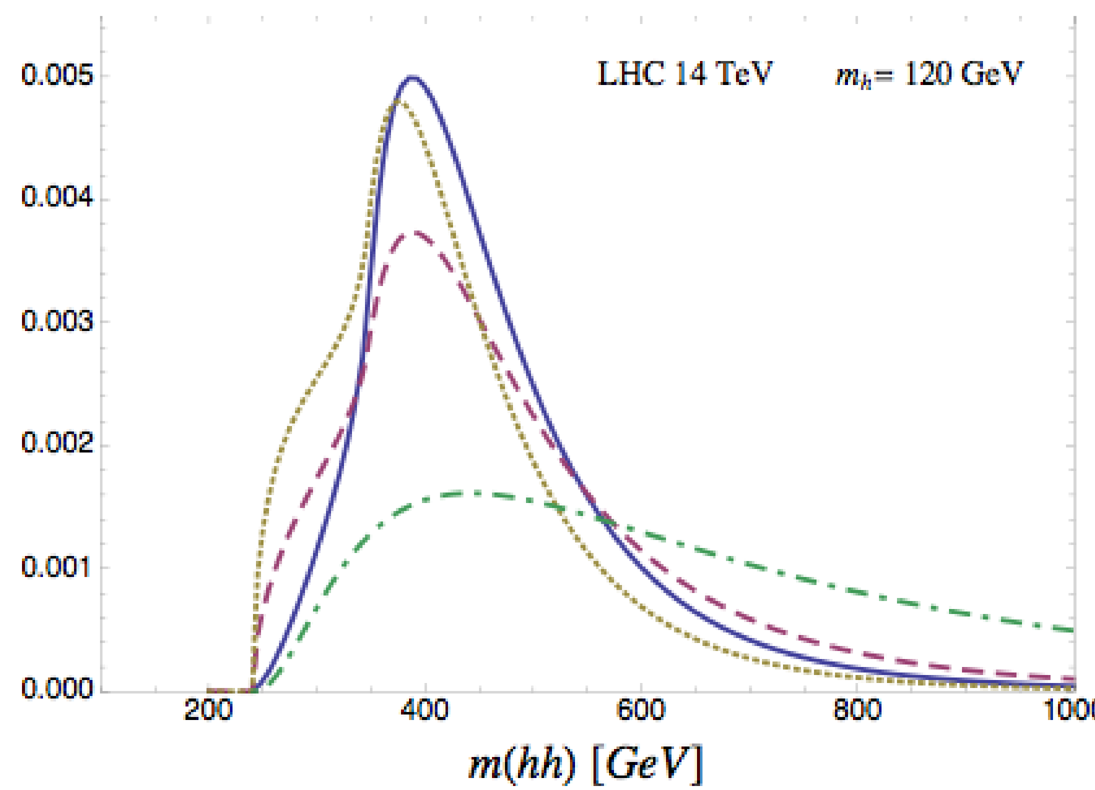

[Contino et al. 2012]

TOP IN THE HIGGS ERA

Is this good or bad news (for top physics) ?

- ☺ Renewed interest and strong motivation for **precision measurements** in top physics, first of all the top mass.
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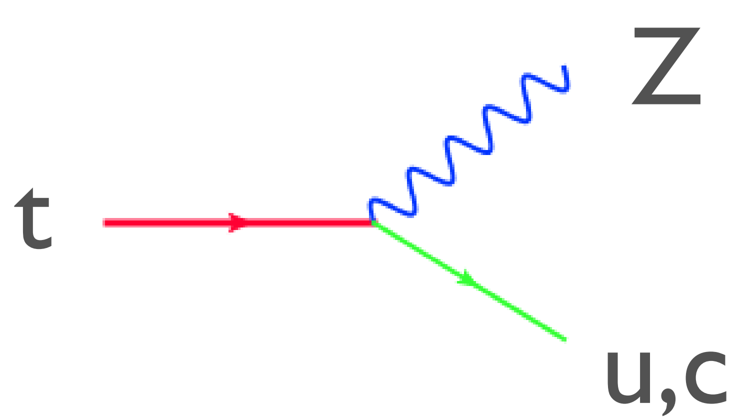
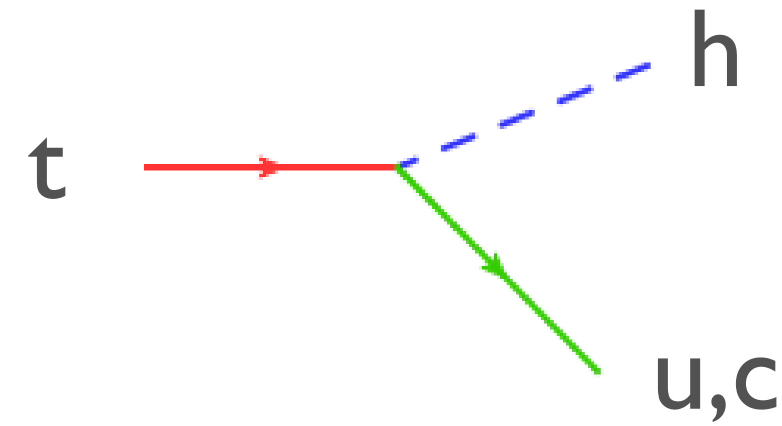
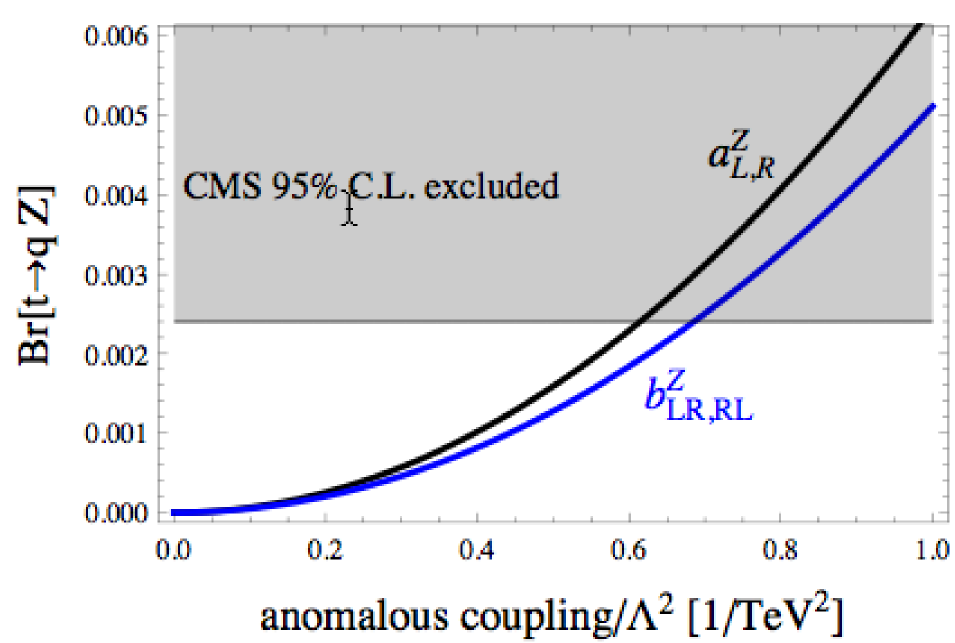
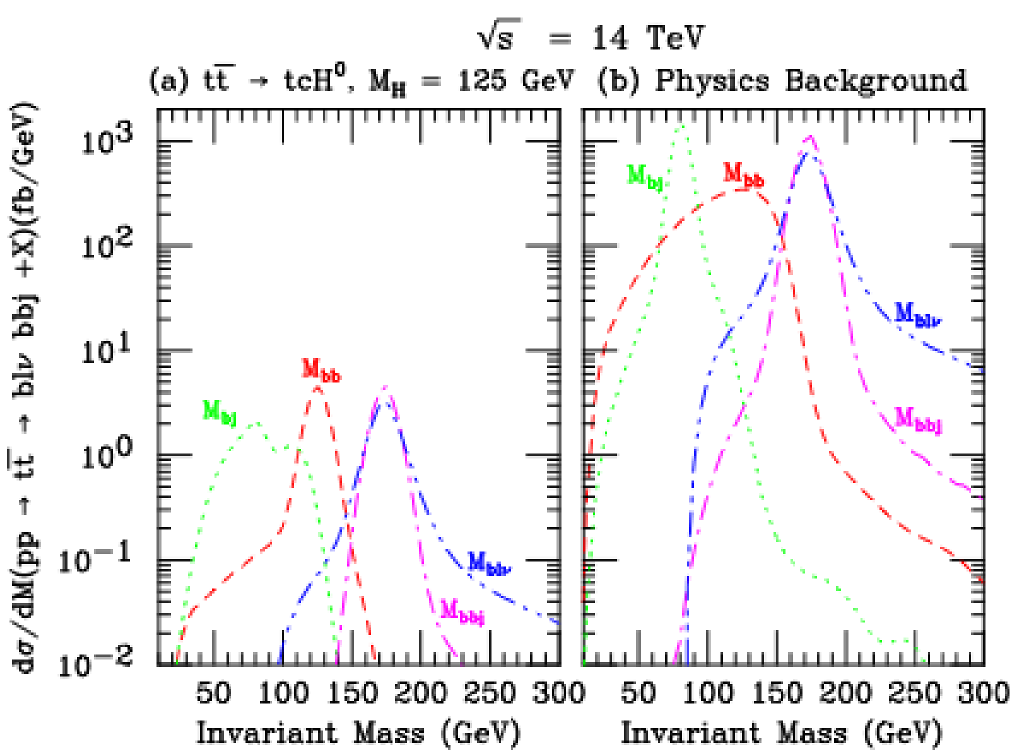
FLAVOR PHYSICS

The study of FCNC couplings can bring new information:









[Drobnak, 2012 based on CMS and ATLAS results]

[Kao et al. 2011 , Kai-Feng et al 2013]

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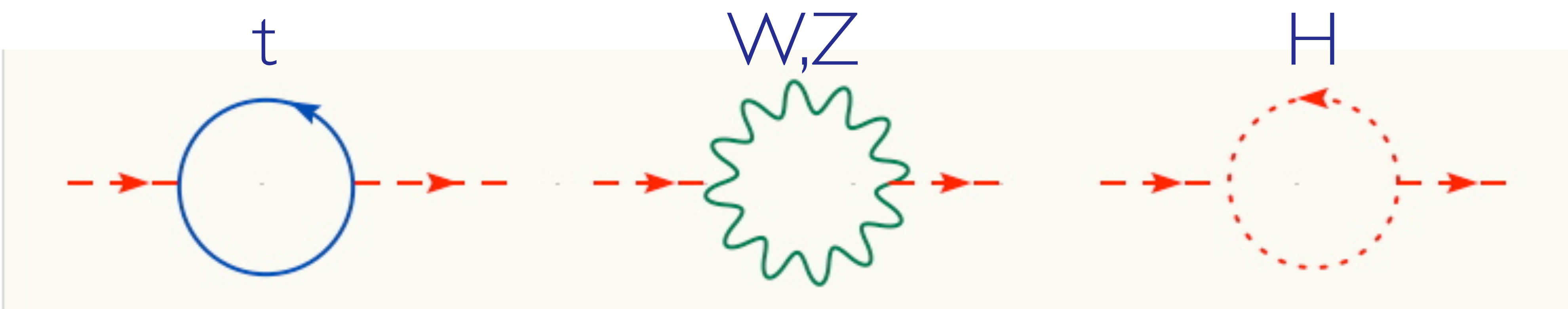
- ☺ A new handle on **flavor physics** in general.
- ☺ Still our best **gateway to BSM** physics at the weak scale....

GATEWAY TO NEW PHYSICS

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:

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

GATEWAY TO NEW PHYSICS

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

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

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.

GATEWAY TO NEW PHYSICS

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Many BSM models point to the top:

- SUSY → top ⇒ EWSB, light (natural) stops
- Little Higgs → vectorial top partners
- Strong Dynamics → ETC, colorons, ...4t interactions

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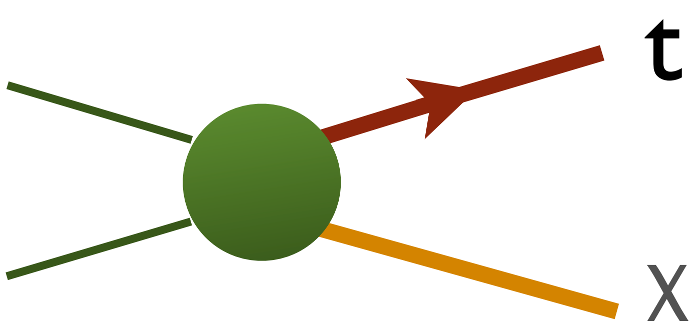
Strategies:

- Direct searches of top partners
- Searches for exotic top signatures
- Precision measurement in tt events

GATEWAY TO NEW PHYSICS

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



monotops

[Andrea et al. 2011]

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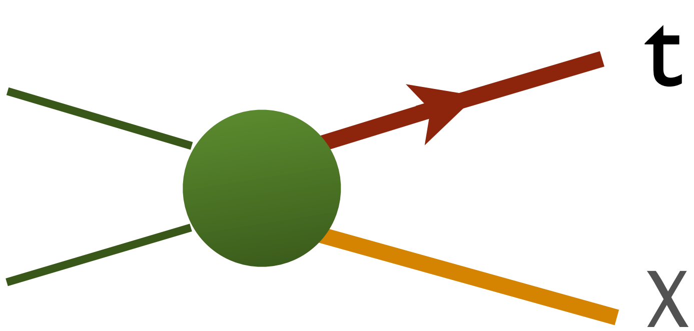

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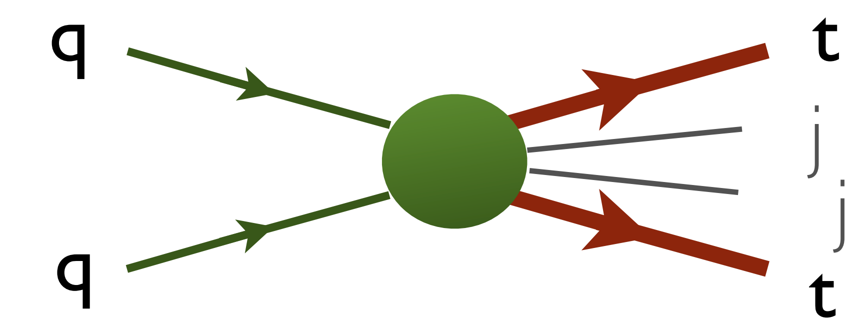

$t t$ ($\bar{t}\bar{t}$) (+ jets)

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

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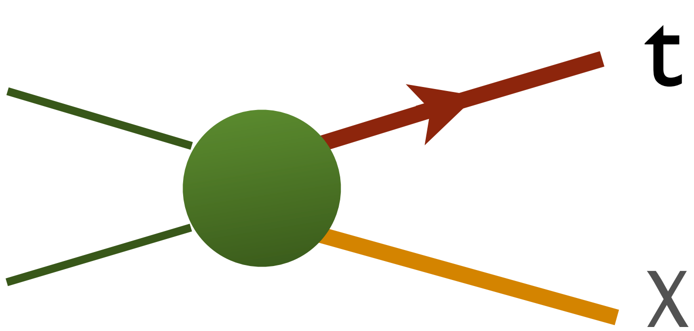

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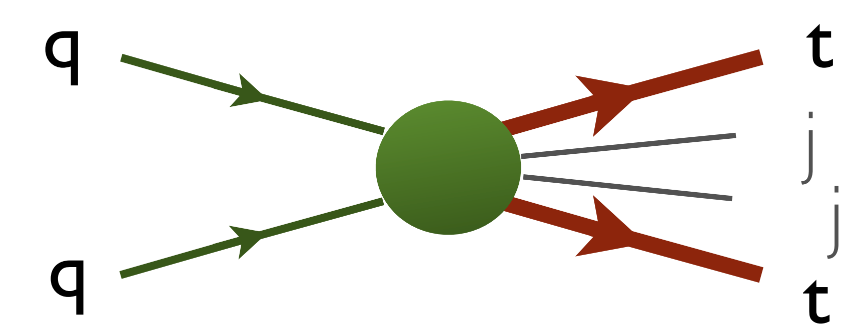

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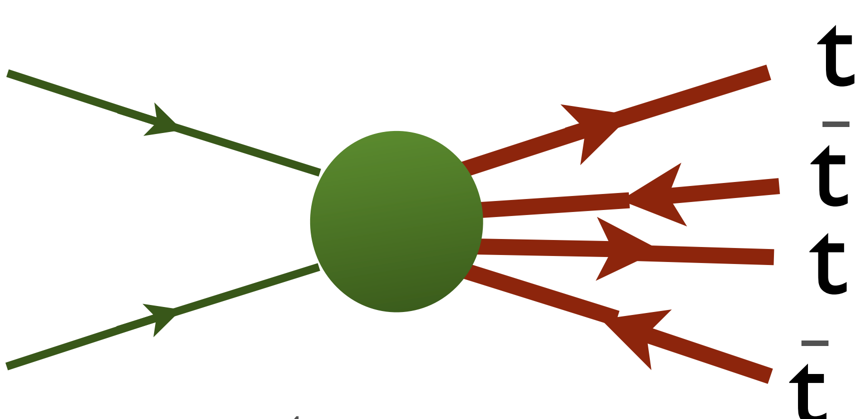

4 tops

[Tait et al, 2008, Gregoire et al,, 2011, Servant et al. , 2010, Cacciapaglio et al. 2011, Degrande 2010 , ...]

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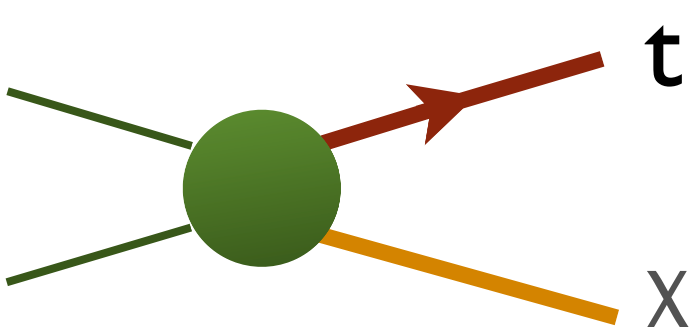

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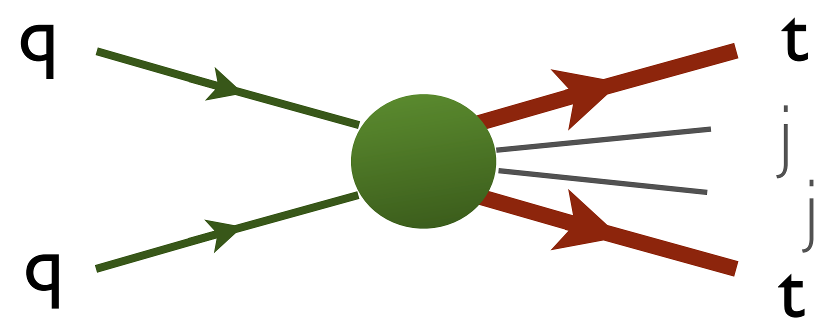
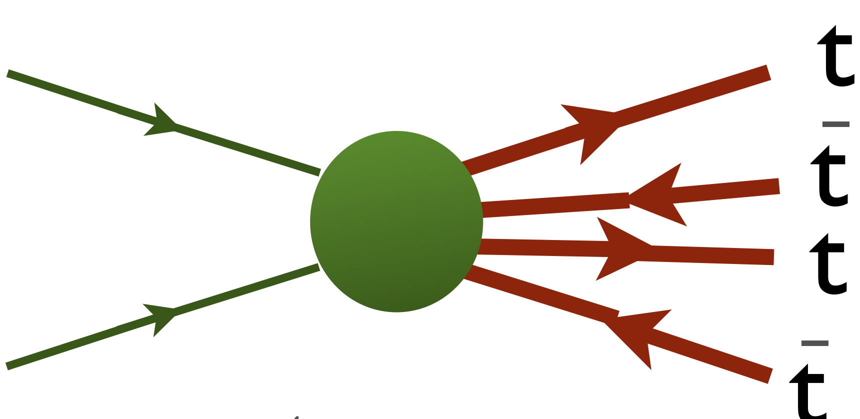


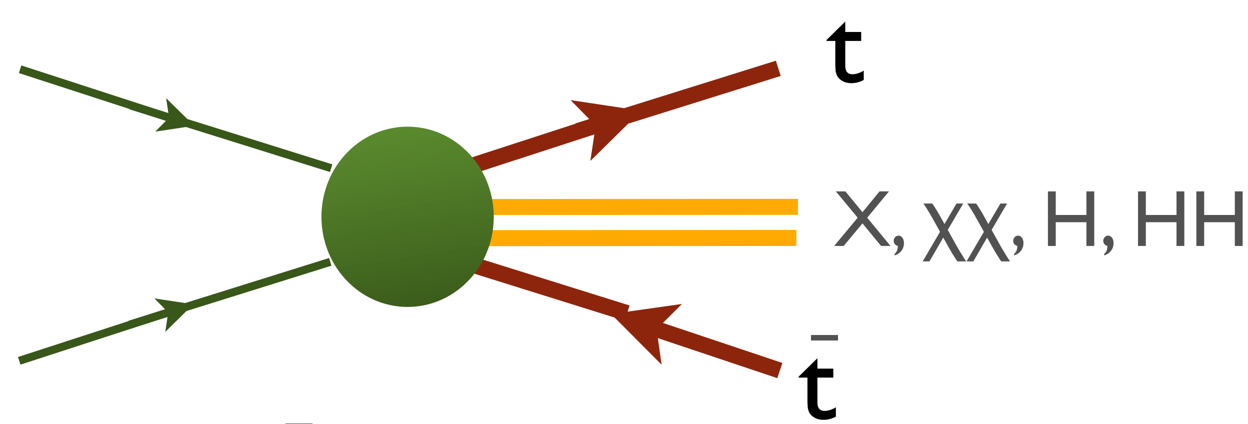
tt ($\bar{t}\bar{t}$) (+ jets)

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



4 tops

[Tait et al, 2008, Gregoire et al,, 2011, Servant et al. , 2010, Cacciapaglio et al. 2011, Degrande 2010 , ...]

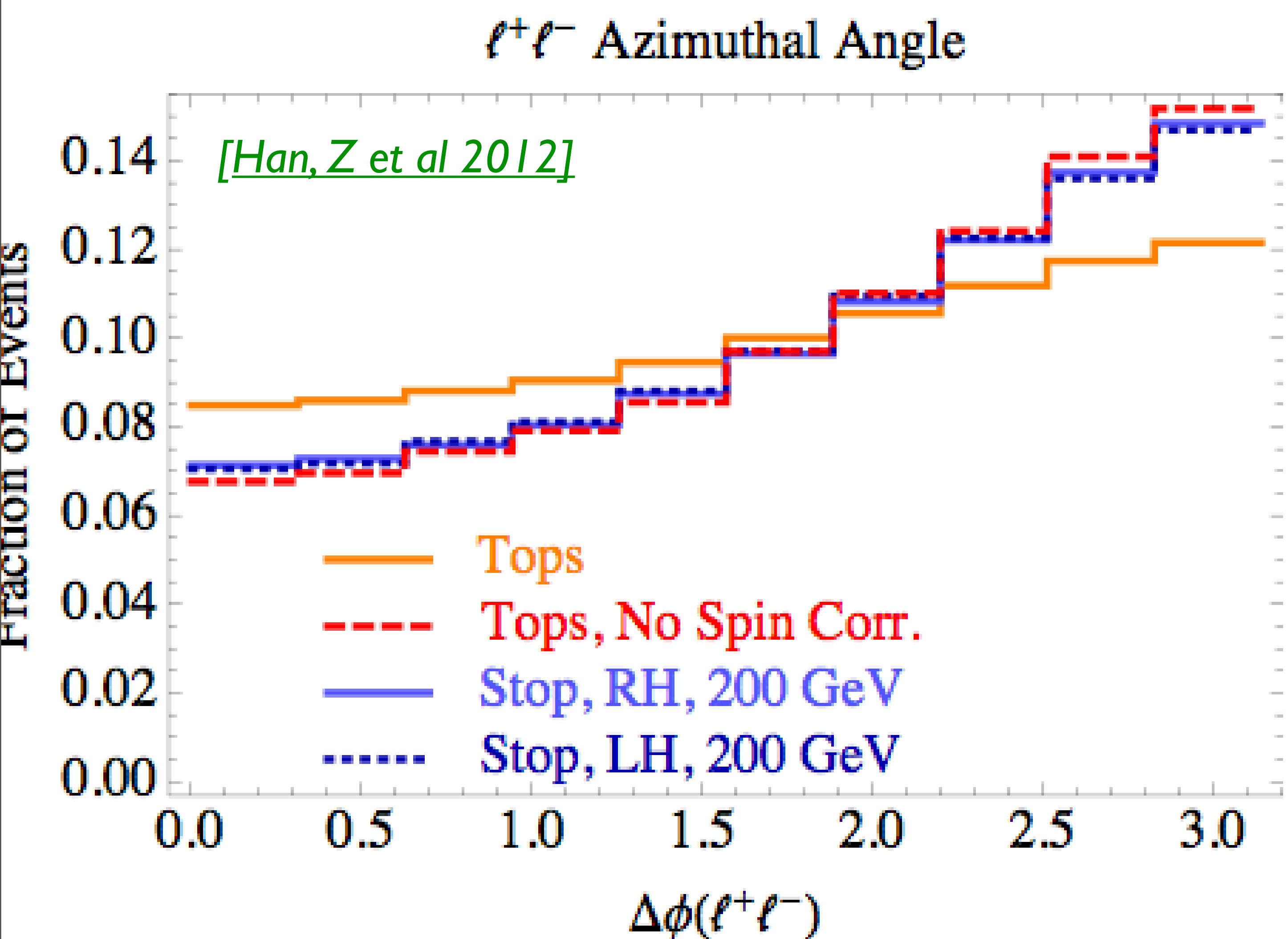


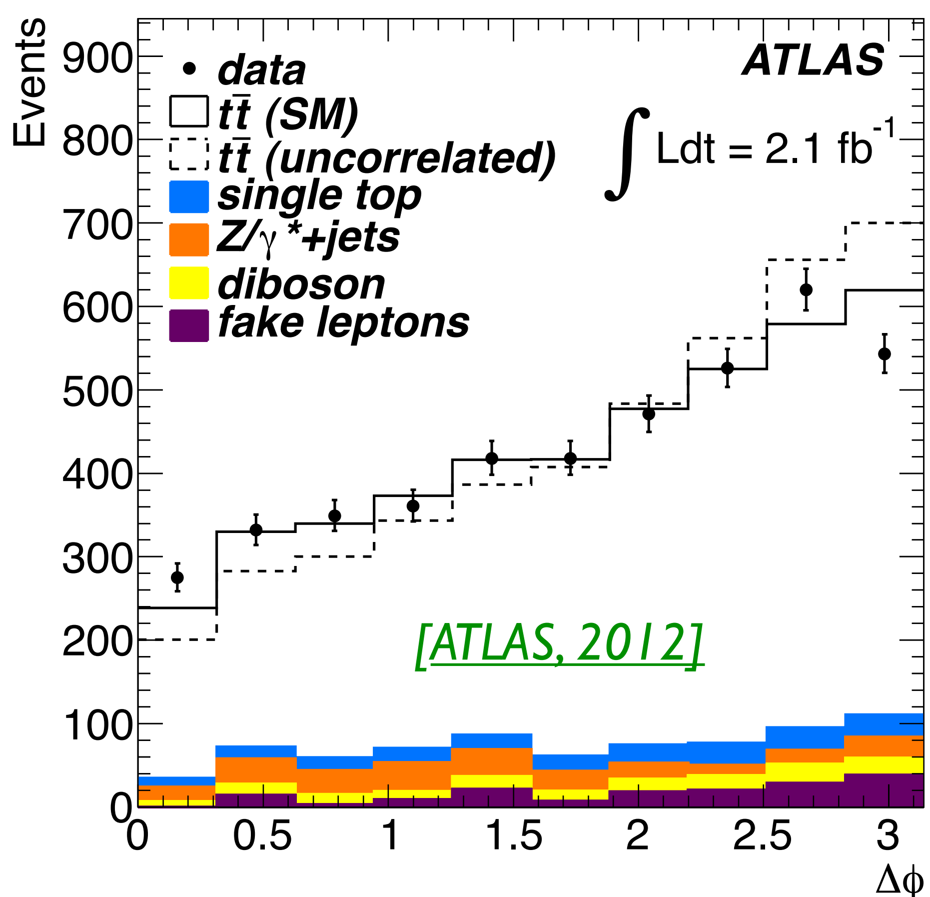
$t\bar{t}$ + $\not{E}_T$, H,...

[Too long list here]

GATEWAY TO NEW PHYSICS

Light stops are still viable. Spin correlation measurement could reveal their presence.





$$pp \to \tilde{t}\tilde{t}^* \to t\bar{t}\,\tilde{\chi}^0\tilde{\chi}^0$$

TOP IN THE HIGGS ERA

Is this good or bad news (for the top) ?

☺ Renewed interest and strong motivation for **precision measurements** in top physics, first of all the top mass.

☺ A new realm of possibilities for studying **top-Higgs interactions** has opened up.

☺ A new handle on **flavor physics** in general.

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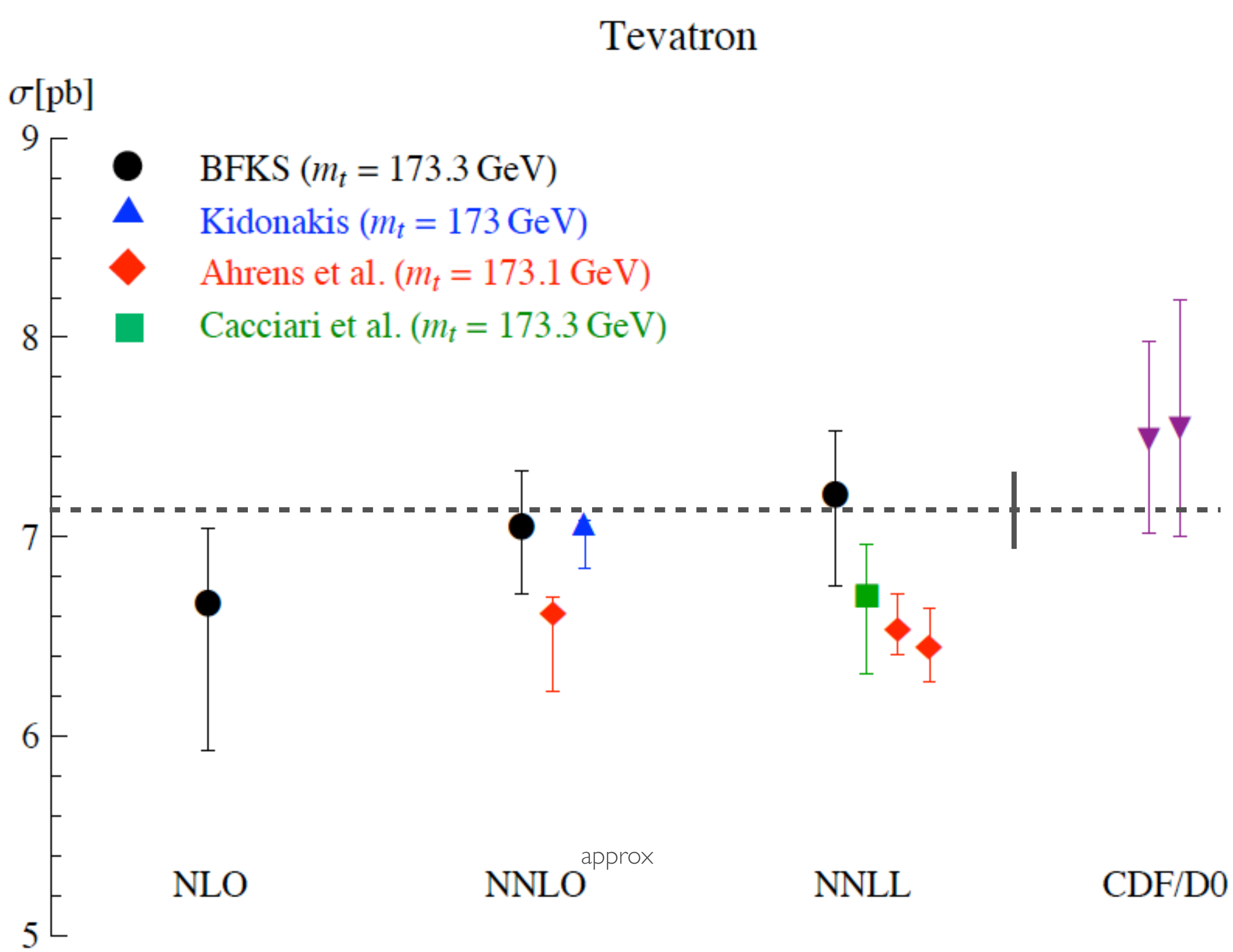
SIGMA(T TBAR) AT NNLO

- A long history of theoretical achievements.
- Until two months ago σ(t tbar) analyzed exclusively in approximate NNLO QCD



[Beneke, Falgari, Klein, Schwinn 2011]

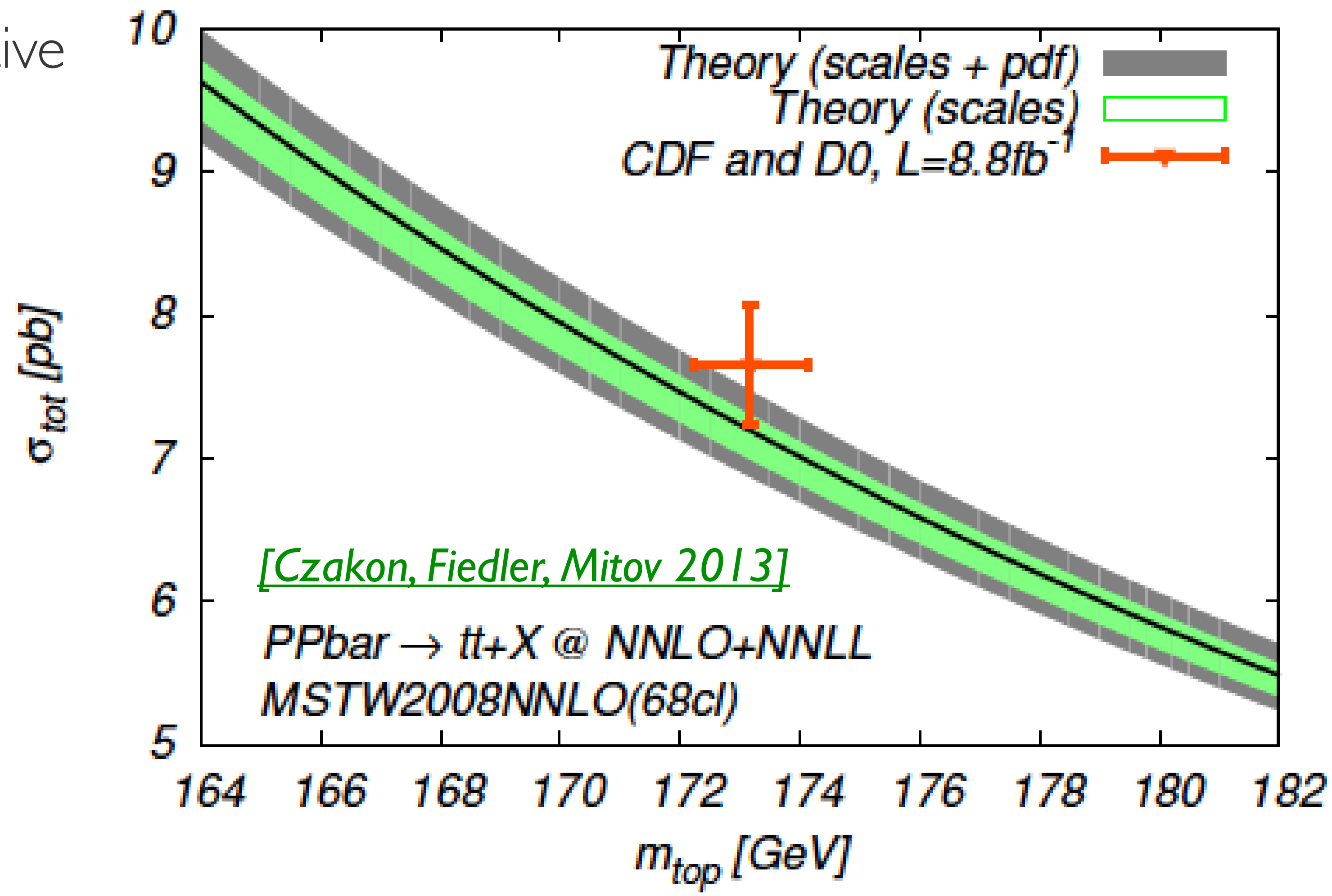
[Beneke, Falgari, Klein,Schwinn 2009-2011]
[Ahrens, Ferroglia, Neubert, Pecjak,Yang 2010-2011]
[Kidonakis 2003-2011]
[Aliev, Lacker, Langenfeld, Moch, Uwer,Wiedermann 2010]
[Cacciari, Czakon, Mangano, Mitov, Nason 2011]

SIGMA(T TBAR) AT NNLO+NNLL

Monumental MILESTONE in perturbative QCD:

[Bärnreuther, Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Mitov 2012]
[Czakon, Fiedler, Mitov 2013]

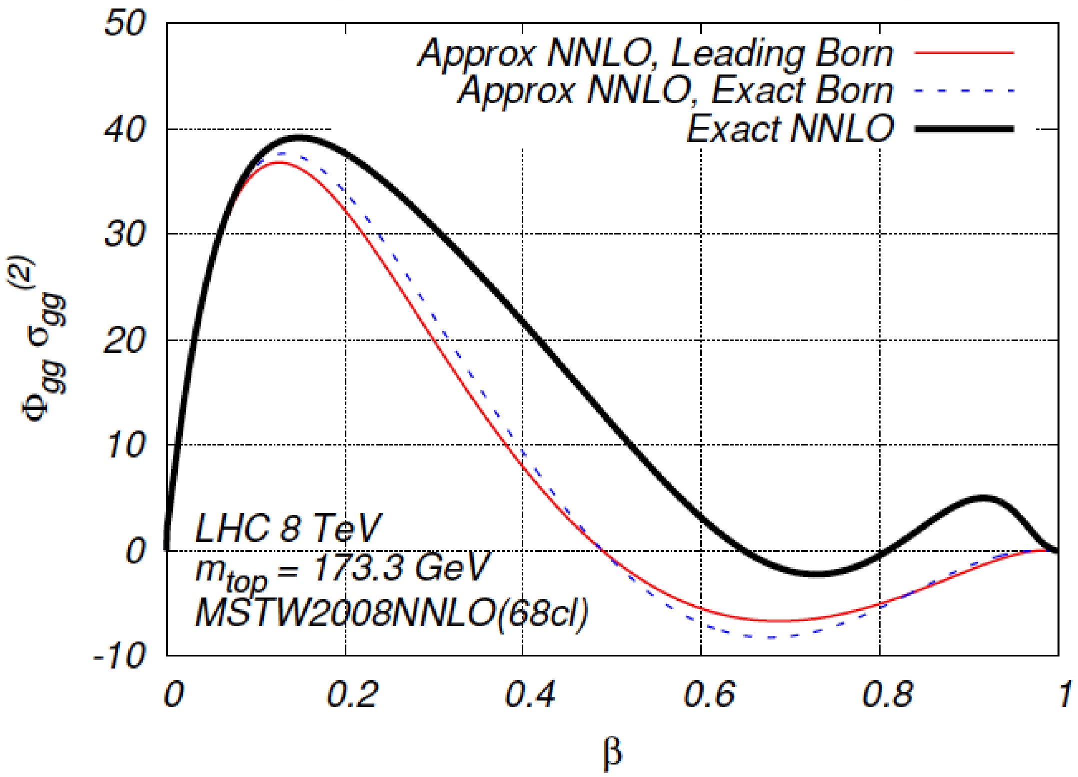
- First ever hadron collider calculation at NNLO with more than 2 colored partons.
- First ever NNLO hadron collider calculation with massive fermions.



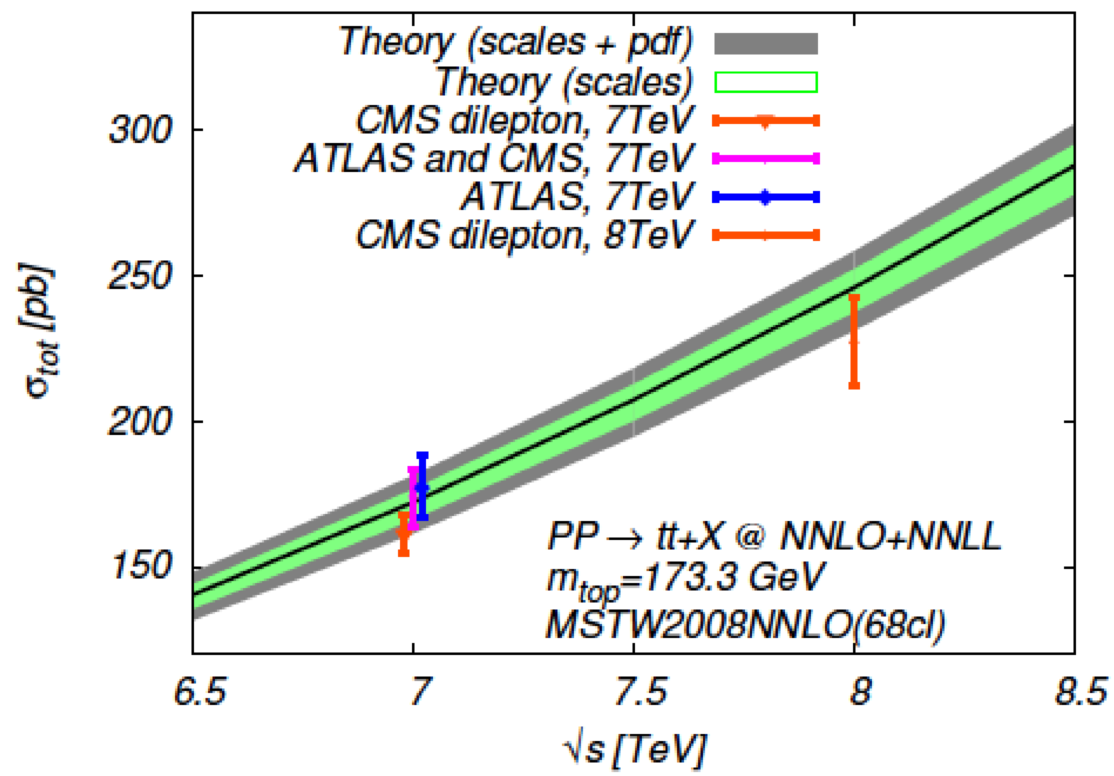
- Two loop hard matching coefficient extracted and included
- Very weak dependence on unknown parameters (sub 1%): gg NNLO, A, etc.
- ~ 50% scales reduction compared to the NLO +NNLL analysis of

SIGMA(T TBAR) AT NNLO+NNLL

[Czakon, Fiedler, Mitov 2013]



[Czakon, Fiedler, Mitov 2013]

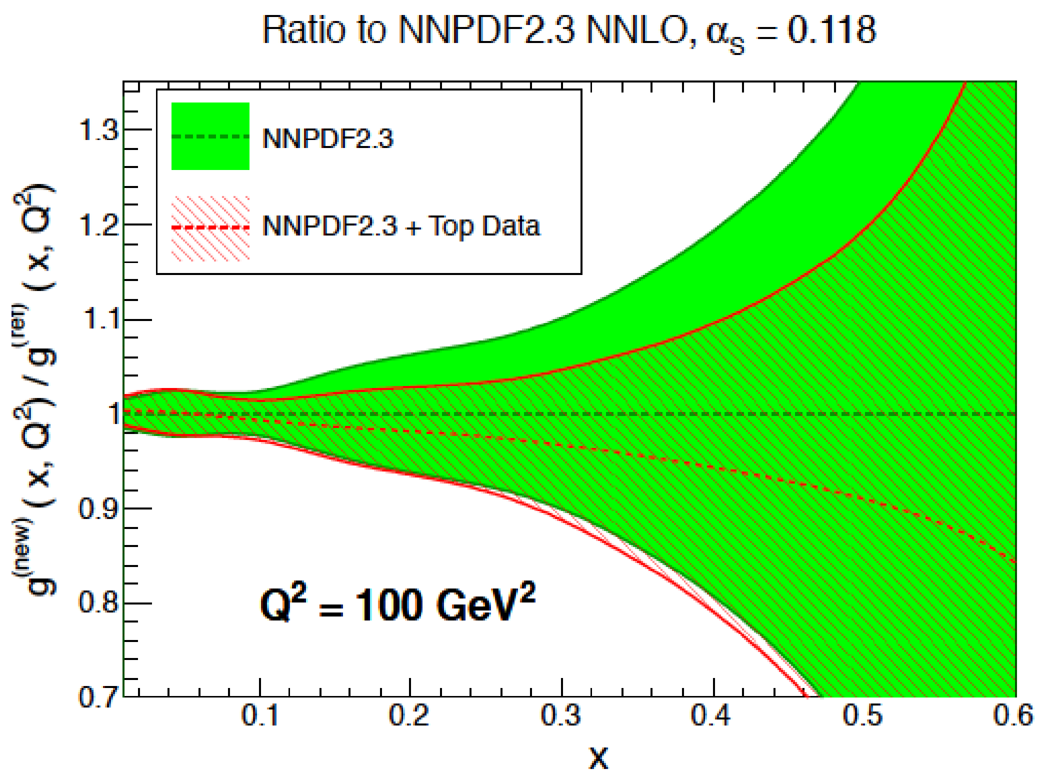


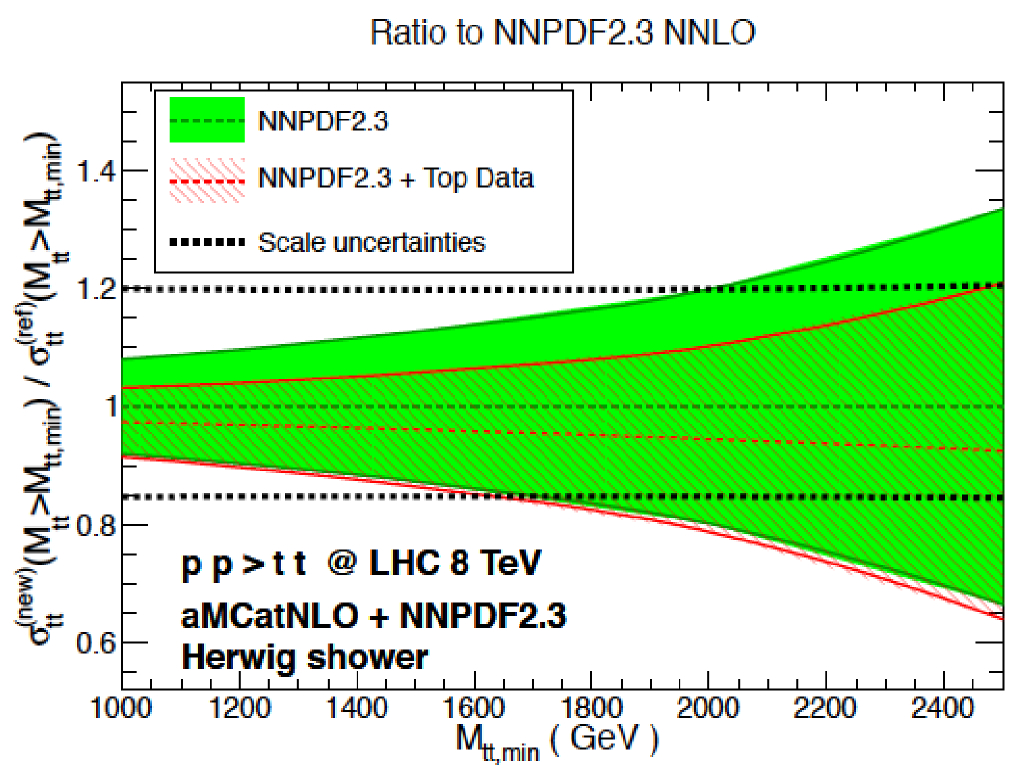
Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.164	$+0.110(1.5\%)$ $-0.200(2.8\%)$	$+0.169(2.4\%)$ $-0.122(1.7\%)$
LHC 7 TeV	172.0	$+4.4(2.6\%)$ $-5.8(3.4\%)$	$+4.7(2.7\%)$ $-4.8(2.8\%)$
LHC 8 TeV	245.8	$+6.2(2.5\%)$ $-8.4(3.4\%)$	$+6.2(2.5\%)$ $-6.4(2.6\%)$
LHC 14 TeV	953.6	$+22.7(2.4\%)$ $-33.9(3.6\%)$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

- 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.



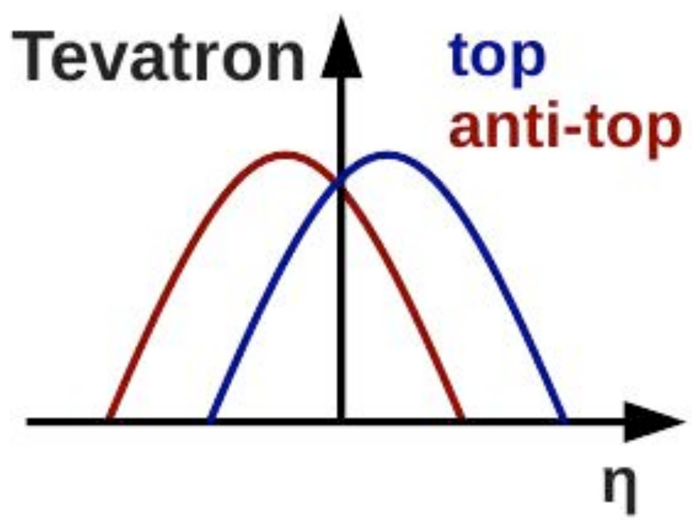


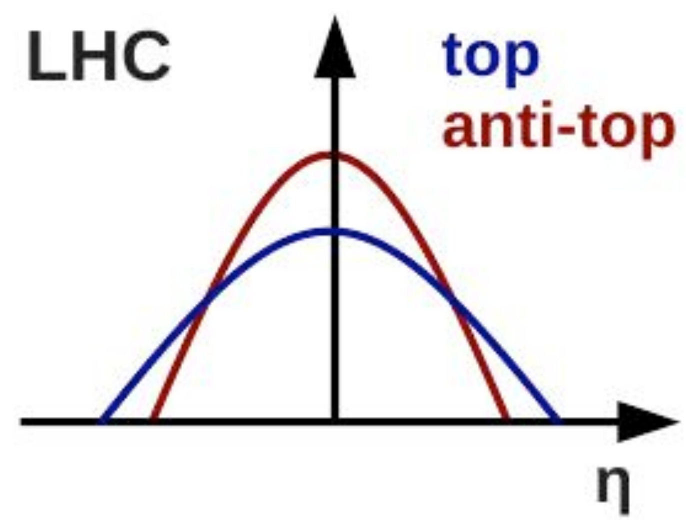
[Czakon, Mangano, Mitov, Rojo 2013]

skip next slide

TTBAR ASYMMETRY

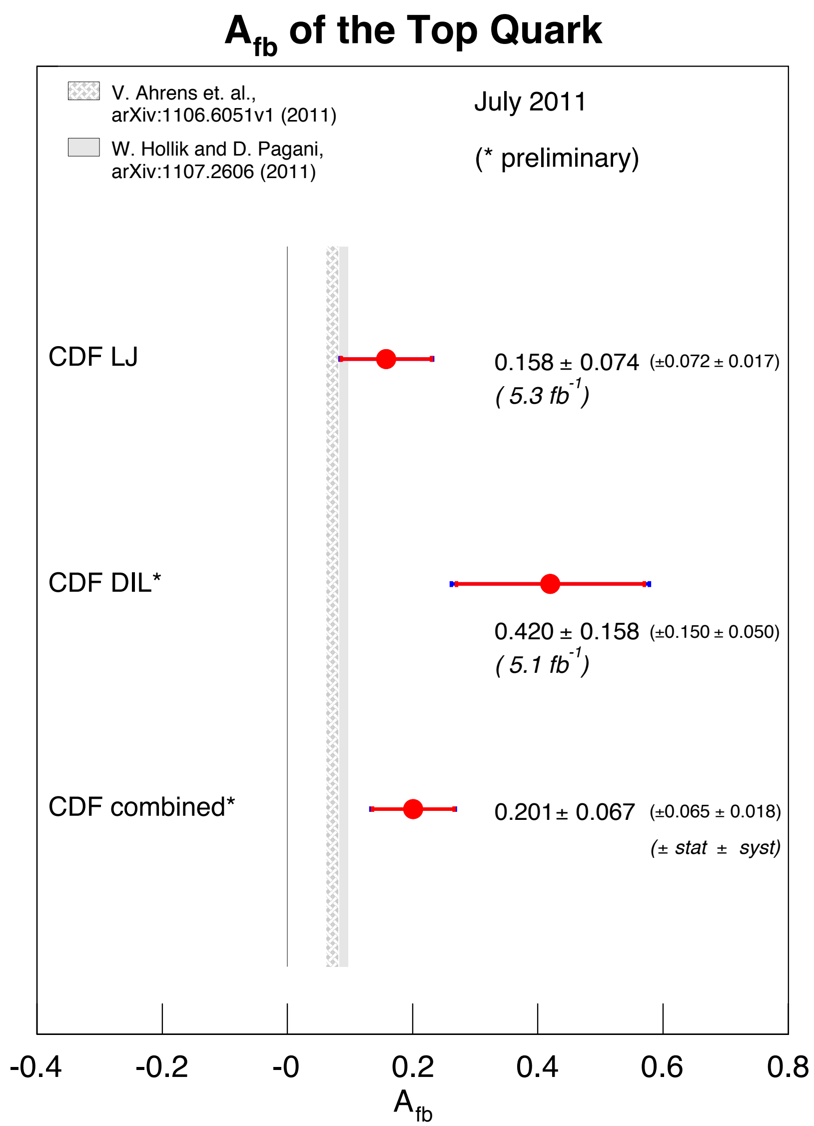
$$A_{CC}^{t\bar{t}} = \frac{\sigma(\Delta y > 0) - \sigma(\Delta y < 0)}{\sigma(\Delta y > 0) + \sigma(\Delta y < 0)}$$

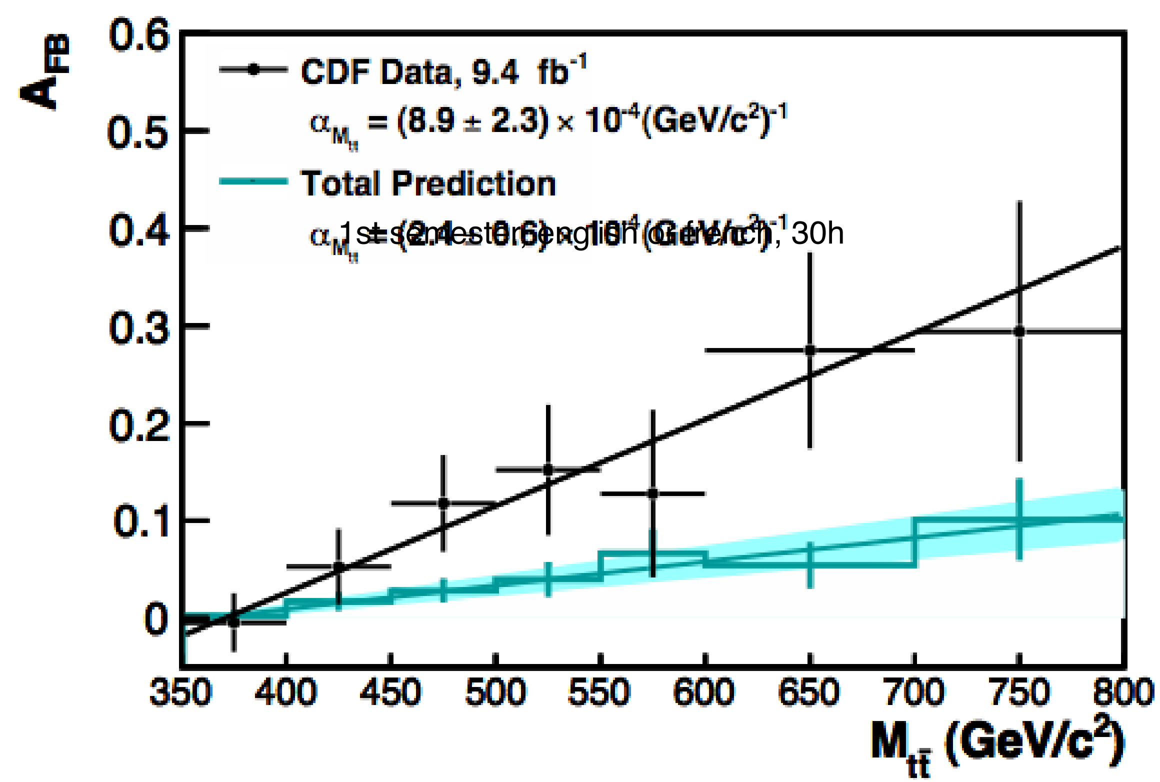




$$\Delta y^{\mathrm{TEV}} = y_t - y_{\bar{t}} \qquad \Delta y^{\mathrm{LHC}} = |y_t| - |y_{\bar{t}}|$$

TTBAR ASYMMETRY





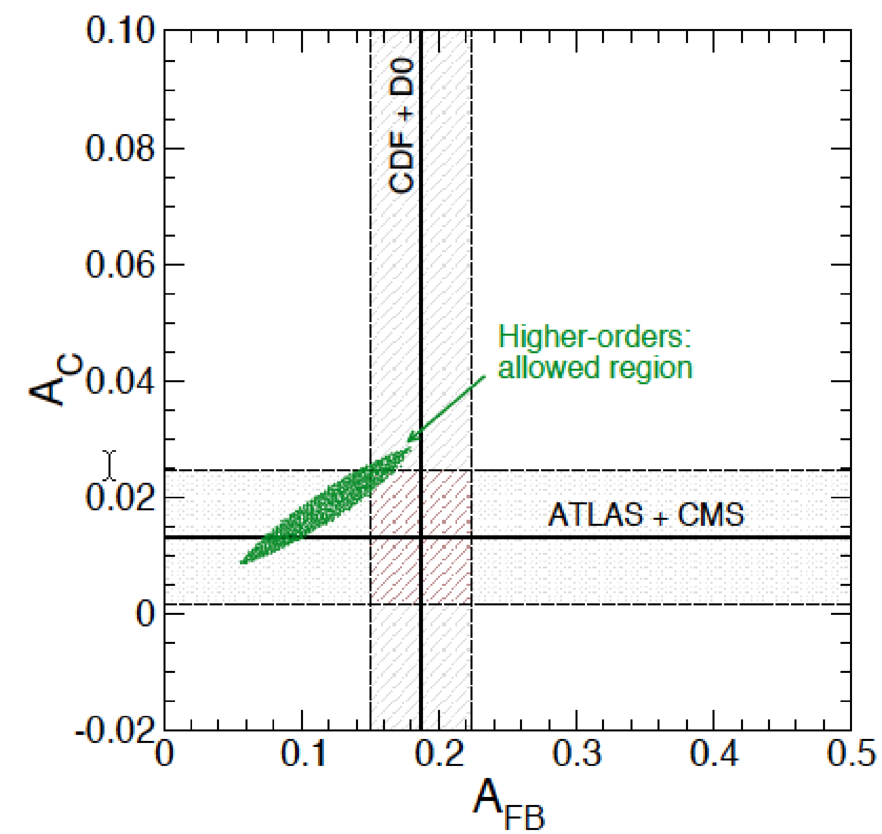
Similar asymmetry seen in D0 but no pattern in m_{tt} .

TTBAR ASYMMETRY

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

1. Approx NNLO results indicate no major changes [Almeida et al 2010, Ahrens 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 [Hollik & Pagani 2011]

[Aguilar-Saavedra Perez-Victoria, 2013]



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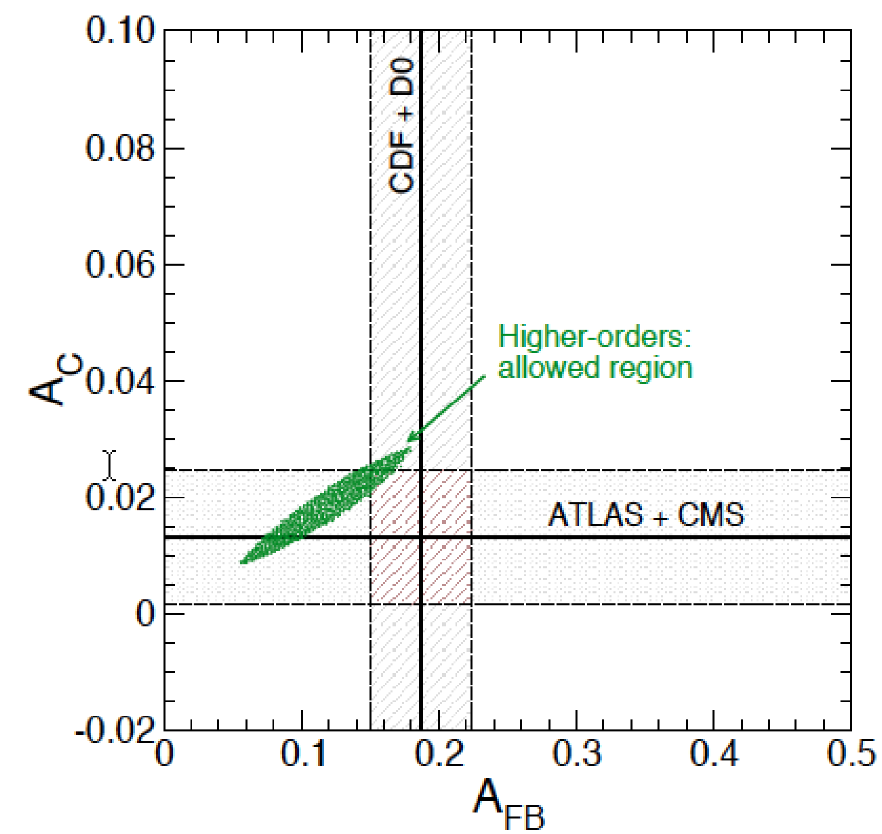

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Note, however, the interesting pattern:

t tbar : LO=0 + Virtual>0 (large) + Real<0 (small) = 0.05

t tbar j : LO<0 (-0.08) + Virtual>0 (large) + Real<0 (small) = -0.02

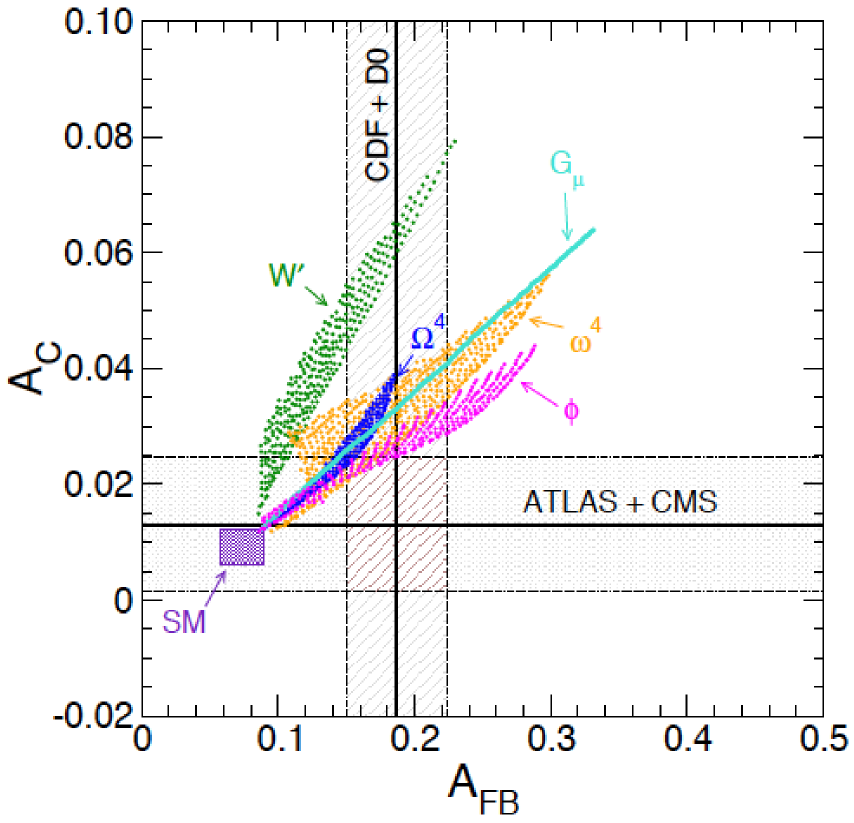
t tbar jj : LO <0

Virtuals always dominate : what about the two-loop contributions? to be seen...

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

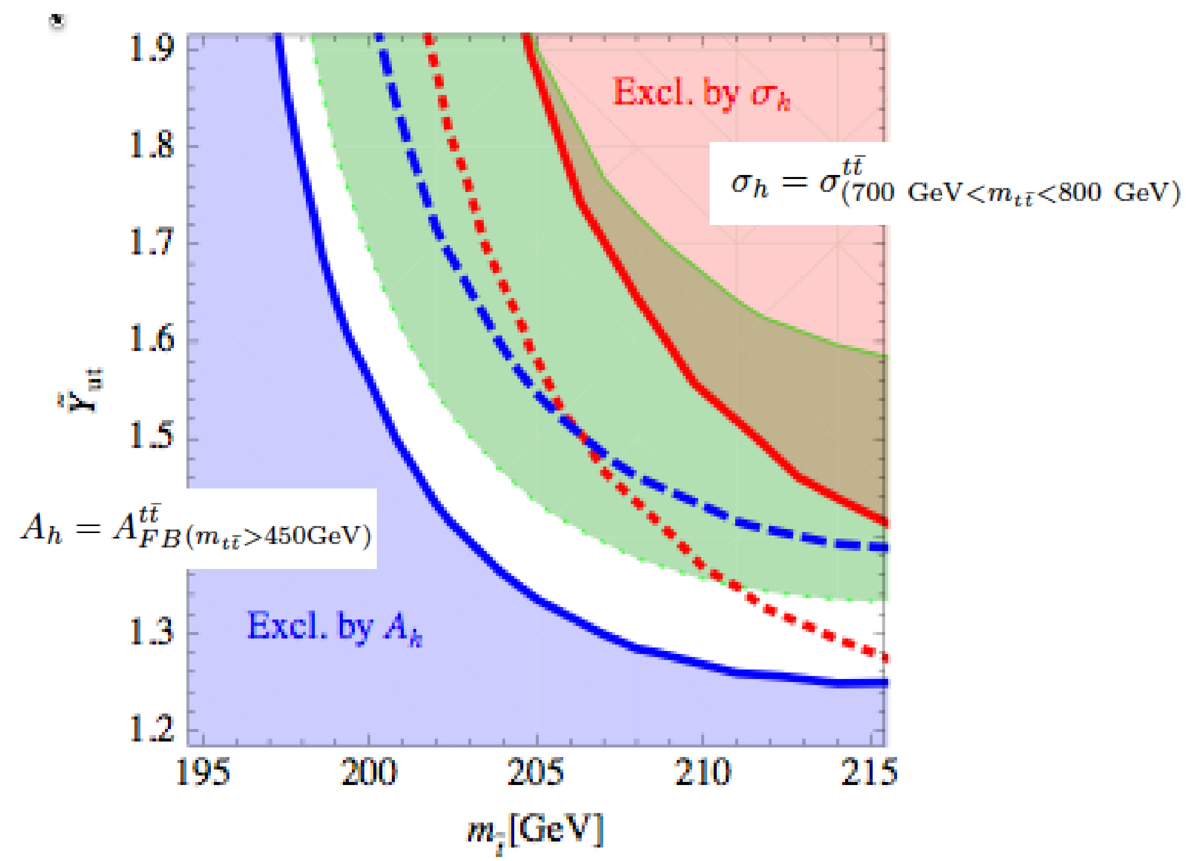
BSM INTERPRETATIONS

[Aguilar-Saavedra Perez-Victoria, 2013]



$$pp \to X(s\,\mathrm{or}\,t) \to t\bar{t}$$

[Isidori and Kamenik, 2011]



$$pp \to \tilde{t}\tilde{t}^* \to t\bar{t}\,\tilde{\chi}^0\tilde{\chi}^0$$

Note that the NP ranges are similar to the QCD HO ones. None of these models is motivated by other measurements

Interference with t-channel neutralino exchange. Light stop scenario. Not exclude by direct ATLAS and CMS searches.

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(SEMI) AUTOMATIC MC'S AT NLO

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

- POWHEG-Box library : tt, single top channels
- POWHEL : ttj, ttbb, ttW, ttZ, ttH
- Sherpa + external loop codes : tt,...
- **aMC@NLO** : process directly generated by the user.

AUTOMATIC TOP PHYSICS AT NLO

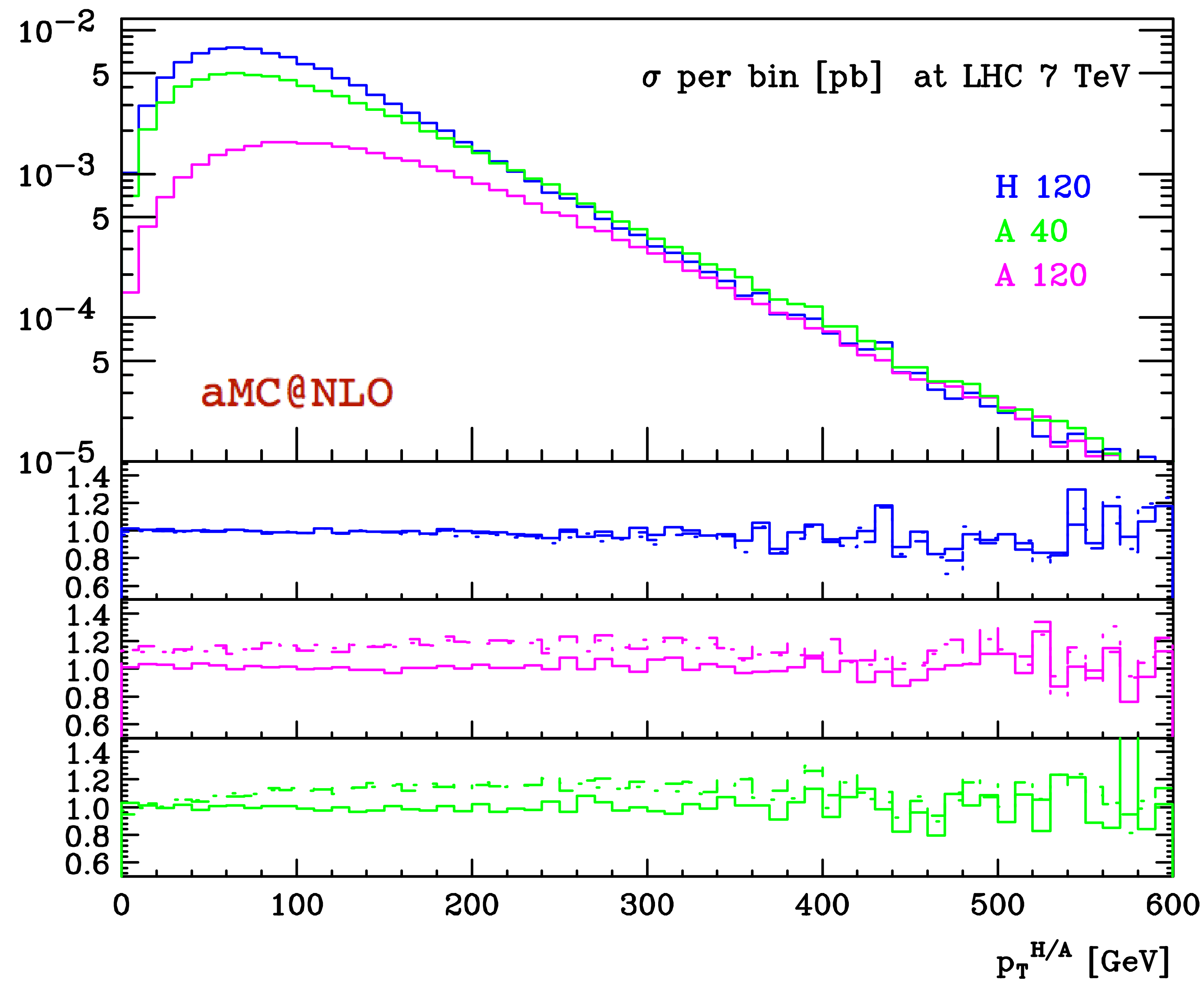
$$pp \to t\bar{t}\, H$$

NLO results were 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.

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.

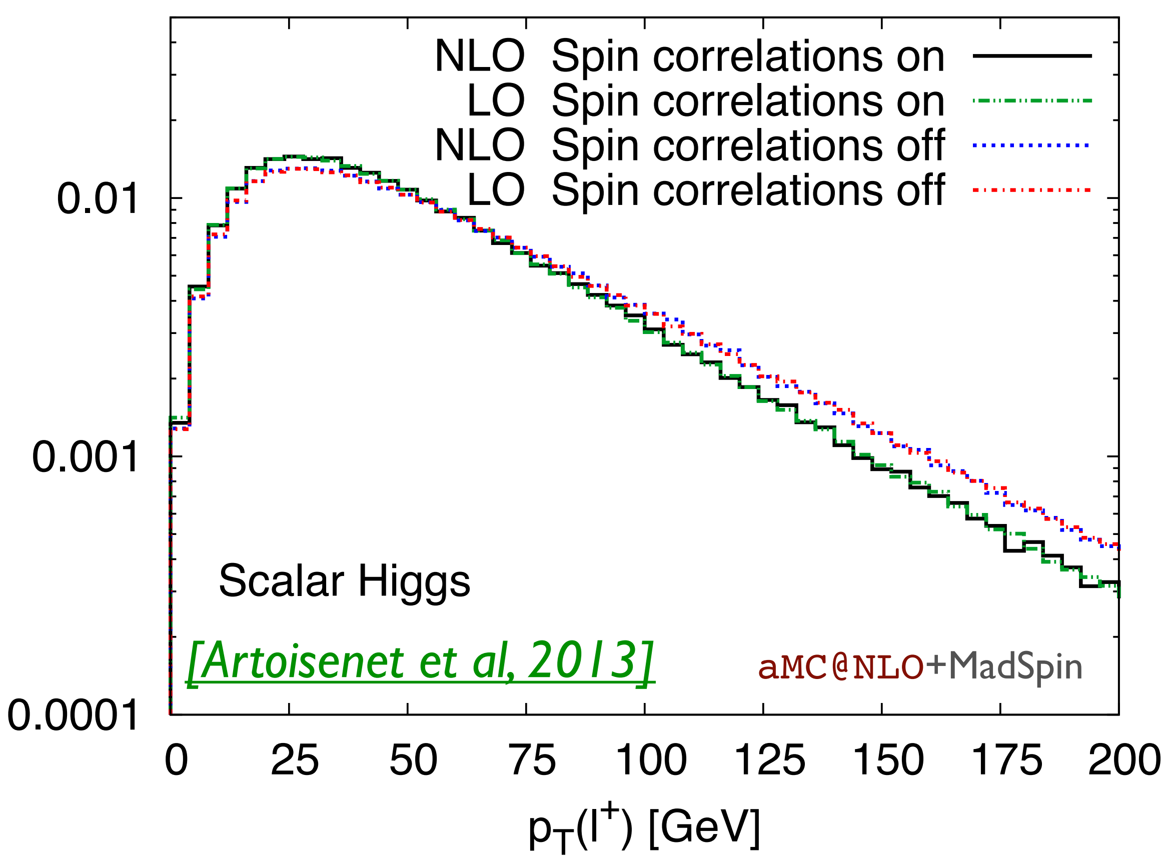
[Frederix et al, 2011]



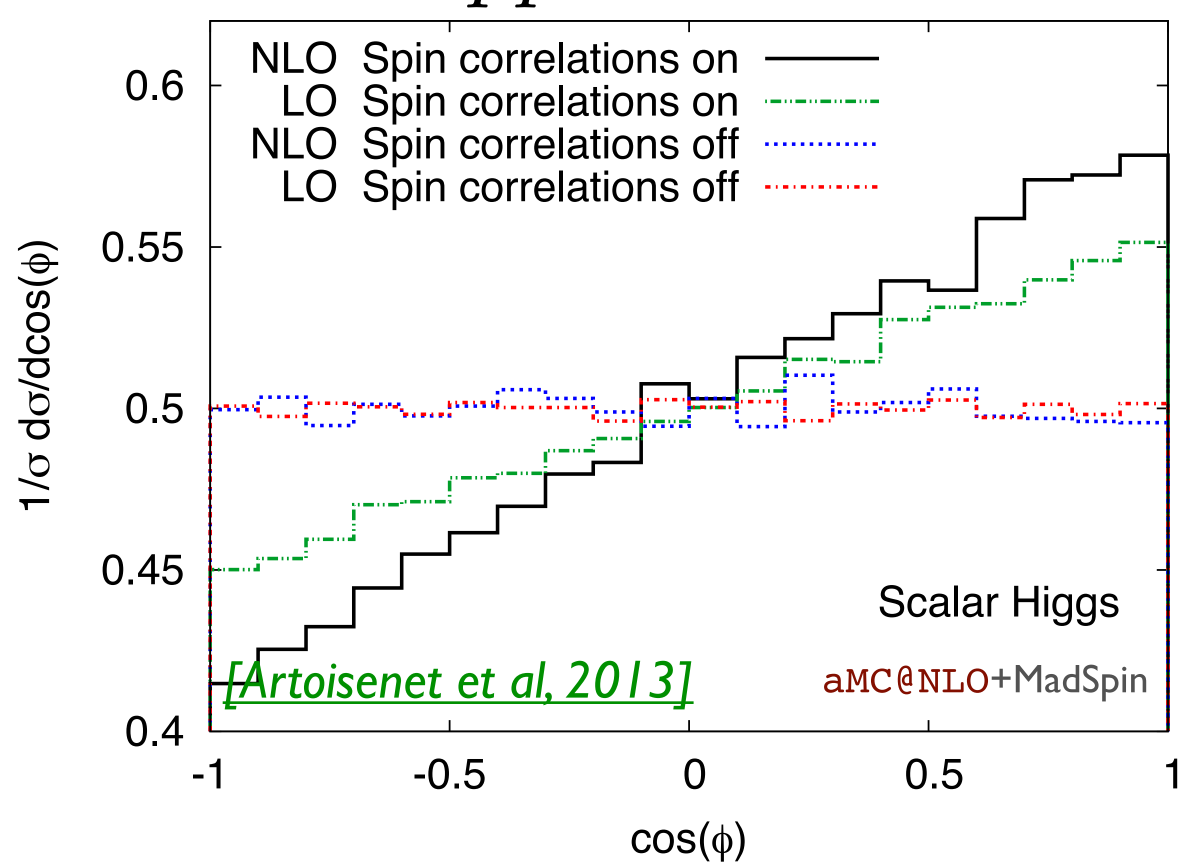
AUTOMATIC TOP PHYSICS AT NLO

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.

$$pp \to t\bar{t}H$$



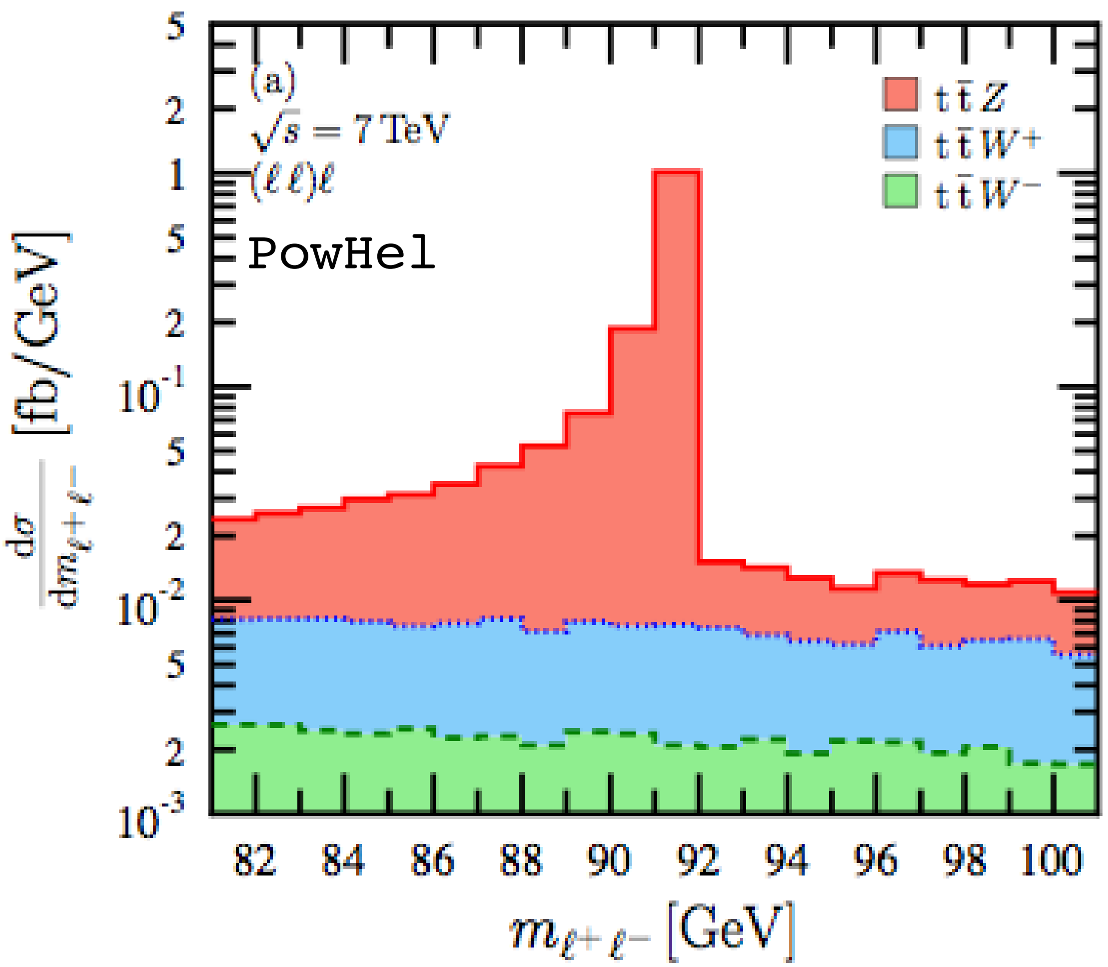
$$pp \to t\bar{t}H$$



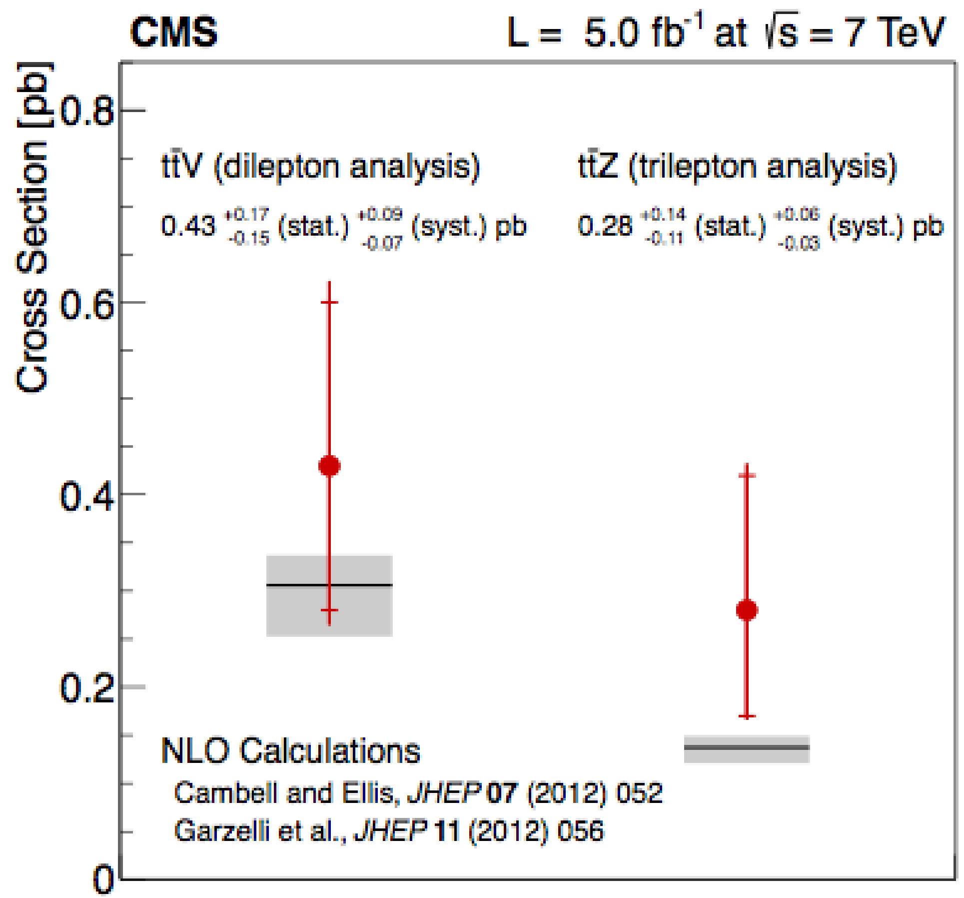
The effects of the spin correlations on the pt shape of the charged lepton is more important than that of NLO QCD corrections!

AUTOMATIC TOP PHYSICS AT NLO

$$pp \to t\bar{t}Z \;\&\; pp \to t\bar{t}W$$



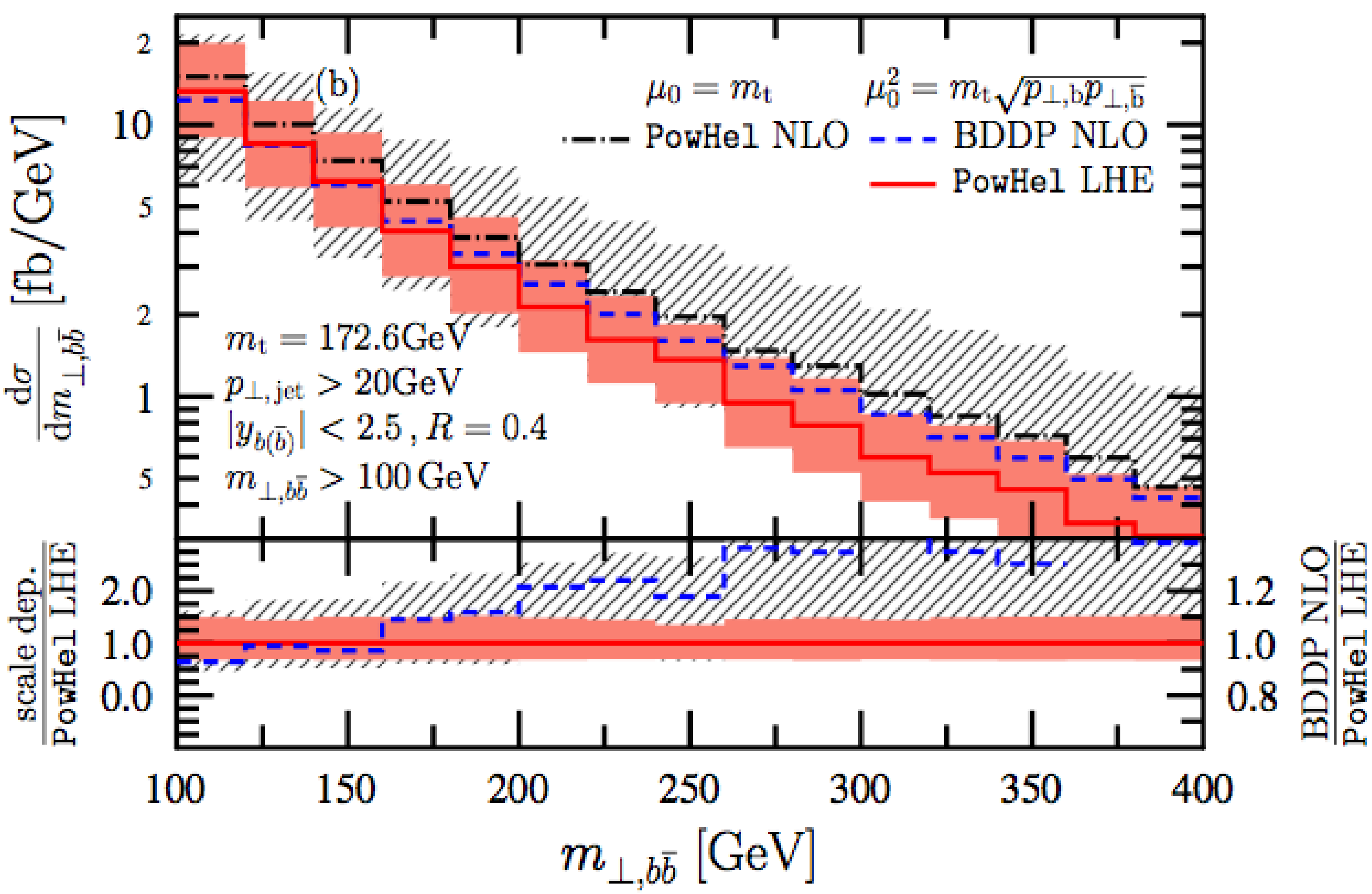
[Garzelli et al. 2012]



[CMS collaboration 2013]

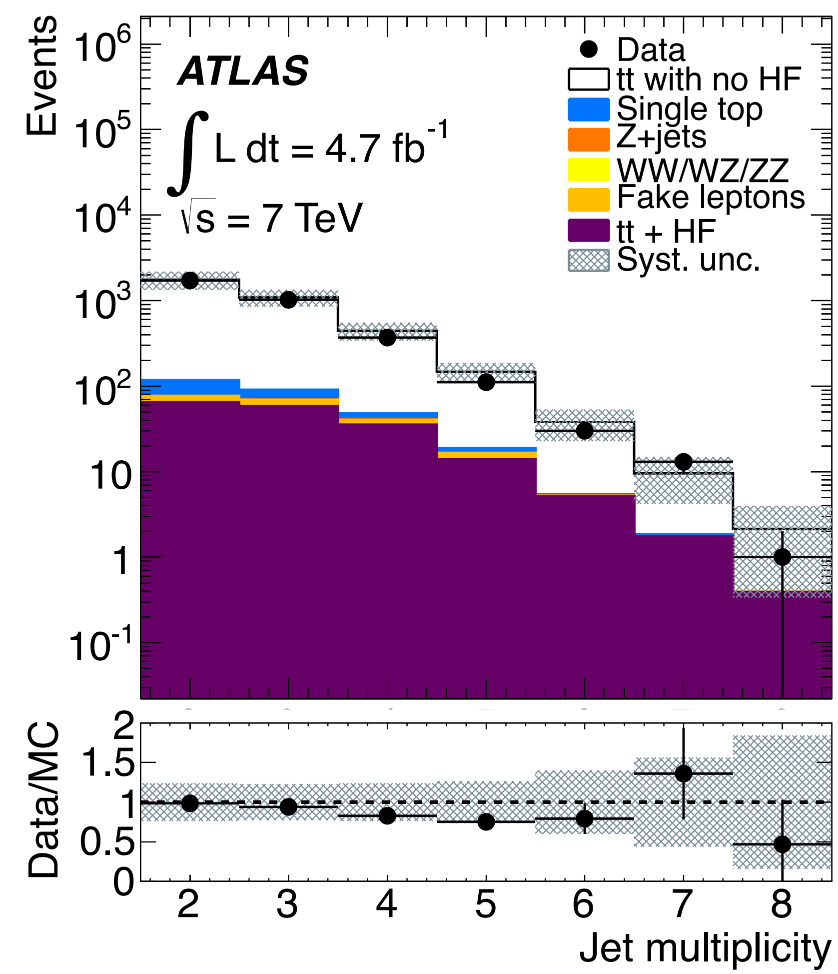
AUTOMATIC TOP PHYSICS AT NLO

$pp \to t\bar{t}b\bar{b}$



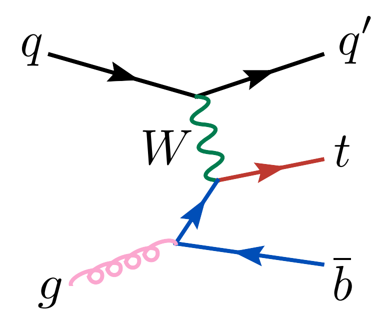
[Kardos and Trocsanyi, 2013]

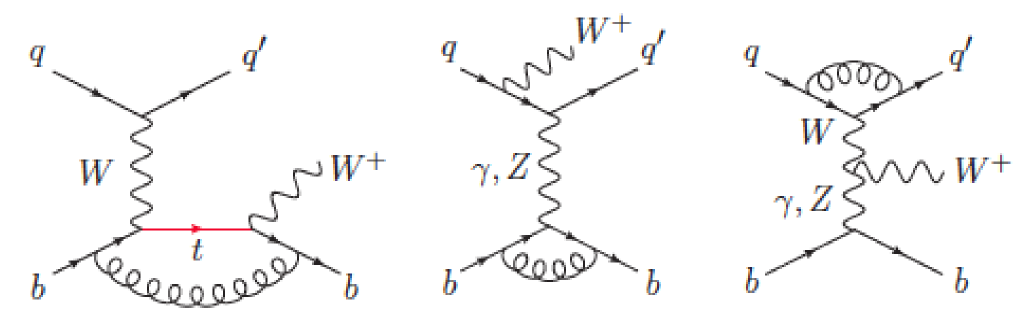
$pp \to t\bar{t}b\bar{b}$ & $pp \to t\bar{t}jj$

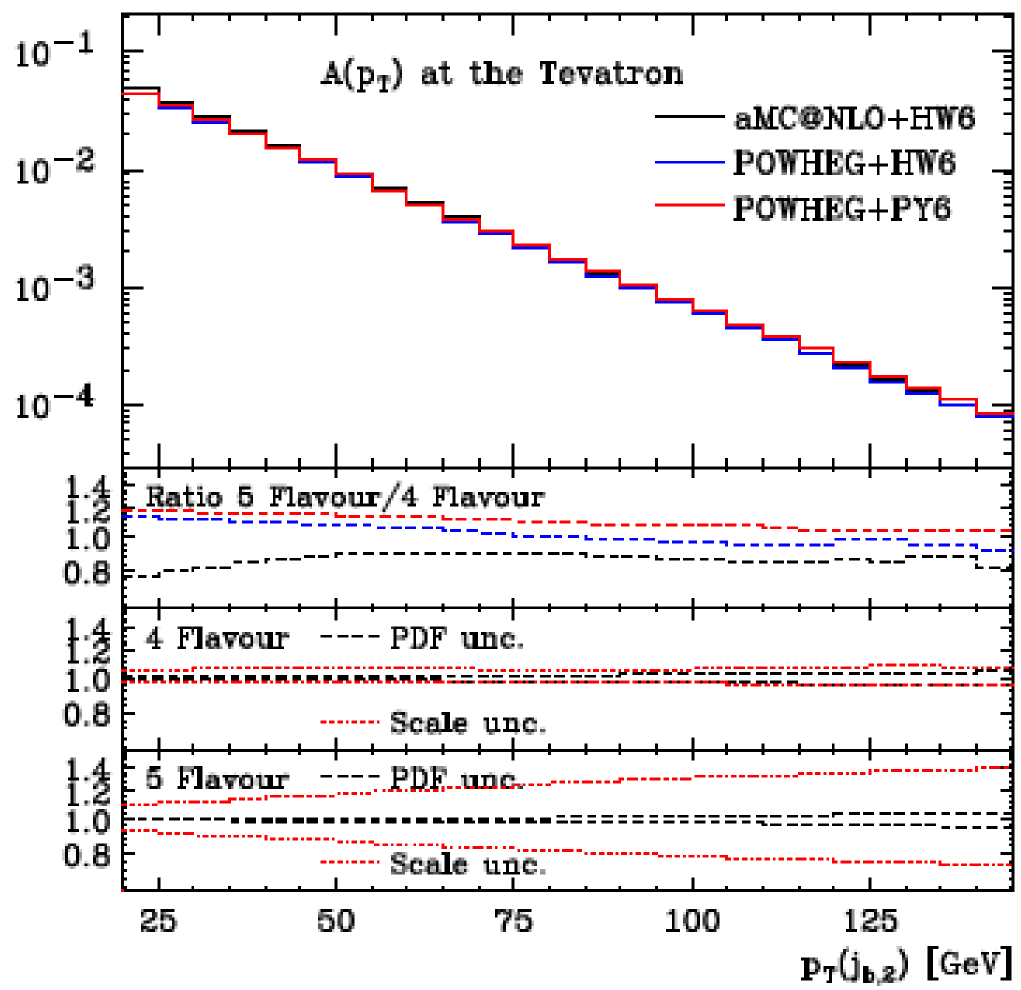


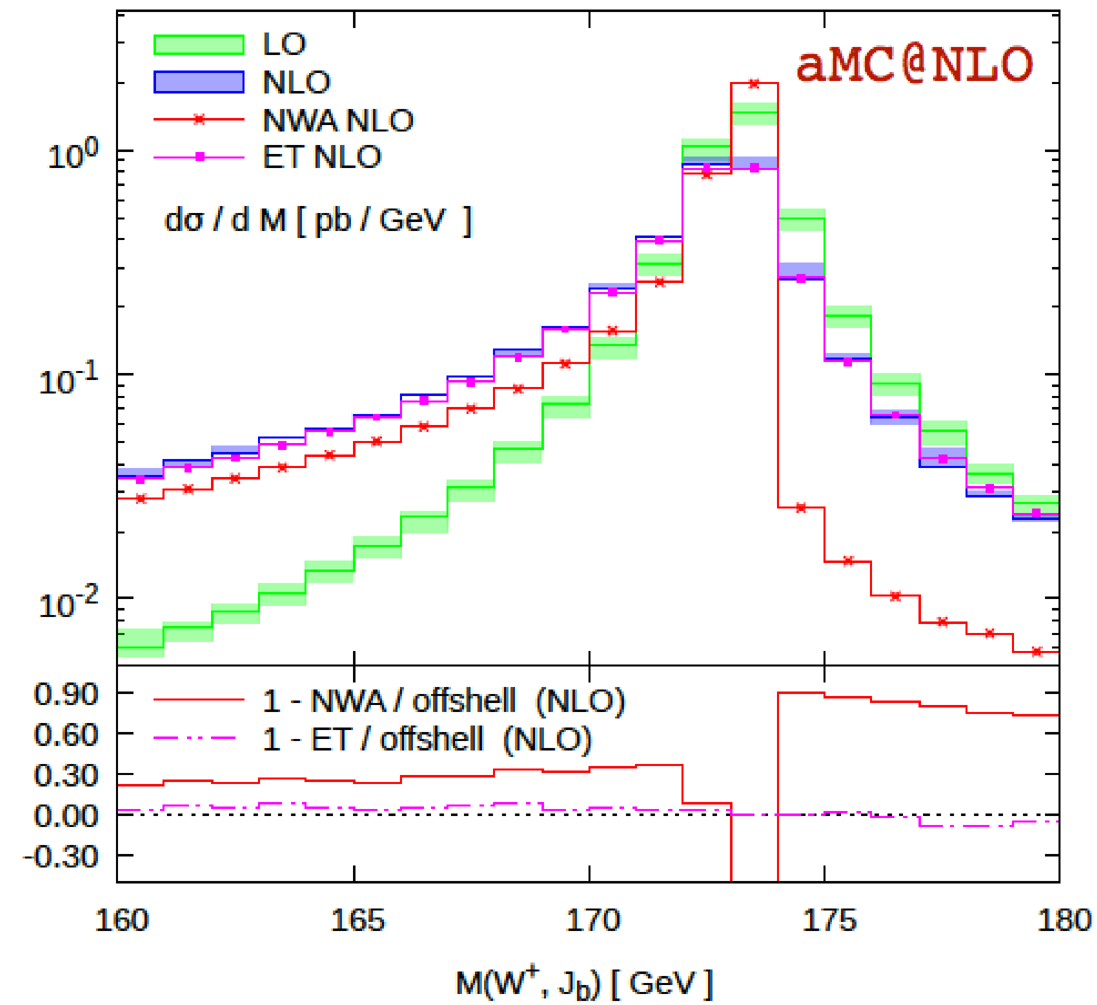
[ATLAS collaboration 2013]

AUTOMATIC TOP PHYSICS AT NLO









[Frederix et al., 2012]

[Papanastasiou et al., 2013, to appear]

AUTOMATIC TOP PHYSICS AT NLO

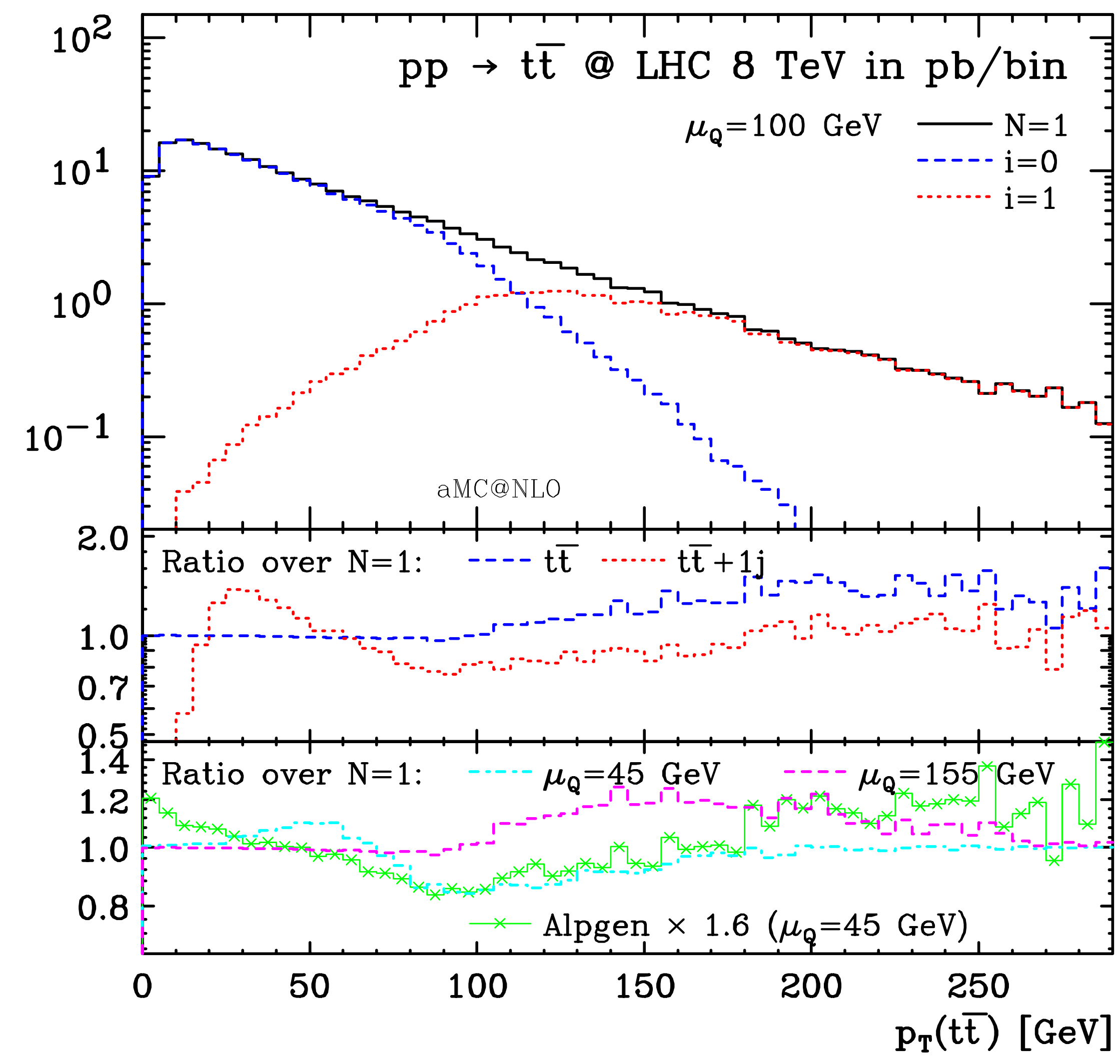
[Frederix and Frixione, 2012]

- 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

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

FXFX MERGING IN aMC@NLO



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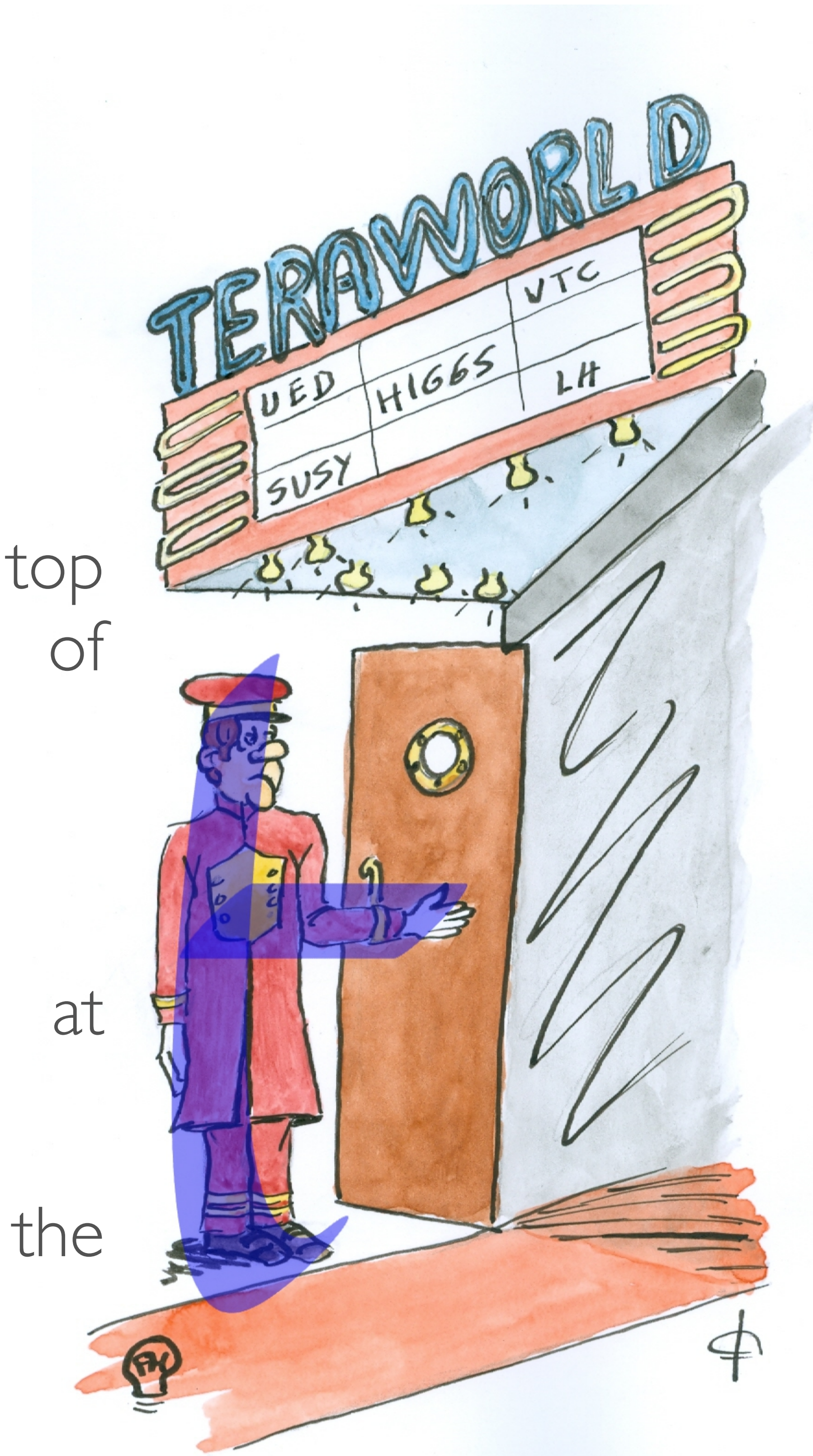


TTBAR XSEC NLO PREDICTIONS

A long history of hard work and amazing results:

- 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
- Inclusion of spin correlations in the decays at NLO — Bernreuther et al. 2001; Melnikov and Shulze, 2009; Campbell and Ellis, 2012
- Full WbWb final state — Denner et al. 2012; Bevilacqua et al. 2012

TTBAR + JETS PREDICTIONS

Another story of hard work and amazing results:

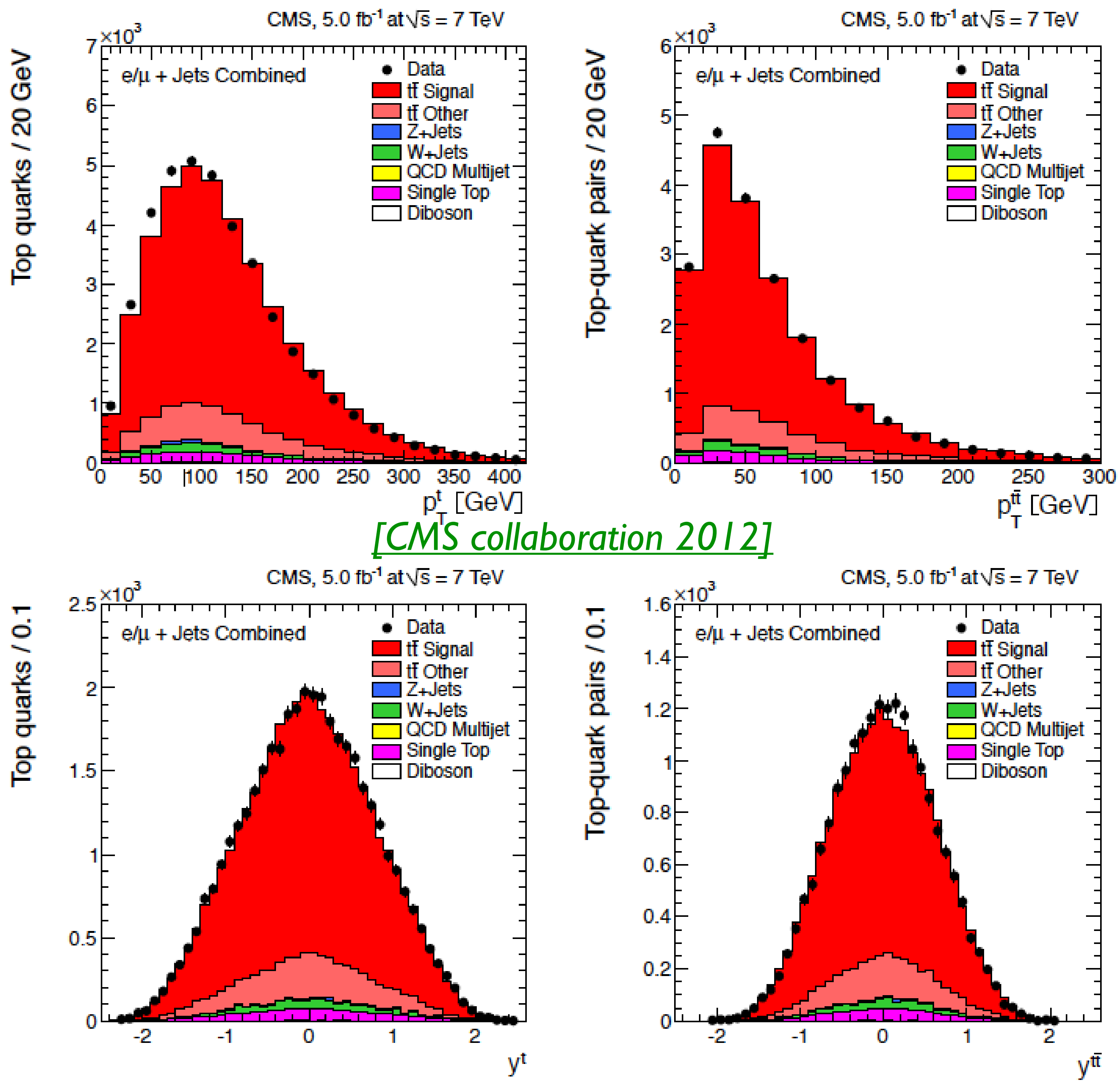
	References	process available from aMC@NLO
• tt+1jet at NLO	Dittmaier et al. 2007	yes
• tt+1jet at NLO with decays	Melnikov et al. 2011	yes
• tt+1jet with PS	Alioli et al. 2011 Kardos et al. 2011	yes
• tt+2jets at NLO	Bevilacqua et al, 2011	no
• ttbb at NLO	Bredenstein et al, 2010	yes
• ttbb at NLO with PS	Kardos and Trocsanyi, 2013	yes
• tt+jets merged samples at NLO	Frederix, Frixione, 2012	yes
• tttt at NLO	Bevilacqua and Worek, 2012	yes

TTBAR + BOSON PREDICTIONS

Recent results

Process	References	process available from aMC@NLO
ttH at NLO	Hirschi et al. 2011, Beenaker et al. 2001, Dawson et al.,2002	yes
ttH at NLO with PS and spin correlations	Frederix et al., 2011, Garzelli et al., 2011	yes
ttZ at NLO	Hirschi et al. 2011, Melnikov et al. 2011, Kardos et al. 2011	yes
ttZ at NLO with PS	Garzelli et al. 2012	yes
ttγ at NLO	Hirschi et al. 2011, Melnikov et al. 2011	yes
ttW at NLO	Hirschi et al. 2011, Campbell and Ellis 2012, Garzelli et al. 2012	yes
ttW at NLO with PS	Garzelli et al. 2012	yes

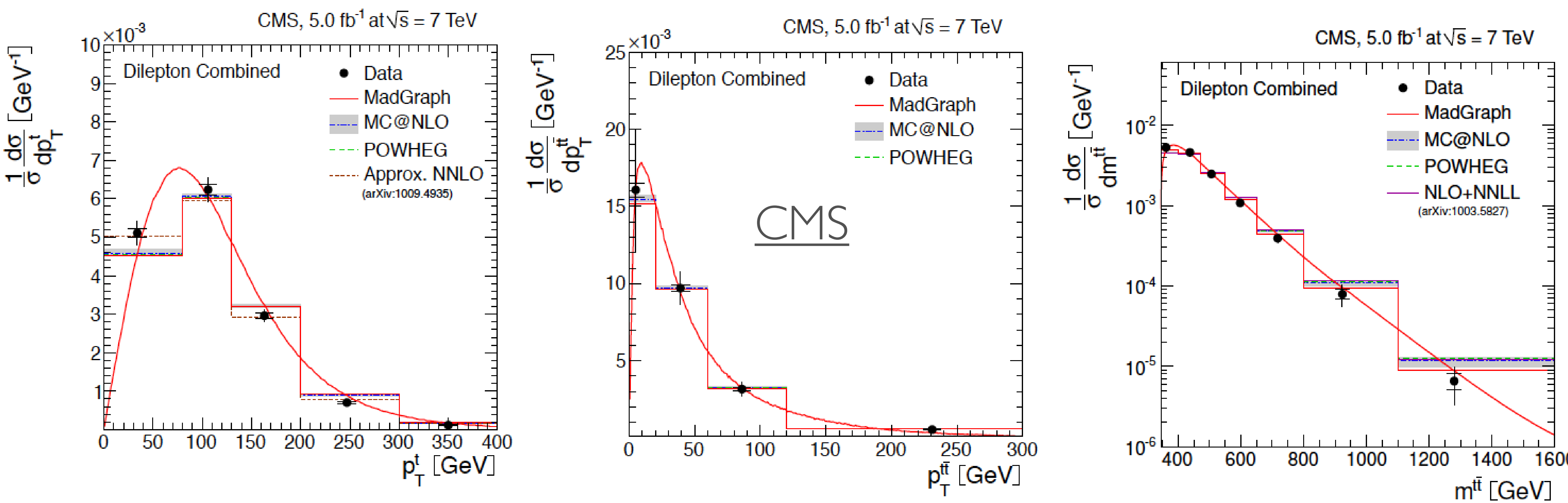
TTBAR DIFFERENTIAL DISTRIBUTIONS



[CMS collaboration 2012]

TTBAR DIFFERENTIAL DISTRIBUTIONS

[CMS collaboration 2012]



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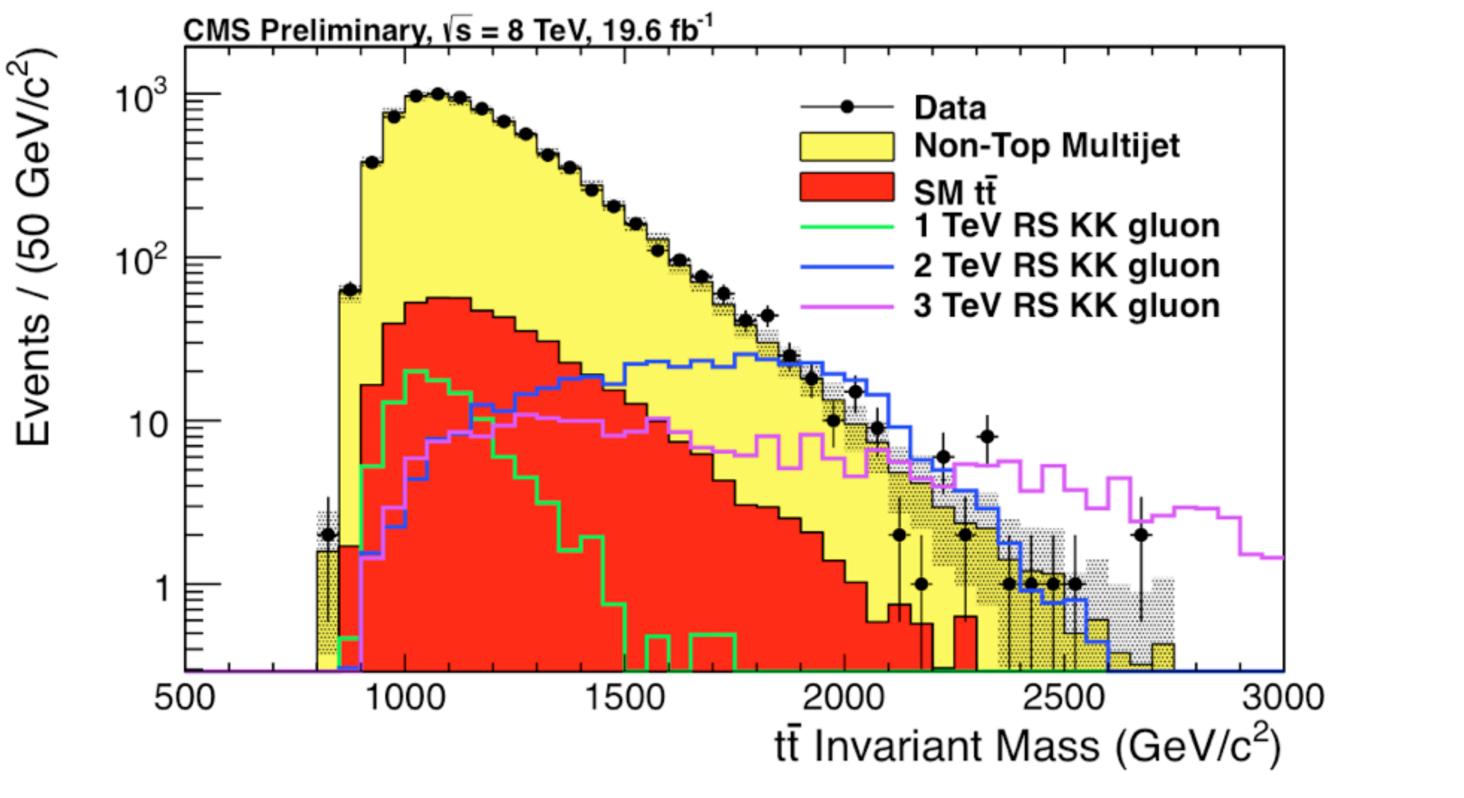
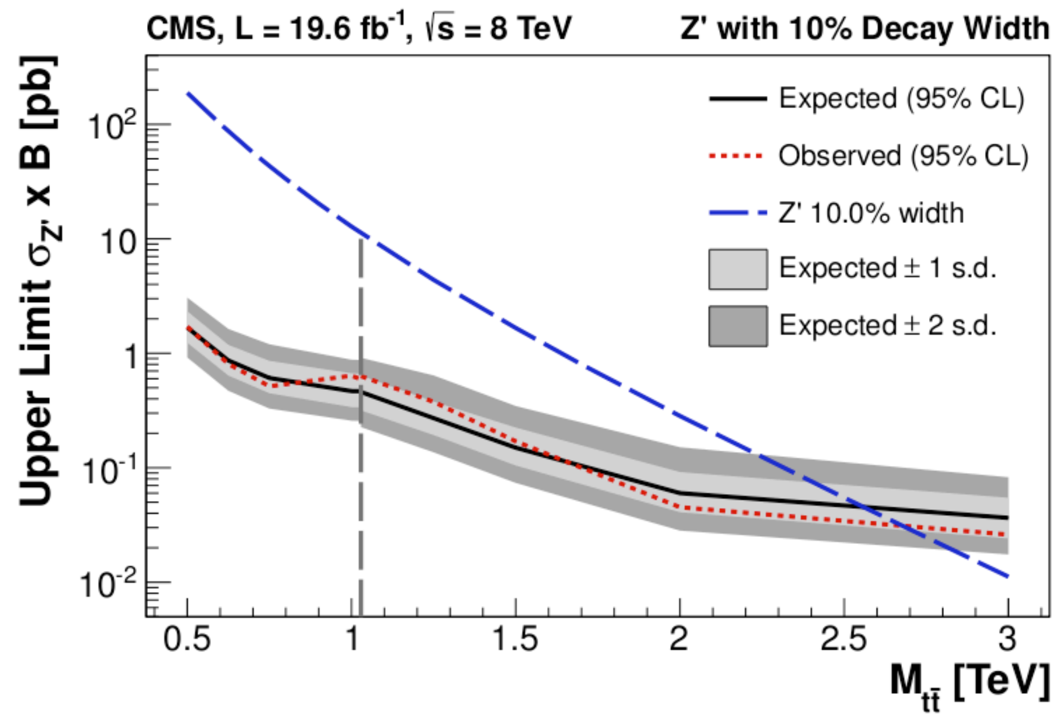


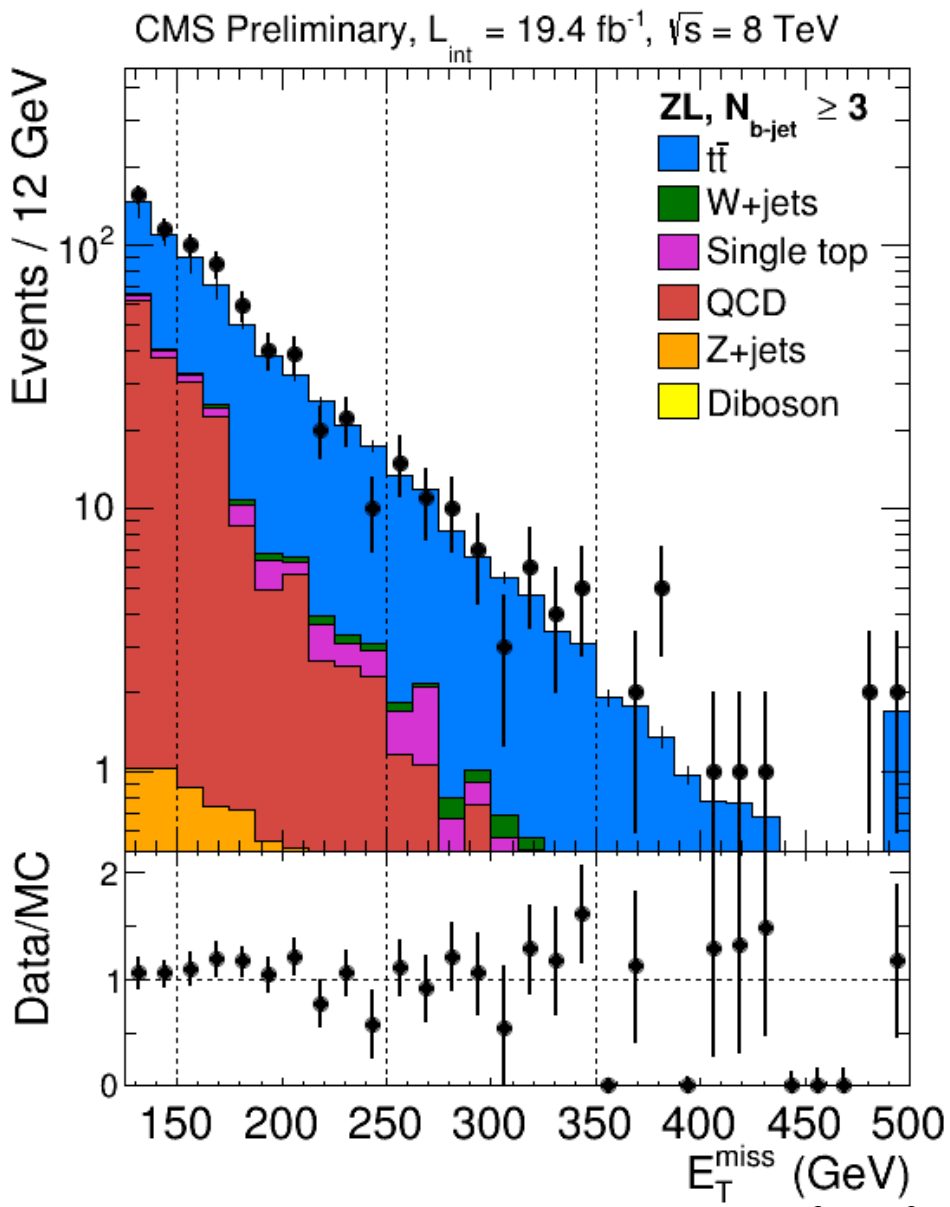


all hadronic final state

limits from one lepton final state m_{tt}

TOP AS A BACKGROUND TO SUSY

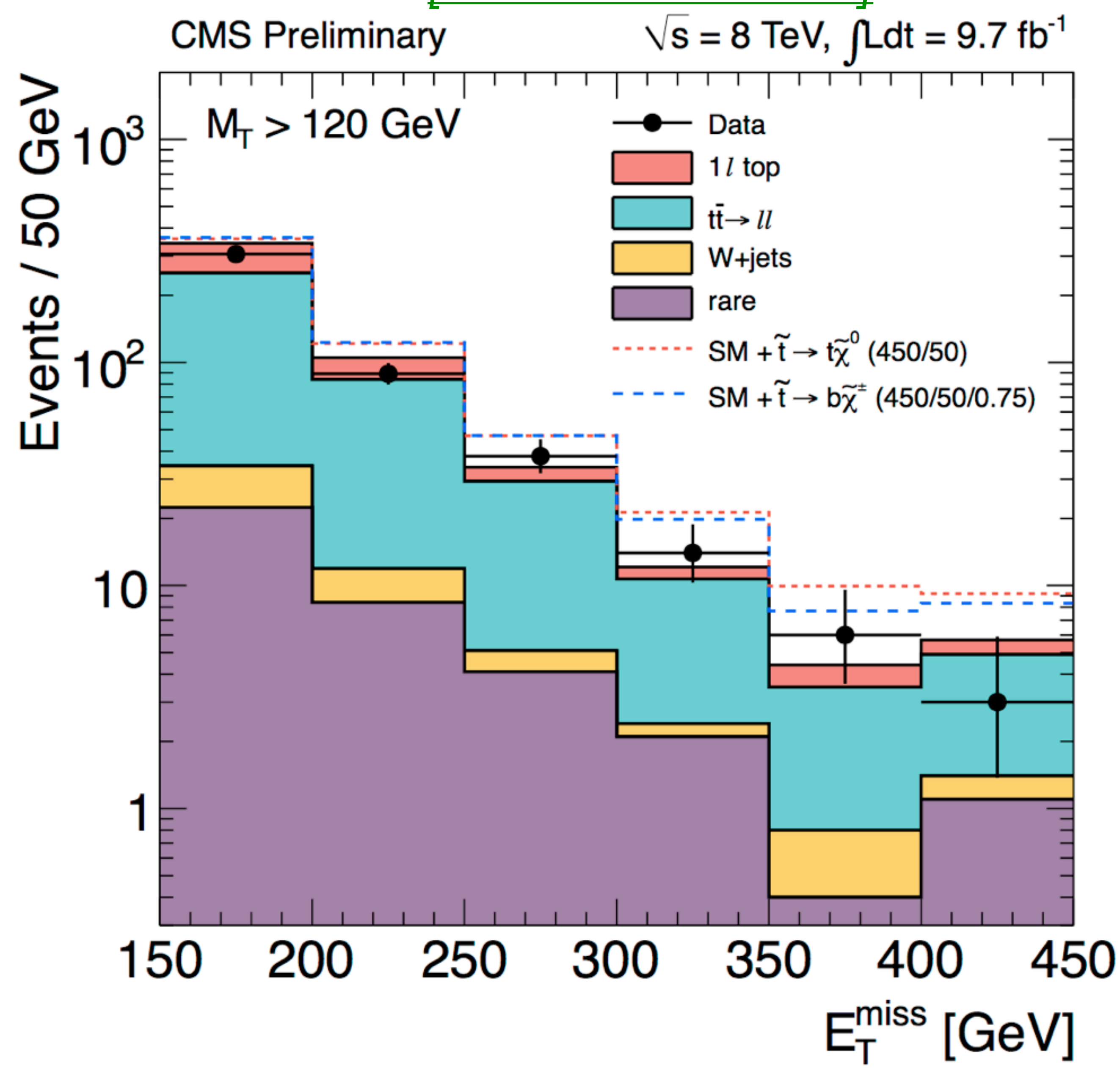
[CMS collaboration 2013]



$$pp \to \tilde{g}\tilde{g} \to b\bar{b}b\bar{b}\,\tilde{\chi}^0\tilde{\chi}^0$$

$$pp \to \tilde{g}\tilde{g} \to t\bar{t}t\bar{t}\,\tilde{\chi}^0\tilde{\chi}^0$$

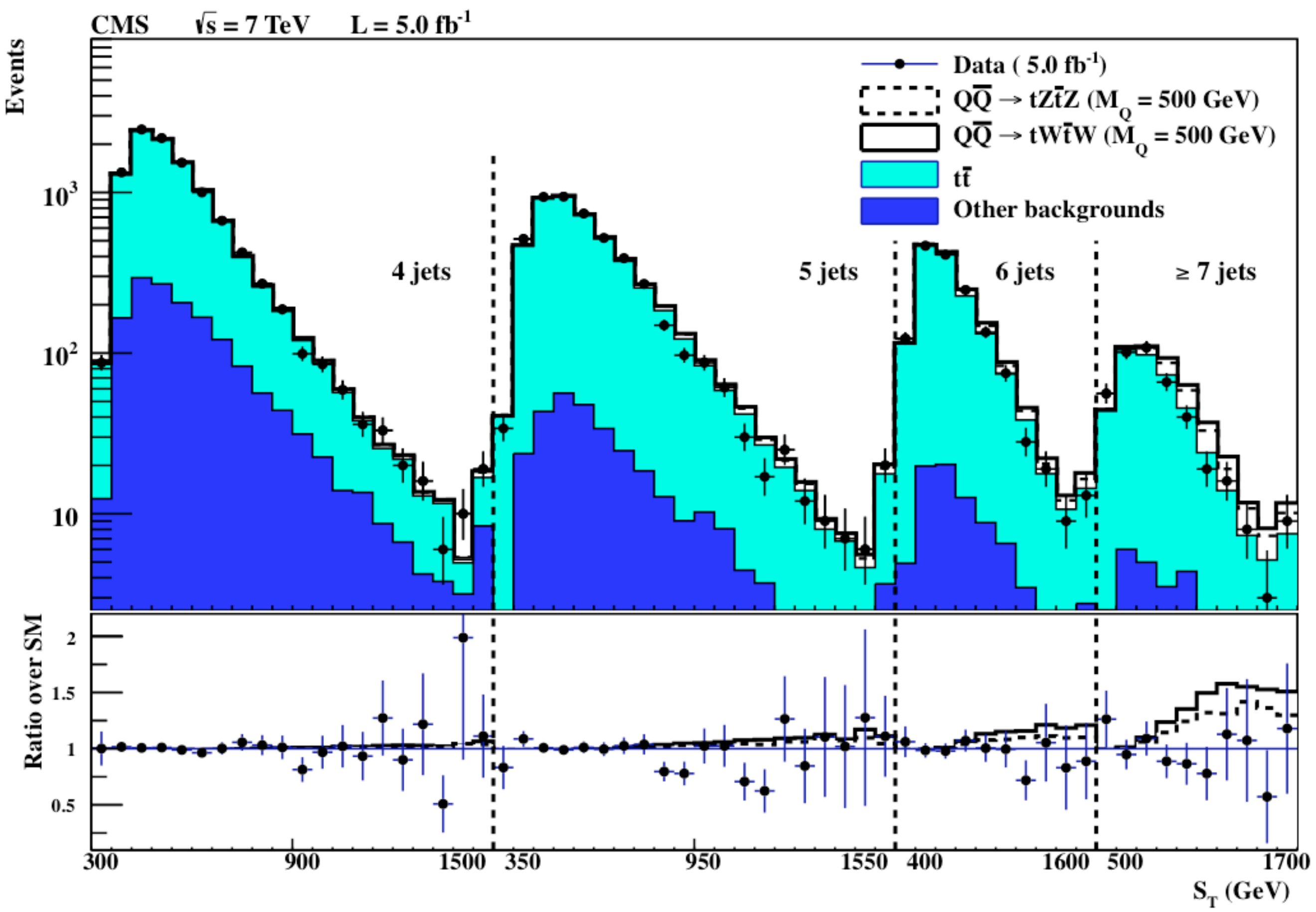
[CMS collaboration 2013]



$$pp \to \tilde{t}\tilde{t}^* \to t\bar{t}\,\tilde{\chi}^0\tilde{\chi}^0$$

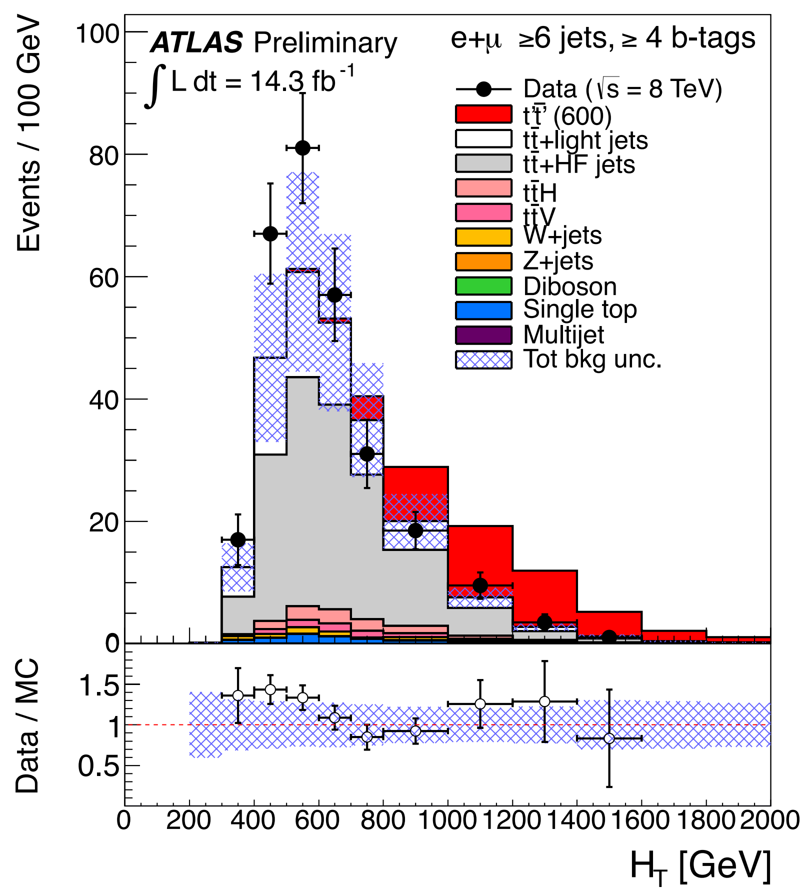
TOP AS A BACKGROUND TO T' OR B'

[CMS collaboration 2013]



$$pp \to Q\bar{Q} \to t\bar{t}ZZ, t\bar{t}WW$$

[ATLAS collaboration 2013]



$$pp \to Q\bar{Q} \to t\bar{t}hh$$