Theoretical results in top quark physics

Kirill Melnikov

TTP KIT

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Outline

1) Introduction

2) The top quark mass

3) Simple processes (top quark pair and single top production)

4) Complex processes with top quarks

5) BSM physics in top production and decay

6) Conclusion

Introduction

There are several well-known reasons that make top quark an interesting object to study:

1) top quark is the SM particle with the strongest coupling to the Higgs boson; for this reason, it is thought to be key for understanding many fundamental questions of particle physics, such as the unnatural smallness of the Higgs boson mass and the stability of electroweak vacuum ;

2) it is the heaviest SM particle with a very short lifetime, that decays into leptons, jets and missing energy; for this reason, processes with top quarks provide important backgrounds to searches for physics beyond the Standard Model ;

3) conversely, the top quark physics provides us with a great playground to prepare for detailed studies of BSM signals both in theory and experiment;

4) top quark interactions with neutral gauge bosons are among the least currently known, it is important to improve on that;

5) top quark it is the only ``free quark" that we have access to.

Introduction

Top quark physics is special because most of the time top quark is produced as a free on-shell quark that decays well before its properties are affected by long-distance non-perturbative QCD effects.

$$\Lambda_{\rm QCD} \ll \Gamma_t \ll m_t$$

An important consequence of this is that strong interaction effects do not de-polarize top quarks during their (short) lifetime; this allows us to explore Lorentz structure of QCD and weak interaction vertices that involve top quarks.

$$\frac{\Delta S}{S} \approx \frac{\Lambda_{\rm QCD}^2}{m_t \Gamma_t} \ll 1$$

These features open up a way to study complex processes with top quarks -- such as various associated production processes -- in higher orders of perturbative QCD, including all the correlations between top quark decay products. Errors of the on-shell approximation are known to be very small, at the level of O(1%) or below.

The top quark mass

The top quark mass

Among the many parameters of the top quark, its mass stands out in its significance. Indeed, it determines the top Higgs Yukawa coupling and plays a central role in the current discussions about the (meta)stability of the Universe.

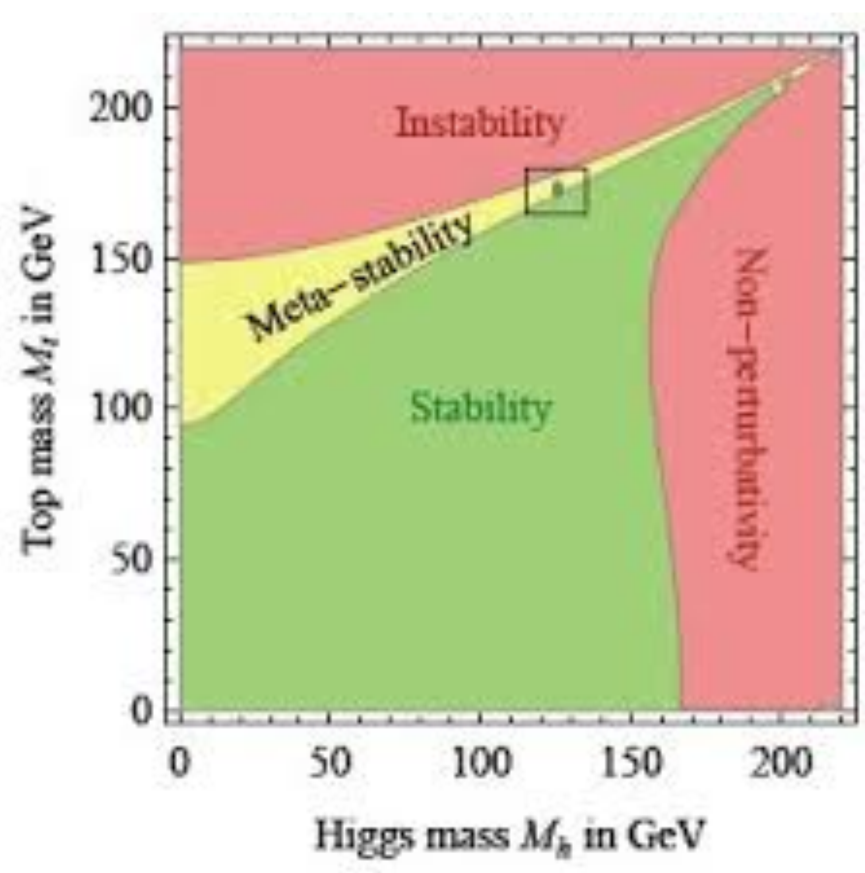
The top quark mass is measured very precisely (CMS combination m_t = 172.38(65) GeV) but there is an important question about what this result really means since numerical differences between top quark masses defined in different perturbative schemes are known to be large (i.e. several GeV).

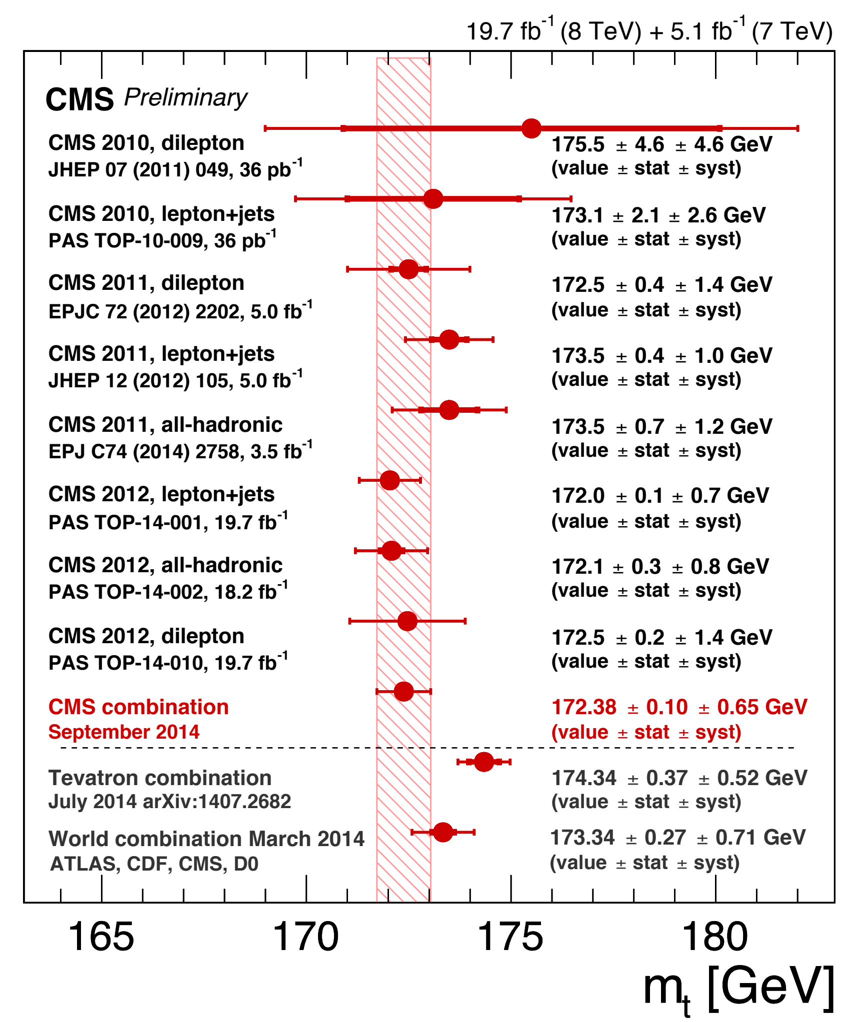
The current thinking is that the ``Monte Carlo mass" is measured by CMS and ATLAS but this notion is quite confusing.

There are two issues related to top quark mass measurements that are often lumped together :

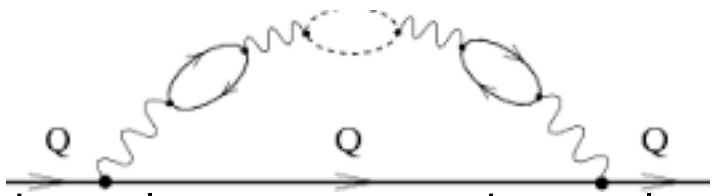
1) ``intrinsic" effects that make the notion of the top quark pole mass theoretically ill-defined;

2) generic non-perturbative effects that affect the extraction of the top quark mass in experiments;





The top quark mass



Perturbative instabilities of the pole mass of a quark are known since long ago -- the pole mass is not well-defined to all orders in perturbation theory (renormalons). However, if one works to fixed order in perturbation theory, the pole mass is well-defined and can be used.

This option is often discarded since the use of the pole mass in perturbative computations leads to large shifts from one order in perturbation theory to the other; if we do not want to deal with these shifts, we try to switch to a different -- ``short distance" mass parameter. This is the standard story in B-physics.

However, the top quark physics seems to be different -- we do not observe large corrections when we use the top quark pole mass in perturbative computations. For example:

1) The relation between the pole and the MS masses of a top quark to a four-loop order; ``convergent series", the change in the pole mass is still below 200 MeV and there is no sign of the asymptotic nature of these series.

Marquard, Smirnov, Smirnov, Steinhauser

$$m_{t,\mathrm{pole}} = (163.643 + 7.557 + 1.617 + 0.501 + 0.195)\ \ \mathrm{GeV}$$

2) The top quark width, expressed through the pole mass does not show signs of perturbative instabilities.

$$\Gamma_t = \frac{G_F m_{t,\mathrm{pole}}^3}{8\sqrt{2}\pi} |V_{tb}|^2 \left(1 - 0.09 + 0.02 + \ldots .\right)$$

Melnikov, Czarnecki

The reason is the smaller value of the strong coupling constant $\alpha_s(m_t)$ that delays the impact of n! behavior perturbative coefficients to really high orders !

The top quark mass

Similar to a measurement of any other observable at hadron colliders, extraction of the top quark mass is affected by non-perturbative effects. This is an issue that exists even if a short-distance mass definition for the top quark mass is chosen.

Let us imagine an idealized situation where parton shower is not needed for the extraction of the top quark mass but an observable, from which the top quark mass is determined, is predicted with the standard QCD accuracy, i.e. up to power corrections.

$$\frac{\mathrm{d}\sigma}{\mathrm{d}M} \approx T(M, m_t, \alpha_s)\left[1 + c\left(\frac{\Lambda_{\mathrm{QCD}}}{M}\right)^n\right] \qquad \delta m_t \sim \frac{c\,T}{\partial T/\partial m_t}\left(\frac{\Lambda_{\mathrm{QCD}}}{M^*}\right)^n$$

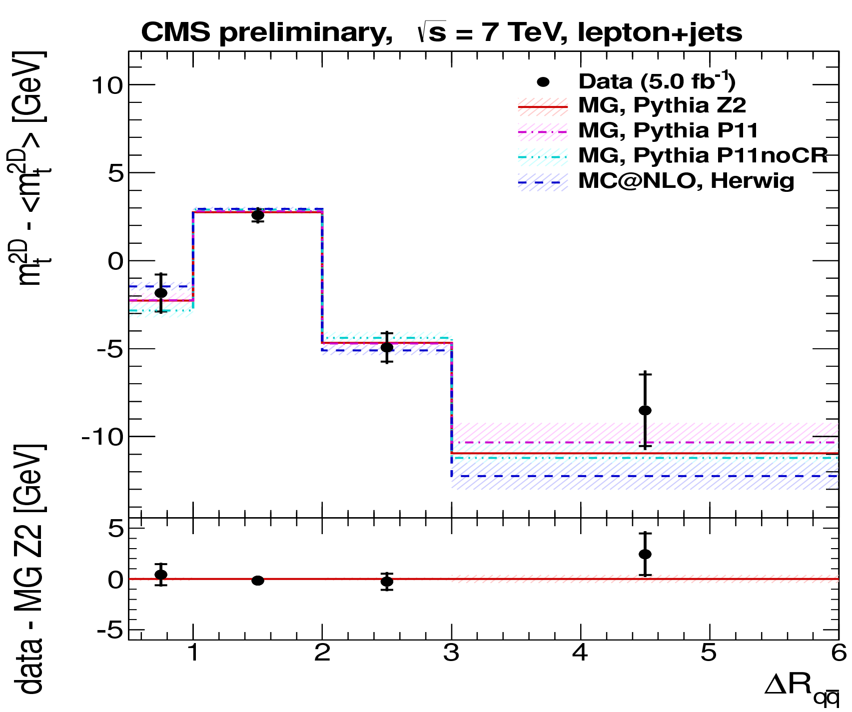
$$\frac{\partial T}{\partial m_t} \sim k\frac{T}{m} \qquad \boxed{\delta m_t \sim \frac{c\,m_t}{k}\left(\frac{\Lambda_{\mathrm{QCD}}}{m_t}\right)^n}$$

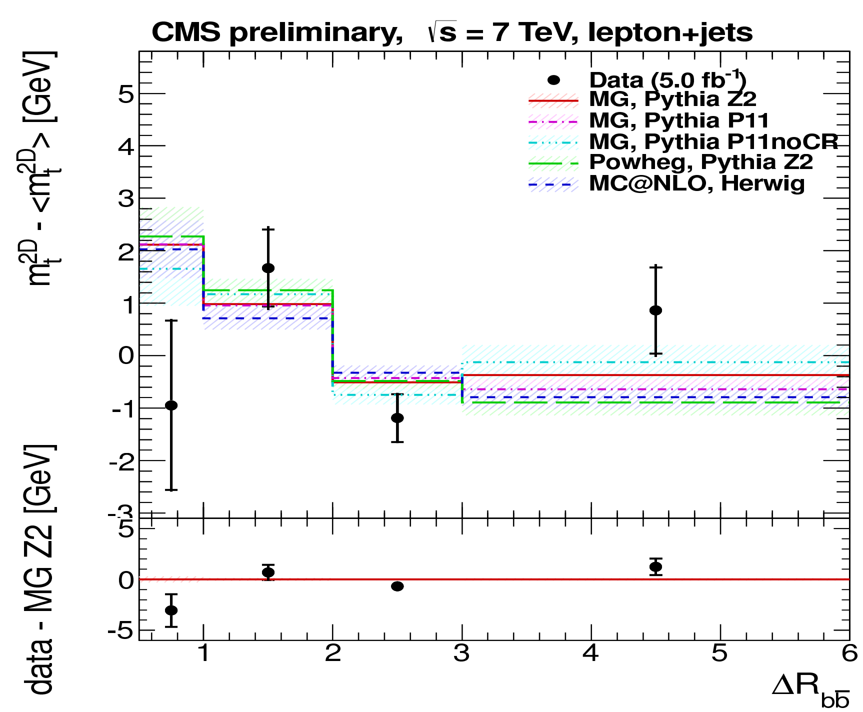
For a typical observable, k=1, n=1; this implies that the top quark mass can not be extracted with precision that is better than the non-perturbative QCD scale.

To improve on that, we need to carefully study observables that are used to extract the top quark mass and understand power corrections to them.

Power corrections and the top quark mass

Currently, estimates of power corrections are based on hadronization models in parton shower event generators. These models -- on average -- properly describe large amount of data but they are heuristic. For this reason, estimates of power corrections provided by parton showers may or may not be correct; if they are not, most of the determinations of the top quark mass may be systematically biased.





CMS studied the extracted top quark mass as a function of kinematic cuts; if some non-perturbative effects were missed by parton showers, inconsistencies in extracted top quark masses could have been found.

We need the top quark mass determined from well-defined observables, computable in perturbative QCD, with well-understood power corrections.

Simple processes: top pair and single top production

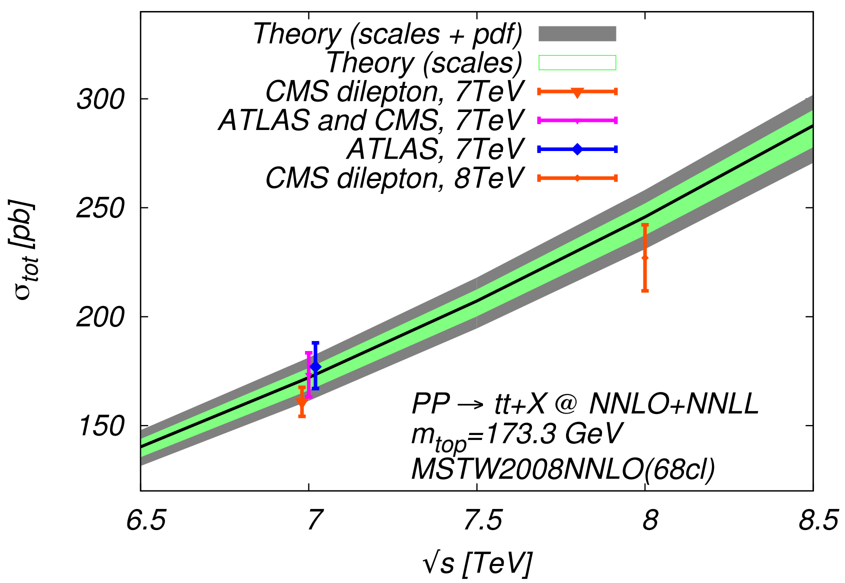
Top pair production

Calculations of top quark pair production cross sections in perturbative QCD have a long history; NLO QCD corrections were computed in 1988 for the first time and then refined to make the results more physical (kinematic distributions, top decays etc.).

A few years ago these NLO results were extended to NNLO. This landmark calculation of NNLO QCD corrections to one of the basic processes at the LHC (Tevatron) signaled the beginning of an era of NNLO QCD phenomenology at hadron colliders.

This calculation gives us a theory prediction for the top quark pair production cross section that 1) perfectly agrees with experiments; 2) exhibits small residual uncertainty (4%); 3) renormalization/factorization scale, top mass and PDF errors have now comparable impact on the theory uncertainty of the total cross section.

Many interesting spin-offs of the calculation that go beyond the total cross section.



Collider	$\sigma_{\rm tot}$ [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	$+0.259(3.7\%)$ $-0.374(5.3\%)$	$+0.169(2.4\%)$ $-0.121(1.7\%)$
LHC 7 TeV	167.0	$+6.7(4.0\%)$ $-10.7(6.4\%)$	$+4.6(2.8\%)$ $-4.7(2.8\%)$
LHC 8 TeV	239.1	$+9.2(3.9\%)$ $-14.8(6.2\%)$	$+6.1(2.5\%)$ $-6.2(2.6\%)$
LHC 14 TeV	933.0	$+31.8(3.4\%)$ $-51.0(5.5\%)$	$+16.1(1.7\%)$ $-17.6(1.9\%)$

Czakon, Mitov, Fiedler

Forward-backward asymmetry

Measurement of the forward-backward asymmetry of top quarks at the Tevatron caused quite an excitement in recent years.

Experimental and theoretical results showed persistent tension -- especially in the regions of large rapidities and/or large invariant masses of top quark pairs. These discrepancies were explored in the context of physics beyond the Standard Model but no convincing explanation consistent with other data emerged so far.

$$A_{\mathrm{FB}} = \frac{N(y_t > 0) - N(y_t < 0)}{N_{\mathrm{total}}}$$

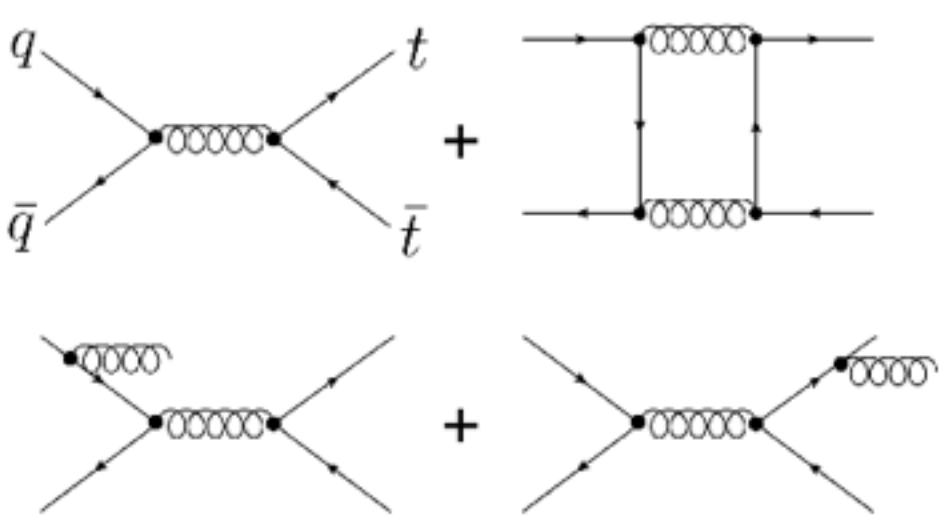
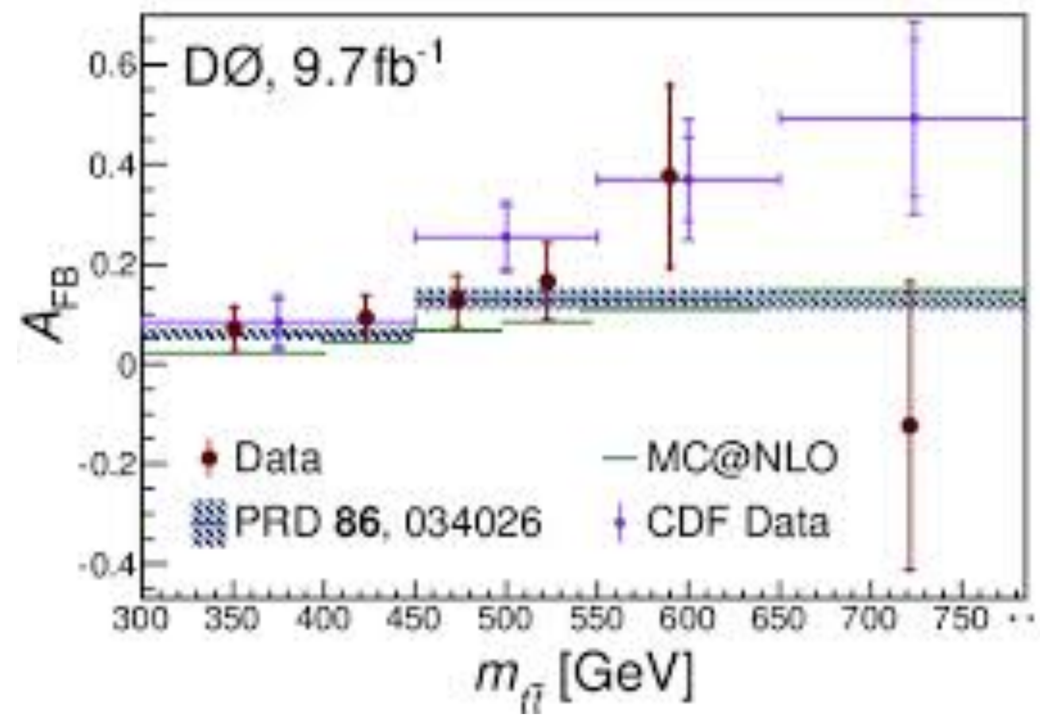


FIG. 1: Interfering $q\bar{q} \to t\bar{t}$ (above) and $q\bar{q} \to t\bar{t}j$ (below) amplitudes.



Forward-backward asymmetry

The Standard Model predictions for the asymmetry were scrutinized as well. Unfortunately, sources of potentially large radiative effects were not identified. However, a few interesting observations were made.

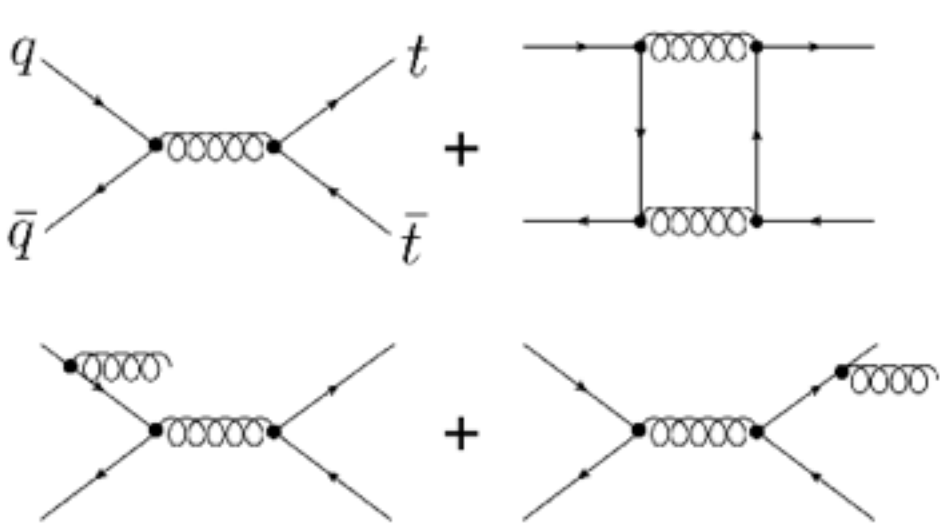
For example, a ``color coherence” effect in parton shower Monte-Carlos was discovered; the existence of this effect leads to non-vanishing forward-backward asymmetry in parton showers in spite of their collinear nature.

Skands, Webber, Winter

Another interesting observation was related to the asymmetry in tt+jet final state. In this case, O(100%) radiative corrections to the asymmetry were found; however, it was also argued that these large effects are particular to tt+j final state and nothing similar is possible in the inclusive asymmetry.

Dittmaier, Uwer, Weinzierl

Schulze, Melnikov



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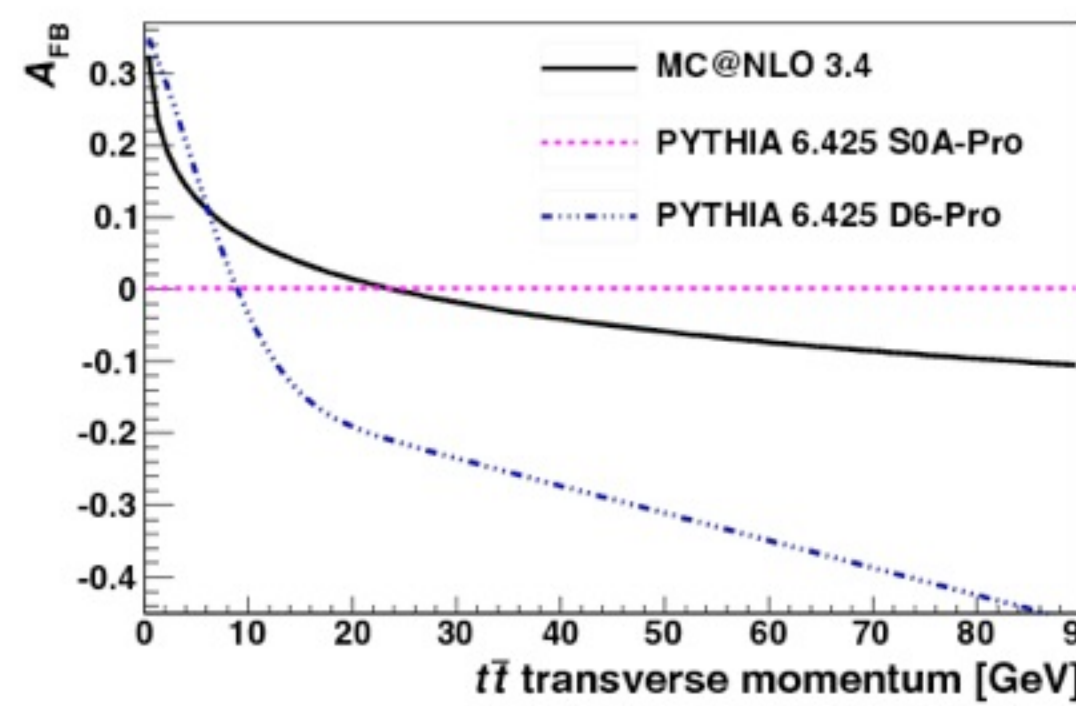
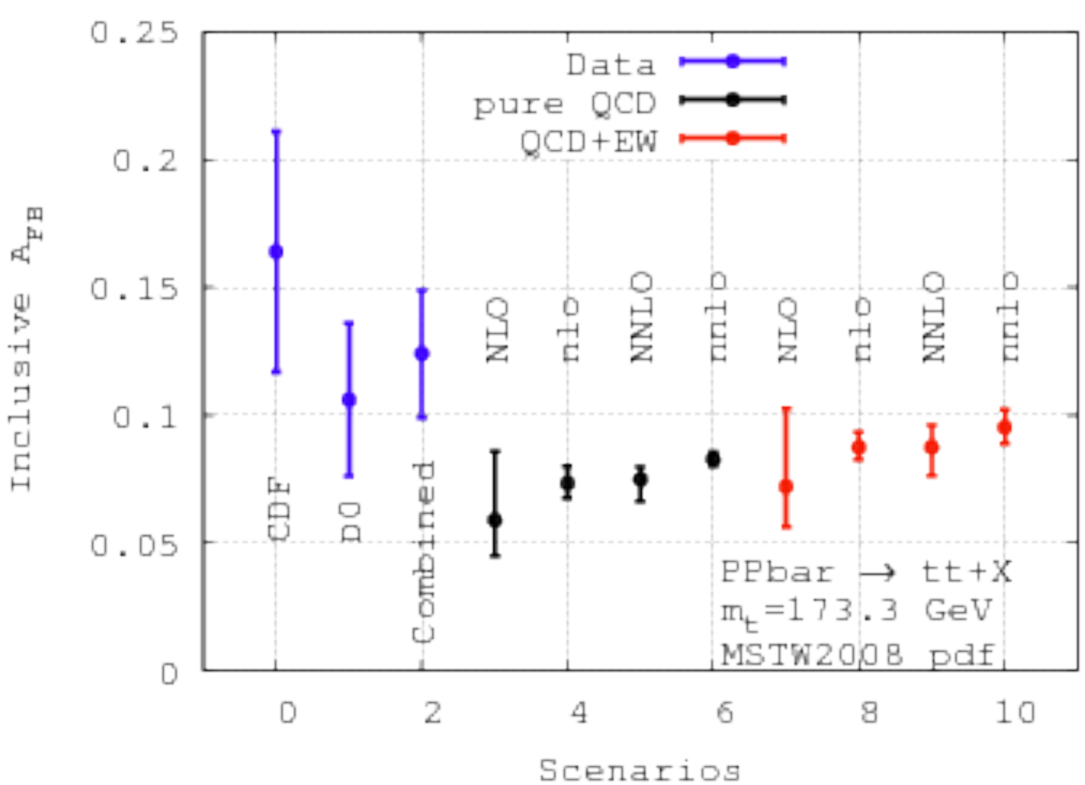


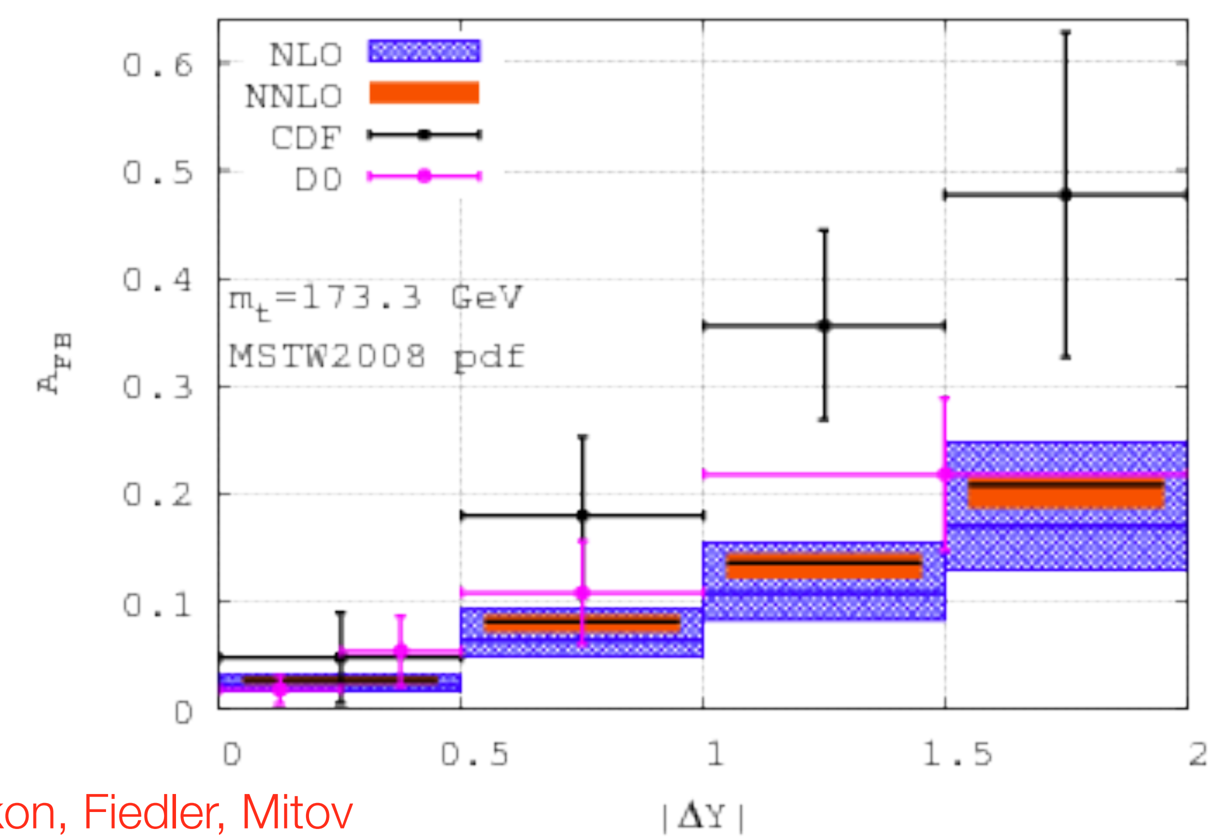
D0 colaboration

Forward backward asymmetry

Nevertheless, in spite of the indications that large QCD corrections to the asymmetry are unlikely, it was important to compute those corrections explicitly. This was recently done.

The NNLO QCD corrections turned out to be moderate -- as expected ; this excludes the possibility that pQCD predictions to A_{FB} are pathological. However, the dependence of the asymmetry on the rapidity still does not look good; the resolution of this issue will have to wait further.





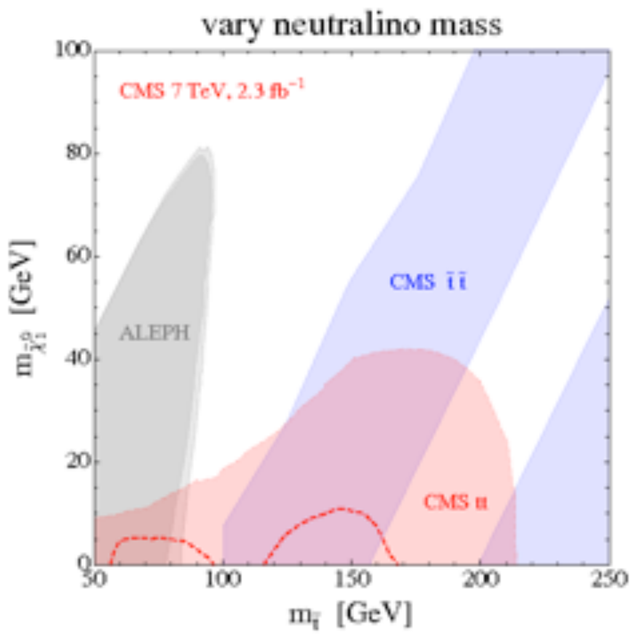
Czakon, Fiedler, Mitov

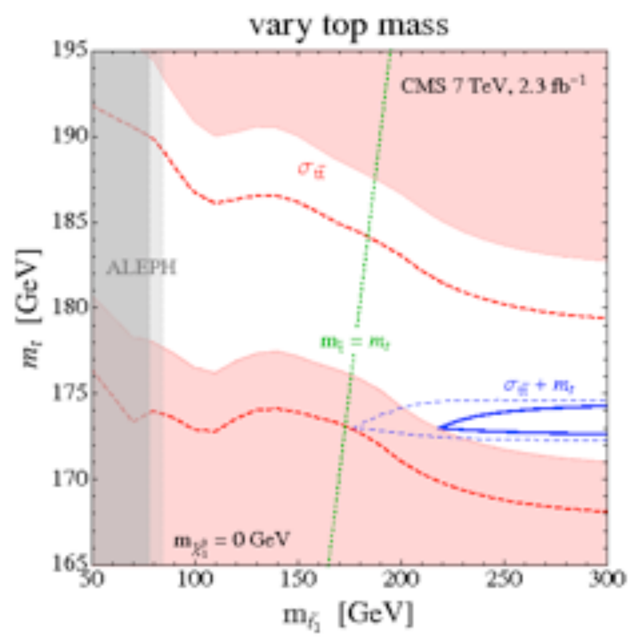
Exclusion of stealthy stops

Very precise results for top pair production cross section can be used to constrain contributions of yet undiscovered particles to ``top pair production cross section".

The problem is that stops -- that are degenerate in mass with top quarks and that decay to top quarks with very little missing energy -- are kinematically indistinguishable from tops (except for spin correlations). However, they increase the ``top quark" production cross section. If we know the top cross section sufficiently precise, we can detect the excess !

As we just discussed, thanks to the recent NNLO QCD computation, the residual uncertainty on the cross-section is reduced to just O(4) percent; this improvement is necessary and sufficient for providing informative constraints on stop pair production cross-section.





$$\sigma_{\tilde{t}\tilde{t}} \sim 0.14\ \sigma_{tt}$$

$$m_{\tilde{t}} = m_t$$

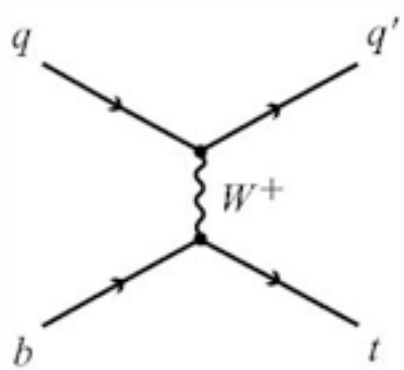
$$\sigma_{\tilde{t}\tilde{t}} \sim \sqrt{\delta\sigma^2_{tt,\mathrm{exp}} + \delta\sigma^2_{tt,\mathrm{th}}}$$

Czakon, Mitov, Papucci, Rudermann, Weiler

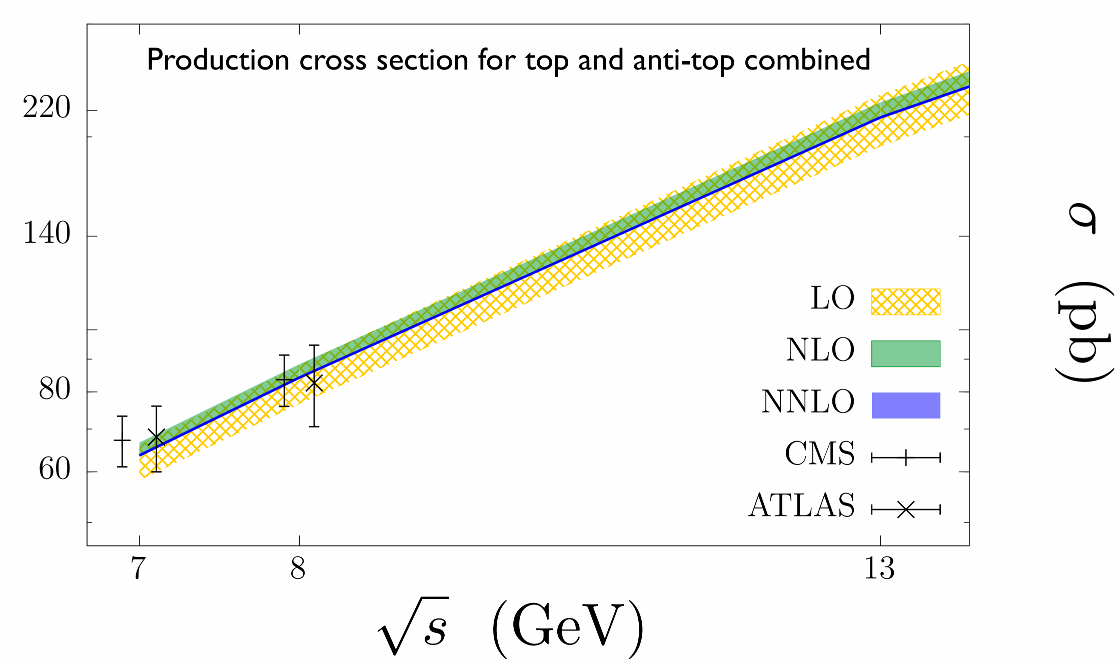
t-channel single top production at NNLO

Measurement of the single top production cross section is interesting for several reasons, including direct constraint(s) on the tWb coupling (incl. V_{tb}).

The total cross-section for t-channel single top production at the LHC receives very small NLO corrections suggesting that NNLO QCD computations are not needed. However, this result is the consequence of significant cancellation between sizable corrections to different channels, which makes computation of the NNLO QCD corrections desirable.



The NNLO and NLO results are close (-1.6% NNLO QCD); we observe reduced dependence on unphysical scales -> good theoretical control. Also with the cut on the top quark transverse momentum, the size of NLO QCD corrections increases; the NNLO QCD corrections remain small for all values of the transverse momentum .



$p_\perp$	$\sigma_{\rm LO}$, pb	$\sigma_{\rm NLO}$, pb	$\delta_{\rm NLO}$	$\sigma_{\rm NNLO}$, pb	$\delta_{\rm NNLO}$
0 GeV	$53.8^{+3.0}_{-4.3}$	$55.1^{+1.6}_{-0.9}$	$+2.4\%$	$54.2^{+0.5}_{-0.2}$	-1.6%
20 GeV	$46.6^{+2.5}_{-3.7}$	$48.9^{+1.2}_{-0.5}$	$+4.9\%$	$48.3^{+0.3}_{-0.02}$	-1.2%
40 GeV	$33.4^{+1.7}_{-2.5}$	$36.5^{+0.6}_{-0.03}$	$+9.3\%$	$36.5^{+0.1}_{+0.1}$	-0.1%
60 GeV	$22.0^{+1.0}_{-1.5}$	$25.0^{+0.2}_{+0.3}$	$+13.6\%$	$25.4^{-0.1}_{+0.2}$	$+1.6\%$

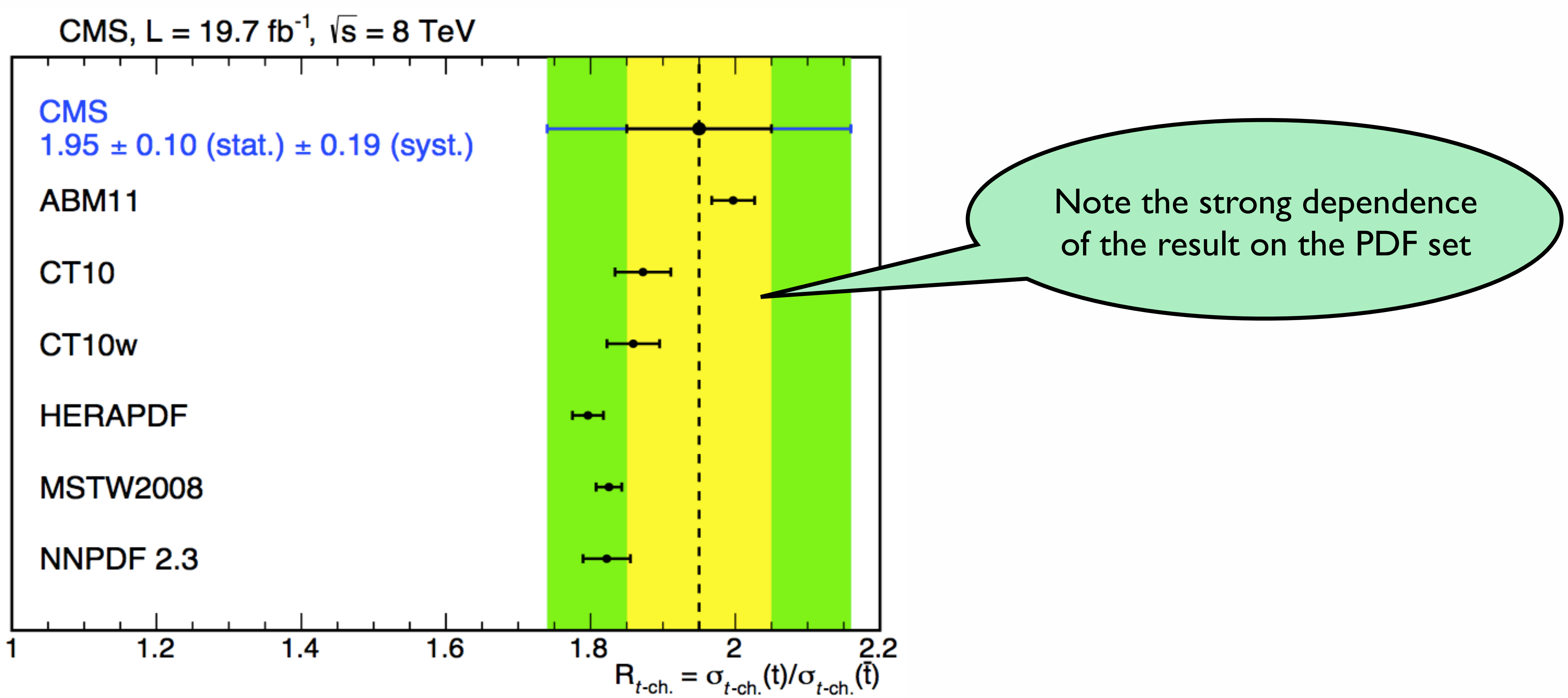
Burcherseifer, Caola, Melnikov

$$\frac{\delta V_{tb}}{V_{tb}} \sim \frac{\delta\sigma}{\sigma}$$

An O(1%) determination of V_{tb} should be possible !

t-channel single top production at NNLO

Another interesting observable is the ratio of single top and single anti-top production cross sections. It appears to be very stable against higher-order QCD corrections and can be used to constrain the ratio of up-quark and down-quark distributions in a proton, for relatively large values of the Bjorken x.



$\sigma_{t,\mathrm{LO}}/\sigma_{\bar{t},\mathrm{LO}} = 1.85$ $\sigma_{t,\mathrm{NLO}}/\sigma_{\bar{t},\mathrm{NLO}} = 1.83$ $\sigma_{t,\mathrm{NNLO}}/\sigma_{\bar{t},\mathrm{NNLO}} = 1.83$

Burcherseifer, Caola, Melnikov

Complex processes with top quarks

Complex processes with top quarks

Another impressive development in recent years is the emergent ability to describe top-like final states with very high degree of realism, including next-to-leading order corrections (QCD and EW), matching to parton showers and merging of different jet-multiplicity samples. This significant effort is spearheaded by POWHEG, aMC@NLO, OpenLoops, Sherpa, etc.

Currently, it is technically feasible to perform the following computations:

1) tt + 0 jets: full WbWb final state @ NLO (off-shell effects, massive b-quarks etc.);
2) tt + 1 jet: narrow width: production and decay at NLO, spin correlations;
3) tt + 2jets: stable top quarks;

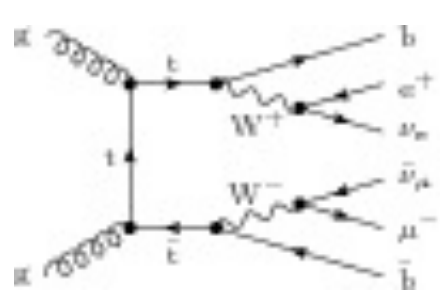
4) tt + V : narrow widths, production and decay at NLO, showers
5) tt + H : bWbWH final state @NLO

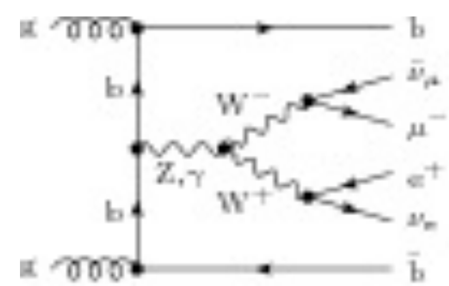
It is understood how to merge processes with top pairs and different number of jets for stable top quarks and how to match such processes to parton showers. Parton showers for unstable top quarks (narrow width) matched to NLO computations are also being developed.

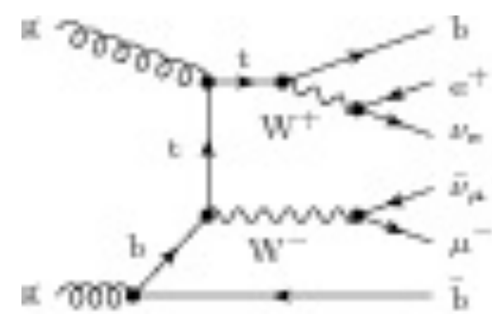
This is too vast a topic so that I will not try to cover everything and will only show a few examples.

Complex processes with top quarks: bWbW final state

Consider pp -> tt or bbWW final state with massive b-quarks. The calculation can be performed in the 4-flavor scheme, so no b-quark PDF is needed.

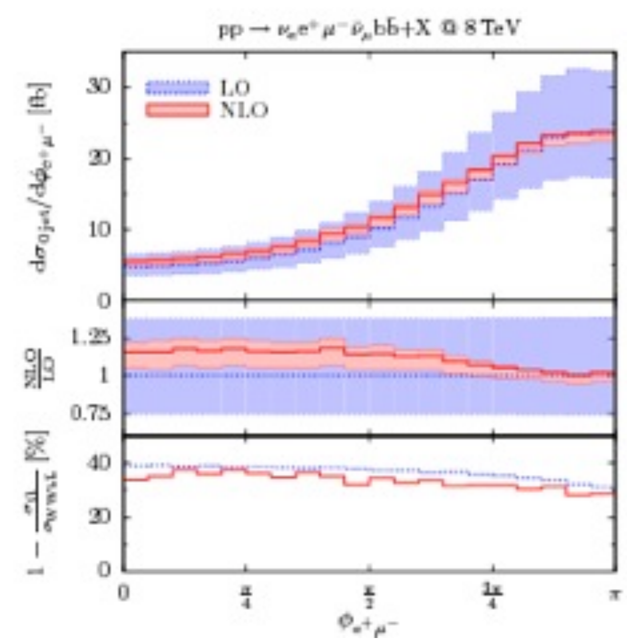






Loose requirements on the number of b-jets enhance contributions due to soft b-jets and lead to larger ``off-shell" contributions to the final results than in the case of ``top pair'' production cross section. These off-shell contributions can, however, be identified with the associated tW production.

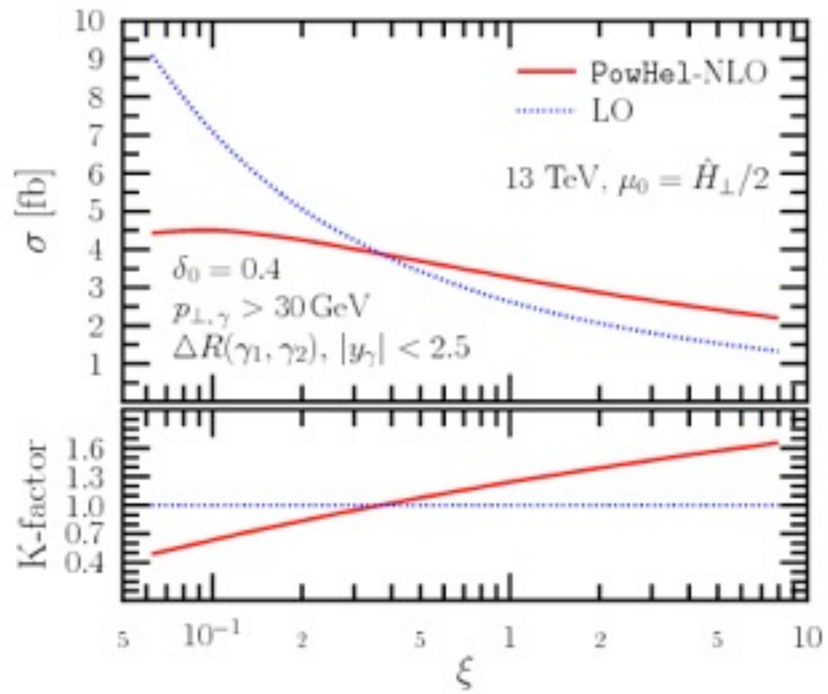
This observation has important consequences: it has been pointed out long ago that a simple separation of top production processes into pair and single top production becomes unphysical at NLO QCD if decays are allowed. The technical ability to describe the ``meta"-process pp-> WbWb exactly, forgoing simplifications offered by the narrow-width approximation, make it possible to base classification of relevant processes on the definition of the fiducial volume cross sections rather than on their partonic content.

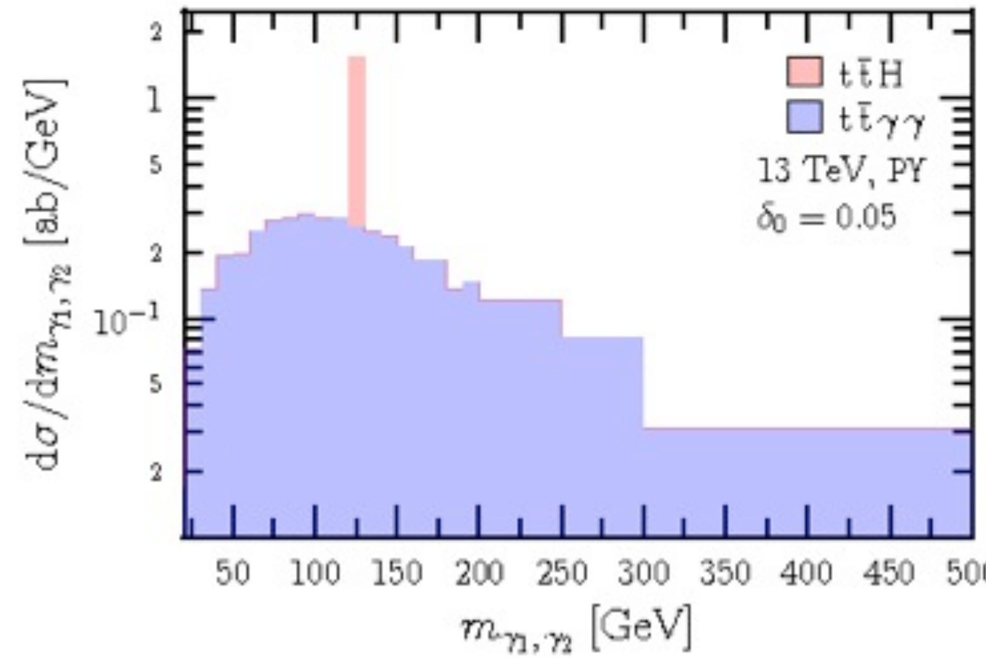


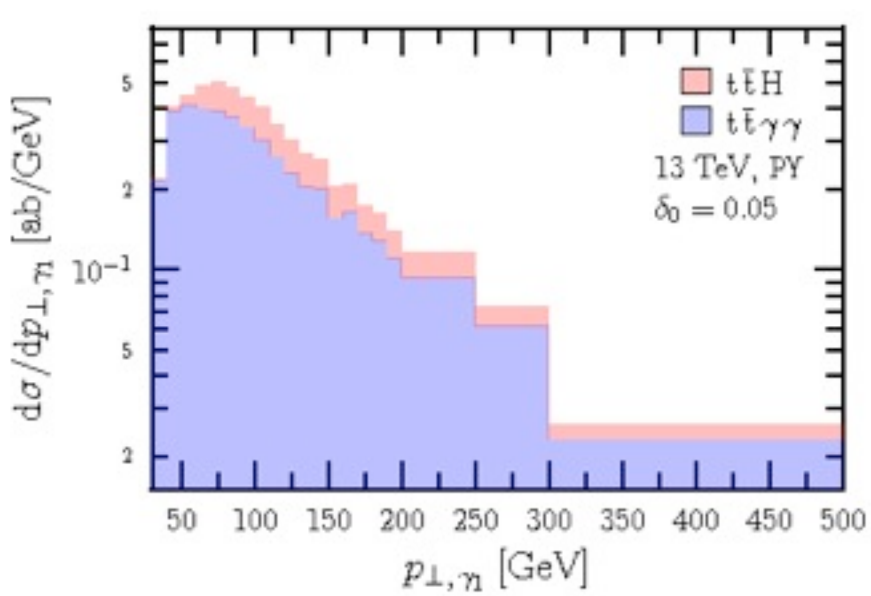
F. Cascioli, S. Kallweit, P. Maierhofer, S. Pozzorini

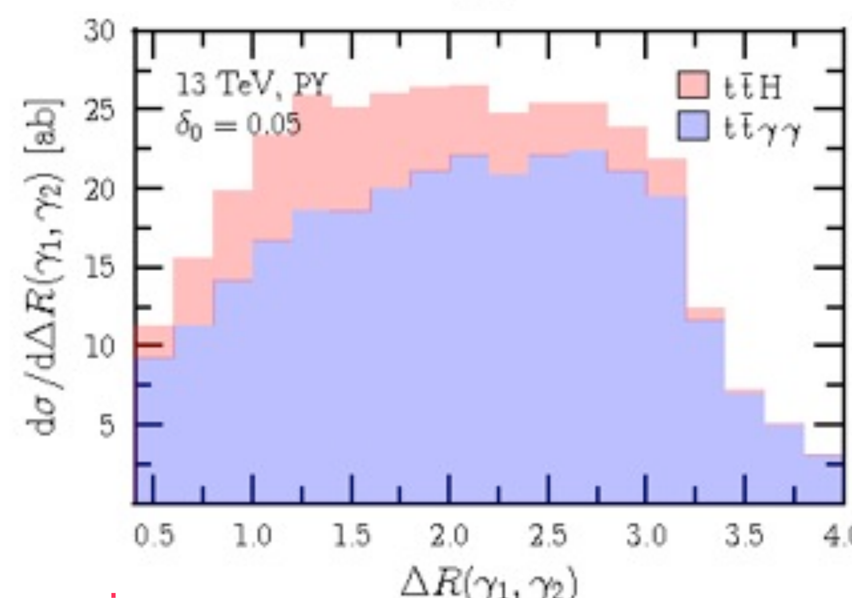
Top pair production in association with two photons

In certain cases, complicated signals and backgrounds can now be computed through NLO QCD and compared directly to each other. Below an example of pp -> tt + 2 gamma and pp -> tt H (2gamma) simulations at NLO QCD. Note that emissions of photons from decay products of top quarks is not included in the calculation (it is known to be significant).









Kardos, Troscanyi

BSM effects in top quark production and decay

BSM physics in top production and decay

Given the enormity of the BSM landscape, it may be useful to adopt a more humble approach in searching for new phenomena in top physics. The idea is to modify the Standard Model Lagrangian by introducing local (non-renormalizable) operators suppressed by powers of the energy scale of physics beyond the Standard Model.

Zhang, Willenbrock

Consider, for example, the top quark decay. The two dimension-six operators will affect the SM prediction for top decay and for W-boson helicity fractions.

$$\mathscr{O}^{(3)}_{\phi q} = i\left(\phi^\dagger \tau^i D_\mu \phi\right)\left(\bar{q}\gamma^\mu \tau^i q\right) + h.c. \qquad \mathscr{O}_{tW} = \bar{q}\sigma_{\mu\nu}\tau^i t\tilde{\phi}W_i^{\mu\nu},$$

$$\frac{\Gamma(t \to b e^+ \nu_e)}{GeV} = 0.1541 + \left[0.019 C^{(3)}_{\phi q} + 0.026 C_{tW} + 0 C^{(3)}_{ql}\right]\frac{\mathrm{TeV}^2}{\Lambda^2}.$$

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta} \equiv \frac{3}{8}(1+\cos\theta)^2 F_R + \frac{3}{8}(1-\cos\theta)^2 F_L + \frac{3}{4}\sin^2\theta F_0 \qquad F_0 = \frac{m_t^2}{m_t^2 + 2m_W^2} - \frac{4\sqrt{2}\mathrm{Re}C_{tW}v^2}{\Lambda^2 V_{tb}}\frac{m_t m_W (m_t^2 - m_W^2)}{(m_t^2 + 2m_W^2)^2},$$

$$\frac{C_{tW}}{\Lambda^2} = 0.088^{+0.44}_{-0.45}\mathrm{TeV}^{-2} \qquad \frac{C^{(3)}_{\phi q}}{\Lambda^2} = 0.3^{+1.4}_{-1.2}\mathrm{TeV}^{-2}$$

Degrande

Of course, such constraints are only possible if SM predictions for the relevant quantities are sufficiently precise. Asymptotically, one can only reach to the scales of new physics that are as high as the inverse square root of the error.

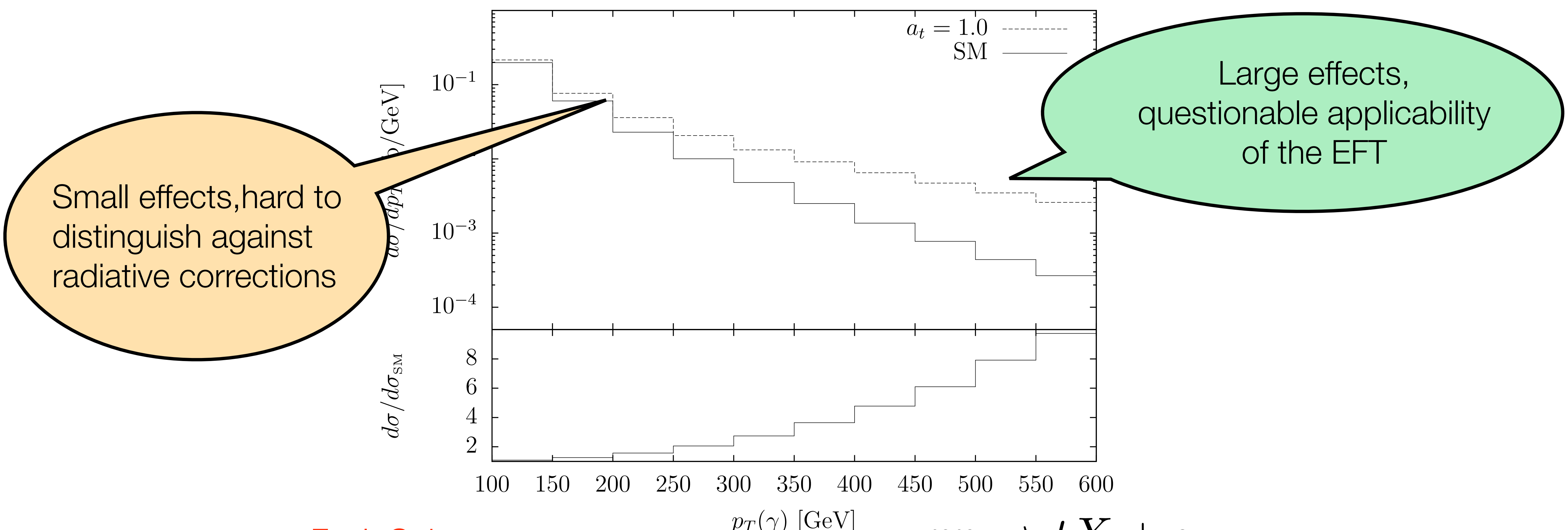
BSM physics in top production and decay

Of course, one can exploit the enhancement that occurs in kinematic distributions because one deals with higher-dimensional operators but it is not always clear if large effects are consistent with the applicability of effective field theory description.

An example: top quark with the anomalous magnetic moment.

$$\mathcal{L}_{tt\gamma} = -a_t \frac{Q_t e}{4m_t} \bar{t}\sigma_{\mu\nu} t F^{\mu\nu}$$

$$-3.0 < a_t < 0.45, \quad a_{t,\mathrm{SM}} \approx 0.03$$



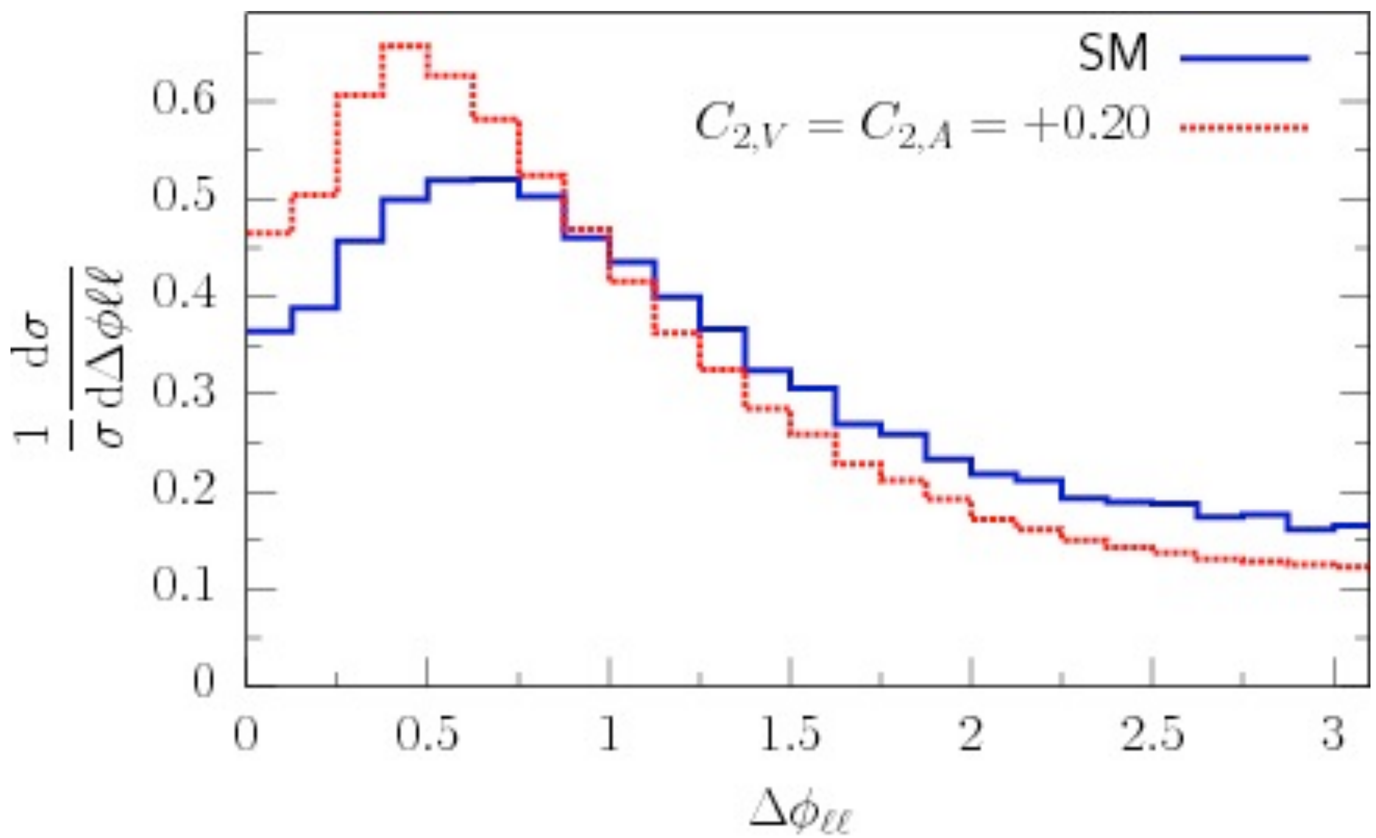
Fael, Gehrmann

$$pp \to tX + \gamma$$

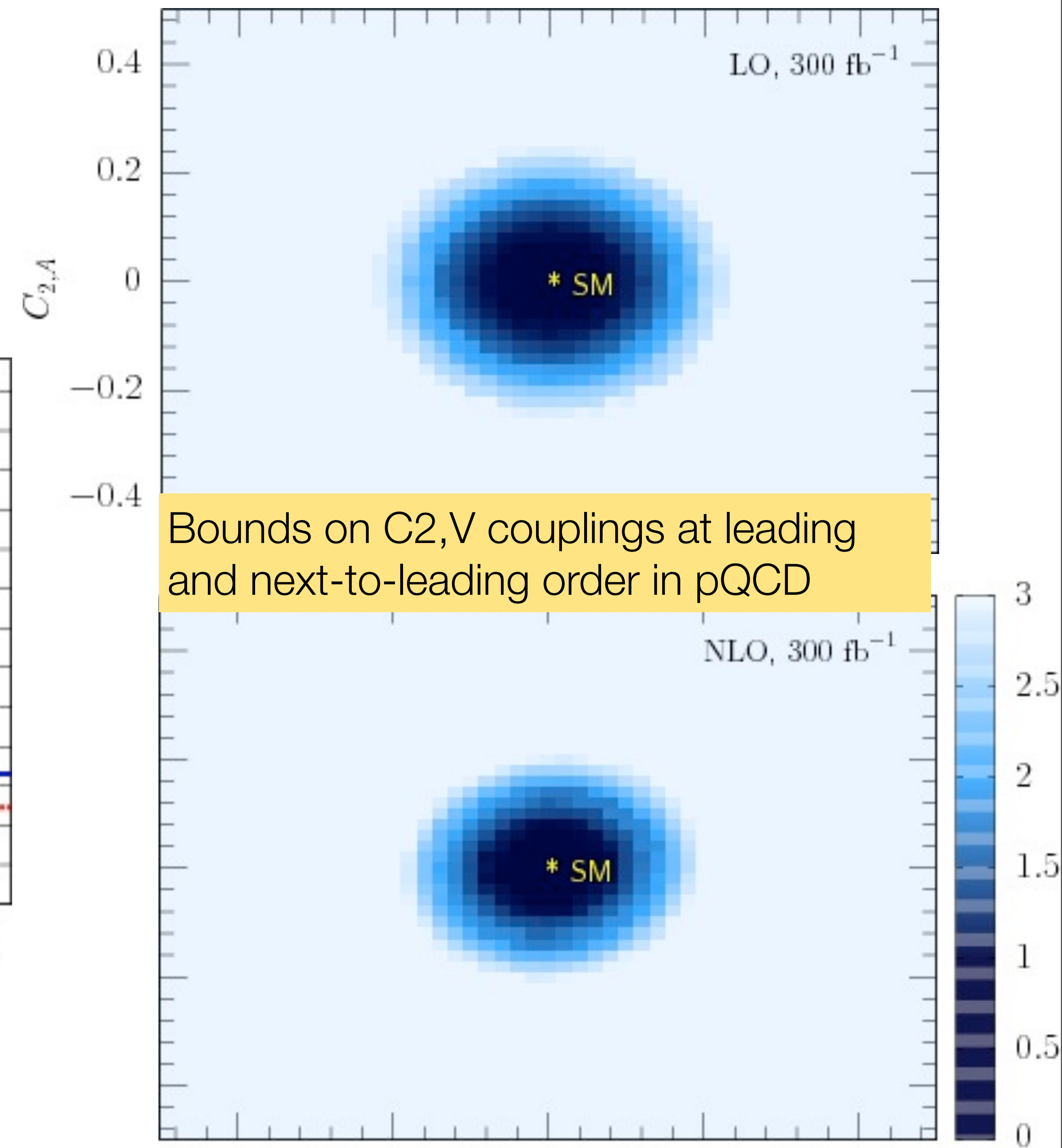
Higher orders and BSM tests for tops

Studies where BSM contributions are combined together with radiative corrections are starting to appear. One can argue that the coupling constants can be determined to a better precision when the NLO computations are available.

$$\mathcal{L}_{ttZ} = eC^{Z}_{2,V}\,\bar{u}(p_t)\frac{i\sigma^{\mu\nu}q_{\nu}}{M_Z}v(p_{\bar{t}})Z_{\mu}$$



Schulze, Rontsch



Bounds on C2,V couplings at leading and next-to-leading order in pQCD

Conclusions

There has been quite an impressive theoretical progress in our understanding of top quark physics:

1) Simple top quark observables are known with very high perturbative precision (NNLO QCD). Further progress will be related to making these contributions more realistic (e.g. decays, kinematic distributions etc.). This will require significant amount of effort to improve existing computational algorithms, but is otherwise straightforward.

2) Existing NNLO QCD computations already offer a variety of interesting physics insights -- from precise determination of important input parameters (PDFs, couplings) to the exclusion of exotic contributions to cross sections.

3) We need more thoughtful attitude to the extraction of the top quark mass. For practical purposes working with pole mass might be OK. We need theory of power corrections to hadron collider observables to move further.

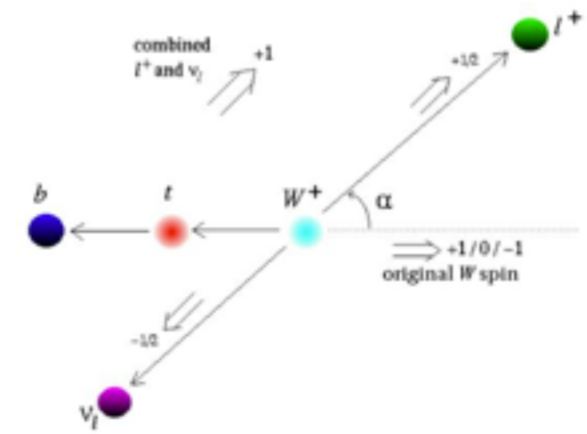
4) In many cases, complex processes with top quarks can be handled automatically through NLO QCD. In some cases this provides interesting physics insights and gives us more opportunities to properly define ``top cross sections". Again, more realism is desirable e.g. , top decays, gluon and photon emissions from top decay products etc.

5) BSM contributions to top production and decay described in EFT framework are starting being combined with NLO QCD computations; this increases the sensitivity of the LHC to Wilson coefficients of EFT operators in kinematic regimes where EFT framework is viable.

Top decays and W helicity fractions

Another interesting ``precision frontier'' is appearing in the studies of top quark decays where helicity fractions of W-bosons are measured.

$$\frac{\mathrm{d}\Gamma_t}{\mathrm{d}\cos\theta_l} = \Gamma_t \left\{ \frac{3}{4}\sin^2\theta_l F_L + \frac{3}{8}\left(1+\cos\theta_l\right)^2 F_+ + \frac{3}{8}\left(1-\cos\theta_l\right)^2 F_- \right\}$$



Theory predictions for helicity fractions are known through NNLO QCD.

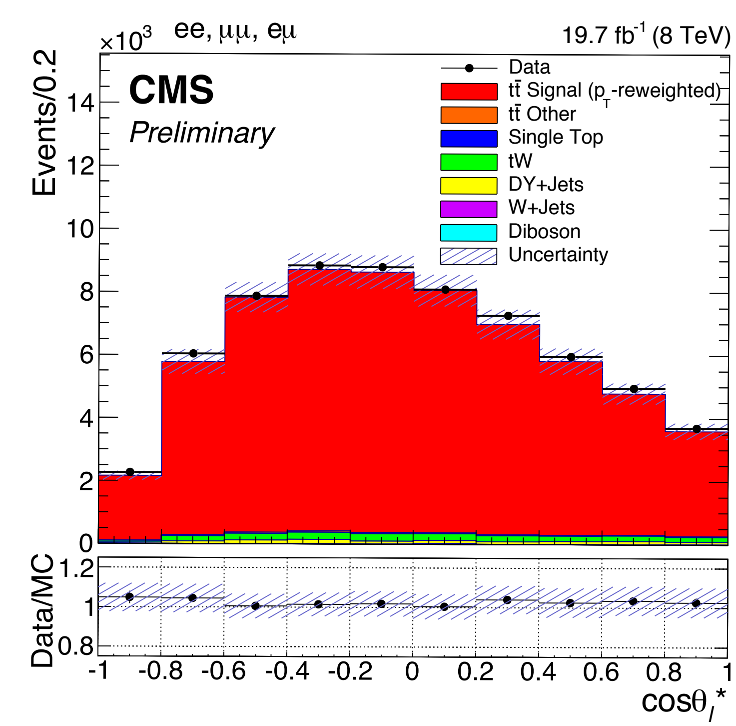
$$F_L = \frac{m_t^2}{m_t^2+2m_W^2}, \quad F_+ = 0, \quad F_- = \frac{2m_W^2}{m_t^2+2m_W^2}$$

$$F_L^{\rm NNLO} = 0.687(5), \quad F_+^{\rm NNLO} = 1.7(1)\times 10^{-3}, \quad F_-^{\rm NNLO} = 0.311(5)$$

Czarnecki, Koerner, Piclum

Measurements (at 20/fb) are approaching the 5% precision (example -- dilepton channel)

$$F_L^{\rm CMS} = 0.65(3), \quad F_+^{\rm CMS} = 0.018(26), \quad F_-^{\rm CMS} = 0.329(25)$$



Quoted results for NNLO helicity fractions are inclusive, which is not what is measured experimentally. Fully differential calculations for decay at NNLO exist, can (and perhaps should) be used for more detailed comparison.

Gao, Li, Zhu
Bruchersifer, Caola, Melnikov