Precise predictions of top quark fully differential decay

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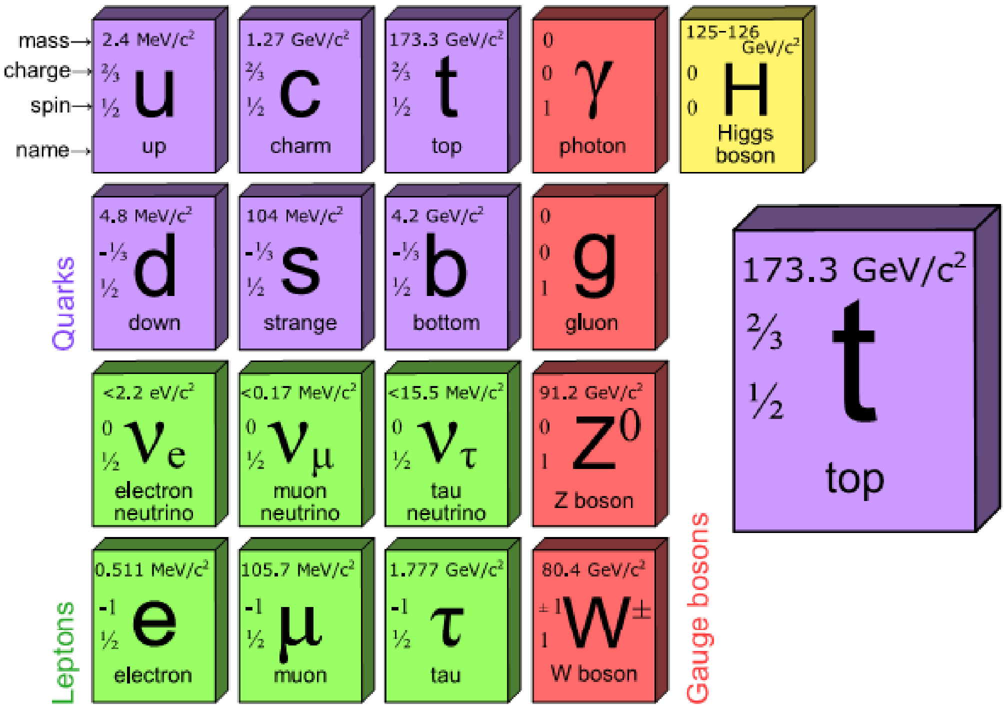
PHENO 2013, University of Pittsburgh, 2013/05/07

Outline

- **Why precise predictions for top quark decay are important?**
- **How to deal with the NNLO QCD corrections to fully-differential heavy-to-light quark decay?**
- **Application : the current most precise predictions for top quark fully-differential decay**
- **Conclusions and outlook**

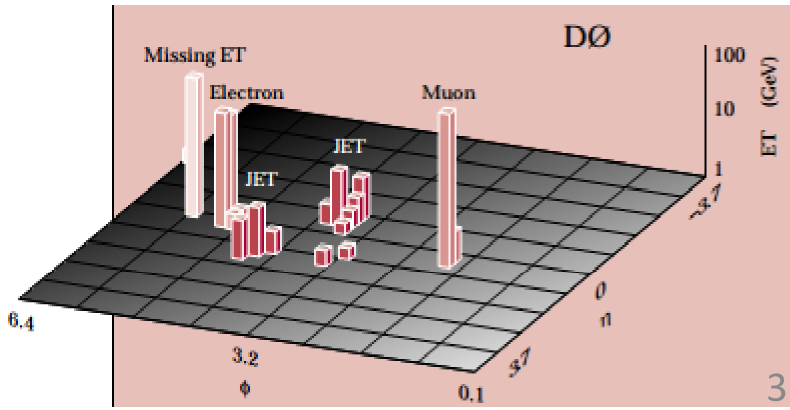
- # Top quark: unique probe at the LHC



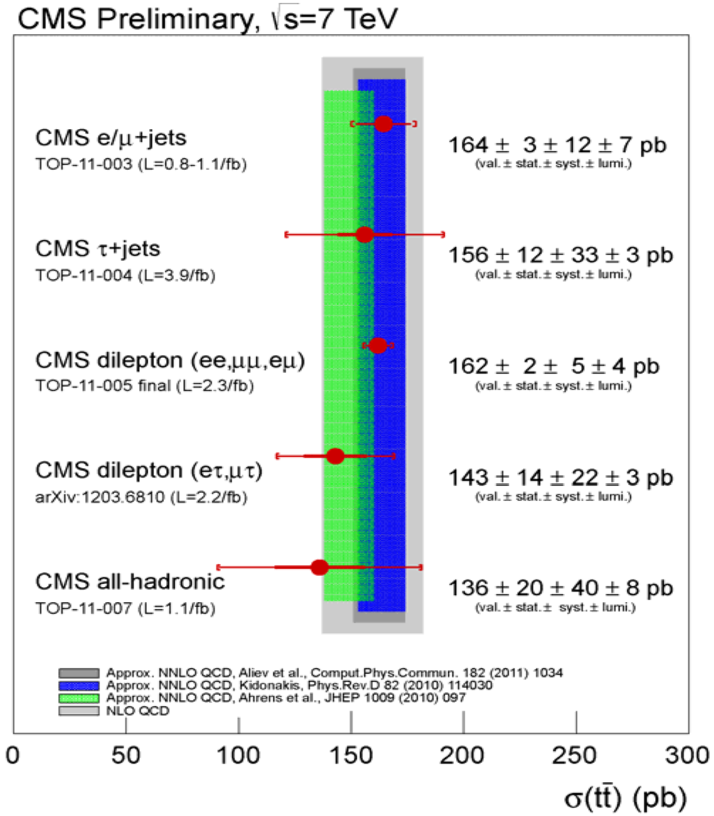
- Strongly interacted, high statistics ~950 pb @14 TeV with characteristic signature
- Short lifetime 5×10^{-25} s, decay before hadronization and depolarization, study properties of a free quark, test of pQCD
- Closely related to EWSB, involved in various new physics search

Tevatron 2012: 173.2 $\pm$ 0.6 $\pm$ 0.8 GeV

CMS 5.0 fb^{-1}: 173.4 $\pm$ 0.4 $\pm$ 0.9 GeV

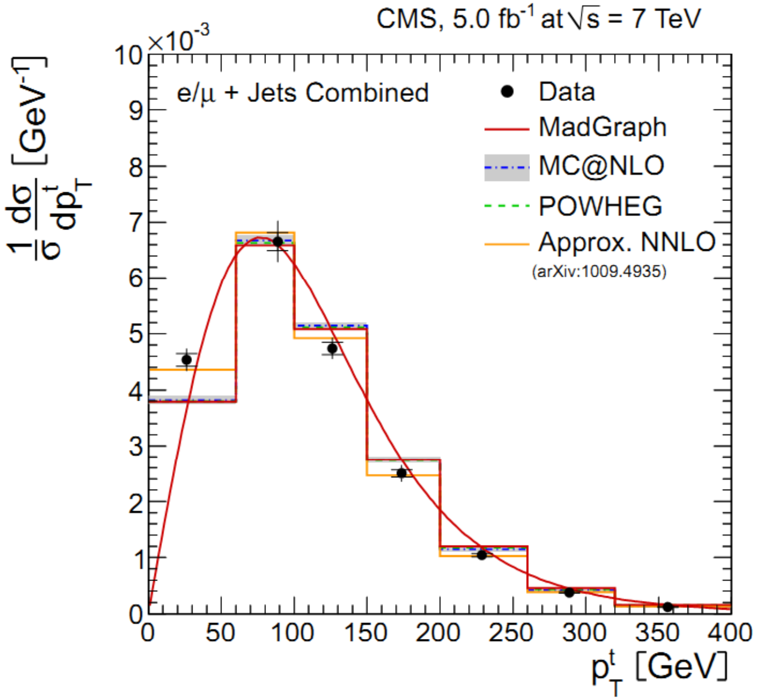


- **Top measurements at the LHC:**



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	$^{+22.7(2.4\%)}_{-33.9(3.6\%)}$	$^{+16.2(1.7\%)}_{-17.8(1.9\%)}$

Very precise measurements could be expected for inclusive rate as well as kinematic distributions

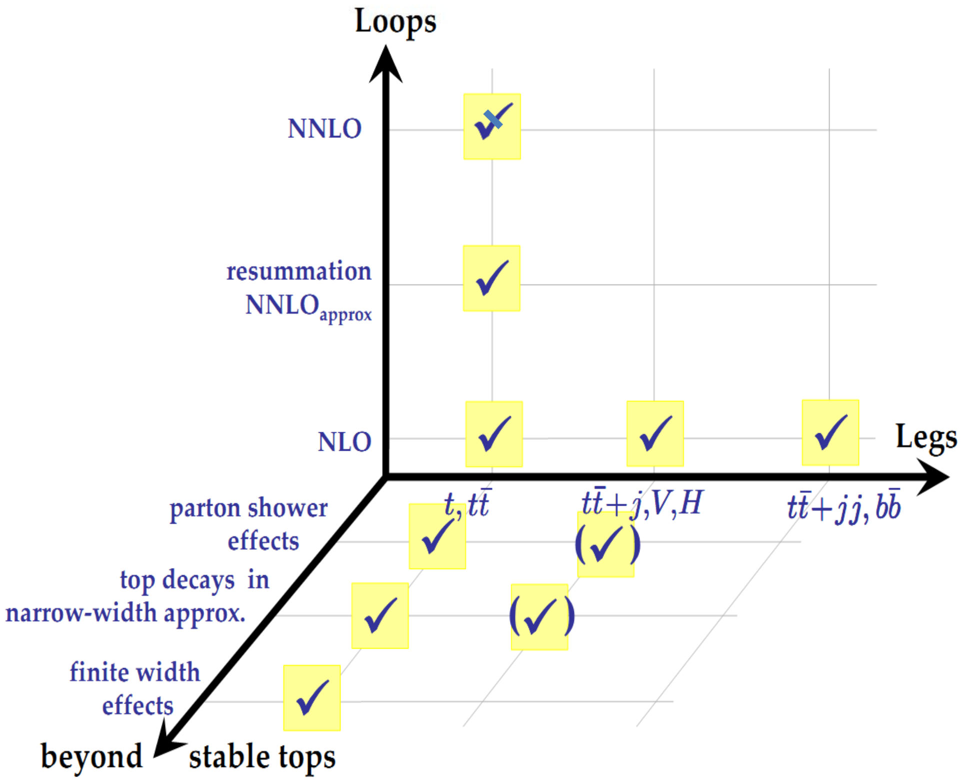


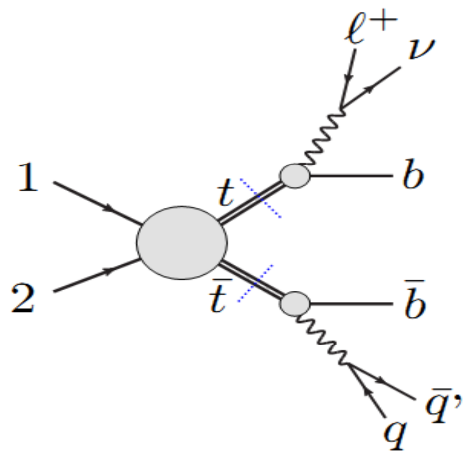
We need more and more precise theoretical predictions !!!

P. Barnreuther, M. Czakon, A. Mitov, P. Fiedler, 2012, 2013

• Precise predictions for top quark

Narrow-width approx., $\Gamma/M < 1\%$





Production with decay at NLO in QCD

Single top: Q. Cao, C.-P. Yuan, et.al., 2004, R. K. Ellis, et.al., 2004

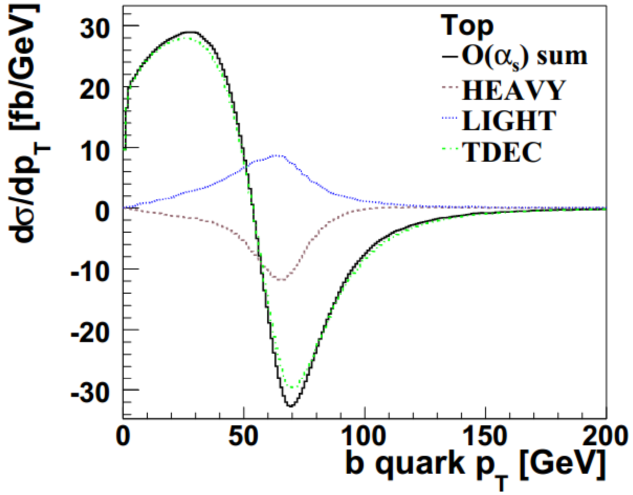
Top pair: K. Menikov, et.al., 2009, Z. G. Si, et.al., 2010

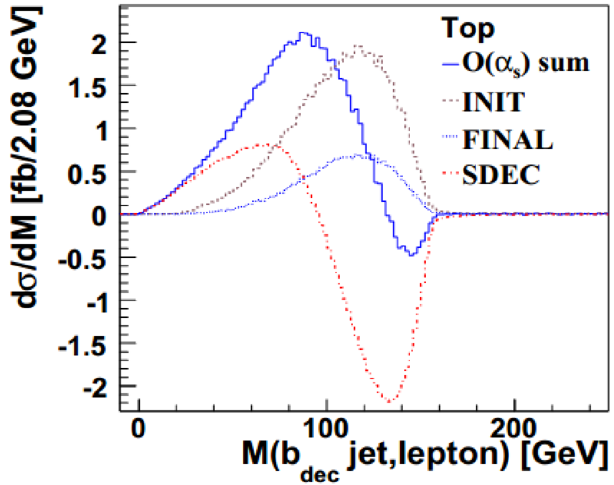
Top pair + j, A: K. Menikov, et.al., 2011

Beyond NW, NLO QCD corrections to WWbb production: A. Denner, et.al., 2010, G. Bevilacqua et al., 2010

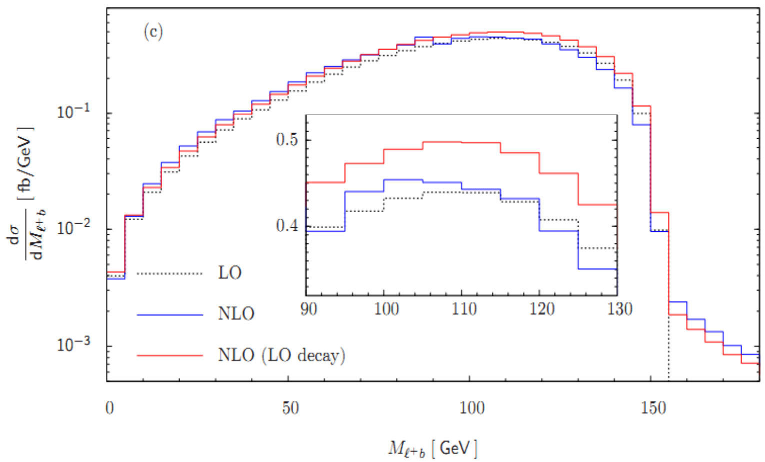
- # Examples showing effects of top quark decay

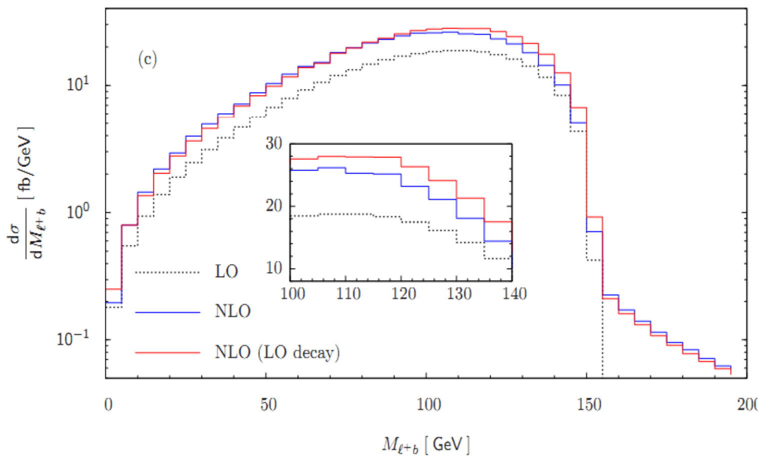
In single top quark production at the LHC: R. Schwienhorst, S. Heim, C.-P. Yuan, C. Muller, Q. Cao, 2010





In top quark pair production at the Tevatron and LHC: K. Melnikov, M. Schulze, 2009





• Fully differential decay of top quark at NNLO

➢ NNLO QCD corrections based on top quark self-energy (3-loop)

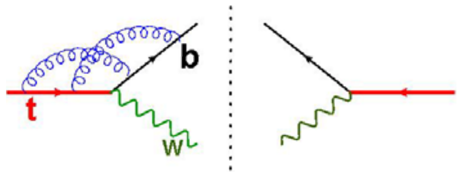
Inclusive width: A. Czarnecki and K. Melnikov, 1999 (M_W<<M_T); K. G. Chetyrkin, et. al., 1999, I. R. Blokland, et. al., 2004 (expansions on M_W/M_T);

Helicity fraction: A. Czarnecki, et. al., 2010 (expansions on M_W/M_T).

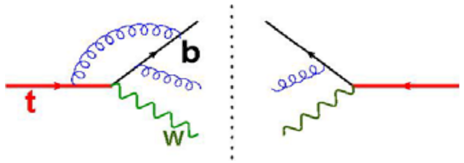
➢ First we work in the case of zero bottom quark mass and neglect the width of W boson. Both of these effects will be taken into account later through corrections to the LO results. W boson leptonic decay with full spin correlations are included.

➢ The contribution at NNLO can be divided into three classes:

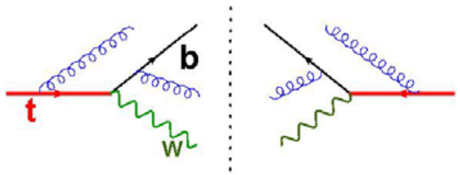
a) $t \to bW$ at two-loop and one-loop square



b) $t \to bWg$ at one loop

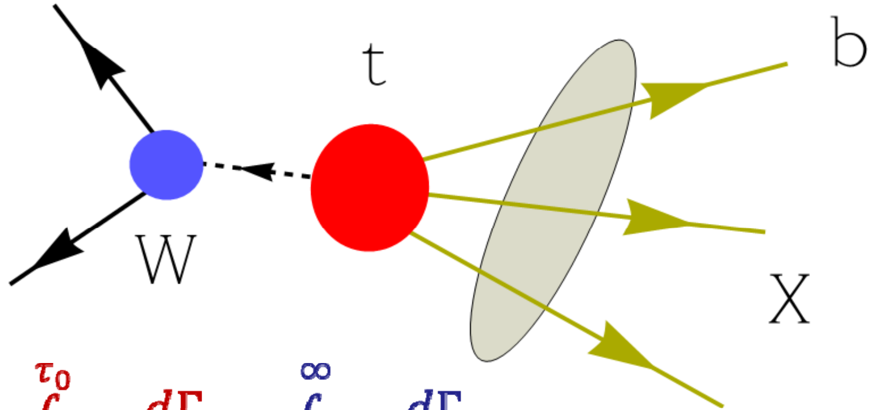


c) $t \to bWq\bar{q}/bWgg$ at tree level



- **Extract the double-unresolved singularities**

$$\tau = (p_b + p_X)^2 / m_t^2$$



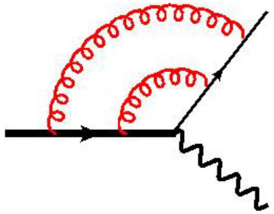
$$\Gamma_t^{NNLO} = \int_0^{\tau_0} d\tau \frac{d\Gamma_t}{d\tau} + \int_{\tau_0}^{\infty} d\tau \frac{d\Gamma_t}{d\tau} = \Gamma_A + \Gamma_B$$

- Motivated by qT subtraction, we introduce a phase space slicing method used for heavy-to-light decay by setting a small cut-off in τ ;
- Above the cut-off both the singly unresolved limit of b) and doubly unresolved limit of c) are absent, and the decay can be calculated using a NLO calculation of top decay with an additional jet;
- Below the cut-off, they are dominated by singular soft and/or collinear dynamics, the result can be predicted by QCD factorization.

• Threshold behaviors below the cut-off from SCET

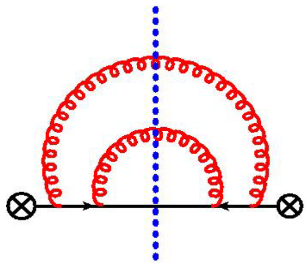
$$\frac{1}{\Gamma_t^{(0)}}\frac{\mathrm{d}\Gamma_t}{\mathrm{d}\tau} = \mathcal{H}\left(x \equiv \frac{m_W^2}{m_t^2}, \mu\right)\int \mathrm{d}k\,\mathrm{d}m^2 J(m^2,\mu)\, S(k,\mu)\, \delta\left(\tau - \frac{m^2 + 2E_J k}{m_t^2}\right) +$$ **Non-singular terms**

$\mathcal{H}(x,\mu)$: hard function. Integrating out hard modes of QCD in matching to SCET.



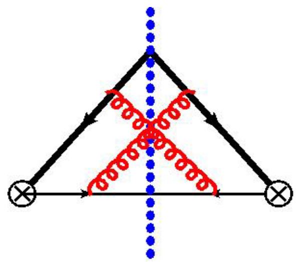
R. Bonciani et al , 2008; H. M. Asatrian et al,, 2008; M. Beneke et al, 2009; G. Bell,2009.

$\mathcal{J}(m^2,\mu)$: quark jet function. Probability of finding a jet with mass m, generated by collinear radiations.



T. Becher et al., 2006.

$\mathcal{S}(k,\mu)$: soft function. The probability of measuring the light-cone component of the soft radiation



T. Becher et al, 2006.

Expansion up to NNLO: free of divergences, with $\delta(\tau)$ and plus distributions $[\mathrm{Ln}^n(\tau)/\tau]_+$ up to $n=3$.

• Numerical results: total width

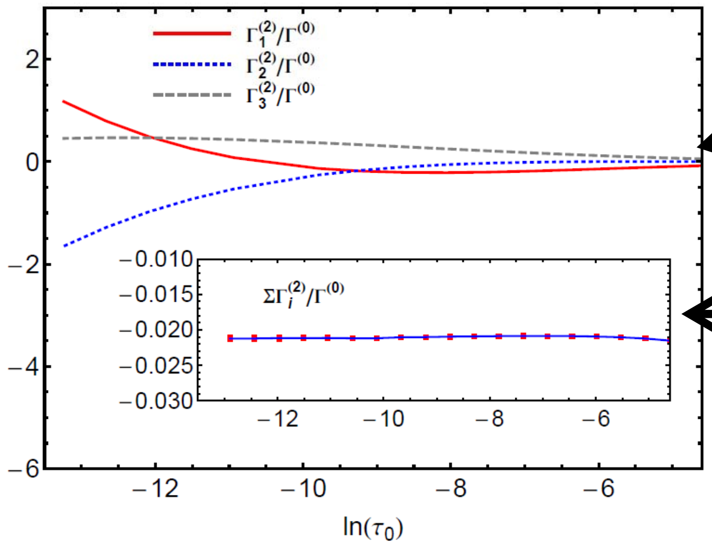
In percentage

GeV

m_t	$\Gamma_t^{(0)}$	δ_f^b	δ_f^W	δ_{EW}	$\delta_{QCD}^{(1)}$	$\delta_{QCD}^{(2)}$
172.5	1.4806	−0.26	−1.49	1.68	−8.58	−2.09
173.5	1.5109	−0.26	−1.49	1.69	−8.58	−2.09
174.5	1.5415	−0.25	−1.48	1.69	−8.58	−2.09

Full agreement with previous studies (NPB314,1 M.Jezabek;PRD43,3759 C.S.Li et al; NPB358 46 A. Denner et al; G. Eilam et al PRL 66,3105; NPB544,520 A.Czarnecki et al; PRD60, 114015 K. Chetyrkin; I.R. Blokland PRL 93,062001)

Cutoff τ_0 dependence

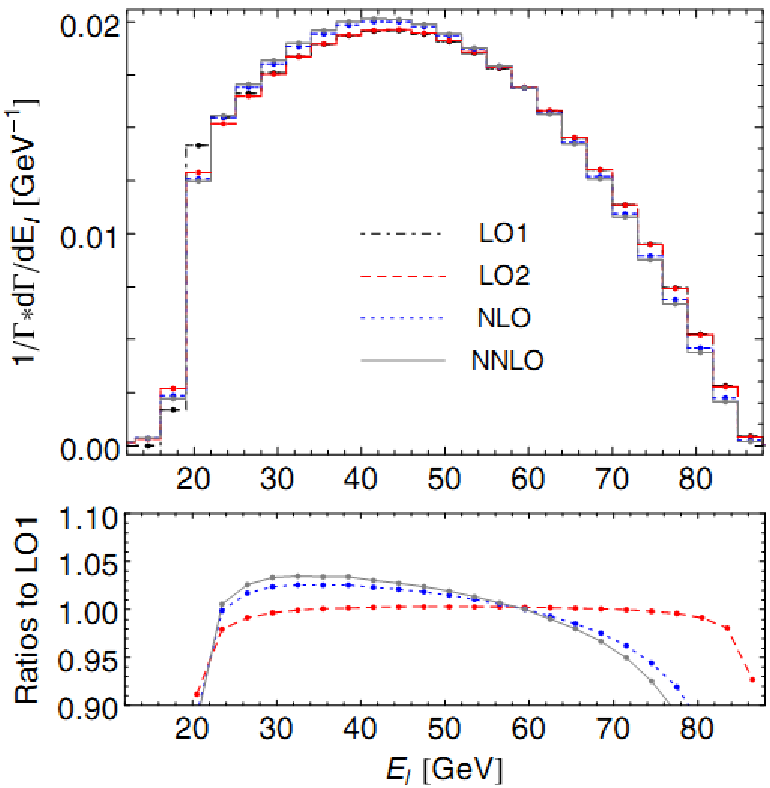


Each of the three contributions in the NNLO corrections depends strongly on the cut-off parameter

While their sum only shows very weak dependence

• Numerical results: differential distributions

Distributions of top quark semileptonic decay **$t \rightarrow W^+(l^+\nu)+b$** up to NNLO in QCD, also including other corrections as in the case of total width. All distributions are normalized to unit area for shape comparisons.



Normalized distribution of charged lepton energy in top quark rest frame

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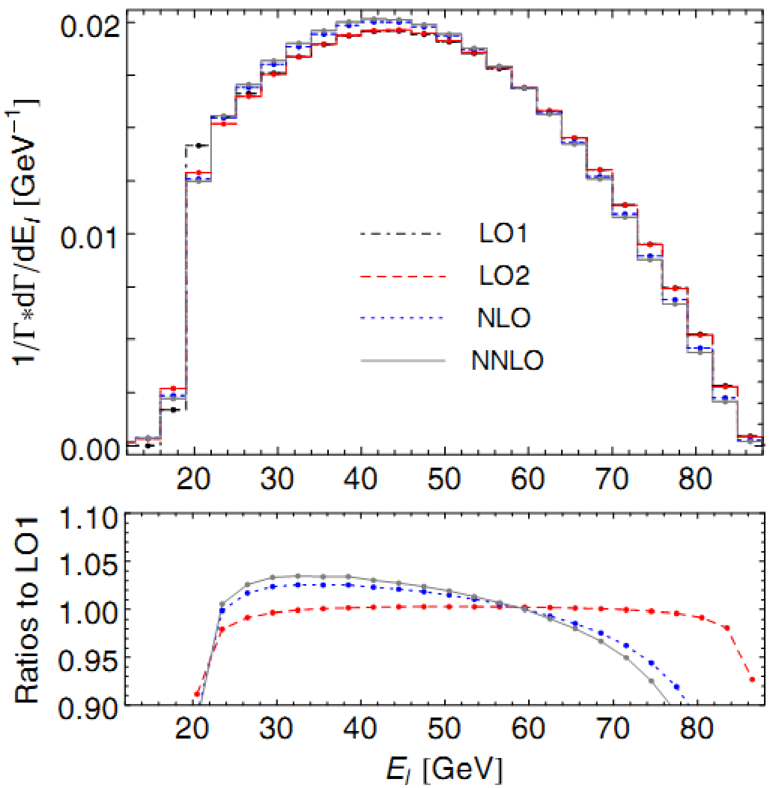

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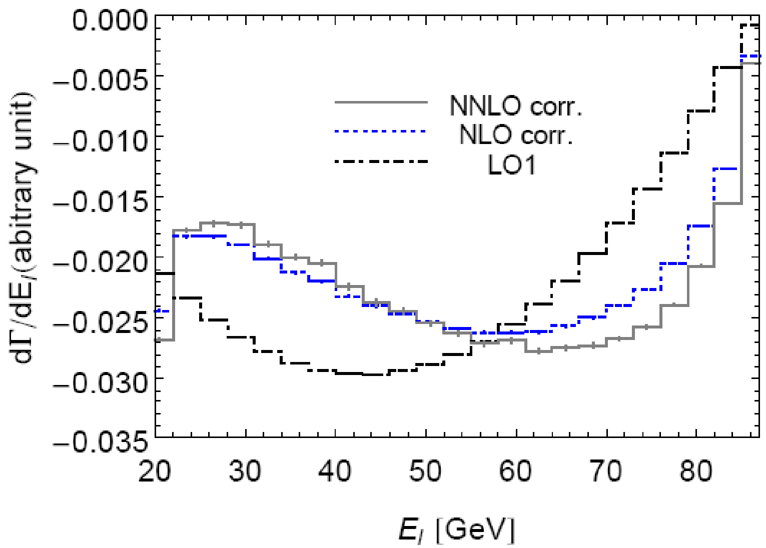
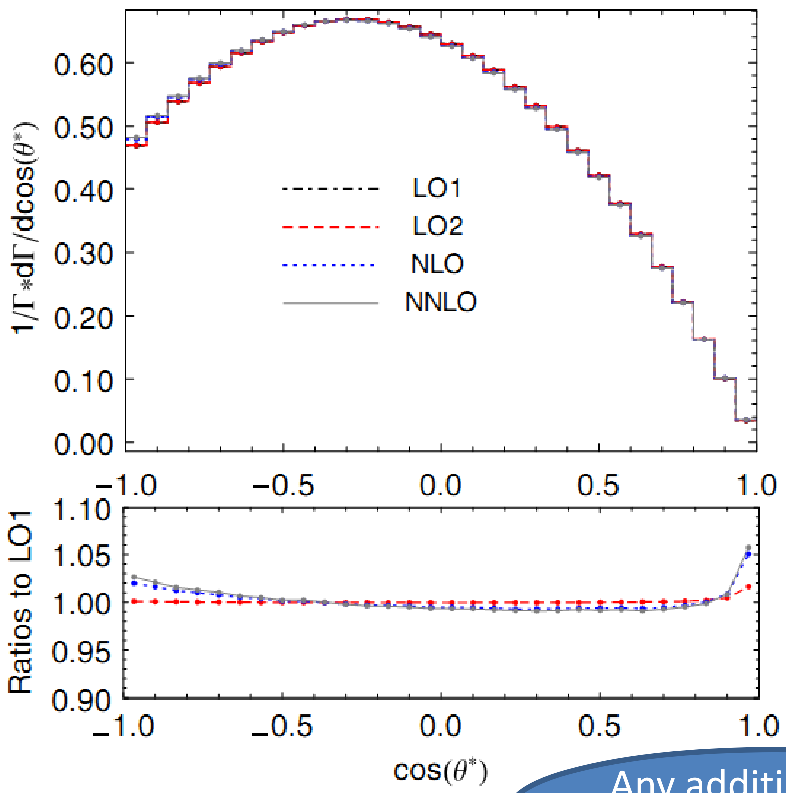


Shape of corrections at each order

- # Numerical results: differential distributions

Decay angle between charged lepton and the opposite of top quark momentum in W boson rest frame:

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta^*} = \frac{3}{4}\left(1-\cos^2\theta^*\right) F_0 + \frac{3}{8}\left(1-\cos\theta^*\right)^2 F_\mathrm{L} + \frac{3}{8}\left(1+\cos\theta^*\right)^2 F_\mathrm{R}$$



$$F_0 = 0.67 \pm 0.03\ (\mathrm{stat.}) \pm 0.06\ (\mathrm{syst.})$$
$$F_\mathrm{L} = 0.32 \pm 0.02\ (\mathrm{stat.}) \pm 0.03\ (\mathrm{syst.})$$
$$F_\mathrm{R} = 0.01 \pm 0.01\ (\mathrm{stat.}) \pm 0.04\ (\mathrm{syst.})$$

ATLAS, 1.04fb^{-1},1205.2484

W boson helicity fractions directly got from fit of our numerical curves:

- LO1: 0.6996(L), 0.3004(-), 0(+)
- LO2: 0.6989(L), 0.3007(-), 0.0004(+)
- NLO: 0.6914(L), 0.3072(-), 0.0014(+)
- NNLO: 0.6889(L), 0.3094(-), 0.0017(+)

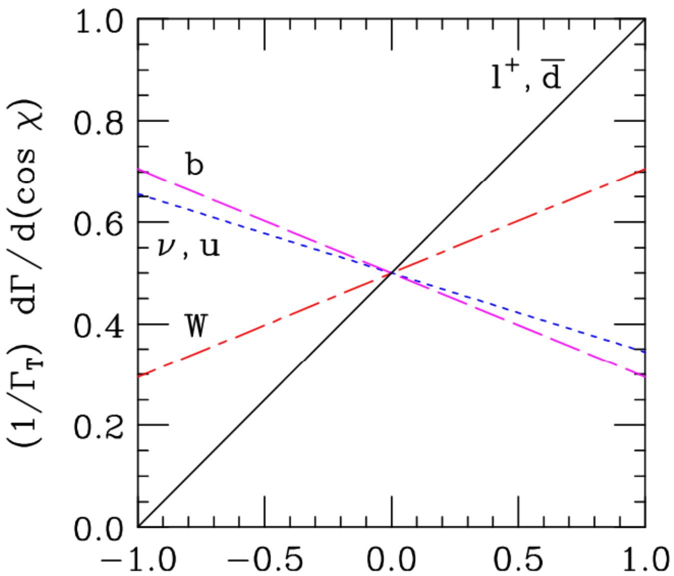
Agree with PRD81, 111503 A. Czarnecki et al.

Any additional cuts can be applied

• Numerical results: polarized top quark decay

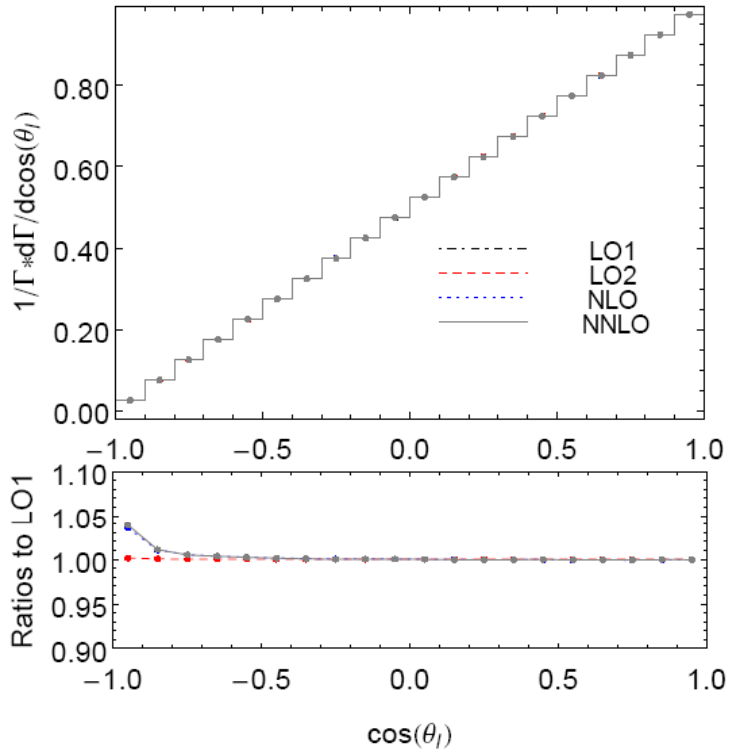
Decay angle with respect to the top quark spin direction in top rest frame:

$$\frac{1}{\Gamma_T}\frac{d\Gamma}{d(\cos\chi_i^t)} = \frac{1}{2}\left(1 + \alpha_i \cos\chi_i^t\right)$$



The charged lepton direction is maximally correlated with the top quark spin, α=1 exactly at LO. (M. Jezabek , et. al., 1994)

Validation of top spin effects at NNLO



- LO1: α=1
- LO2: α=1
- NLO: α=0.9982
- NNLO: α=0.9980

• Conclusions and outlook

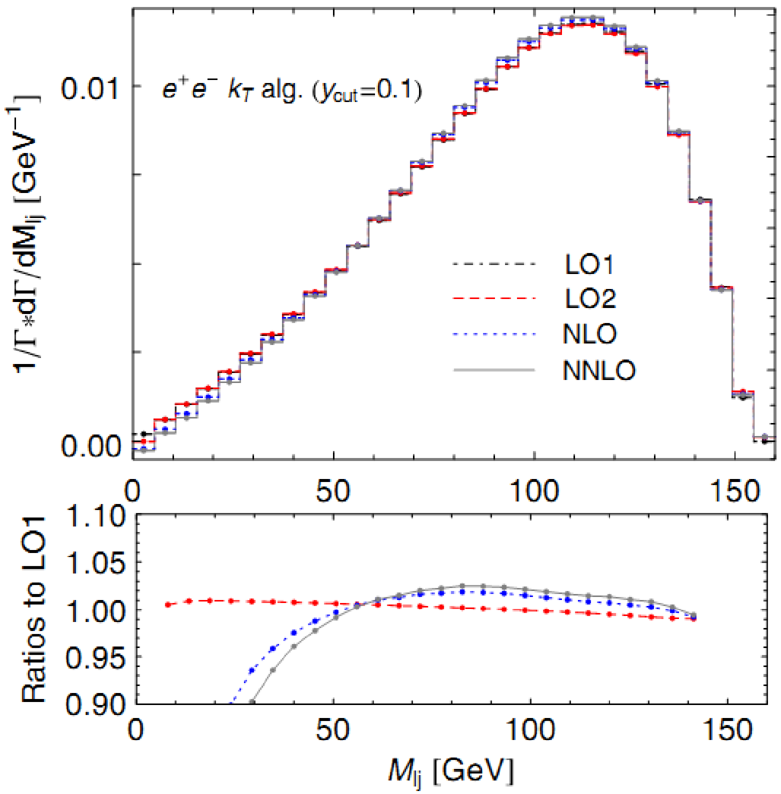
- We provide the current most precise fully-differential predictions for top quark semileptonic decay, including NNLO QCD effects as well as other important corrections, which are helpful for top quark mass measurement and the test of weak-charged current structure.

- Another direct application of the calculation is for NNLO corrections to b-quark semileptonic decay, $b \rightarrow X_u l^- v$.

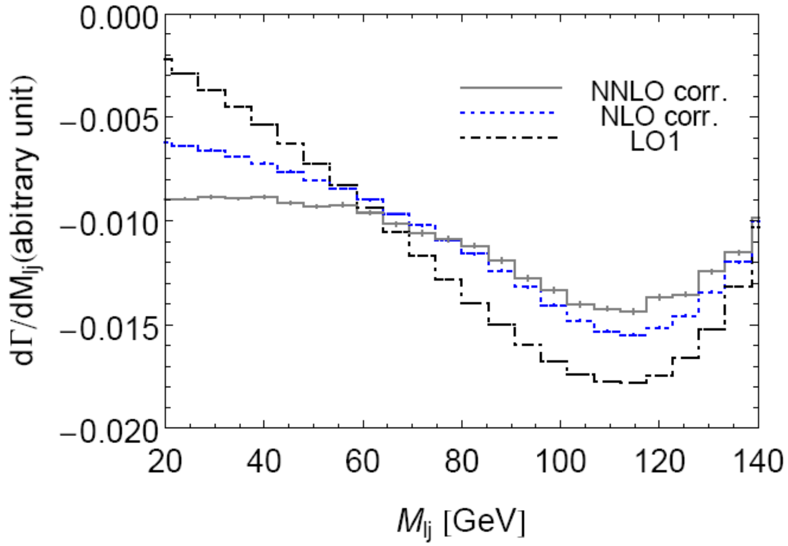
- Our calculations (MC code is publically available at Hepforge) are complementary to the NNLO QCD predictions for top quark pair production and could be eventually used for combination of top quark production and decay at NNLO in QCD.

- **Numerical results: differential distributions**

Distributions of top quark semileptonic decay **$t \rightarrow W^+(l^+\nu)+b$** up to NNLO in QCD, also including other corrections as in the case of total width. All distributions are normalized to unit area for shape comparisons.



Normalized distribution of invariant mass of charged lepton and the hardest jet



Shape of corrections at each order