Linear Collider Workshop 2012

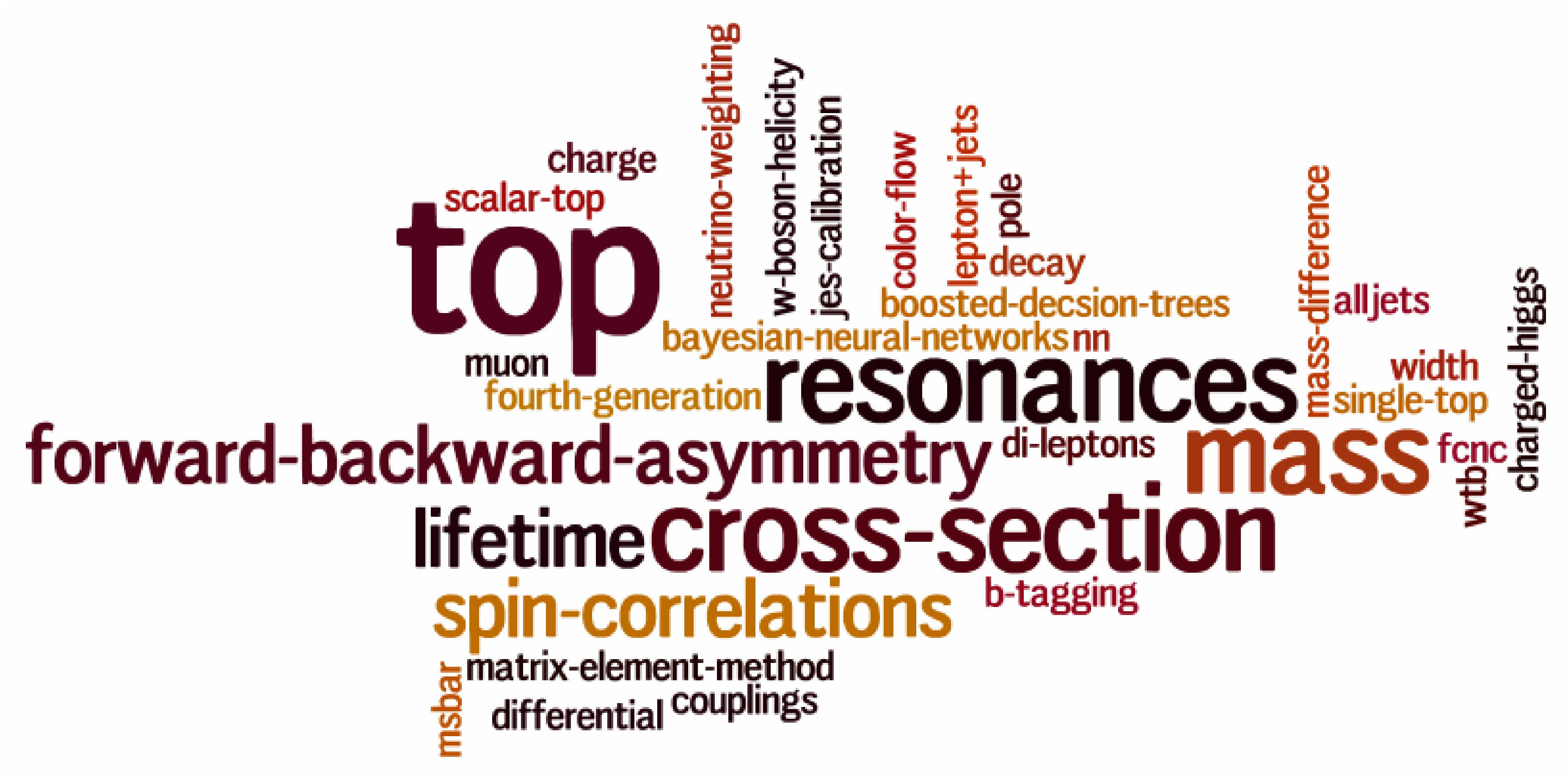
Loops, Top and QCD

Higher Order Corrections to Top Quark Production at Hadron Colliders

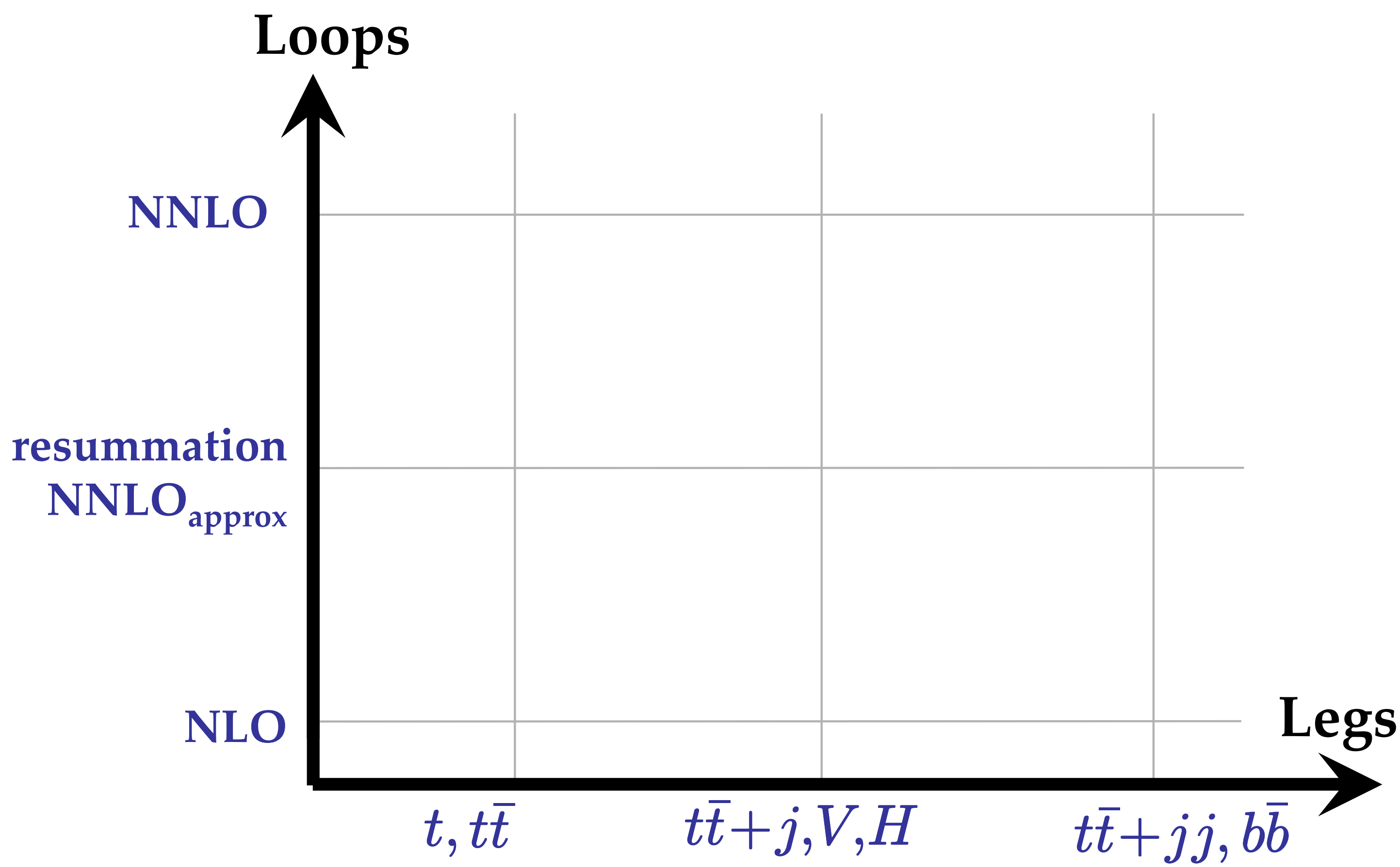
Markus Schulze

Argonne NATIONAL LABORATORY

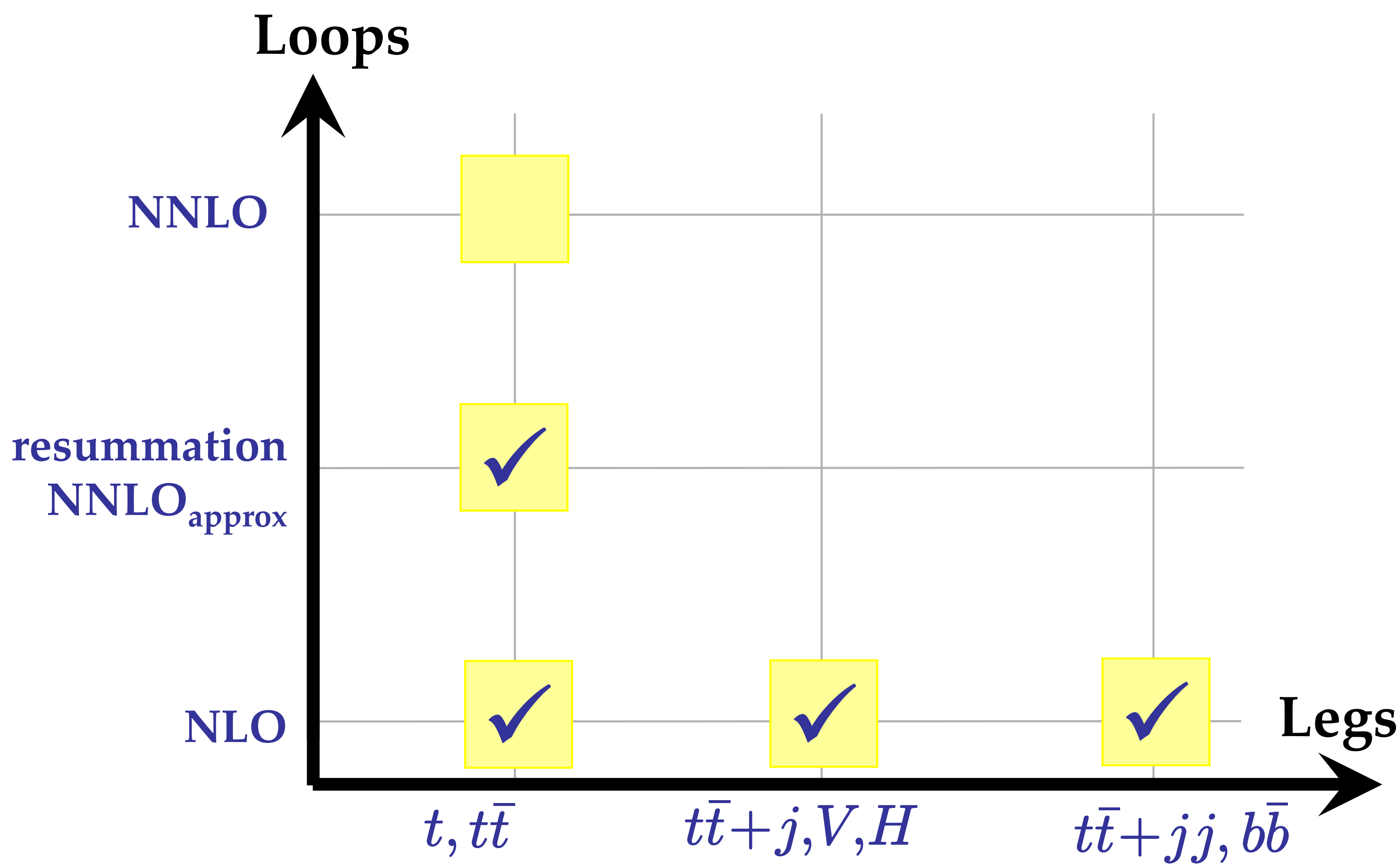
Top quark physics: a wide field



Directions


Loops
NNLO
resummation
$NNLO_{approx}$
NLO
Legs
$t, t\bar{t}$
$t\bar{t}+j, V, H$
$t\bar{t}+jj, b\bar{b}$

Directions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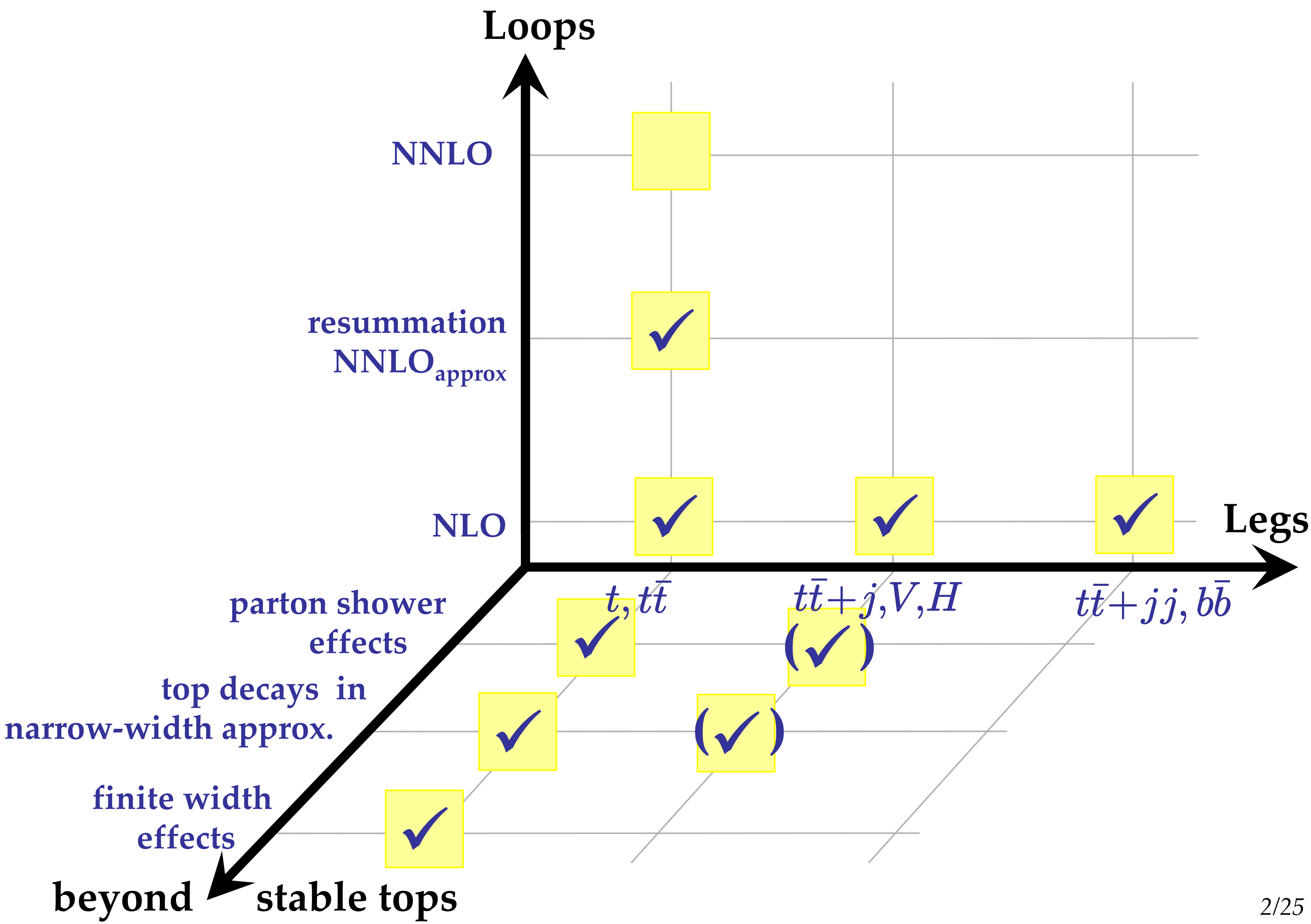
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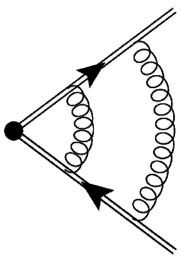
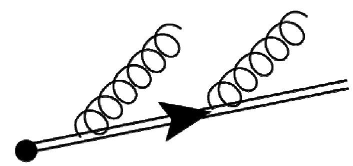
parton shower effects
top decays in narrow-width approx.
finite width effects
beyond stable tops
✓
(✓)

Loops:
Towards $t\bar{t}$ production at NNLO QCD

Resummation and $\text{NNLO}_{\text{approx}}$



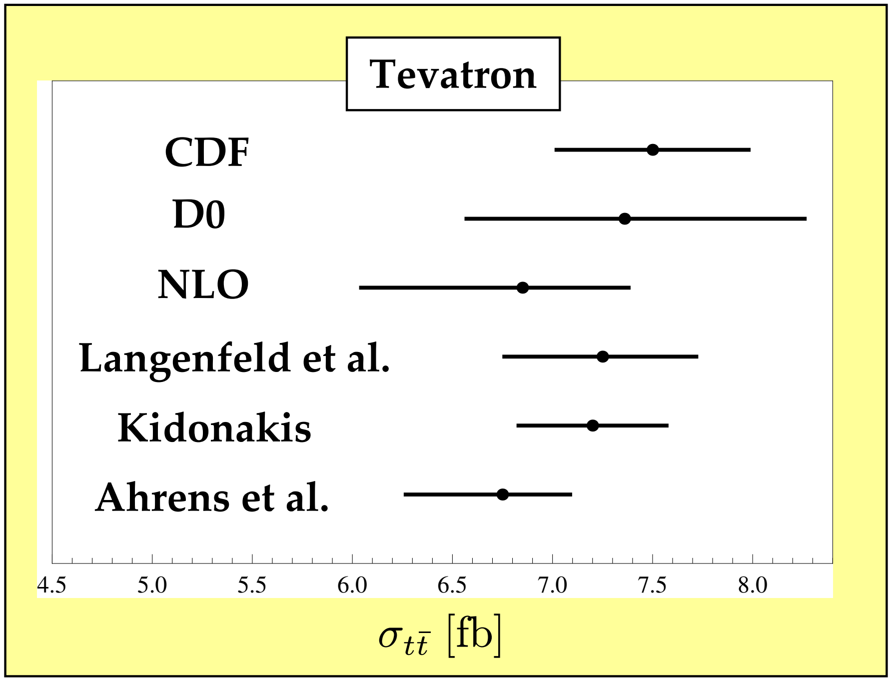
Close to threshold, the total cross section receives velocity (β) enhanced contributions due to Coulomb interaction and soft gluon emission



$$\sigma^{(2)} \sim \sigma_{\text{LO}} + \frac{\alpha_s}{4\pi}\left(\# \frac{1}{\beta} + \# \log^{1,2}(\beta) + \text{finite}\right)$$

$$+ \left(\frac{\alpha_s}{4\pi}\right)^2 \left(\# \frac{1}{\beta^2} + \frac{1}{\beta}\{\# + \# \log^{1,2}(\beta)\} + \# \log^{1,2,3,4}(\beta) + \text{finite}\right)$$

Resummation and NNLO$_{approx}$



[Bonciani,Catani,Mangano,Nason]

[Langenfeld,Moch,Uwer]

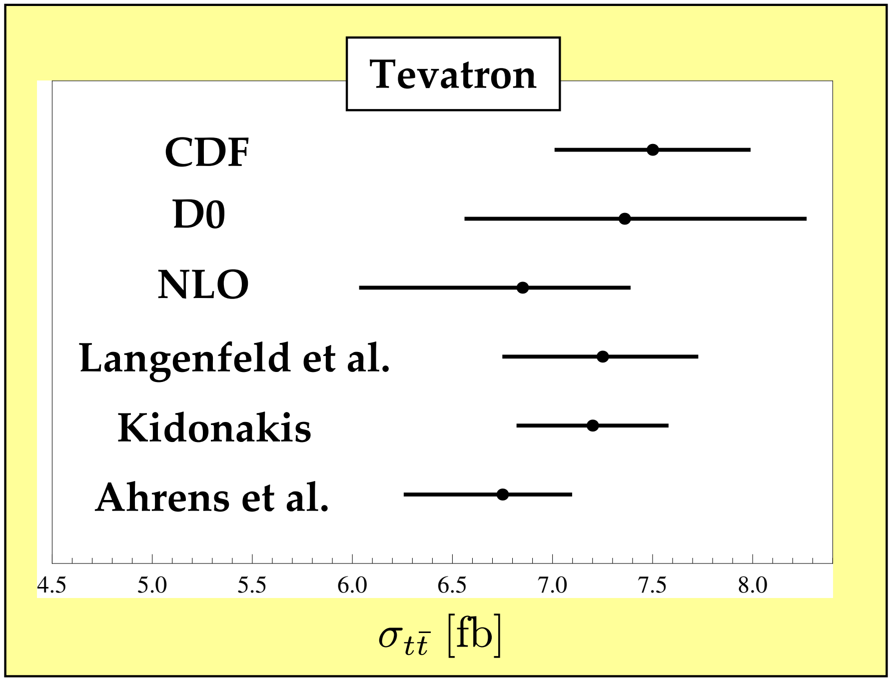
[Beneke,Czakon,Falgari,Klein,Mitov,Schwinn]

[Kidonakis]

[Ahrens,Ferroglia,Neubert,Pecjak,Yang]

Slightly different central values result from ambiguities in treating approximate higher order contributions. At the Tevatron, the spread of different results is about as large as NLO uncertainty.

Resummation and $\text{NNLO}_{\text{approx}}$



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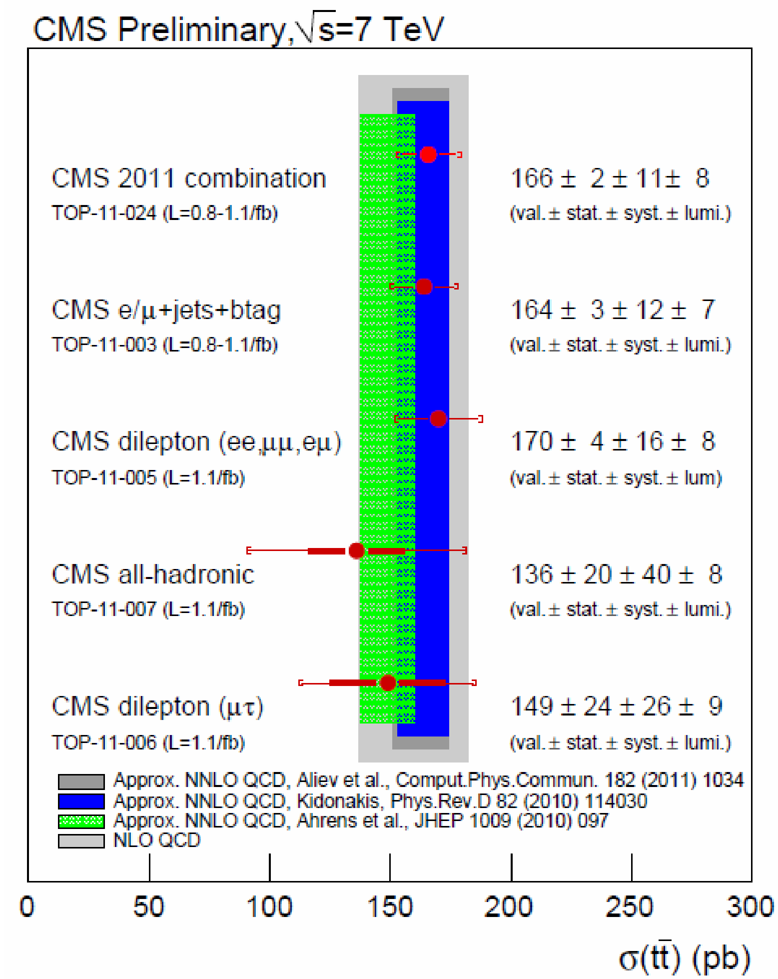
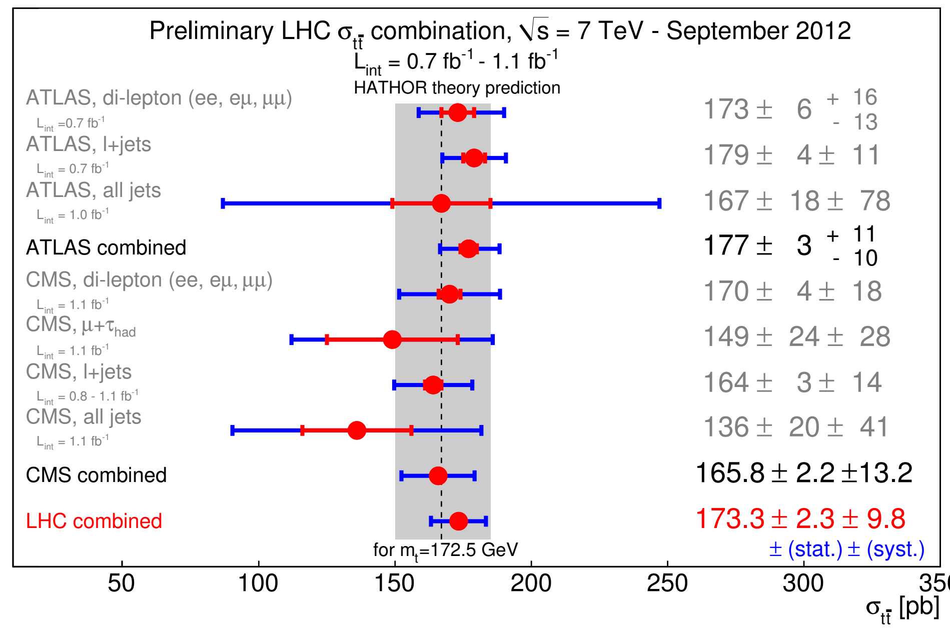
[Kidonakis]
[Ahrens,Ferroglia,Neubert,Pecjak,Yang]

	$A_{\text{FB}}^{p\bar{p}}$ [%]
NLO	$4.81^{+0.45+0.13}_{-0.39-0.13}$
NLO+NNLL	$4.88^{+0.20+0.17}_{-0.23-0.18}$
$\text{NNLO}_{\text{approx.}}$	$5.2^{+0.0}_{-0.6}$

Slightly different central values result from ambiguities in treating approximate higher order contributions. At the Tevatron, the spread of different results is about as large as NLO uncertainty.

Resummation and NNLO$_{\text{approx}}$

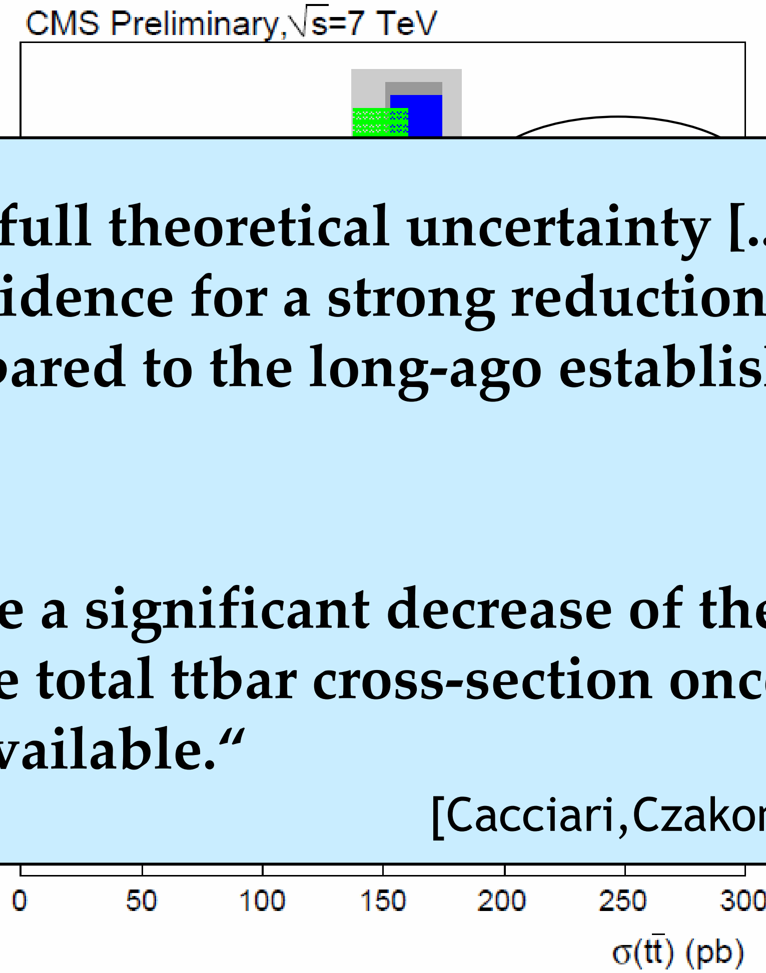




$$\sigma_{\text{tot}}^{\text{NLO+NNLL}}(7\,\text{TeV}) = 158.7^{+12.2(7.7\%)}_{-13.5(8.5\%)}\ [\text{scale}]\ ^{+4.3(2.7\%)}_{-4.4(2.8\%)}\ [\text{MSTW pdf}]\ \ \text{pb}$$

[Cacciari,Czakon,Mangano,Mitov,Nason] (2011)

Resummation and NNLO$_{\text{approx}}$



"Addressing the full theoretical uncertainty [...], we conclude that we see no evidence for a strong reduction of the theoretical uncertainty compared to the long-ago established NLO+NLL analysis."

"We [...] speculate a significant decrease of the theoretical uncertainty in the total ttbar cross-section once the full NNLO result becomes available."

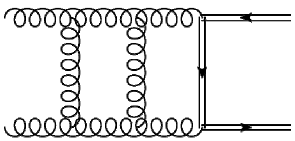
[Cacciari,Czakon,Mangano,Mitov,Nason]

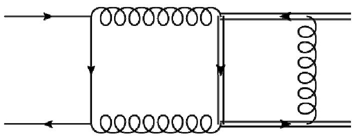
$$\sigma_{\text{tot}}^{\text{NLO+NNLL}}(7\,\text{TeV}) = 158.7^{+12.2(7.7\%)}_{-13.5(8.5\%)}\ [\text{scale}]\ ^{+4.3(2.7\%)}_{-4.4(2.8\%)}\ [\text{MSTW pdf}]\ \ \text{pb}$$

[Cacciari,Czakon,Mangano,Mitov,Nason] (2011)

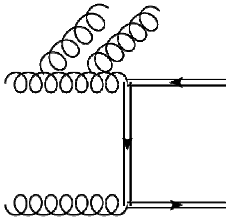
Full NNLO QCD

1. two-loop virtual correction

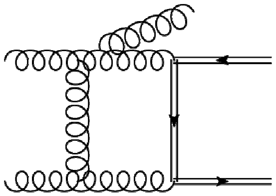




2. double-real emission



3. real-virtual (one-loop) corrections



Full NNLO QCD

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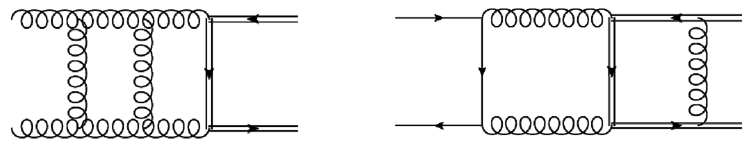


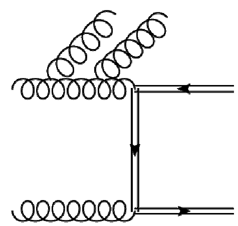
$q\bar{q}$ numerical [Czakon] (2008)

partial analytic [Bonciani,Ferroglia,Gehrmann,Maitre,Studerus] (2008-9)

gg numerical [Czakon,Mitov,Moch] (2007)

analytic leading-N_c [Bonciani,Ferroglia,Gehrmann,Manteuffel,Studerus] (2010)

2. double-real emission



antenna subtraction [Boughezal,Gehrmann-DeRidder,Ritzmann], [Glover,Pires] (2004-12)

stripper approach [Czakon] (2011)

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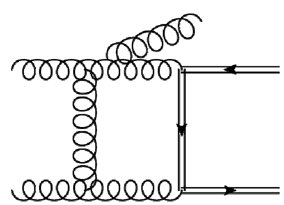


[Dittmaier,Uwer,Weinzierl], [Melnikov, M.S], [Körner,Merebashvili,Rogal], [Bevilacqua,Czakon,Papadopoulos,Worek] (2007,10)

one-loop soft/collinear limits

[Bern,DelDuca,Kilgore,Schmidt] (1989), [Catani,Grazzini] (2000), [Boughezal,Melnikov,Petriello] (2011)

[Bierenbaum,Czakon,Mitov] (2011), [Gehrmann,Monni] (2011)

Full NNLO QCD

Since 2011, a complete set of tools/techniques is available to calculate the *full* NNLO corrections to hadronic ttbar production.

This project is undertaken by M.Czakon, P. Bärnreuther, A. Mitov

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

Current status:

- qqb and qq channels: done (published)
- qg and qbg channels: to appear soon
- gg channels: work in progress

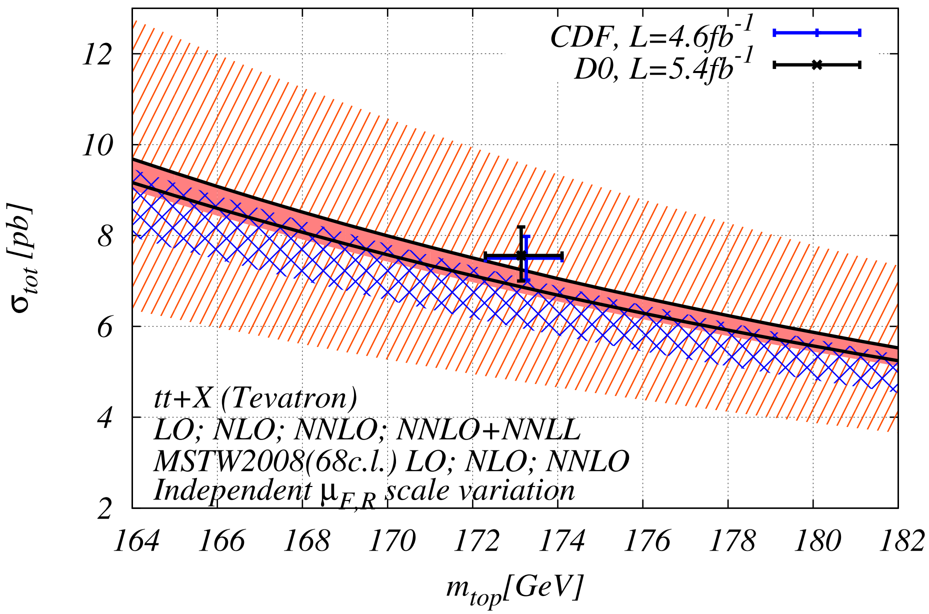
Full NNLO QCD

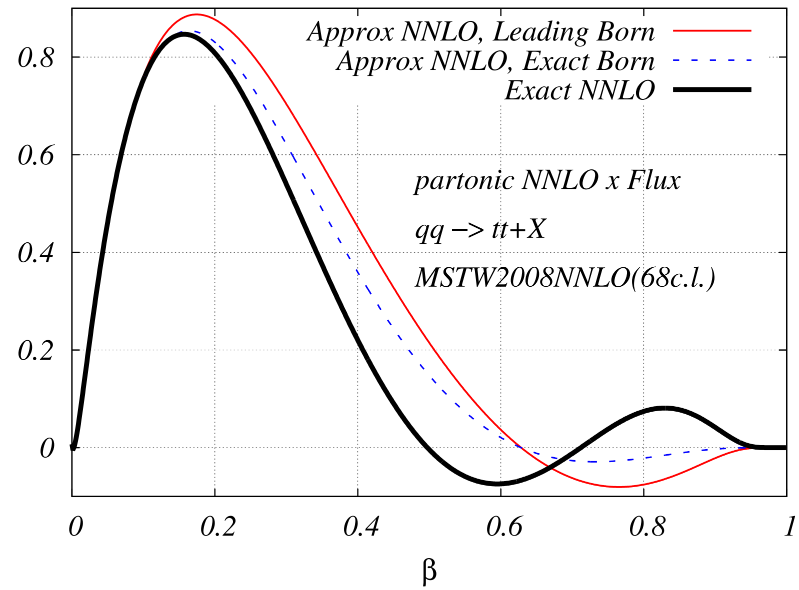
Full NNLO QCD for qqb→ttb (Tevatron)

[M.Czakon, P. Bärnreuther, A. Mitov] (2012)

$\sigma_{\rm tot} = 7.067 \pm 3\%(\rm scales) \pm 2\%(\rm pdfs)$ pb

$\sigma_{\rm tot} = \sum_{i,j} \int d\beta \; \phi_{ij}(\beta^2, \mu) \times \hat{\sigma}_{ij}(\beta, \mu)$

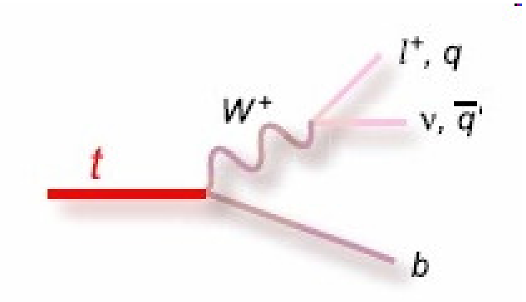




- NLO+NNLL: $\sigma_{\rm tot}$ = 7.021±5%(scales) pb
- missing pieces (gg,qg) are small (<1%) at the Tevatron
- separate publication on $A_{\rm FB}$ in preparation

Beyond stable tops:
Top quark decays and finite-width effects

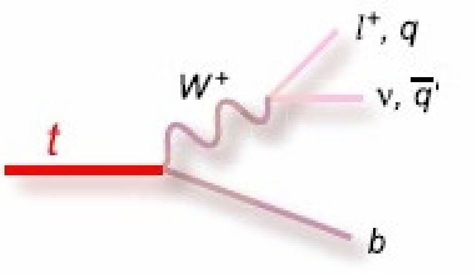
Top quark decays



Top quarks are not stable particles. We only observe their decay products (jets,leptons) in experiments.

- **The decay process is subject to higher order corrections as well (virtual corrections, additional jet radiation).**
- **Those corrections affect acceptance cuts and production dynamics through spin correlations.**

Top quark decays



Top quarks are not stable particles. We only observe their decay products (jets,leptons) in experiments.

- **The decay process is subject to higher order corrections as well (virtual corrections, additional jet radiation).**
- **Those corrections affect acceptance cuts and production dynamics through spin correlations.**

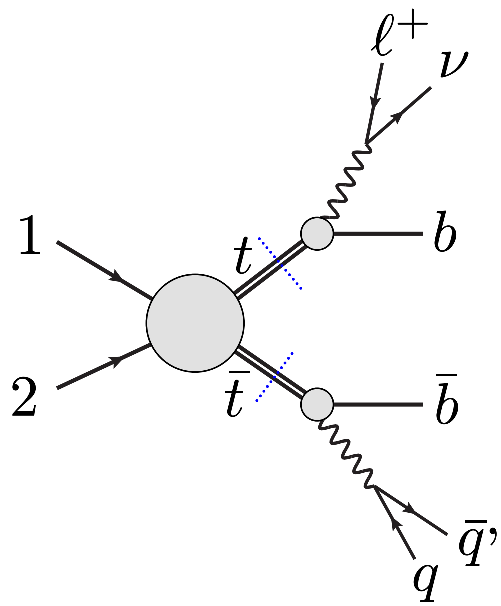
$\Rightarrow$ **There is no reason why corrections to the decay process are equal to or less important than the production process.**

Example: $$\sigma_{\text{tot}} = \frac{N_{\text{obs}}}{\mathcal{L}} \cdot \frac{1}{A} \quad \text{with } A = \frac{\sigma_{\text{cuts}}}{\sigma_{\text{tot}}}$$

To claim that the total cross section has been measured with NLO accuracy, one needs to calculate A at NLO QCD. Otherwise potential biases are introduced.

Narrow-width approximation

Thanks to their small width and large mass,
top quarks can be treated in a parametric approximation
which is valid up to $\mathcal{O}(\Gamma_t/m_t)$.

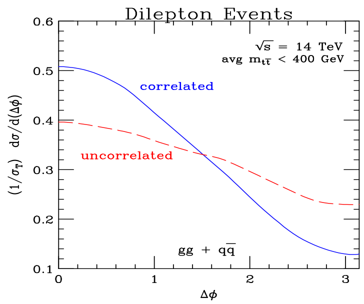


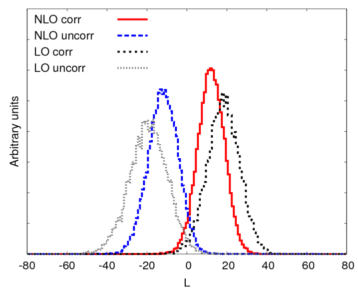
→ **“intuitive“ separation into production and decay**

(neglects largely off-shell and non-resonant diagrams)

Selection of recent NLO results

Spin Correlations

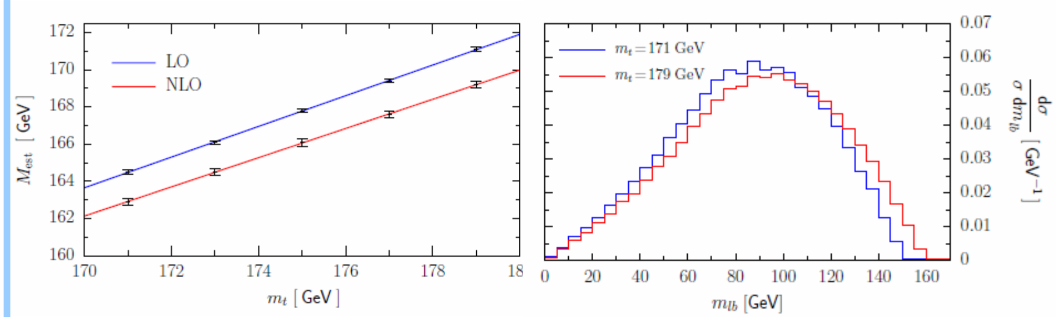




[Bernreuther,Brandenburg,Si,Uwer]

[Mahlon,Parke], [Melnikov, M.S.]

Mass determination from kinematic distributions



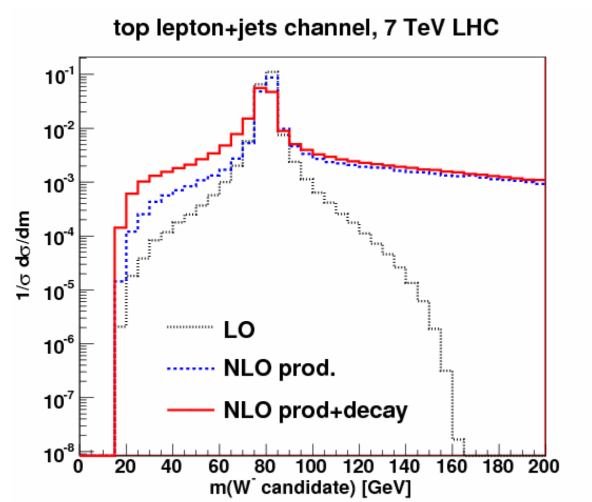
[Biswas,Melnikov,M.S.]

Lepton A_{FB} + el.weak corrections

		with cuts	without cuts
A^{ℓ} (%)	QCD:	3.0 (3)	3.1 (3)
	QCD + EW:	3.6 (2)	3.8 (3)
A^{ℓ} (%)	QCD:	5.2 (5)	5.8 (5)
$(M_{t\bar{t}} \geq 450$ GeV)	QCD + EW:	6.4 (5)	7.0 (5)
A^{ℓ} (%)	QCD:	1.6 (1)	1.5 (1)
$(M_{t\bar{t}} < 450$ GeV)	QCD + EW:	1.9 (1)	1.8 (1)
$A^{\ell\ell}$ (%)	QCD:	4.0 (4)	4.0 (4)
	QCD + EW:	4.8 (4)	4.8 (4)
$A^{\ell\ell}$ (%)	QCD:	7.0 (6)	6.3 (6)
$(\lvert\Delta y_\ell\rvert \geq 1)$	QCD + EW:	8.5 (6)	7.5 (6)
$A^{\ell\ell}$ (%)	QCD:	1.9 (2)	1.6 (1)
$(\lvert\Delta y_\ell\rvert < 1)$	QCD + EW:	2.3 (2)	1.9 (2)
$A^{\ell\ell}$ (%)	QCD:	6.7 (5)	7.1 (6)
$(M_{t\bar{t}} \geq 450$ GeV)	QCD + EW:	8.2 (5)	8.7 (6)
$A^{\ell\ell}$ (%)	QCD:	2.3 (2)	2.0 (2)
$(M_{t\bar{t}} < 450$ GeV)	QCD + EW:	2.7 (2)	2.3 (2)

[Bernreuther,Si]

Finite bottom quark mass effects

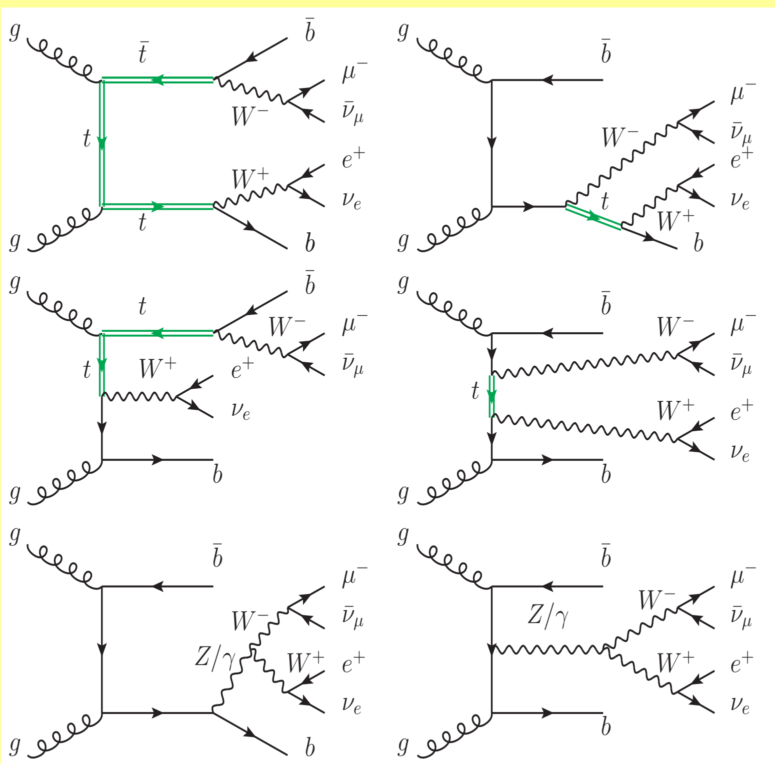


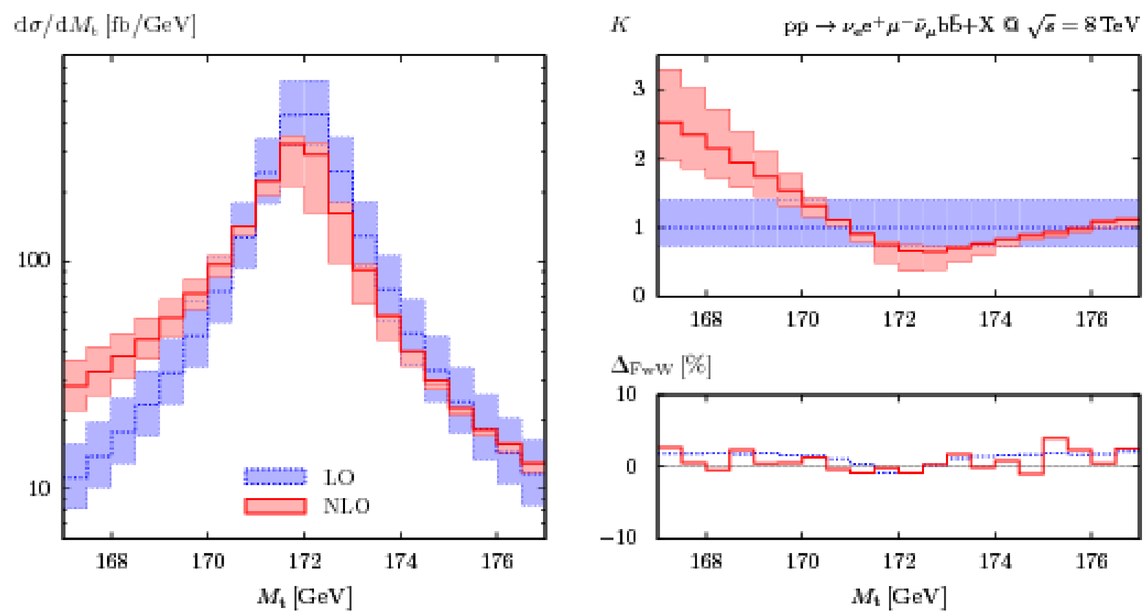
[Campbell,Ellis] (MCFM)

Finite-width effects in ttbar production

In late 2010, full NLO QCD calculations for $WWb\bar{b}$ became available.

[Bevilacqua,Czakon,vHameren,Papadopoulos,Worek], [Denner,Dittmaier,Kallweit,Pozzorini]





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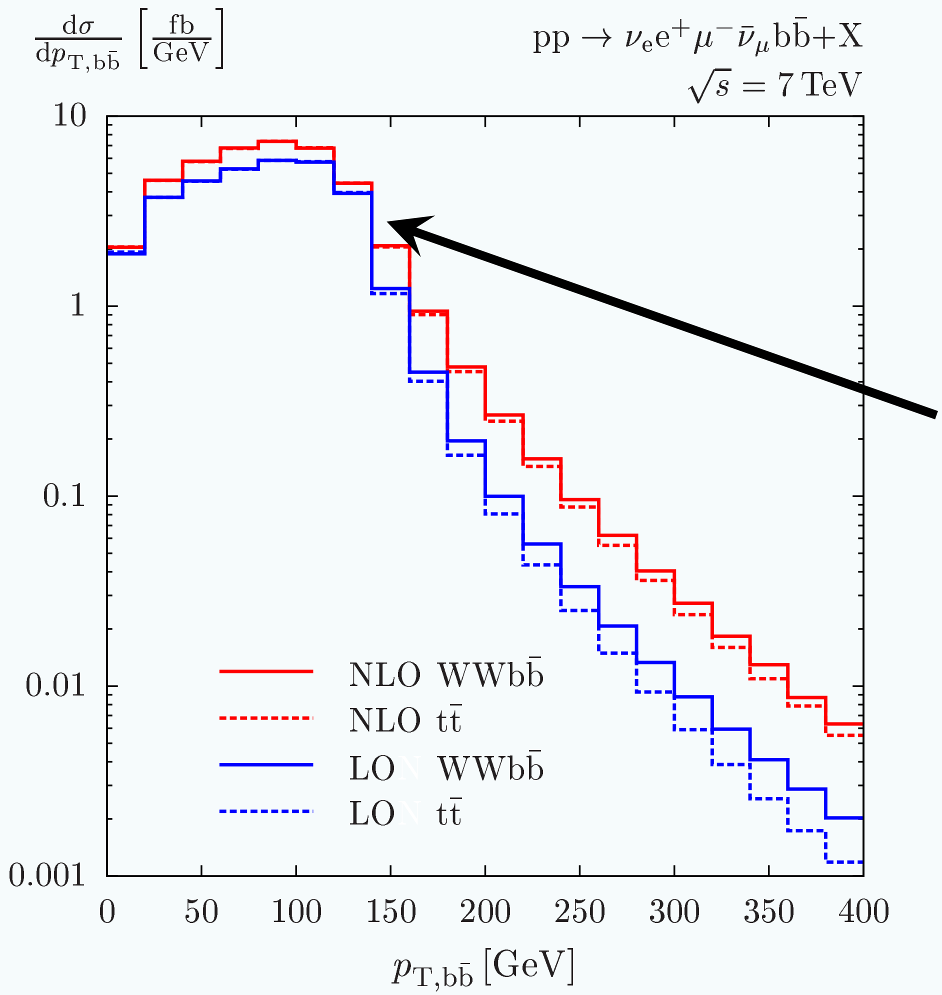
Tuned benchmark comparison to determine finite-width effects at the LHC:

[Denner,Dittmaier,Kallweit,Pozzorini,M.S.] (2012)

Collider	$\sqrt{s}$ [TeV]	approx.	$\sigma_{t\bar{t}}$ [fb]	σ_{WWbb} [fb]	$\sigma_{t\bar{t}}/\sigma_{WWbb} - 1$
Tevatron	1.96	LO	$44.691(8)^{+19.81}_{-12.58}$	$44.310(3)^{+19.68}_{-12.49}$	$+0.861(19)\%$
		NLO	$42.16(3)^{+0.00}_{-2.91}$	$41.75(5)^{+0.00}_{-2.63}$	$+0.98(14)\%$
LHC	7	LO	$659.5(1)^{+261.8}_{-173.1}$	$662.35(4)^{+263.4}_{-174.1}$	$-0.431(16)\%$
		NLO	$837(2)^{+42}_{-87}$	$840(2)^{+41}_{-87}$	$-0.41(31)\%$

Finite-width effects in ttbar production

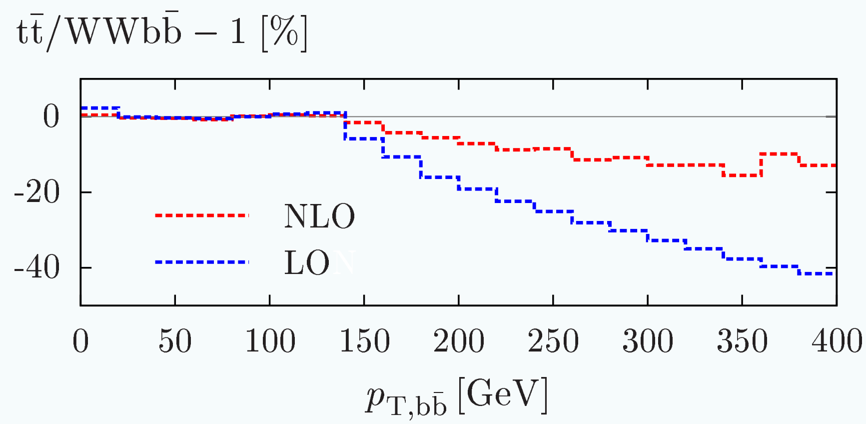


kinematic boundary for

$$p_T^{bjet} \approx \frac{m_t^2 - M_W^2}{2m_t} \approx 65\ \text{GeV}$$

beyond $p_T^{b\bar{b}} > 2 \times 65\ \text{GeV}$

$b\bar{b}$**-pair needs to be boosted**



Top quark decay at NNLO QCD

Fully differential NNLO QCD correction based on SCET

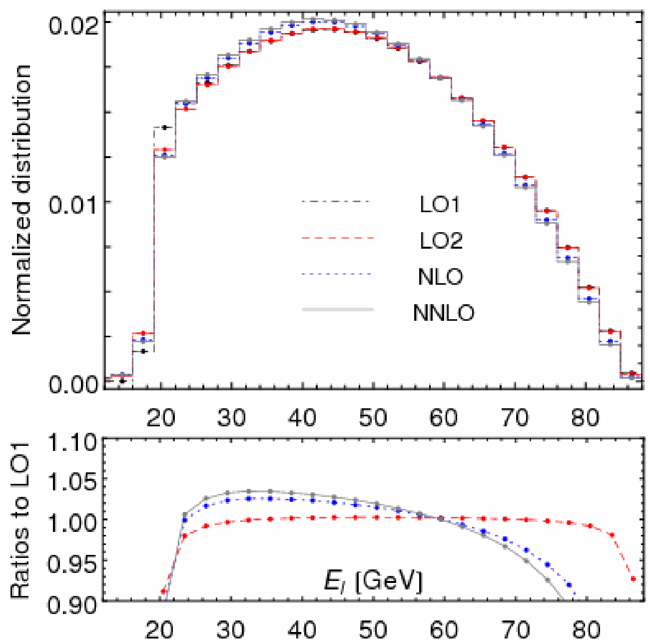
[Jun Gao,Chong Sheng Li,Hua Xing Zhu] (2012)

$$\Gamma_t = \int_0^{\tau_0} \mathrm{d}\tau \frac{\mathrm{d}\Gamma_t}{\mathrm{d}\tau} + \int_{\tau_0}^{\infty} \mathrm{d}\tau \frac{\mathrm{d}\Gamma_t}{\mathrm{d}\tau} := \Gamma_A + \Gamma_B \qquad \tau = (p_b + p_X)^2/m_t^2$$

if τ_0 is chosen small enough:

$\Gamma_A \sim \mathcal{H}(x,\mu) \otimes J(m^2,\mu) \otimes S(k,\mu)$ can be calculated from SCET results

Γ_B can be calcuated from NLO QCD corrections to $t \to Wb$+jet



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

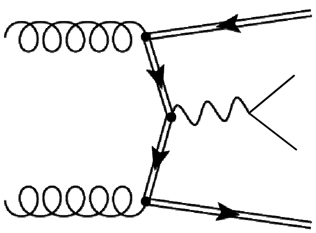
GeV percent

full agreement with earlier works:
Blokland,Czarnecki,Körner,Melnikov,Piclum,
Slusarczyk,Tkachov

Legs:
Associated top quark pair production

Associated top quark pair production

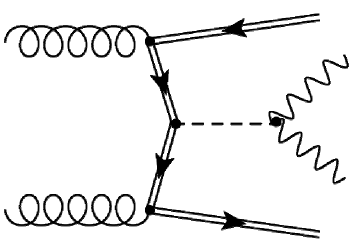
$t\bar{t} + Z$:



$$\sigma^{\rm NLO}_{t\bar{t}+Z}(14\,{\rm TeV}) = 1.1\ {\rm pb}$$ → after branchings: $\sim \mathcal{O}(1\,{\rm fb}(\ell\ell))$

[Lazopoulos,McElmurry,Melnikov,Petriello], [Garzelli,Kardos,Papadopoulos,Trocsanyi]

$t\bar{t} + H$:

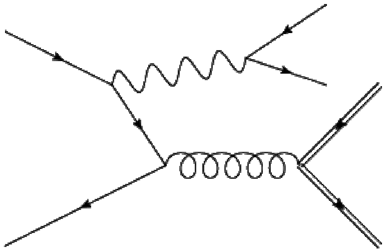


$$\sigma^{\rm NLO}_{t\bar{t}H}(14\,{\rm TeV}) = 0.61\ {\rm pb}\ \ \pm 9\%({\rm scale})\ \pm 9\%({\rm PDFs})$$

→ after branchings: $\sim \mathcal{O}(5\,{\rm fb}(bb),\ 1\,{\rm fb}(WW))$

[Beenakker,Dittmaier,Krämer,Plümper,Spira,Zerwas], [Dawson,Jackson,Orr,Reina,Wackeroth]
[Frederix,Frixione,Hirschi,Maltoni,Pittau,Torielli], [Garzelli,Kardos,Papadopoulos,Trocsanyi]

$t\bar{t} + W^{\pm}$:

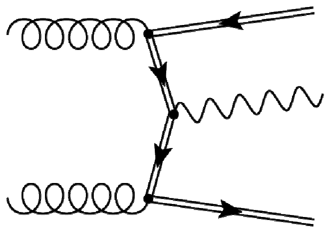


$$\sigma^{\rm NLO}_{t\bar{t}+W^+}(14\,{\rm TeV}) = 0.51\ {\rm pb}\ \ \pm 30\%({\rm scale})\ \pm 8\%({\rm PDFs})$$

→ after branchings: $\sim \mathcal{O}(0.5\,{\rm fb}(\ell\nu))$

[Campbell,Ellis],
[Garzelli,Kardos,Papadopoulos,Trocsanyi],
[Hirschi,Frederix,Frixione,Garzelli,Maltoni]

Associated top quark pair production



$$t\,\bar{t} + \gamma:$$

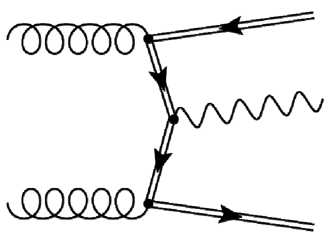
$$\sigma^{\rm NLO}_{t\bar{t}+\gamma}(14\,{\rm TeV}) = 2.9\ {\rm pb}\ \ \pm 14\%({\rm scale})$$

→ after branchings: $\sim \mathcal{O}(140\,{\rm fb}(\ell\ell))$

this is not just $\sigma \times \mathcal{B}r$

Associated top quark pair production

$t\,\bar{t} + \gamma$:

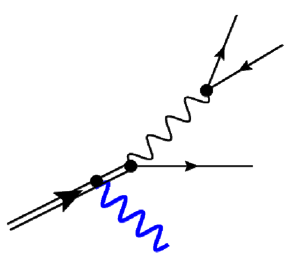


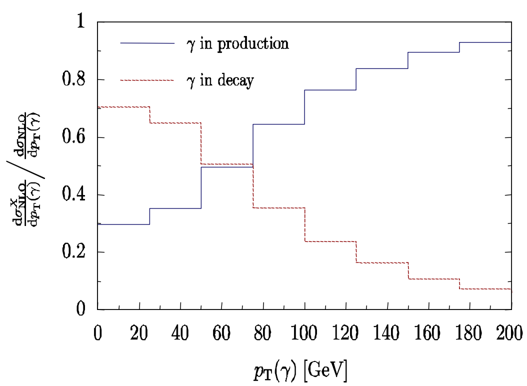
$\sigma^{\rm NLO}_{t\bar{t}+\gamma}(14\,{\rm TeV}) = 2.9$ pb $\pm 14\%({\rm scale})$

→ after branchings: $\sim \mathcal{O}(140\,{\rm fb}(\ell\ell))$

this is not just $\sigma \times \mathcal{B}r$

radiation off top quark decay products gives a sizable contribution:





$$\sigma^{\rm tot}_{t\bar{t}\gamma} = 138 \text{ fb}$$
$$= 61(\text{prod}) + 77(\text{decay}) \text{ fb}$$

[Melnikov,Scharf,M.S.]

Similar effects in $t\bar{t}+$ jets:

[Dittmaier,Uwer,Weinzierl], [Melnikov,Scharf,M.S], [Alioli,Moch,Uwer]
[Kardos,Papadopolous,Trocsanyi]
[Bredenstein,Denner,Dittmaier,Pozzorini], [Bevilacqua,Czakon,Papadopoulos,Worek]

Associated top quark pair production

Measuring electroweak couplings at the LHC in

I. $t\bar{t} + H$

$\sigma_{t\bar{t}+H} \sim y_t^2$: allows a direct measurement of y_t

can be compared to $\hat{y}_t$ from gg→H which is sensitive to NP

extensively studied:

1999: [Dawson,Juste,Reina,Wackeroth]
2002: [Belyaev,Reina], [Maltoni,Rainwater,Willenbrock]
2004: [Duehrssen,Heinemayer,Logan,Rainwater,Weiglein,Zeppenfeld]
2009: [Duehrssen,Lafaye,Plehn,Rauch,Zerwas]
2012: [Peskin]
+ others

	full measurements			r
	σ_{symm}	σ_{neg}	σ_{pos}	σ_{sy}
Δ_{WWH}	± 0.24	-0.21	$+0.27$	± 0
Δ_{ZZH}	± 0.31	-0.35	$+0.29$	± 0
Δ_{ttH}	± 0.53	-0.65	$+0.43$	± 0
Δ_{bbH}	± 0.44	-0.30	$+0.59$	± 0
$\Delta_{\tau\tau H}$	± 0.31	-0.19	$+0.46$	± 0
$\Delta_{\gamma\gamma H}$	± 0.31	-0.30	$+0.33$	± 0
Δ_{ggH}	± 0.61	-0.59	$+0.62$	± 0

Table 7: Errors on the measurements includi with reduced sensitivity (center) and only $t\bar{t}$ luminosity.

LHC (14TeV), 30 fb^{-1}; M$_H$=120 GeV

LHC(14 TeV), 300fb^{-1}; δy_t(ttH)≈ ± 15%

Note: error estimates for tagging boosted objects are not yet well understood

Associated top quark pair production

Measuring electroweak couplings at the LHC
in

II. $t\bar{t} + \gamma$

- top quark electric charge is determined from b-W charge tagging in ttb
- The study of ttb+gamma is an independent and direct measurement and serves as a starting point for determining anomalous couplings

2004/05 [Baur,Juste,Orr,Rainwater]:

$$\Gamma_\mu^{t\bar{t}V} \sim \gamma_\mu \left(F_{1,V} + \gamma_5 F_{1,A}\right) + \sigma_{\mu\nu} \frac{q^\nu}{2m_t} \left(\mathrm{i}F_{2,V} + \gamma_5 F_{2,A}\right)$$

coupling LHC (14 TeV)	30 fb^{-1} [%]	300 fb^{-1} [%]
ΔF_{1V}^γ	$^{+0.23}_{-0.14}$	$^{+0.079}_{-0.045}$
ΔF_{1A}^γ	$^{+0.17}_{-0.52}$	$^{+0.051}_{-0.077}$
ΔF_{2V}^γ	$^{+0.34}_{-0.35}$	$^{+0.19}_{-0.20}$
ΔF_{2A}^γ	$^{+0.35}_{-0.36}$	$^{+0.19}_{-0.21}$

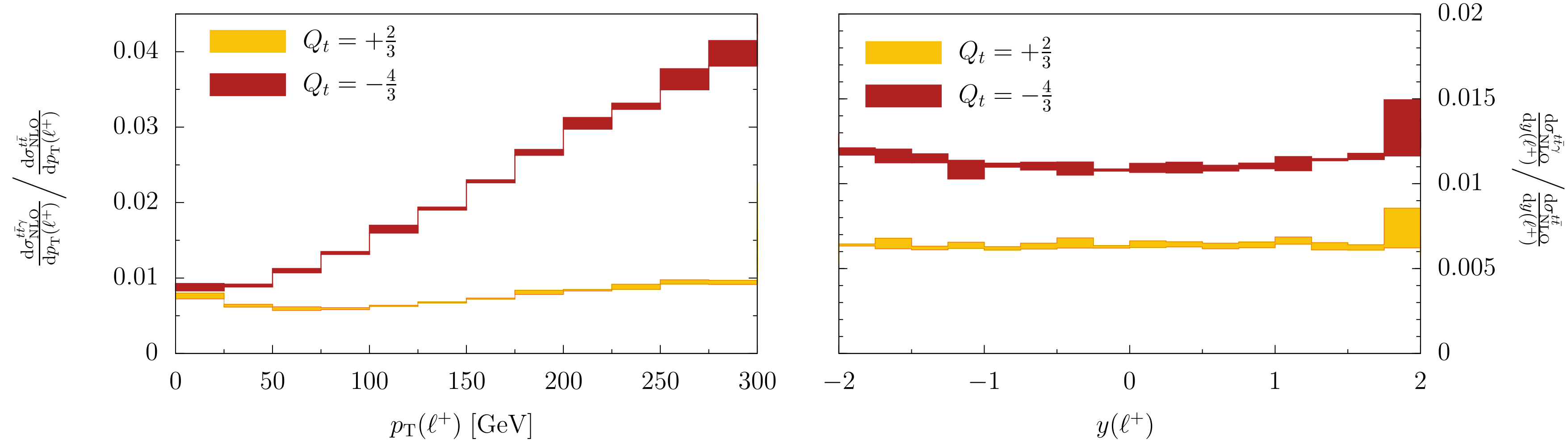
Associated top quark pair production

Measuring electroweak couplings at the LHC in

II. $t\bar{t} + \gamma$

- cross section ratios $\sigma_{t\bar{t}\gamma} / \sigma_{t\bar{t}}$

2011 [Melnikov,Scharf,M.S.]



$$\frac{\sigma_{t\bar{t}\gamma}^{Q_t=2/3}}{\sigma_{t\bar{t}}} = \begin{cases} 5.66^{+0.03}_{-0.02} \times 10^{-3}, & \text{LO;} \\ 6.33^{+0.26}_{-0.14} \times 10^{-3}, & \text{NLO,} \end{cases} \qquad \frac{\sigma_{t\bar{t}\gamma}^{Q_t=-4/3}}{\sigma_{t\bar{t}}} = \begin{cases} 10.4^{+0.2}_{-0.2} \times 10^{-3}, & \text{LO;} \\ 11.2^{+0.3}_{-0.2} \times 10^{-3}, & \text{NLO.} \end{cases}$$

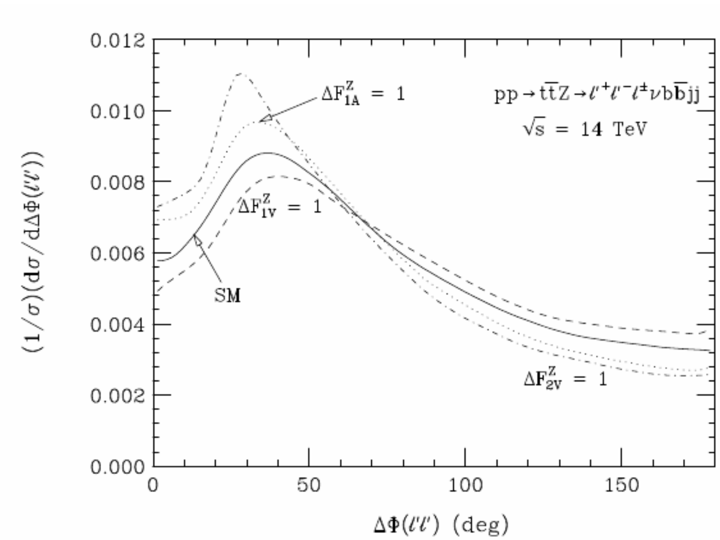
Associated top quark pair production

Measuring electroweak couplings at the LHC
in
III. $t\bar{t} + Z$

2004/05 [Baur,Juste,Orr,Rainwater]

$$\Gamma_\mu^{t\bar{t}V} \sim \gamma_\mu \left(F_{1,V} + \gamma_5 F_{1,A}\right) + \sigma_{\mu\nu}\frac{q^\nu}{2m_t}\left(\mathrm{i}F_{2,V} + \gamma_5 F_{2,A}\right)$$

$\Delta\phi(\ell^+,\ell^-)$ from $Z \to \ell^+\ell^-$ is a good analyzer



coupling	LHC (14 TeV)	300 fb^{-1} [%]
ΔF^Z_{1V}		$+0.87$ -0.46
ΔF^Z_{1A}		$+0.15$ -0.20
ΔF^Z_{2V}		$+0.52$ -0.52
ΔF^Z_{2A}		$+0.54$ -0.53

New directions
at a
Linear Collider

$$e^+e^- \to t\bar{t}$$

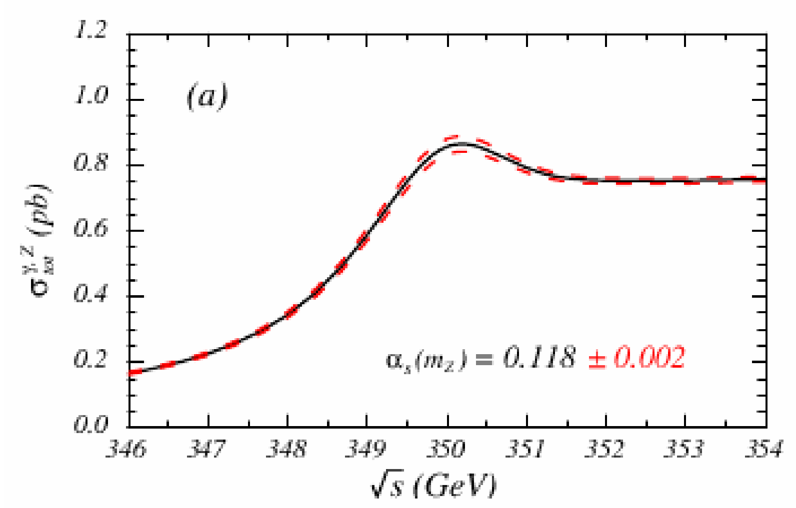
New directions at a Linear Collider

Cross section and mass

NR QCD: describes threshold region

$$\sigma_{t\bar{t}}(\sqrt{s} = 500\text{GeV}) \approx 600 \text{ fb}$$

$\Gamma_t \gg \Lambda_{\text{QCD}}$ → tops cannot form narrow toponium resonance



- convergence of pert. series depends on top quark mass definition
  pole mass: large corrections, shifts pole by 0.5 GeV
  → "threshold masses" are free of renormalon ambiguities
  (similar discussion is desirable for hadron collider measurements)

- experimental precision on σ is expected to be 5% or better

- measure top quark mass from threshold scan → $\delta m_t \approx 100$ MeV

at this level of precision many of the before mentioned aspects of top quark physics become relevant: NNLO, spin correl., off-shell effects, finite b mass, ISR+ Bremsstrahlung

New directions at a Linear Collider

Top quark couplings

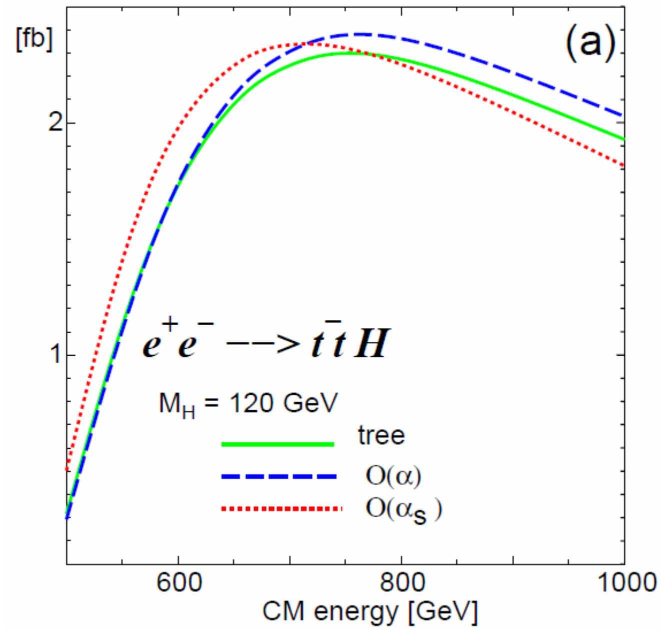
$$e^+e^- \rightarrow t\bar{t} + H$$

- $E_{\text{thresh}} = 2 * m_t + m_H = 470$ GeV

  → large gain from increased CM energy
  σ(800 GeV)/σ(500 GeV) ~ 7

$$\sqrt{s} = 500 \text{ GeV}, \; \mathcal{L} = 1000\text{fb}^{-1}: \; \delta y_t / y_t \approx 33\%$$

$$\sqrt{s} = 800 \text{ GeV}, \; \mathcal{L} = 1000\text{fb}^{-1}: \; \delta y_t / y_t \approx 5.5 \; \%$$



[Dawson,Juste,Reina,Wackeroth]

$$\sqrt{s} = 500 \text{ GeV}, \; \mathcal{L} = 1\text{ab}^{-1}: \; \delta y_t / y_t \approx 10\%$$

[R.Yonamine, K.Ikematsu, T.Tanabe, K.Fujii, Y.Kiyo, Y.Sumino, H.Yokoya]

New directions at a Linear Collider

Top quark couplings

$$pp \to t\bar{t} + Z/\gamma \;\; \text{vs.} \;\; e^+e^- \to Z/\gamma \to t\bar{t}$$

$$\Gamma_\mu^{t\bar{t}V} \sim \gamma_\mu \left(F_{1,V} + \gamma_5 F_{1,A}\right) + \sigma_{\mu\nu} \frac{q^\nu}{2m_t} \left(\mathrm{i}F_{2,V} + \gamma_5 F_{2,A}\right)$$

coupling	LHC, 300 fb^{-1}	ILC(500 GeV) polarized beam
$\Delta\widetilde{F}_{1V}^{\gamma}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, 200 fb^{-1}
$\Delta\widetilde{F}_{1A}^{\gamma}$	$^{+0.051}_{-0.048}$	$^{+0.011}_{-0.011}$, 100 fb^{-1}
$\Delta\widetilde{F}_{2V}^{\gamma}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, 200 fb^{-1}
$\Delta\widetilde{F}_{2A}^{\gamma}$	$^{+0.16}_{-0.17}$	$^{+0.014}_{-0.014}$, 100 fb^{-1}
$\Delta\widetilde{F}_{1V}^{Z}$	$^{+0.43}_{-0.83}$	$^{+0.012}_{-0.012}$, 200 fb^{-1}
$\Delta\widetilde{F}_{1A}^{Z}$	$^{+0.14}_{-0.14}$	$^{+0.013}_{-0.013}$, 100 fb^{-1}
$\Delta\widetilde{F}_{2V}^{Z}$	$^{+0.38}_{-0.50}$	$^{+0.009}_{-0.009}$, 200 fb^{-1}
$\Delta\widetilde{F}_{2A}^{Z}$	$^{+0.50}_{-0.51}$	$^{+0.052}_{-0.052}$, 100 fb^{-1}

[American LC Working group]
[Baur,Juste,Orr,Rainwater]

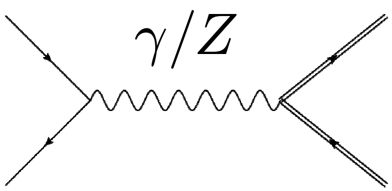
New directions at a Linear Collider

Top quark couplings

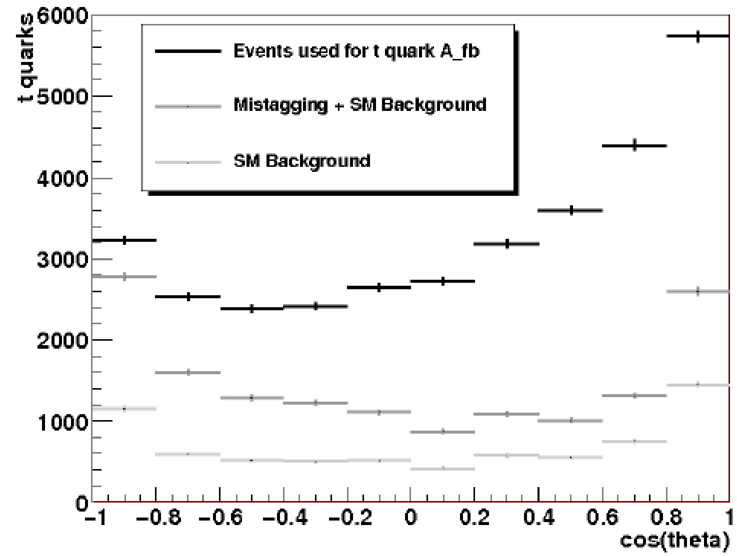
$$e^+e^- \to t\bar{t}$$

[Devetak,Nomerotski,Peskin] (2011)

Study A_{FB} with polarized beams to determine t-tb-Z couplings



→ **LO asymmetry ~ 35%**



- 1% precision on A_{FB} is achievable in fully hadr. channel (requires two b-tags + b charge tagging)

- polarized beams at CM energy of 500 GeV and 500 fb^{-1}:

$$\delta F_L^Z \approx 6\% \qquad \delta F_R^Z \approx 12\%$$

allows to place strong limits on New Physics models

Conclusions

- **Our theoretical understanding of top quark physics at the LHC is in very good shape**

  - NLO QCD + el.weak corrections are known for realistic final states
  - spin correlations, off-shell effects, finite b-mass effects
  - soon: full NNLO QCD for total cross section

- **Associated production of top quark pairs opens up a new era of studying electroweak top quark couplings**

  -ttb+Z,γ, W, H are known at NLO QCD
  - y_t, F_Z, F_γ can be determined to roughly ~ 20% accuracy with $300fb^{-1}$

- **The ILC can significantly improve those measurements**

  - cross section to 5% accuracy (→ m_t 1 permille accuracy)
  - y_t, F_Z, F_γ can be determined to roughly 1-5% (800GeV)