Recent theoretical developments for top-quark production

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— Univ. Freiburg —

Top quark heaviest known elementary particle

Yukawa coupling $\lambda_t \sim 1 \Rightarrow$ link to EW symmetry breaking:

- top-loop corrections to $M_H \Rightarrow$ hierarchy problem

$$\Rightarrow \delta M_H = -\frac{\lambda_t^2}{8\pi^2}\Lambda_{\text{UV}}^2 + \dots$$

$\Rightarrow$ top-partners in BSM models (stop in MSSM, T in Little-Higgs...)

Top established at Tevatron:

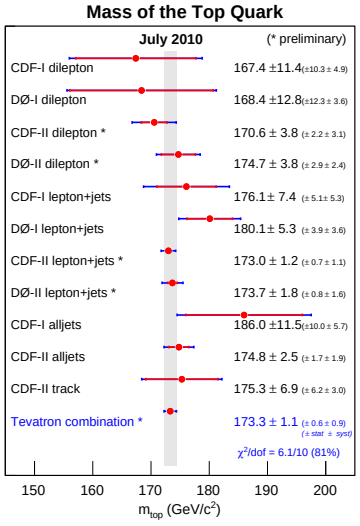
plethora of measurements (Γ_t, spin correlations, charge asymmetry. . .)

room for new physics (V_{tb}, FCNC tcZ -couplings, heavy resonances in $t\bar{t}$. . .)

Top quark precision physics:

$$\Delta\sigma_{t\bar{t}}/\sigma_{tt} \sim 7\% \quad , \quad \Delta m_t/m_t < 1\%$$

$\Rightarrow$ Challenge for theory! (Focus of this talk)



Large LHC cross section $\sigma_{t\bar{t}}(14\text{TeV}) \approx 900$ pb

\+ Plenty of tops to study

– Background for other processes

Top-pair production

QCD production, two LO subprocesses:

$$q\bar{q} \to t\bar{t} : \begin{cases} 90\% \\ 20 - 10\% \end{cases} \quad , \quad gg \to t\bar{t} \begin{cases} 10\% \\ 80 - 90\% \end{cases} \quad \begin{matrix} \text{Tevatron} \\ \text{LHC} 7 - 14 \end{matrix}$$

(NLO QCD corrections (Nason, Dawson Ellis 88,Beenakker et.al. 89/91,...)

EW corrections (Bernreuther/Fuecker/Si; Kühn/Scharf/Uwer, 05/06)

Parton shower matching (Frixione/Nason/Webber 03, Frixione/Nason/Ridolfi 07))

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Single top production

EW production $\sim V_{tb}$, LO Production channels

$$q\bar{q}' \xrightarrow{W^+} t\bar{b} \begin{cases} 0.54\text{pb} \\ 7.8\text{pb} \end{cases} \quad b\bar{q} \to t\bar{q}' \begin{cases} 1.15\text{pb} \\ 150\text{pb} \end{cases} \quad gb \to W^- t \begin{cases} 0.14\text{pb} & \text{TeV} \\ 44\text{pb} & \text{LHC}14 \end{cases}$$

(NLO QCD (Smith/Willenbrock 96; Giele et.al. 96; Stelzer et.al. 97...)

EW corrections (Beccaria et.al. 06)

Parton shower matching (Frixione et.al. 05; Alioli et.al. 09; Re 10))

Hadron collider cross sections from QCD factorization

(Collins, Soper, Sterman)

$$\sigma_{NN'}(s) = \sum_{pp'} \int dx_1 dx_2 \; f_{N/p}(x_1, \mu_f) f_{N'/p'}(x_2, \mu_f) \; \hat{\sigma}_{pp'}(s x_1 x_2, \mu_f)$$

- $\hat{\sigma}_{pp'}$: partonic cross section: compute in perturbation theory
- $f_{p/N}(x)$: Parton distribution function for parton p in hadron N : fitted to experiment

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PDF uncertainties for top: (e.g. Guffanti/Rojo arXiv:1008.4671 [hep-ph])

	CTEQ6.6	MSTW2008	NNPDF2.0	ABKM09	HERAPDF1.0
$\sigma_{t\bar{t}}^{\text{NLO}}(7\text{TeV})[pb]$	147.7 ± 6.4	159.0 ± 4.7	160.0 ± 5.9	131.9 ± 4.8	136.4 ± 4.7

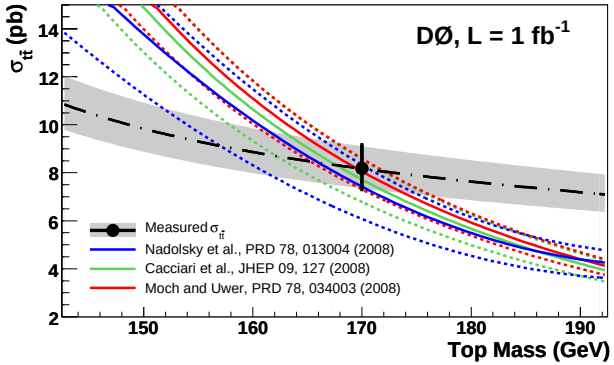
- Different α_s values
- Differences in gluon pdf at large x (impact of Tevatron jet-data)

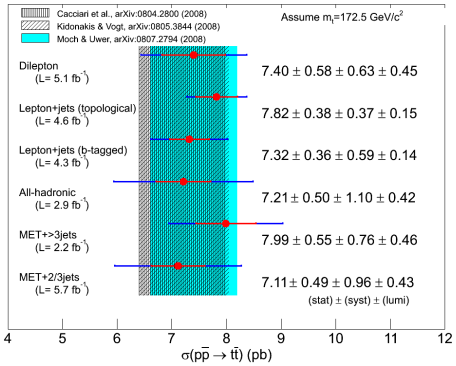
Total $t\bar{t}$ cross section

Experimental knowledge of $t\bar{t}$ cross section:

Tevatron: $\Delta\sigma_{t\bar{t}} = 6.8\%$; LHC Goal: $\Delta\sigma_{t\bar{t}} \approx 5\%$

Sensitivity to m_t, gluon PDFs, ...





Theory status: NLO + higher-order soft gluons $\Rightarrow \Delta\sigma_{t\bar{t}} \approx 10\%$

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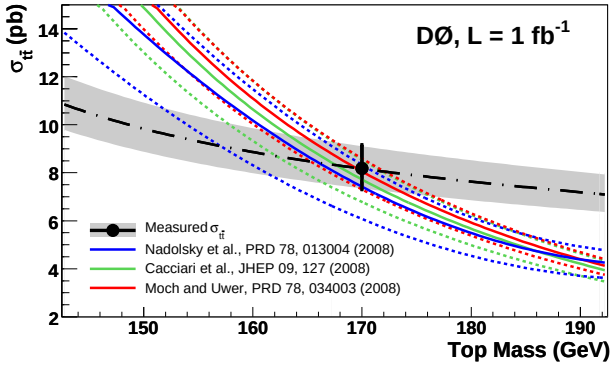

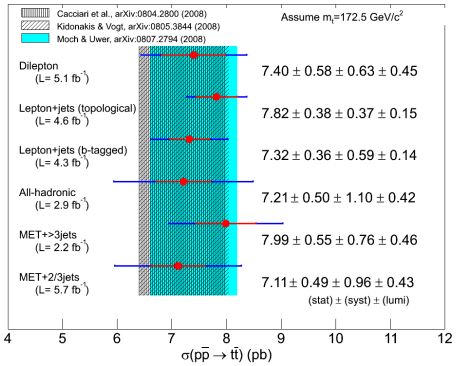

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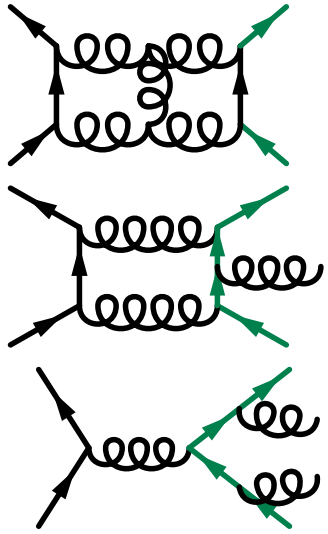
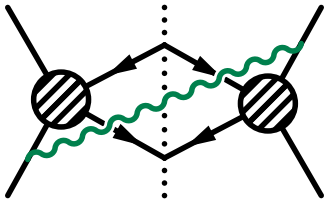
Building blocks for NNLO:

- two-loop $t\bar{t}$, ($m_t \to 0$: Czakon/Mitov/Moch 07;
  $q\bar{q}$: Czakon 08; Bonciani et.al. 08/09)
- one-loop $t\bar{t} + j$ (Dittmaier/Uwer/Weinzierl 07)
  $t\bar{t}$ squared
  (Körner et.al. 05-09, Anastasiou/Mert-Aybert 08)
- tree $t\bar{t} + jj$ (IR subtraction: Czakon 10)

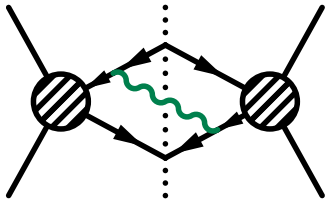


NLO corrections to σ_{tot} enhanced for $\beta = \sqrt{1 - 4m_t^2/\hat{s}} \to 0$

Soft corrections: (Resummation in Mellin space: Sterman 87; Catani, Trentadue 89, Kidonakis,Sterman 97, Bonciani et.al. 98, ...)



$\Rightarrow \alpha_s \log^2(\beta^2)$



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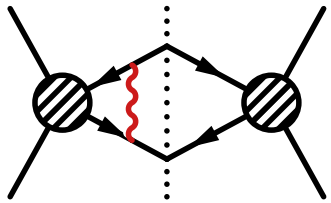
Coulomb gluon corrections (Fadin, Khoze 87; Peskin, Strassler 90, NRQCD,...)



$\Rightarrow \alpha_s \dfrac{1}{\beta}$

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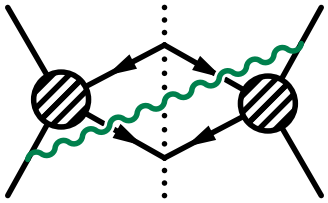

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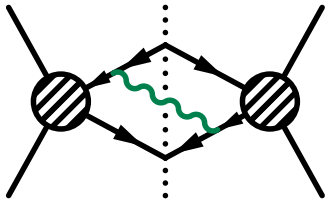

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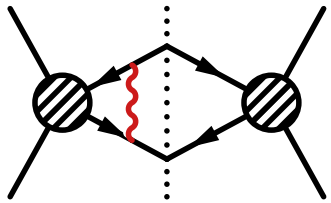

$\Rightarrow \alpha_s \dfrac{1}{\beta}$

Counting of threshold corrections:

$$\hat{\sigma}_{pp'} \propto \sigma^{(0)} \exp\left[\underbrace{\ln\beta\, g_0(\alpha_s \ln\beta)}_{\text{(LL)}} + \underbrace{g_1(\alpha_s \ln\beta)}_{\text{(NLL)}} + \underbrace{\alpha_s g_2(\alpha_s \ln\beta)}_{\text{(NNLL)}} + \ldots\right]$$
$$\times \sum_{k=0} \left(\frac{\alpha_s}{\beta}\right)^k \times \{1\,(\text{LL,NLL}); \alpha_s, \beta\,(\text{NNLL}); \ldots\}\,,$$

Application of β-summation to $t\bar{t}$

- NLL summation of $\ln \beta$ terms (Bonciani et.al. 98)
- Development of NNLL resummations:
  - 2-loop soft anomalous dimension (Becher/Neubert; Kidonakis; Mitov/Sterman/Sung; Beneke/Falgari/CS; Ferroglia et.al. 09)
  - soft/Coulomb factorization (Beneke, Falgari, CS 09/10)

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- $\text{NNLO}_{\text{approx}}$ (also implemented in HATHOR, Aliev et.al. 10)
  - α_s^2 expansion of NNLL (Moch, Uwer (Langenfeld) 08/09)
  + all potential corrections (Beneke, Czakon, Falgari, Mitov CS, 09)

$$\text{e.g. } \sigma_{q\bar{q}}^{(2)} = \frac{3.61}{\beta^2} + \frac{1}{\beta}\left(-140.4\ln\beta^2 + 32.1\ \ln\beta + 3.95 \right)$$
$$+910.2\ln\beta^4 - 1315.5\ln\beta^3 + 592.3\ln\beta^2 + 528.6\ \ln\beta + C_{qq}^{(2)}$$

- Combined $\ln\beta$, β^{-1} NNLL summation

(Beneke, Falgari, Klein, CS, in progress)

Resummation for other observables:

- Pair invariant mass cross sections (Kidonakis,Sterman 97)

$$\frac{d\sigma(t\bar{t})}{dM_{t\bar{t}}} \quad \Rightarrow \left[\frac{\log^n(1-z)}{1-z}\right]_+ , \; z = \frac{M^2_{t\bar{t}}}{\hat{s}}$$

- One particle inclusive cross sections: (Laenen, Oderda, Sterman 98)

$$\frac{d\sigma(t+X)}{ds_4} \quad \Rightarrow \left[\frac{\log^n\left(s_4/m^2\right)}{s_4}\right] \quad , \; s_4 = p_X^2 - m_t^2$$

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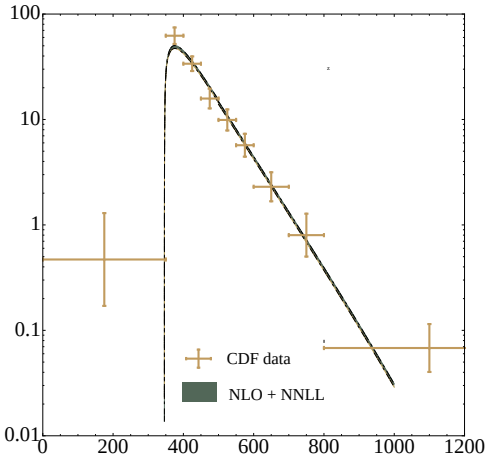
Applications to top-pairs:

- $\mathcal{O}(\alpha_s^2)$ expansion (Kidonakis et.al. 01/03, Ahrens et.al. 09, Kidonakis 10)
- NNLL $M_{t\bar{t}}$ distribution (Ahrens et.al. 10)



(Ahrens et.al. 10)

Single Top:

- $\mathcal{O}(\alpha_s^2)$ expansion (Kidonakis 06-10)
- NNLL resummation (Zhu et.al. 10)

$\sigma_{t\bar{t}}$(pb)	Tevatron	LHC7	LHC10	LHC14
NLO	$6.50\,^{+0.32+0.33}_{-0.70-0.24}$	$150\,^{+18+8}_{-19-8}$	$380\,^{+44+17}_{-46-17}$	$842\,^{+97+30}_{-97-32}$
$\text{NNLO}_{\text{approx}}(\beta)$	$7.13\,^{+0.00+0.36}_{-0.33-0.26}$	$162\,^{+3+9}_{-3-9}$	$407\,^{+11+17}_{-5-18}$	$895\,^{+29+31}_{-7-33}$
$\text{NNLO}_{\text{approx}}(\beta)$ + NNLL (Beneke, Falgari, Klein, CS in progress)	$7.14\,^{+0.13+0.36}_{-0.19-0.26}$	$162\,^{+4+9}_{-2-9}$	$407\,^{+14+17}_{-4-18}$	$896\,^{+36+31}_{-7-33}$
NLO + NNLL ($M_{t\bar{t}}$) (Ahrens et.al. 10)	$6.48\,^{+0.17+0.32}_{-0.21-0.25}$	$146\,^{+7+8}_{-7-8}$	$368\,^{+20+19}_{-14-15}$	$813\,^{+50+30}_{-36-35}$
$\text{NNLO}_{\text{approx}}(s_4)$ (mt=173; Kidonakis 10)	$7.08\,^{+0.00+0.36}_{-0.24-0.27}$	$163\,^{+7+9}_{-5-9}$	$415\,^{+17+18}_{-21-19}$	$920\,^{+50+33}_{-39-35}$

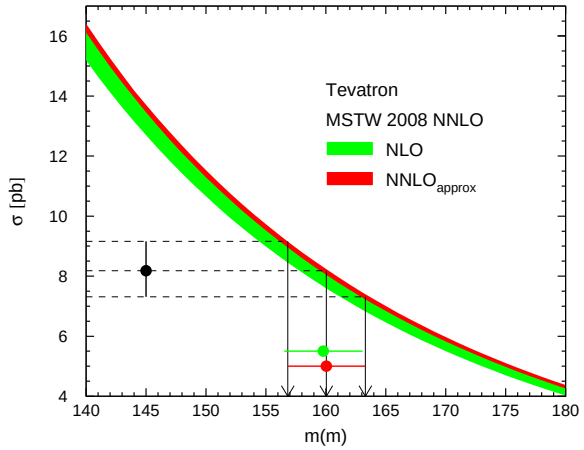
($m_t = 173.1$ GeV, $\mu_f = mt$, MSTW08NNLO)

Application: (Moch, Langenfeld, Uwer 09)

Comparison to Tevatron data:

$$m_t(\overline{\text{MS}}) = 160.0^{+3.3}_{-3.2}\ \text{GeV}$$

$$\Rightarrow \quad m_t(\text{pole}) = 168.9^{+3.5}_{-3.4}\ \text{GeV}$$



Top quark unstable: $t \to bW^+ \to bff'$

Narrow-width approximation (NWA):

$$\frac{i}{p^2 - m_t^2 + i m_t \Gamma_t} \Rightarrow \frac{2\pi}{2\Gamma_t m_t} \delta(p^2 - m_t^2)$$

$$\sigma_{pp' \to b\bar{b}\,4f} \Rightarrow \sigma_{pp' \to t\bar{t}} \times \frac{\Gamma_{t \to b f_1 f_2}}{\Gamma_t} \frac{\Gamma_{\bar{t} \to \bar{b} f_3 f_4}}{\Gamma_t}$$

expect finite width corrections $\mathcal{O}(\Gamma_t/m_t) \sim 1\%$

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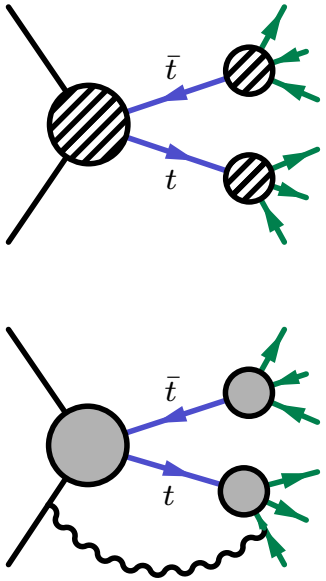
Radiative corrections:

(Double) pole approximation

- Factorizable corrections to production/decay
- Nonfactorizable corrections

  (Cancellations for σ_{tot}: Melnikov, Yakovlev; Fadin et.al. 93)

(For $e^- e^+ \to W^- W^+ \to 4f$ see Berends et. al. 98; Denner et.al. 99, Jadach et.al 99, Beneke et.al 07/08)



Including top decay

Top pairs

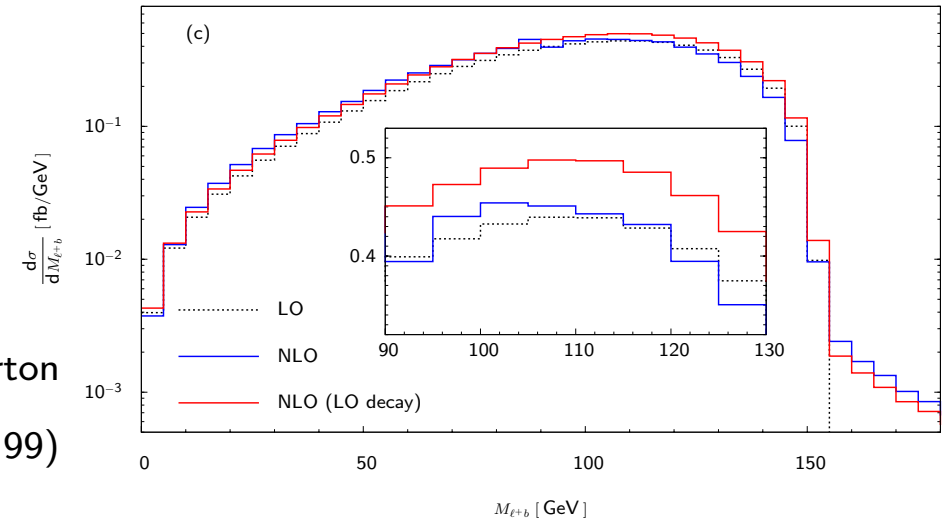
- Factorizable corrections, spin correlations, NWA

  (Bernreuther et.al. 04/10,

  Melnikov/Schulze 09)

- Nonfact. corrections (parton level: Beenakker, Berends, Chapovsky 99)

$M_{\ell+b}$: (Melnikov/Schulze 09)



Single top

- Factorizable corrections, NWA

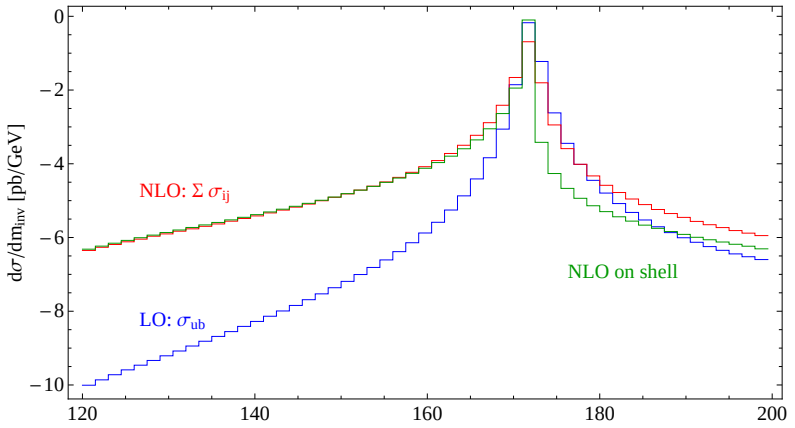
  (Campbell/Ellis/Tramontano 04,

  spin-correll.: Cao et.al. 04/05)

- Nonfactorizable corrections

  (Falgari, Mellor, Signer 10)

m_{inv}: (Falgari, Mellor, Signer 10)



Higgs production:

$$H \to W^+W^-,\ Hqq \to W^+W^-qq$$

- Background from $t\bar{t}$, $t\bar{t}+$ jets
- NWA underestimates $t\bar{t}$ background (Kauer/Zeppenfeld 01)

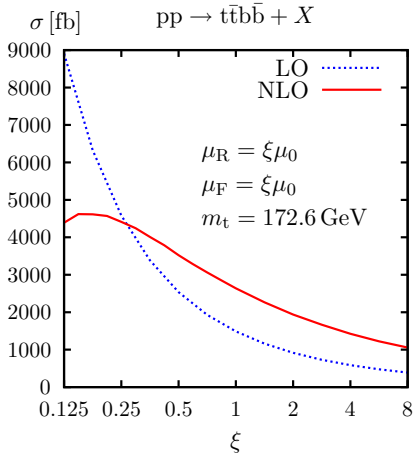
Associated $t\bar{t}H$ production:

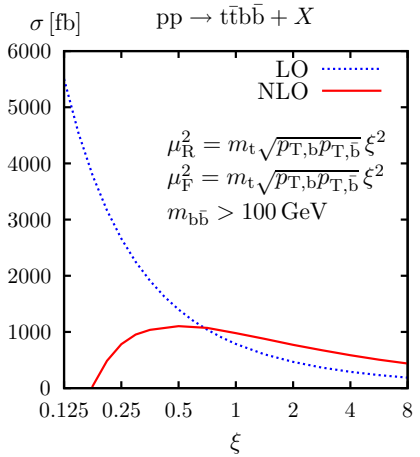
- $t\bar{t}b\bar{b}$, $t\bar{t}+$ jets background

Recent NLO-multileg progress:

- $t\bar{t}j$ (Dittmaier/Uwer/Weinzierl 07);
- $t\bar{t}b\bar{b}$ (Bredenstein et.al. 08-10);
- $t\bar{t}jj$ (Bevilacqua et.al. 10)
- (1-loop amp $b\bar{b}W^+W^-$: v.Hameren et.al. 09)

Complicated multiscale processes:
scale choice?





(Bredenstein et.al. 10)

(Selected) recent theory activities for production cross sections

- Total $\bar{t}t$ cross section: towards NNLO, NNLL resummation
- Corrections to top-production $\otimes$decay:
  NLO+spin correlations, nonfactrizable corrections
- Top as background: $t\bar{t}+j$, $t\bar{t}+jj$ at NLO

Not discussed ($\Rightarrow$ TOP2010 proceedings)

- top-mass definitions

  (see e.g. Hoang/Stewart arXiv:0808.0222 [hep-ph]; Corcella arXiv:1008.4498 [hep-ph])
- Charge asymmetry (BSM e.g. Ferrario/Rodrigo arXiv:1007.4328 [hep-ph];

  higher order SM: Almeida/Sterman/Vogelsang 08; Ahrens et.al.; Bernreuther/Si 10)
- Spin correlations (Mahlon arXiv:1007.1716 [hep-ph])
- Top and BSM ($t\bar{t}t\bar{t}$ final states in strong EWSB, light $Q = 5/3$ top partners,. . .)