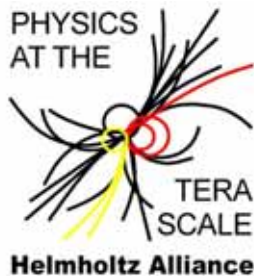
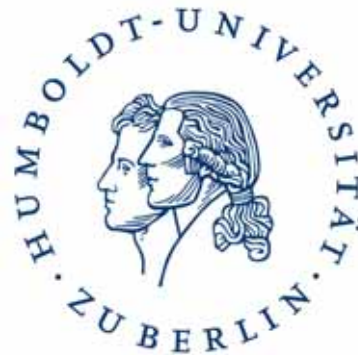


Top-quark physics: New results and recent developments

Peter Uwer



GK1504



1. Introduction
2. Recent progress on hadronic top-quark pair production
3. Beyond inclusive $t\bar{t}$ production
4. A new method to measure the top mass
5. Conclusion

- Top-quark = heaviest elementary fermion discovered so far
 - Unique properties in the SM! Behaves as predicted in the SM ? Still point like ?
 - Top mass important parameter in the SM
 - Very sensitive to EWSB
 - Top plays important role in many SM extensions

Top-quark physics is important

- per se
 - for consistency checks of the SM
 - for new physics searches
- SM extensions
→ background

The top-quark in the Standard Model

Top-quark interactions determined by the gauge structure of the SM

1. family	2. family	3. family	$T_3(SU(2)_L)$	$Y(U(1)_Y)$	$Q=T_3+Y$
$\begin{pmatrix} u_L, u_L, u_L \\ d_L, d_L, d_L \end{pmatrix}$	$\begin{pmatrix} c_L, c_L, c_L \\ s_L, s_L, s_L \end{pmatrix}$	$\begin{pmatrix} t_L, t_L, t_L \\ b_L, b_L, b_L \end{pmatrix}$	1/2	1/6	2/3
u_R, u_R, u_R	c_R, c_R, c_R	t_R, t_R, t_R	-1/2	1/6	-1/3
d_R, d_R, d_R	s_R, s_R, s_R	b_R, b_R, b_R	0	2/3	2/3
			0	-1/3	-1/3

$-ieQ\gamma^\mu$

$\frac{-ie}{\sqrt{2}s_w} V_{tq} \gamma_\mu P_L$

$\frac{-ie}{s_w c_w} (T_3 \gamma_\mu P_L - s_w^2(\theta_w) Q \gamma_\mu)$

$-ig_s T_a \gamma_\mu$

Only “2” free parameters:

- Top quark mass / Yukawa coupling
- CKM matrix

→ Top quark properties can be precisely predicted in the SM

Cabibbo-Kobayashi-Maskawa (CKM) matrix

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

eigenstates of the
weak interaction

mass eigenstates

[CKMFitter 2012, taken from A.Lenz DESY Theory Workshop 2012]

$$V_{CKM} = \begin{pmatrix} 0.97425^{+0.00022}_{-0.00014} & 0.22543^{+0.00059}_{-0.00095} & 0.00355^{+0.00015}_{-0.00012} \\ 0.22529^{+0.00060}_{-0.00094} & 0.97342^{+0.00022}_{-0.00015} & 0.04126^{+0.00060}_{-0.00104} \\ 0.00857^{+0.00033}_{-0.00030} & 0.04051^{+0.00060}_{-0.00104} & 0.999142^{+0.000043}_{-0.000025} \end{pmatrix}$$

Assumes
unitarity + 3 families

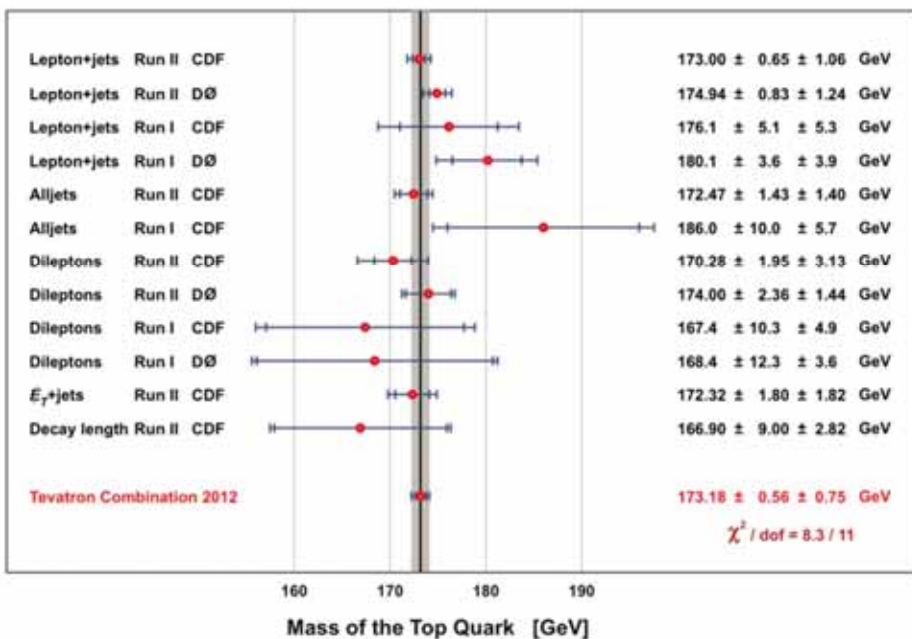


→ direct measurement
important

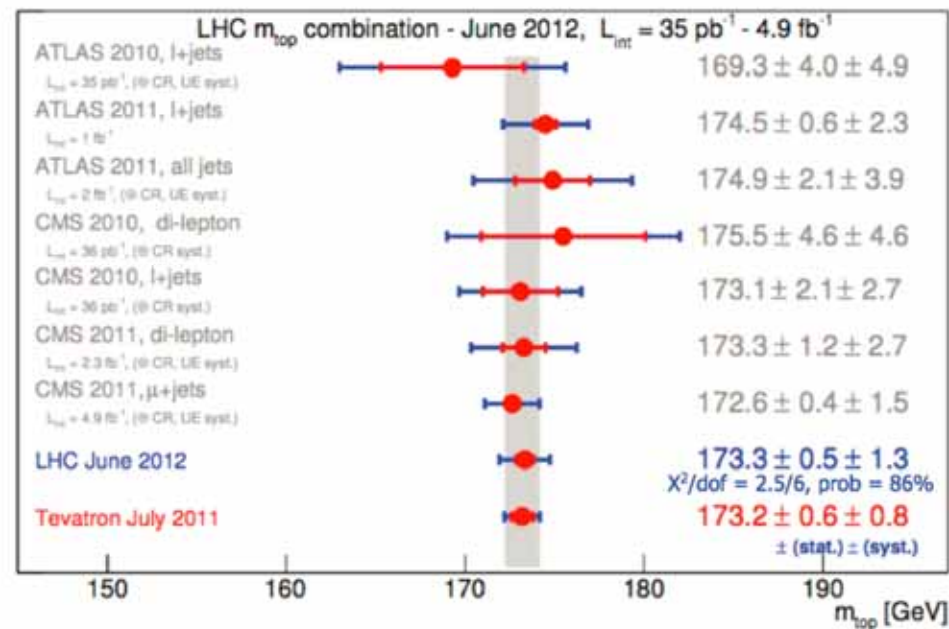
Experimental status — Top-quark mass



Tevatron



LHC

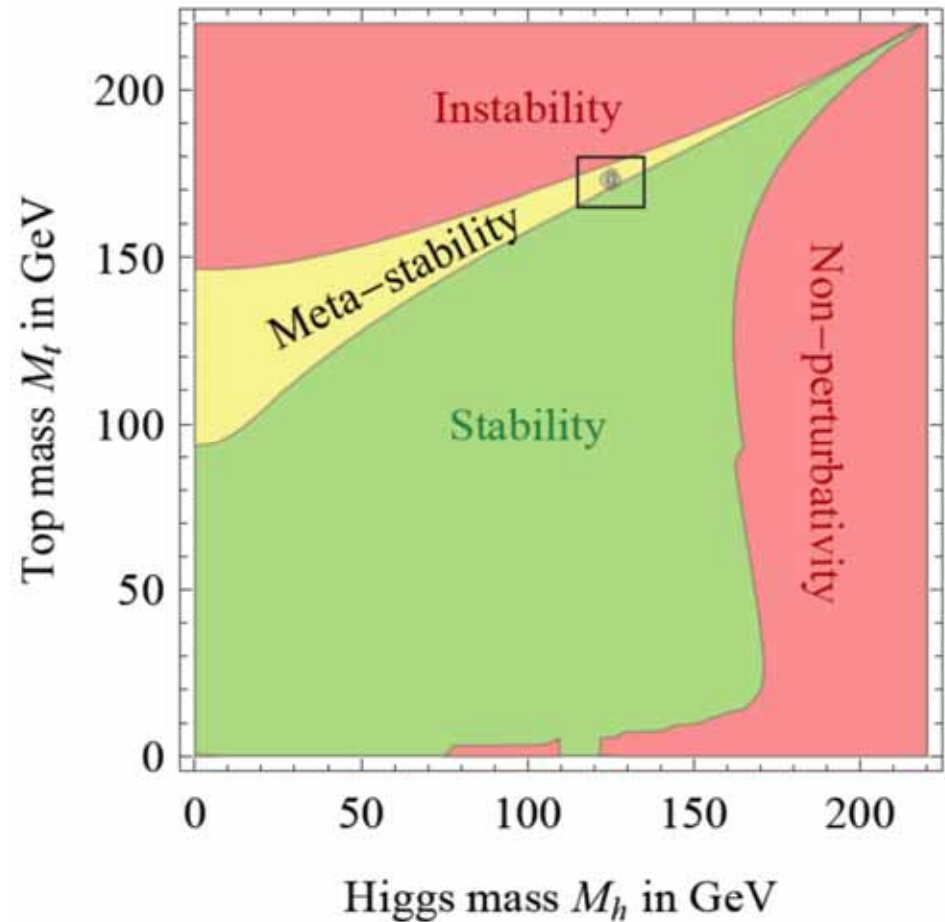
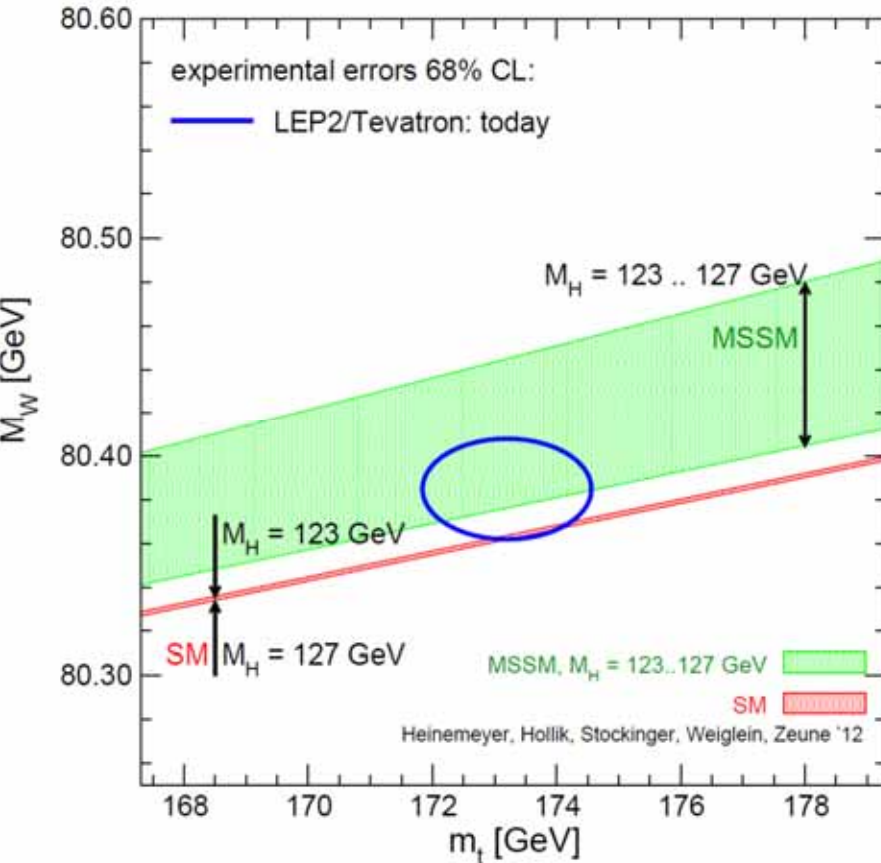


Top-quark mass measured to high accuracy

Why do we care about the top-quark mass ?

[Heinemeyer, Hollik, Stockinger, Weiglein, Zeune '12]


[Degrassi, Di Vita, Elias-Miro, Spinosa, Giudici '12, Alekhin, Djouadi, Moch '12]

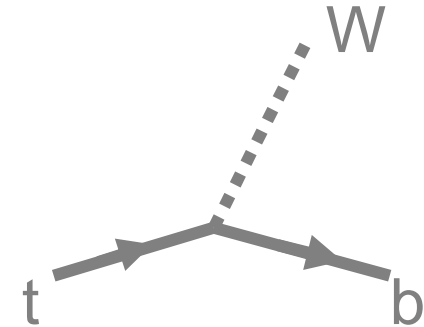


Top-quark decay

Main decay in the SM:

$$|V_{tb}| \approx 1 \quad \rightarrow \quad t \rightarrow Wb$$





Width calculable in the SM:

$$\Gamma_t = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{m_W^2}{m_t^2}\right)^2 \left(1 + \frac{2m_W^2}{m_t^2}\right) \left(1 - \frac{2\alpha_s}{3\pi} \left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right)$$

$$\approx 1.48 \text{ GeV}$$

Two-loop QCD and one-loop EW corrections also known!

Life time:

$$\Gamma \approx 1.4\text{GeV} \rightarrow \tau_t \approx 4 \times 10^{-25} \text{ s} < \tau_{\text{QCD}} \approx 3 \times 10^{-24} \text{ s}$$

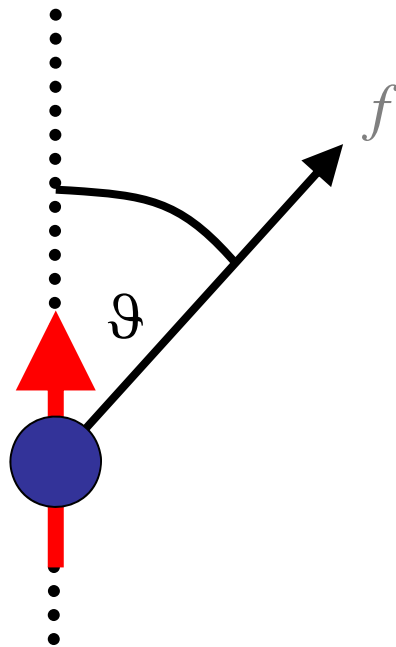
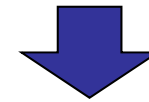
“Top-quark decays before it can hadronize“

[Bigi, Dokshitzer, Khoze, Kühn, Zerwas '86]

Unique property: Top quark behaves like a quasi-free/bare quark

Measurement of the top-quark polarisation

- Basic ingredients:**
- Top quark decays before hadronization
 - Parity violating decay $t \rightarrow Wb$



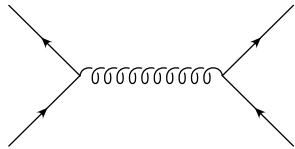
Polarisation can be studied through the angular distribution of the decay products!

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\vartheta} = \frac{1}{2} (1 + \kappa_f \cos\vartheta)$$

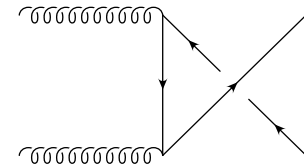
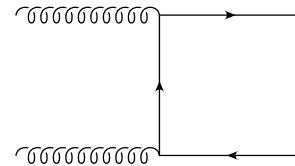
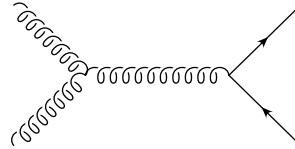
	ℓ^+, \bar{d}	ν_ℓ^+, u	b	W^+	least energetic jet from $q\bar{q}'$
κ_f	1	-0.31	-0.41	0.41	0.51

QCD NLO corrections known! [Czarnecki, Jezabek, Kühn 91, Brandenburg, Si, PU '02]

Top-quark pair production



~90% @ Tevatron, 10% @ LHC



~10% @ Tevatron, 90% @ LHC

Partonic cross sections

$$\hat{\sigma}_{q\bar{q}} = \frac{8\pi\alpha_s^2}{27\hat{s}}\beta\left(1 + \frac{\rho}{2}\right)$$

$$\hat{\sigma}_{gg} = \frac{4\pi\alpha_s^2}{12\hat{s}} \left[\left(1 + \rho + \frac{\rho^2}{16}\right) \ln\left(\frac{1+\beta}{1-\beta}\right) - \beta \left(\frac{7}{4} + \frac{31}{16}\rho\right) \right]$$

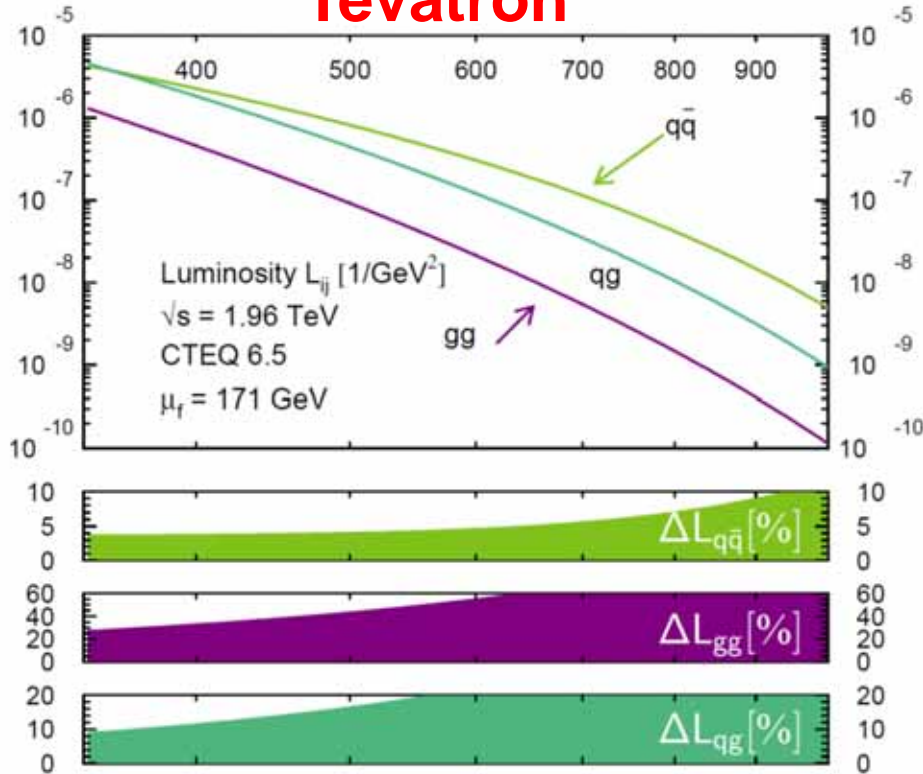
$$\beta = \sqrt{1 - 4m_t^2/\hat{s}}$$

$$\rho = 4m_t^2/\hat{s}$$

NLO corrections also known

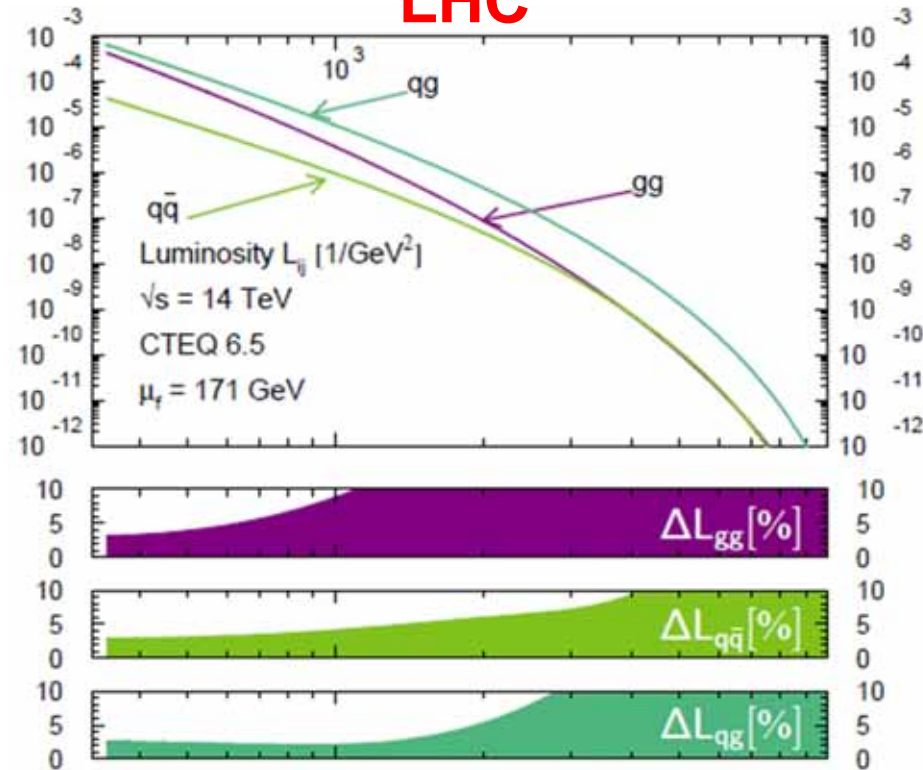
- Spin averaged total cross section [Dawson, Ellis, Nason '89, Beenakker et al '89,'91]
- Differential distributions [Mangano, Nason, Ridolfi 92],
- Spin dependent cross section [Bernreuther, Brandenburg, Si, P.U. '04]
- Analytic results for spin averaged cross section [Czakon, Mitov 08]

Tevatron



1 TeV

LHC



$$L_{ij}(\hat{s}, s_{\text{had}}, \mu_f^2) = \frac{1}{s_{\text{had}}} \int_{\hat{s}}^{s_{\text{had}}} \frac{ds}{s} f_{i/p} \left(\mu_f^2, \frac{s}{s_{\text{had}}} \right) f_{j/p} \left(\mu_f^2, \frac{\hat{s}}{s} \right)$$

$$\sigma_{pp \rightarrow t\bar{t}X}(s_{\text{had}}, m_t^2) = \sum_{i,j=q,\bar{q},g} \int_{4m_t^2}^{s_{\text{had}}} d\hat{s} L_{ij}(\hat{s}, s_{\text{had}}, \mu_f^2) \hat{\sigma}_{ij \rightarrow t\bar{t}}(\hat{s}, m_t^2, \mu_f^2, \mu_r^2)$$

- State of the art until recently:

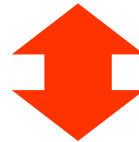
NLO + NLL **QCD**

[Dawson, Ellis, Nason '89, Beenakker et al '89,'91, Bernreuther, Brandenburg, Si, PU '04, Czakon, Mitov 08]

[Bonciani, Catani, Mangano, Nason '98, Kidonakis, Laenen, Moch, Vogt 01]

$$\frac{\Delta\sigma_{\text{th}}}{\sigma_{\text{th}}} \approx \left\{ \begin{array}{l} +5\% \text{ (scale)} \quad +6\% \text{ (pdf) Tevatron} \\ -10\% \text{ (scale)} \quad -4\% \text{ (pdf)} \\ \pm 11.5\% \text{ (scale)} \quad \pm (2-3)\% \text{ (pdf) LHC} \end{array} \right.$$

[Moch, PU 08, Cacciari, Frixione, Mangano, Nason, Ridolfi 08, Kidonakis, Vogt 08]



$$\sigma_{t\bar{t}} = 161.9 \pm 2.5(\text{stat.})_{-5.0}^{+5.1}(\text{syst.}) \pm 3.6(\text{lumi}) \text{ pb}, \quad \delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim 4.2\%$$

[Christian Schwanenberger, DESY TH workshop]

NLO + NLL **QCD** not sufficient

Experimental accuracy about 5 %

→ need to go beyond NLO+NLL accuracy

Possible corrections (percent level):

QCD NNLO

$$\sim \alpha_s^4$$

Bound state
effects

$$”\sim \left(\alpha_s^3 \frac{1}{\beta}\right) \beta”$$

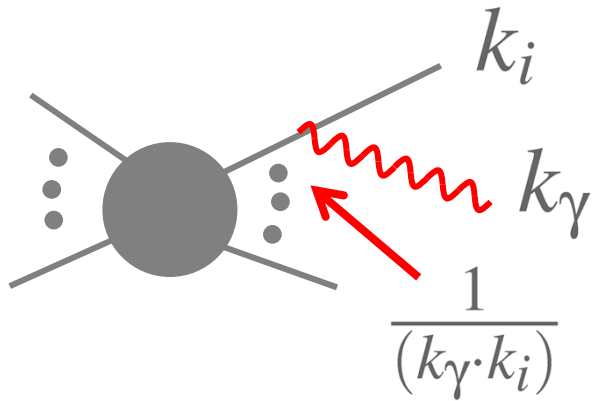
Mixed weak-QCD
corrections

$$\sim \alpha_s^2 \alpha$$

finite width

$$\Gamma_t / m_t$$

1) Soft limits



$$\mathcal{M}_{n+1} \xrightarrow{k_\gamma \rightarrow 0} \frac{(\varepsilon \cdot k_i)}{(k_\gamma \cdot k_i)} \mathcal{M}_n$$

$$|\mathcal{M}_{n+1}|^2 \rightarrow \sum_{i,j} \frac{(k_i \cdot k_j)}{(k_\gamma \cdot k_i)(k_\gamma \cdot k_j)} |\mathcal{M}_n|^2$$



2) Phase space integration

$$(k_i \cdot k_j)^\varepsilon \int \frac{d^{d-1}k_\gamma}{(2\pi)^{d-1} 2E_\gamma} \frac{(k_i \cdot k_j)}{(k_\gamma \cdot k_i)(k_\gamma \cdot k_j)} \sim \int \frac{dE_\gamma d\Omega_{d-1}}{E_\gamma^{1+2\varepsilon} (1 - \cos^2 \vartheta)}$$

$$\rightarrow \frac{1}{\varepsilon^2}, \frac{1}{\varepsilon}, \ln^2 \left(\frac{E_\gamma^{\max}}{\sqrt{(k_i \cdot k_j)}} \right), \ln \left(\frac{E_\gamma^{\max}}{\sqrt{(k_i \cdot k_j)}} \right)$$

universal behavior!

Large logarithmic corrections if

$$E_\gamma^{\max} \ll \sqrt{(k_i \cdot k_j)} = Q$$

i.e. $\beta \rightarrow 0$ (threshold), or $1 - \frac{M_{t\bar{t}}}{\hat{s}} \rightarrow 0$

Cross section in Mellin space

$$\hat{\sigma}(N) = \int_0^1 d\rho \rho^{N-1} \sigma(\rho) \quad (\rho = 4m_t^2/\hat{s})$$

$\rho \gg 1$, large N
 "Threshold region"
 Soft-collinear factorization

$\rho \rightarrow 0$, small N
 High energy behavior
 BFKL

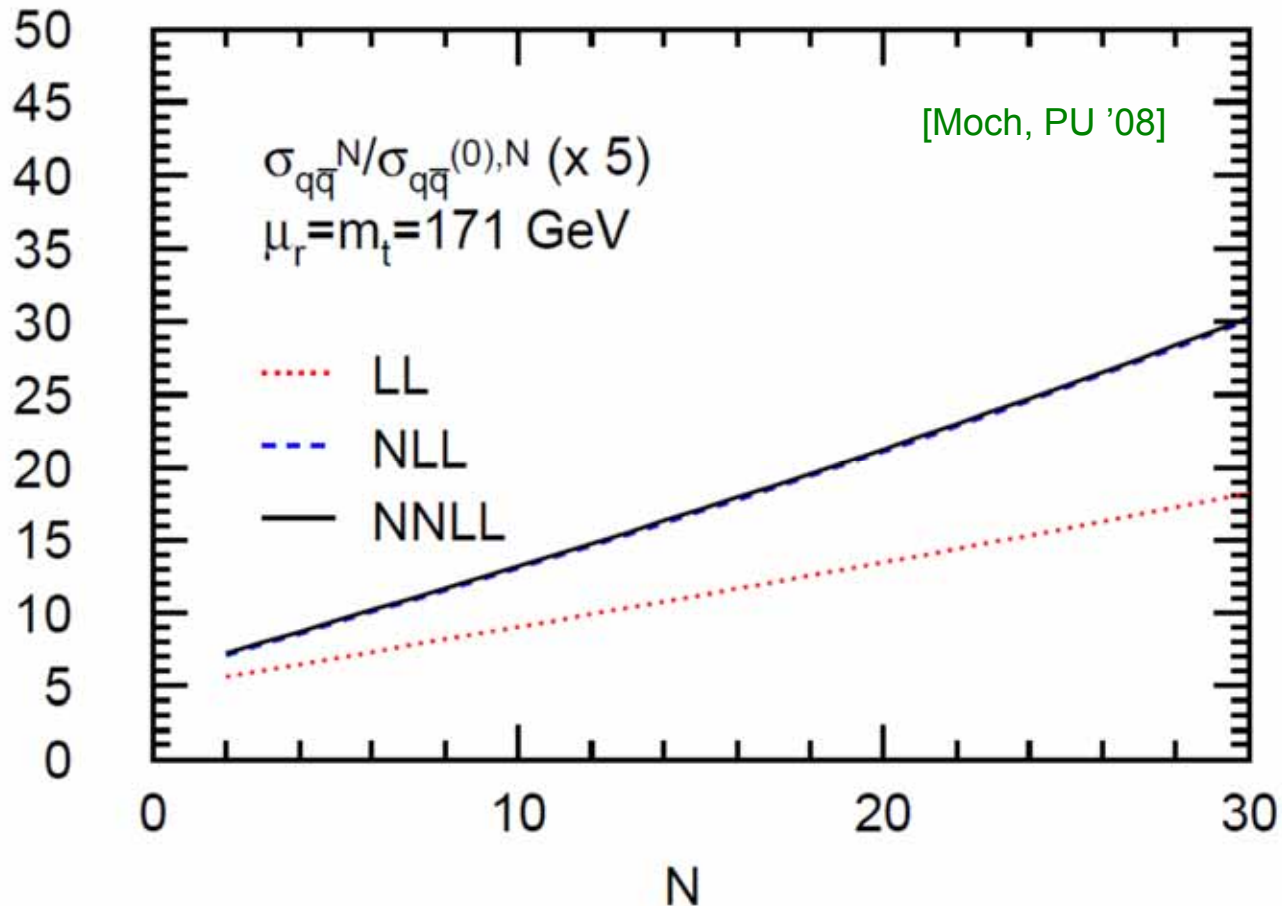
$$\hat{\sigma} = \sigma_{LO} \left(1 + \sum_{j=1}^{\infty} \sum_{k=1}^{2j} b_{jk} \alpha_s^j \ln^k N \right)$$

$$\hat{\sigma} \sim \frac{\alpha_s^2}{m_t^2} \sum_{j=0}^{\infty} \alpha_s^j \sum_{k=0}^{\infty} c_{jk} \left(\frac{\alpha_s}{N} \right)^k$$

Resummation

$$\frac{1}{N} \leftrightarrow \text{const}_\rho \quad \frac{1}{N^2} \leftrightarrow \ln(\rho)$$

Resummation beyond NLL



Similar results for gg , missing constants guessed
→ Small effect, use resummation to generate $\text{NNLO}_{\text{approx}}$
Include knowledge on Coulomb singularity and full scale (in)dependence

[Ahrens, Baernreuther, Beneke, Bonciani, Cacciari, Catani, Czakon, Ferroglia, Kidonakis, Laenen, Mangano, Mitov, Moch, Nason, Neubert, Pecjak, Ridolfi, Schwinn, Sterman, PU, Vogt, Yang...]

■ Beyond NLO + NLL QCD:

$$(\beta = \sqrt{1 - 4m^2/s})$$

- NNLO approx {
- Soft gluon resummation $(\ln(\beta), \ln^2(\beta) \dots)$
 - Threshold corrections $(1/\beta, 1/\beta^2 \dots)$
 - Full scale NNLO (in)dependence (RGE: $\ln(\mu), \ln^2(\mu)$)
 - Combined soft and Coulomb resummation [Beneke et al]

NEW '12:

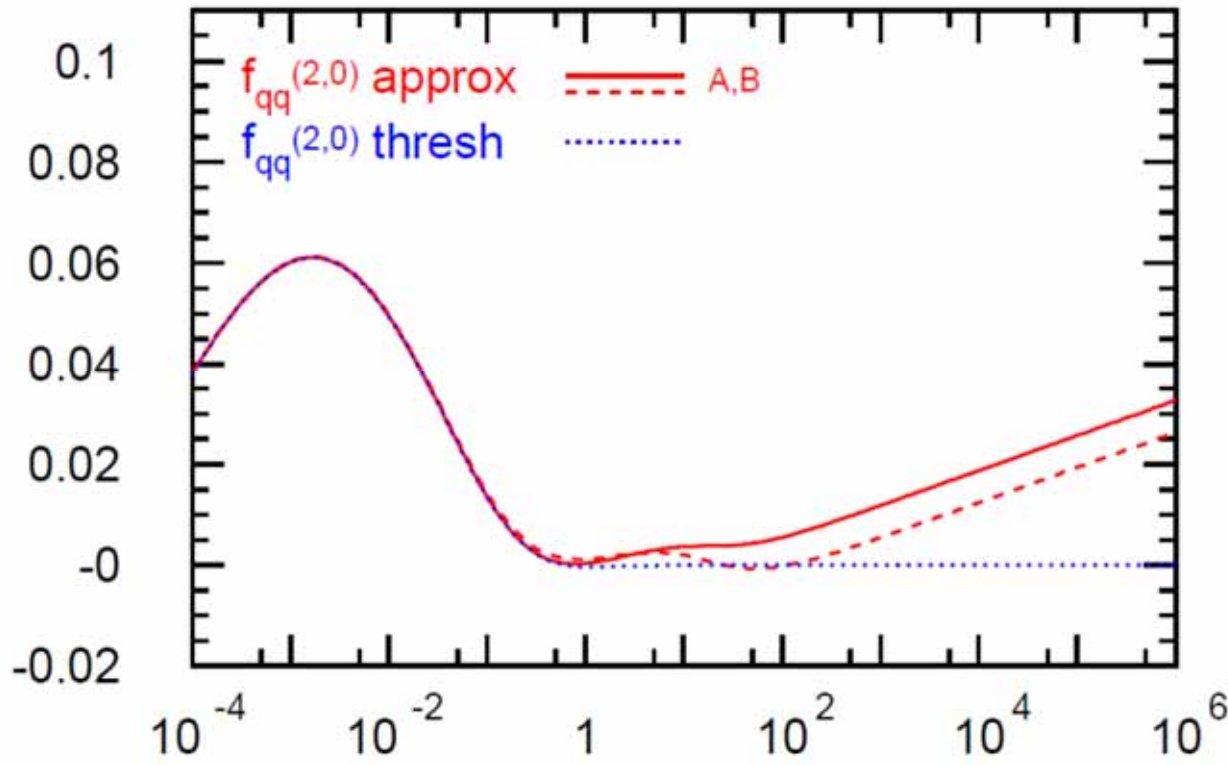
- High energy behavior [Ball, Ellis '01, Moch, PU, Vogt '12]
- NNLO QCD for $qq \rightarrow tt$ [Baernreuther, Czakon, Mitov '12]

High energy behavior through BFKL dynamics



[Moch, PU, Vogt '12]

$$\sigma_{ij} = \frac{\alpha_s^2}{m_t^2} \left(\underset{\text{LO}}{f_{ij}^{(0)}} + 4\pi\alpha_s \underset{\text{NLO}}{f_{ij}^{(1,0)}} + (4\pi\alpha_s)^2 \underset{\text{NNLO}}{f_{ij}^{(2,0)}} + \dots \right) \quad (\mu_r = \mu_f = m_t)$$



threshold

$$\eta = \frac{s}{4m^2} - 1$$

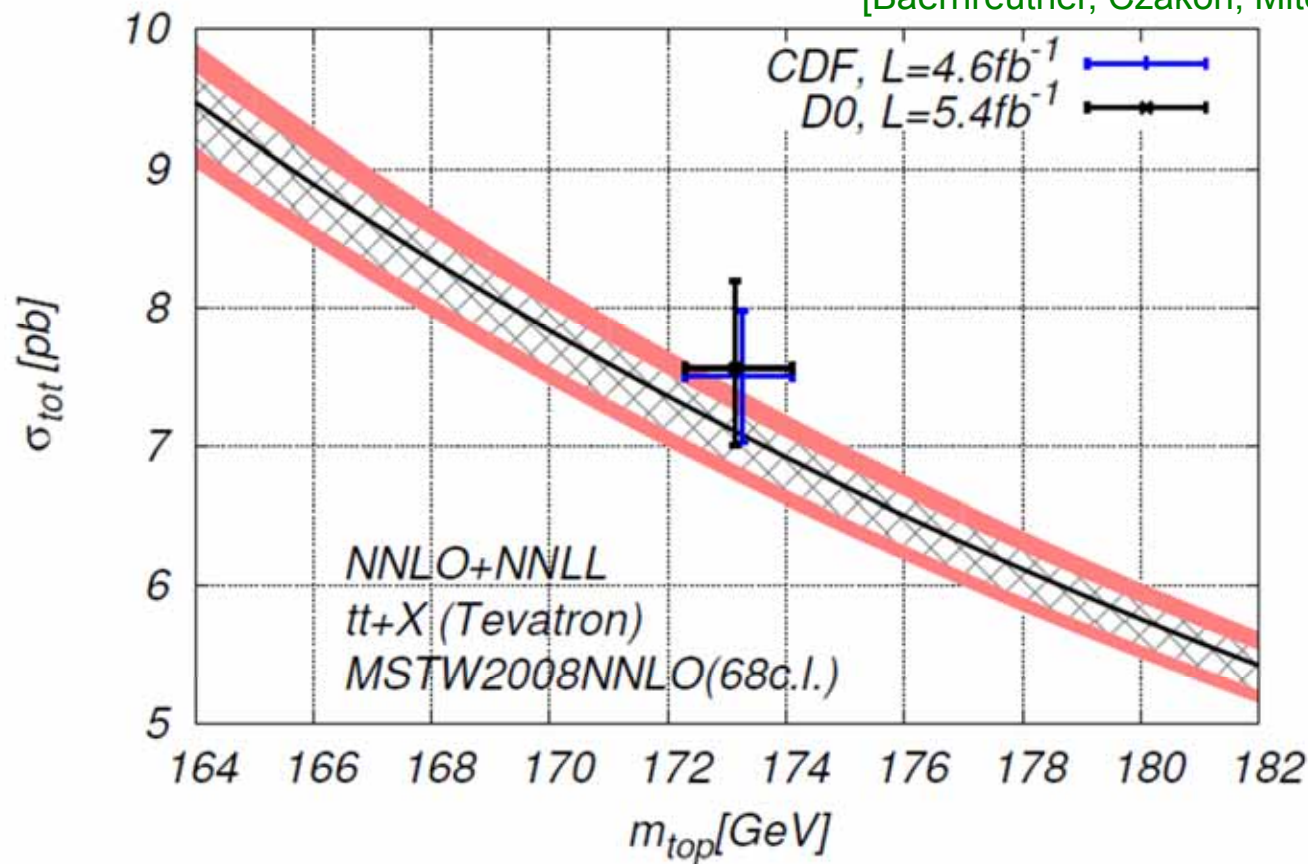
high energy

→ Recently confirmed by direct calculation [Czakon, Mitov '12]

Recent progress: $qq \rightarrow tt$ @ NNLO/NNLL



[Baernreuther, Czakon, Mitov arXiv:1204.5201]



Tevatron: $\sigma_{tot}^{res} = 7.067 \begin{matrix} +0.143 (2.0\%) \\ -0.232 (3.3\%) \end{matrix} [\text{scales}] \begin{matrix} +0.186 (2.6\%) \\ -0.122 (1.7\%) \end{matrix} [\text{pdf}]$

$gg \rightarrow tt$ @ NNLO is underway

~3%

Comparison with NNLO_{approx}



Fixed order NNLO: [Baernreuther, Czakon, Mitov arXiv:1204.5201]

$$\sigma_{\text{tot}}^{\text{NNLO}} = 7.005 \begin{array}{l} +0.202 (2.9\%) \\ -0.310 (4.4\%) \end{array} [\text{scales}] \begin{array}{l} +0.170 (2.4\%) \\ -0.122 (1.7\%) \end{array} [\text{pdf}]$$

NNLO_{approx} [HATHOR, Aliev, Lacker, Langenfeld, Moch, PU, Wiedermann '10]

$$\sigma_{\text{tot}}^{\text{NNLO}_{\text{approx}}} = 7.058 \begin{array}{l} +0.196 (2.8\%) \\ -0.315 (4.4\%) \end{array} (\text{scales}) \begin{array}{l} +0.17 (2.4\%) \\ -0.12 (1.7\%) \end{array} (\text{pdf})$$

Based on threshold logs + RGE + Coulomb singularity

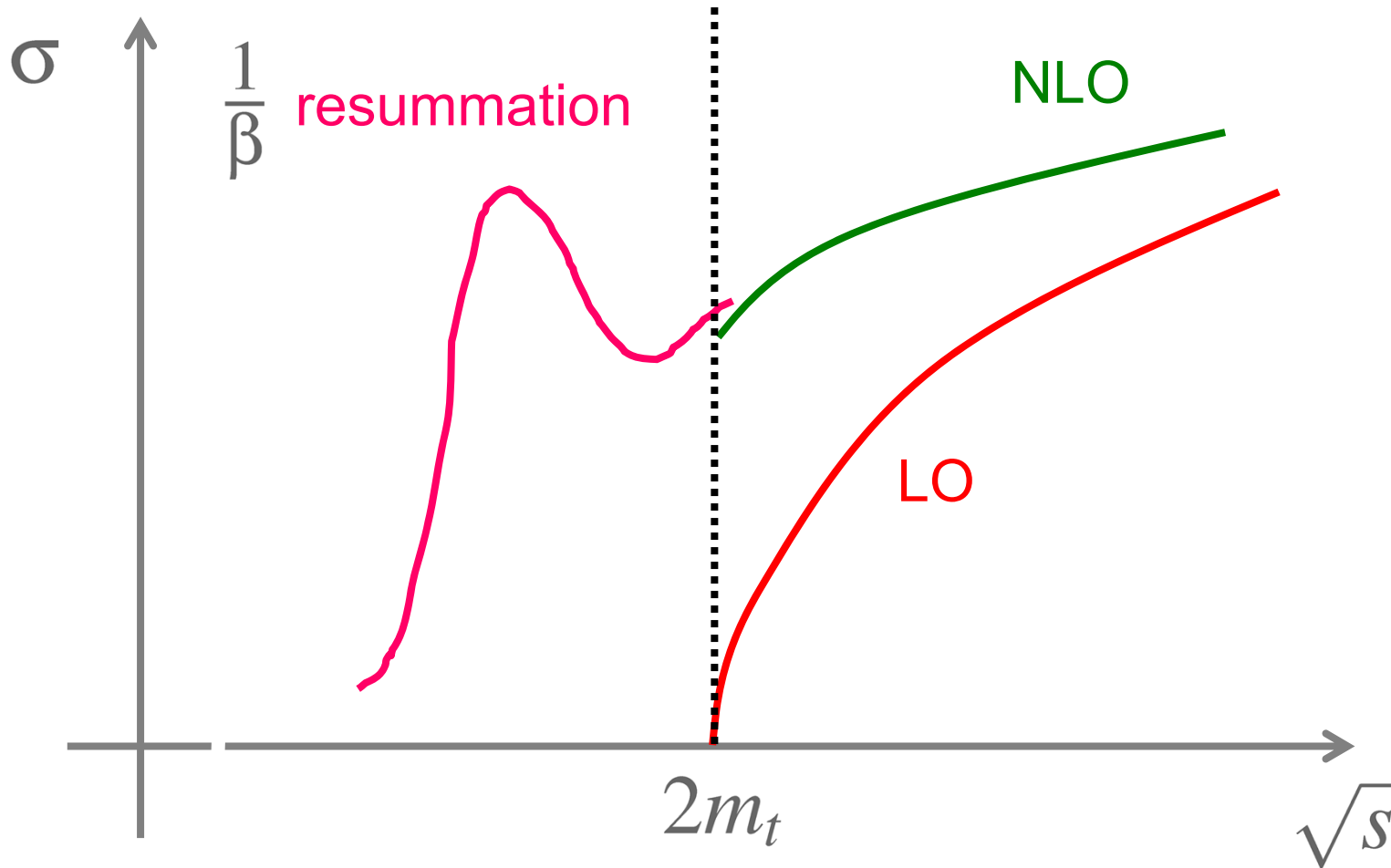
No qg contribution included in NNLO!



Agreement better than 1 % !

HATHOR = HAdronic Top and Heavy quark crOSS section calculatoR

“Boundstate” effects



NRQCD approach:

[Bodwin, Braaten, Lepage 95]

$$M \frac{d\sigma_{P_1 P_2 \rightarrow T}}{dM}(S, M^2) = \sum_{i,j} \int_{\rho}^1 d\tau \left[\frac{d\mathcal{L}_{ij}}{d\tau} \right](\tau, \mu_f^2) M \frac{d\hat{\sigma}_{ij \rightarrow T}}{dM}(\hat{s}, M^2, \mu_f^2).$$

$t\bar{t}$ – system with specific spin and color

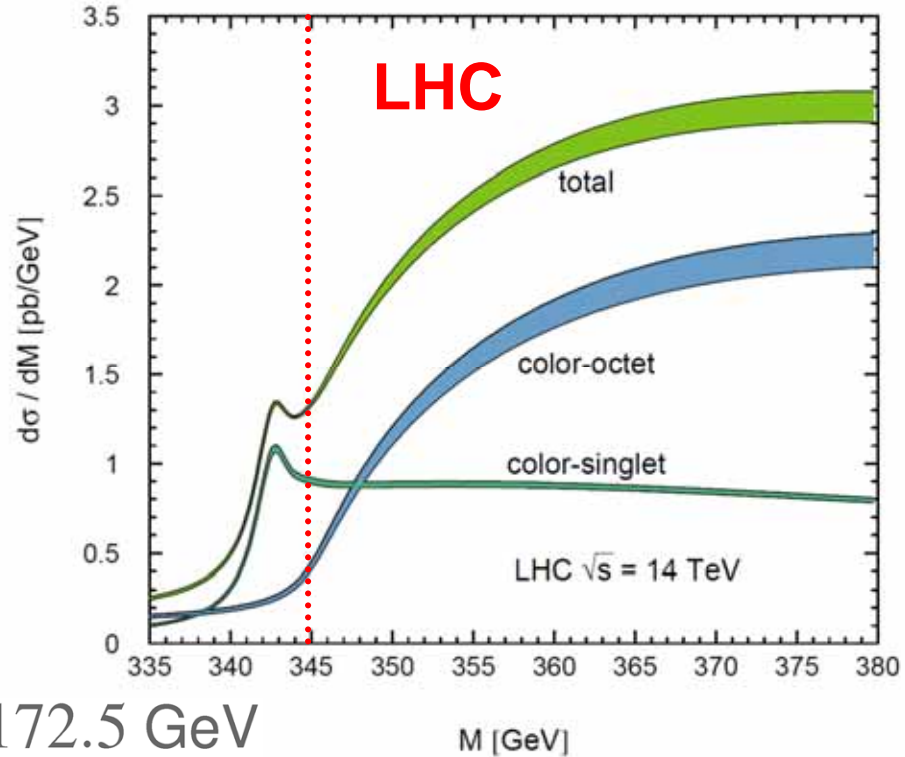
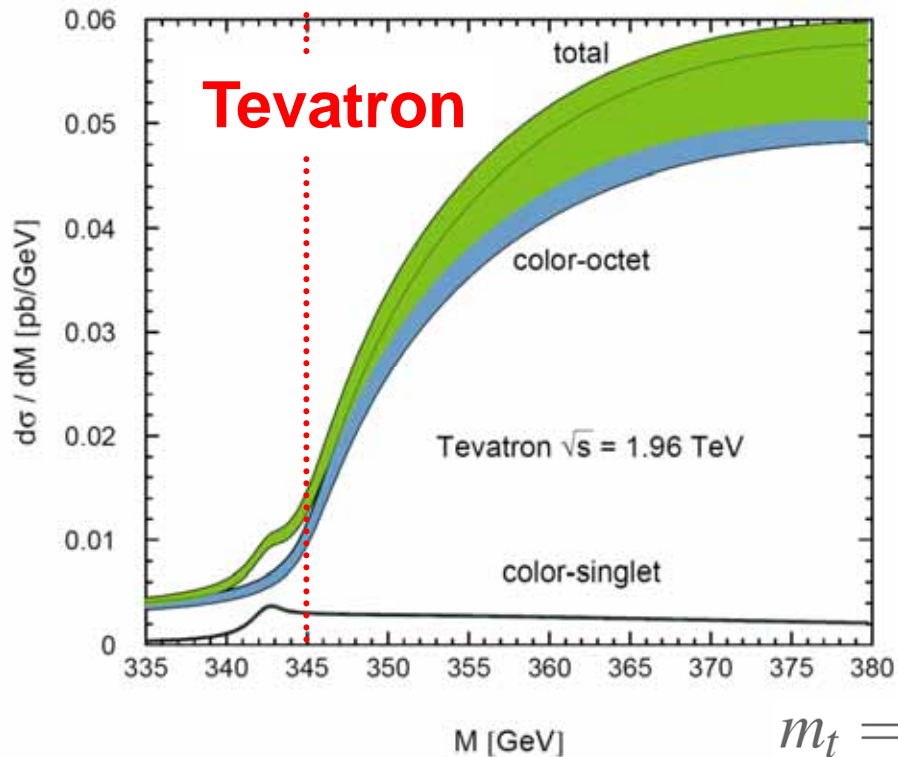
$$M \frac{d\hat{\sigma}_{ij \rightarrow T}}{dM}(\hat{s}, M^2, \mu_f^2) = F_{ij \rightarrow T}(\hat{s}, M^2, \mu_f^2) \frac{1}{m_t^2} \text{Im} G^{[1,8]}(M + i\Gamma_t),$$

Quarkonium production,
hard scattering

non-relativistic
Schrödinger
Greensfunction
“bound state effects”

(Would-be) Bound state effects at threshold

[Hagiwara, Sumino, Yokoya 08]
[Kiyo, Kühn, Moch, Steinhauser, PU 08]



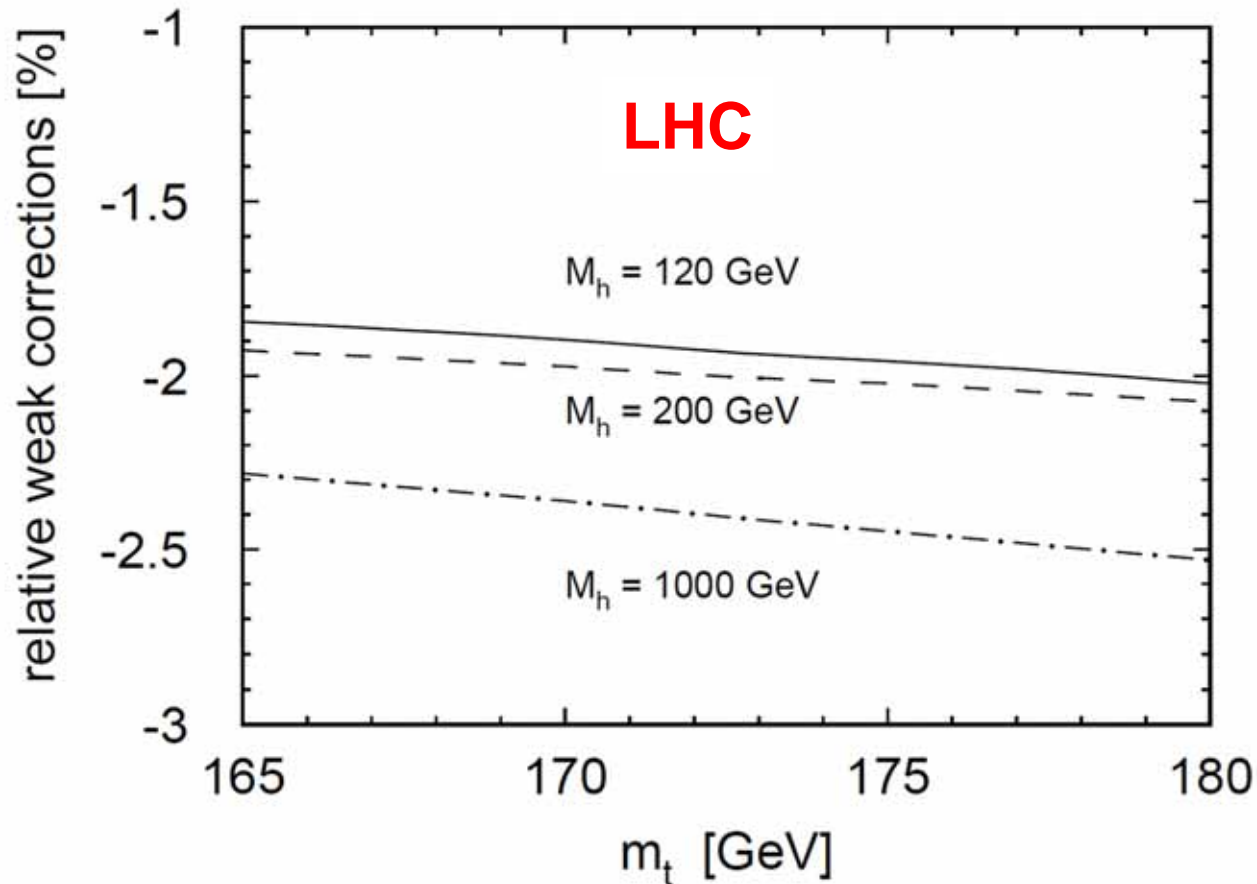
“Resonance structure” from would be bound state

$\sim +1\%$ shift of total cross section at LHC

Weak corrections

[Beenakker et al 94, Bernreuther, Fückler, Si 06', 07]

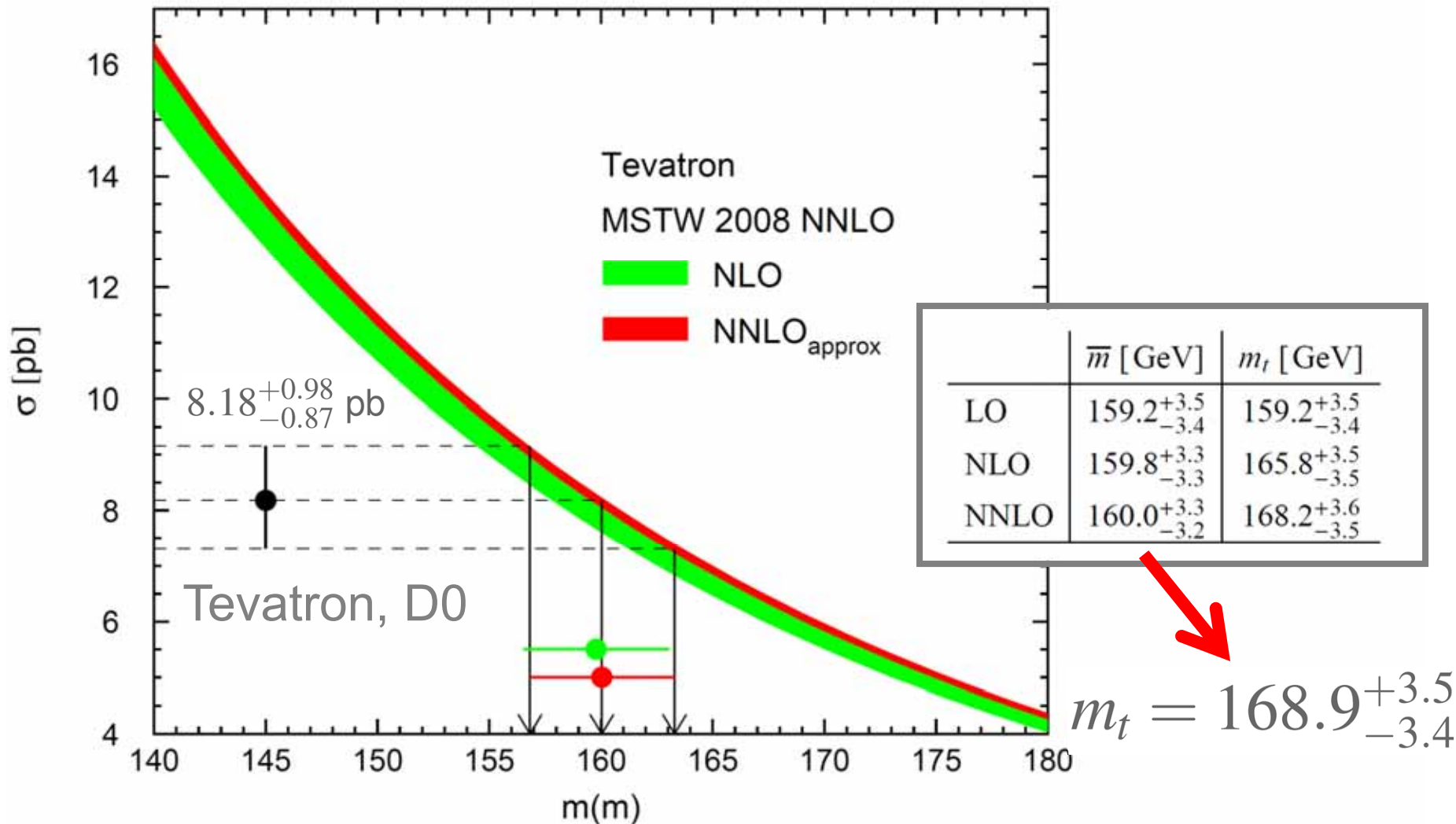
[Kühn, Scharf, PU 06,07]



mixed weak corrections of order $\alpha\alpha_s^2$

First direct determination of the \overline{m}_S mass

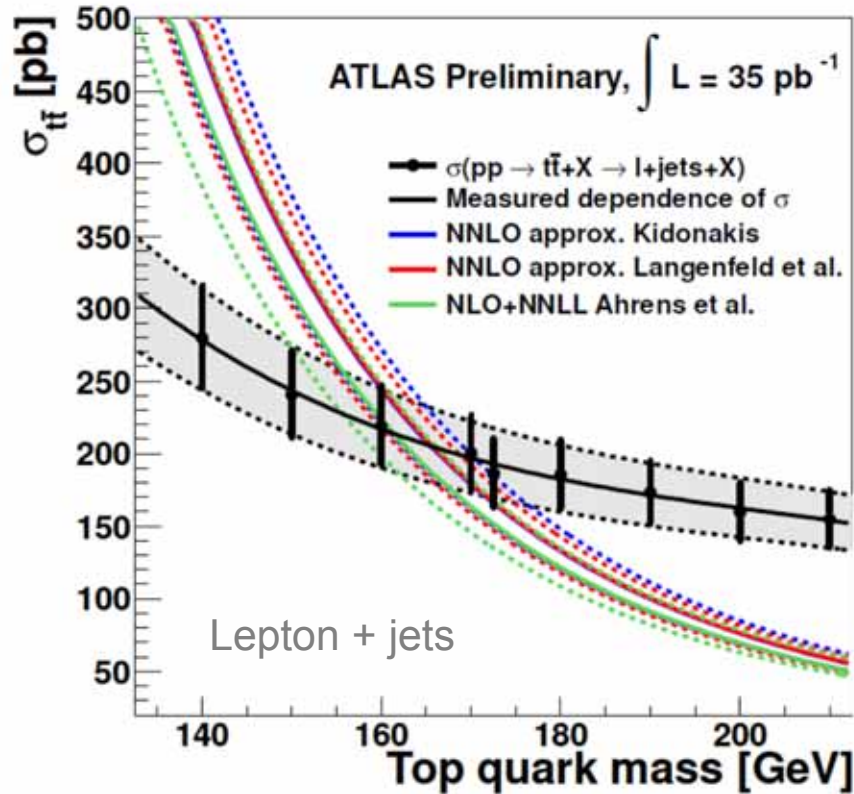
[Langenfeld, Moch, PU 09]



Recent measurements

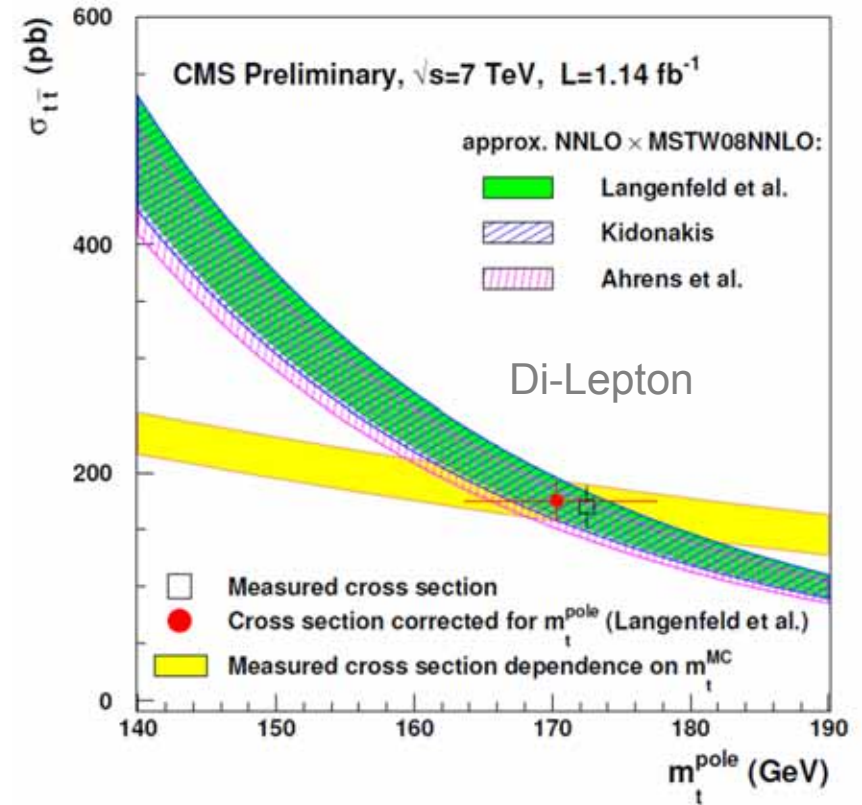


ATLAS-CONF-2011-054, 35 1/pb



Approx. NNLO \times MSTW08NNLO	$m_t^{\text{pole}} / \text{GeV}$
Langenfeld et al.	$166.4^{+7.8}_{-7.3}$
Kidonakis	$166.2^{+7.8}_{-7.4}$

CMS-PAS-TOP-11-008, 1.1 1/fb



Approx. NNLO \times MSTW08NNLO	$m_t^{\text{pole}} / \text{GeV}$	$m_t^{\overline{\text{MS}}} / \text{GeV}$
Langenfeld et al.	$170.3^{+7.3}_{-6.7}$	$163.1^{+6.8}_{-6.1}$
Kidonakis	$170.0^{+7.6}_{-7.1}$	-

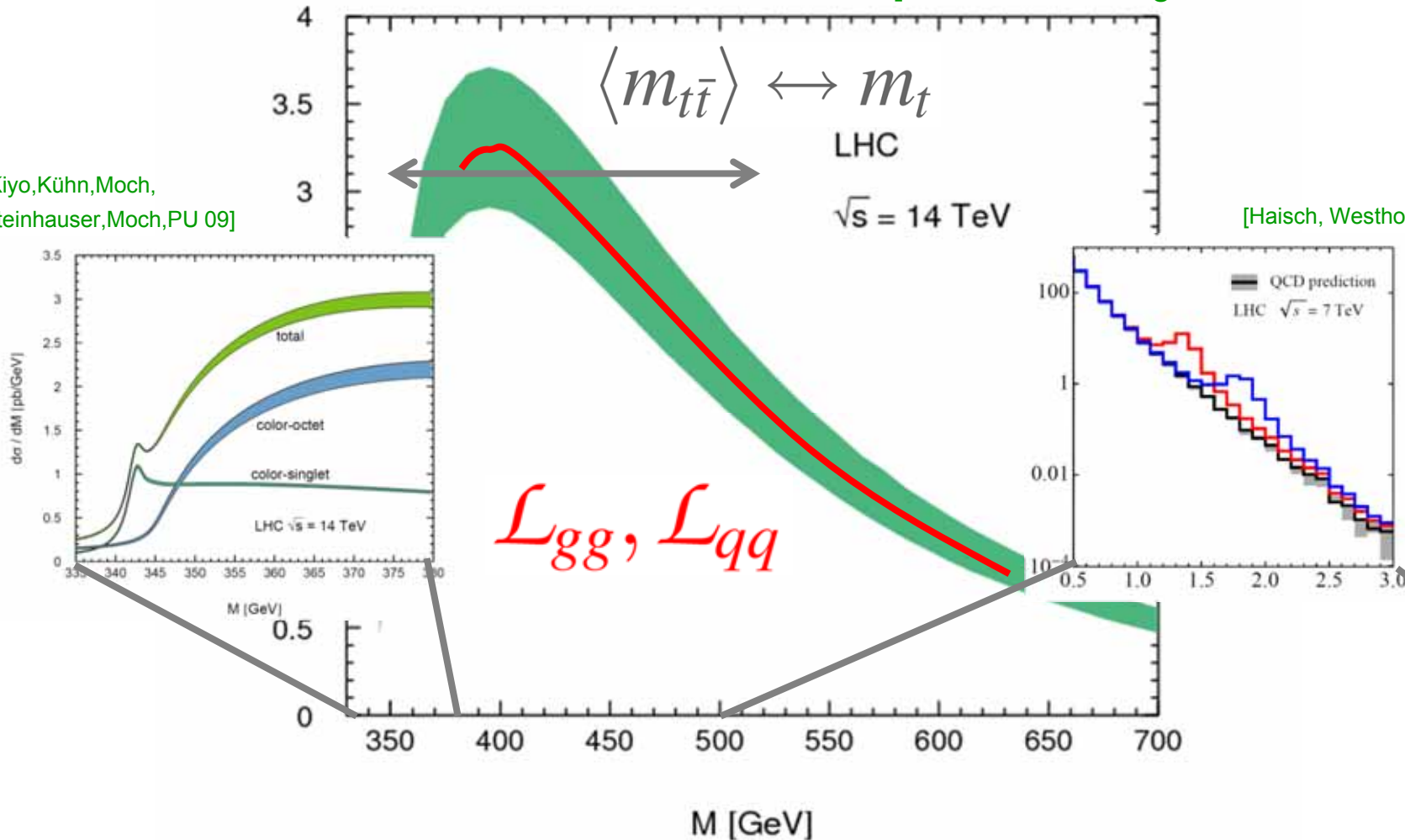
Differential distributions

Example: $m_{t\bar{t}}$ -distribution in top-quark pair production

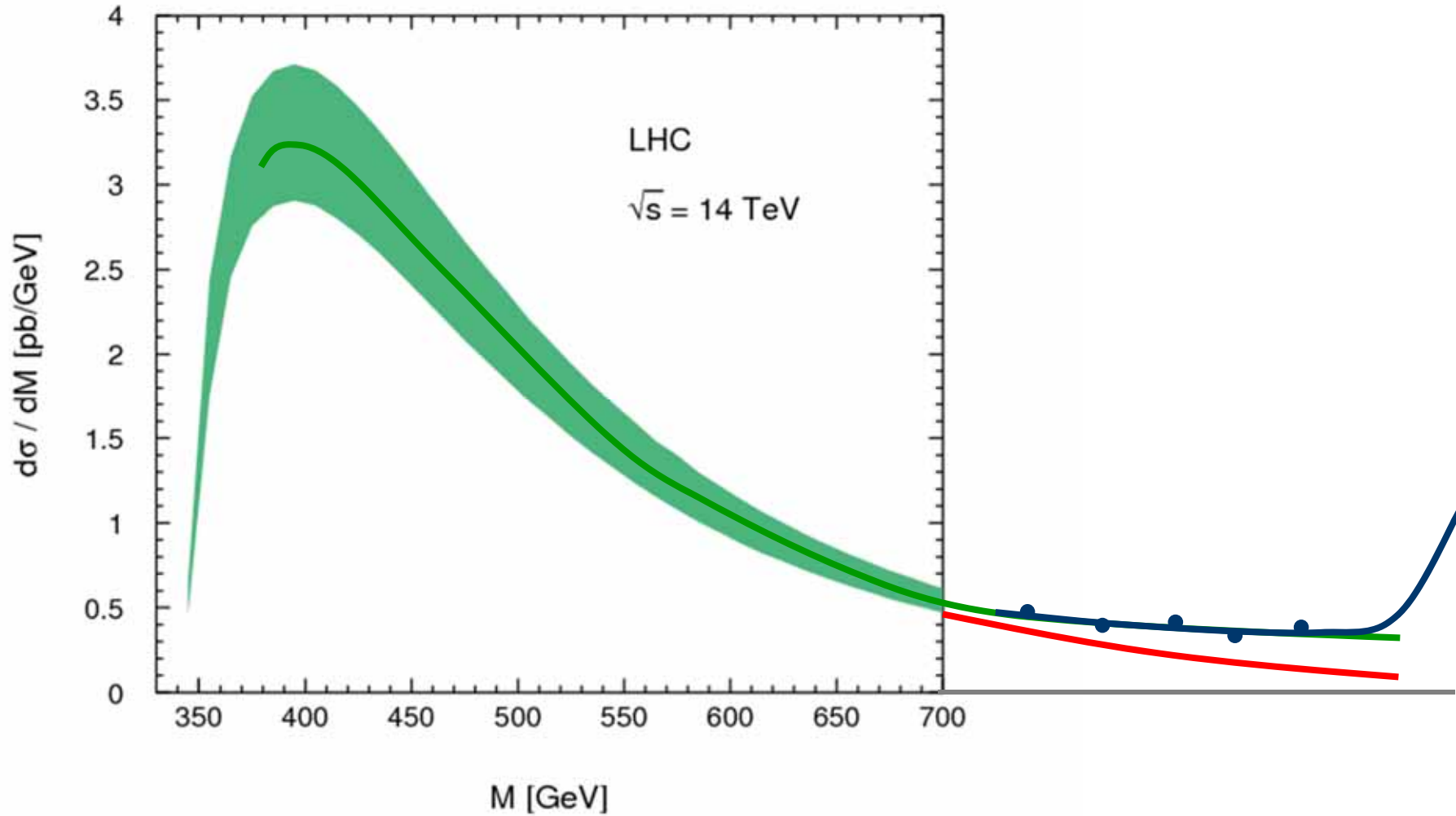
[HVQMNR, Mangano, Nason, Ridolfi]

[Kiyo, Kühn, Moch, Steinhauser, Moch, PU 09]

[Haisch, Westhoff 11]



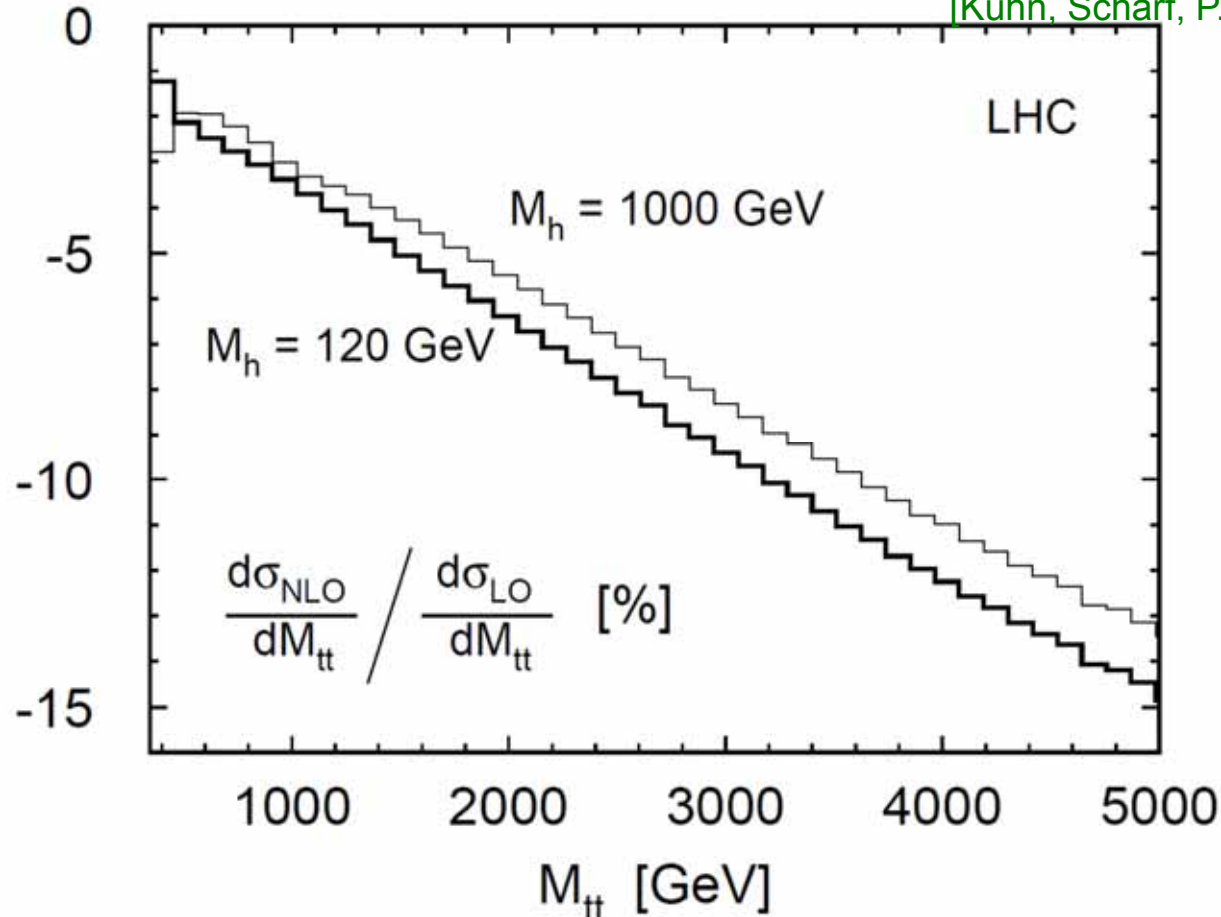
Precise predictions are important



Weak corrections — Sudakov suppression

[Beenakker et al 94, Bernreuther, Fückler, Si 06', 07]

[Kühn, Scharf, P.U 06,07]



→ relevant when searching for new physics, using the m_{tt} spectrum
 could hide a possible raise of the cross section if not taken into account

Top-quark spin correlation

Due to parity invariance of **QCD**, top's produced in $qq \rightarrow tt$ and $gg \rightarrow tt$ are essentially **unpolarized**

[Dharmaratna, Goldstein, '90,
Bernreuther, Brandenburg, PU 95]

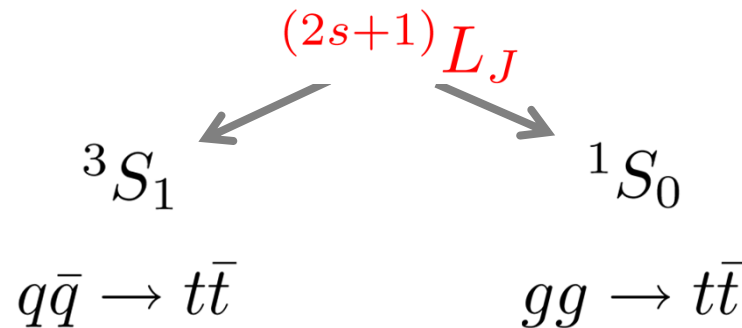
But:

Spins of top quark and antiquark are correlated

[Bernreuther, Brandenburg 93,
Mahlon, Parke 96, Stelzer, Willenbrock 96,
Bernreuther, Brandenburg, Si, PU 04]

Quantum mechanics:

close to
threshold:



→ Spins are parallel or anti-parallel close to threshold

$$C_{t\bar{t}} = \frac{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) - \sigma(\uparrow\downarrow) - \sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow) + \sigma(\downarrow\downarrow) + \sigma(\uparrow\downarrow) + \sigma(\downarrow\uparrow)}$$

- Search for **new physics**
 - i.e. CP violating interactions, Higgs with undefined parity, properties of s-channel resonance
- Affect the **angular distributions** of the decay products
 - important for event selection
- Test of the decay as a **quasi free quark**
 - precise test of the **production and decay** mechanism

Spin correlations: Lepton opening angle distr.



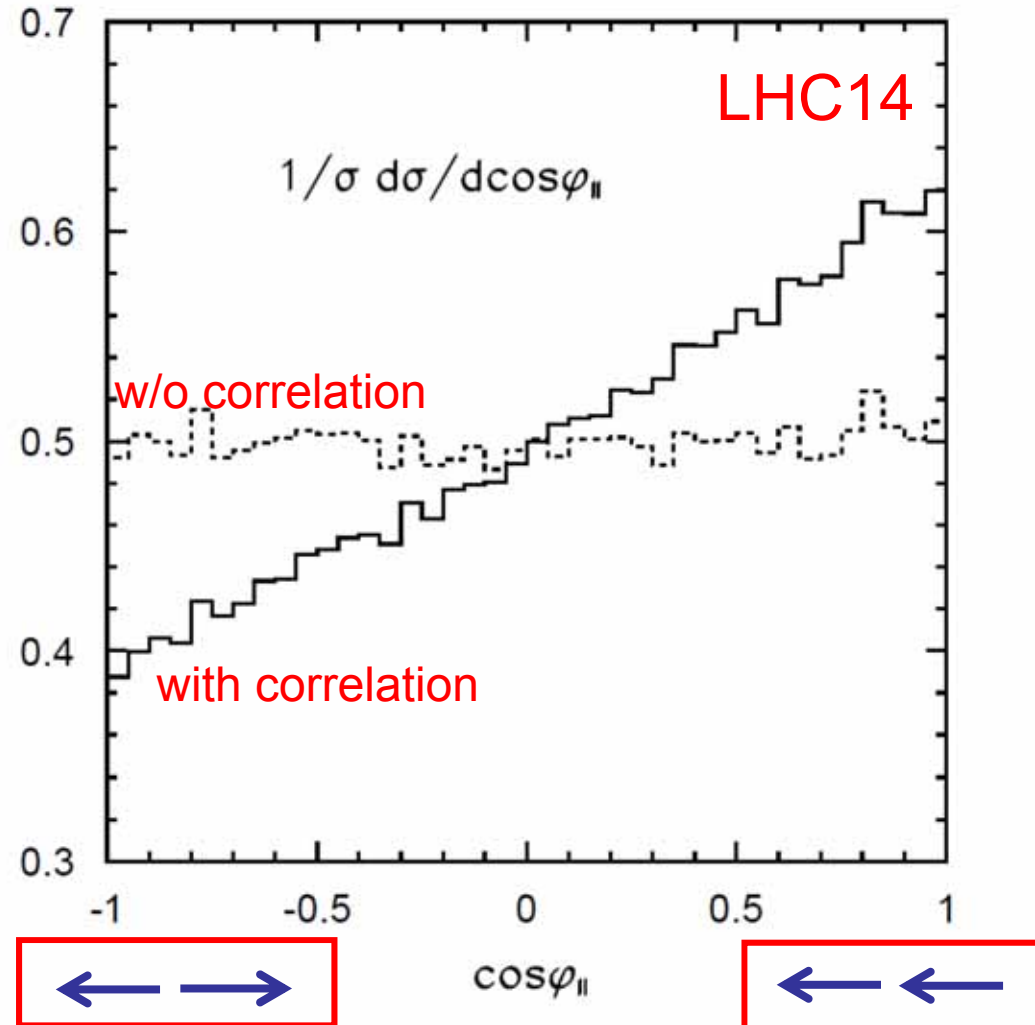
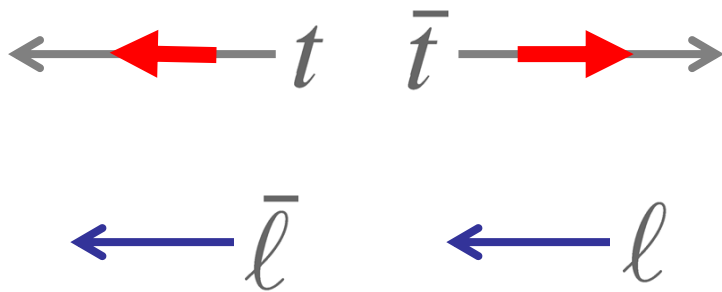
[Bernreuther, Si 10]

LHC:

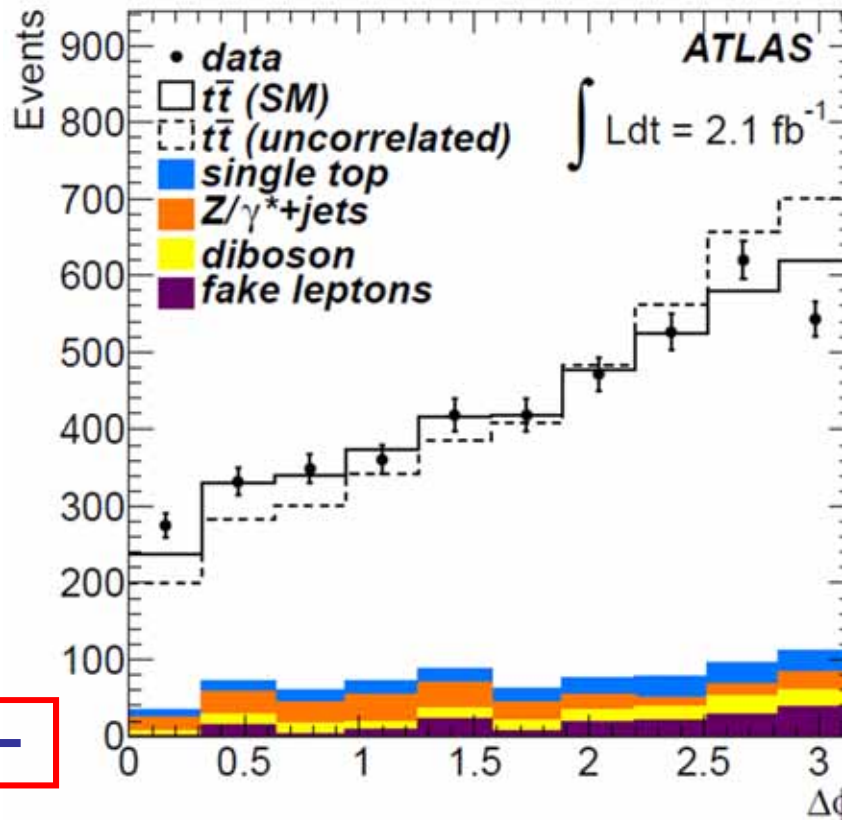
gg dominates



1S_0



[arXiv:1203.4081]



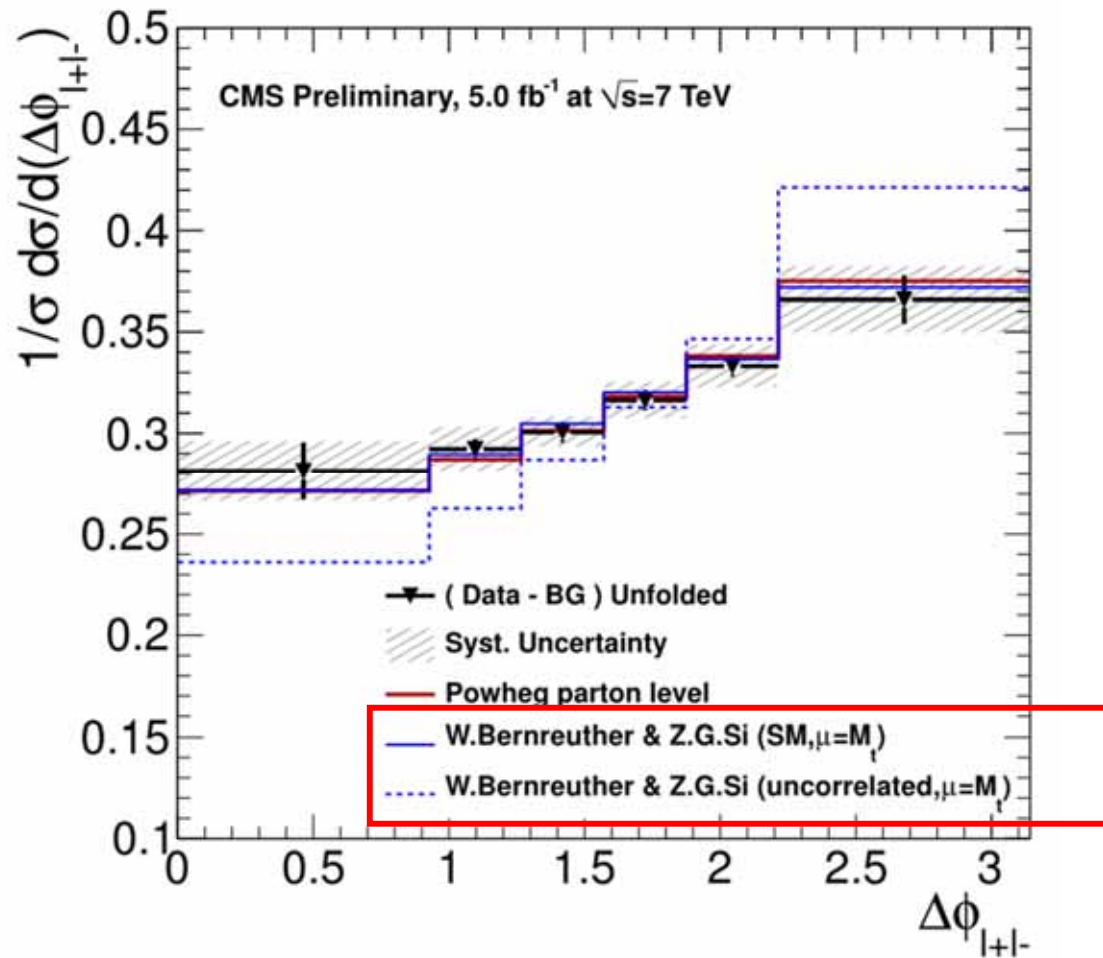
First
Observation of
spin-correlations
(5.1 σ)



Ansatz: $d\sigma = f \times d\sigma^{\text{no-corr.}} + f^{\text{SM}} \times d\sigma^{\text{SM}}$

$$f^{\text{SM}} = 1.30 \pm 0.14 \text{ (stat)} \begin{matrix} +0.27 \\ -0.22 \end{matrix} \text{ (syst)}$$

LHC measurement



Why important ?

- Many top-quark pairs produced in association with jets
- Top-quark decay affects reconstruction + cuts
- Consistent inclusion of parton shower



Experimental analysis needs to take effects into account

→ Detailed understanding required

Many new results, mainly due to

- more sophisticated methods for one-loop calculation
(i.e. unitarity method, improved conventional approach, more cpu power)
→ High multiplicity final states
- conceptual developments
(i.e. complex mass scheme)
→ Finite width effects
- better modelling of final state
(i.e. top decay, consistent matching with parton shower)
→ Powheg and MC@NLO

Progress beyond top-quark pair production

$$t\bar{t} + 1\text{-Jet} + X$$

[Dittmaier, PU, Weinzierl 08],
[Bevilacqua, Czakon, Papadopoulos, Worek 10]
[Melnikov, Schulze 10]
[Melnikov, Scharf, Schulze 11]
[Kardos, Papadopoulos, Trocsanyi 11]
[Ailioli, Moch, PU 11]

NLO
+ decay
+ shower

$$t\bar{t} + \gamma + X$$

[Duan, Zhang, Han, Guo, Wang 09]
[Melnikov, Scharf, Schulze 11]

NLO
+ decay

$$t\bar{t}b\bar{b} + X$$

[Bredenstein, Denner, Dittmaier, Pozzorini 08-10]
[Bevilacqua, Czakon, Papadopoulos, Pittau, Worek 09]

NLO

$$t\bar{t} + 2\text{-Jets} + X$$

[Bevilacqua, Czakon, Papadopoulos, Worek 11]

NLO

$$WWb\bar{b} + X$$

[Bevilacqua, Czakon, van Hameren, Papadopoulos, Worek '10]
[Denner, Dittmaier, Kallweit, Pozzorini 10, 12]

NLO

$$tt\bar{t}\bar{t} + X$$

[Bevilacqua, Worek 12]

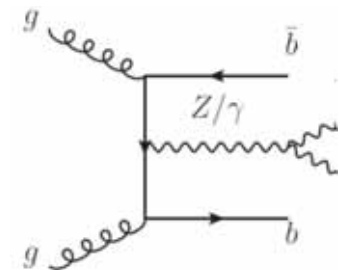
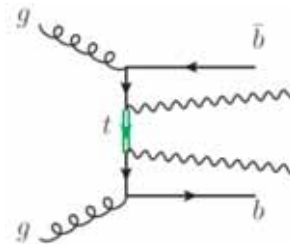
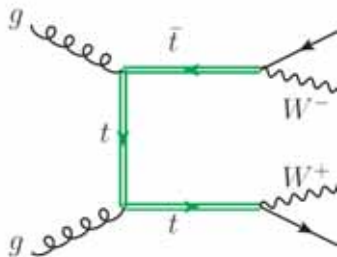
NLO

- Off-shell effects and non-factorizable corrections

[Bevilacqua, Czako, van Hameren, Papadopoulos, Worek '10]

[Denner, Dittmaier, Kallweit, Pozzorini 10, 12]

Full NLO corrections including decay in complex mass scheme



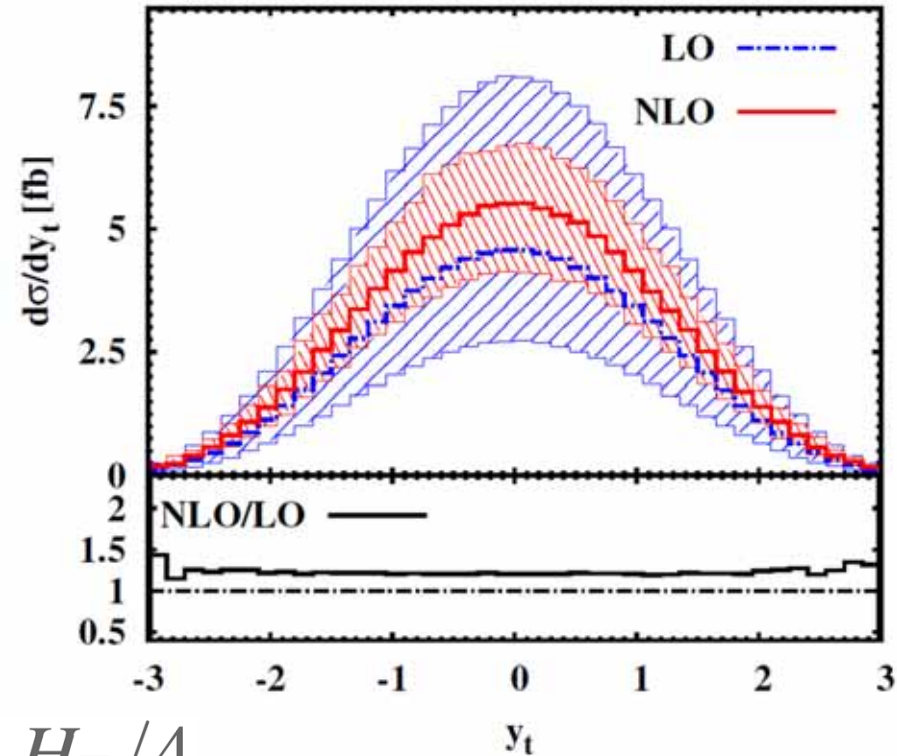
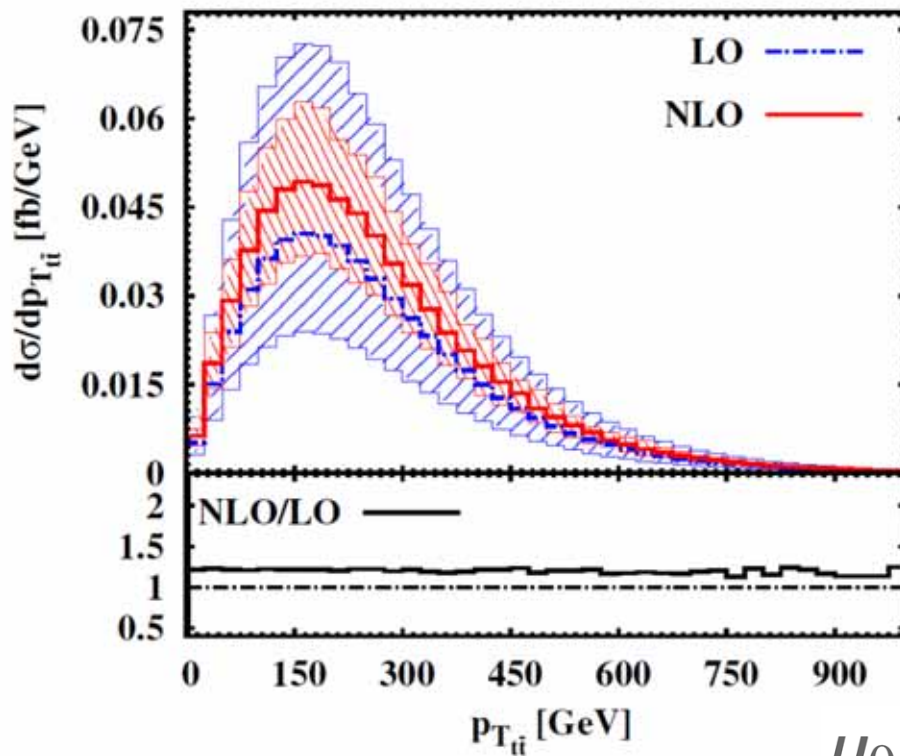
LO sample diagrams

- More realistic final state
- Effects could be large for specific observables
- Valuable information for mass measurements

- Production of 4 top-quarks

[Bevilacqua, Worek 12]

$$\sigma_{t\bar{t}t\bar{t}}^{\text{NLO}}(\text{LHC}_{14\text{TeV}}, m_t = 173.2 \text{ GeV}, \text{MSTW2008nlo}) = 16.87^{+4.04(+24\%)}_{-4.26(-25\%)} \text{ fb}.$$



$$\mu_0 = H_T/4$$

→ Dynamical scale H_T works remarkable well

Theory well prepared for precision physics with tops

Some basic facts about theory parameters



...and their determination

- Parameters are only defined in a specific model
- In general: Parameters \neq Observables
- Precise values depend on specific conditions
- Determination through comparison with experiment

Top-quark

No parameter determination without theory

(e.g. states, confinement)

Top-quark mass is “just” a parameter like α_s

→ renormalisation scheme dependent,
only indirect determination possible

Different mass definitions

$$\Sigma_R(p) = \text{[Diagram: self-energy loop]} - \text{[Diagram: tadpole]} + \text{[Diagram: gluon loop]} + \text{[Diagram: counterterm]} \\ (Z_\Psi - 1)\not{p} - (Z_0 - 1)m_R$$

- Pole mass scheme

$$\frac{i}{\not{p} - m_R - \Sigma_R(p)} \rightarrow \frac{i}{\not{p} - m_{\text{Pole}}} + \dots$$

↖ $\Sigma_R(m_{\text{Pole}}) = 0$

- $\overline{\text{MS}}$ mass

Chose constants minimal to cancel $1/\epsilon$ poles in $\Sigma_R(p)$

- 1S mass [Hoang, Teubner 99]

Position of would-be 1S boundstate

- Potential subtracted mass [Beneke 98]

$$m_t^{\text{PS}} = m_{\text{Pole}} + \frac{1}{2} \int_{|\vec{q}| < \mu} \frac{d^3 q}{(2\pi)^3} \tilde{V}_c(\vec{q})$$

Each scheme well defined in perturbation theory → conversion possible

Conversion between schemes



Example:

- Pole mass \leftrightarrow $\overline{\text{MS}}$ mass:

$$m_t = \bar{m}(\mu) \left(1 + \frac{\alpha_s(\mu)}{\pi} \left[\frac{4}{3} + \ln \left(\frac{\mu}{m_t} \right) \right] \right)$$

Important:

- Diff. between pole and $\overline{\text{MS}}$ mass is higher order in coupling constant
- Numerically significant

$$m_t \approx \bar{m}(\mu) (1 + 4\% + \dots)$$

$$m_t = (165.0 + 7.6 + 1.6 + 0.51) \text{ GeV} \quad [\text{Chetyrkin, Steinhauser 99}]$$

No meaningful parameter determination without at least NLO theory

- Template method
- Matrix element method

Issues:

- Intrinsic limitations of pole mass ($\sim \Lambda_{\text{QCD}}$)
- Precise relation

$$m_{\text{MC}} = m_{\text{Pole}} (1 \pm \Delta)$$

- Reconstruction of top momentum from color neutral hadrons / color reconnection

Not independent

Color reconnection:

$$\Delta m \stackrel{?}{=} 500 \text{ MeV}$$

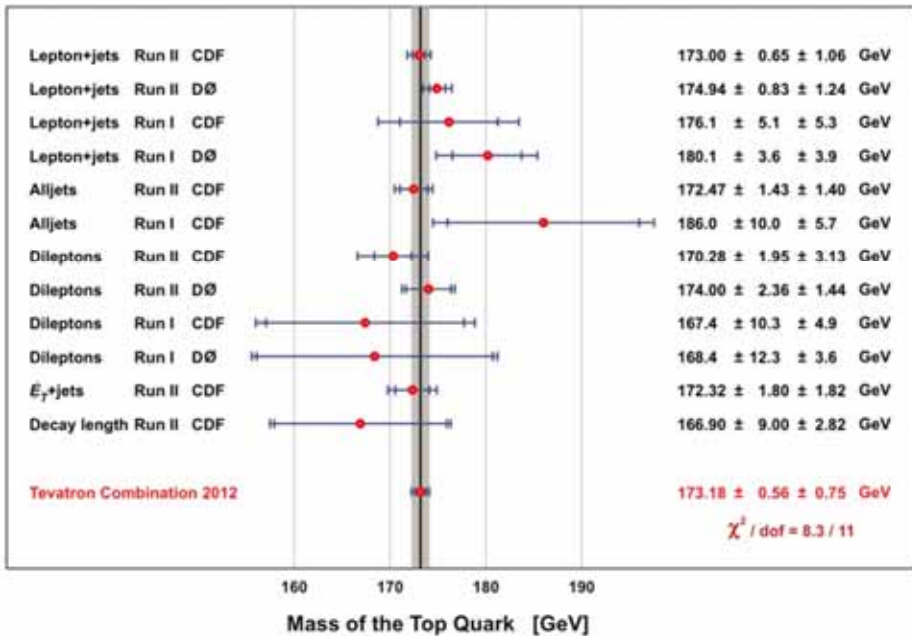
[Skands, Wicke '08]

Relation: measured mass \leftrightarrow pole mass:

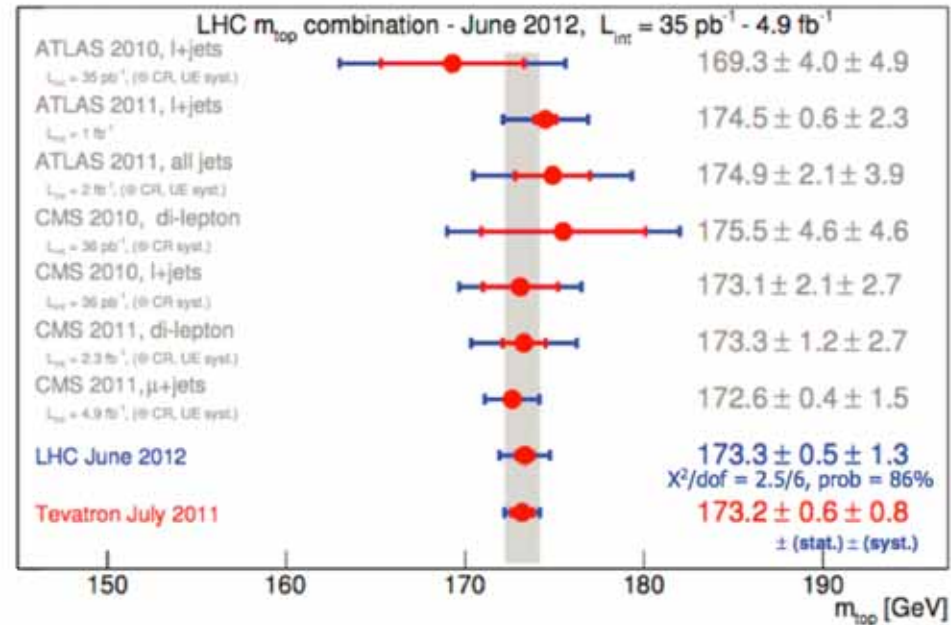
$$m_{\text{MC}} = m_{\text{Pole}} (1 \pm \Delta)$$

$$\Delta \stackrel{?}{=} \left\{ \begin{array}{l} \frac{\Lambda}{m} \approx 0.13\% \\ \frac{\Gamma}{m} \approx 0.8\% \\ \frac{\alpha_s}{\pi} \approx 3.7\% \end{array} \right.$$

Tevatron



LHC



Different channels and different experiments give consistent results



Large effects unlikely



[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]

Use $t\bar{t}+1$ -jet events

- Large event rates ($\sim 30\%$ of inclusive $t\bar{t}$ events)
- NLO corrections available [Dittmaier, Uwer, Weinzierl '07, '08, Melnikov, Schulze '10, Melnikov, Scharf, Schulze '12]
- NLO+shower available [Alioli, Moch, PU '11, Kardos, Papadopoulos, Trocsanyi '11]

Similar to b-quark mass measurement at LEP

using 3-jet rates [Bilenky, Fuster, Rodrigo, Santarmaria '95]

- Less sensitive to color reconnection
- Mass parameter fixed through NLO calculation
- \overline{MS} mass in principle possible

Top-quark mass from jet rates



[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]

To enhance mass sensitivity study:

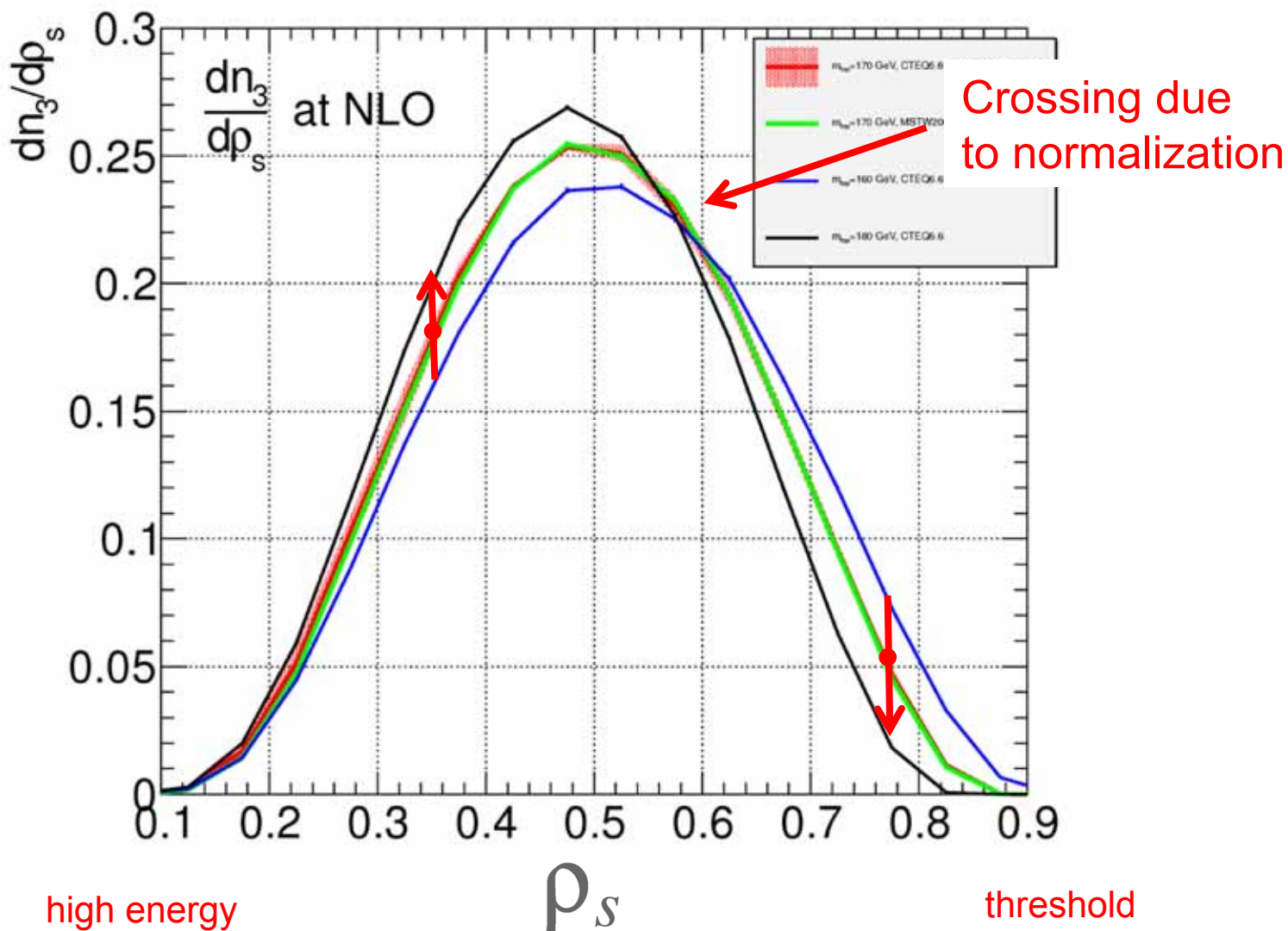
$$\frac{dn_3}{d\rho_s}(m_{\text{Pole}}) = \frac{1}{\sigma_{t\bar{t}+1\text{Jet}}} \frac{d\sigma_{t\bar{t}+1\text{Jet}}}{d\rho_s}(m_{\text{Pole}})$$

with $\rho_s = \frac{2m_0}{\sqrt{s_{t\bar{t}+1\text{Jet}}}}$, $m_0 = O(m)$ “1 - Distance from threshold”

i.e. $m_0 = 170 \text{ GeV}$

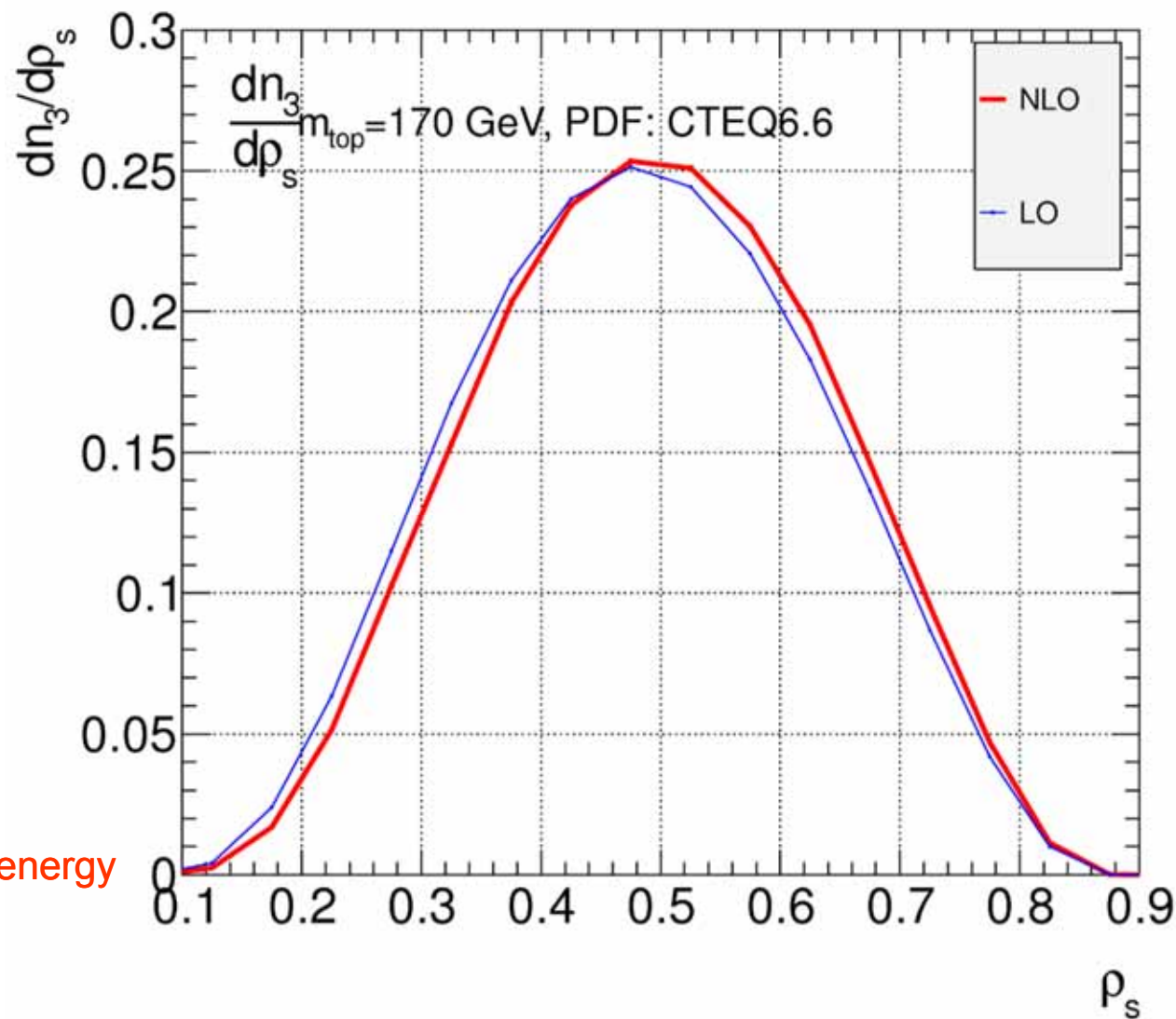
Mass dependence

[Work in progress S. Alioli, J.Fuster, A. Irlles, S. Moch, PU, M. Vos]



Impact of higher order corrections

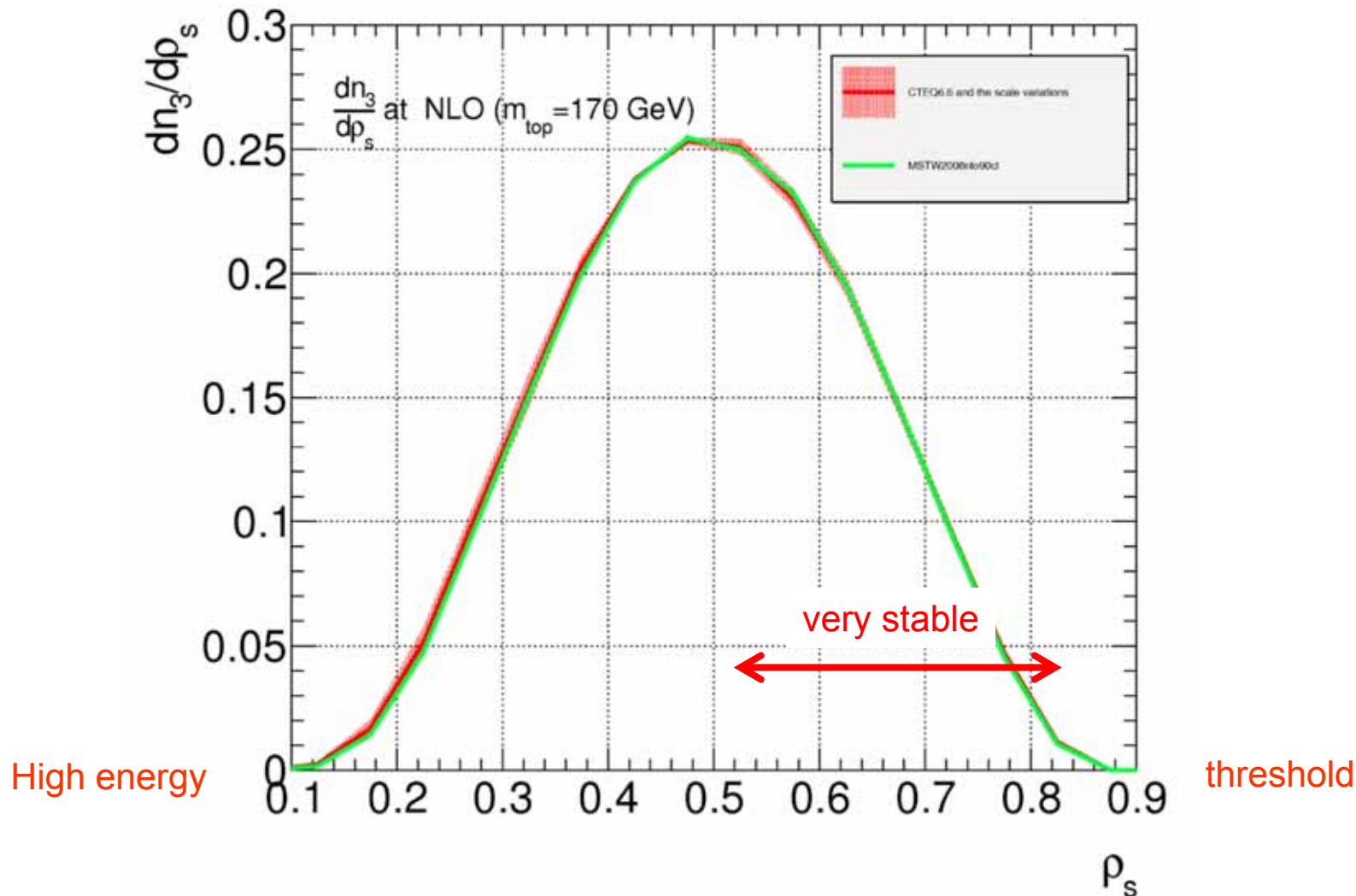
[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]



- Consistent with scale variation
- ttj: Corrections in general moderate
- Hard corrections → small ρ

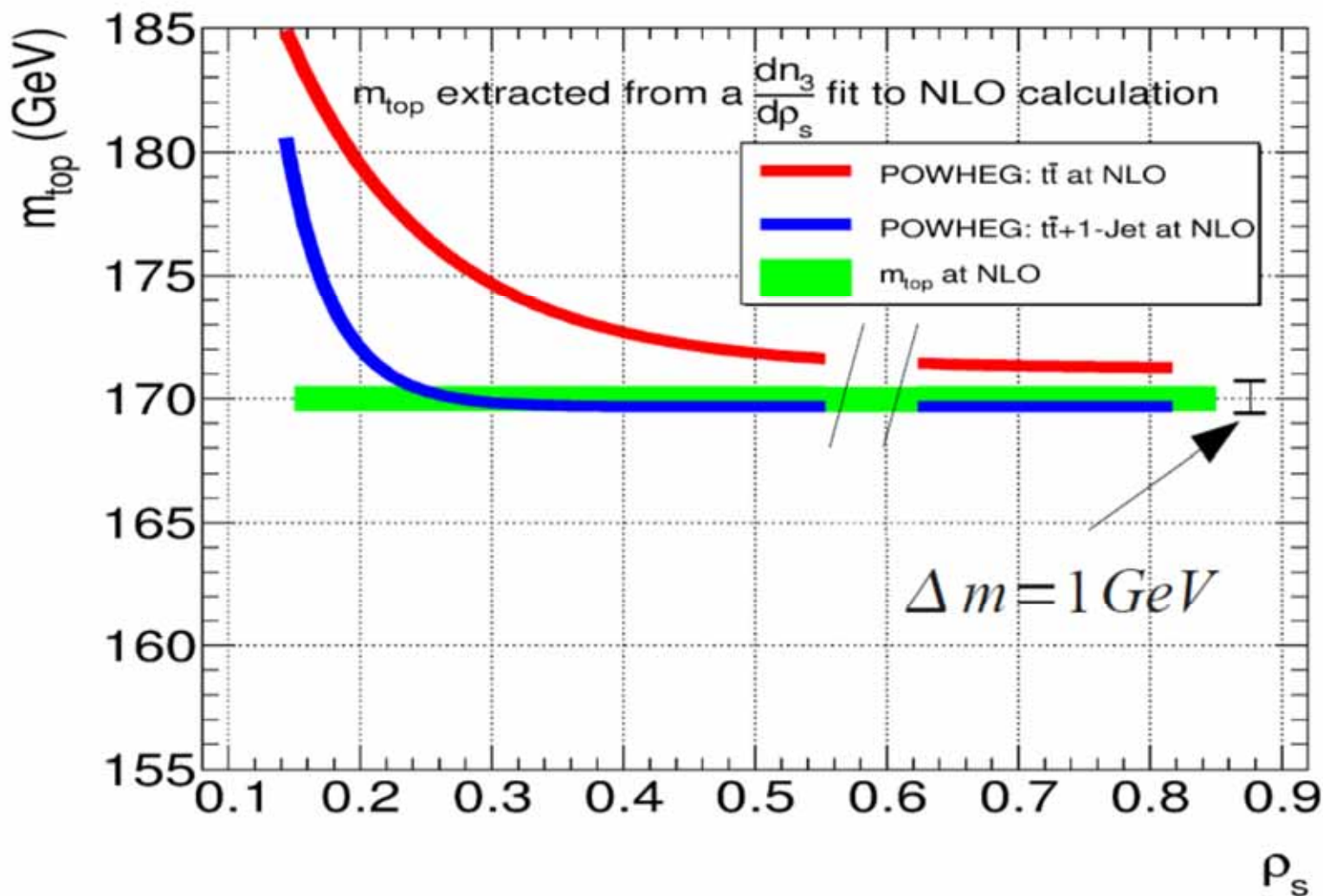
Scale and PDF uncertainties

[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]



Toy experiment

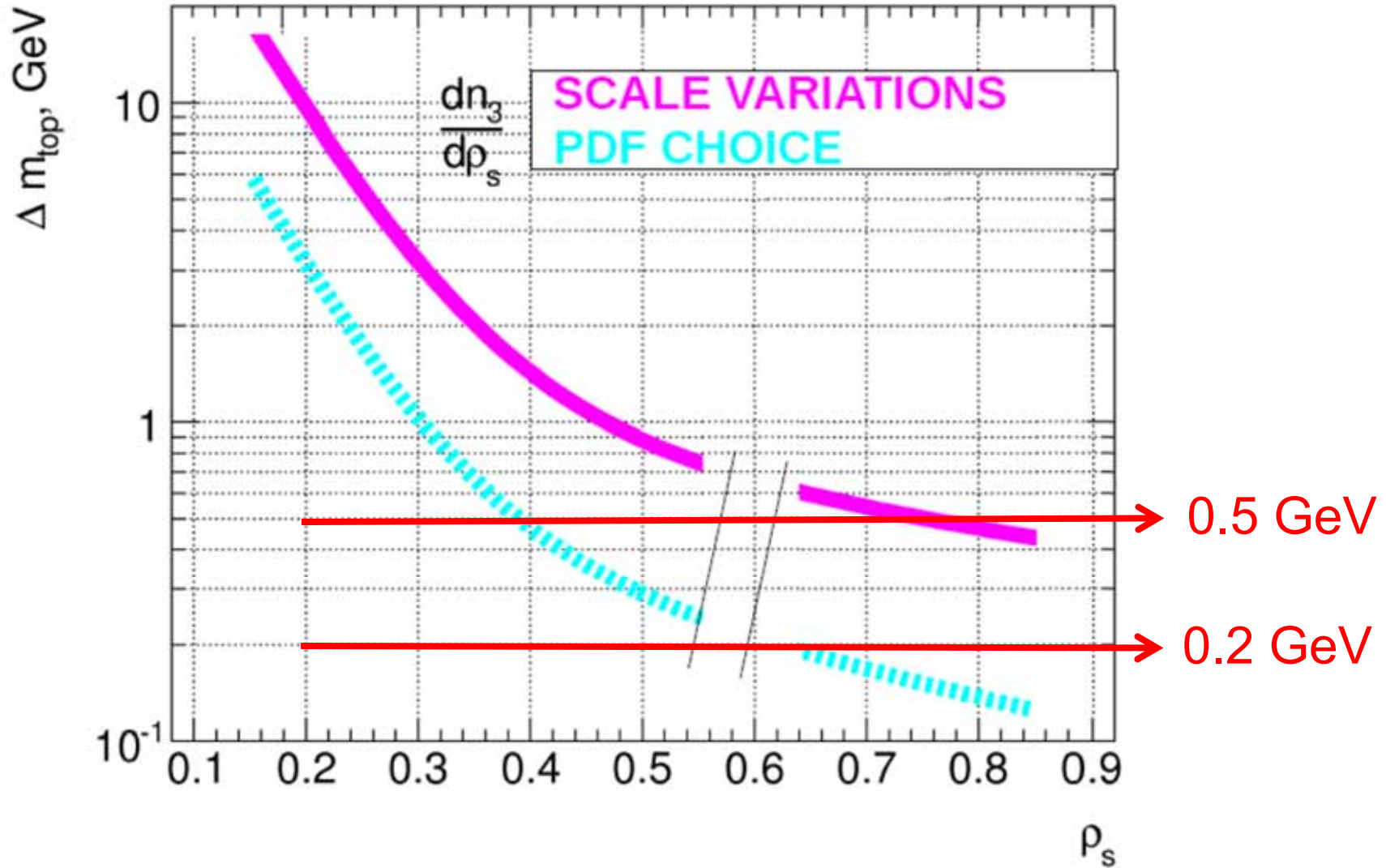
[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]



Impact of scale and PDF uncertainties



[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]



Estimate of uncertainties



[Work in progress S. Alioli, J.Fuster, A. Irles, S. Moch, PU, M. Vos]

	Source of uncertainty	Impact on the top quark mass	
Theoretical uncertainties	μ variations	~ 0.5 GeV	} 1 GeV
	PDF choice	~ 0.2 GeV	
Experimental uncertainties	MC comparison	$\sim 0.4 \pm 0.3$ GeV	
	JES	~ 0.8 GeV	
	Statistics (5 fb ⁻¹)	~ 1.2 GeV	

$$\Delta JES = \pm 3\%$$

→ Interesting alternative





Time to collect the fruits

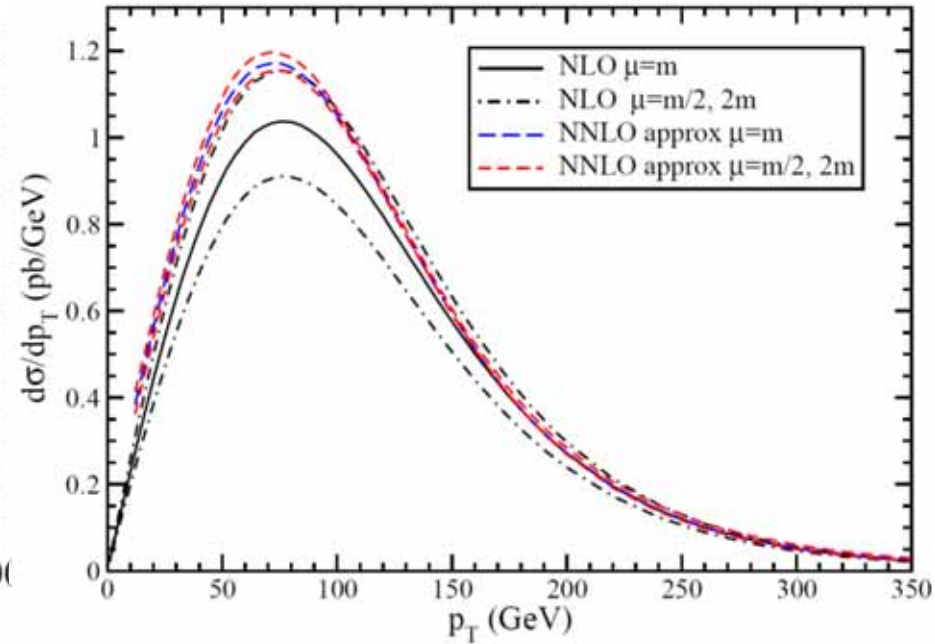
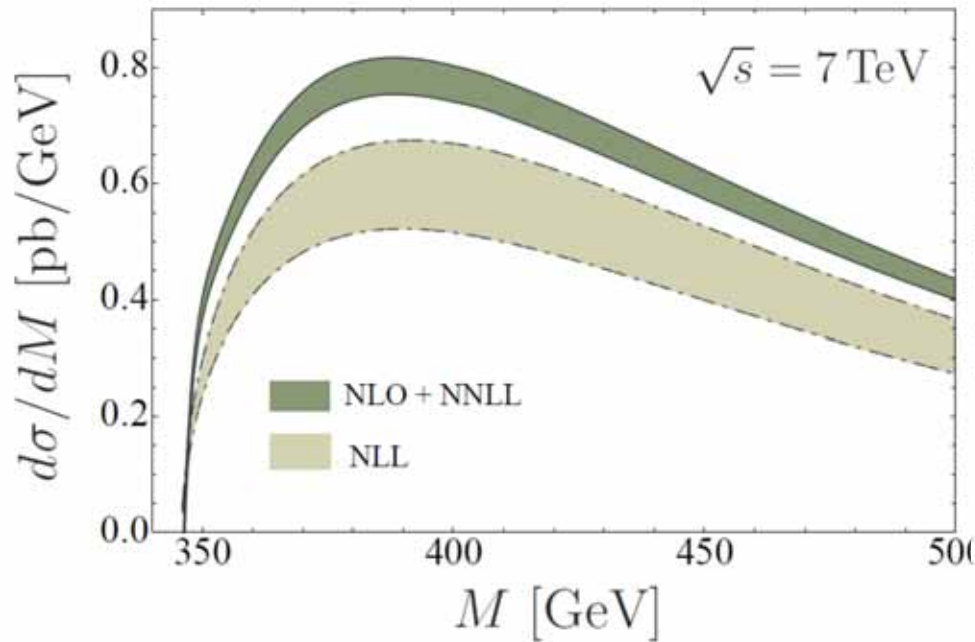
- Improved mass measurements
- Spin correlations
- Charge asymmetry
- New physics ?

Beyond inclusive cross section



[Ahrens, Ferroglia, Neubert, Pecjak, Yang '10]

[Kidonakis '10]



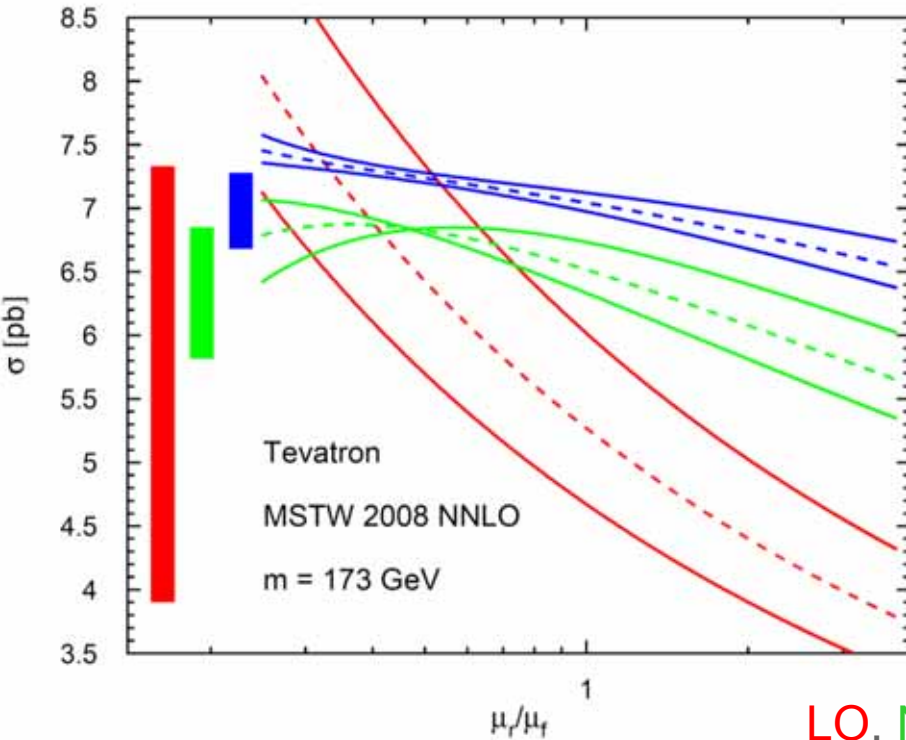
Results available also for forward-backward charge asymmetry

[Almeida, Stermann, Vogelsang 08][Ahrens, Ferroglia, Neubert, Pecjak, Yang 10,11][Kidonakis 11]

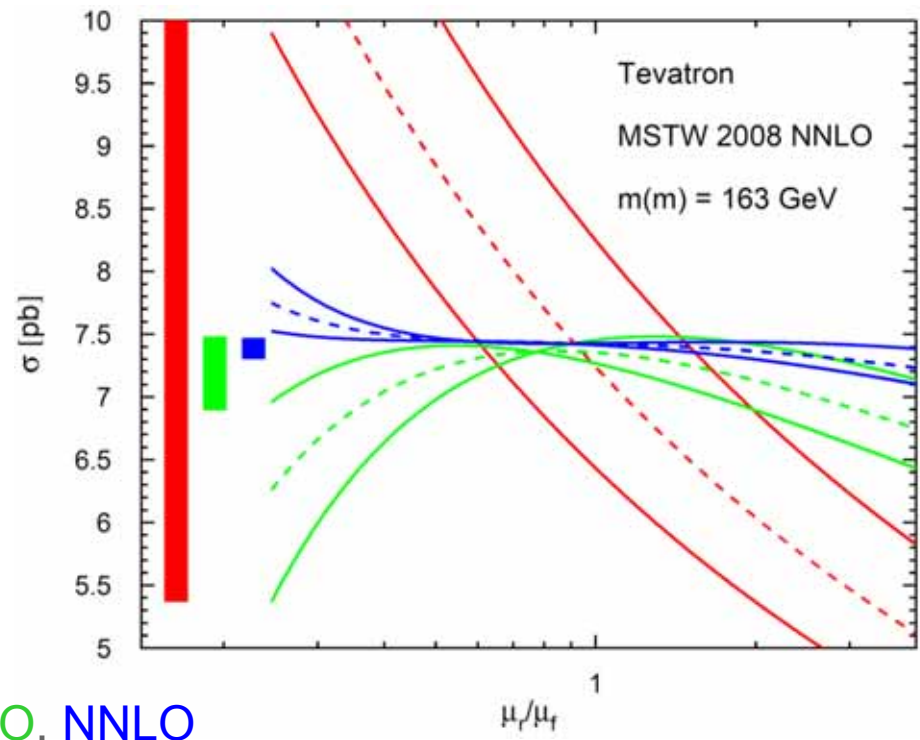
→ No significant change of one-loop predictions

First direct determination of the \overline{MS} mass

[Langenfeld, Moch, PU 09]



Pole-mass / on-shell



Running mass

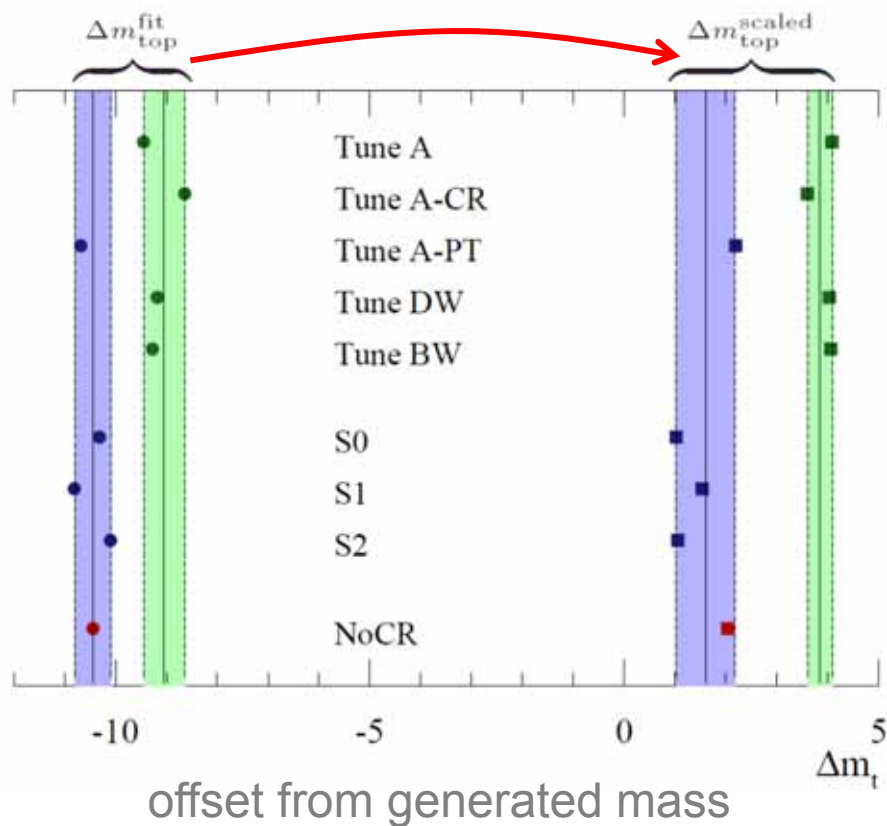
→ Perturbation theory better behaved !

Non-perturbative effects

Non-perturbative effects at the LHC

[Skands, Wicke '08]

Simulate top mass measurement using different models/tunes for non-perturbative physics / colour reconnection



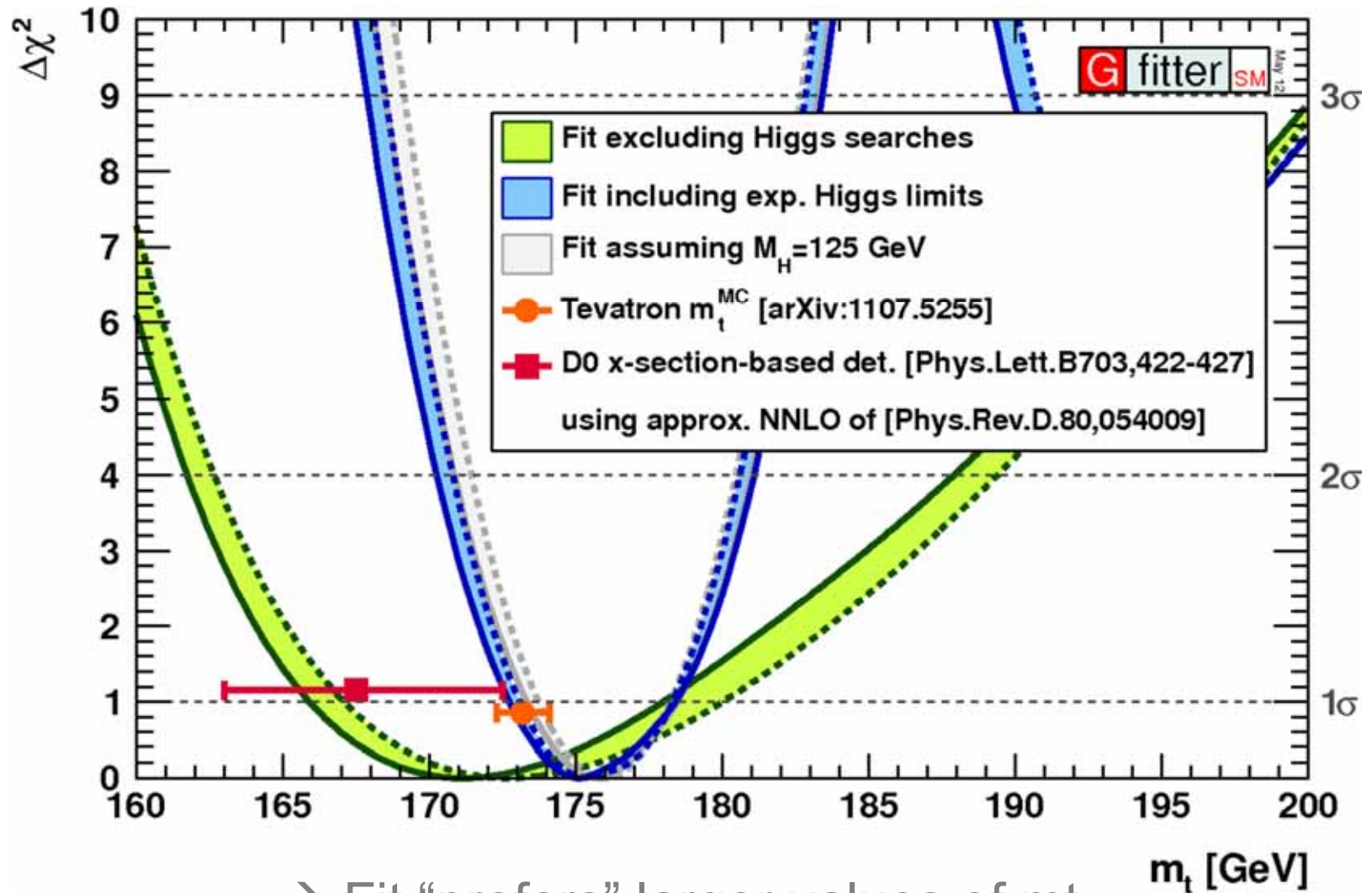
different offset for different tunes!

Non-perturbative effects result in uncertainty of the order of 500 MeV

blue: pt-ordered PS

green: virtuality ordered PS

EW precision fit



→ Fit “prefers” larger values of m_t

Application: Top mass from cross section

[Sven Moch, prepared for Top2012 Winchester]

- Determine top quark mass from Tevatron cross section data
 - $\sigma_{t\bar{t}} = 7.56^{+0.63}_{-0.56}$ pb D0 coll. arXiv:1105.5384
 - $\sigma_{t\bar{t}} = 7.50^{+0.48}_{-0.48}$ pb CDF coll. CDF-note-9913
- Fit of m_t for individual PDFs
 - parton luminosity at Tevatron driven by $q\bar{q}$
 - $\overline{\text{MS}}$ -scheme for $m_t^{\overline{\text{MS}}}(m_t)$, then scheme transformation to pole mass m_t^{pole} at NNLO

	ABM11	JR09	MSTW08	NN21
$m_t^{\overline{\text{MS}}}(m_t)$	$162.0^{+2.3+0.7}_{-2.3-0.6}$	$163.5^{+2.2+0.6}_{-2.2-0.2}$	$163.2^{+2.2+0.7}_{-2.2-0.8}$	$164.4^{+2.2+0.8}_{-2.2-0.2}$
m_t^{pole}	$171.7^{+2.4+0.7}_{-2.4-0.6}$	$173.3^{+2.3+0.7}_{-2.3-0.2}$	$173.4^{+2.3+0.8}_{-2.3-0.8}$	$174.9^{+2.3+0.8}_{-2.3-0.3}$
(m_t^{pole})	$(169.9^{+2.4+1.2}_{-2.4-1.6})$	$(171.4^{+2.3+1.2}_{-2.3-1.1})$	$(171.3^{+2.3+1.4}_{-2.3-1.8})$	$(172.7^{+2.3+1.4}_{-2.3-1.2})$

→ Consistent with direct measurements