MITP 2014

High precision fundamental constants at the TeV scale

Top quark mass determination from kinematic distributions

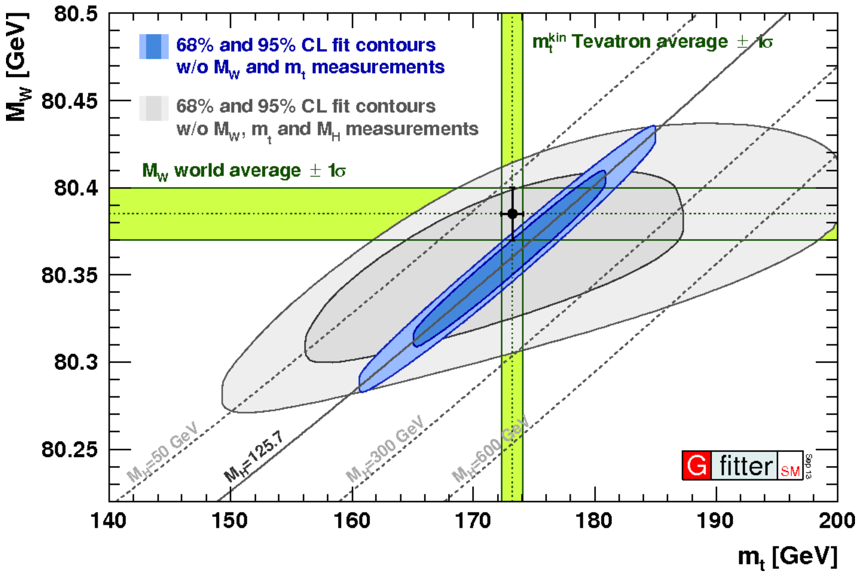
Markus Schulze

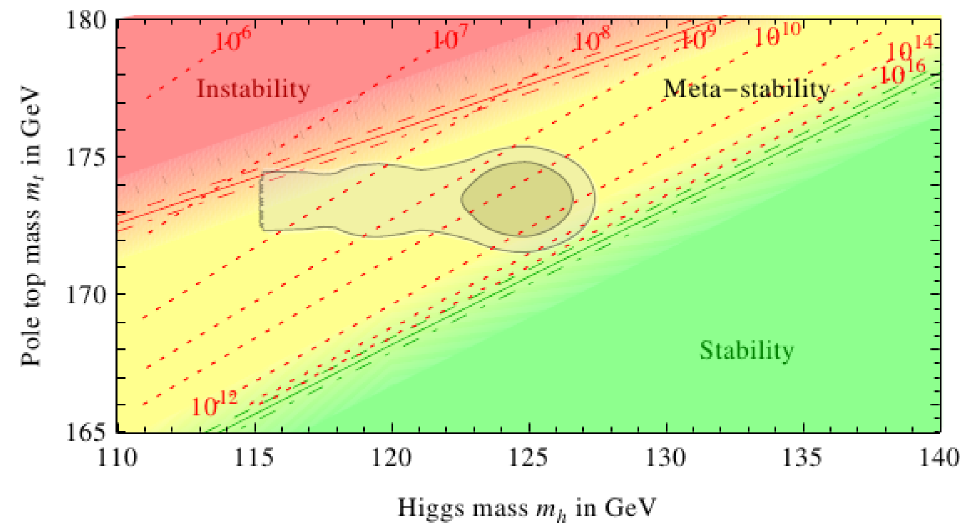
CERN

Top quark mass determination from kinematic distributions

General motivation

$$\mathcal{L}_{\rm mass} = -v\left(\lambda_e^i \bar{e}_{\rm L}^i e_{\rm R}^i + \lambda_u^i \bar{u}_{\rm L}^i u_{\rm R}^i + \lambda_d^i \bar{d}_{\rm L}^i d_{\rm R}^i + {\rm h.c.}\right) - M_W^2 W_\mu^+ W^{-\mu} - \frac{M_W^2}{2\cos^2\theta_W} Z_\mu Z^\mu \; ;$$





- El. weak precision test: 5.4 MeV uncertainty in $M_{\rm W} \leftrightarrow$ 0.9 GeV uncertainty in $m_{\rm top}$
- El. weak vacuum stability: Change of $m_{\rm top}$ by ± 2.1 GeV $\leftrightarrow$ $\mu_{\rm neg} = 10^8$ – 10^{16} GeV

Top quark mass determination from kinematic distributions

$$\mathcal{O}^{\mathrm{exp}}(\{\mathbf{Q}\}) = \mathcal{O}^{\mathrm{theor}}(\mathbf{m_t}, \{\mathbf{Q}\})$$

Top quark mass determination from kinematic distributions

$$\mathcal{O}^{\text{exp}}(\{\mathbf{Q}\}) = \mathcal{O}^{\text{theor}}(\mathbf{m_t}, \{\mathbf{Q}\})$$

$$\Downarrow$$

$$\mathcal{O}^{\text{exp}}(\{\mathbf{Q}\}) = \mathcal{O}^{\text{theor}}(\mathbf{m_t}, \{\mathbf{Q}\}, \alpha_{\mathbf{s}}, \text{RS}, \mathbf{\Lambda}_{\text{QCD}}, \{\mathbf{p_t}, \mathbf{p_{\bar{t}}}\}, \mathbf{\Gamma_t}, \text{MC})$$

- Higher orders, renormalization scheme
- Non-perturbative effects (*e.g.* bound state, renormalons)
- Reconstruction of top quark momenta
- Finite width effects
- Monte Carlo modeling, tunes
- Contamination from New Physics

Top quark mass determination from kinematic distributions

Top mass extraction at hadron colliders

- Total cross section

  Known at NNLO QCD;
  Relatively low sensitivity to m_{top}

- Matrix element method

  Method which gave smallest uncertainties at Tevatron;
  Currently only LO matrix elements are used in likelihood functions;
  Difficult to identify leading uncertainties

- Kinematic distributions

  Known to NLO QCD; Good sensitivity to m_{top};
  Reduces dependence on uncertainties of production mechanism;
  Sensitive to finite width effects, details of b-jet fragmentation

Top quark mass determination from kinematic distributions

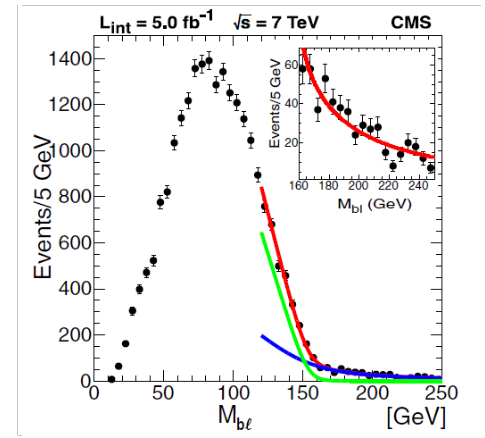
Kinematic distributions

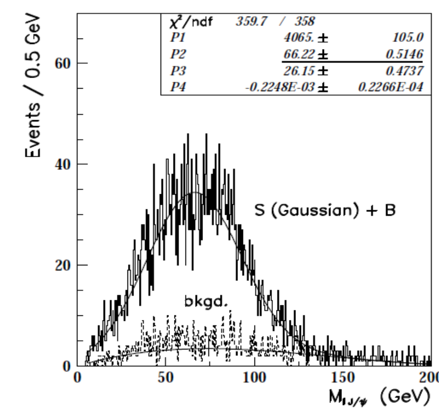
- End-point methods
- J/ψ method
- $m_{\mathrm{lb/lB}}$ distribution
- Other lepton-related observables (E_{l}, E_{b})
- "Threshold scan" (ttb+jet)

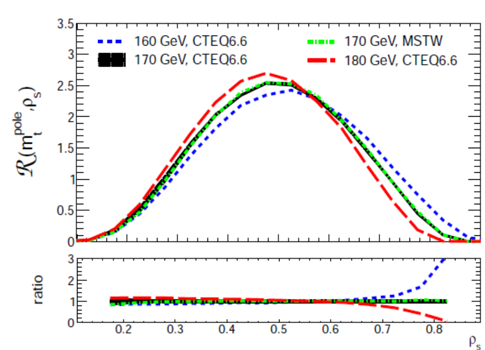
Top quark mass determination from kinematic distributions

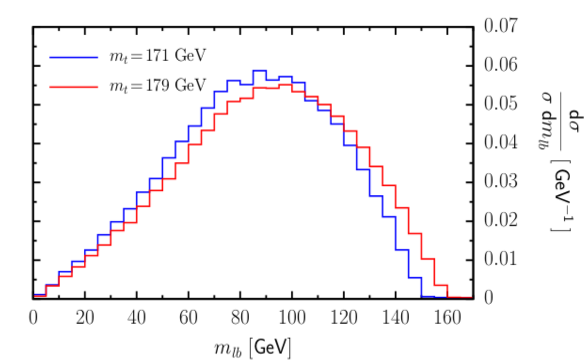
Kinematic distributions

- End-point methods [CMS `13]
- J/ψ method [Kharchilava `99]
- $m_{\mathrm{lb/lB}}$ distribution [Corcella,Mangano,Seymour,Mescia `00] [Biswas,Melnikov,M.S. `10] [Heinrich,Maier,Nisius,Schlenk,Winter`13]
- Other lepton-related observables (E_l, E_b) [Beneke,Efthymiopoulos,Mangano,Womersley `00] [Biswas,Melnikov,M.S. `10]
- "Threshold scan" (ttb+jet) [Alioli,Fuster,Irles,Moch,Uwer,Vos `13]









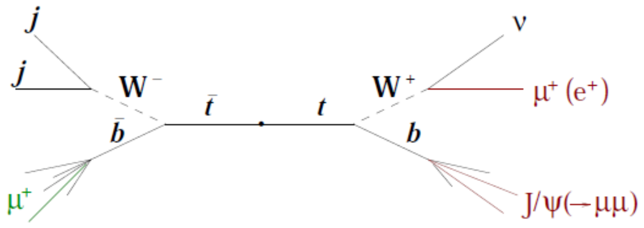
Top quark mass determination from kinematic distributions

The J/ψ method

- Basic idea:

  Study $m_{l,J/\psi}$ from top quark decay in a "*very*" leptonic decay channel

  → Clean final state **vs.** low event rate



- One in 10^5 top quark pairs decays in this channel.

  Hence, an integr. luminosity of ~100 fb^{-1} is required to obtain $\mathcal{O}(1\,\mathrm{GeV})$

- With relaxed assumptions, uncert. of $\mathcal{O}(1.5\,\mathrm{GeV})$ seems possible with 20 fb^{-1}

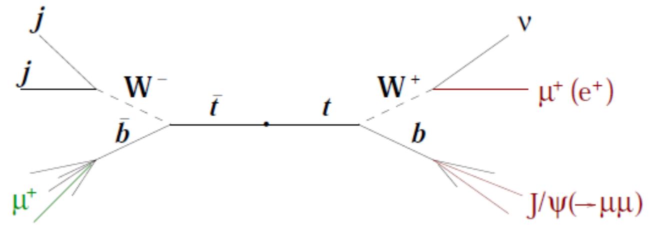
Top quark mass determination from kinematic distributions

The J/ψ method

- Basic idea:

  Study $m_{l,J/\psi}$ from top quark decay in a "*very*" leptonic decay channel

  → Clean final state **vs.** low event rate



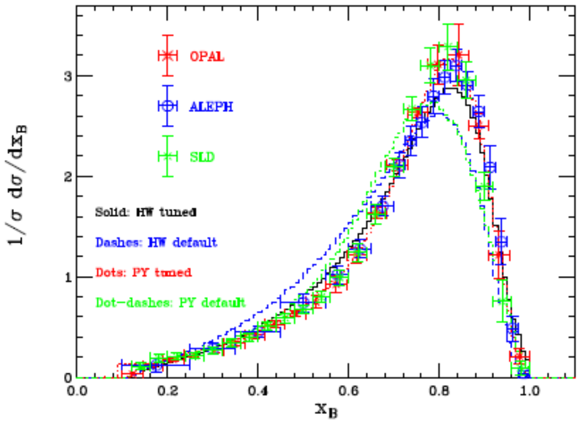
- Theoretical treatment:

  Include B-meson fragmentation function

$$D_{b\to B}(\mu,x) = \int_x^1 \frac{\mathrm{d}\xi}{\xi} D_b(\mu,\xi) D_{\mathrm{np}}\left(\frac{x}{\xi}\right)$$

  $B\to J/\psi$ transition is well studied in B-factories

[ALEPH,OPAL,SLD]



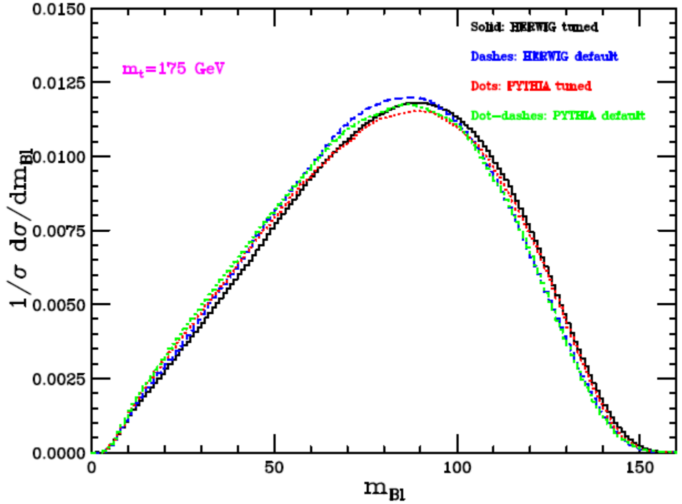
Top quark mass determination from kinematic distributions

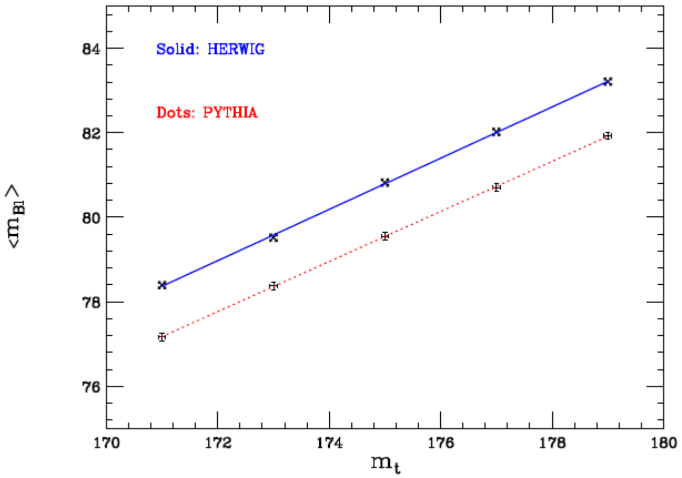
The J/ψ method

- Early studies show promising sensitivity to m_{top}

[Corcella,Mangano,Seymour,Mescia `00]

Consider m_{lB} from $t \to Wb \to l\nu B$, assume $\Delta\langle m_{\text{lB}}\rangle = 0.4$ GeV





$$\langle m_{Bl}\rangle_{\text{Pythia}} = 0.59\ m_t - 24.11\ \text{GeV}, \quad \langle m_{Bl}\rangle_{\text{Herwig}} = 0.61\ m_t - 25.31\ \text{GeV}$$

→ Uncertainty from comparing HERWIG vs. PYTHIA

Δm_{top} = 1.5-2 GeV

Top quark mass determination from kinematic distributions

The J/ψ method

- Similar analysis at NLO QCD [Biswas,Melnikov,M.S. `10]

$$D_b(\mu, x) = \delta(1-x) + \frac{\alpha_s(\mu) C_{\rm F}}{2\pi} \left[\frac{1+x^2}{1-x} \ln\left(\frac{\mu^2}{m_b^2}\right) - 2\log(1-x) - 1 \right]_+ + \mathcal{O}(\alpha_s^2)$$

$$D_{\rm np} = \begin{cases} x^\alpha (1-x)^\beta / B(\alpha+1, \beta+1), \\ (1+\delta)(2+\delta)(1-x)x^\delta. \end{cases}$$

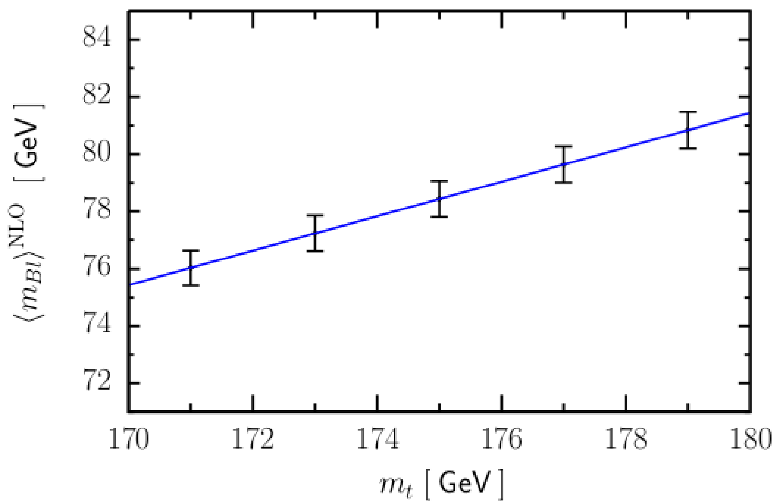
Top quark mass determination from kinematic distributions

The J/ψ method

- Similar analysis at NLO QCD [Biswas,Melnikov,M.S. `10]

$$D_b(\mu, x) = \delta(1-x) + \frac{\alpha_s(\mu) C_F}{2\pi}\left[\frac{1+x^2}{1-x}\ln\left(\frac{\mu^2}{m_b^2}\right) - 2\log(1-x) - 1\right]_+ + \mathcal{O}(\alpha_s^2)$$

$$D_{\rm np} = \begin{cases} x^\alpha(1-x)^\beta / B(\alpha+1, \beta+1), \\ (1+\delta)(2+\delta)(1-x)x^\delta. \end{cases}$$



$$\langle m_{Bl}\rangle^{\rm NLO} = 0.601 m_t - 26.7 \text{ GeV}, \quad \delta_{\rm rms} = 0.004;$$

$$\langle m_{Bl}\rangle_{\rm Pythia} = 0.59\, m_t - 24.11 \text{ GeV},$$

$$\langle m_{Bl}\rangle_{\rm Herwig} = 0.61\, m_t - 25.31 \text{ GeV}$$

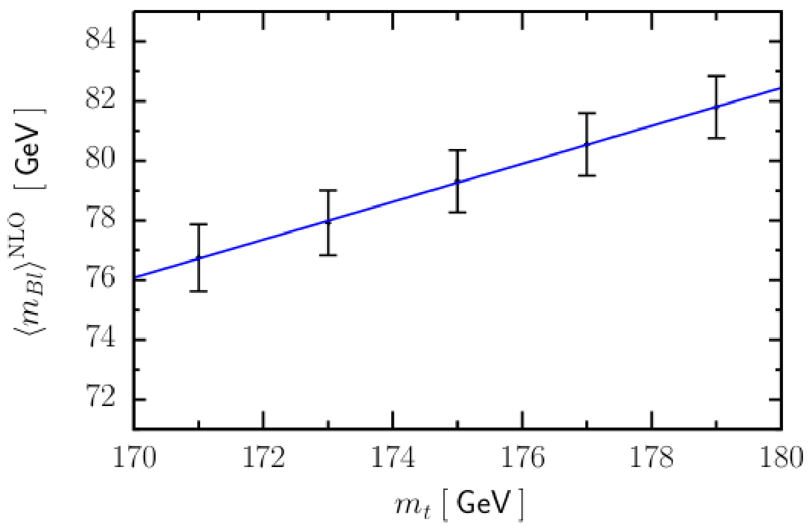
→ Uncertainty from NLO scale variation and variation of $D_{\rm np}$ parameters

$$\Delta m_{\rm top} = 0.8 \text{ GeV}$$

Top quark mass determination from kinematic distributions

The J/ψ method

- Include full production and decay process at NLO QCD including realistic selection cuts [Biswas,Melnikov,M.S. `10]

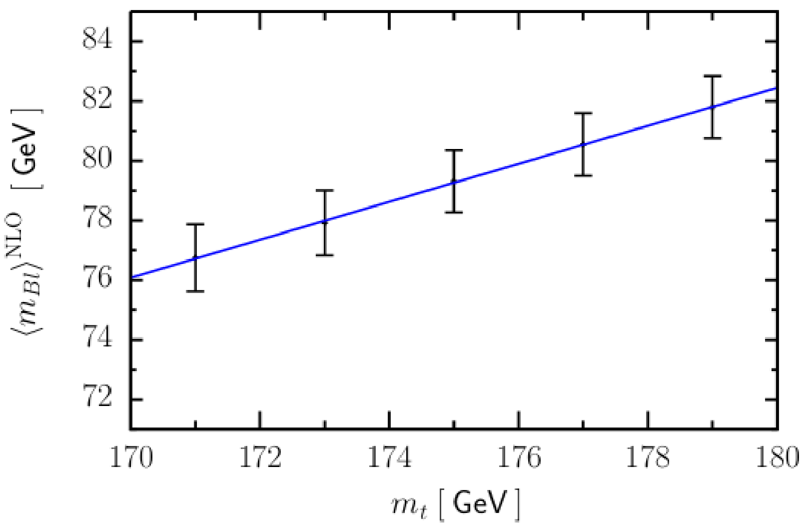


$$\langle m_{Bl} \rangle^{\rm NLO}_{\rm prod} = 0.6365\ m_t - 32.12\ {\rm GeV}, \quad \delta_{\rm rms} = 0.053$$

Top quark mass determination from kinematic distributions

The J/ψ method

- Include full production and decay process at NLO QCD including realistic selection cuts [Biswas,Melnikov,M.S. `10]



$$\langle m_{Bl} \rangle^{\mathrm{NLO}}_{\mathrm{prod}} = 0.6365\ m_t - 32.12\ \mathrm{GeV}, \quad \delta_{\mathrm{rms}} = 0.053$$

→ Uncertainty budget from scale variation (μ_{ren},μ_{fac},μ_{frag} independently), two different parameters of D_{np}, and two different pdf sets (MSTW,CTEQ)

$\Delta m_{\mathrm{top}} = 1.5$ GeV

Top quark mass determination from kinematic distributions

m_{top} estimator

- Basic idea: Construct an estimator for m_{top}

[Beneke,Efthymiopoulos,Mangano,Womersley `00]

$$M_{\mathrm{est}}^2 = m_W^2 + \frac{2\langle m_{lb}^2\rangle}{1-\langle\cos\theta_{lb}\rangle}$$

→ at LO, $M_{\mathrm{est}}=m_{\mathrm{top}}$

$$\langle m_{lb}^2\rangle = \frac{m_t^2 - m_W^2}{2}\left(1-\langle\cos\theta_{lb}\rangle\right), \quad \langle\cos\theta_{lb}\rangle = \frac{m_W^2}{m_t^2+2m_W^2}$$

Hence, we expect a strong correlation.

Top quark mass determination from kinematic distributions

m_{top} estimator

- Basic idea: Construct an estimator for m_{top}

[Beneke,Efthymiopoulos,Mangano,Womersley `00]

$$M_{est}^2 = m_W^2 + \frac{2\langle m_{lb}^2\rangle}{1-\langle\cos\theta_{lb}\rangle}$$

→ at LO, $M_{est}=m_{top}$

$$\langle m_{lb}^2\rangle = \frac{m_t^2 - m_W^2}{2}\left(1-\langle\cos\theta_{lb}\rangle\right), \quad \langle\cos\theta_{lb}\rangle = \frac{m_W^2}{m_t^2+2m_W^2}$$

Hence, we expect a strong correlation. In reality $M_{est} \neq m_{top}$ due to:

- kinematic selection cuts
- higher orders
- lepton b-jet pairing
- experimental effects (JES,b-tagging,...)

Accounting for the first three points points is possible within pert. QCD

Top quark mass determination from kinematic distributions

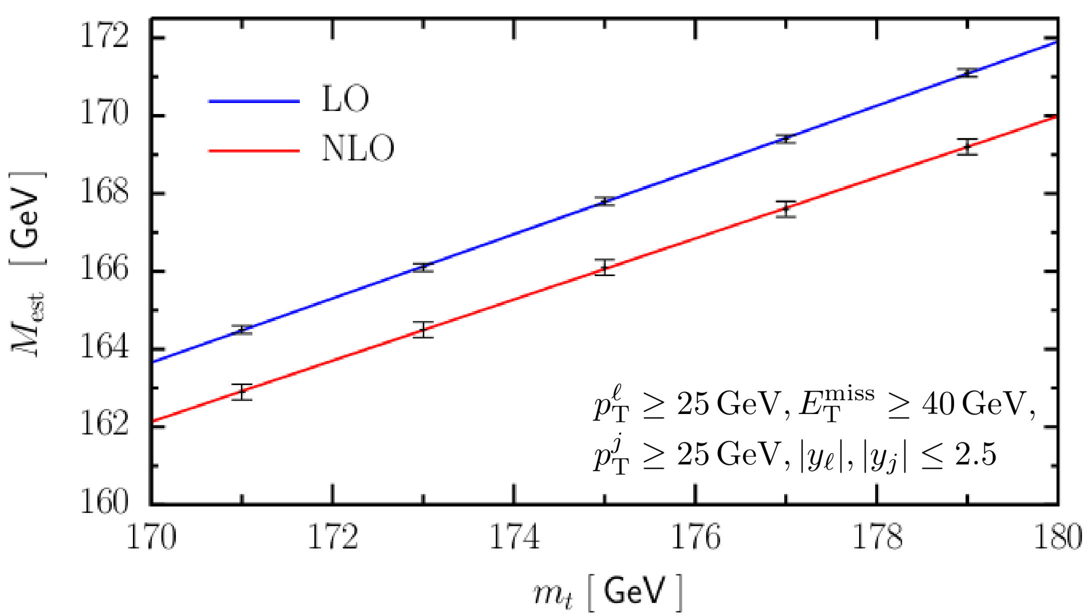
m_{top} estimator

- Basic idea: Construct an estimator for m_{top}

$$M_{\text{est}}^2 = m_W^2 + \frac{2\langle m_{lb}^2\rangle}{1 - \langle\cos\theta_{lb}\rangle}$$

[Biswas,Melnikov,M.S. `10]

NLO QCD results (14 TeV) for $pp \to t\bar{t} \to (bW \to b\ell\nu)\,(\bar{b}W \to bjj)$



$$M_{\text{est}}^{\text{LO}} = 0.8262 m_t + 23.22\ \text{GeV}$$

$$M_{\text{est}}^{\text{NLO}} = 0.7850 m_t + 28.70\ \text{GeV}.$$

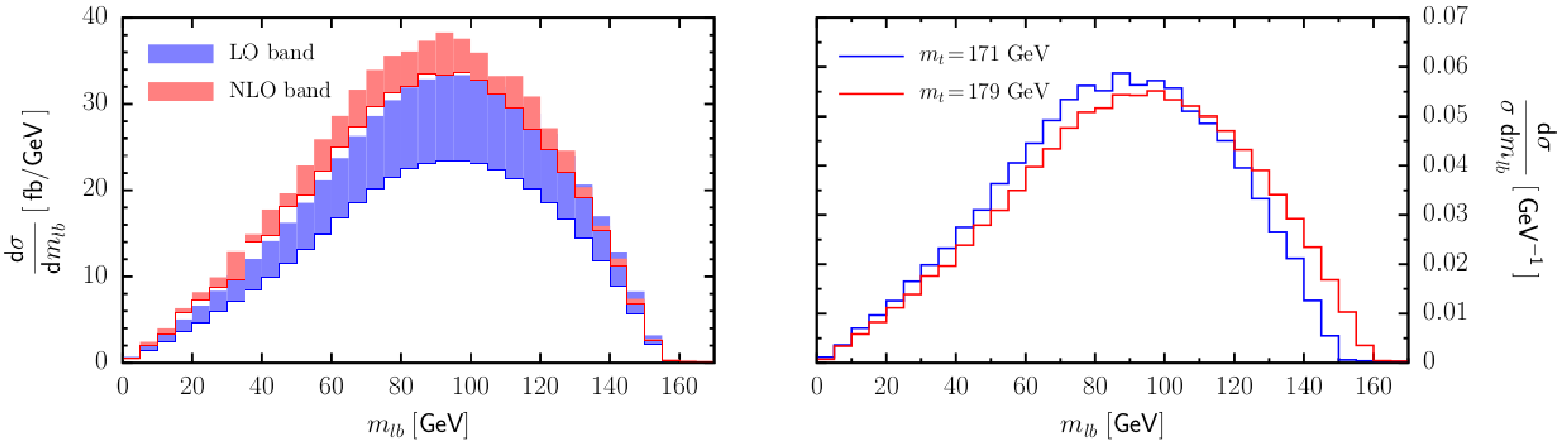
$\to \Delta m_{\text{top}} = 0.25$ GeV

expect additional uncert. of
± 0.7 GeV (b-fragm.)
± 0.6 GeV (JES)

Top quark mass determination from kinematic distributions

m_{lb} distribution

- Shape of m_{lb} distribution

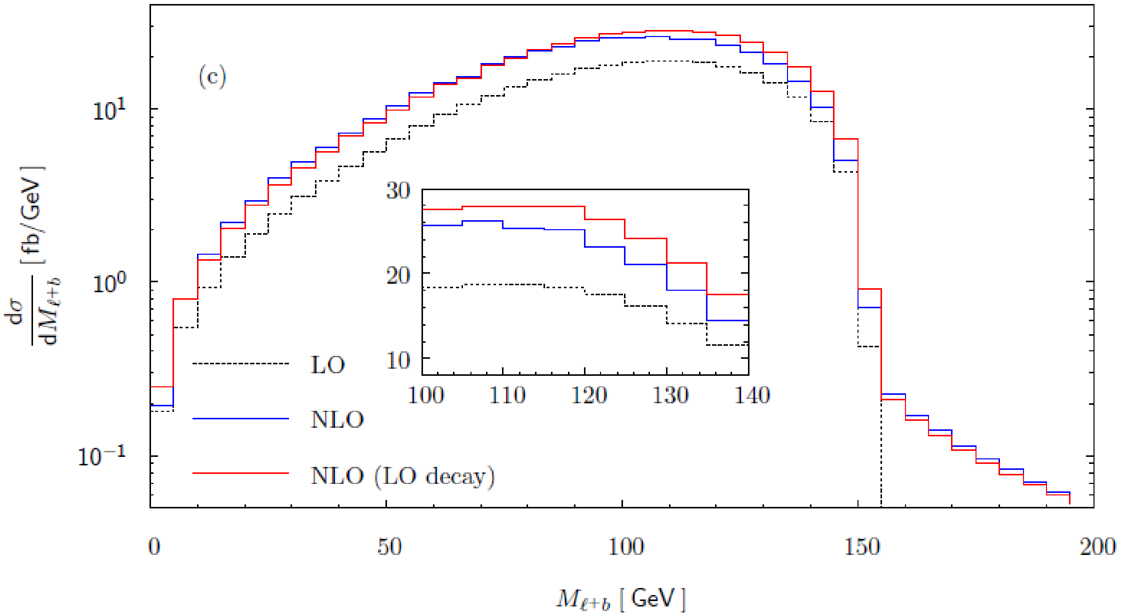


→ Good sensitivity within the range $m_{\mathrm{top}} \in [171..179]$ GeV

Top quark mass determination from kinematic distributions

m_{lb} distribution

- Shape of m_{lb} distribution



NLO correction to decay leads to shape changes

[Melnikov,M.S. `10]

Top quark mass determination from kinematic distributions

m_{lb} distribution

Finite width effects and non-factorizable corrections

thanks to $WWb\bar{b}$ calculations by [Denner,Dittmaier,Kallweit,Pozzorini]

+ HELAC and GOSAM+Sherpa groups

Collider	$\sqrt{s}$ [TeV]	approx.	$\sigma_{\mathrm{t\bar{t}}}$ [fb]	$\sigma_{\mathrm{WWb\bar{b}}}$ [fb]	$\sigma_{\mathrm{t\bar{t}}}/\sigma_{\mathrm{WWb\bar{b}}} - 1$
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	$837(2)^{+42}_{-87}$	$840(2)^{+41}_{-87}$	$-\,0.41(31)\%$
LHC	14	LO	$3306.3(1)^{+1086.8}_{-763.6}$	$3334.6(2)^{+1098.5}_{-771.2}$	$-\,0.849(7)\%$
		NLO	$4253(3)^{+282}_{-404}$	$4286(7)^{+283}_{-407}$	$-\,0.77(19)\%$

Top quark mass determination from kinematic distributions

m_{lb} distribution

Finite width effects and non-factorizable corrections

thanks to $WWb\bar{b}$ calculations by [Denner,Dittmaier,Kallweit,Pozzorini]

+ HELAC and GOSAM+Sherpa groups

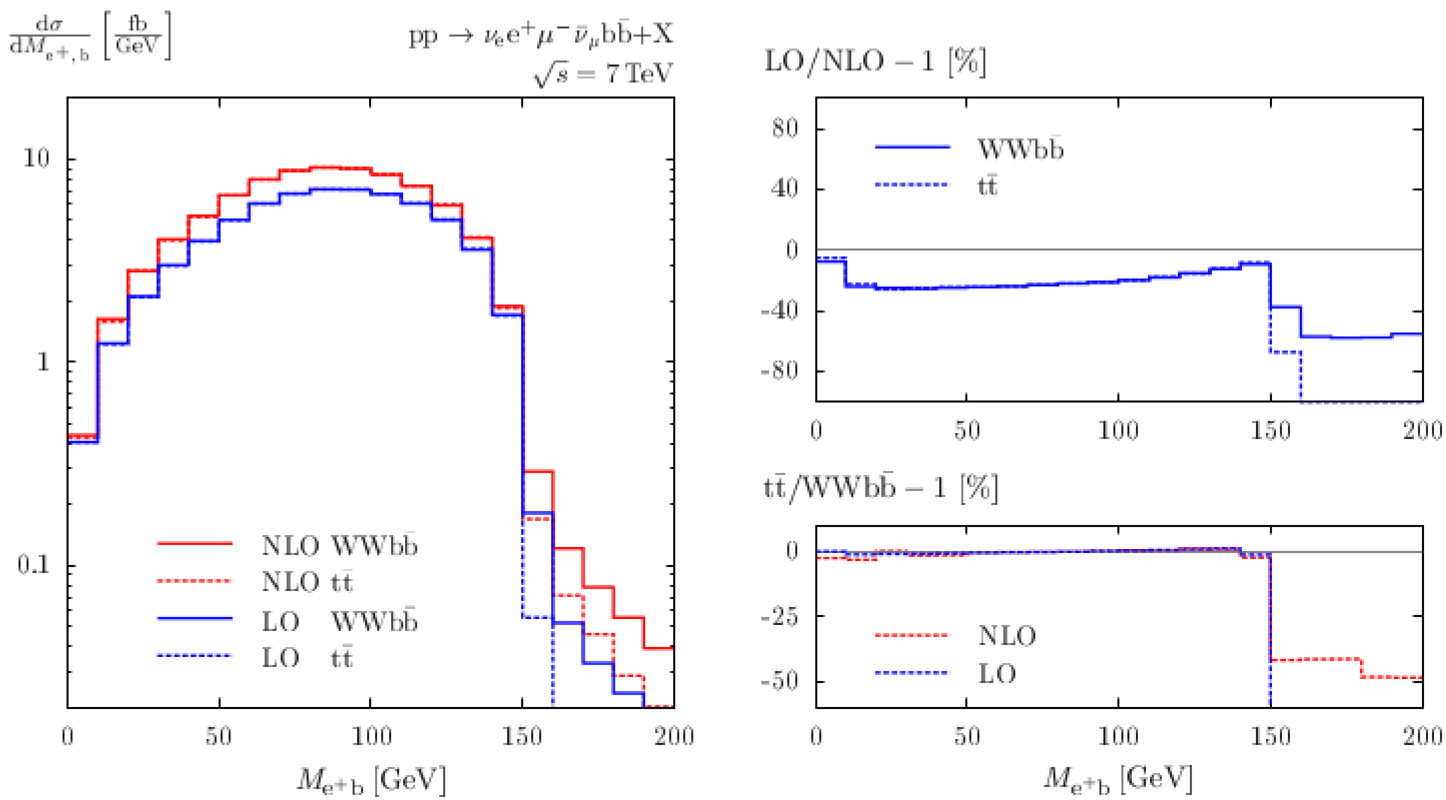
Collider	$\sqrt{s}$ [TeV]	approx.	$\sigma_{\mathrm{t\bar{t}}}$ [fb]	$\sigma_{\mathrm{WWb\bar{b}}}$ [fb]	$\sigma_{\mathrm{t\bar{t}}}/\sigma_{\mathrm{WWb\bar{b}}} - 1$
Tevatron	1.96	LO	$44.691(8)^{+19.81}_{-12.58}$	$44.310(3)^{+19.68}_{-12.49}$	$+0.861(19)\%$
		NLO	$42.16(3)^{+0.00}_{-2.91}$	$41.75(5)^{+0.00}_{-2.63}$	$+0.98(14)\%$
LHC	7	LO	$659.5(1)^{+261.8}_{-173.1}$	$662.35(4)^{+263.4}_{-174.1}$	$-0.431(16)\%$
		NLO	$837(2)^{+42}_{-87}$	$840(2)^{+41}_{-87}$	$-0.41(31)\%$
LHC	14	LO	$3306.3(1)^{+1086.8}_{-763.6}$	$3334.6(2)^{+1098.5}_{-771.2}$	$-0.849(7)\%$
		NLO	$4253(3)^{+282}_{-404}$	$4286(7)^{+283}_{-407}$	$-0.77(19)\%$

Top quark mass determination from kinematic distributions

m_{lb} distribution

Study of finite width effects and non-factorizable corrections

[Denner,Dittmaier,Kallweit,Pozzorini,M.S.]

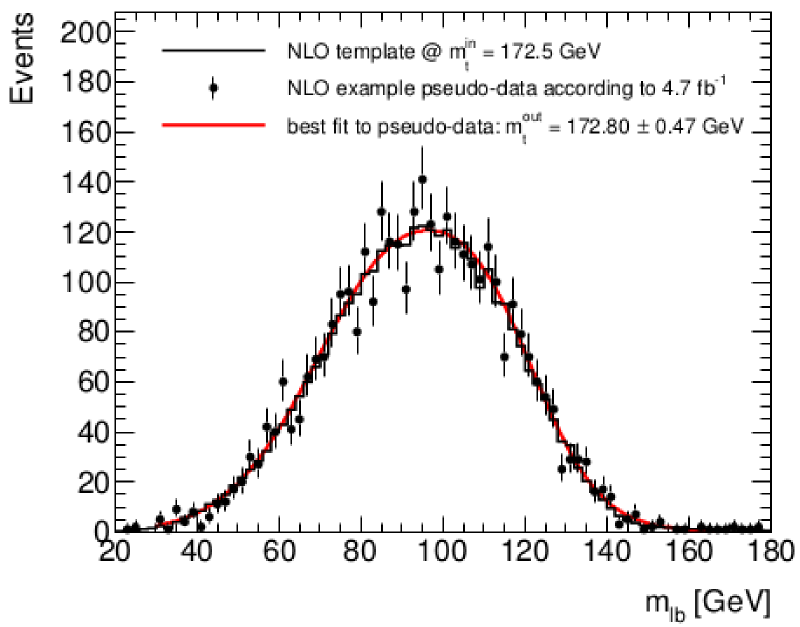


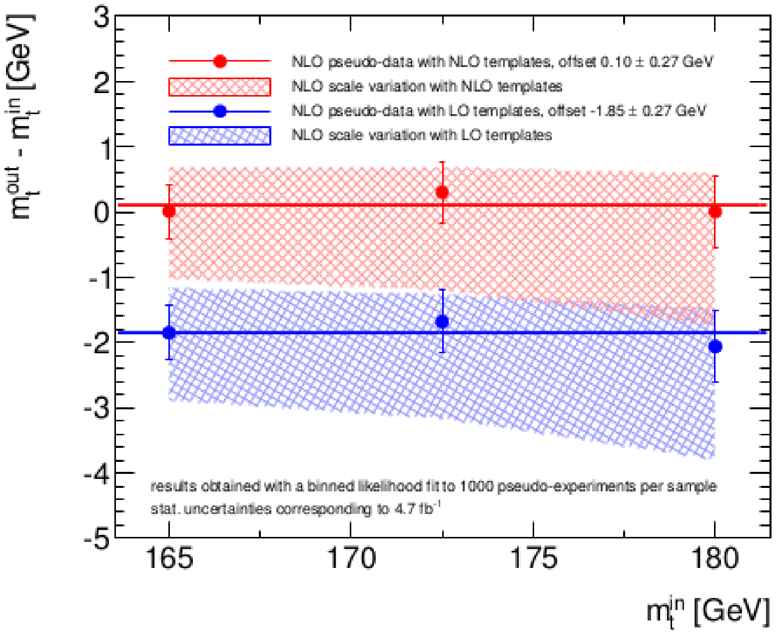
Top quark mass determination from kinematic distributions

m_{lb} distribution

- Template fit to (pseudo) data

[Heinrich,Maier,Nisius,Schlenk,Winter `13]





Pseudo data always generated with NLO QCD.

Templates are either generated at NLO (red) or LO (blue).

SUMMARY

- Certain types of kinematic distributions have good sensitivity to m_{top}. Up to know those methods have been rarely applied to real data.

- Uncertainty estimates from kinematic distributions $\sim \pm 1.5$ GeV. Good theoretical control. No obvious show stopper.

- Reducing uncertainties to $\sim \pm 0.5$ GeV will probably require a combination of several methods (→ study correlated errors).

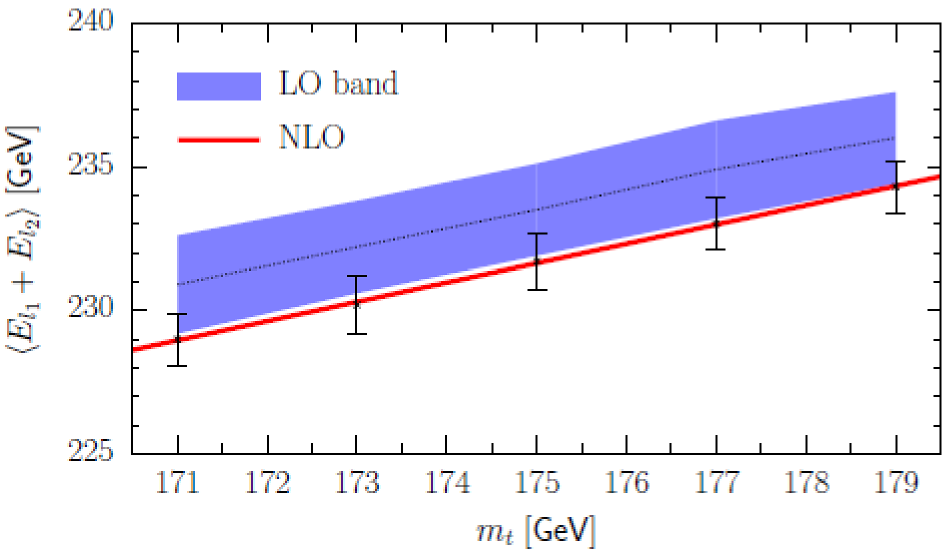
- Significant improvements require more precise B-meson frag. function.

- Possibility of BSM physics hiding in top data (*e.g.* $ttb+E_{\mathrm{T,miss}}$) which shifts m_{top} is not fully excluded.

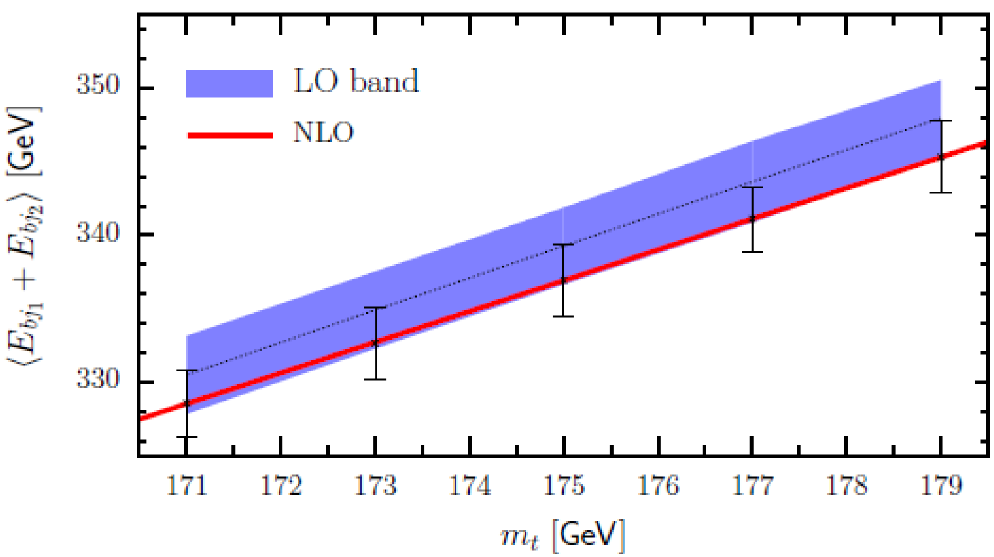
EXTRAS

EXTRAS

[Biswas,Melnikov,M.S. `10]



→ Δm_{top} = 1.5 GeV



→ Δm_{top} = 1.2 GeV

EXTRAS

	Ref. analysis	Projections				
CM Energy	8 TeV	14 TeV			33 TeV	100 TeV
Cross Section	240 pb	951 pb			5522 pb	25562 pb
Luminosity	$20fb^{-1}$	$100fb^{-1}$	$300fb^{-1}$	$3000fb^{-1}$	$3000fb^{-1}$	$3000fb^{-1}$
Theory (GeV)	-	1.5	1.5	1.0	1.0	0.6
Stat. (GeV)	7.00	1.8	1.0	0.3	0.1	0.1
Total	**-**	**2.3**	**1.8**	**1.1**	**1.0**	**0.6**
Total (%)	**-**	**1.3**	**1.0**	**0.6**	**0.6**	**0.4**

Table 6. Extrapolations based on the J/Ψ method.