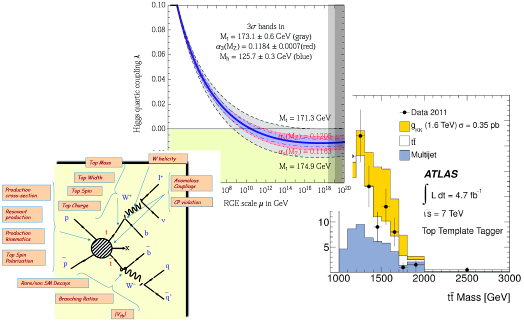
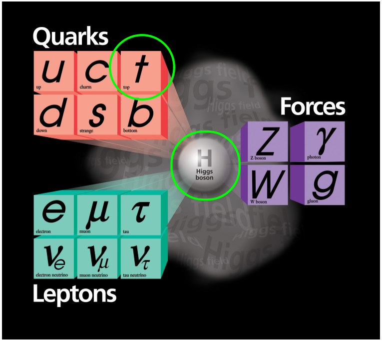
Top Quark Physics

M. Beneke (TU München)

KITP Conference "Stress-testing the Standard Model at the LHC"
May 26, 2016





The two stars at LHC
[yet to be eclipsed]

Spin $\frac{1}{2}$

Electric charge $+\frac{2}{3}$

$$\begin{aligned}\mathcal{L} &= \bar{t}\left(i\not\partial - y_t v\right)t + g_s\,\bar{t}\,\not A^a T^a t + \ldots \\ &\quad + g_w V_{tb}\,\bar{b}\,\not W^+ t + \text{h.c.} + \ldots \\ &\quad - y_t\,\bar{t}t\,H + \ldots\end{aligned}$$

Spin $\frac{1}{2}$

Electric charge $+\frac{2}{3}$

Universal strong interaction responsible for production.
$\sigma_{t\bar{t}} = 240\,\mathrm{pb}$ at LHC (8 TeV)
[950 pb at 14 TeV]

$$\begin{aligned}\mathcal{L} &= \bar{t}\left(i\not{\partial} - y_t v\right) t + g_s\,\bar{t}\,\not{A}^a T^a t + \ldots \\ &\quad + g_w V_{tb}\,\bar{b}\,\not{W}^+ t + \mathrm{h.c.} + \ldots \\ &\quad - y_t\,\bar{t}t\,H + \ldots\end{aligned}$$

Spin $\frac{1}{2}$

Electric charge $+\frac{2}{3}$

Scattering on the Higgs vacuum field $v = \langle 0|\phi(x)|0\rangle$.
EXCEPTIONALLY LARGE MASS

Universal strong interaction responsible for production.
$\sigma_{t\bar t} = 240\,\text{pb}$ at LHC (8 TeV)
[950 pb at 14 TeV]

$$\mathcal{L} = \bar t \left(i\not\partial - y_t v\right) t + g_s \,\bar t \not A^a T^a t + \ldots$$

$$+ g_w V_{tb}\, \bar b \not W^+ t + \text{h.c.} + \ldots$$

$$-y_t\, \bar t t\, H + \ldots$$

Spin $\frac{1}{2}$

Electric charge $+\frac{2}{3}$

Scattering on the Higgs vacuum field $v = \langle 0|\phi(x)|0\rangle$.
EXCEPTIONALLY LARGE MASS

Universal strong interaction responsible for production.
$\sigma_{t\bar t} = 240\,\mathrm{pb}$ at LHC (8 TeV)
[950 pb at 14 TeV]

$$\begin{aligned}\mathcal{L} \;&= \bar t\,\big(i\partial\!\!\!/ - y_t v\big)\,t + g_s\,\bar t\,A\!\!\!/^{a}T^{a}t + \dots\\ &\quad + g_w V_{tb}\,\bar b\,W\!\!\!\!/^{\,+}\,t + \text{h.c.} + \dots\\ &\quad - y_t\,\bar t t\,H + \dots\end{aligned}$$

Non-universal weak interaction responsible for decay $t \to b + W^+$,
$\tau \sim 5\cdot 10^{-25}$ s.
QUASI-FREE QUARK [spin correlations]

Spin $\frac{1}{2}$

Electric charge $+\frac{2}{3}$

Scattering on the Higgs vacuum field $v = \langle 0|\phi(x)|0\rangle$.
EXCEPTIONALLY LARGE MASS

Universal strong interaction responsible for production.
$\sigma_{t\bar t} = 240\,\text{pb}$ at LHC (8 TeV) [950 pb at 14 TeV]

$$\mathcal{L} = \bar t\,(i\not\partial - y_t v)\,t + g_s\,\bar t\,\not{A}^a T^a t + \ldots$$

$$+ g_w V_{tb}\,\bar b\,\not{W}^+ t + \text{h.c.} + \ldots$$

$$- y_t\,\bar t t\,H + \ldots$$

Non-universal weak interaction responsible for decay $t \to b + W^+$,
$\tau \sim 5 \cdot 10^{-25}$ s.
QUASI-FREE QUARK [spin correlations]

STRONG TOP-HIGGS INTERACTION related to top mass

Window to EWSB
Main contributor to hierarchy problem
Top partners? Composite?
Determines the fate of the Universe?

Beyond the SM

$$\mathcal{L} \supset -\,\underbrace{y_t\, t\bar{t}h}_{m_t,\,[m_Z]} - \underbrace{\frac{\lambda}{4}\,h^4}_{m_H,\,[m_Z]}$$

BSM effects must be either small or are most likely much more dramatic and diverse.

Beyond the SM

$$\mathcal{L} \supset -\underbrace{y_t\, t\bar{t}h}_{m_t,\,[m_Z]} - \underbrace{\frac{\lambda}{4}\, h^4}_{m_H,\,[m_Z]}$$

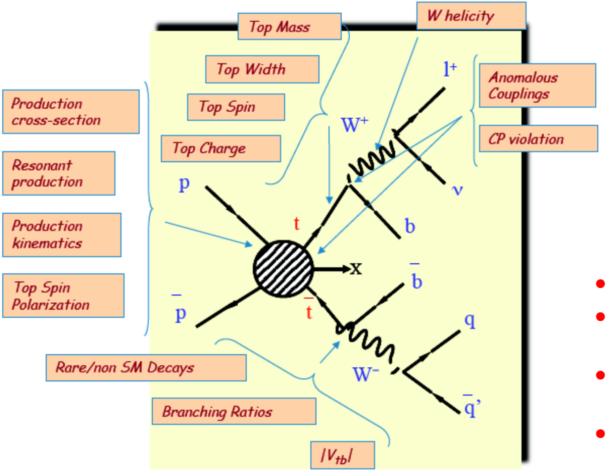
BSM effects must be either small or are most likely much more dramatic and diverse.

- $$\Delta\mathcal{L} = -\frac{c_{\rm NP}}{\Lambda^2}(\phi^\dagger\phi)(\bar{Q}_3\widetilde{\phi}t_R) + \text{h.c.} \quad\Rightarrow\quad m_t = \frac{y_t v}{\sqrt{2}}\left(1 + \frac{c_{\rm NP}}{\Lambda^2}\,\frac{v^3}{\sqrt{2}m_t}\right)$$
- But more generally

$$(\phi^\dagger\phi)(\bar{Q}_i\widetilde{\phi}U_j),\ \phi^\dagger i\overleftrightarrow{D^\mu}\phi(\bar{Q}_i\gamma_\mu Q_j),\ \bar{Q}_i\sigma^{\mu\nu}\Phi U_j X_{\mu\nu},\ \ldots$$

imply new flavour-changing interactions, electric dipole moments, ...

Automated computation in SM effective theory including NLO QCD corrections [Zhang, Maltoni, 1305.7386; …; Degrande et al., 1412.5594; …; Franzosi, Zhang, 1503.08841; Zhang, 1601.06163; …]



- Invariant mass $M_{t\bar{t}}^2$
- Transverse momentum $p_{t,\perp}$
- Forward-backward or charge asymmetry
- Angular distributions, spin correlations

+ single top production

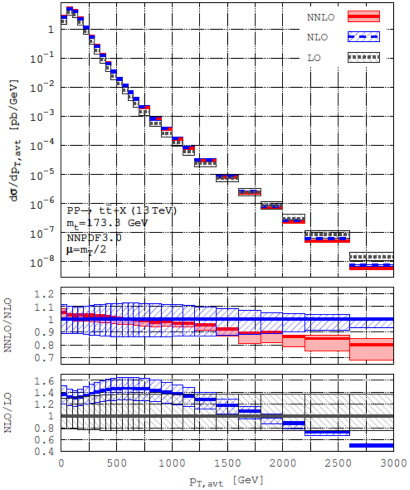
The top quark precision physics frontier – NNLO

- Differential top decay
  [Brucherseifer, Caola, Melnikov, 1301.7133]
- Top pair inclusive XS
  [Czakon, Mitov + Bärnreuther, Fiedler, 1204.5201, 1303.6254]
- Differential t-channel single-top, “factorizable corrections” only
  [Brucherseifer, Caola, Melnikov, 1404.7166],
  further pieces
  [Assadsolimani et al., 1409.3654].
- Top pair distributions
  [Czakon, Fiedler, Heymes, Mitov, 1601.05375]

The top quark precision physics frontier – NNLO

- Differential top decay
  [Brucherseifer, Caola, Melnikov, 1301.7133]
- Top pair inclusive XS
  [Czakon, Mitov + Bärnreuther, Fiedler, 1204.5201, 1303.6254]
- Differential *t*-channel single-top, "factorizable corrections" only
  [Brucherseifer, Caola, Melnikov, 1404.7166], further pieces
  [Assadsolimani et al., 1409.3654].
- Top pair distributions
  [Czakon, Fiedler, Heymes, Mitov, 1601.05375]

⇒ Mitov's talk



[A. Mitov, LHC Top WG meeting, May 2016]

Topics of this talk

- Beyond NNLO

  Resummation, $\text{NNNLO}_{\text{approx}}$, and another issue

- Top mass

  Inclusive XS, Jet reconstruction, Pole Mass, e^+e^- threshold

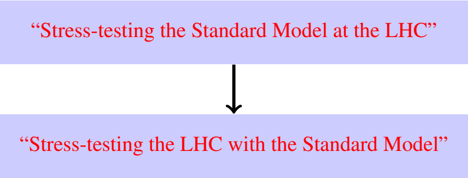
Topics of this talk

- Beyond NNLO

  Resummation, $\mathrm{NNNLO}_{\mathrm{approx}}$, and another issue

- Top mass

  Inclusive XS, Jet reconstruction, Pole Mass, e^+e^- threshold



"Stress-testing the Standard Model at the LHC"

"Stress-testing the LHC with the Standard Model"

Beyond NNLO

Resummation – NNLL

- Partonic thresholds
  - PIM ($\hat{s} \to M_{t\bar{t}}^2$), 1PI (($p_{t+X}^2 \to m_t^2$), soft "double logs"
    [Ahrens et al., 1003.5827, 1103.0550]

$$\frac{d\hat{\sigma}}{dX} = \mathrm{tr}\,(\mathbf{H} \cdot \mathbf{S})$$

  - Total cross section ($\hat{s} \to 4m_t^2$ or $\beta \to 0$), Coulomb singularities + soft "double logs"
    [MB, Falgari, Klein, Schwinn, 1109.1536, + Piclum, Ubiali, Yan, 1206.2454]

$$\hat{\sigma}_{pp'}(\hat{s},\mu) = \sum_{R=\mathbf{1},\mathbf{8}} H^R_{pp'}(m_t,\mu) \int d\omega\, J_R(E - \frac{\omega}{2})\, W^R(\omega,\mu)$$

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

$$\times\ \{1\ \text{(LL,NLL)};\ \alpha_s,\ \beta\ \text{(NNLL)};\ \ldots\}$$

  - Extensions to $t\bar{t}$ + Higgs or vector boson.
    [Li et al. 1409.1460, Kulesza et al. 1509.02780, Broggio et al. 1510.01914]

Resummation – NNLL

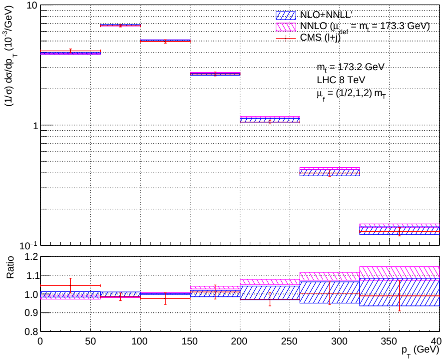
- Partonic thresholds
  - PIM ($\hat{s} \to M_{t\bar{t}}^2$), 1PI (($p_{t+X}^2 \to m_t^2$), soft “double logs”
    [Ahrens et al., 1003.5827, 1103.0550]
$$\frac{d\hat{\sigma}}{dX} = \mathrm{tr}\,(\mathbf{H}\cdot\mathbf{S})$$
  - Total cross section ($\hat{s} \to 4m_t^2$ or $\beta \to 0$), Coulomb singularities + soft “double logs”
    [MB, Falgari, Klein, Schwinn, 1109.1536, + Piclum, Ubiali, Yan, 1206.2454]
$$\hat{\sigma}_{pp'}(\hat{s},\mu) = \sum_{R=\mathbf{1},\mathbf{8}} H^R_{pp'}(m_t,\mu)\,\int d\omega\; J_R(E-\frac{\omega}{2})\,W^R(\omega,\mu)$$
$$\hat{\sigma}_{pp'} \;=\; \hat{\sigma}^{(0)}_{pp'}\sum_{k=0}\left(\frac{\alpha_s}{\beta}\right)^k \exp\Big[\underbrace{\ln\beta\,g_0(\alpha_s\ln\beta)}_{\text{(LL)}}+\underbrace{g_1(\alpha_s\ln\beta)}_{\text{(NLL)}}+\underbrace{\alpha_s g_2(\alpha_s\ln\beta)}_{\text{(NNLL)}}+\ldots\Big]$$
$$\times\ \{1\ \text{(LL,NLL)};\ \alpha_s,\ \beta\ \text{(NNLL)};\ \ldots\}$$
  - Extensions to $t\bar{t}$ + Higgs or vector boson.
    [Li et al. 1409.1460, Kulesza et al. 1509.02780, Broggio et al. 1510.01914]

Hadronic cross section not parametrically dominated by partonic thresholds.

NNLL resummation, boosted

- Boosted top + soft gluon ($M_{t\bar{t}} \gg 4m_t^2, p_t \gg m_t, \ldots$)
  [Ferroglia, Pecjak + Scott, Wang, Yang, 1205.3662, ..., 1601.07020]

$$\frac{d\hat{\sigma}}{dX} = \mathrm{tr}\,(\mathbf{H}\cdot\mathbf{S}) \otimes [\mathrm{fragmentation}]^2$$



[Pecjak et al., 1601.7020]

- NNLL + matched to NNLO for large p_t, $M_{t\bar{t}}$ could be future state-of-the-art.

NNNLO$_{\text{approx}}$ – the NNLO/LL history

Impact of NNLO and resummation [TOPIXS, [MB, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan, 1206.2454]]

$\sigma_{t\bar{t}}$[pb]	Tevatron	LHC ($\sqrt{s}$ =7 TeV)	LHC ($\sqrt{s}$ =8 TeV)
NLO	$6.68^{+0.36+0.23}_{-0.75-0.22}$	$158.1^{+19.5+6.8}_{-21.2-6.2}$	$226.2^{+27.8+9.2}_{-29.7-8.3}$
NNLO$_{\text{app}}$	$7.06^{+0.26+0.29}_{-0.34-0.24}$	$161.1^{+12.3+7.3}_{-11.9-6.7}$	$230.0^{+16.7+9.7}_{-15.7-9.0}$
NNLO	$7.01^{+0.27+0.29}_{-0.37-0.24}$	$167.1^{+\ 6.7+7.7}_{-10.7-7.1}$	$239.1^{+9.2+10.4}_{-14.8-9.6}$
NNLL	$7.15^{+0.24+0.30}_{-0.10-0.25}$	$168.5^{+\ 6.3+7.7}_{-\ 7.5-7.2}$	$241.0^{+8.7+10.5}_{-11.1-9.7}$

$m_t = 173.3$ GeV, $\alpha_s(M_Z) = 0.1171$, (N)NLO MSTW08 PDFs, first error theoretical uncertainty, second PDF+α_s at 68% CL.

Theoretical error: independent soft/hard/Coulomb scale variations, resummation ambiguities.

NNNLO$_{\text{approx}}$ – the NNLO/LL history

Impact of NNLO and resummation [TOPIXS, [MB, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan, 1206.2454]]

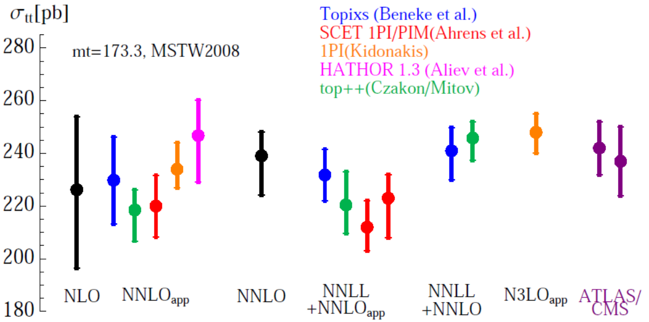
$\sigma_{t\bar{t}}$[pb]	Tevatron	LHC ($\sqrt{s}$ =7 TeV)	LHC ($\sqrt{s}$ =8 TeV)
NLO	$6.68^{+0.36+0.23}_{-0.75-0.22}$	$158.1^{+19.5+6.8}_{-21.2-6.2}$	$226.2^{+27.8+9.2}_{-29.7-8.3}$
NNLO$_{\text{app}}$	$7.06^{+0.26+0.29}_{-0.34-0.24}$	$161.1^{+12.3+7.3}_{-11.9-6.7}$	$230.0^{+16.7+9.7}_{-15.7-9.0}$
NNLO	$7.01^{+0.27+0.29}_{-0.37-0.24}$	$167.1^{+6.7+7.7}_{-10.7-7.1}$	$239.1^{+9.2+10.4}_{-14.8-9.6}$
NNLL	$7.15^{+0.24+0.30}_{-0.10-0.25}$	$168.5^{+6.3+7.7}_{-7.5-7.2}$	$241.0^{+8.7+10.5}_{-11.1-9.7}$

$m_t = 173.3$ GeV, $\alpha_s(M_Z) = 0.1171$, (N)NLO MSTW08 PDFs, first error theoretical uncertainty, second PDF+α_s at 68% CL.
Theoretical error: independent soft/hard/Coulomb scale variations, resummation ambiguities.

- Tevatron ($q\bar{q}$)
  significant resummation/NNLO effect [+8%],
  reduction of theoretical uncertainty [8% → 3%] (excluding PDF + α_s error),
  threshold approximation worked well.

- LHC (gg)
  small resummation [+1%]/significant NNLO effect [+4%],
  significant reduction of theoretical uncertainty [13% → 4.5%],
  threshold expansion did not work that well.

NNLO/NNLL resummation, comparison



[Schwinn, MIAPP Top Quark Physics Day, August 2014]

- PDF+α_s uncertainty NOT included here.

NNNLO$_{\text{approx}}$ approaches

A MB, Falgari, Klein, Schwinn, 1109.1536

NNLL soft+Coulomb expanded to NNNLO + incomplete subleading terms

B Kidonakis, 1405.7046

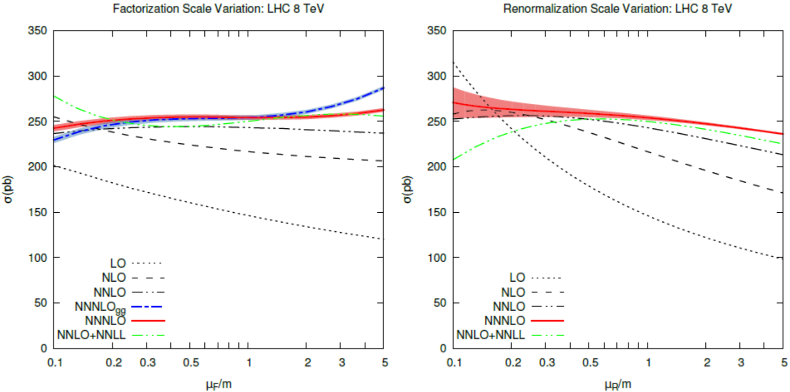
NNLL soft gluon corrections to 1PI kinematics at NNNLO

C Muselli, Bonvini, Forte, Marzani, Ridolfi, 1505.02006

Most complete and sophisticated of the three approaches: Threshold behaviour as in A (in moment space, $N \to \infty$) matched to high-energy behaviour $(\hat{s}/(4m_t)^2 \to \infty, N \to 1)$. Gluon-gluon only ($\to$ LHC).

	Tevatron	LHC (7 TeV)	LHC (8 TeV)	LHC (13 TeV)
A	$+4.7\%$	$+3.0\%$	$+2.8\%$	$+2.1\%$
B	$+5.1\%$	$+4.0\%$	$+3.6\%$	$+2.7\%$
C [wo large-x]	—	$+3.0\%$	$+2.8\%$	$+2.3\%$
C	—	$+4.3\%$	$+4.5\%$	$+4.3\%$

NNNLO$_{\text{approx}}$ results (I)



[Muselli et al., 1505.02006]

NNNLO$_{\text{approx}}$ results (II)

Exactly known terms in the threshold expansion (*gg* singlet, as example)

$$
\begin{aligned}
f^{(3,0)}_{gg(1)} = {} & 147456.\ln^6\beta - 59065.6\ln^5\beta - 286099.\ln^4\beta + 349463.\ln^3\beta \\
& + \frac{1}{\beta}\left[121278.\ln^4\beta + 103557.\ln^3\beta - 164944.\ln^2\beta + 56418.5\ln\beta\right] \\
& + \frac{1}{\beta^2}\left[22166.\ln^2\beta + 39012.1\ln\beta - 2876.61\right] + \underbrace{\left\{1/\beta,\ln^{2,1}\beta,\text{const}\right\}}_{\text{partly known}} + \text{scale dep.}
\end{aligned}
$$

LHC ($\sqrt{s} = 7\,\text{TeV}$)

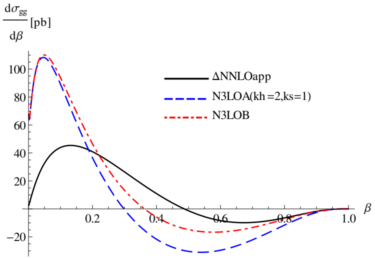
NNLO: $+12.1\,\text{pb}$
NNNLO: $+5.0\,\text{pb}$

but

- NNNLO + all orders only $+1.9\,\text{pb}$
- O(200%) uncertain from scale dependence and sub-leading terms

→ NNNLO$_{\text{approx}}$ with some doubts

$$\frac{d\Delta\sigma_{pp'\to t\bar{t}}}{d\beta} = \frac{8\beta m_t^2}{s(1-\beta^2)^2} L_{pp'}(\beta,\mu_f)\Delta\hat{\sigma}_{pp'\to t\bar{t}}(\beta,\mu_f)$$



Beyond NNLO Outlook

- NNLO+NNLL Q/m_t resummation for high-Q observables.
  EW resummation?

- Threshold resummation not guaranteed to produce most of the next order, but better than nothing.
  NNNLL feasible for total cross section.

Divergence in fixed-order calculations?

- Note: fixed order is ill-defined from N^{4}LO due to $1/\beta^4$ term, which cannot be integrated!

  $$\int_0 d\beta \, \frac{8\beta m_t^2}{s(1-\beta^2)^2} \, \mathcal{L}_{ij}(\beta) \times \alpha_s^2 \beta \times \frac{\alpha_s^4}{\beta^4} = \infty$$

  Would already appear at N^{3}LO, but there happens to be no α_s^3/β^3 term at this order.

- Resummation cures the divergence, but is a small effect on the total XS and should not be required to compute the total XS.
  Fixed-order should work.

Divergence in fixed-order calculations?

- Note: fixed order is ill-defined from N^{4}LO due to $1/\beta^4$ term, which cannot be integrated!

  $$\int_0 d\beta\, \frac{8\beta m_t^2}{s(1-\beta^2)^2}\, \mathcal{L}_{ij}(\beta) \times \alpha_s^2 \beta \times \frac{\alpha_s^4}{\beta^4} = \infty$$

  Would already appear at N^{3}LO, but there happens to be no α_s^3/β^3 term at this order.

- Resummation cures the divergence, but is a small effect on the total XS and should not be required to compute the total XS.
  Fixed-order should work.

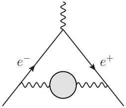
???

Threshold-subtracted dispersion relations (I) [MB, Ruiz-Femenia, 2014, hopefully soon]

Vacuum polarization contribution to the anomalous magnetic moment of the electron

$$a_e^{(\mathrm{vp})} = -\frac{\alpha}{\pi}\int_0^1 dx\,(1-x)\,\Pi\left(\frac{-x^2}{1-x}\,m^2\right) = \frac{\alpha}{\pi^2}\int_0^\infty \frac{ds}{s}\,\mathrm{Im}\,\Pi(s)\,K(s)$$

$$K(s) = \int_0^1 dx\,\frac{x^2(1-x)}{x^2+(1-x)s/m^2}$$



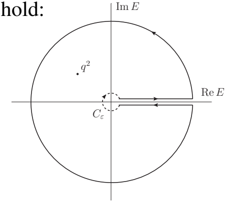
- Mishima, 1311.7109 claims there is an additional positronium bound state contribution of relative $\mathcal{O}(\alpha^3)$.
- Quickly refuted [Melnikov, Vainshtein, Voloshin 1402.5690; Eides, 1402.5860; Hayakawa, 1403.0416], but the technical arguments are not completely satisfactory.
- Correct result can be obtained in either of two ways:

perturbative $\Pi(E) \supset -\frac{\alpha^4}{8}\,\frac{\zeta_3}{E/m} \Rightarrow \mathrm{Im}\,\Pi(E) \supset \mathrm{const}\times\delta(E) \Rightarrow a_e^{(\mathrm{vp})} \supset \frac{\alpha^5}{8\pi}\,\zeta_3\,K(4m_e^2)$

“non-perturbative” $a_e^{(\mathrm{vp})} \supset \underbrace{\frac{\alpha^5}{4\pi}\,\zeta_3\,K(4m_e^2)}_{\text{positronium}} - \underbrace{\frac{\alpha^5}{8\pi}\,\zeta_3\,K(4m_e^2)}_{\text{resummed continuum}}$

Threshold-subtracted dispersion relations (II)

Dispersion relation needs to be subtracted not only at infinity but also at threshold:

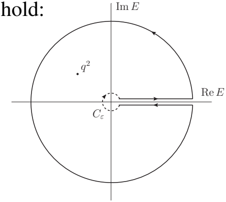


$$\Pi^{(4)}(q^2) = \frac{q^2}{8\,(4m^2 - q^2)}\alpha^4\zeta(3) + \frac{q^2}{\pi}\int_{(2m+\varepsilon)^2}^{\infty} ds\,\frac{\mathrm{Im}\,\Pi^{(4)}(s+i\eta)}{s\,(s-q^2)}$$

etc. in higher loop orders.

Threshold-subtracted dispersion relations (II)

Dispersion relation needs to be subtracted not only at infinity but also at threshold:



$$\Pi^{(4)}(q^2) = \frac{q^2}{8\,(4m^2-q^2)}\alpha^4\zeta(3) + \frac{q^2}{\pi}\int_{(2m+\varepsilon)^2}^{\infty} ds\,\frac{\mathrm{Im}\,\Pi^{(4)}(s+i\eta)}{s\,(s-q^2)}$$

etc. in higher loop orders.

Back to $t\bar{t}$

- $\Pi \to A(t\bar{t} \to t\bar{t})_{\text{forward}}$, $\mathrm{Im}\,\Pi \to \hat{\sigma}_{t\bar{t}}$, kernel → parton luminosity.
- Fixed-order computations can be done with subtracted convolutions with parton luminosity + threshold terms added back.
- Will miss the delta-function term at NNNLO if calculation is performed as phase-space integral of virtual + real.
  Additional NNNLO contribution

$$\Delta\sigma_{t\bar{t}} \approx \{0.1, 0.2, 0.6\}\,\text{pb} \qquad \text{at } \sqrt{s}_{\text{LHC}} = \{7, 8, 13\}\,\text{TeV}$$

Numerically negligible (small octet colour factor).

Top Mass

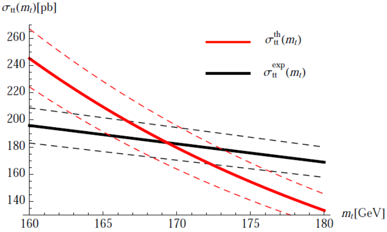
Top mass from inclusive XS

$$\sigma_{t\bar{t}}^{\rm exp}(m_t^{\rm MC}) \to \sigma_{t\bar{t}}^{\rm th}(m_t, \alpha_s, {\rm PDF})$$

Top mass from inclusive XS

$$\sigma_{t\bar{t}}^{\text{exp}}(m_t^{\text{MC}}) \to \sigma_{t\bar{t}}^{\text{th}}(m_t, \alpha_s, \text{PDF})$$

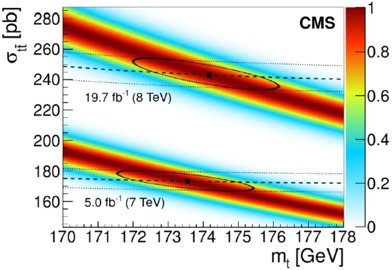
	m_{t} [GeV]
NNPDF3.0	$173.8^{+1.7}_{-1.8}$
MMHT2014	$174.1^{+1.8}_{-2.0}$
CT14	$174.3^{+2.1}_{-2.2}$



[MB, Falgari, Klein, Schwinn, 1109.1536]

2011 ATLAS 7 TeV data and NLO+NNLL theory

$$m_t = (169.8^{+4.9}_{-4.7})\ \text{GeV}$$



[CMS $e\mu$ channel, 1603.02303]

See also Langenfeld et al. (2009), D0 [latest: 1605.06168], CDF, ...

Decorrelation of m_t^{MC} and m_t [Kieseler, Lipka, Moch, 1511.00841]

Top mass from inclusive XS (II)

- Rule of thumb

$$\frac{\Delta\sigma_{t\bar{t}}}{\sigma_{t\bar{t}}} = 3\% \quad \Rightarrow \quad \Delta m_t \approx 1\,\text{GeV}$$

- CMS has 4% exp uncertainty, 5.5% th error (apparently including PDF uncertainty).

  Small improvements possible, ±1 GeV seems hard.

- PDF constraints from top production depend on m_t.

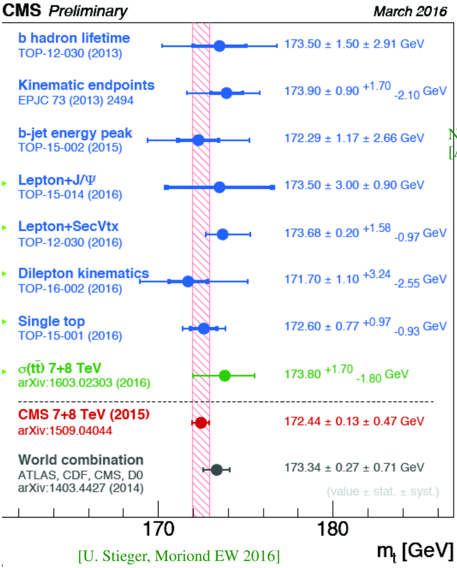
- Any of the common top mass definitions could be used.

  $\overline{\text{MS}}$ mass has been advocated to lead to (empirically) smaller theoretical uncertainties. [Langenfeld, Moch, Uwer, 0906.5275, ...]

  Unclear why – opposite should be true, if observable is dominated by threshold.

- Other inclusive production cross sections can be used (e.g., +jet [Alioli et al., 1303.6415]) or distributions (sensitivity vs. statistics and theoretical uncertainties).

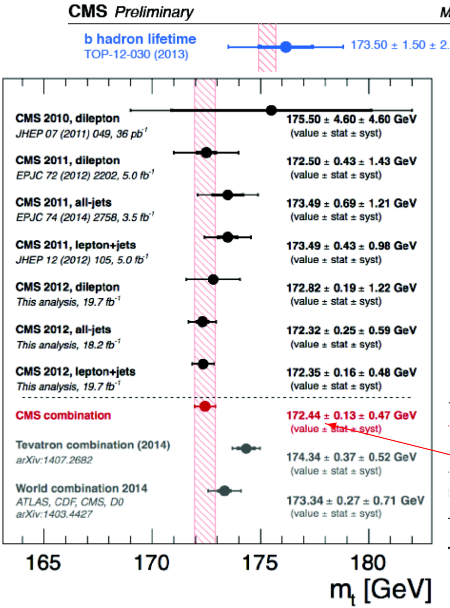
Top mass from mass reconstruction and kinematics



[U. Stieger, Moriond EW 2016]

NLO QCD production+decay, narrow width approx
[Agashe, Franceschini, Kim, Schulze, 1603.03445]

Top mass from mass reconstruction and kinematics



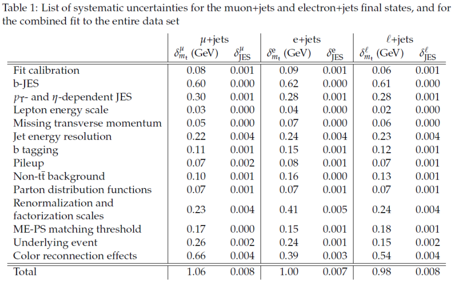


Table 1: List of systematic uncertainties for the muon+jets and electron+jets final states, and for the combined fit to the entire data set

	μ+jets		e+jets		ℓ+jets	
	$\delta^{\mu}_{m_t}$ (GeV)	$\delta^{\mu}_{\mathrm{JES}}$	$\delta^{e}_{m_t}$ (GeV)	$\delta^{e}_{\mathrm{JES}}$	$\delta^{\ell}_{m_t}$ (GeV)	$\delta^{\ell}_{\mathrm{JES}}$
Fit calibration	0.08	0.001	0.09	0.001	0.06	0.001
b-JES	0.60	0.000	0.62	0.000	0.61	0.000
p_T- and η-dependent JES	0.30	0.001	0.28	0.001	0.28	0.001
Lepton energy scale	0.03	0.000	0.04	0.000	0.02	0.000
Missing transverse momentum	0.05	0.000	0.07	0.000	0.06	0.000
Jet energy resolution	0.22	0.004	0.24	0.004	0.23	0.004
b tagging	0.11	0.001	0.15	0.001	0.12	0.001
Pileup	0.07	0.002	0.08	0.001	0.07	0.001
Non-$t\bar{t}$ background	0.10	0.001	0.16	0.000	0.13	0.001
Parton distribution functions	0.07	0.001	0.07	0.001	0.07	0.001
Renormalization and factorization scales	0.23	0.004	0.41	0.005	0.24	0.004
ME-PS matching threshold	0.17	0.000	0.15	0.001	0.18	0.001
Underlying event	0.26	0.002	0.24	0.001	0.15	0.002
Color reconnection effects	0.66	0.004	0.39	0.003	0.54	0.004
Total	1.06	0.008	1.00	0.007	0.98	0.008

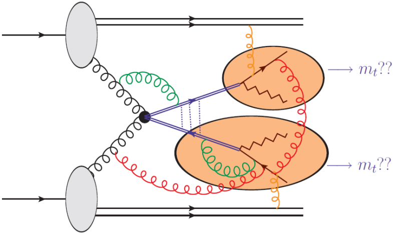
[CMS, 1209.2319 – 2011 data]

$$m_t = 172.44 \pm 0.13 \pm 0.47\,\mathrm{GeV}$$

(b-JES, colour-rec, UE, scale-dep)

Which mass?

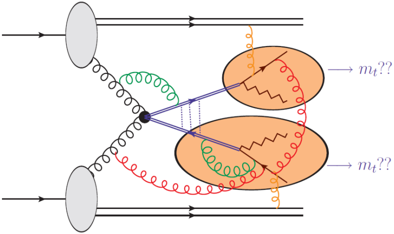
"The Monte Carlo mass"
"It's the pole mass, stupid!"
"Pole mass is ambiguous by $\mathcal{O}(1\,\mathrm{GeV})$ due to confinement/renormalons"



[from A. Signer, Top Quark Physics]

Which mass?

“The Monte Carlo mass”
“It’s the pole mass, stupid!”
“Pole mass is ambiguous by $\mathcal{O}(1\,\mathrm{GeV})$ due to confinement/renormalons”



[from A. Signer, Top Quark Physics]

- *Perturbative* factorization theorem for $d\sigma/dM_t^2 dM_{\bar{t}}^2$ (central jets) similar to [Fleming, Hoang, Mantry, Stewart, 0711.2079] for e^+e^-.

  Perturbative corrections to extracted mass $\mathcal{O}(1\,\mathrm{GeV})$ not necessarily related to mass definition.

- Want NNLL resummation + shower à la GENEVA.

- Intrinsic *non-perturbative* $\mathcal{O}(\Lambda_{\mathrm{QCD}})$ uncertainty remains. Reduce numerically with jet cleaning methods?

For now, the pole mass.

How ambiguous is the top pole mass really?

- Physics → $\mathcal{O}(\Lambda_{\rm QCD})$ — No free quark, not a physical quantity, meson mass differs by $\mathcal{O}(\Lambda_{\rm QCD})$

  Loop integrals are $\int_0 dk$, $\mathcal{O}(\Lambda_{\rm QCD})$ from infrared/strong coupling region

- Formal [MB, Braun, 1994; Bigi Shifman, Uraltsev, Vainshtein, 1994] — Factorial renormalon divergence in the conversion coefficients

$$m_P = m(\mu_m)\left[1 + \sum_{n=1}^{\infty} c_n(\mu, \mu_m, m(\mu_m))\, \alpha_s^n(\mu)\right]$$

$$c_n(\mu, \mu_m, m(\mu_m)) \underset{n\to\infty}{\longrightarrow} N c_n^{(\rm as)}(\mu, m(\mu_m)) \equiv N \frac{\mu}{m(\mu_m)}\, \tilde{c}_n^{(\rm as)}$$

$$\tilde{c}_{n+1}^{(\rm as)} = (2b_0)^n \, \frac{\Gamma(n+1+b)}{\Gamma(1+b)} \left(1 + \frac{s_1}{n+b} + \frac{s_2}{(n+b)(n+b-1)} + \cdots\right)$$

- Ambiguity of the Borel integral is EXACTLY $\mathcal{O}(\Lambda_{\rm QCD})$, no Logs of $m/\Lambda_{\rm QCD}$ [MB, 1994]
  ⇒ b, s_1, s_2 known (s_3 up to 5-loop beta-fn). BUT NOT N.

- What is $\mathcal{O}(\Lambda_{\rm QCD})$? 1 GeV, 100 MeV?
  Depends on value of N.

Know

- Four-loop conversion exactly [Marquard, Smirnov, Smirnov, Steinhauser, 1502.01030]

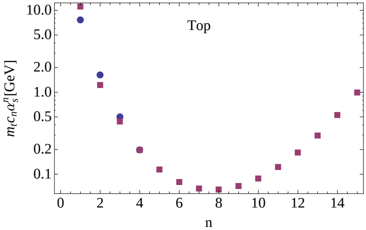
$$m_P = 163.643 + 7.557 + 1.617 + 0.501 + (0.195 \pm 0.005)\,\mathrm{GeV}$$

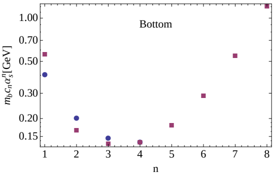
- All orders at order n with accuracy $\mathcal{O}(1/n^3, 1/2^n)$, GIVEN N.

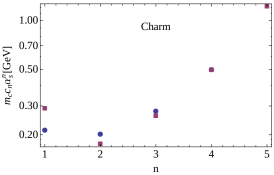
$\Longrightarrow$ Determine N from $n = 4$ with few percent accuracy [MB, Marquard, Nason, Steinhauser, 1605.03609]

$$N = 0.4616^{+0.027}_{-0.070}\,(\mu \text{ and } \mu_m) \pm 0.002\,(c_4)$$

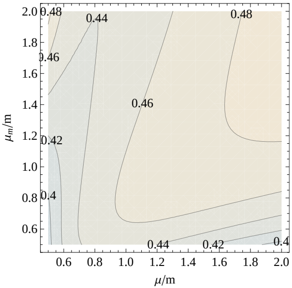
In good agreement with previous less accurate determinations [Pineda, hep-ph/0105008; Hoang et al, 0803.4214; Ayala et al. 1407.2128]

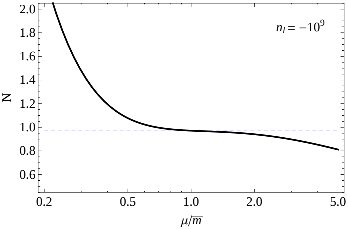






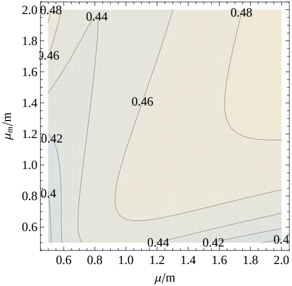
Checks and result [MB, Marquard, Nason, Steinhauser, 1605.03609]

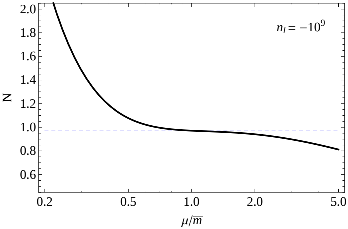




$$\lim_{|n_l|\to\infty} N = \frac{C_F}{\pi} \times e^{\frac{5}{6}} = 0.97656\ldots$$

Checks and result [MB, Marquard, Nason, Steinhauser, 1605.03609]





$$\lim_{|n_l|\to\infty} N = \frac{C_F}{\pi} \times e^{\frac{5}{6}} = 0.97656\ldots$$

$$\delta^{(5+)} m_P = \underbrace{0.250^{+0.015}_{-0.038}\,(N)}_{\text{5 loops and beyond}} \pm 0.001\,(c_4) \pm 0.010\,(\alpha_s) \underbrace{\pm 0.071\,(\text{ambiguity})}_{\text{intrinsic uncertainty}}\ \text{GeV}$$

$$m_P^{\rm c}/\overline{m} = 1.06164^{+0.00009}_{-0.00023}\,(N) \pm 0.00001\,(c_4) \pm 0.00086\,(\alpha_s) \pm 0.00043\,(\text{ambiguity})$$

Ultimate intrinsic uncertainty of the top pole mass is about 70 MeV.
Given the $\overline{\text{MS}}$ mass, the top quark pole mass is determined with an accuracy of 0.92 per mil.

$t\bar{t}$ Threshold in e^+e^-

NNNLO + summation in (PNR)QCD

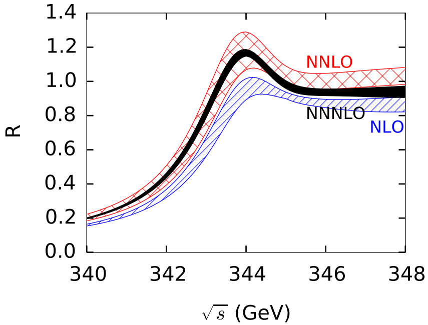
[MB, Kiyo, Marquard, Penin, Piclum, Steinhauser, 1506.06864]

Photon exchange and Z-vector coupling only.

$m_{t,\mathrm{PS}}(20\,\mathrm{GeV}) = 171.5\,\mathrm{GeV}$, $\Gamma_t = 1.33\,\mathrm{GeV}$,

$\alpha_s(m_Z) = 0.1185 \pm 0.006$, $\sin^2\theta_W = 0.2229$,

$\mu = (50\ldots 80\ldots 350)\,\mathrm{GeV}$, $\mu_w = 350\,\mathrm{GeV}$.



Complete NNNLO QCD combines many third-order pieces [MB, Kiyo, Schuller, hep-ph/0501289; MB, Kiyo, 0804.4004, 1312.4791; MB, Piclum, Rauh, 1312.4792; Marquard, Piclum, Seidel, Steinhauser, 0904.0920, 1401.3004]

Including Higgs, QED and non-resonant process $W^+W^-b\bar{b}$ ("single-top")

[MB, Jantzen, Ruiz-Femenia, 1004.2188, MB, Maier, Piclum, Rauh, 1506.06865]

+ electroweak and code release

[MB, Kiyo Maier, Piclum, 1605.03010]

$\delta m_t \approx 30\,\mathrm{MeV}$???

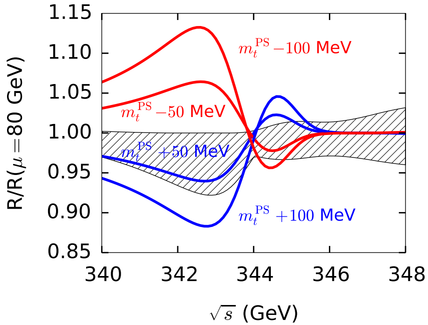
Position shift: 310 MeV (LO to NLO) 150 MeV (to NNLO) 64 MeV (to NNNLO)

Improvement of factor 3 in uncertainty in peak height.

Sensitivity to m_t vs. theoretical uncertainty

NNNLO $$\frac{\delta\sigma}{\sigma} = \pm(2\ldots3.5)\%$$

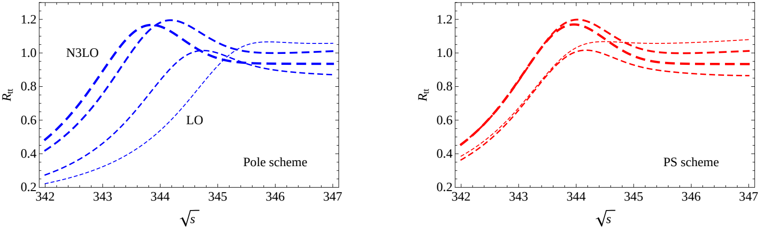
Shaded band — Relative scale uncertainty, superimposed variation with shifted top mass input normalized to reference.



[MB, Kiyo, Marquard, Penin, Piclum, Steinhauser, 1506.06864]

Which mass?

- Pole mass leads to large shifts in the peak position of the $t\bar{t}$ cross section



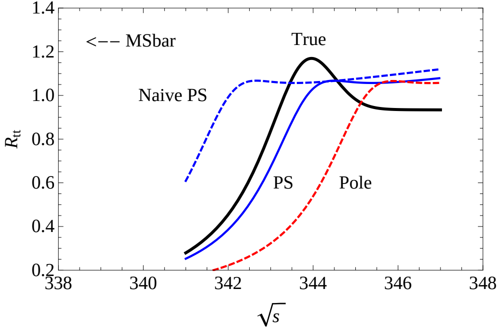
- Solution: intermediate mass definition, which can be related precisely to the $\overline{\text{MS}}$ mass (→ top Yukawa coupling) AND avoids spurious shifts. Potential-subtracted mass [MB, 1998]

$$m_{\text{PS}}(\mu_f) \equiv m_{\text{pole}} + \frac{1}{2}\int_{|\vec{q}\,|<\mu_f} \frac{d^3\vec{q}}{(2\pi)^3}\,\tilde{V}_{\text{Coulomb}}(\vec{q}\,)$$

$$m_{\text{PS}}(\mu_f) - \overline{m}(\overline{m}) = \underbrace{[m_{\text{PS}}(\mu_f) - m_{\text{pole}}]}_{\text{known to } \mathcal{O}(\mu_f\alpha_s^4) \text{ [hep-ph/0501289]}} + \underbrace{[m_{\text{pole}} - \overline{m}(\overline{m})]}_{\text{known to } \mathcal{O}(m_t\alpha_s^4) \text{ [1502.01030]}}$$

Cancellation of large perturbative contributions from the IR. Conversion precision ≈ 20 MeV.

What if we had only LO?



Top mass shift

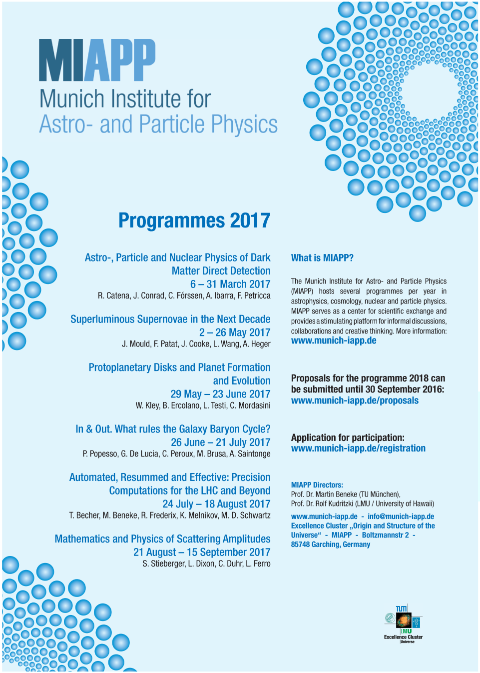
Scheme	δm_t
Pole	+950 MeV
PS naive	−650 MeV
$\overline{\text{MS}}$	−8.5 GeV
PS	+265 MeV

Summary

Explosion of Top Physics since LHC turn-on – sheer numbers make a difference

- Many new observables accessible.
- Precision drives theoretical developments in Quantum Field Theory
- Top physics – together with Higgs the most plausible gateway to “New Physics”

- NNLO the new standard. NNLO+NNLL desirable.
  NNNLO total XS too hard for now.
- Top mass reconstruction could be a new frontier for parton showers with resonances, parton showers combined with analytic resummation, and jet cleaning techniques.



MIAPP

Munich Institute for
Astro- and Particle Physics

Programmes 2017

Astro-, Particle and Nuclear Physics of Dark Matter Direct Detection
6 – 31 March 2017
R. Catena, J. Conrad, C. Fórssen, A. Ibarra, F. Petricca

Superluminous Supernovae in the Next Decade
2 – 26 May 2017
J. Mould, F. Patat, J. Cooke, L. Wang, A. Heger

Protoplanetary Disks and Planet Formation and Evolution
29 May – 23 June 2017
W. Kley, B. Ercolano, L. Testi, C. Mordasini

In & Out. What rules the Galaxy Baryon Cycle?
26 June – 21 July 2017
P. Popesso, G. De Lucia, C. Peroux, M. Brusa, A. Saintonge

Automated, Resummed and Effective: Precision Computations for the LHC and Beyond
24 July – 18 August 2017
T. Becher, M. Beneke, R. Frederix, K. Melnikov, M. D. Schwartz

Mathematics and Physics of Scattering Amplitudes
21 August – 15 September 2017
S. Stieberger, L. Dixon, C. Duhr, L. Ferro

What is MIAPP?

The Munich Institute for Astro- and Particle Physics (MIAPP) hosts several programmes per year in astrophysics, cosmology, nuclear and particle physics. MIAPP serves as a center for scientific exchange and provides a stimulating platform for informal discussions, collaborations and creative thinking. More information: **www.munich-iapp.de**

Proposals for the programme 2018 can be submitted until 30 September 2016:
www.munich-iapp.de/proposals

Application for participation:
www.munich-iapp.de/registration

MIAPP Directors:
Prof. Dr. Martin Beneke (TU München),
Prof. Dr. Rolf Kudritzki (LMU / University of Hawaii)

www.munich-iapp.de - info@munich-iapp.de
Excellence Cluster „Origin and Structure of the Universe“ - MIAPP - Boltzmannstr 2 - 85748 Garching, Germany

Thank you for your attention

Automated, Resummed and Effective: Precision Computations for the LHC and Beyond
24 July – 18 August 2017
T. Becher, M. Beneke, R. Frederix, K. Melnikov, M. D. Schwartz

Registration deadline: 24 October 2016