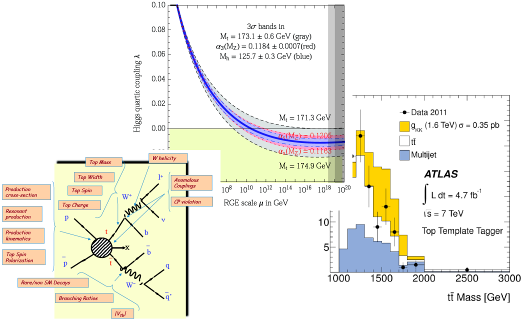
What do we know about the top quark?

[want to know/do not know/don't want to know/why]

M. Beneke (TU München)

"Precision theory for precise measurements at LHC and future colliders"
Quy-Nhon, Vietnam, September 29, 2016



Spin $\frac{1}{2}$

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

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

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

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

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$\sigma_{t\bar{t}} = 240\,\text{pb}$ at LHC (8 TeV)
[950 pb at 14 TeV]

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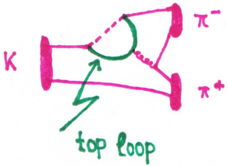
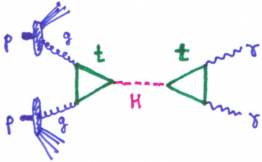
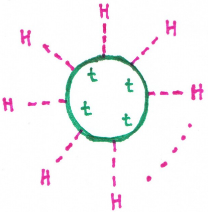
STRONG TOP-HIGGS INTERACTION related to top mass

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

Pre-eminence of top quantum fluctuations





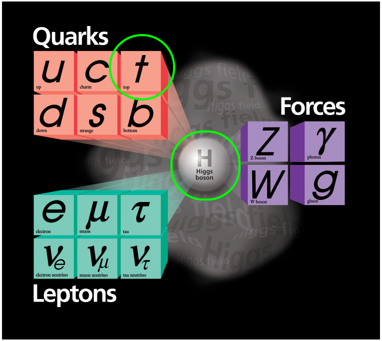


- Top crucial for flavour physics (FCNC), no CP violation without top
  Top flavour not important for collider physics, $V_{\mathrm{CKM}} \approx 1$ – in the SM!

- Electroweak precision observables
  Higgs production $pp \to H \to \gamma\gamma$

- Stability of the ground state (electroweak vacuum)

SM top quantum fluctuation background to indirect searches for New Physics



TOP is a special quark
owing to the Higgs
in the SM
and maybe beyond

Top 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.

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- Heavy New Physics (beyond LHC reach): Effective Theory

$$\mathcal{L} = \mathcal{L}_{\rm SM}(\psi_{\rm SM}) + \sum_{i,d>4} \frac{c_i}{\Lambda^{d-4}}\, \mathcal{O}_i(\psi_{\rm SM})$$

Linearly or non-linearly realized SM EW gauge symmetry.

- Light New Physics

$$\mathcal{L} = \mathcal{L}_{\rm SM}(\psi_{\rm SM}) + \mathcal{L}_{\rm BSM}(\psi_{\rm SM}, \psi_{\rm BSM})$$

Usually includes top partner fields.

Heavy top NP

- Break-up of mass-Yukawa relation

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

- But more generally

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

$\Rightarrow$ Top flavour physics: new flavour-changing interactions

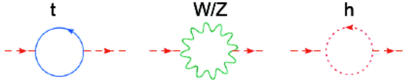
$\Rightarrow$ Quantum structure of the top: anomalous magnetic and electric dipole moments, top-gauge boson form factor modifications, ...

$\Rightarrow$ Indirect effects of anomalous couplings on lepton-flavour violation (Barr-Zee terms), neutron EDM, ...

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; Maltoni et al. 1607.05330; ...]

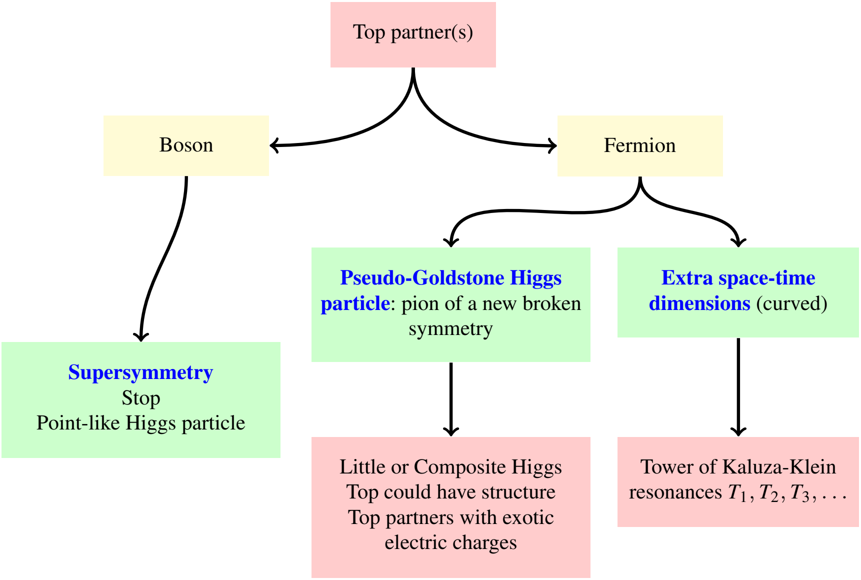
Light top NP: The Unbearable Lightness of the Higgs Boson

- Instability of Higgs mass with respect to quantum fluctuations.



$$(125\,\mathrm{GeV})^2 = m_{H0}^2 + \left[-(2\,\mathrm{TeV})^2 + (700\,\mathrm{GeV})^2 + (500\,\mathrm{GeV})^2\right]\left(\frac{\Lambda}{10\mathrm{TeV}}\right)^2$$

- Need to cancel the top quark contribution → light top partners. Partners of other quarks/leptons can be much heavier.

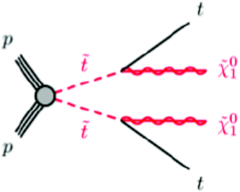

Top partner(s)
Boson
Fermion
Supersymmetry
Stop
Point-like Higgs particle
Pseudo-Goldstone Higgs particle: pion of a new broken symmetry
Extra space-time dimensions (curved)
Little or Composite Higgs
Top could have structure
Top partners with exotic electric charges
Tower of Kaluza-Klein resonances $T_1, T_2, T_3, \ldots$

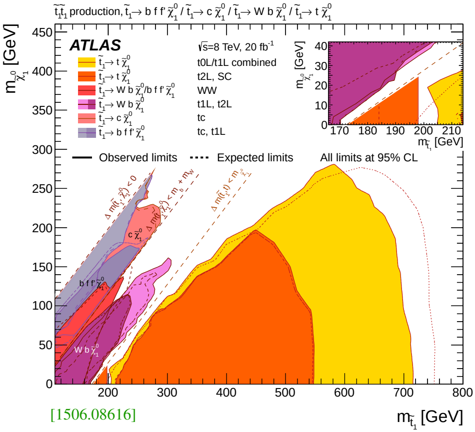
Top squarks (“Stop”)

- Supersymmetry $\Rightarrow$ equal no. of fermion and boson states.

$$t(\uparrow), t(\downarrow) \Leftrightarrow \tilde{t}_1, \tilde{t}_2$$

- $pp \to \tilde{t}_1\tilde{t}_1 \to ???$





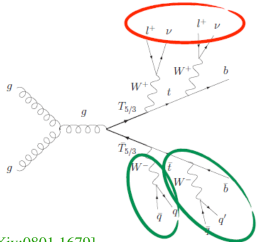
[1506.08616]

Quarks with exotic electric charge

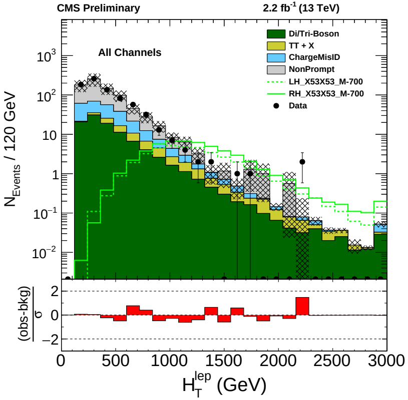
- Little Higgs/Composite Higgs
  Top partners in multiplets of the new global symmetry

- Massive quarks with unconventional electric charges possible

$$T = \begin{pmatrix} B \\ T \\ T'_{\frac{2}{3}} \\ T'_{\frac{5}{3}} \end{pmatrix}$$



[arXiv:0801.1679]



[CMS-PAS-B2G-15-006; preliminary 13 TeV result $m_{T_{5/3}} = 700$ GeV]

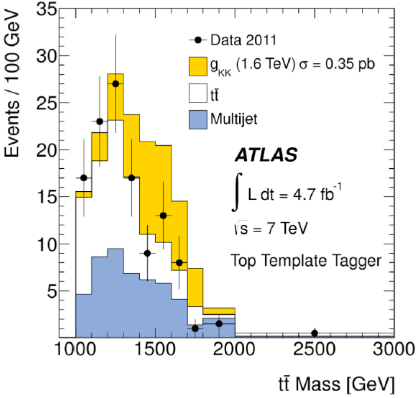
- Search for same sign di-leptons

Extra dimensions: Gluon Kaluza-Klein excitations decaying to top pairs

- KK resonances have stronger couplings to the heavier quarks
- $pp \to g_{\rm KK} \to t\bar{t}$
- (Smeared) peak in the $t\bar{t}$ mass distribution

$$M_{\rm KK} > 2.2\,\text{TeV}$$

[ATLAS 8 TeV data, 1505.07018]



Recap: top collider and precision physics motivations

- Top-Higgs connection – privileged role in understanding EWSB beyond the SM Higgs mechanism

- Precise mass required to compute SM quantum fluctuation background
  In general: precision constrains anomalous couplings.

- Background for new physics, template process for searches, involved in top partner searches

- A very special QCD parton

  - large mass, unstable parton
  - "bare quark", no hadronization, no bound states, spin correlations
  - challenges for parton showers (decayed top+non-resonant)
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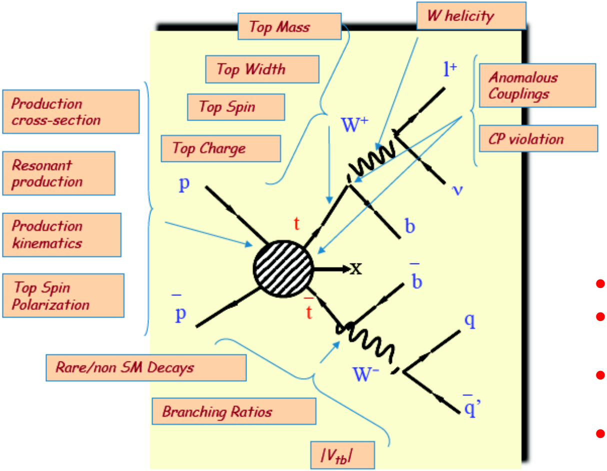
- Last but not least, George Mallory: "It is there."
  Historical note: his corpse was found only in 1999, 75 years after his legendary attempt on Everest, where he disappeared at an altitude of 8500m.



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

+ single top production

The top quark precision frontier

- Differential top decay – NNLO (2012/13)
  [Gao, Li, Zhu, 1210.2808; Brucherseifer, Caola, Melnikov, 1301.7133]
- Top pair inclusive XS – NNLO (2012/13)
  [Czakon, Mitov + Bärnreuther, Fiedler, 1204.5201, 1303.6254] + NNLL resummation matched to NNLO
- Top pair distributions – NNLO (2015/16)
  [Czakon, Fiedler, Heymes, Mitov, 1601.05375; Czakon, Heymes, Mitov, 1606.03350]
- Differential t-channel single-top – NNLO (2014/2016 ...)
  [Brucherseifer, Caola, Melnikov, 1404.7166 ("factorizable corrections"); Assadsolimani et al., 1409.3654 (some further pieces); Berger, Gao, Yuan, Zhu, 1606.08463 (factorizable corrections + decay in NWA)]
- e^+e^- top pair threshold – NNNLO (2015)
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- Pole-$\overline{\text{MS}}$ top mass relation – NNNNLO (2015)
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- $2 \to 3$ ($t\bar{t}H$, $t\bar{t}V$) – NLO (+NNLL)
  Decaying top/non-resonant, electroweak corrections – NLO

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Many aspects covered by subsequent talks. Can be complementary, brief and biased.

- $2 \to 3$ ($t\bar{t}H$, $t\bar{t}V$) – NLO (+NNLL)
  Decaying top/non-resonant, electroweak corrections – NLO

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Inclusive pair production XS – beyond NNLO

$\sigma^{\rm th}_{t\bar{t}}(m_t, \alpha_s, \text{PDF})$ – constrains any of these + anomalous couplings (colour-magnetic dipole moment)

$\sigma_{t\bar{t}}$[pb]	Tevatron	LHC ($\sqrt{s}$ =8 TeV)	LHC ($\sqrt{s}$ =13 TeV)
NLO	$6.68^{+0.36+0.23}_{-0.75-0.22}$	$226.2^{+27.8+9.2}_{-29.7-8.3}$	$747.1^{+90.4+26.1}_{-90.5-21.6}$
NNLO$_{\rm app}$	$7.06^{+0.26+0.29}_{-0.34-0.24}$	$230.0^{+16.7+9.7}_{-15.7-9.0}$	$753.2^{+64.1+26.8}_{-58.1-24.0}$
NNLO	$7.01^{+0.27+0.29}_{-0.37-0.24}$	$239.1^{+9.2+10.4}_{-14.8-9.6}$	$788.4^{+27.2+28.8}_{-43.9-25.8}$
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TOPIXS code [MB, Falgari, Klein, Piclum, Schwinn, Ubiali, Yan, 1206.2454]. $m_t = 173.3$ 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.

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NNNLO$_{\rm approx}$ estimates

	Tevatron	LHC (8 TeV)	LHC (13 TeV)
MB, Falgari, Klein, Schwinn, 1109.1536	+4.7%	+2.8%	+2.1%
Kidonakis, 1405.7046	+5.1%	+3.6%	+2.7%
Muselli et al., 1505.02006 [wo large-x]	—	+2.8%	+2.3%
[with large-x]	—	+4.5%	+4.3%

Top mass from inclusive XS

- Rule of thumb

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

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

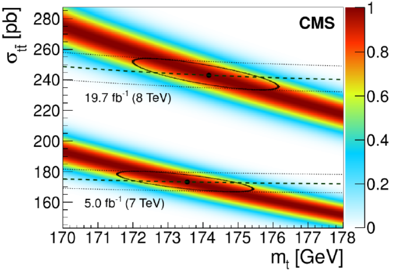
- CMS has 4% exp uncertainty, 5.5% th error (apparently including PDF uncertainty).

  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.

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



[CMS $e\mu$ channel, 1603.02303]

Divergence in fixed-order calculations?

- Note: fixed order total cross section seems ill-defined from N^4LO 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^3LO, but there happens to be no α_s^3/β^3 term at this order.

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- Already at N^{3}LO there is an extra term, which would be missed in a standard virtual+real computation. [MB, Ruiz-Femenia, 1606.02434]

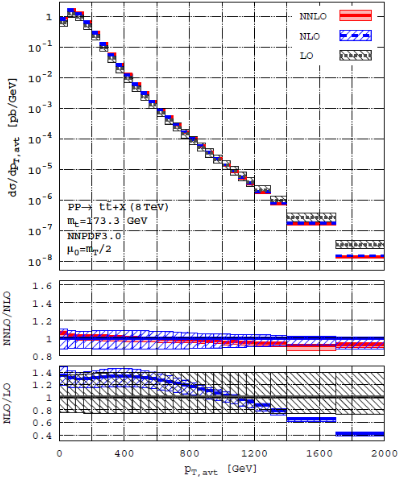
$$\sigma^{\rm N3LO}_{N_1N_2\to t\bar{t}X}(s) = \frac{\pi^2\zeta_3\alpha_s^5}{s} \sum_{pp'=q\bar{q},gg} \sum_{R_\alpha=1,8} (-D_{R_\alpha})^3 \sigma^{R_\alpha}_{pp'} L_{pp'}(4m_t^2/s,\mu_f)$$
$$+ \sum_{p,p'=q,\bar{q},g} \int_{(2m_t+\varepsilon)^2/s}^1 d\tau \, L_{pp'}(\tau,\mu_f) \, \hat{\sigma}^{\rm N3LO}_{pp'}(s\tau,\mu_f)$$

- Additional NNNLO contribution numerically negligible (small octet colour factor).

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

NNLL resummation, boosted

- NNLO distributions set the new state-of-the-art [Czakon, Fiedler, Heymes, Mitov, 2016]
  What next?



[Czakon, Heymes, Mitov, 1606.03350]

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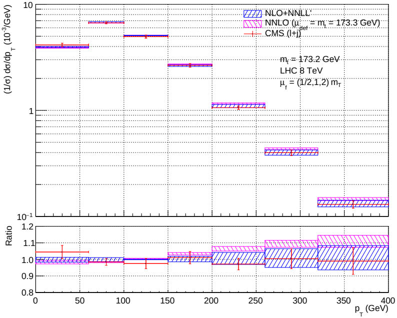
  What next?

- 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]

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

NNLL, not matched to NNLO



[Pecjak et al., 1601.7020]

- NNLL + matched to NNLO for large p_t, $M_{t\bar{t}}$ could be future state-of-the-art.
- Include EW corrections (resummed?)

$$\alpha_{\mathrm{EW}} \ln^2 p_t/m_t$$

Top mass (relations)

Pole mass physically suggestive for "bare quark", but still undefined by an amount $\mathcal{O}(\Lambda_{\rm QCD})$. $\overline{\rm MS}$ good book-keeping parameter, more suitable for high-scale evolution.

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

Know

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

$$m_P = 163.643 + 7.557 + 1.617 + 0.501 + 0.195\,\text{GeV} \quad (\mu = \mu_m = m(\mu))$$

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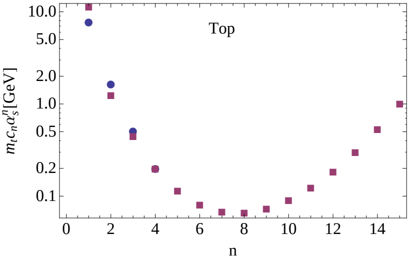
- All orders at order n with accuracy $\mathcal{O}(1/n^3, 1/2^n)$ [MB, 1994]

$$c_{n+1}(\mu,\mu_m,m(\mu_m)) \underset{n\to\infty}{\longrightarrow} N\,\frac{\mu}{m(\mu_m)}\,(2b_0)^n\,\frac{\Gamma(n+1+b)}{\Gamma(1+b)}\left(1+\frac{s_1}{n+b}+\frac{s_2}{(n+b)(n+b-1)}+\cdots\right)$$

up to normalization N.
Unique situation in 4d renormalizable QFT.

All-order relation

Determine N from $n = 4$ with few percent accuracy and predict the entire (factorially divergent) series and its "ambiguity".
[MB, Marquard, Nason, Steinhauser, 1605.03609]



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

Given the $\overline{\text{MS}}$ mass, the top quark pole mass is determined with an accuracy of 0.92 per mil.
Ultimate intrinsic uncertainty of the top pole mass is about 70 MeV.
Somewhat smaller than believed before. Certainly much less than 1 GeV.

Top mass from mass reconstruction and kinematics

Combination dominated by lepton+jet channel

ATLAS	$m_t = 172.84 \pm 0.34 \pm 0.61\,\text{GeV}$
CMS	$m_t = 172.44 \pm 0.13 \pm 0.47\,\text{GeV}$
	(b-JES, colour-rec, UE, scale-dep)
CDF	$m_t = 172.85 \pm 0.52 \pm 0.99\,\text{GeV}$
D0	$m_t = 174.98 \pm 0.41 \pm 0.63\,\text{GeV}$
	Tevatron com. $174.30 \pm 0.37 \pm 0.54\,\text{GeV}$

Few permille accuracy.
Should one worry about D0?
Which mass?

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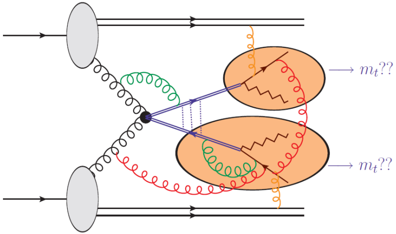
Looks like a highway race where the casuality is usually an uninvolved third-party. — Here the casuality is theory.

Which mass?

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



[from A. Signer, Top Quark Physics]

Some remarks

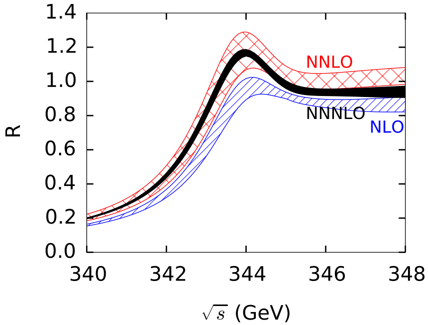
- Issue is not the renormalon ambiguity (see above) – if anything slow convergence of perturbative corrections in the pole scheme.
- *Perturbative* corrections to extracted mass $\mathcal{O}(1\,\text{GeV})$ not necessarily related to mass definition.
- Intrinsic *non-perturbative* $\mathcal{O}(\Lambda_{\text{QCD}})$ uncertainty remains independent of the mass definition. Reduce numerically with jet cleaning methods? Go boosted?

- Learn from e^+e^-. — *Perturbative* factorization theorem for $d\sigma/dM_t^2 dM_{\bar{t}}^2$ (central jets) [Fleming, Hoang, Mantry, Stewart, 0711.2079]
  Comparison to MC [Butenschoen et al. 1608.01318]

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

NNNLO + summation in (PNR)QCD
[MB, Kiyo, Marquard, Penin, Piclum, Steinhauser, 1506.06864]
Photon exchange and Z-vector coupling only.
$m_{t,\mathrm{PS}}(20\,\mathrm{GeV}) = 171.5\,\mathrm{GeV}, \Gamma_t = 1.33\,\mathrm{GeV},$
$\alpha_s(m_Z) = 0.1185 \pm 0.006, \sin^2\theta_W = 0.2229,$
$\mu = (50\ldots80\ldots350)\,\mathrm{GeV}, \mu_w = 350\,\mathrm{GeV}.$

Match $[\delta m_t]_{\mathrm{exp}} \approx 30\,\mathrm{MeV}$???



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]

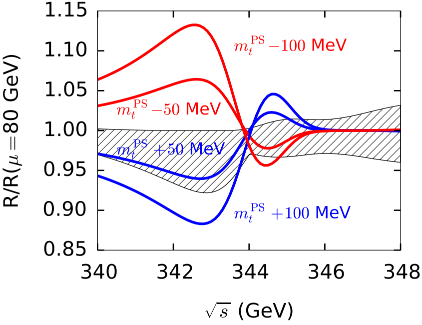
Including Higgs, QED and non-resonant process $W^+W^-b\bar{b}$ ("single-top") [MB, Jantzen, Ruiz-Femenia, 1004.2188, MB, Maier, Piclum, Rauh, 1506.06865]
Electroweak corrections and code release [MB, Kiyo Maier, Piclum, 1605.03010]

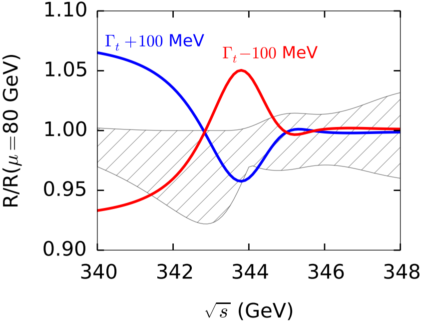
Position shift: 310 MeV (LO to NLO) 150 MeV (to NNLO) 64 MeV (to NNNLO)
Improvement of factor 3 in uncertainty in peak height.

Sensitivity to m_t vs. theoretical uncertainty

NNNLO $$\frac{\delta\sigma}{\sigma} = \pm\,(2\ldots 3.5)\%$$

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

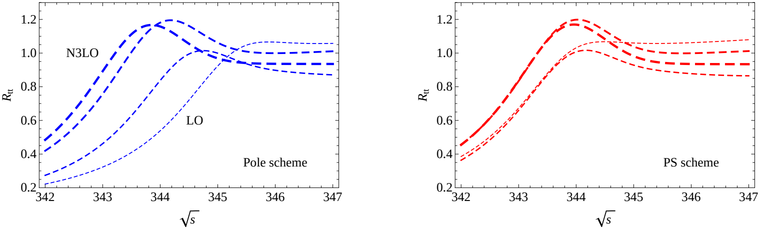




[MB, Kiyo, Marquard, Penin, Piclum, Steinhauser, 1506.06864]

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 ($\rightarrow$ 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 $\approx 20\,\text{MeV}$.

Unstable top

Top width $\approx$ 1.4 GeV $\gg \Lambda_{\mathrm{QCD}}$.
No asymptotic states. Parton $\neq$ jet (+soft), unless $Q \gg m_t$.

$$pp \to t\bar{t} + X \quad \Longrightarrow \quad pp \to W^+W^-b\bar{b} + X$$

Not a problem of principle

- Complex mass scheme – generic method
- Unstable particle effective field theory – for merging with resummations [e.g. $e^+e^- \to W^+W^-b\bar{b} + X$ in case of $t\bar{t}$ threshold]

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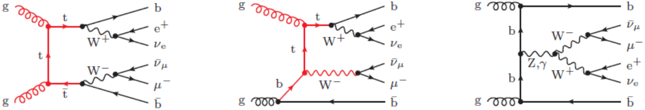
But a big increase in complexity

- Higher multiplicity with no coupling suppression
- Intrinsically multi-scale problem $\Gamma \ll m, Q$
- Matrix element with sharp peaks
- Parton shower must be modified. Usually $E_J Q_0 \gg m_t \Gamma_t$
- Change of thinking about a process: top final state $\to$ "top cuts" on a physical final state

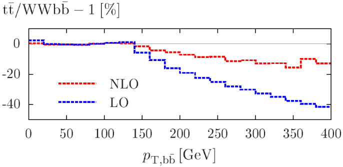
Time is ripe for precision top physics to address these issues.
A lot of progress recently.



Not $t\bar{t}$, not single top, but $pp \to W^+W^-b\bar{b}$

- NLO QCD to $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ [Denner et al., 2011; Bevilacqua et al. 2011]
  NLO EW to $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b}$ [Denner, Pellen; 2016]
  NLO QCD to $pp \to e^+\nu_e\mu^-\bar{\nu}_\mu b\bar{b} + \text{jet}$ [Bevilacqua, Hartanto, Kraus, Worek, 2016]

Large EW corrections in distributions at large p_t.
Large non-resonant in certainn tails

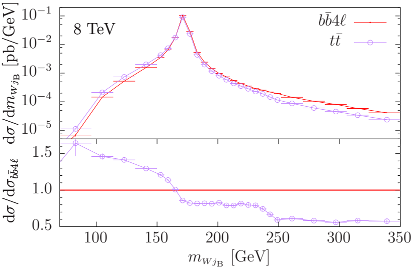


[from 1208.4053]

- NLO matched to parton showers with special treatment of an intermediate resonance

  Within the POWHEG framework [Jezo, Nason, 1509.09071; Jezo, Lindert, Nason, Oleari, Pozzorini, 1607.04538: single top and top pair]

  Within MG5_aMC@NLO [Frederix, Frixione, Papanastasiou, Prestel, Torielli, 1603.01178: single top]



[from 1607.4538]

Asymmetric distortion → shift in mass determination (≈ 0.5 GeV).

Can now discuss top mass schemes as in any other NLO computation. No MC mass.

Summary

Explosion of Top Physics Results (EXP+Th) since LHC turn-on – sheer numbers make a difference

- Many new observables accessible.
- Top precision calculations at the frontier of applied Quantum Field Theory
- Top is a very special parton for collider physics and the most important quark for EW physics
- Top physics – together with Higgs the most plausible gateway to “New Physics”

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- NNLO QCD the new standard. NNLO+NNLL desirable.
  NNNLO too hard for now, even total XS.
- Time for a paradigm change: physical final states, non-resonant/off-shell effects, also in parton showers.
- Top mass reconstruction could be a new frontier for parton showers with resonances, parton showers combined with analytic resummation, and jet cleaning techniques.
- Run II directs attention to boosted regime.