Top-ology

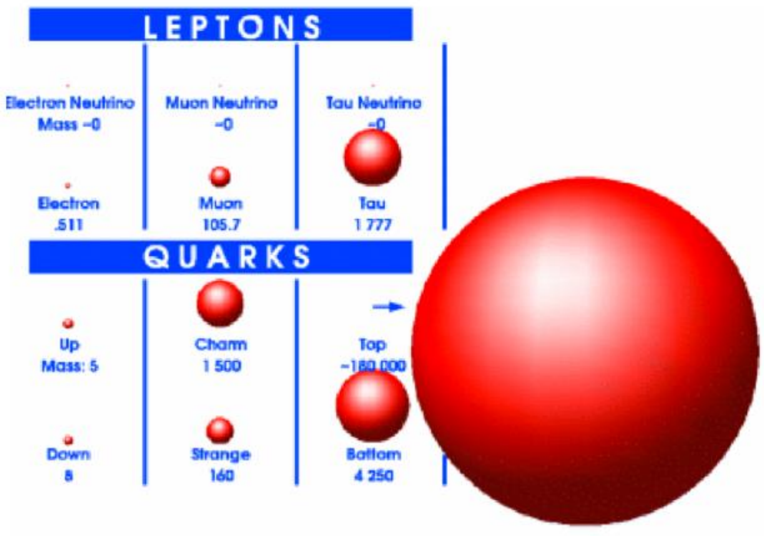
VALERY KHOZE

The main aim is to discuss the salient features of the top quark and the importance and prospects of the precise measurements of its unique properties.

The Brief Happy Life of the Top Quark

Гатчина,
21.04.2022

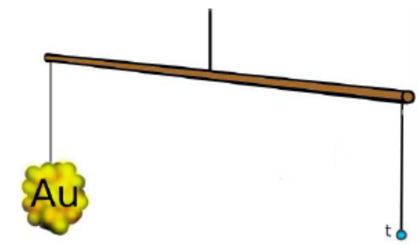
1. TOP AND SM



- Top as calibration tool for new physics particles (SUSY and other exotics)
- Top production major background it new physics searches
- One of crucial motivations for New Physics

Basic facts about the top quark

Large mass $m_t \approx 173$ GeV



Strong Yukawa coupling $\zeta t \sim 1$ $t\bar{t}H$

$$v/\sqrt{2} = (2G_F\sqrt{2})^{-1/2} \approx 176 \text{ GeV} \qquad m_f = \zeta_f \frac{v}{\sqrt{2}},$$

Short lifetime $\tau \sim 5 \times 10^{-25}$ s

$I(J^P) = 0(\frac{1}{2}+)$ Charge $= \frac{2}{3}\, e$

- Top mass-an important ingredient for EW precision analyses.
- Stability of the Universe. Andreassen, Frost, Schwartz 2017

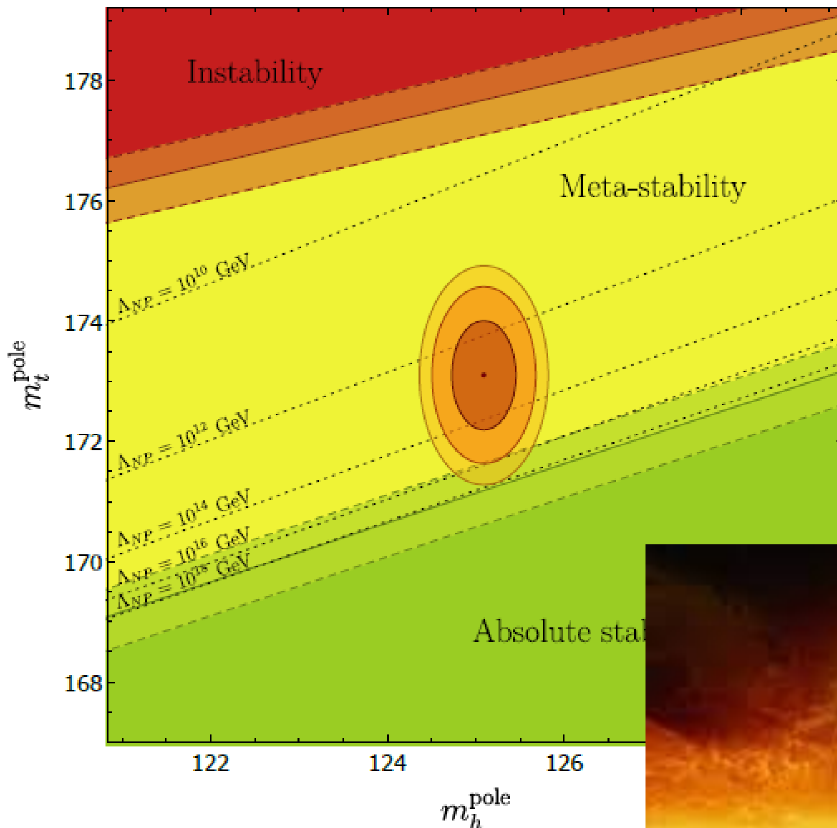
Scale-invariant Instantons and the Complete Lifetime of the Standard Model

Anders Andreassen*, William Frost†, and Matthew D. Schwartz‡

The vacuum need … shifts as, for examp …

… onally undergo dramatic … configuration with lower

The fate of our universe



div … div … cor … cou … res … me … effe … mi … der

… rates are infrared … one expects such … ar how higher-loop … ith a careful power … over the one-loop … y incomplete treat- … ing and finite mass … e functional deter- … e-invariant bounce.

of … tha … ma … Usi …

planes, with uncertainty bands. To rule out abs … uncertainty on the top quark pole mass would h … the uncertainty on $\alpha_s(m_Z)$ pushed below 0.00025

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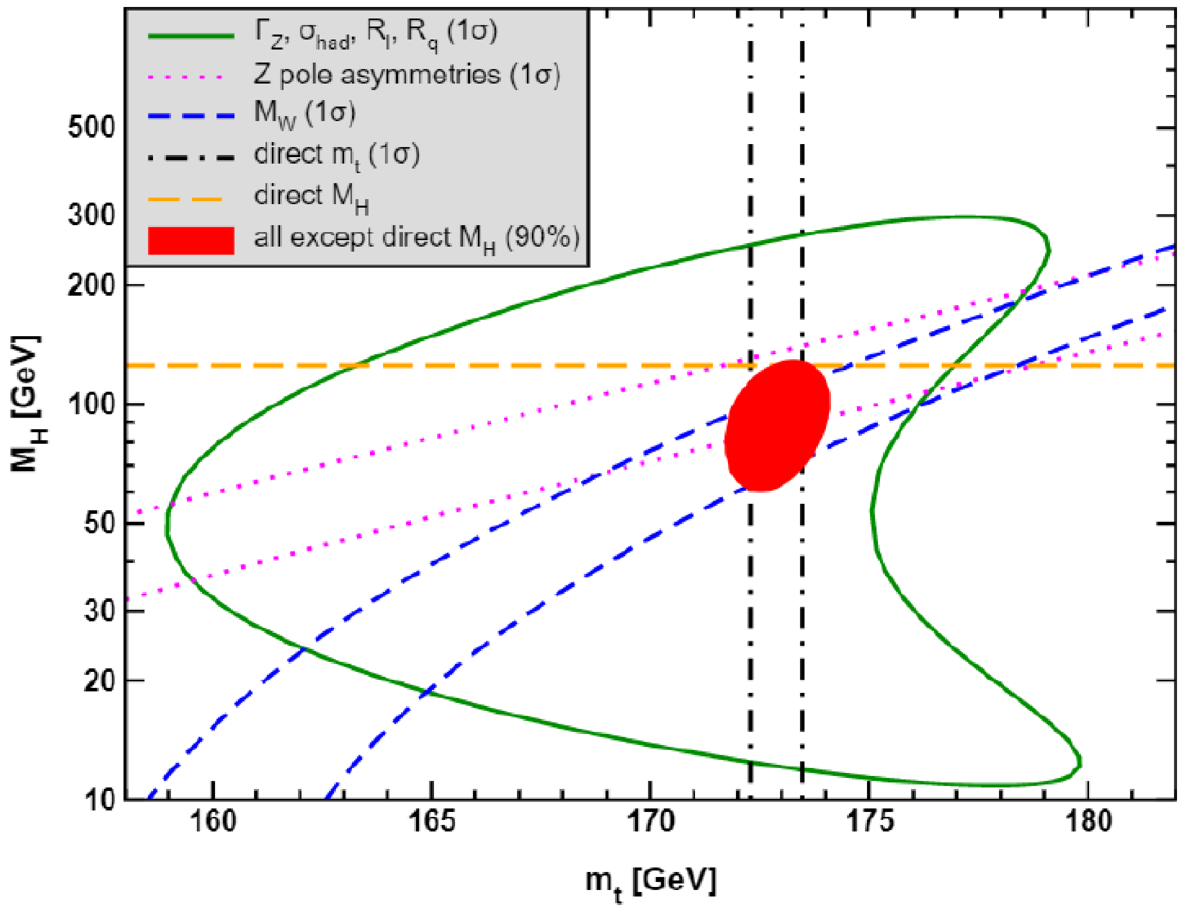
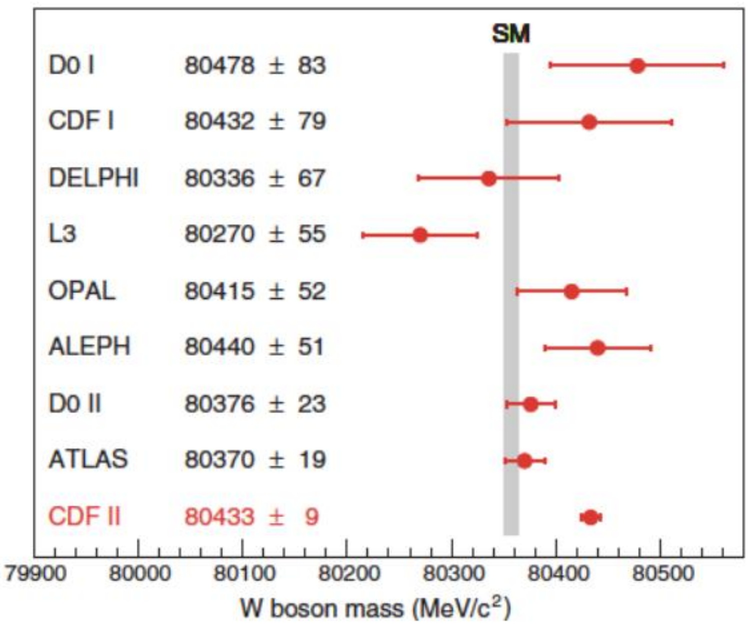
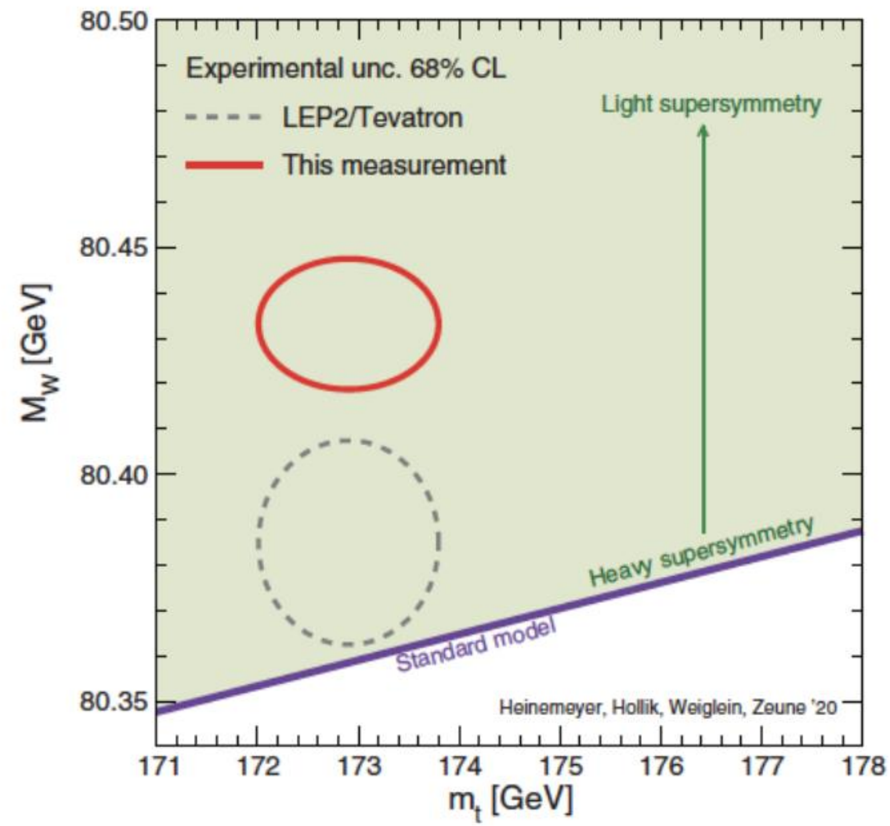


Figure 10.4: Fit result and one-standard-deviation (39.35% for the closed contours and 68% for the others) uncertainties in M_H as a function of m_t for various inputs, and the 90% CL region ($\Delta\chi^2 = 4.605$) allowed by all data. $\alpha_s(M_Z) = 0.1185$ is assumed except for the fits including the Z lineshape. The width of the horizontal dashed band is not visible on the scale of the plot.

new MW from CDF

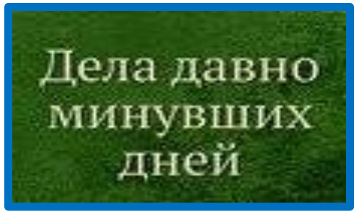




CERN-EP Seminar TODAY on Thursday 21 April at 16h30

2. ECHO FROM THE PAST

(10 years before top discovery)



Early- eighties (DTK)

How to illustrate LPHD (Yuri's talk at this seminar) Freedom from hadronization enslavement- idea of ultra-heavy quark Q with mass heavier than W.

Free coloured parton under the complete jurisdiction of PT QCD!

- Last days of a short visit to CERN -1985 (PZ)

I.Bigi, Yu.L. Dokshitzer, VAK , J. H.Kuhn and P. M. Zerwas,
Production and Decay Properties of Ultra-heavy Quarks
(PL **B181** (1986), 157-163)

Asymptotically

$$\Gamma(Q \to q + W) \simeq 180\,\mathrm{MeV} \times |V(Qq)|^2 (m_Q/m_W)^3$$

and the lifetime drops below 10^{-23} s.

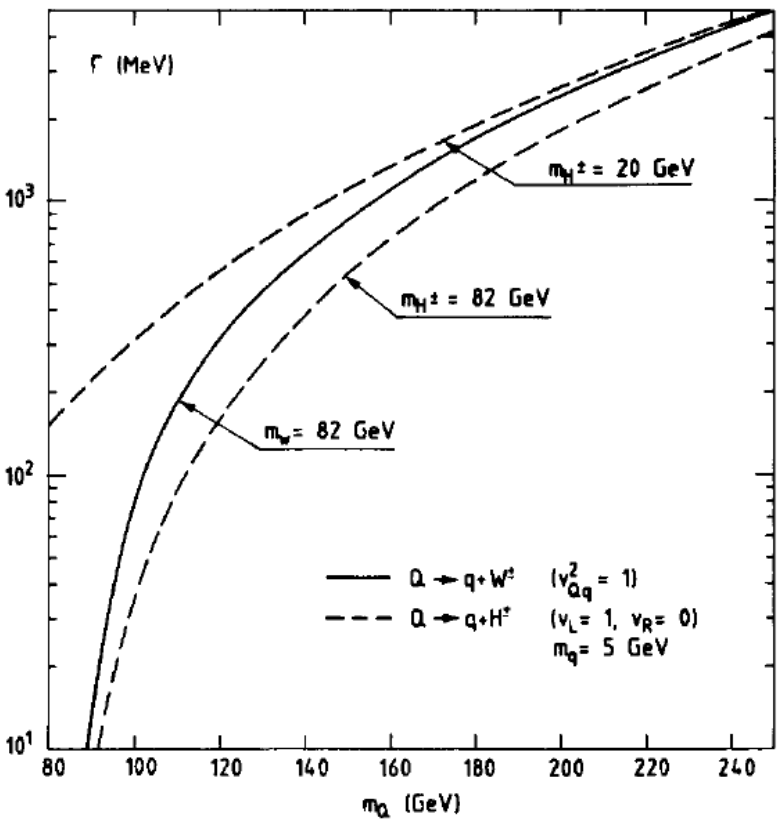
For Q an up-type quark

we expected $|V(Qq)|$ to be close to unity

Q≡t,q≡b

$$\tau_Q < t_{\mathrm{Had}} \sim \Lambda_{\mathrm{QCD}}^{-1} \sim 10^{-23}\ \mathrm{sec.}$$

$$\Gamma_t \sim \frac{G_F}{\sqrt{2}} \frac{m_t^3}{8\pi} = (180\ \mathrm{MeV}) \left[\frac{m_t}{m_W}\right]^3$$



10 years prior to the top quark experimental discovery

Volume 181, number 1,2 PHYSICS LETTERS B 27 November 1986

PDG

PRODUCTION AND DECAY PROPERTIES OF ULTRA-HEAVY QUARKS ☆

I. BIGI [1]
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Leningrad Nuclear Physics Institute, Leningrad, USSR

J. KÜHN
Max-Planck-Institut für Physik, D-8000 Munich, Fed. Rep. Germany

and

P. ZERWAS
CERN, CH-1211 Geneva 23, Switzerland

RAPALLO PAPER

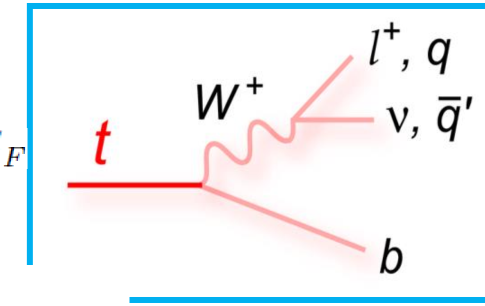
Received 8 September 1986

The widths of ultra-heavy quarks that can decay into W, Z or Higgs bosons are discussed. If the lifetimes become much shorter than the typical strong interaction time scale $\Lambda_{QCD}^{-1} \sim 10^{-23}$ s, then open-flavor hadrons and quarkonium bound states cannot be formed any more. Consequences for the jet evolution are investigated. On the other hand, if such quarks can decay only through tiny mixing angles – as it could happen for sequential down-type quarks and for SU(2) singlet quarks in E_6 models – then these bound states do form. Production rates for quarkonia in e^+e^- annihilation and in hadronic collisions are estimated and their decay signatures are discussed.

semi-weak decay

$$\Gamma(t \to bW^+) = \frac{G_F M_W^2}{8\pi\sqrt{2}} \frac{|V_{tb}|^2}{m_t^3} \left[\frac{(m_t^2 - m_b^2)^2}{M_W^2} + m_t^2 + m_b^2 - 2M_W^2 \right] \times \sqrt{[m_t^2 - (M_W + m_b)^2][m_t^2 - (M_W - m_b)^2]}.$$

G_F



$$\Gamma(t \to bW^+) \approx 1.55 \text{ GeV}$$

1.4 GeV (QCD and EW corr.)

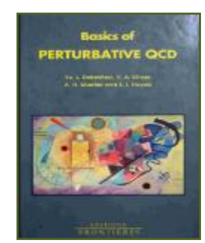
which corresponds to a top lifetime $\tau_t \approx 0.4 \times 10^{-24}$ s, or 0.4 yoctosecond.

The confining effects of the strong interaction act on a time scale of a few yoctoseconds set by 1/the scale energy of quantum chromodynamics, Λ_{QCD}.

Lessons from BDKKZ (Rapallo) paper

- A top quark decays long before it can be hadronized. No dressed hadronic states containing top (t-flavoured hadrons). (also J.Kuhn)
- Original spin orientation is preserved, spin correlations. The primary quark polarization in $e^+e^- \to \gamma, Z^0 \to Q\bar{Q}$ can manifest itself e.g. via parity violation in the FS distributions .
- The characteristics of top production and of accompanying hadrons could be calculable in PT QCD

(Some nice QCD results - **lost in translation** in BDKKZ-paper)



\+ Series of ADTK works

- no discrete lines in toponium ($t\bar{t}$) spectroscopy, Threshold scan –bread and butter of future e^+e^- colliders.
- Limits on the existence of a light charged Higgs: $t \to H^+ b$ decay

- The binding force in a heavy quarkonium state is essentially Coulombic. The revolution time of the $(Q\overline{Q})$ bound state is then estimated as $t_R \sim$ (1/Rydberg energy)= $9/(4m_Q\alpha_s^2)$. If the lifetime of the $(Q\overline{Q})$ system becomes shorter than the revolution time t_R, then the quarkonium bound state cannot be formed any more.

  Setting $\alpha_s = 0.15$ to illustrate the point one finds this to happen for $m_Q \gtrsim 125$ GeV

- As Q-mass is raised from 100 to 200 GeV, the bound-state resonances lose their separate identify and smear together into a broad threshold enhancement.

  variation of the threshold cross section with energy becomes a quantitative prediction of QCD, largely independent of nonperturbative phenomenological considerations, such as the choice of the quark-antiquark potential.

- The interquark potential is given essentially by the short distance Coulombic part. The excitation curve is built up primarily by the superposition of the nS states. .

Prior to the top discovery

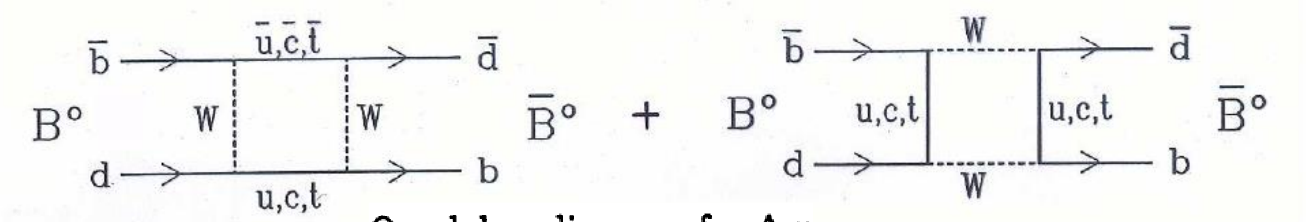
By 1987 –general belief was that top is lighter than 60 GeV (TRISTAN "failure")

- m_t >41GeV (UA1 –isolated lepton +jets) $S\bar{p}pS$
- m_t ≤ 200 GeV (EW phenomena)
- The discovery of $B\overline{B}$ mixing (ARGUS@DORIS 1987)

$< B^0 >$ and $< \overline{B^0} >$ are not mass eigenstates

$e^+e^- \to \Upsilon(4S) \to B^0\bar{B}^0$, $B^0 \to \ell^+ X$ $\overline{B^0} \to \ell^- \overline{X}$

The observation of like-sign leptons from B-meson decays-evidence for $B\overline{B}$ mixing



Quark box diagrams for Δm

Within SM the mixing parameter is proportional to the fourth power of top mass. Immediately a series of theory papers, first establishing the low limit m_t >60GeV

N. Uraltsev, VAK "PHYSICAL CONSEQUENCES OF THE LARGE B0 anti-B0 MIXING,'' LENINGRAD-87-1290, Yad. Fiz. 1988

M. Vysotsky

m_t ~100-150 GeV (with some reasonable assumptions)

THRESHOLD PRODUCTION OF HEAVY TOP QUARKS

(V.S.Fadin, VAK, 1987)

- the threshold cross section for $e^+e^- \to t\bar{t}$ to leading-logarithmic order in QCD,

in non-relativistic approximation.

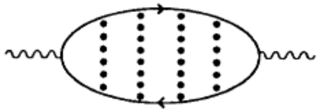
To LO in QED via the optical theorem the total cross section for top pair production is

$$\sigma(e^+e^- \to t\bar{t}) = \frac{4\pi\alpha_{\rm QED}}{s}[-{\rm Im}\Pi_t(q^2)]$$

where $\Pi_t(q^2)$ is the top-quark contribution to the photon vacuum polarization.

Near threshold in the non-relativistic approximation the leading contribution to $\Pi_t(q^2)$ is given by the sum of ladder diagrams with exchange of any number of Coulomb uncrossed gluons

Taking the constant Γ_t in the fermion propagators in the coordinate space we arrived at the Schrödinger equation



$$[H-(E+i\Gamma_t)]G(\mathbf{r},E+i\Gamma_t)=\delta^{(3)}(\mathbf{r}) \qquad E=\sqrt{s}-2m_t$$

$G(\mathbf{r},E)$ is the standard Green's function $G(\mathbf{r},\mathbf{r}';E)$, evaluated at $\mathbf{r}'=0$.

$$\Pi_t(E) = -\frac{2}{3}\frac{e^2}{m_t^2}G(\mathbf{r}=0,\mathbf{r}'=0,E+i\Gamma_t).$$

One-photon contribution to the total cross section for $t\bar{t}$ production

$$\sigma(e^+e^-\to t\bar{t}) = \frac{8\pi^2\alpha_{\rm QED}^2}{3m_t^4}\,{\rm Im}\,G(0,0;E+i\Gamma_t)\ .$$

the effect of the top-quark width is to cause the Schrödinger Green's function to be evaluated off the real axis (N. Nikolaev)

Using the well known expression for the explicit form of G (0,0) for fixed α_s (M.Braun-1968) we arrived at explicit analytic result

$$\Im G_{E+i\Gamma_t}(0,0) = \frac{m_t^2}{4\pi}\left[\frac{p_2}{m_t} + \frac{2p_0}{m_t}\arctan\frac{p_2}{p_1} + \right.$$
$$\left. + \sum_{n=1}^{\infty}\frac{2p_0^2}{m_t^2 n^4}\,\frac{\Gamma_t p_0 n + p_2(n^2\sqrt{E^2+\Gamma_t^2} + p_0^2/m_t)}{(E + p_0^2/(m_t n^2))^2 + \Gamma_t^2}\right]$$

$$p_0 = \frac{2}{3}m_t\alpha_S$$

inverse Bohr radius

$$p_{1,2} = \left[\frac{m_t}{2}\left(\sqrt{E^2+\Gamma_t^2} \mp E\right)\right]^{1/2}$$

The sum corresponds to the contribution from an infinite set of bound states, at energies $E_n = -p_0^2/(m_t n^2) = -4m_t\alpha_S^2/(9n^2)$

The first term-Born result, modified by the width effects.
The second-one loop correction.

THRESHOLD FACTOR

(A.Sommerfeld-1931)

Analogously to QED (A.D. Sakharov-1948-Coulombic effects in lepton pair production)
QCD Coulomb effects in the CS channel leads to a sharp rise of the total x-section

At narrow width the standard threshold factor $\beta_t = \sqrt{1 - \frac{4m_t^2}{\hat{s}}}$ ➡ $\beta_t |\Psi^{(s)}(0)|^2$

$$|\Psi^{(s)}(0)|^2 = \frac{X_{(s)}}{1 - \exp(-X_{(s)})}, \quad X_{(s)} = \frac{4}{3}\frac{\pi\alpha_S}{\beta_t}.$$

At $\beta_t \to 0$, $\beta_t |\Psi^{(s)}(0)|^2 \to \frac{4}{3}\pi\alpha_S$

For the octet channel (important in pp collisions) due to Coulombic repulsion, decrease at $\beta_t \to 0$,

$$|\Psi^{(8)}(0)|^2 = \frac{X_{(8)}}{\exp(X_{(8)}) - 1}, \quad X_{(8)} = \frac{1}{6}\frac{\pi\alpha_S}{\beta_t}.$$

$\alpha_s / \beta_t \gtrsim 1$,

Detailed studies of $t\bar{t}$ threshold behaviour in pp collisions V.Fadin, T.Sjostrand, VAK-1990

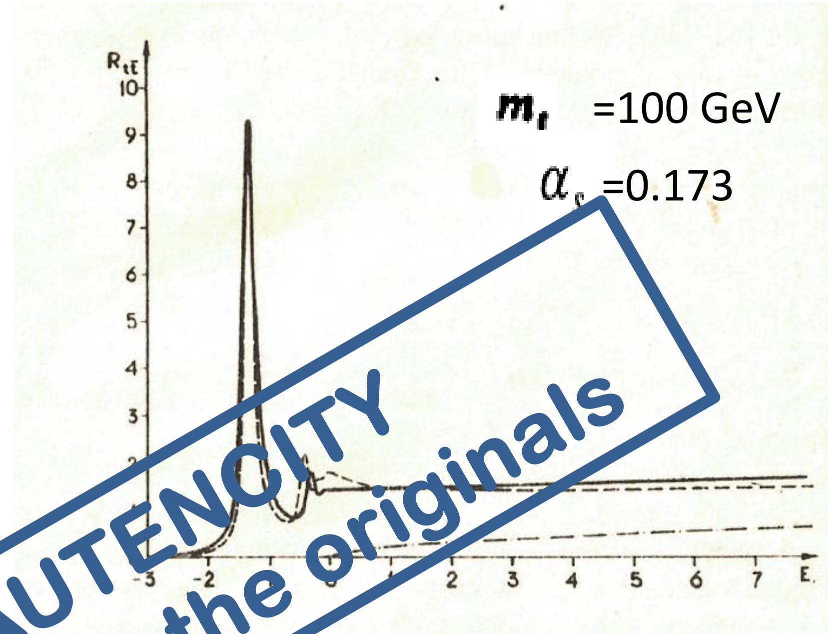
FK-1987-88 papers fully accounted also for modifications due to the QED effects caused by initial electrons:
Sudakov-like decrease of maxima, radiative tail etc

For illustration 'running' α_s at

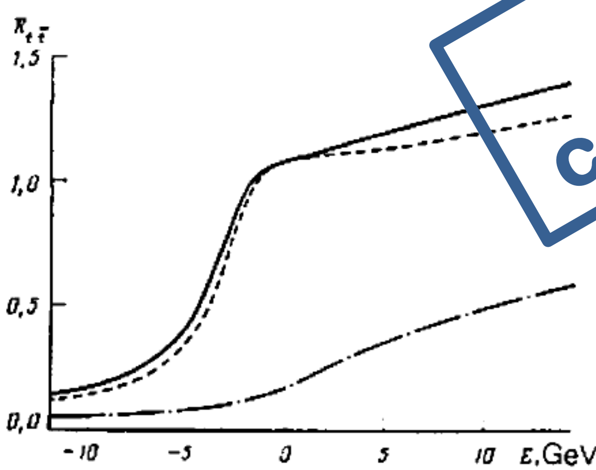
$\vec{q}_t^{\,2} \simeq m_t\sqrt{E^2+\Gamma_t^2}$ (dashed curves)

$$\alpha_s = 4\pi\left[7.67\,\ln(m_t\sqrt{E^2+\Gamma_t^2})/\Lambda^2\right]^{-1}.$$

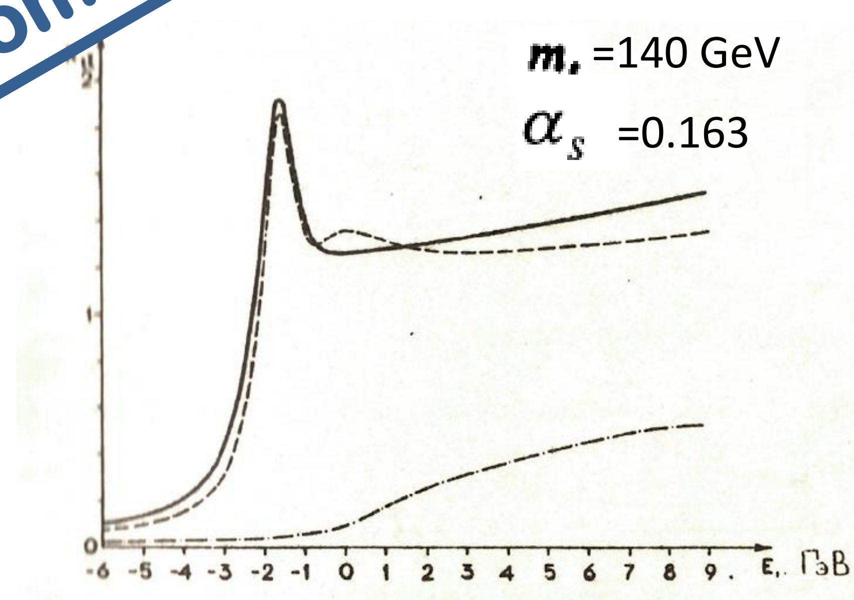
(dash-dotted curves: no QCD interactions)



FOR AUTENCITY
copies from the originals



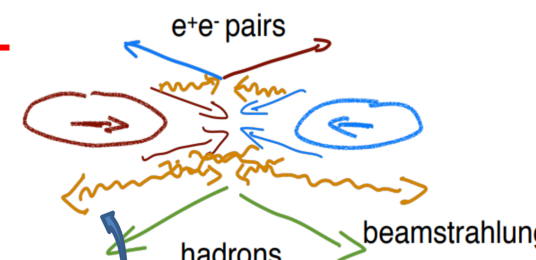
m_t = 200 GeV and α_s = 0.150



$E = \sqrt{s} - 2m_t$

M. Strassler and M.Peskin (PRD- 1991)

In this paper, following the ideas of Fadin and Khoze, we study in detail the shape of the $t\bar{t}$ threshold, which is strongly dependent on the value of the t-quark mass and which exhibits a complex, intricate structure. In carrying out our analysis, we make two improvements in the physics of their calculation which have an important qualitative effect. Since the quark-antiquark potential is close to a Coulomb potential at the short distances relevant for $t\bar{t}$ binding, Fadin and Khoze in their analysis used the exact solution of the nonrelativistic Coulomb problem. This made it awkward for them to take proper account of the running of the QCD coupling. We will introduce a simple numerical technique which can straightforwardly treat an arbitrary quark-antiquark potential and is thus well suited to including effects of asymptotic freedom. This technique also allows us to include the effect of Higgs-boson exchange on the quark-antiquark potential.



Has led to a burst of activity: papers accounted for HO QCD and EW effects, bremsstrahlung, beamstrahlung (LC), beam energy spread….

>100

crossing bunches interact with force field created by the other bunch

DOES TOP MASS FS RECONSTRUCTION SURVIVE QCD INTERCONNECTION ?

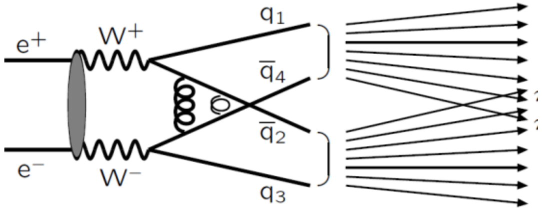
(T.Sjostrand, VAK -1994- 1999)

First studies in the context of W-boson mass measurements at LEP 2.
Plans/hopes to reconstruct m_W via hadronic W-decays (W-CS-object !)

$\Gamma_W, \Gamma_Z, \Gamma_t \approx 2$ GeV

Not too far from threshold:

$$\tau = \frac{1}{\Gamma} \approx \frac{0.2 \text{ GeV fm}}{2 \text{ GeV}} = 0.1 \text{ fm} \ll r_{had} \approx 1 \text{ fm}$$



$1/N_C^2$ effects,

⇒ hadronic decay systems overlap, between pairs of resonances (WW, ZZ, $t\bar{t}$, . . .)
⇒ cannot be considered separate systems!

1. Perturbative: $\langle \delta m_W \rangle \lesssim 5$ MeV.
2. Colour rearrangement: many models conservatively $\langle \delta m_W \rangle \lesssim 40$ MeV. **(SK I, SK II)-models**
3. Bose-Einstein: conservatively $\langle \delta m_W \rangle \lesssim 40$ MeV.

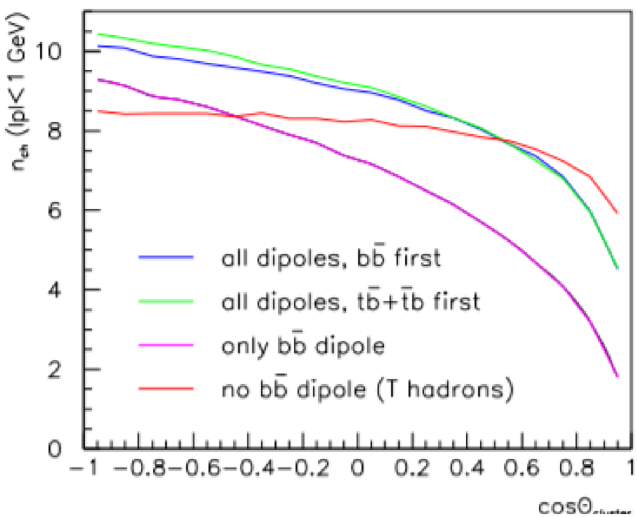
In sum: $\langle \delta m_W \rangle_{tot} < m_\pi$, $\langle \delta m_W \rangle_{tot}/m_W \lesssim 0.1\%$; a small number that becomes of interest only because we aim for high accuracy. Strong (MC) model dependence

Top events close to threshold

$t\bar{t}$ systems are colour connected: even
$e^+e^- \to t\bar{t} \to bW^+\bar{b}W^- \to b\bar{b}\ell^+\nu_\ell \ell'^- \bar{\nu}'_\ell$
contains nontrivial interconnection effects!

(the simplest example)

Hadronic multiplicity as function of $\theta_{b\bar{b}}$:



$m_t = 174$ GeV

$E_{cm} = 360$ GeV

$\Delta E = 12$ GeV

$= E_{cm} - 2m_t$

Some hadrons originate from the joint action of both t-quarks)
(collectivization)

υ_t

$$\mathcal{I} = \mathcal{I}_{\text{indep}} + \mathcal{I}_{\text{dec-dec}} + \mathcal{I}_{\text{prod-dec}}$$

$$\mathcal{I} \propto \frac{\omega^2}{\Gamma_t^2 + \omega^2}\left(\widehat{tb} + \widehat{\bar{t}\bar{b}}\right) + \frac{\Gamma_t^2}{\Gamma_t^2 + \omega^2}\widehat{b\bar{b}}$$

Dokshitzer, VAK, Stirling(1993)

Curves: various scenarios for QCD radiation from $\widehat{tb}$, $\widehat{\bar{t}\bar{b}}$ and $\widehat{b\bar{b}}$ colour dipoles, realistically

SK Conclusion: $\langle \delta m_t \rangle$ ~30 MeV

Add W hadronic decays, $t\bar{t} \to b\bar{b}q_1\bar{q}_2q_3\bar{q}_4$ $\langle \delta m_t \rangle \gtrsim 100$ MeV

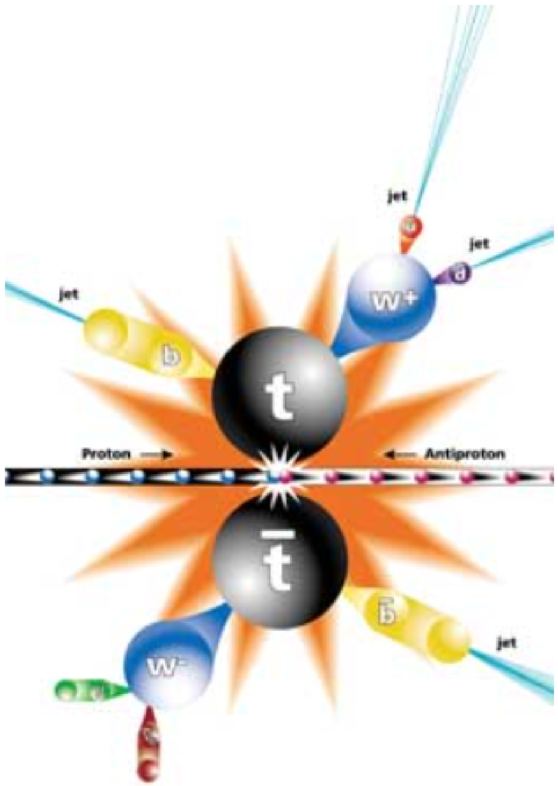
pp-collisions –add cross-talk with hadronic environment (top is coloured!)

$\langle \delta m_t \rangle \gtrsim$ 500 MeV

Very strong (MC) model dependence!

April 1995: Discovery of the top quark at Fermilab

The Standard Model of particle physics holds that all matter is made from a small alphabet of elementary particles consisting of six quarks and six leptons. The heaviest of these, the top (or t) quark, is unstable and can only be detected when it is created artificially, for example in the collisions between the high-energy proton and antiproton beams at Fermilab in Batavia, Illinois. Physicists have been convinced that the top quark must exist since 1977, when its partner, the bottom (or b) quark, was discovered. Little did they know it would be nearly two decades before the top was finally found.

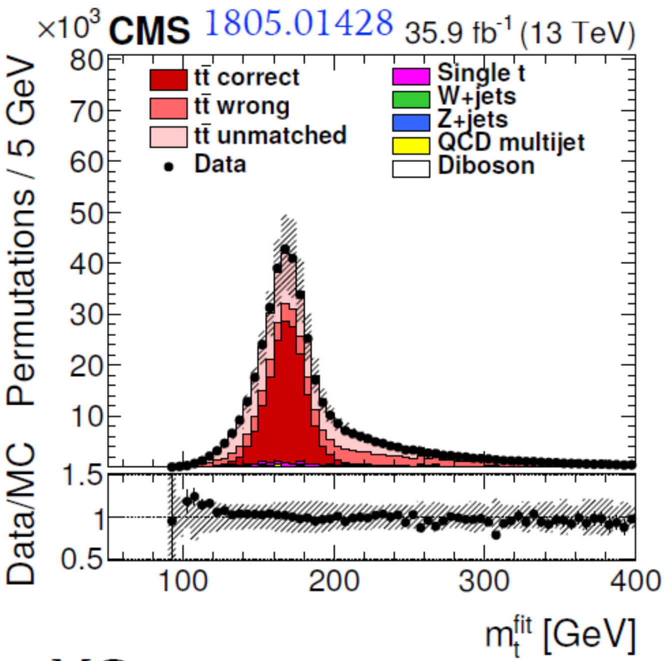


Produced in conjunction with its antiparticle the t-bar, the top quark quickly decays into a variety of daughter particles. The best way to search for the top was to look for its decay into a W boson and the next lightest quark, the b quark. A chief problem is the fact that the energetic b's and W's are also unstable and quickly decay into particle jets that typically emanate from less- interesting background collisions. Identifying the top quark required distinguishing a real top signature from those of background processes that can mimic one.

In 1985, when the Fermilab Tevatron collider was first activated, the search for the top quark was well underway, but early efforts at SLAC and at DESY in Germany proved fruitless. As the 1980s drew to a close, CERN, at that time the most powerful accelerator with energies up to 315 GeV, had failed to find the top quark. Experiments had determined that the mass of the top could be no lower than 77 GeV - beyond the limits of CERN's energy beams.

Direct measurements

Note the dirty environment: a colored particle at a hadron collider!



Good precision thanks to the huge amount of data

Current world average from PDG: $m_t^{MC} = 172.9 \pm 0.4$ GeV

The following measurements extract a t-quark mass from the kinematics of $t\bar{t}$ events. They are sensitive to the top quark mass used in the MC generator that is usually interpreted as the pole mass, but the theoretical uncertainty in this interpretation is hard to quantify.

OUR AVERAGE of 172.76 ± 0.30 GeV is an average of top mass measurements from LHC and Tevatron Runs. The latest Tevatron average, 174.30 ± 0.35 ± 0.54 GeV, was provided by the Tevatron Electroweak Working Group (TEVEWWG).

PDG-2021

Summary of the direct mass measurement

- Inclusion of nuisances parameters in the fit helps to hone in on systematic uncertainties on the top quark mass.
- Including $m_{\ell b}^{reco}$ for events formerly excluded by the P_{gof} cut, $m_{\ell b}^{reco} / m_t^{fit}$ and R_{bq}^{reco} decreases the uncertainty in the direct measurement by additional 150 MeV

The final result is:

$$m_t^{MC} = 171.77 \pm 0.38\,\text{GeV}\ \left(\frac{\sigma_{m_t}}{m_t} = \pm 0.22\%\right)$$

This includes $\sigma_{stat} = 0.04$ GeV and $\sigma_{calibration} = 0.03$ GeV
- Its biggest uncertainty source is JEC flavor bottom as in prior analyses.
- The limit from simulation statistic of variation samples still considerable.

This result surpasses the prior measurement on the same data by 0.25 GeV and is the most precise top quark mass measurement by 0.12 GeV.

Summary

The two presented top quark mass measurements extract the mass of the top quark for different mass definition with different leading uncertainties.

Both have a phenomenal precision in their respective category.

$$m_t^{\text{pole}} = 172.94^{+1.37}_{-1.34}\,\text{GeV}$$

$$m_t^{\text{MC}} = 171.77 \pm 0.38\,\text{GeV}$$

THE STATE- OF- THE -ART.

- Direct LHC+Tevatron measurements –top mass reconstruction: precision ~500 MeV.
  Expectations for HL LHC- a few hundred MeV.
  Based on MC template fits. Requires further MC improvements.

  The dirty environment: a coloured particle at a hadron collider!

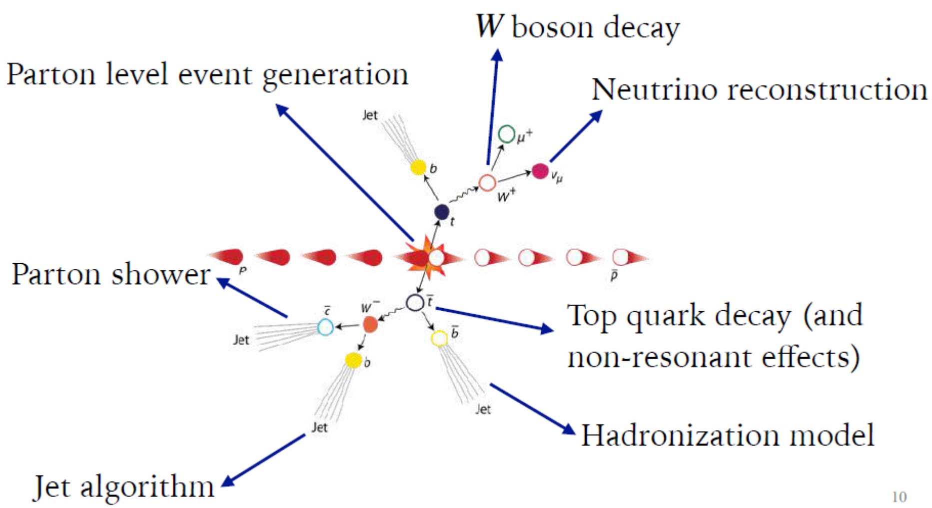
- Threshold scan at a e^+e^- collider : theory predictions reach NNNLO precision and an NNLL resummation.
  The 'threshold mass' can be converted to the $\overline{MS}$ scheme with intrinsic uncertainty $\mathcal{O}(10\ \mathrm{MeV})$

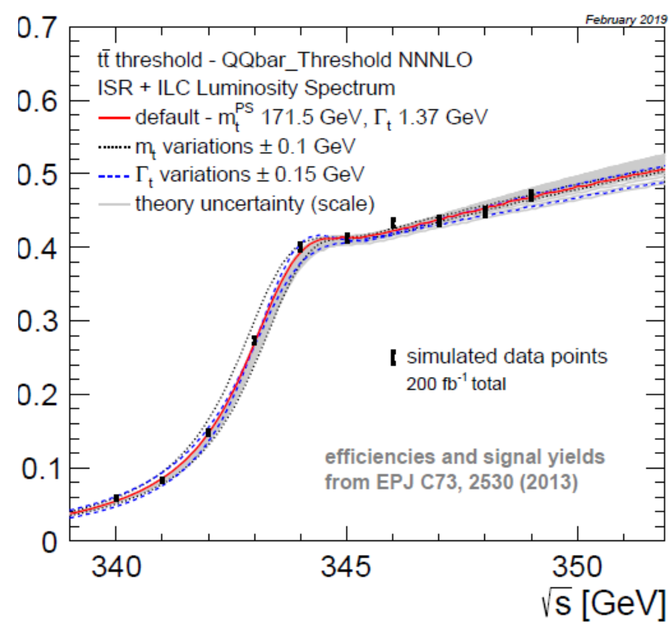
  The "golden" top mass determination.

GENERAL BELIEF

The highest precision for the top quark mass is expected from a scan of the pair-production threshold in e^+e^- collisions, which, in contrast to "conventional" measurements at the LHC, provide the mass in a theoretically well-defined framework, eliminating the interpretation uncertainties associated with the use of MC generator masses which are present otherwise.

Unfortunately no such observable at the LHC !





FCC-ee plans: 5 years of running at 345-365 GeV
with L(integr)=1.5 ab^-1 –top mas statistical uncertainties on the level of 2 MeV.

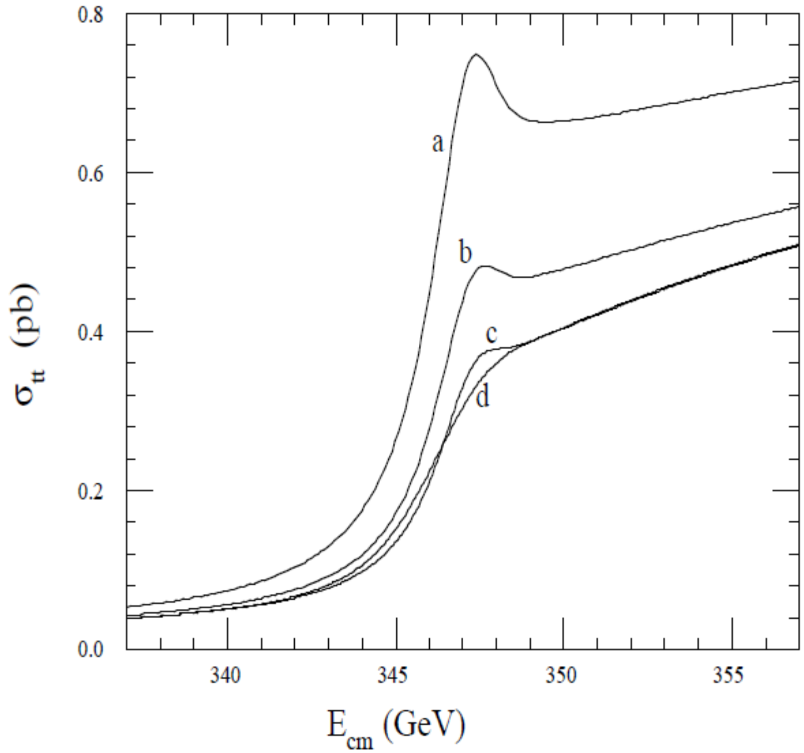
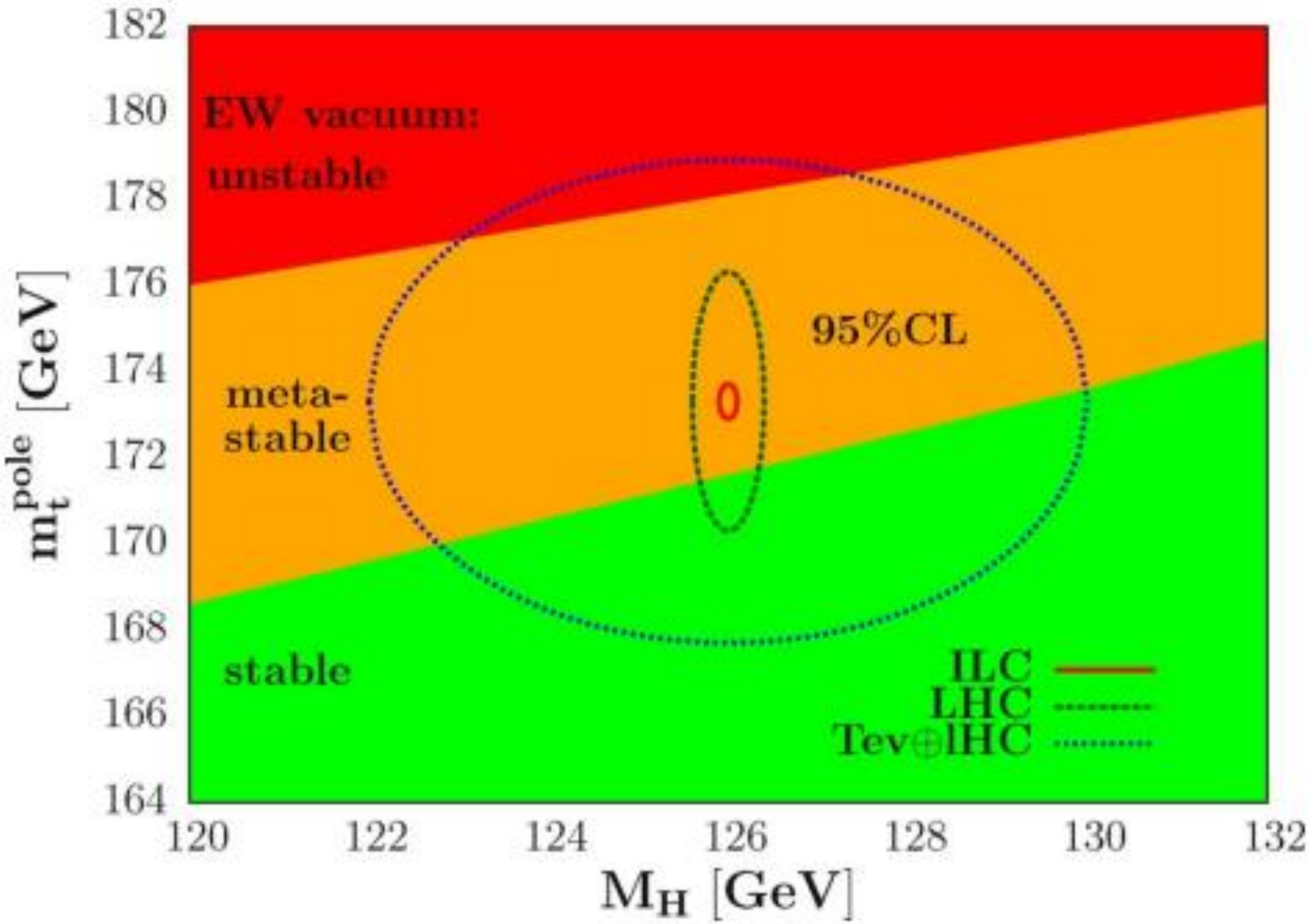


Figure 4: Production cross section for top-quark pairs near threshold for $m_t = 175$ GeV. The theoretical cross section is given by curve (a). The following energy redistribution effects have been applied to the theory for the remaining curves: (b) initial-state radiation (ISR); (c): ISR and beamstrahlung; (d): ISR, beamstrahlung, and single-beam energy spread.

Remnants of toponium S-wave resonance.
Steep rise ⟹ the base for precise top mass determination

Production of colour singlet $t\bar{t}$ state!
Far superior to the single (coloured) t- mass reconstruction.

THE FATE OF OUR UNIVERSE

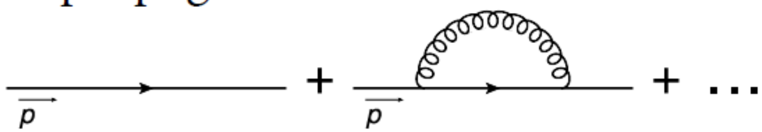


What is the top quark mass?

- There are different definitions for a mass
- Kinematic: reconstructed object fitted to Monte Carlo event generators (so-called MC mass) — Direct measurements
- Field theoretic: a (renormalized) parameter in the Lagrangian density (scheme-dependent) — Indirect measurements
  - Pole (on-shell) mass
  - $\overline{\text{MS}}$ mass
  - 1S mass
  - MSR mass
  - …

The pole mass

Defined in perturbation theory as the pole of the renormalized dressed propagator



$$\sim \frac{i}{\not{p} - m_t^0 - \Sigma(p, m_t^0, \mu)}$$

Well-defined for stable particles; imaginary for unstable, weakly-interacting particles; but the top quark has color…

The top quark (as a colored particle) has no pole mass non-perturbatively

Reflected in perturbation theory as the infrared renormalons (related to the asymptotic nature of perturbative series)

A classic example: the perturbative relation between the pole mass and the $\overline{\text{MS}}$ mass

$$m_t^{\text{pole}} \approx \bar{m}_t \left(1 + 0.42\,\alpha_s + 0.83\,\alpha_s^2 + 2.4\,\alpha_s^3 + 8.5\,\alpha_s^4 + \cdots\right)$$

an intrinsic ambiguity of $\mathcal{O}(\Lambda_{\text{QCD}})$

Top Quark Mass Schemes

- High precision demands to take into account the properties of mass schemes and that one picks an adequate scheme
- Very well understood: $O(\alpha_S^4)$ results! Marquard, Smirnov, Smirnov, Steinhauser'15

- Pole mass m_t^{pole} not adequate for some high-precision applications due to a renormalon ambiguity:

  Δm_t^{pole} = 110 MeV Beneke, Nason, etal '16

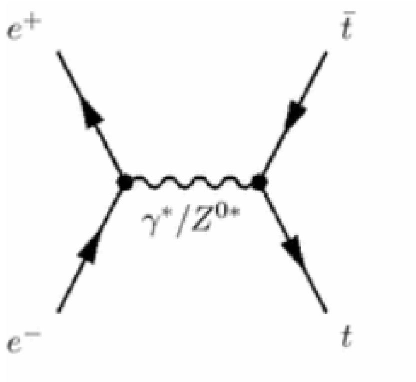
  Δm_t^{pole} = 250 MeV AHH, Lepenik,Preisser '17

- Pole ambiguity arises because linear IR effects absorbed into the mass

- Ambiguity-free masses only absorb effects above their renormalization scale μ ("short-distance masses"): $m_t(\mu)$ ⟵ μ = dynamical scale of the process

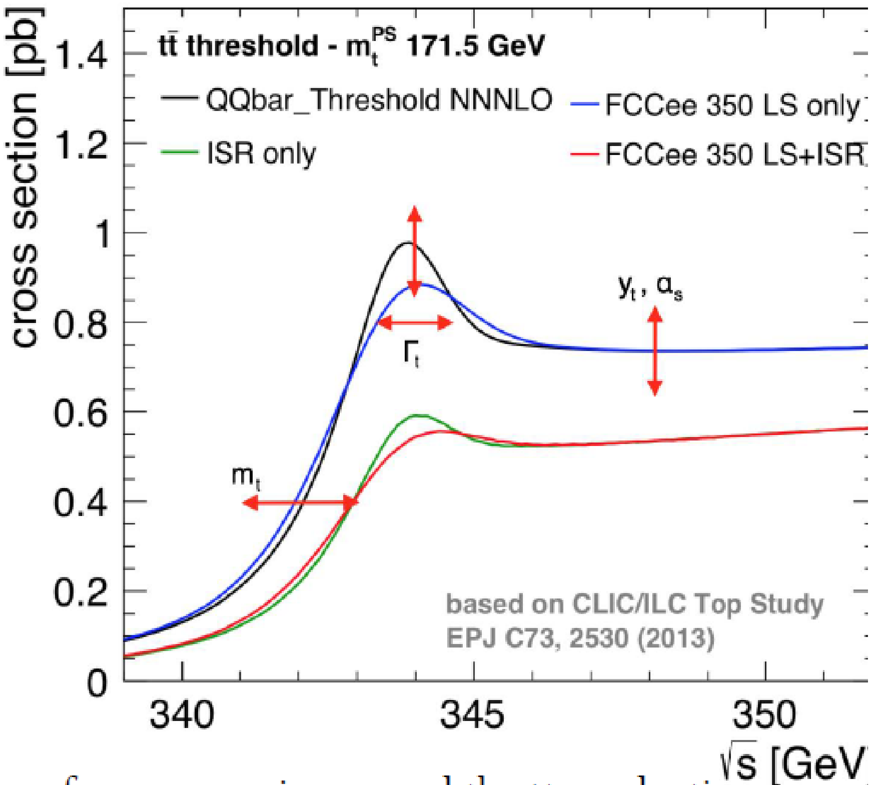
To rule out absolute stability of the Universe (AFS-2018) with 3σ require accuracy ~250 MeV

Top production threshold scan at FCC



Top quark parameters are evaluated by comparison of the production rates to the theoretical prediction, which exists at the N³LO QCD precision[1] and NNLL resummation[2] level level.

FCC-ee provides an advantage over linear colliders due to the absence of a pronounced beamstrahlung tail in the luminosity spectrum (LS).



For L=200 fb^{-1} evenly split across eight different center-of-mass energies around the tt production threshold (340, 341, 341.5, 342, 343, 343.5, 344, and 345~GeV), top mass can be determined with a statistical precision of better than 9 MeV when assuming SM values for Γ_t and Y_t.

3.1% uncertainty on Y_t from the combination of HL-LHC and FCC-ee.

Simultaneous fit of m_t and Γ_t results in a statistical precision of 17 and 45 MeV respectively.

RESURRECTION

0-0 transition

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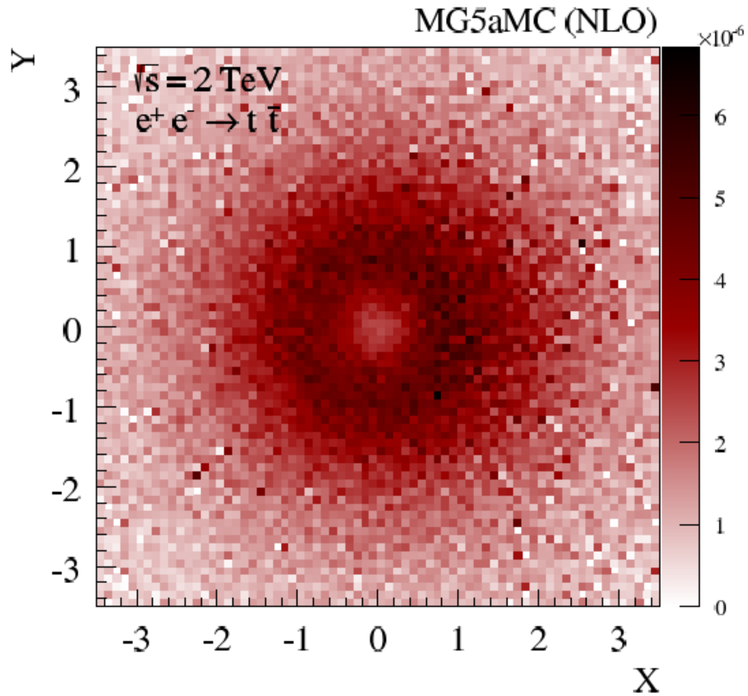
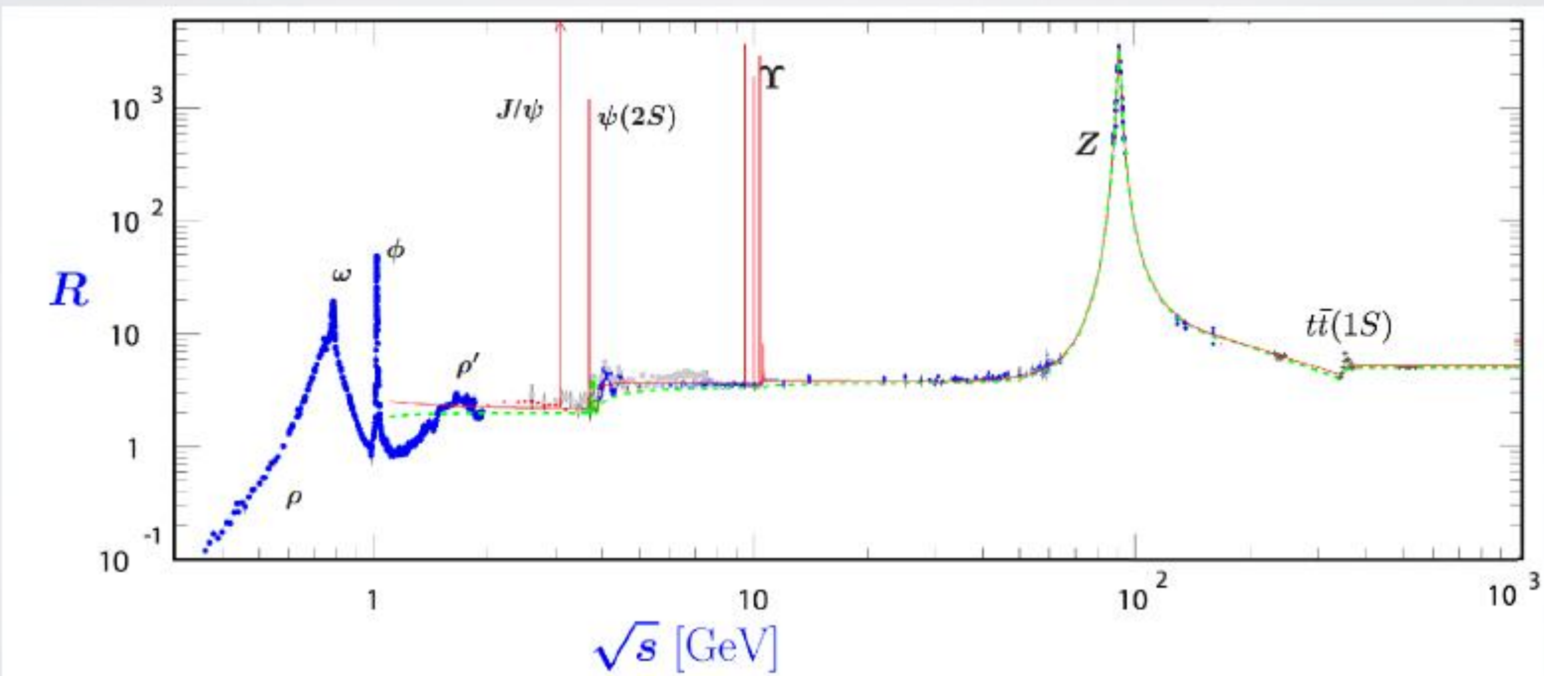


FIG. 1. Idealized gluon radiation pattern for $e^+e^- \to t\bar{t}$ at $\sqrt{s} = 2$ TeV, showing the expected dead cone suppression at the origin. This is an NLO calculation with up to two additional partons in the final state. To define the effective $t^* \to tg$ kinematics, the "gluon" corresponds to the sum of emissions within the top hemisphere, imposing a cut of $E_g >$ 50 GeV. The X and Y coordinates are then normalized such that the dead cone peak is at $X^2 + Y^2 \simeq 1$.

* Top physics precision program: top mass, top width, top Yukawa, α_s
* Top threshold scan: high precision mass measurement ($\Delta M_t \approx$ 30-70 MeV)
* Severe theory challenges (!)
* High precision top Yukawa measurement (needs ~550 GeV)
* Top: telescope to BSM physics ↪ Backup slide
* Top electroweak couplings: deviations guideline to distinguish BSM models




THANK YOU

BACKUP

Top Quark Mass Schemes

- Most popular **short-distance mass schemes**:

MSbar:
$$m_t^{\rm pole} - \overline{m}_t(\mu) = \frac{4}{3}\left(\frac{\alpha_s(\mu)}{\pi}\right)\overline{m}_t(\mu) + \ldots$$
$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\overline{m}_t(\mu) = -\overline{m}_t(\mu)\left(\frac{\alpha_s(\mu)}{\pi}\right) + \ldots$$

Meaningful for $\mu > m_t$

Threshold masses:		
	kinetic	Bigi, Shifmann, Uraltsev '97
	1S	AHH, Ligeti, Manohar '98
	PS	Beneke '98
	RS	Pineda '01

Constructed from ttbar threshold and B physics observables, renormalon study

MSR:
$$m_t^{\rm pole} - m_t^{\rm MSR}(R) = \frac{4}{3}\left(\frac{\alpha_s(R)}{\pi}\right)R + \ldots$$

AHH, Jain, Scimemi, Stewart '08

$$\frac{\mathrm{d}}{\mathrm{d}\ln R}m_t^{\rm MSR}(R) = -\frac{4}{3}R\left(\frac{\alpha_s(R)}{\pi}\right) + \ldots$$

Meaningful for $R < m_t$

- MSbar+MSR: Consistent flavor number dependent RG evolution with threshold matching
- MSR "interpolates" between pole mass and MSbar mass

- Theoretical precision achievable for short-distance masses:
  10-20 MeV for all heavy quarks (QCD only!)

Top quark mass definitions

Direct measurement:

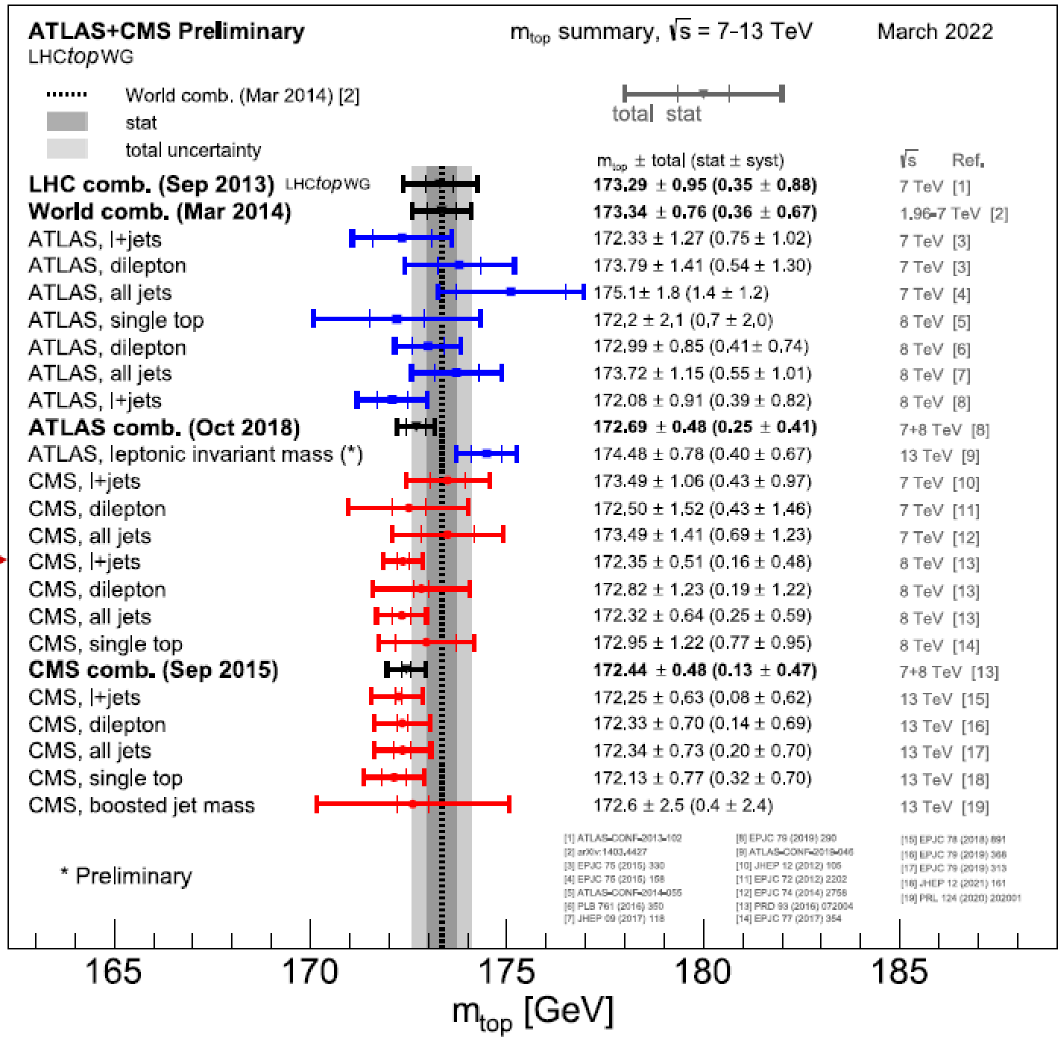
- rely on parton shower simulation
- build templates that dependent on the top quark mass (m_t) parameter in simulation
- yield small uncertainties
- relation to a theoretically well defined mass has an uncertainty of O(0.1–1 GeV

theoretical mass of the top quark depends on the renormalization scheme, choice is the pole mass m_t^{pole}

$$\frac{i}{\not{p} - m_0} \Rightarrow \frac{i}{\not{p} - \underbrace{m_0(\Lambda)}_{\text{'bare' mass}} - \underbrace{\delta m_0(\Lambda)}_{\text{divergent}} - \underbrace{\Sigma' m_0(\Lambda)}_{\text{finite}}} := \frac{i}{\not{p} - m^{\text{pole}}}$$

- extracted via differential cross sections
- non-perturbative corrections must be added
- unfolding procedure yield typically bigger uncertainty than direct measurement

Direct mass measurements



among the most precise measurements at the LHC

the most precise m_t measurement uses the $t\bar{t} \to \ell + \text{jets}$ channel

so far not surpassed with 13 TeV data

narrow width approximation

(TSK-90)

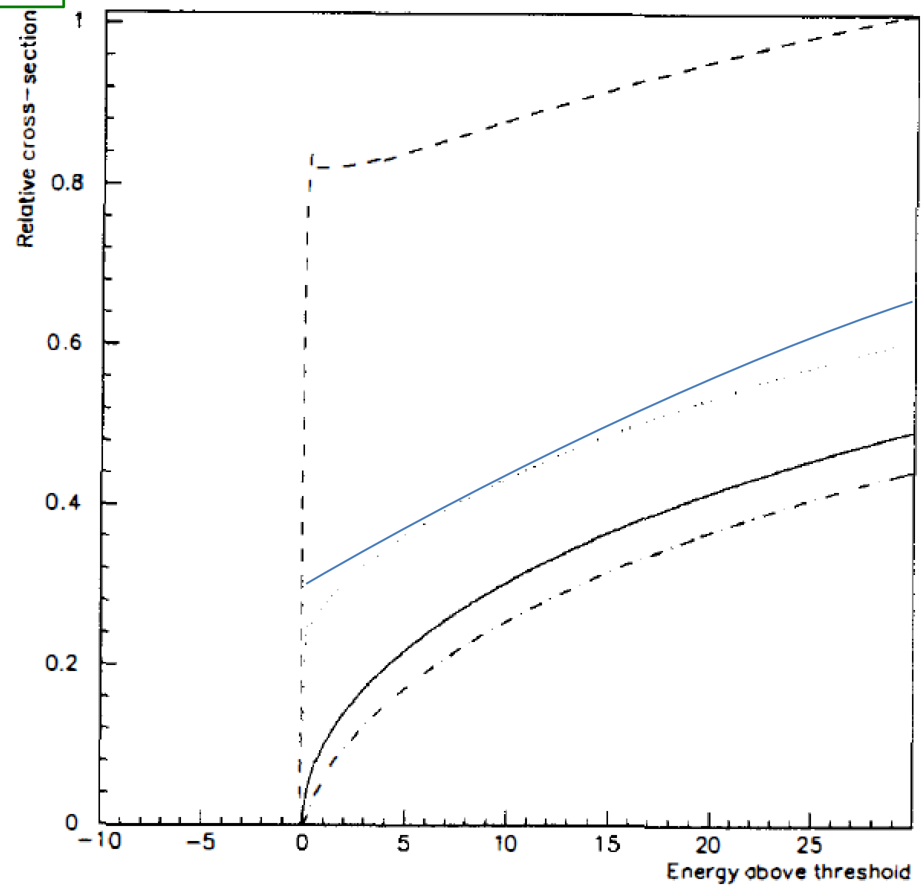


Figure 2: Threshold behaviour for $m_t = 100$ GeV, fix $\alpha_S = 0.196$. Full line is standard threshold factor β_t, dashed the enhanced singlet channel factor $\beta_t|\Psi^{(s)}(0)|^2$, and dash-dotted the suppressed octet channel factor $\beta_t|\Psi^{(8)}(0)|^2$. Dotted gives the combination relevant for the qq channel, 2/7 singlet and 5/7 octet. E is energy above nominal top threshold at $2m_t$.

$e^+e^- \to t\bar{t}(H)$

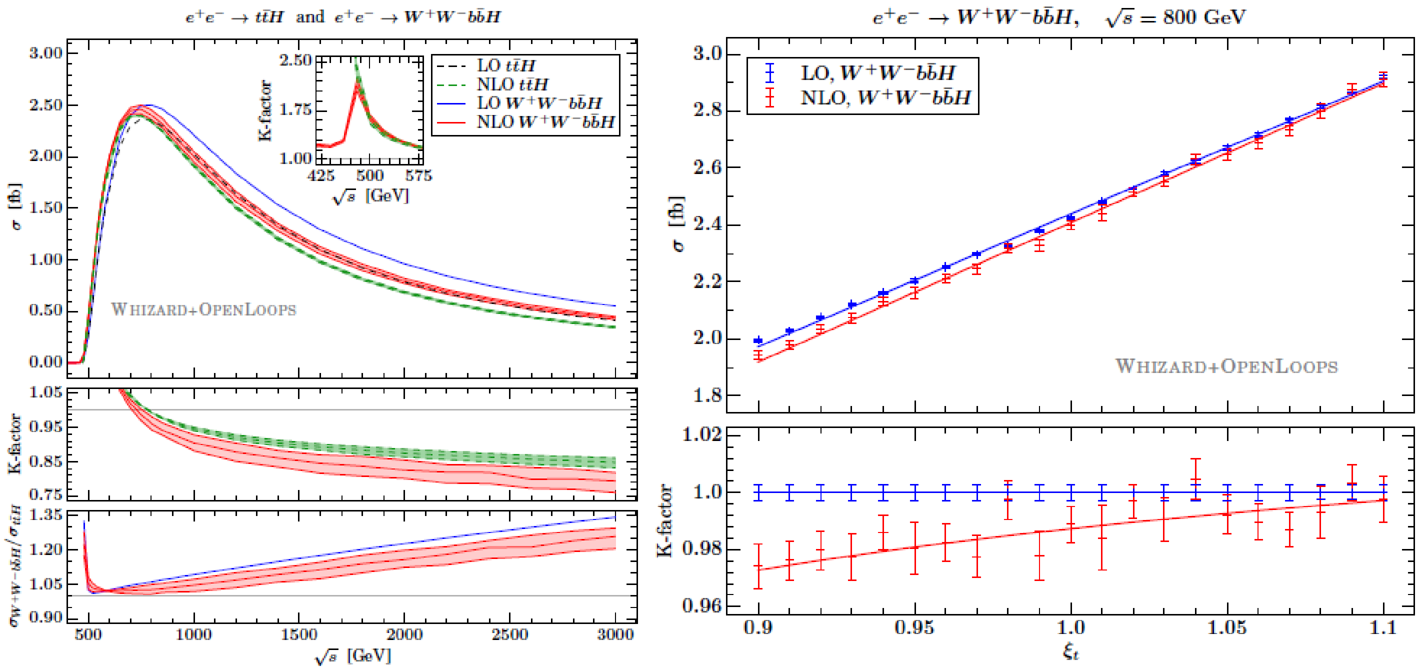
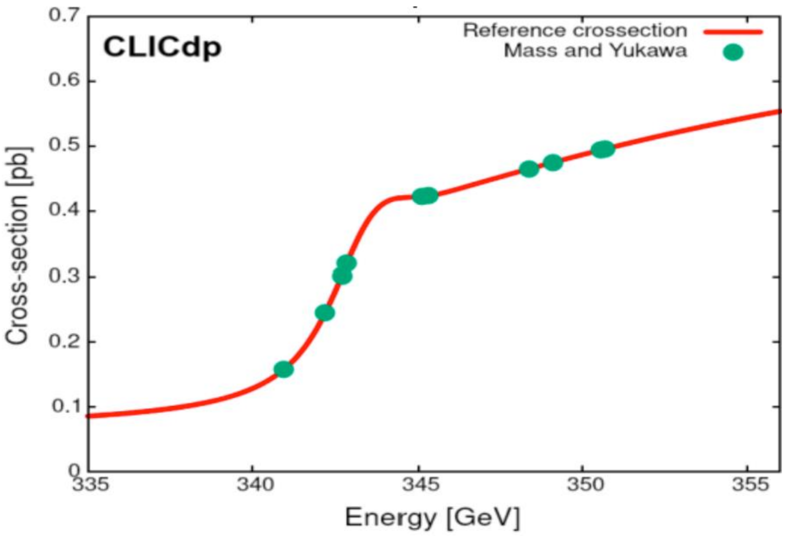


Figure 10: Left panel: Total cross section for $e^+e^- \to W^+bW^-\bar{b}H$ at LO QCD (blue) and NLO QCD (red), respectively. Dashed curves show the on-shell process $e^+e^- \to t\bar{t}H$. The ratio plots show the K-factor (NLO QCD over LO QCD) and the off-shell over the on-shell process. The inset shows the K-factor close to threshold. Right panel: Dependence of the total cross section for $e^+e^- \to W^+bW^-\bar{b}H$ at LO QCD (blue) and NLO QCD (red), respectively, on the signal strength modifier for the top-Yukawa coupling, $\xi_t = y_t/y_t^{SM}$. Figures taken from Ref. [37].

Snowmass e+e- forum
April 4th, 2022



Top-quark threshold scan

◆ Optimisation of scan points including beam spectrum; here optimising on mass and Yukawa coupling.

◆ The expected top-quark mass precision of 25MeV can be improved by 25% without losing precision on width or Yukawa.
https://arxiv.org/abs/2103.00522