Top Precision Physics at LCs

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$\int dk\,\Pi$ Doktoratskolleg Particles and Interactions

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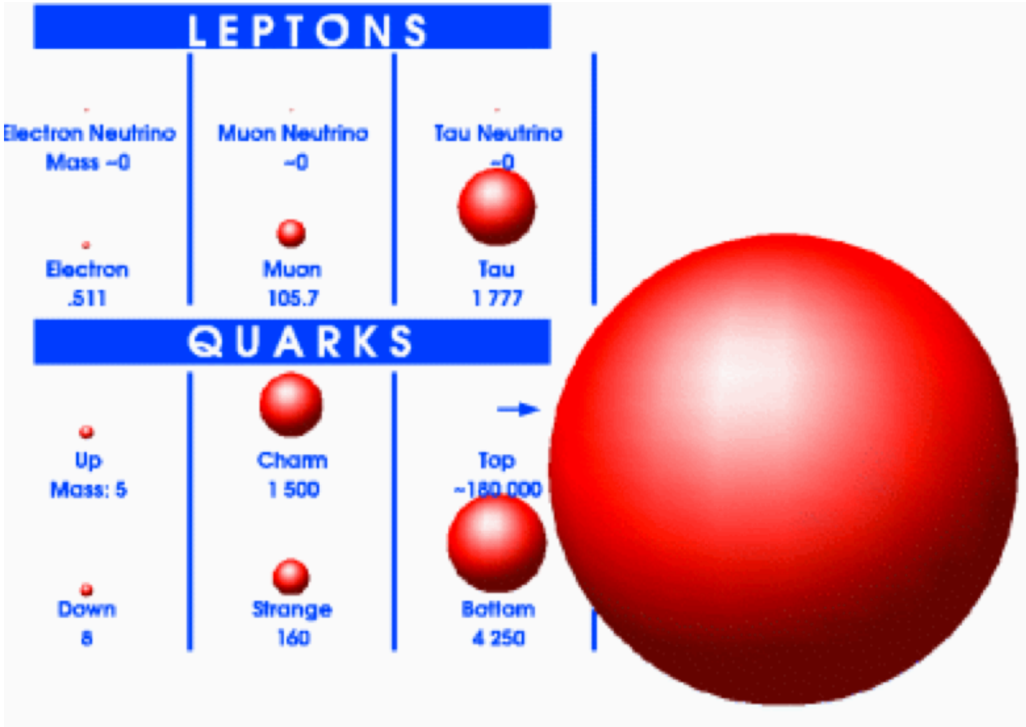
Outline

- Fixed-order calculations
- Boosted top production
- MC generators
- Mass schemes and couplings
- Top pair threshold
- MC top mass problem and direct reconstruction
- Conclusions

.. not just the heaviest SM particle

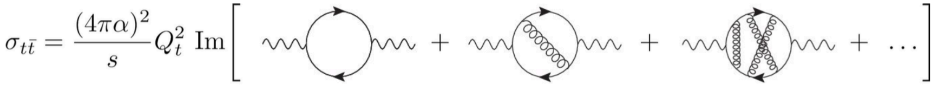


- Top quark: heaviest known particle
- Most sensitive to the mechanism of mass generation
- Peculiar role in the generation of flavor.
- Top might not be the SM-Top, but have a non-SM component.
- Top as calibration tool for new physics particles (SUSY and other exotics)
- Top production major background it new physics searches
- One of crucial motivations for New Physics

- Very special physics laboratory: $\Gamma_t \gg \Lambda_{QCD}$
  - Top treated a particle: p_T, spin, $\boldsymbol{\sigma}_{tot}$, $\boldsymbol{\sigma}$(single top), $\boldsymbol{\sigma}$(tt+X),.. $\rightarrow q \gg \Gamma_t$
  - Quantum state sensitive low-E QCD and unstable particle effects: m_t, endpoint regions $\rightarrow q \sim \Gamma_t$
  - Multiscale problem: p_T, m_t, Γ_t, Λ_{QCD}, . . . (depends on resolution of observable)

Status on FO Calculations

Stable Tops:



Kühn, Chetyrkin, Steinhauser, AHH,.. ‘96

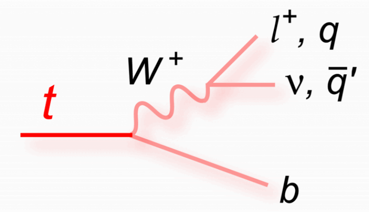
- Total inclusive cross section known to O(α_S^2) (FO)
- Total inclusive cross section known to O(α_S^3) (FO-Pade)
- NLO EW corrections (FO)

Maier, Marquard.. ‘17
AHH, Mateu Zebarjad ‘08
Kiyo, Maier, Maierhofer, Marquard ‘09
Fleischer, Leike, Riemann, Wertenbach ‘03

- Full differential ttbar (subtractions)

Gao, Zhu‘16
Chen, Dekkers, Heisler, Bernreuther ‘16

Top Decay (NWA):



- Total decay rate O(α_S^2) (FO)
- Fully differential O(α_S^2) (FO subtractions)

Charnecki etal ‘10
Gao, Li ‘12
Bruchseifer, Caola, Melnikov ‘13

- NLO EW corrections

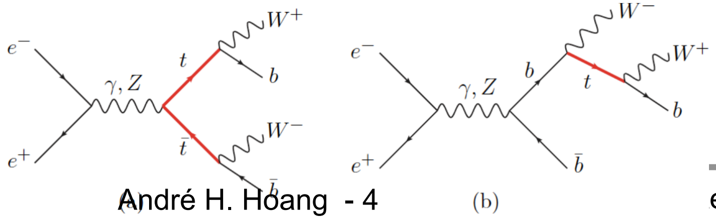
’90s

“Off-shell” Top quarks:

→ essential for reconstructed top invariant mass, endpoint decay spectra

- Full off-shell $e^+e^- \to WWbb$ O(α_S) (FO)

Guo, Ma, Zhang, Wang ‘08
MadGraph5@NLO, WHIZARD, ...
Standard now

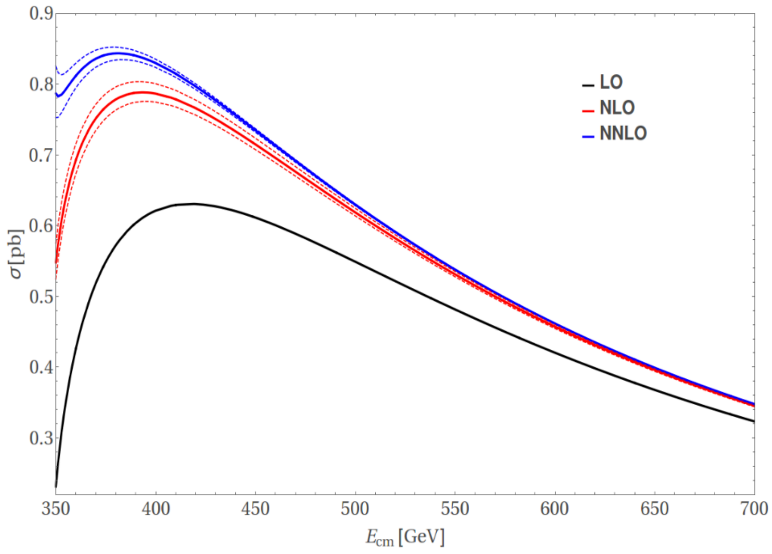


Status on FO Calculations

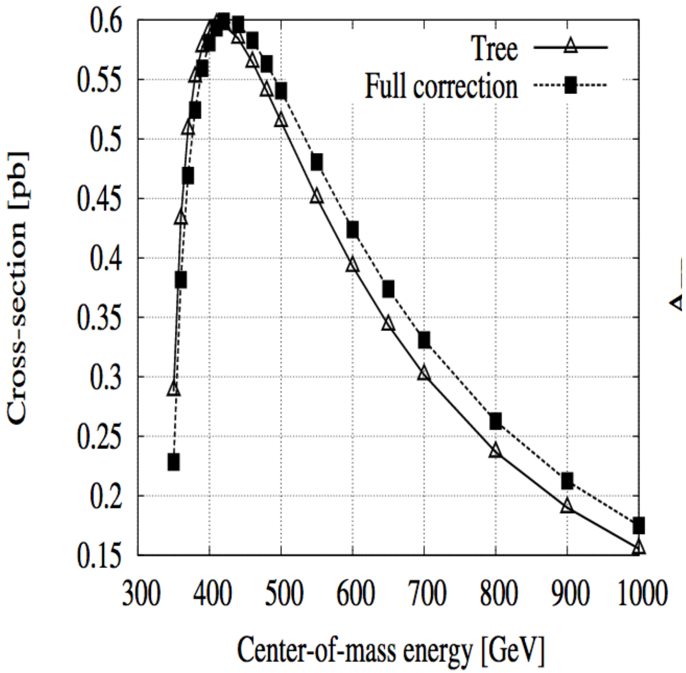
Is this good enough? In general not!

Example: total ttbar cross section

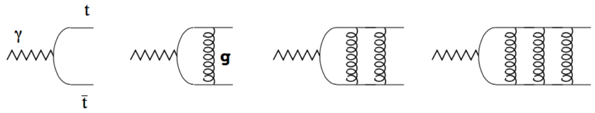
Chen, Dekkers, Heisler, Bernreuther ‘16



Fleischer, Leike, Riemann, Werthenbach ‘03



- Huge correction at threshold $E_{cm} \approx 2m_t$
- **Coulomb effects** ~ $(\alpha_S/v)^n$
- Resummation mandatory (very well developed)



- **EW Sudakovs logarithms** for very large energies: $\log(E_{cm}/m_t)$
- Fixed-order fine for FCC-ee

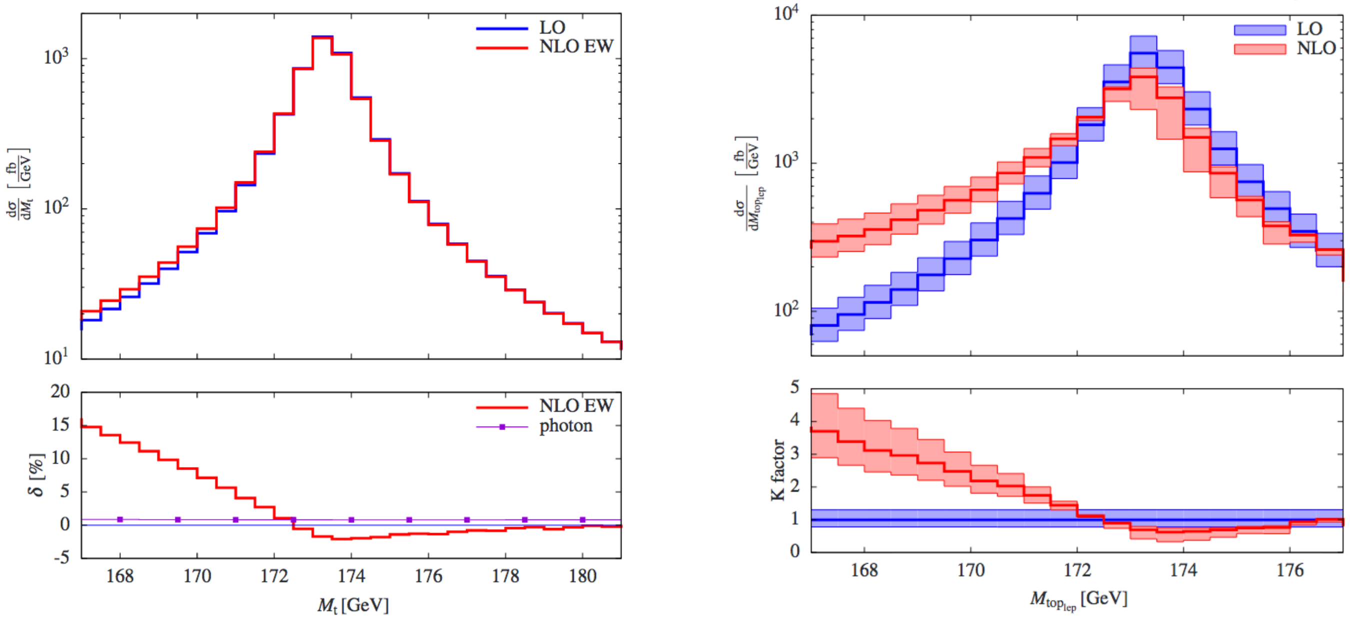
Status on FO Calculations

Is this good enough? In general not!

Example: ‘reconstructed’ top invariant mass

Pellen, Denner ’17

From an LHC paper (sorry for that..)

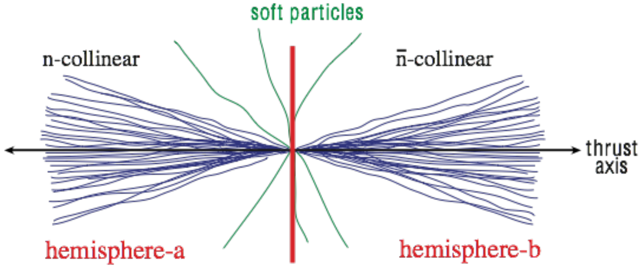


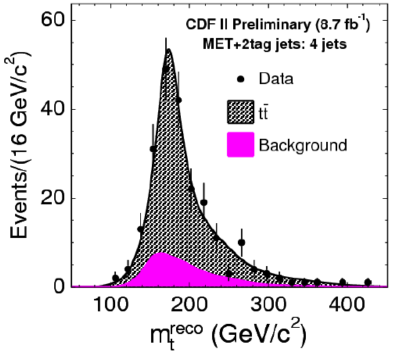
- Scale variation does not cover uncertainty.
- Fixed-order not sufficient, e.g. large QCD logs $\log(m_t/\Gamma_t)$
- **Combined QCD/electroweak resummation** mandatory (not worked out yet, but possible using knowledge from flavor physics)
- **Hadronization effects** large at threshold and resonances

Factorization for Boosted Top Quarks

Basic event structure:

- Top and antitop boosted back-to-back: $M_{tt} \gg m_t$
- Top jets in the resonance region: $M_{J,top} \sim m_t$
- LHC: central top jets: $|\eta_J| \lesssim 1$ (beam separation)
- [Veto on additional hard (gluon) jet]





- Top and ant-top decays separated (→ factorization)
- Soft radiation between jets not sensitive to top decay (top-bottom collinear color line)
- Single-top treatment of top and anti-top decays
- Clean separation of scales: p_T (or E_{cm}) $\gg m_t \gg \Gamma_t \gg \Lambda_{QCD}$
- Factorized cross section:

One systematic avenue to make (QCD+ew) resumed + hadron level predictions for top decay sensitive observables.

$$\sigma \sim H_Q \times H_m \times B \otimes D \otimes S$$

“hard” “mass mode” “jet” “decay” “soft”

Factorization for Boosted Top Quarks

Stable Tops:

from on-shell top parton momenta ↓

Ferroglia, Pecjak, Yang, '12

Pejcak, Scott, Wang, Yang, '16

- Systematic resummation of QCD logarithms log(M_{tt}/m_t)
- Applies for inclusive (hard) differential distributions (x→1)

$$\frac{d\hat{\sigma}_{ij}^{\rm NLP}}{dM_{t\bar{t}}\,d\Theta} = \frac{16\pi^2\alpha_s^2(\mu_r)}{M_{t\bar{t}}^5}\sqrt{\frac{M_{t\bar{t}}+2m_t}{2M_{t\bar{t}}}}\sum_\alpha c_{ij,\alpha}(\cos\theta_t)\times H_{ij,\alpha}(z, M_{t\bar{t}}, Q_T, Y, \mu_r, \mu_f)\,J^\alpha(E)\,.$$

"Off-shell" Tops: → "top state" = (top + u.collinear radiation)$_{\text{color singlet}}$

- Systematic resummation of QCD logarithms log(M_{tt}/m_t), log(m_t/Γ_t)

Fleming, AH, Mantry, Stewart '07

- Applies for event-shape-type observables (e.g. top jet mass, 2-jettiness)
- **Hadron level** prediction: non-perturbative effects through factorization

Bachu, Ahm Mateu, Pathak, Stewart '20

$$\left(\frac{d^2\sigma}{dM_t^2\,dM_{\bar{t}}^2}\right)_{\rm hemi} = \sigma_0\,H_Q(Q,\mu_m)H_m\Big(m,\frac{Q}{m},\mu_m,\mu\Big) \times \int_{-\infty}^{\infty} d\ell^+ d\ell^-\, B_+\Big(\hat{s}_t - \frac{Q\ell^+}{m},\Gamma,\mu\Big)\,B_-\Big(\hat{s}_{\bar{t}} - \frac{Q\ell^-}{m},\Gamma,\mu\Big)\,S_{\rm hemi}(\ell^+,\ell^-,\mu)$$

- Systematic treatment of grooming → see Aditya's talk

AH, Mantry, Pathak, Stewart '17 + '19

- Can provide testing ground for Monte-Carlo generators

MC Generators

- Multipurpose MC generators (Pythia, Herwig, Whizard, Sherpa) can simulate <u>all aspects</u> of particle production and decay at the observable level

Sjöstrand, etal. ‘15
Bellm, etal. ‘16
Bellm, etal. ‘16

- Fast machinery from LHC, just change initial state
- Less modeling for color neutralization processes needed
- NLO-matched MC generators standard.
- NNLO-matched MC generators available

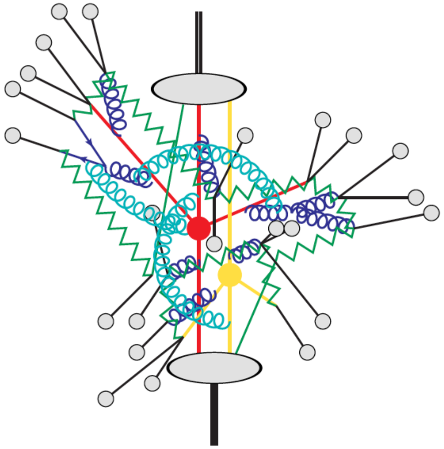
Mazzitelli, Monni, Nason, Bicocca, Re, Wiesemamnn, Zanderighi ‘20

- LO matrix elements
- Parton shower (Markov chain):

  p_T-ordered dipole (mom. recoil local)

  coherent branching (non-global restricted)
- Hadronization model

  string, cluster



All fine?

Not so fast..

MC Generators

How precise are they?

- Parton shower provides approximation to **collinear and soft radiation**
  - → Top quarks: theory input applies to quasi-collinear tops only!
  - → No systematic treatment of finite lifetime effects
  - → No systematic treatment of MPIs, color-reconnection

- The theoretical precision is tied to the precision of the parton showers, for a few very simple observable NLL, mostly LL or less.

- Tuned hadronization models compensate for the deficiency.

- In general we have observable precision > theoretical precision

- MCs are not high-precise tools to extract QCD parameters or provide estimate of hadronization corrections to high-order perturbative analytical calculations

- NLO/NNLO-matching does only improve the first hard gluon radiation. Does not improve observables governed by parton shower dynamics.

MC Generators

- Deficiency mostly affects direct top quark mass measurements:

  → **MC Top Quark Mass Problem: m_t^{MC}**

- NLL precise parton showers with full coherence and improved models are an important step that needs to be taken (many different aspects, work already ongoing).

e.g. second order kernel

double emssion

amplitude evolution (full coherence,

non-global logs, color reconnection)

Li, Skands '16

Höche Prestel' 14, '15

Forshaw, Holguin, Plätzer '19

Gieseke, Kirchgaesser, Plätzer,' Siodmok '19

Martinez, Forshaw, De Angelis, Plätzer, Seymour '18

New generation of MCs needed! (Markow chain MCs will be gone eventually)

→ Definitely possible, community should support it more enthusiastically.

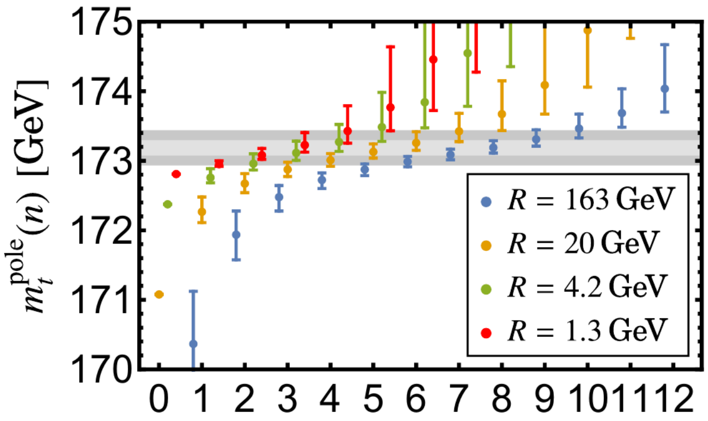
Top Quark Mass Schemes

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

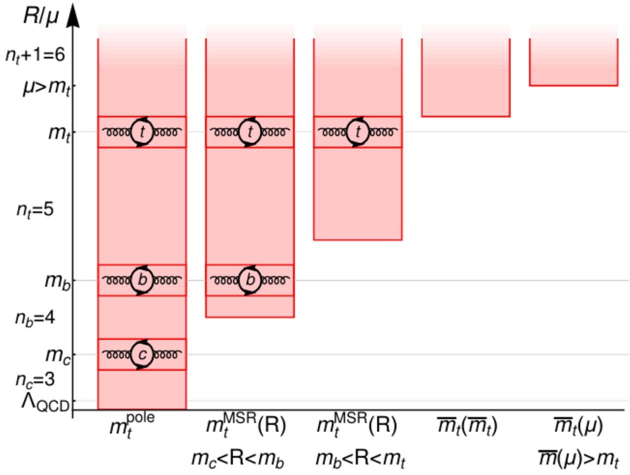
- Pole mass m_t^{pole} not adequate for high-precision applications due to a renormalon ambiguity:

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

  Δm_t^{pole} = 250 MeV AHH, Lepenik,Preisser '17
- Pole ambiguity arises because IR effects absorbed into the mass
- Divergence pattern dependent on scale R that governs the dynamics of the mass dependence



- Ambiguity-free masses only absorb effects above their renormalization scale μ ("short-distance masses"): $m_t(\mu)$



Top Quark Mass Schemes

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

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

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

AHH, Jain, Scimemi, Stewart '08

Meaningful for
$R < m_t$

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

Top Quark Mass Schemes

- Theoretical precision achievable for short-distance masses:
  <u>10-20 MeV for all heavy quarks</u>

- Software tools:

Rundec/CRundec

Herren etal. 1703.03751

- Collections of fixed-order conversion routines (C++, Mathematica)
- RG-evolution for MSbar masses only
- MSR mass not supported

REvolver

REvolver

AH, Lepenik, Mateu 2102.01085

- Core concept, physics scenarios (C++ library & Python, Mathematica interfaces)
- RG-evolution for all all mass relations including lighter flavor threshold corrections
- MSR mass supported
- Fast and exact solutions for RGE running
- Pole mass diagnostic routines

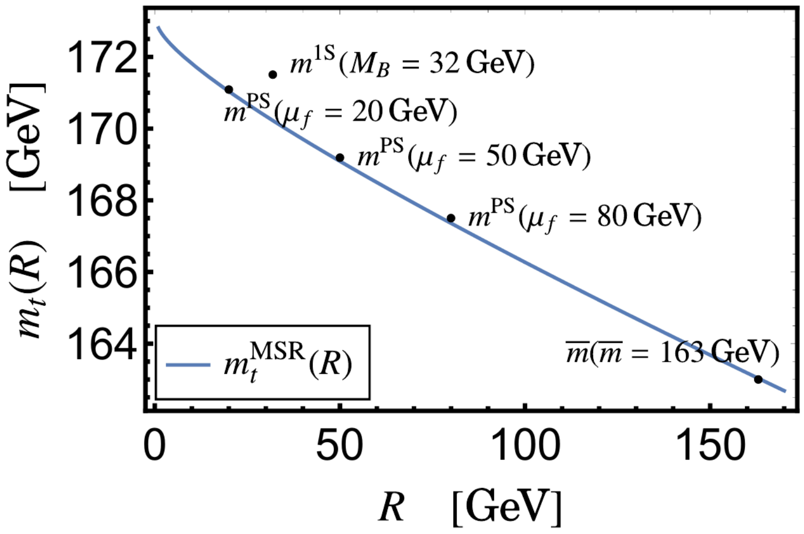
Top Quark Mass Schemes

Has RGE linear in R and numerically very close to threshold masses at their respective scale.

MSR mass is generalization of the MSbar mass for scales R < m_t.

Conversion precision between all short-distance mass better than 30 MeV.

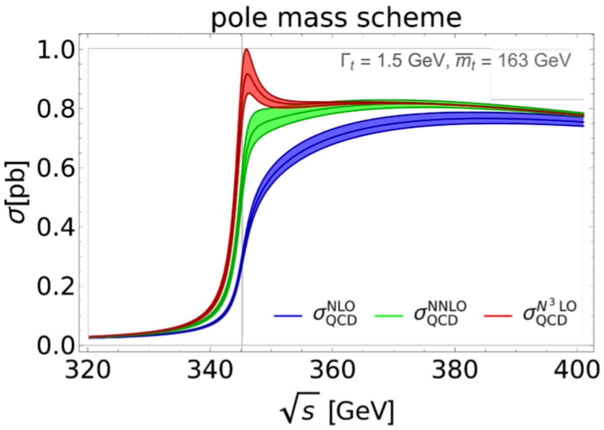
AHH, Jain, Scimemi, Stewart, Lepenik, Preisser ‘17

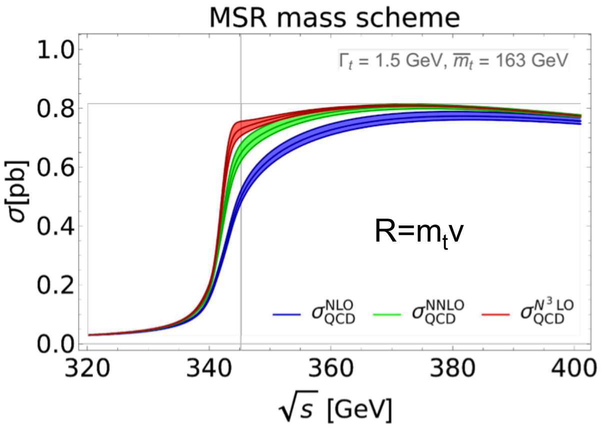


Improved perturbative behavior by choosing appropriate scale R

e.g. total inclusive ttbar FO cross section

Widl, AHH to appear





R=m_tv

Strong Coupling

$$\frac{\mathrm{d}\alpha_s(R)}{\mathrm{d}\log R} = \beta(\alpha_s(R)) = -2\,\alpha_s(R)\sum_{n=0}^{\infty}\beta_n\left(\frac{\alpha_s(R)}{4\pi}\right)^{n+1}$$

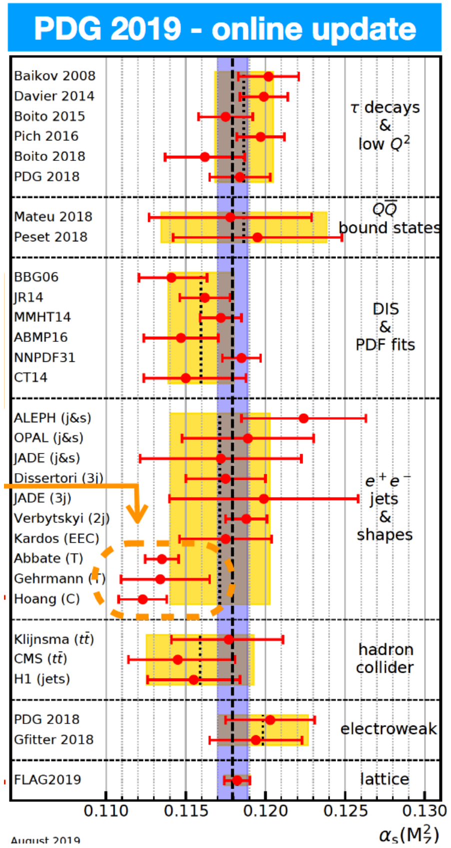
Baikov, Chetyrkin, Kühn ‘17

- Running known to 5 loops (β_4) : fully sufficient
- Uncertainty in $\alpha_S(M_Z)$: debated, under constant scrutiny, but always a limiting factor

example: MSbar-pole mass relation

$\delta\alpha_S = 0.001$ gives 70 MeV uncertainty

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



See: Pier, Andrii, Gabor, Zoltan

Improvement expected, but lots of hard work.

Consistency has actually higher priority at this time!!

Recall: Measurements of QCD parameters more subtle than of physical observables.

BSM Couplings via SM-EFT

- Model-independent effective parametrization of BSM effects through operators beyond dimension 4

$$\mathscr{L}_{\mathrm{EFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i C_i Q_i^{d=6}$$

- Dim 6: typically only “top-philic” operators accounted for which parameterize BSM effects that affect predominantly top observables

$Q_{\varphi \mathrm{t}} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{\mathrm{t}}\gamma^\mu \mathrm{t})$
$Q_{\mathrm{t}\varphi} = (\varphi^\dagger \varphi)(\bar{\mathrm{q}}\,\mathrm{t}\,\tilde{\varphi})$
$Q_{\mathrm{tB}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\mathrm{t})\tilde{\varphi}\mathrm{B}_{\mu\nu}$
$Q_{\varphi \mathrm{q}}^{(1)} = (\varphi^\dagger i \overleftrightarrow{D}_\mu \varphi)(\bar{\mathrm{q}}\gamma^\mu \mathrm{q})$
$Q_{\varphi \mathrm{q}}^{(3)} = (\varphi^\dagger i \overleftrightarrow{D}^I_\mu \varphi)(\bar{\mathrm{q}}\,\tau^I\gamma^\mu \mathrm{q})$
$Q_{\mathrm{tW}} = (\bar{\mathrm{q}}\sigma^{\mu\nu}\mathrm{t})\tau^I\tilde{\varphi}\,\mathrm{W}^I_{\mu\nu}$

$Q_{\mathrm{lt,B}} = (\bar{\mathrm{t}}\gamma^\mu \mathrm{t})(\bar{\mathrm{e}}\gamma_\mu \mathrm{e} + \frac{1}{2}\bar{\mathrm{l}}\gamma_\mu \mathrm{l}) \overset{\mathrm{EOM}}{=} \frac{1}{2}Q_{\varphi \mathrm{t}} + \frac{1}{g'}\bar{\mathrm{t}}\gamma^\mu \mathrm{t}\,D^\nu \mathrm{B}_{\mu\nu} + \ldots$
$Q_{\mathrm{lq,B}} = (\bar{\mathrm{q}}\gamma^\mu \mathrm{q})(\bar{\mathrm{e}}\gamma_\mu \mathrm{e} + \frac{1}{2}\bar{\mathrm{l}}\gamma_\mu \mathrm{l}) \overset{\mathrm{EOM}}{=} \frac{1}{2}Q^{(1)}_{\varphi \mathrm{q}} + \frac{1}{g'}\bar{\mathrm{q}}\gamma^\mu \mathrm{q}\,D^\nu \mathrm{B}_{\mu\nu} + \ldots$
$Q_{\mathrm{lq,W}} = (\bar{\mathrm{q}}\tau^I\gamma^\mu \mathrm{q})(\bar{\mathrm{l}}\tau^I\gamma_\mu \mathrm{l}) \overset{\mathrm{EOM}}{=} -Q^{(3)}_{\varphi \mathrm{q}} - \frac{2}{g}\bar{\mathrm{q}}\tau^I\gamma^\mu \mathrm{q}\,D^\nu \mathrm{W}^I_{\mu\nu} + \ldots$

- Lead to modification of γtt̄ and Ztt̄ couplings
  additional (e^+e^-)(tt̄) point interactions
  and enhanced FCNC top decay vertices

$$ie\left[\gamma^\mu(F_{1V}^{\gamma,Z} + \gamma^5 F_{1A}^{\gamma,Z}) + \frac{i\sigma^{\mu\nu}q_\nu}{2m_t}(F_{2V}^{\gamma,Z} + \gamma^5 F_{2A}^{\gamma,Z})\right]$$

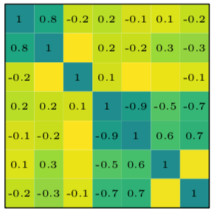
$$\sum_{i,j=\{L,R\}} C_{ij}(\bar{e}_i\gamma^\mu e_i)(\bar{t}_i\gamma_\mu t_j)$$

CP-odd

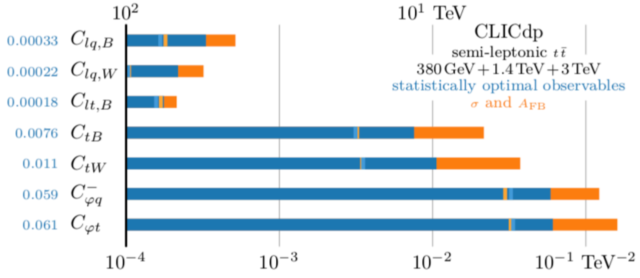
- Accessible through observables where fixed-order predictions are reliable:
  - Total cross section: $\sigma_{\mathrm{tot}}(e^+e^- \to t\bar{t})$
  - Angular distribution: $d\sigma/d\theta_t$
  - Lepton momentum angular distributions in continuum (top spin correlation, CP-odd)
  - Variable beam polarization enhances sensitivity

BSM Couplings via SM-EFT

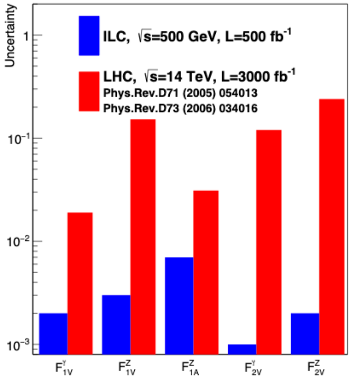
- Global analysis at different cm energies capable disentangling individual operators with high precision



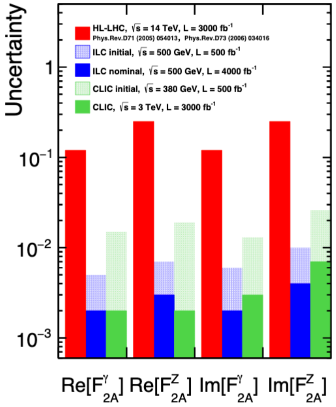
1	0.8	-0.2	0.2	-0.1	0.1	-0.2
0.8	1		0.2	-0.2	0.3	-0.3
-0.2		1	0.1			-0.1
0.2	0.2	0.1	1	-0.9	-0.5	-0.7
-0.1	-0.2		-0.9	1	0.6	0.7
0.1	0.3		-0.5	0.6	1	
-0.2	-0.3	-0.1	-0.7	0.7		1



Abramowicz et al. ‘18



Amjad et al. ‘15



Bernreuther et al. ‘18

- Maybe worth to study quantitatively:

  CP-odd effects through observables where QCD resummation is mandatory

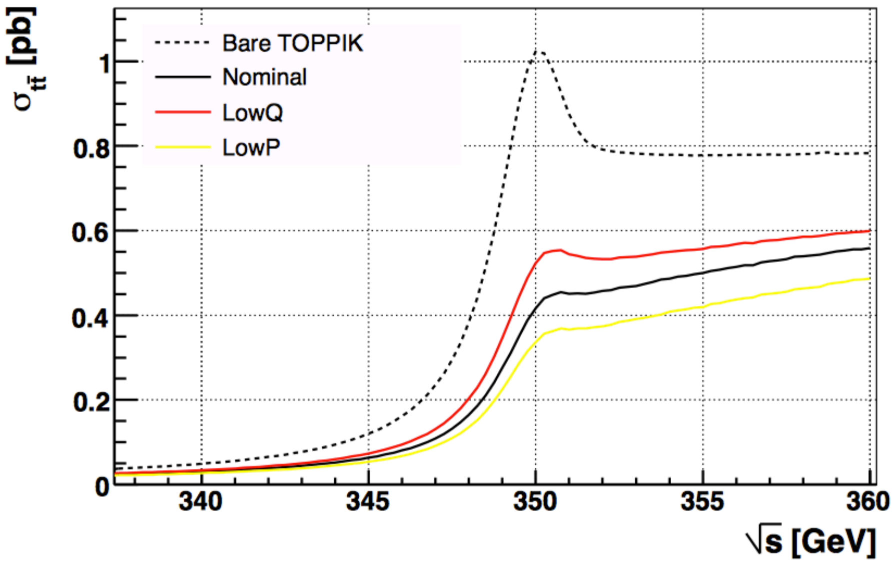
  (e.g. spin observables at the top threshold → large QCD phases) Jezabek, Nagano, Sumino. ‘00

See talks by Tevong You, Mojtab Mohammadi, Reza Goldouzian, Victor Miralles !
(Global interpretations session)

Top Threshold

Top pair total inclusive cross section:

$$\sigma(e+e- \to t\bar{t}+X) \text{ at } E_{cm} \approx 2m_t$$



Principle: m_t from $\sigma_{tt}(m_t)$

Advantages:

- count number of $t\bar{t}$ events
- color singlet state
- background is non-resonant
- physics well understood
  (renormalons, summations)

Crucial difference to top pairs at LHC

- Top decay protects from non-pert effects

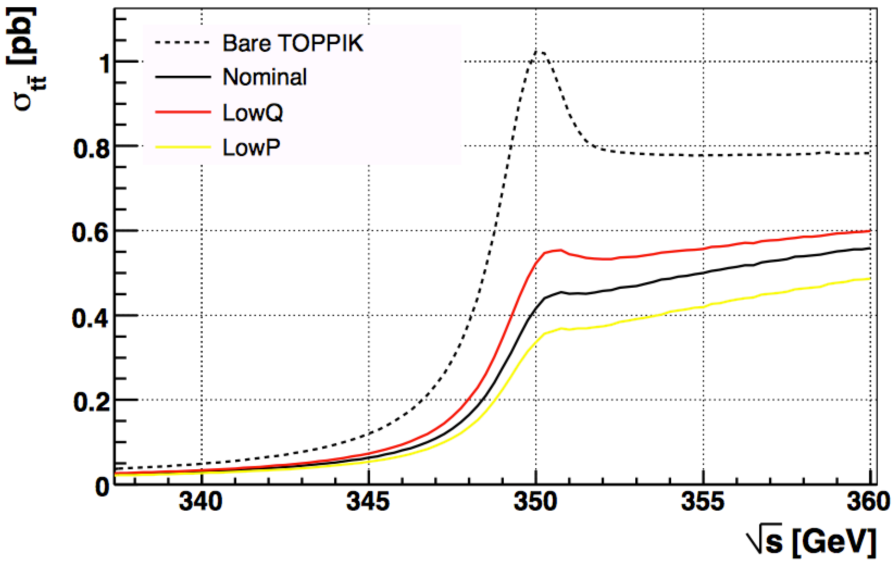
- Remnant of a topionium resonance (“postronium of QCD”): $R_{bind} = m_t \alpha_S \sim 30$ GeV
- Crucial to control e+e- luminosity spectrum
- Binding energy about twice the top quark width:
- Can be calculated in pQCD (nonrelativistic expansion)
- Non-resonant effects very small, little background

$$E_{\text{bind}} \approx \frac{\alpha_s^2 m_t}{2} \approx 2\Gamma_t$$

Top Threshold

Top pair total inclusive cross section:

$$\sigma(e+e- \to t\bar{t}+X) \text{ at } E_{cm} \approx 2m_t$$



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Advantages:

- ▷ count number of $t\bar{t}$ events
- ▷ color singlet state
- ▷ background is non-resonant
- ▷ physics well understood (renormalons, summations)

← Crucial difference to top pairs at LHC

- ➢ Top decay protects from non-pert effects

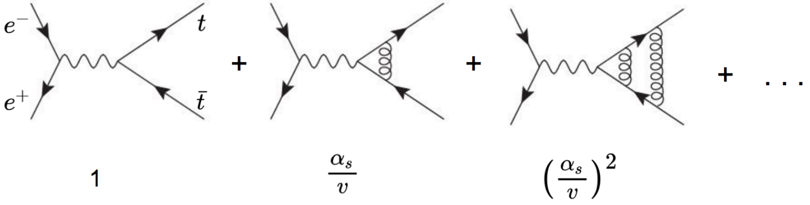
- The only observable know where a threshold structure with resolution $\ll$ 1 GeV is generated by QCD dynamics at much larger scale: $R_{bind} = m_t\,\alpha_S \sim 30$ GeV
- Color single state protects from non-perturbative effects.

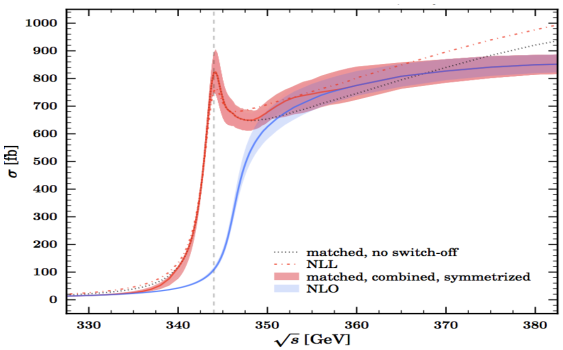
We could not be more lucky!

Unfortunately no such observable at the LHC !

Top Threshold

- Coulomb resummations
- Finite Width effects are leading order
- NRQCD effective field theory counting (α_S~v)





- Total cross section at NNLO (FO in α_S~v)
- Total cross section NNLO+NNLL (sum ln(α_S) ~ ln(v))
- Total cross section NNNLO

AHH, Beneke, Melnikov, Nagano, Ota, Penin, Pivovarov, Signer, Smirnov, Sumion, Teubner, Yakovlev, Yekhovsky ‘01

AHH, Stahlhofen, ‘13

Beneke, Kiyo, Marquard, Piclum, Steinhauser ‘13

- Non-resonant EW effects NNLL
- Non-resonant EW effects NNNLO$_{\text{partial}}$

AHH, Reisser, Ruiz-Femenia ‘04, ‘10

Beneke, Maier, Rauh, Ruiz-Femenia ‘17,

- Top p_t 3-momentum distribution NNLO
- Full differential: NLO+(N)LL in Whizard MC

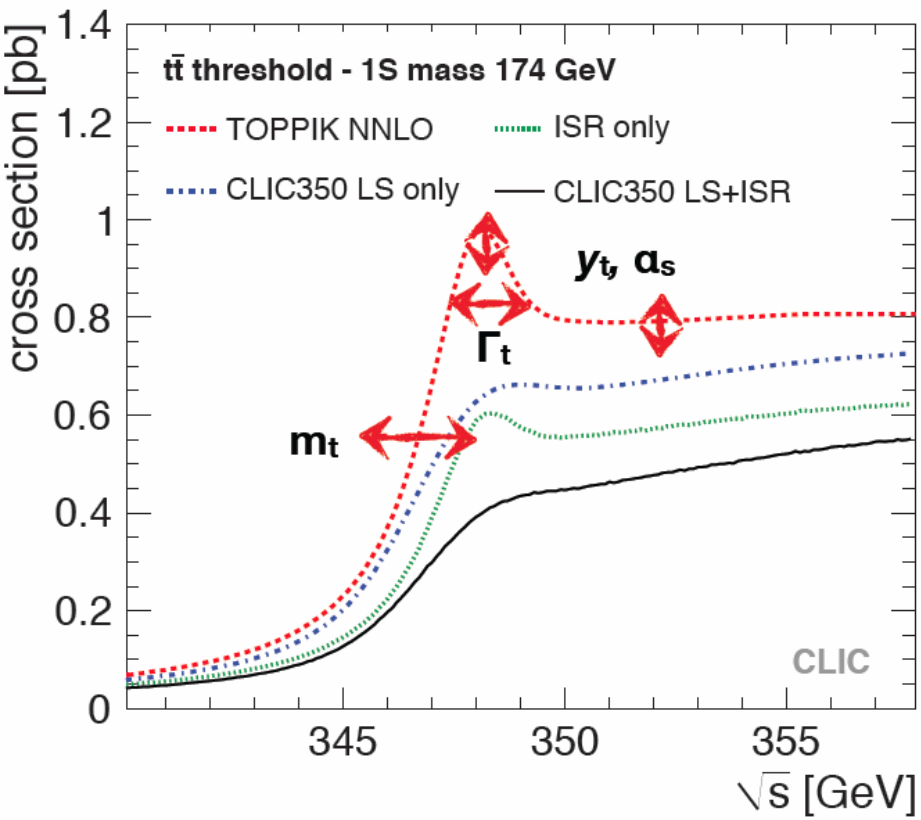
AHH, Teubner ‘00

Chokoufe, AHH, Kilian, Reuter, Stahlhofen, Teubner, Weiss‘17

Total cross section in very good shape.

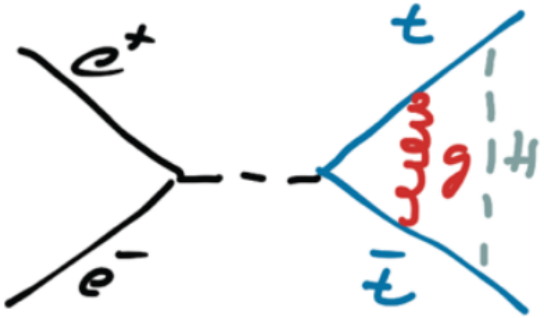
Top Threshold

Experimental Studies:



The cross-section around the threshold is affected by several properties of the top quark and by QCD

- Top mass, width, Yukawa coupling
- Strong coupling constant



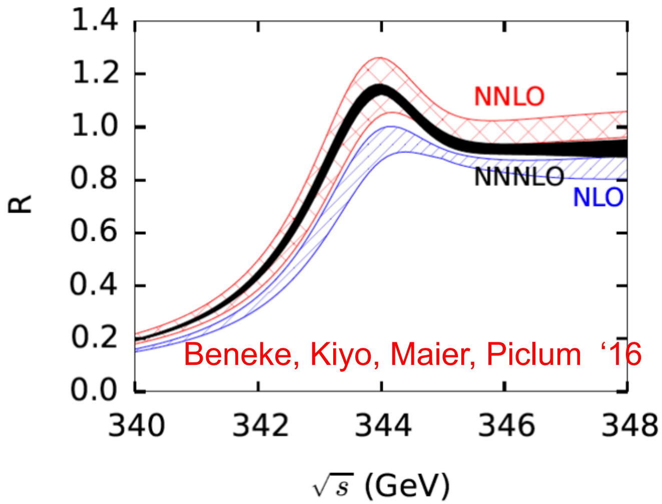
- Effects of some parameters are correlated; dependence on Yukawa coupling rather weak - precise external α_s helps

Frank Simon

Top Threshold

Experimental Studies (total inclusive cross section):

- Total cross section code NNNLO: QQbar_Threshold
- Dependence on the luminosity spectrum
- Use low-scale short-distance mass



Beneke, Kiyo, Maier, Piclum '16

- CLIC simulations study:

Abramowicz etal. '18

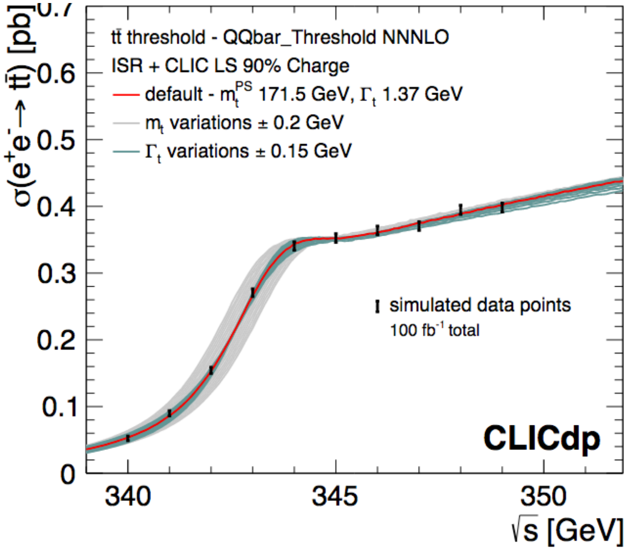
$\Delta m_t^{stat} \sim 40$ MeV, $\Delta m_t^{para} \sim 25 - 50$ MeV

$\Delta \Gamma_t^{stat} \sim 50$ MeV, $\Delta y_t^{para} \sim 50$ MeV

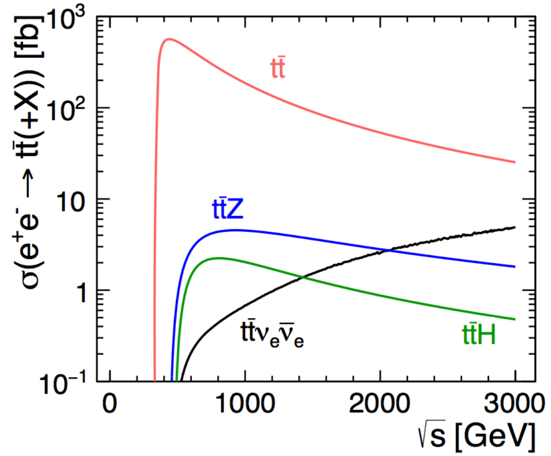
$\Delta y_t^{stat} \sim 10\%$

Very similar for all lepton colliders

See talk by Kacper Nowal (on optimized scan strategies)



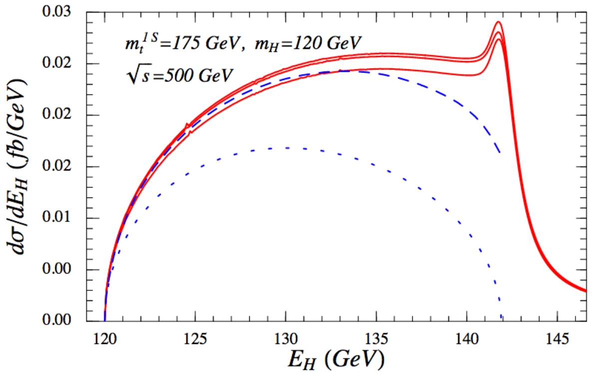
Associated Top Threshold Physics (I)



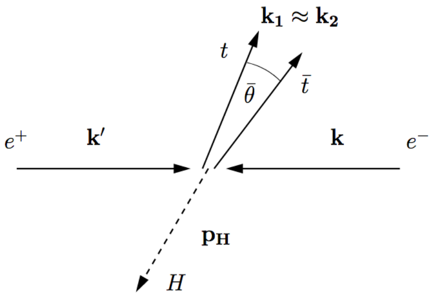
- A future e^+e^- collider with many associated ttbar thresholds
- Technology exists to extend ttbar threshold machinery to them, but much less event

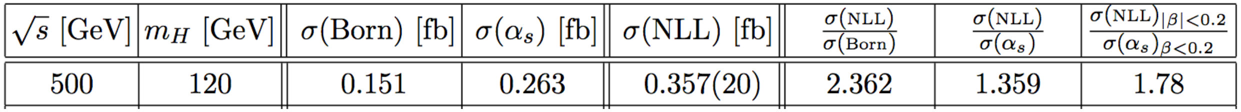
tt + H:

- NLO QCD — Dawson, Reina ‘17,
- NLO EW corrections — Dener, etal,, Belanger, etal. You, etal ‘03,
- NLL threshold enhancement — Farrell, AHH ‘05



- Kinematic threshold enhancement reaching far into the continuum region for associated tt production, enhances cross section
- Similar situation: tt + Z





$\sqrt{s}$ [GeV]	m_H [GeV]	σ(Born) [fb]	$\sigma(\alpha_s)$ [fb]	σ(NLL) [fb]	$\frac{\sigma(\text{NLL})}{\sigma(\text{Born})}$	$\frac{\sigma(\text{NLL})}{\sigma(\alpha_s)}$	$\frac{\sigma(\text{NLL})_{\lvert\beta\rvert<0.2}}{\sigma(\alpha_s)_{\beta<0.2}}$
500	120	0.151	0.263	0.357(20)	2.362	1.359	1.78

Farrell, AHH ‘05

Associated Top Threshold Physics (II)

tt + γ:

Boronat, Fullana, Juster, Gomis, Vos, AHH, Widl, Mateu ‘19

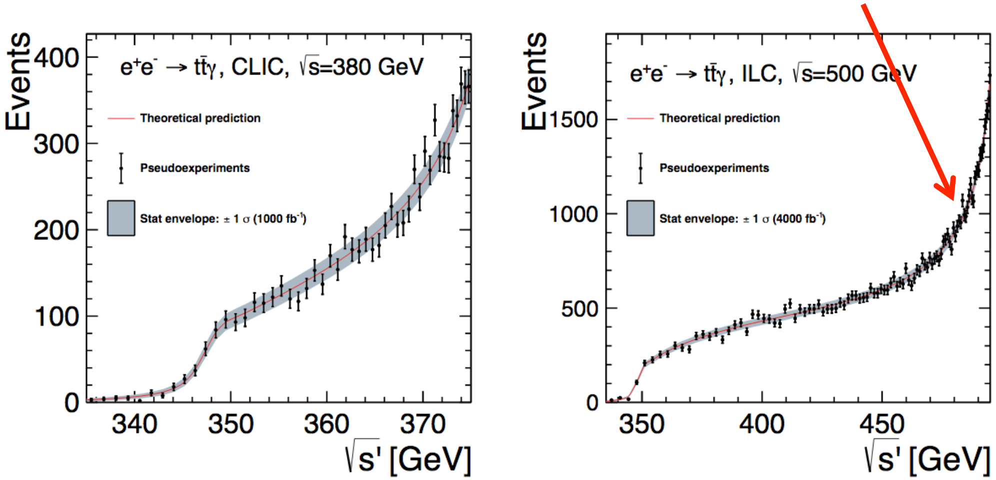
- Radiative return to the tt threshold allows for top threshold top mass measurements at higher energies.

$$\frac{d\sigma_{t\bar{t}\gamma}}{d\cos\theta\, d\sqrt{s'}} = 2\, g(x,\theta)\sqrt{\frac{1-2x}{s}}\,\frac{\alpha_{\rm em}}{\pi}\,\sigma_{t\bar{t}}(s')$$

$$x = \frac{E_\gamma}{\sqrt{s}}\,,$$

$$s' = s\left(1-\frac{2E_\gamma}{\sqrt{s}}\right)$$

ISR enhancement



- Matched threshold (NNLL+NNLO)-continuum (NNNLO) cross section
- Realistic simulation experimental analysis
- Statistics dominated

cms energy	CLIC, $\sqrt{s} = 380$ GeV		ILC, $\sqrt{s} = 500$ GeV	
luminosity [fb^{-1}]	500	1000	500	4000
statistical	140 MeV	90 MeV	350 MeV	110 MeV
theory	46 MeV		55 MeV	
lum. spectrum	20 MeV		20 MeV	
photon response	16 MeV		85 MeV	
total	150 MeV	110 MeV	360 MeV	150 MeV

Associated Top Threshold Physics

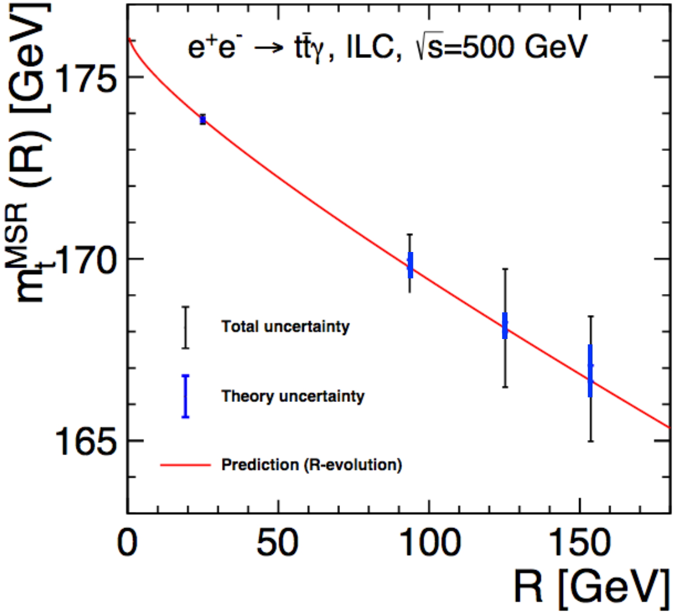
$t\bar{t} + \gamma$:

Boronat, Fullana, Juster, Gomis, Vos, AHH, Widl, Mateu ‘19

- Running MSR mass measurements

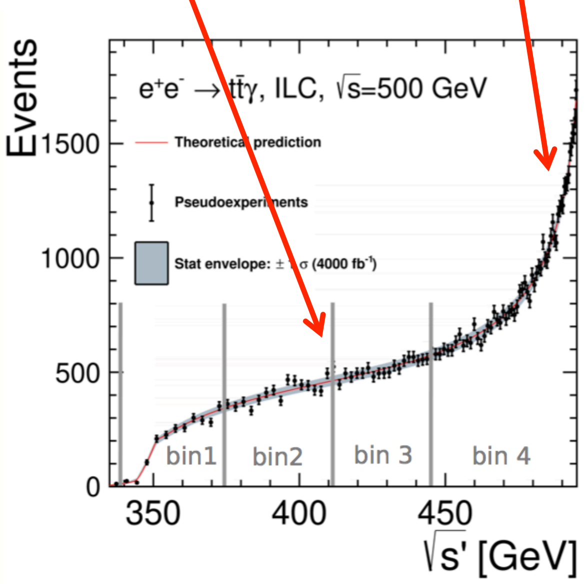
$$\frac{d\sigma_{t\bar{t}\gamma}}{d\cos\theta\, d\sqrt{s'}} = 2\, g(x,\theta)\sqrt{\frac{1-2x}{s}}\,\frac{\alpha_{\rm em}}{\pi}\,\sigma_{t\bar{t}}(s')$$

$$x = \frac{E_\gamma}{\sqrt{s}}\,, \qquad s' = s\left(1 - \frac{2E_\gamma}{\sqrt{s}}\right)$$



Probes top mass sensitivity at scales $m_f v < m_t$

ISR enhancement

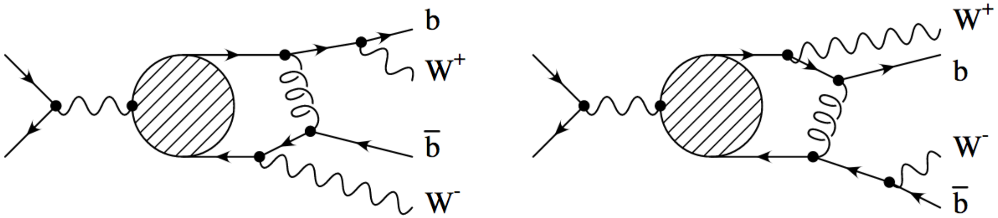


Top Threshold

Differential Cross Sections:

- Has not received much attention in the past, but important to correctly simulate experimental cuts
- Very (!) hard problem due to ultrasoft ($E \lesssim \Gamma_t$) gluon exchange between the top quarks and their decay products. They cancel in the fully inclusive cross section

Melnikov, Yakovlev '93



- Non-factorizable effects possible due to selection cuts (size unknown, but likely not large)

  Effects increase the more restrictive cuts are.

  Small for generous (wide) cuts

  Contribute at NLL/NLO order for differential cross section.

AHH, Reisser, Ruiz-Femenia '10

- Theoretically hard due to existence of Coulomb form factor that is defined in the non-relativistic limit only (usual subtraction techniques known from NLO-revolution do not apply)

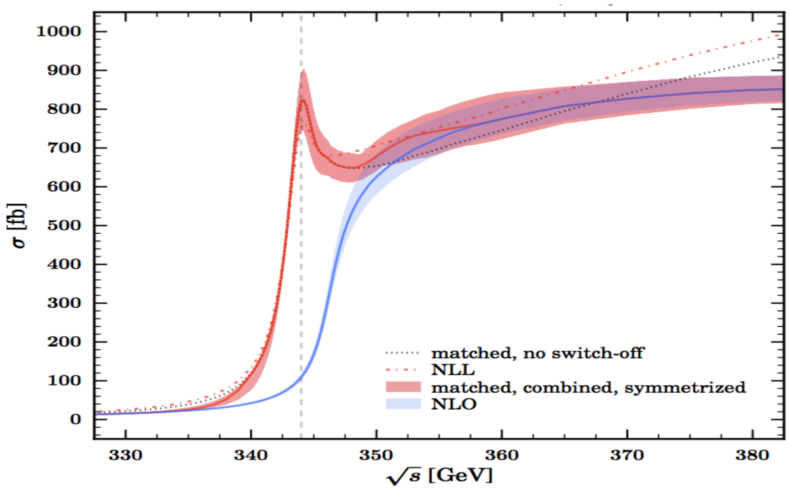
Top Threshold

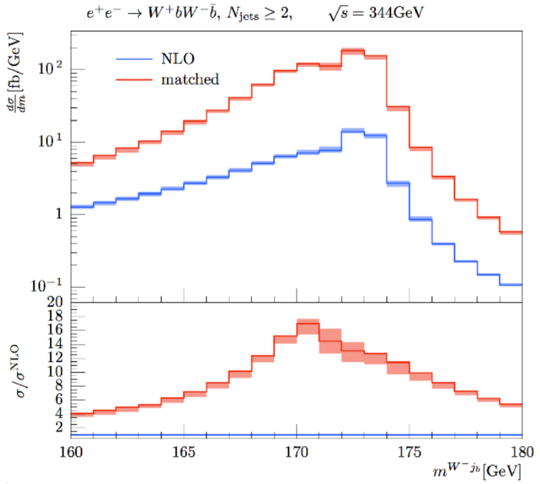
MC for Differential Cross Sections:

Bach, Nejad, AH, Kilian, Reuter '17

- NLO_{FO}+$\text{NLL}_{\text{threshold}}$ implementation in Whizard

- Whizard threshold implementation does NOT contain NLL ulrasoft effects ! Therefore NLO_{FO} + $\text{NLL}_{\text{threshold}}$ only for total cross section, NLO_{FO} + $\text{LL}_{\text{threshold}}$ otherwise.



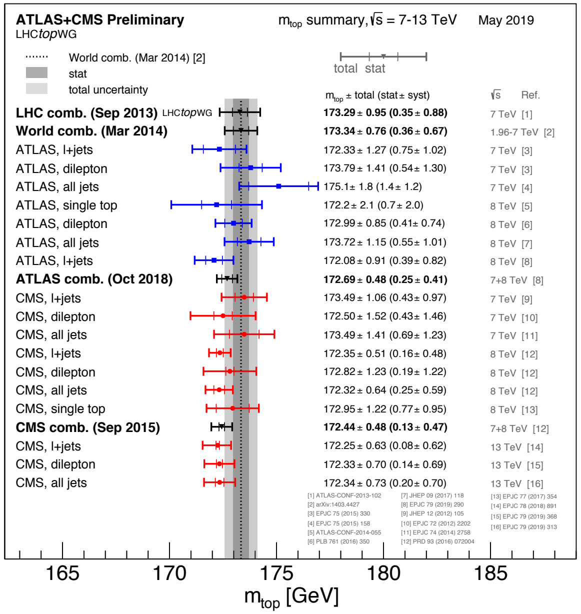


- Ultrasoft non-factorizable corrections still have to be added

- Important: state-of-the-art parton showers do not provide correct LL QCD resummation!

Top Mass from Direct Reconstruction

- Direct mass measurements (template or matrix element fits) are the moste precise method to determine the top mass at the LHC
- Variables (M_{lb}, m^{reco}) cannot be described by FO computation and are described completely by parton shower and hadronization dynamics in Monte-Carlo generators.
- Because MC have limited (observable dependent) precision the measured top mass m_t^{MC} cannot be a priori assigned to a particular mass scheme.



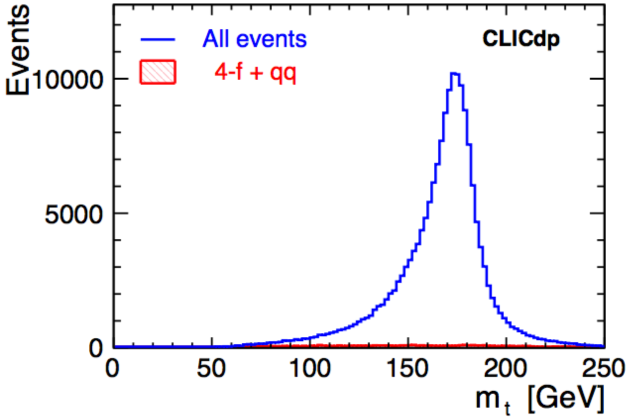
- The situation is not different at a lepton collider, but the systematic uncertainties are much smaller.

Abramowicz etal. 1807.02441

- CLIC simulation study: m_t^{reco} template fit E_{cm}= 380 GeV

$(\Delta m_t^{MC})^{stat} \sim$ 30 MeV $(\Delta m_t^{MC})^{syst} \sim$ 50 MeV

Competitive with threshold measurements.



Top Mass from Direct Reconstruction

Why bother given that we have the top threshold?

- For lepton collision is it much easier to understand the MC top mass interpretation problem and we can use the consistency with the threshold mass measurements as a benchmark to improve the intrinsic precision of MC generators and make them into much more reliable tools.

$$m_t^{\mathrm{MC}} = m_t^{\mathrm{pole}} + \Delta_m^{\mathrm{pert}} + \Delta_m^{\mathrm{non-pert}} + \Delta_m^{\mathrm{MC}}$$

pQCD contribution:

- Perturbative correction
- Depends on MC parton shower setup

analyzed in

Plätzer, Samitz, AHH 1807.06617

Non-perturbative contribution:

- Effects of hadronization model
- May depend on parton shower setup

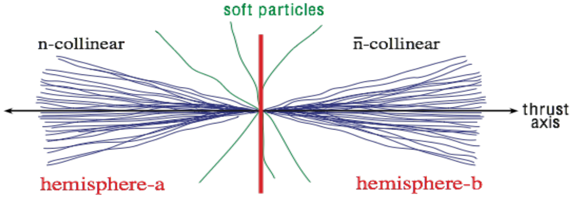
Monte Carlo shift:

- Contribution arising from systematic MC uncertainties not related to top
- E.g. b-jet modeling, finite width, ...

Top Mass from Direct Reconstruction

Plätzer, Samitz, AHH '18

- Analytic parton-level analysis of QCD factorization calculation (NLL') and the Herwig angular-ordered parton shower for the 2-jettiness τ_2 distribution for boosted top pair production in the NWA



1. Herwig shower is NLL precise for τ_2.
2. Definition of generator mass can be computed by comparison to NLL' QCD calculation.
3. Generator mass $m_t^{CB}(Q_0)$ depends on the shower cut Q_0=1.25 GeV.

$$\boxed{m_t^{\rm CB}(Q_0) = m_t^{\rm pole} - \frac{2}{3}Q_0\alpha_s(Q_0) + \mathcal{O}(\alpha_s(Q_0)^2)}$$

$$m_t^{\rm MSR}(Q_0) - m_t^{\rm CB}(Q_0) = 120 \pm 70\ \text{MeV}$$

$$m_t^{\rm pole} - m_t^{\rm CB}(Q_0) = 480 \pm 260\ \text{MeV}$$

- First step of a general long-term project (work in progress, progress expected)
- Result shows that the question is very relevant also for LHC.

Conclusions

- Many useful calculations and tools already exist.
- By the time a future LC comes into operations, however, many additional theoretical developments are needed to take full advantage of the high level of precision expected in the experimental measurements.
- Boosted top quarks are ideal to make (QCD+ew) resummed and hadron level predictions that can be used for experimental analysis or as a tool to test other less precise tools such as Monte-Carlo event generators.
- The top quark Monte-Carlo mass problem can be more easily resolved for a LC than for the LHC.

There are still many interesting unresolved problems to work on to sharpen the theoretical tools for FCC and other future lepton colliders.

Development of a new generation of more precise Monte-Carlo generators must receive high priority and more appreciation in the community as being theory work that is valuable by itself (such as loop calculations).

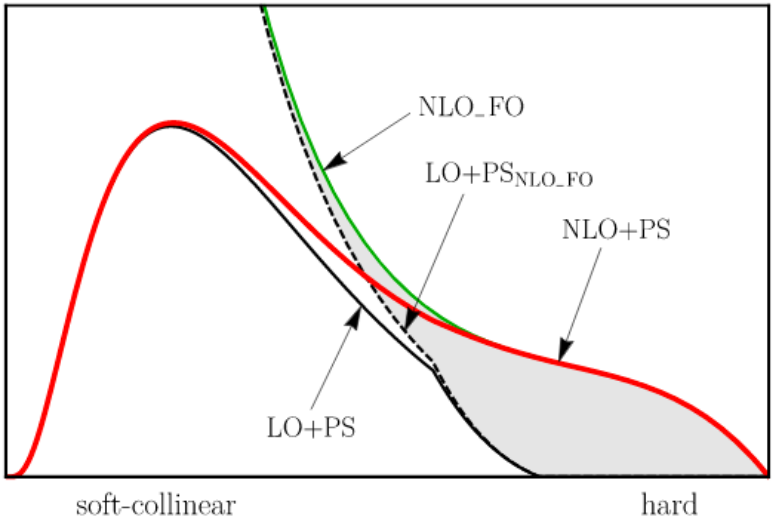
Backup Slides

Status of Top Mass Determinations at the LHC

- NLO matched MC:
  - MadGraph5_aMC@NLO — Alwall etal. '14
  - POWHEG — Alioli, Nason, Oleari, Re '10

→ common: set $m_t^{MC} = m_t^{pole}$ in NLO-matched MCs
(when m_t^{pole} is used for the hard NLO MEs)

→ elevates the first hard emission
($p_{trans} \gtrsim$ 10 GeV) to NLO precision



→ diff. cross sections dominated by soft and collinear radiation not improved:
m_t^{MC} has same meaning as for unmatched MC

→ observables used for direct top mass not improved by NLO-matching

- xx