Precision calculations for CLIC Physics

Alexander Mitov

Cavendish Laboratory

UNIVERSITY OF CAMBRIDGE

Context

- ✓ (My viewpoint) In all likelihood, few years down the road a decision will have to be made

Which future collider to build?

  - ✓ A higher-energy hadron collider? (100 TeV too expensive? Scaled-down version~30 TeV?)
  - ✓ e^+e^- (CLIC?)

- ✓ The physics case will need to be made and it may involve direct comparison between the two

- ✓ How to view precision calculations from BSM perspective:

  1. Compute things that *can* be computed
  2. Compute things that *need* to be computed

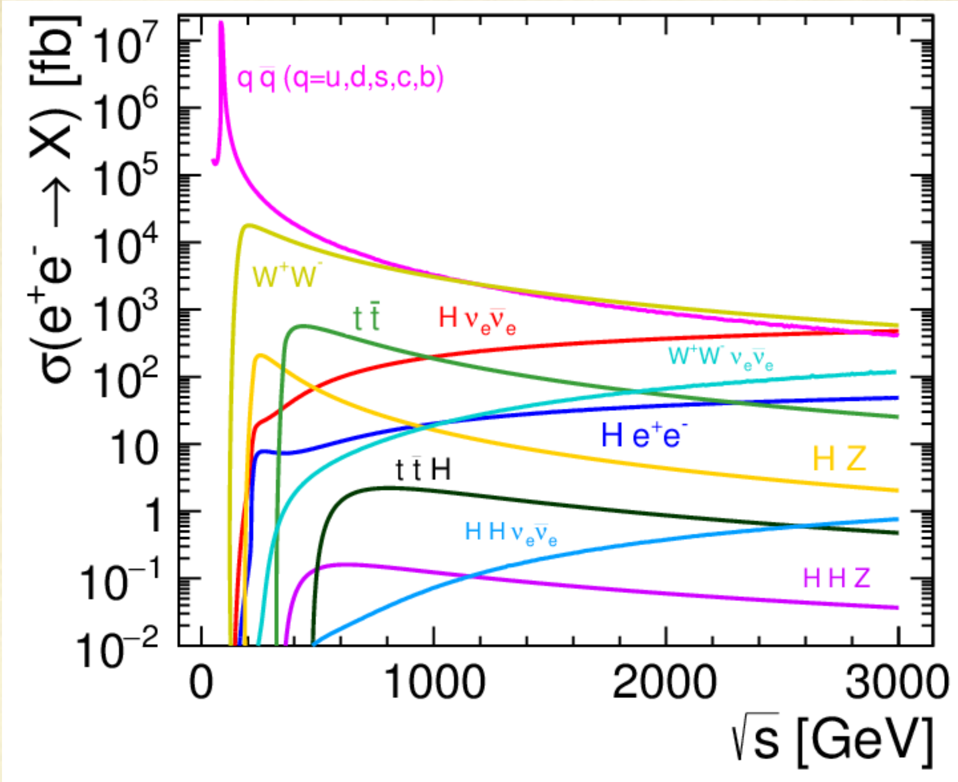
- ✓ In this talk:

  - ✓ An overview of 1., together with some predictions/extrapolations for the far future
  - ✓ Emphasize the importance of 2. as an input from BSM.

"No problem is too big when it is important enough!"

- ✓ Precision calculations are critical – all past colliders (including LHC) are a testament for this

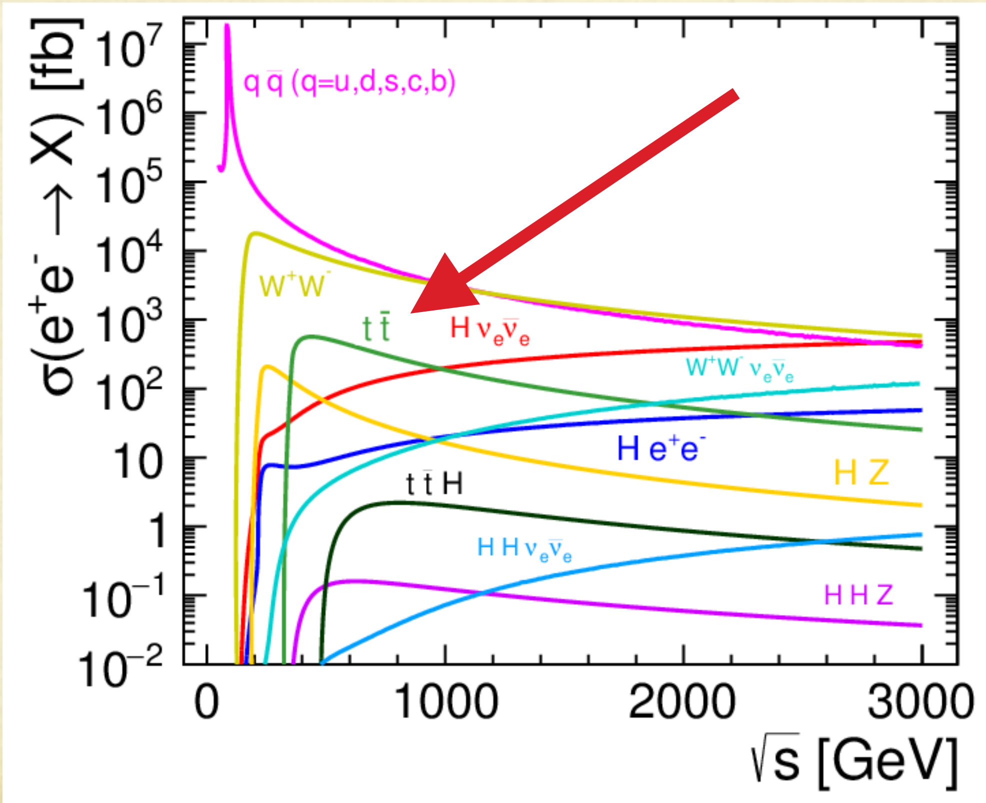
Contents



- ✓ Top physics
  - ✓ N^{3}LO result
  - ✓ Extraction of top mass and width
- ✓ Top and Higgs: extraction of the top-Yukawa
- ✓ Higgs
- ✓ Jet production: taming QCD and measuring α_S
- ✓ W mass and width from WW threshold scan
- ✓ EW precision observables
- ✓ Event generators
  - ✓ GigaZ-like physics: re-measuring much better well-known SM stuff might be needed.

Top production

See also talk by Christoph Englert



3

Stable tops

- ✓ Total inclusive cross-section known at NNLO for a long time (expansion in m/s or numerically):

  Chetyrkin, Kühn, Steinhauser '96
  Harlander, Steinhauser '98

- ✓ NLO EW also known for a long time

  [Beenakker, Hollik, Denner, Dittmaier: since '91]

- ✓ *Fully differential* top-pair production in full NNLO QCD (with stable tops) in the continuum

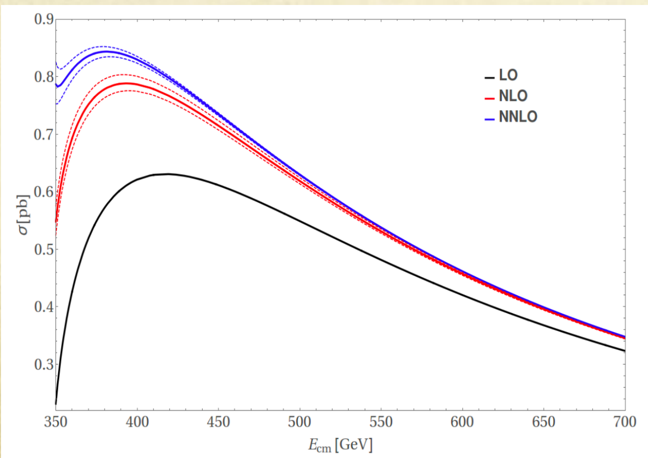
  Gao, Zhu '14
  Chen, Dekkers, Heisler, Bernreuther, Si '16

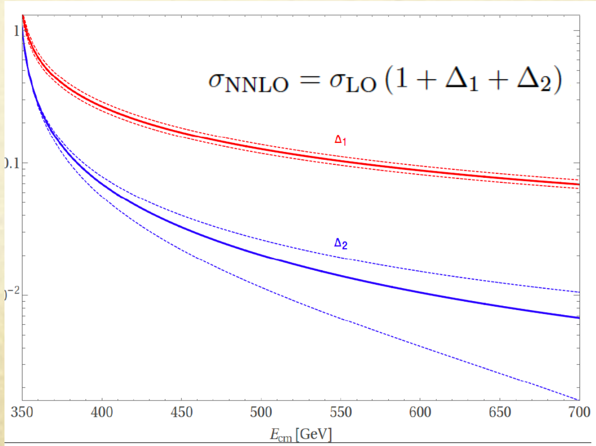
  - ✓ Computed, respectively, within:
    - ✓ Phase-space slicing method
    - ✓ Antenna-subtraction method

  - ✓ No EW corrections included
  - ✓ No tttt final states included
  - ✓ (The well known) lack of convergence close to threshold is evident

  Fadin, Khoze '87
  Strassler, Peskin '91
  Jezabek, Kühn, Teubner '92

From: Chen, Dekkers, Heisler, Bernreuther, Si '16



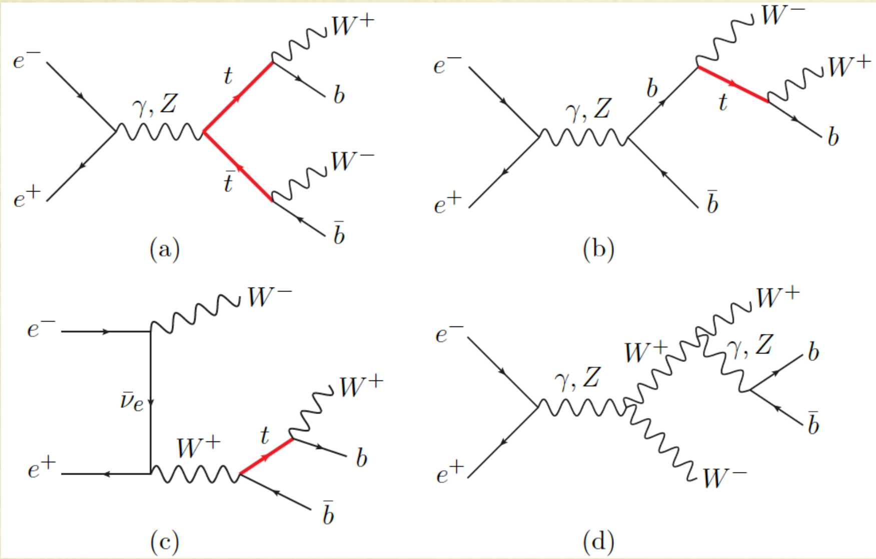


Adding top decay

- ✓ No NNLO QCD result available yet (but it is really easy to do in NWA)
- ✓ Top production and decay in NLO QCD known for a long time

Carl Schmidt '95

- ✓ Thanks to recent advances, full off-shell production $e^+e^- \to WbWb$ available in NLO QCD



Guo, Ma, Zhang, Wang '08
O. Mattelaer, [MadGraph5 AMC@NLO] '14
Weiss, Nejad, Kilian, Reuter [WHIZARD] '15

- ✓ Included are all intermediate states, including single top and no-top

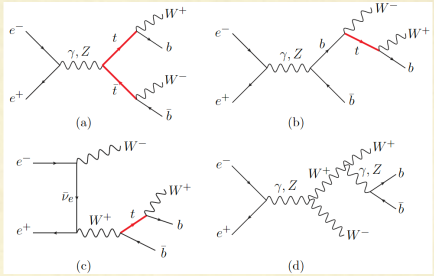
5

Top width

- ✓ NLO QCD — Jezabek, Kuhn '89
- ✓ NNLO QCD — Czarnecki et al '10
- ✓ Measure it with ratios of resonance contributions of $e^+e^- \to W^+W^-bb$

Liebler, Moortgat-Pick, Papanastasiou '15

- ✓ Idea: $$\frac{\sigma^{\text{single-resonant}}}{\sigma^{\text{double-resonant}}} \propto \Gamma_t$$

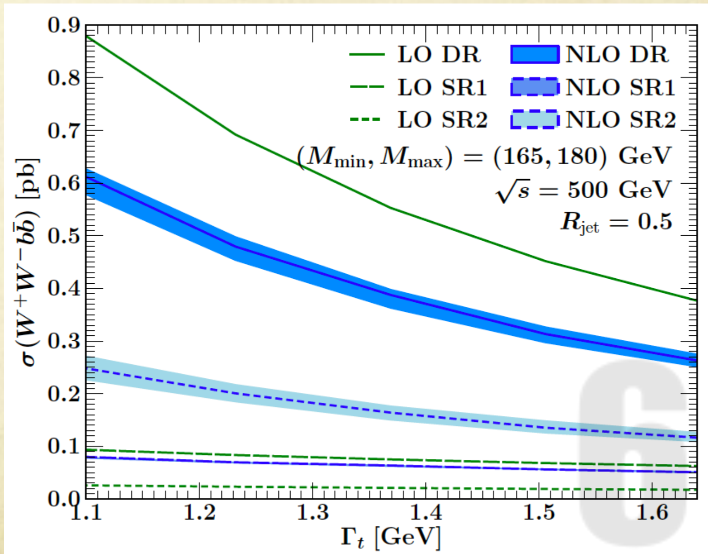


- ✓ We cannot divide diagrams!
- ✓ They can be correlated with kinematic regions for the distribution:

$$\frac{d^2\sigma^{e^+e^-\to W^+W^-b\bar{b}}}{dM(W^+,J_b)\,dM(W^-,J_{\bar{b}})}$$

$$\begin{aligned}
&\text{double resonant:} && M(W^+,J_b)\sim m_t^2 \;\text{ and }\; M(W^-,J_{\bar{b}})\sim m_t^2\\
&\text{single resonant:} && M(W^+,J_b)\sim m_t^2 \;\text{ and }\; \left\{M(W^-,J_{\bar{b}})\ll m_t^2 \;\text{ or }\; M(W^-,J_{\bar{b}})\gg m_t^2\right\}\\
&\text{single resonant:} && \left\{M(W^+,J_b)\ll m_t^2 \;\text{ or }\; M(W^+,J_b)\gg m_t^2\right\} \;\text{ and }\; M(W^-,J_{\bar{b}})\sim m_t^2\\
&\text{non resonant:} && \left\{M(W^+,J_b)\ll m_t^2 \;\text{ or }\; M(W^+,J_b)\gg m_t^2\right\} \;\text{ and }\\
& && \left\{M(W^-,J_{\bar{b}})\ll m_t^2 \;\text{ or }\; M(W^-,J_{\bar{b}})\gg m_t^2\right\}.
\end{aligned} \qquad (3.1)$$

An example:



- ✓ Calculation at NLO with aMC@NLO

B-fragmentation and top decay

- ✓ Detailed study of B-production in top decay requires precision beyond current showers
- ✓ Dedicated study in NLO QCD
  Corcella, Mitov '02
- ✓ Could nowadays be extended to full NNLO + NNLL (soft) + NNLL (collinear) due to:
  - ✓ Top decay at NNLO
    Gao, Li, Zhu '12
    Brucherseifer, Caola, Melnikov '13
  - ✓ Soft-gluon resummation at NNLL
    Cacciari, Catani '01
    Andersen, Gardi '04
  - ✓ Perturbative fragmentation function at NNLO
    Mele, Nason '91
    Melnikov, Mitov '04
  - ✓ Time-like splitting functions at NNLO
    Dokshitzer, Marchesini, Salam '05
    Mitov, Moch, Vogt '06
- ✓ Dedicated ongoing work for adding fragmentation functions a-la LHAPDF by NNPDF collaboration

High-energies: top jets

- ✓ Top jets with NNLL resummation have been investigated within SCET in

  Fleming, Hoang, Mantry, Stewart '16

- ✓ Of interest is the distribution

$$\frac{d^2\sigma}{dM_t^2\, dM_{\bar{t}}^2}$$

Where:

$$M_t^2 = \Big(\sum_{i\in X_t} p_i^\mu\Big)^2$$

$$M_{\bar{t}}^2 = \Big(\sum_{i\in X_{\bar{t}}} p_i^\mu\Big)^2$$

and for $Q \gg m \gg \Gamma$

- ✓ Of primary interest is m_{top} determination but also jet shapes etc.

- ✓ In the future it should be possible to match this to a full NNLO prediction

Nearly massless identified tops

- ✓ At large c.m. energy Q>>m, top production will be dominated by large log(Q/m)
- ✓ Large means that: $\alpha_S(Q)\,\log(Q/m) \sim 1$
- ✓ For observables with identified tops, this will lead to large corrections that need to be resummed.
- ✓ This is routinely done for b-production: FONLL

  Cacciari, Greco, Nason '98-

- ✓ But never before for top
- ✓ First partial applications at the LHC have appeared only recently

  Ferroglia, Pecjak, Li Lin Yang '15-

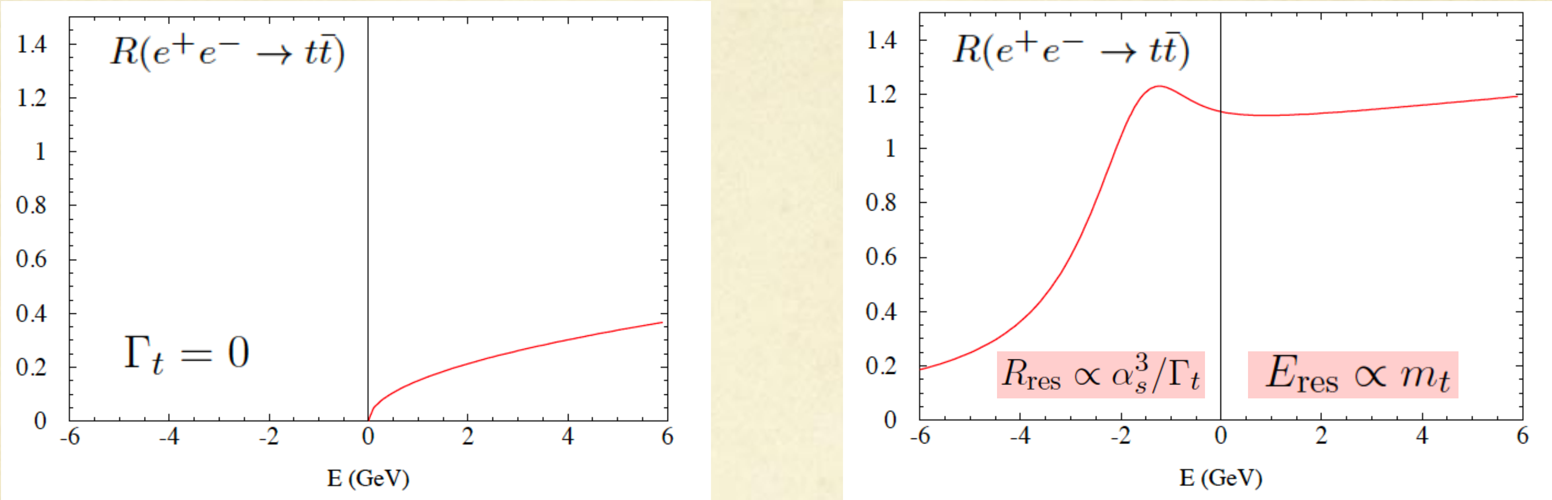
- ✓ As mentioned before, all ingredients for a consistent study at NNLL are available now.

Top at threshold

Life is better when sitting on top of a singularity!

- ✓ A threshold scan gives very clean direct access to:
  - ✓ Top mass
  - ✓ Top width

Plots courtesy of A. Penin



- ✓ Long history of calculations in NRQCD [Pineda, Soto '97] at NNLO:

Hoang, Teubner '98
Melnikov, Yelkhovsky '98
Penin, Pivovarov '98
Beneke, Signer, Smirnov '99
Nagano, Ota, Sumino '99

- ✓ The long list of papers resulted in unprecedented "concordance" paper

Hoang et al hep-ph/0001286

- ✓ Calculations were done with pole mass. Poor convergence. Improved by using running masses

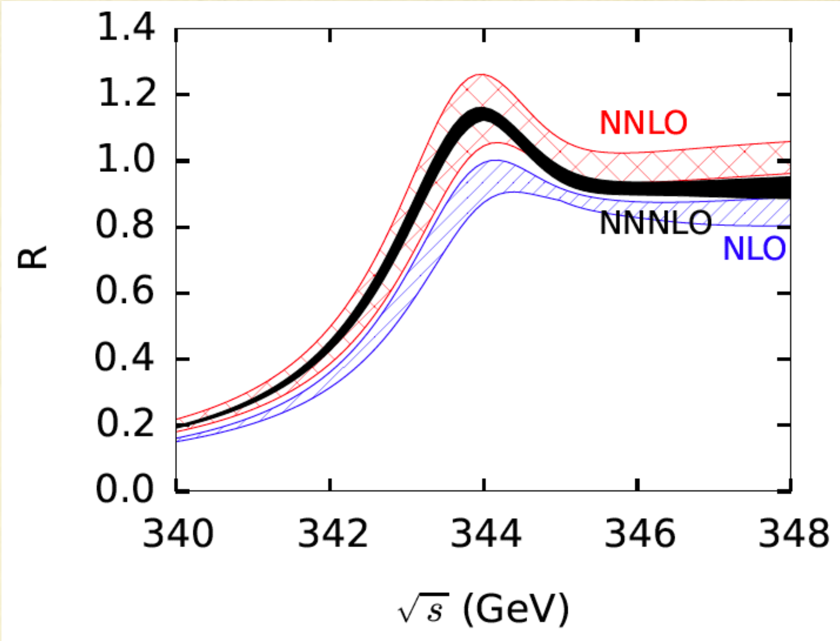
Beneke '98

Total x-section at N3LO

- ✓ A major progress in the last few years: inclusive cross-section now computed in N3LO

  Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser '15

- ✓ Results incorporates a number of partial results



- ✓ Since at threshold $\alpha_S/v \sim 1$,

- ✓ also included is NNLL resummation of log(v) terms

  Hoang, Manohar, Stewart, Teubner '01
  Pineda, Signer '06
  Hoang, Stahlhofen '13

- ✓ Corrections to:
  - ✓ The peak position:

$$E_{res} = E_{res}^{LO}\left[1 + 3.201\alpha_s + 16.434\alpha_s^2 + (15.300\ln\alpha_s + 84.858)\,\alpha_s^3\right]$$

  - ✓ The peak cross-section:

$$\begin{aligned} R_{res} &= R_{res}^{LO}\left[1 - 2.131\alpha_s + (-7.256\ln\alpha_s + 8.375)\alpha_s^2\right. \\ &\quad \left. - \left(16.352\ln^2\alpha_s + 0.682\ln\alpha_s + 66.793\right)\alpha_s^3\right] \end{aligned}$$

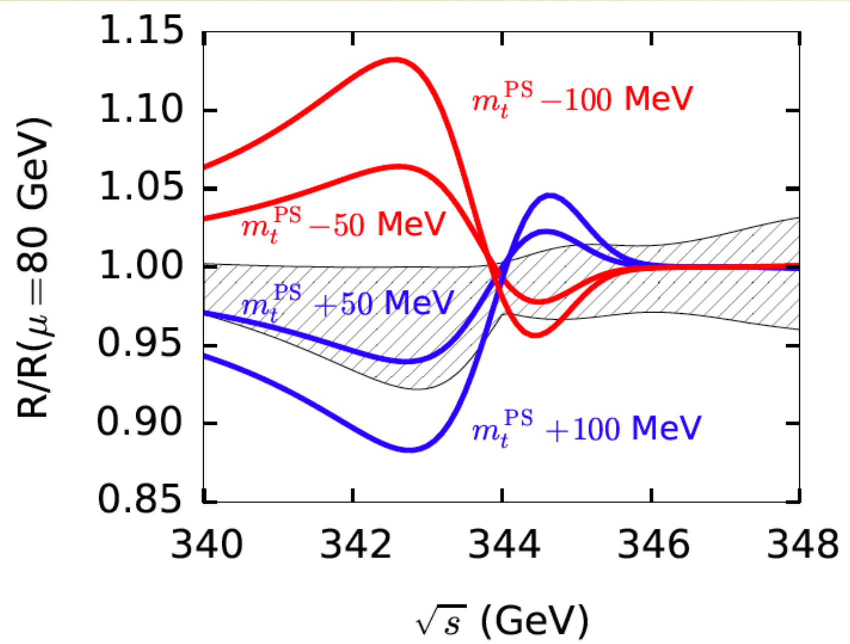
Numbers from:
Penin, Zerf arXiv:1401.7035
(With thanks to A. Penin)

Total x-section at N³LO

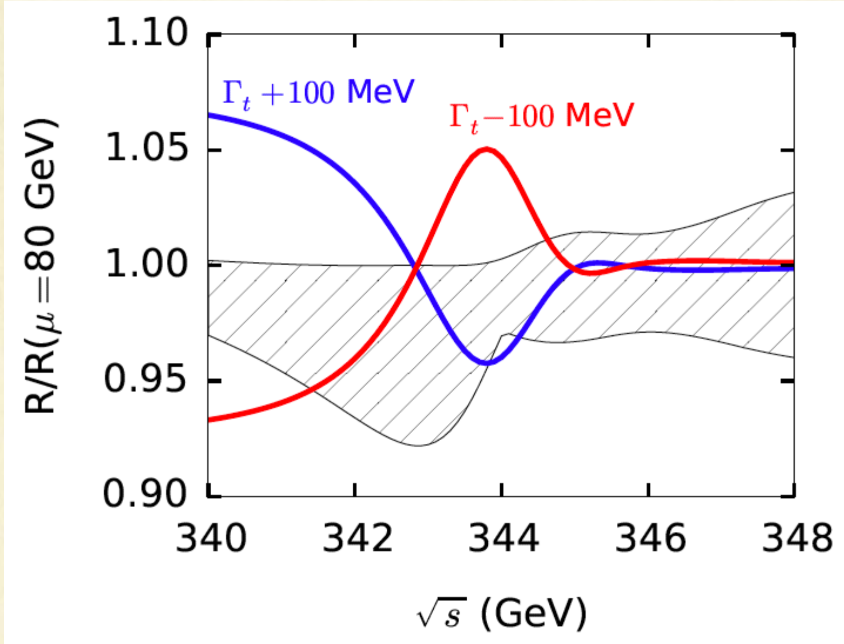
✓ Improved sensitivity to top mass/width at N³LO:

Beneke, Kiyo, Marquard, Penin, Piclum, Steinhauser '15

Top mass



Top width



✓ Results in terms of PS mass. Can be related to MSbar mass with ~ 20 MeV error.

Numeric inputs:

$$m_t^{\rm PS}(\mu_f = 20\,{\rm GeV}) = 171.5\ {\rm GeV},\ \Gamma_t = 1.33\ {\rm GeV},$$
$$\alpha_s(M_Z) = 0.1185 \pm 0.0006\,.$$

μ – renormalization scale varied in [50GeV – 350GeV]

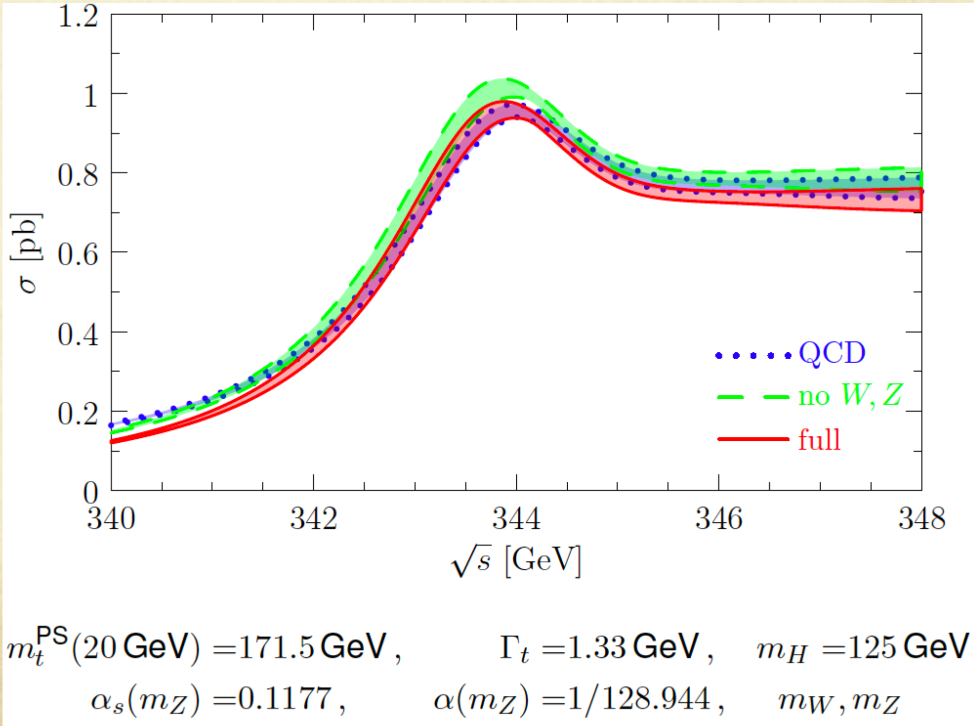
Total x-section at N^{3}LO

- ✓ Public code at N^{3}LO: **QQbar_threshold**

Beneke, Kiyo, Maier, Piclum ‘16

- ✓ N^{3}LO QCD and partial electroweak corrections
- ✓ Non-resonant contributions at NLO
- ✓ Works for top and bottom quarks
- ✓ Various mass schemes: PS, 1S, MS, pole
- ✓ Loose invariant Wb mass cut: $(m_t - m_{Wb})2 >> \Gamma_t m_t$
- ✓ …
- ✓ Still missing: initial state radiation (structure function approach)

Example:
effect of EW corrections



Top mass: precision and scheme dependence

- ✓ Computing in terms of the pole mass is easy and natural.
- ✓ However, that particular mass has non-perturbative corrections that restrict its ultimate precision
- ✓ Recent estimate based on the 4-loop relation: pole mass <--> Msbar mass

Marquard, Smirnov, Smirnov, Steinhauser '15

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

Assuming: $\overline{m}_t = m_t(\overline{m}_t) = 163.643\ \mathrm{GeV}$ and $\alpha_s^{(6)}(m_t) = 0.1088$

- ✓ Exploring the leading asymptotic behavior of the above relation

Beneke '94

- ✓ One can derive an improved relation which predicts (approximately) higher terms in the above expansion.

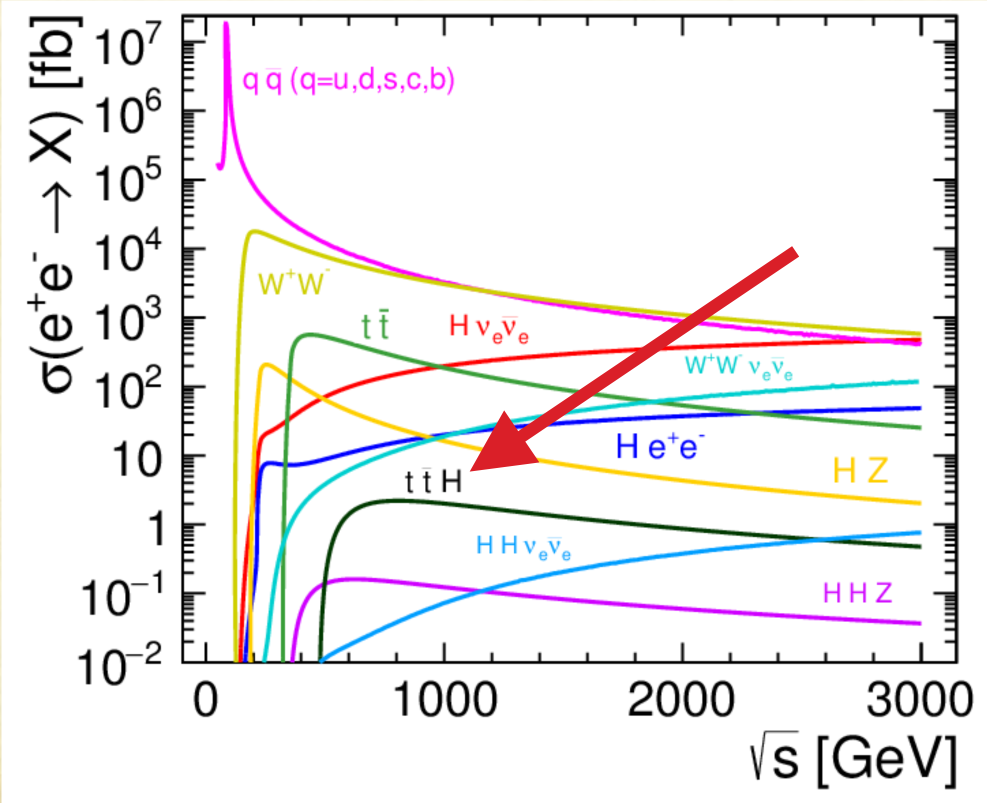
Beneke, Marquard, Nason, Steinhauser '16

- ✓ The ultimate precision is taken for the term where the term-to-term difference is smallest
  - ✓ Error from the terms beyond 4 loops: ~ 250 MeV
  - ✓ Ultimate intrinsic error in the above relation: ~ 70 MeV

However see new work by A. Hoang et al. '17

- ✓ Very important at e^+e^- colliders

Top and Higgs



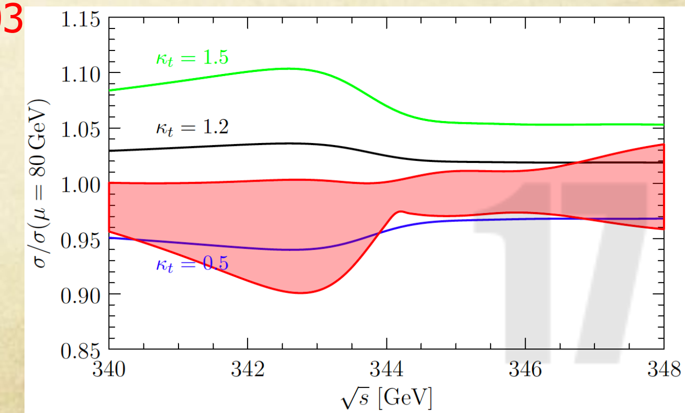
Top and Higgs

- One of the main goals of a future e^+e^- machine is to run at around 500 GeV and measure the Higgs coupling to top
  - This requires good understanding of top production in the continuum
  - Expectations for top-Yukawa precision:
    - 3-4% (compared to 10% at HL-LHC) Azzi et al arXiv:1703.01626
    - 1% at Fcc-hh (from ttH/ttZ) Mangano, Plehn, Reimitz, Schell, Shao ‘15
  - Somewhat surprising comparison; this may not be the last word on this (one is absolute measurement; the other a ratio)
- Lots of studies in NLO QCD + EW already. Dedicated event generators:
  - aMC@NLO
  - WHIZARD

$$\frac{\Delta y_t}{y_t} = \kappa \frac{\Delta\sigma}{\sigma}$$

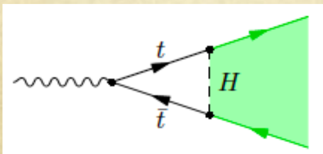
In SM: k~ 0.5

- Many dedicated calculations:
  - NLO QCD Dawson, Reina ‘98
  - EW corrections Denner et al.; Belanger et al., You et al. ‘03
  - NLL threshold logs Farrell, Hoang ‘05



- There is some sensitivity to the value of the top-Yukawa already from $e^+e^- \rightarrow tt$ at threshold:

From diagrams like:



Figures courtesy of A. Maier (2016)

Top and Higgs

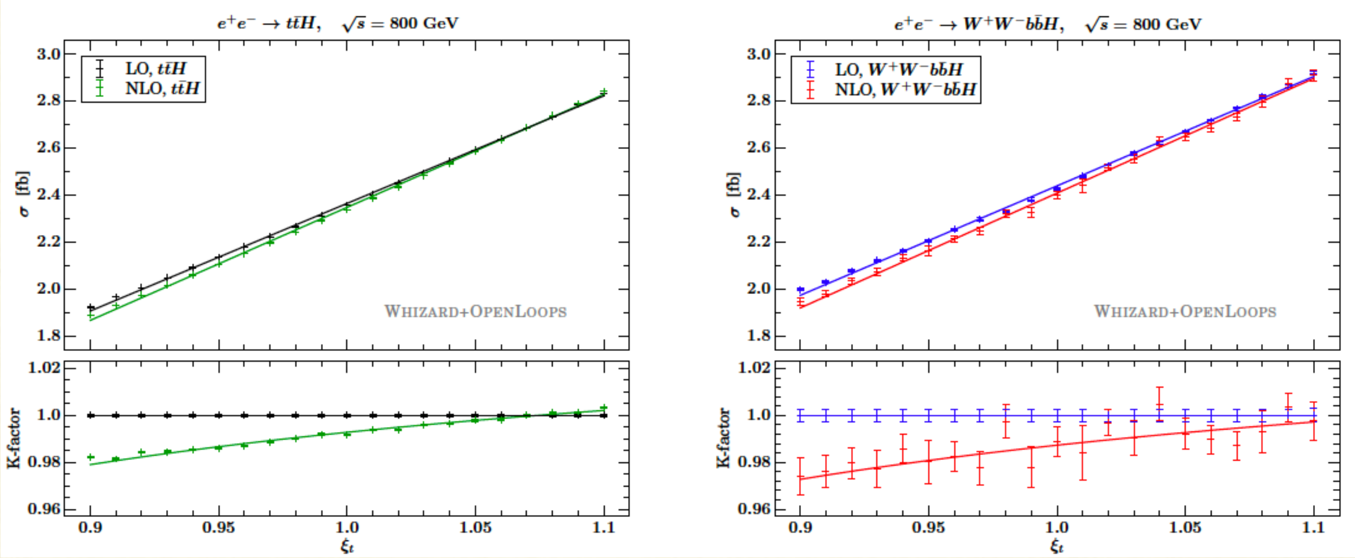
✓ Extensive recent study (WHIZARD MC event generator):

Chokouf Nejad, Kilian, Lindert, Pozzorini, Reuter, Weiss '16

✓ Few % sensitivity to y_t possible from ttH:

Define: $$\frac{\Delta y_t}{y_t} = \kappa \frac{\Delta\sigma}{\sigma}$$ with $$y_t = \xi_t y_t^{\mathrm{SM}}$$ where: $$y_t^{\mathrm{SM}} = \sqrt{2} m_t / v$$

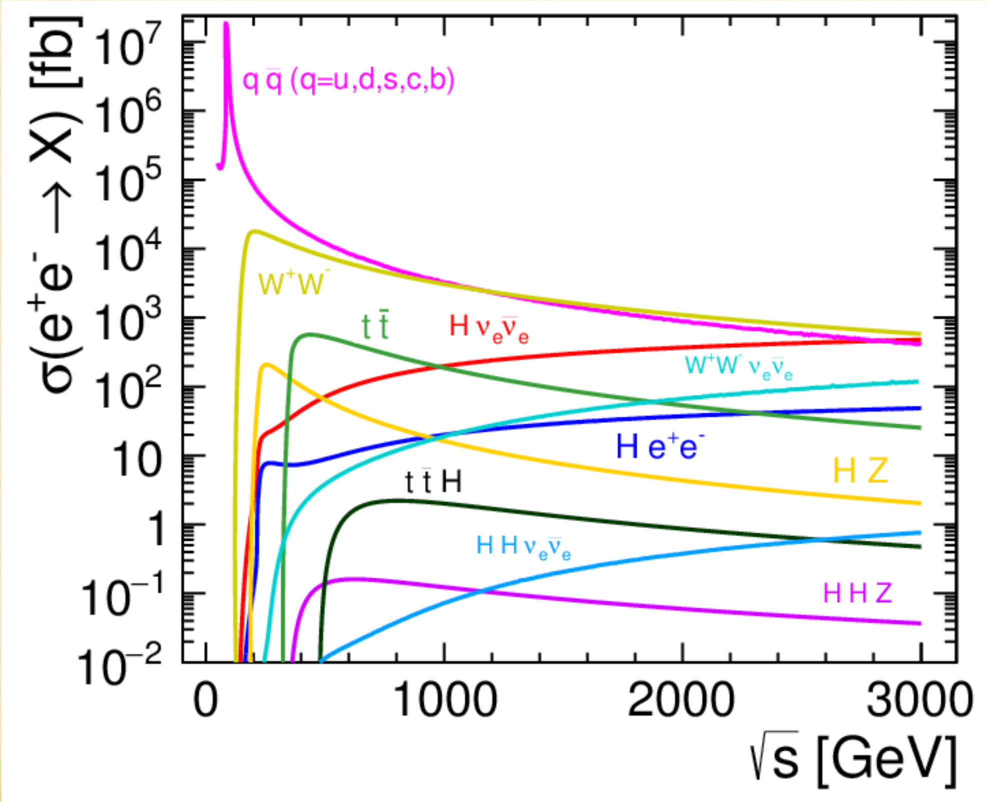
Current precision benchmark for stable and off-shell tops:



$e^+e^- \to$	κ^{LO}	κ^{NLO}	$\kappa^{\mathrm{NLO}}/\kappa^{\mathrm{LO}}$
$t\bar{t}H$	0.514	0.485	0.943
$W^+W^-b\bar{b}H$	0.520	0.497	0.956

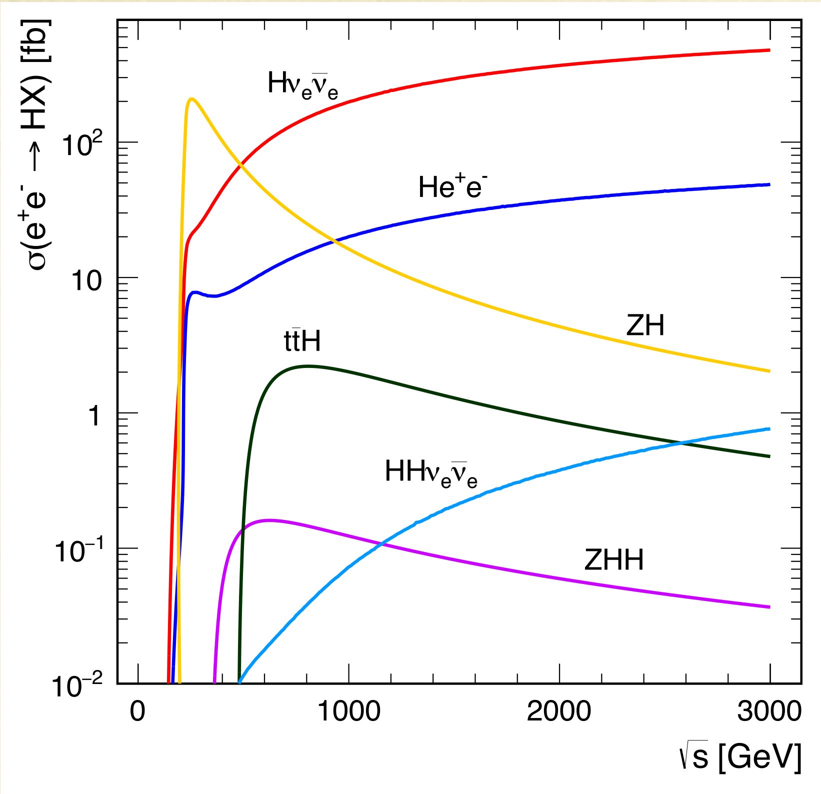
✓ Theory improvement possible: NNLO QCD within reach in the near future!

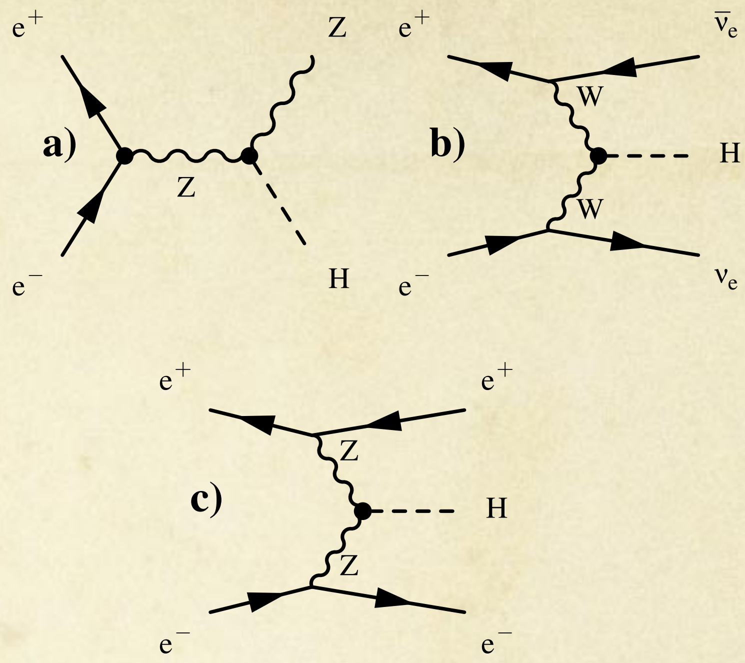
Higgs production

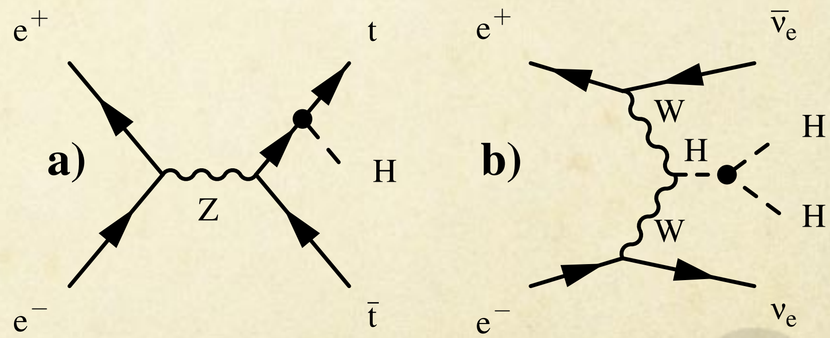


Higgs

✓ Main production channels:







From: arXiv:1608.07538

Higgs

- These are EW processes, so mostly NLO EW corrections enter
- These are available in NLO MC programs like WHIZARD and aMC@NLO
- Some higher order effects are needed and can be included
  - Photon radiation, photon initiated processes, etc.
- QCD enters through Higgs decay which is known through NNLO
- QCD corrections may become important in hadronic backgrounds to
  - HH, with: H->qq
  - H+X
- 4 jet production is known at NLO only (more later) but feasible at NNLO for the future

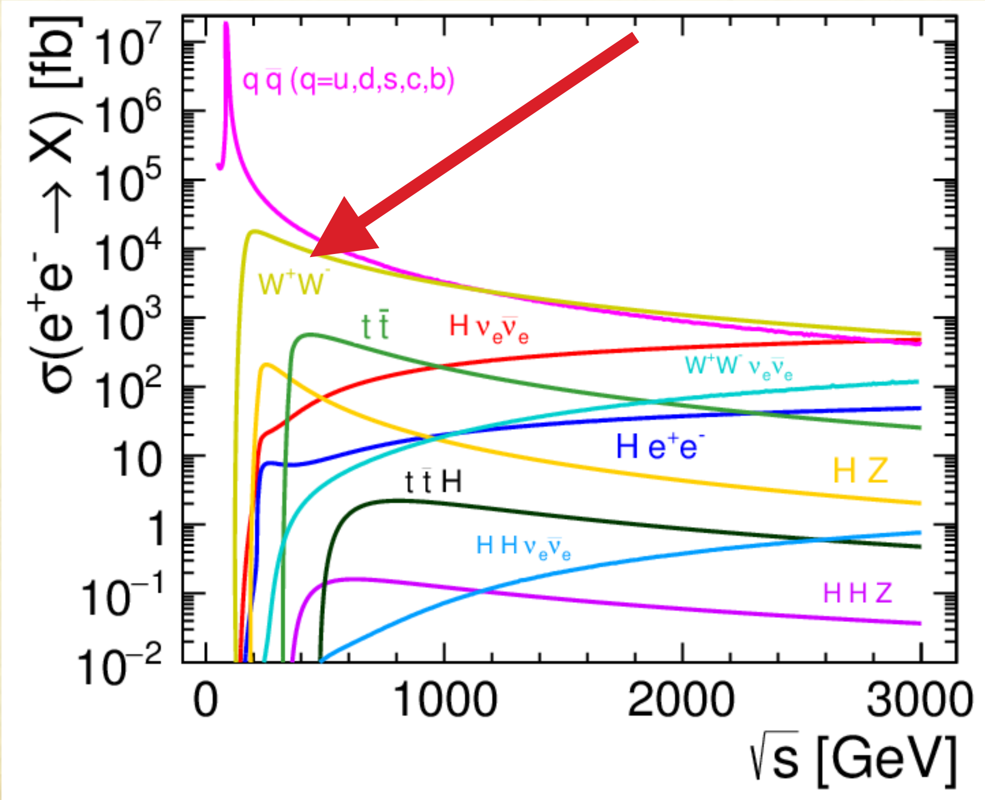
Process	σ/fb
$e^+e^- \to H\nu_e\bar{\nu}_e; H \to b\bar{b}$	137
$e^+e^- \to H\nu_e\bar{\nu}_e; H \to c\bar{c}$	6.9
$e^+e^- \to H\nu_e\bar{\nu}_e; H \to gg$	20.7
$e^+e^- \to q\bar{q}\nu\bar{\nu}$	788
$e^+e^- \to q\bar{q}l\nu$	4310
$e^\pm\gamma \to q\bar{q}e$	16600
$e^\pm\gamma \to q\bar{q}\nu$	29300
$\gamma\gamma \to q\bar{q}$	76600

$1.5\,\mathrm{ab}^{-1}$ at $\sqrt{s} = 1.4\,\mathrm{TeV}$

arXiv:1608.07538

WW production

See also talk by Jiayin Gu

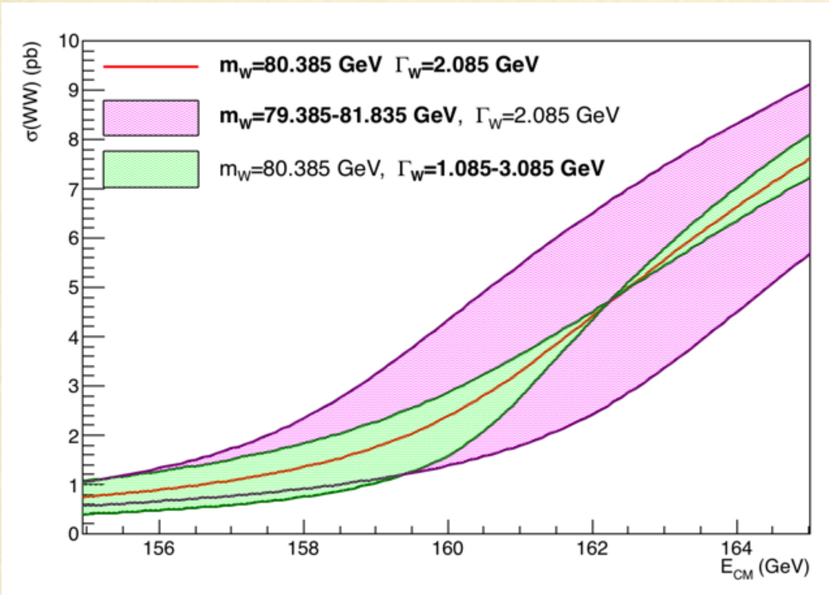


W mass and width

- ✓ Scan the WW threshold to explore its sensitivity to W mass and width

- ✓ State of the art calculation for WW x-section:
  - ✓ YFSWW3 Jadach, Placzek, Skrzypek, Ward, Was '01
  - ✓ RacoonWW Denner, Dittmaier, Roth, Wackeroth '02

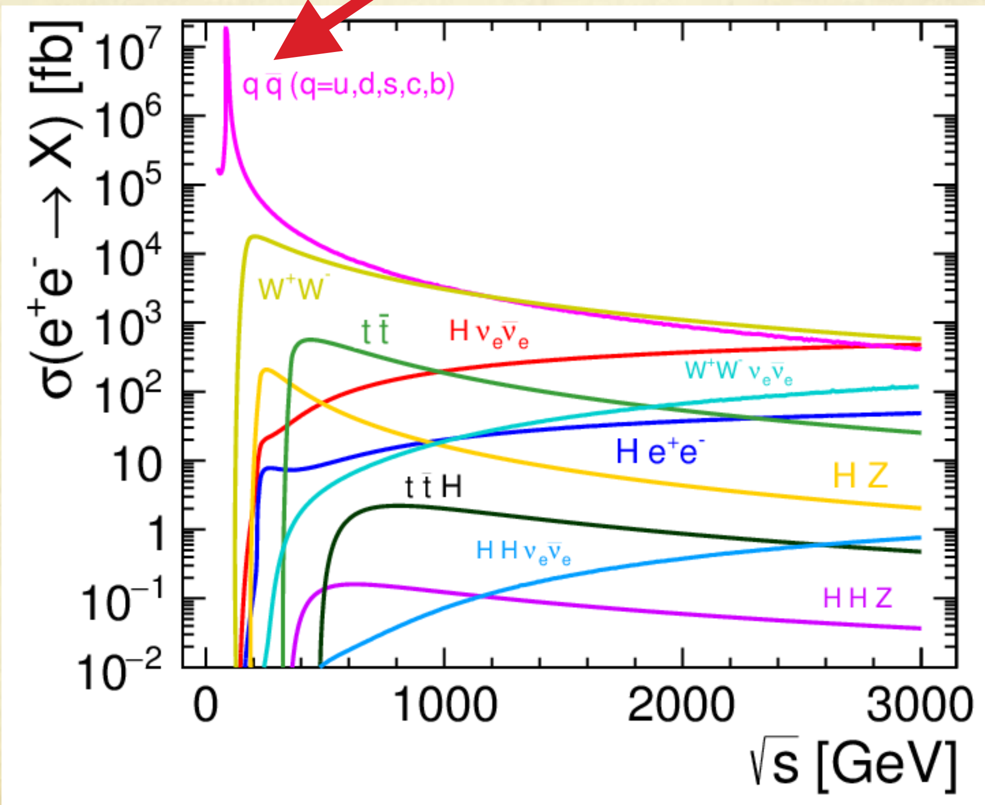
- ✓ Generally these are NLO EW with some higher order QED and some QCD corrections
  - ✓ Some 2-loop contributions Actis, Beneke, Falgari, Schwinn '08



From Paolo Azzurri '17

- ✓ Measuring the WW cross-section in two points can give W mass and width with very good precision (Δm_W < 1 MeV). Theory is likely the limiting factor. Should be possible to improve.

Jet production



24

Jet production

- ✓ Known in NNLO QCD for 2 and 3 jets

  Gehrmann-De Ridder, Gehrmann, Glover, Heinrich ‘07
  S. Weinzierl ‘08
  Del Duca, Duhr, Kardos, Somogyi, Szor, Trocsanyi, Tulipant ‘16

- ✓ NLO EW for 2,3 jets

  Denner, Dittmaier, Gehrmann, Kurz ‘09

- ✓ Automatic resummation through NNLO+NNLL with programs like CAESAR and ARES

  Banfi, Salam, Zanderighi ’03-
  Banfi, McAslan, Monni, Zanderighi ‘14-

- ✓ Known in NLO QCD through 5 jets

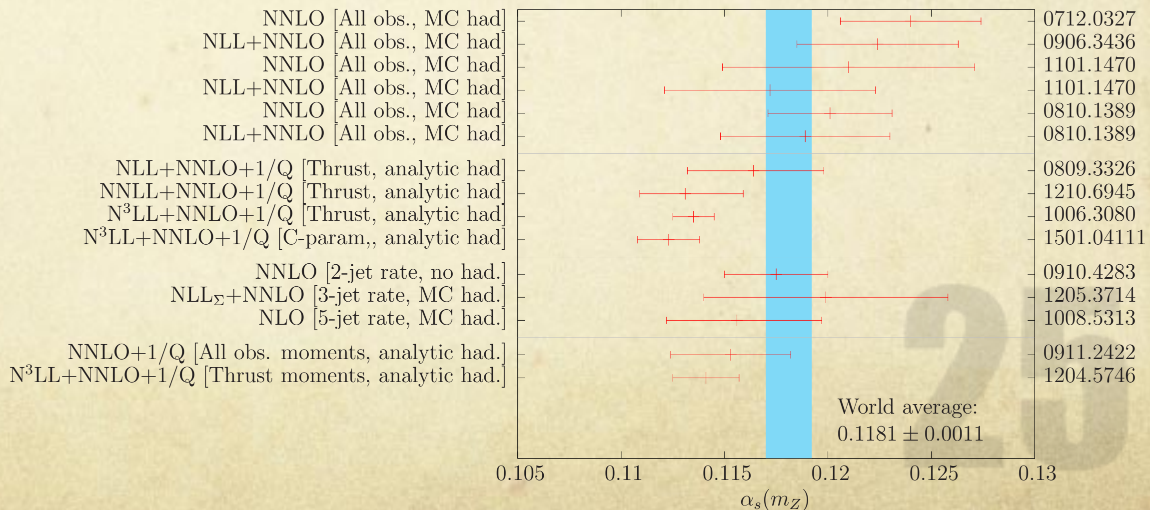
  Frederix, Frixione, Melnikov, Zanderighi ‘10

  - ✓ Jets allow studies of perturbative and non-perturbative QCD
  - ✓ Backgrounds
  - ✓ BSM context?
  - ✓ Extraction of α_S

From: arXiv:1008.5313v2

Observable	$\alpha_s(M_Z)$	Ref.
τ decays	0.1197 ± 0.0016	[67]
Υ decays	0.119 ± 0.0055	[70]
3 jet observables	0.1224 ± 0.0039	[44]
jets in DIS	0.1198 ± 0.0032	[71]
DIS	0.1142 ± 0.0021	[72]
thrust	0.1135 ± 0.0011	[73]
lattice	0.1183 ± 0.0008	[74]
EW fits	0.1193 ± 0.0028	[75]
world average	0.1184 ± 0.0007	[67]
$e^+e^- \to$ five jets	0.1156 ± 0.0038	this paper

From: Gehrmann, Luisoni, Monni ‘15

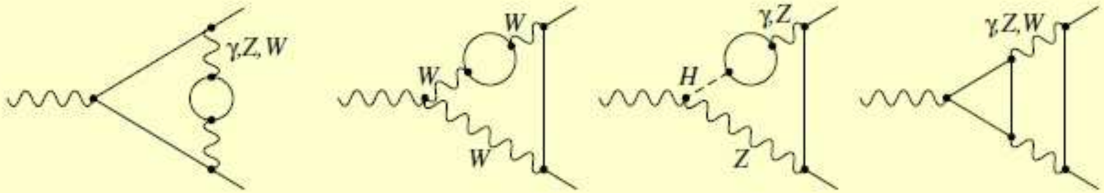


EW Precision Observables

See also talk by Giuliano Panico

Z-decay, etc

- ✓ Full 2-loop EW corrections to $\sin^2\theta^{\rm b}_{\rm eff}$ now available
  - ✓ 2-loop bosonic EW corrections computed; work on dominant 3-loop corrections ongoing
    Dubovyk, Freitas, Gluza, Riemann, Usovitsch '16
  - ✓ Prior results for EW precision observables:



From: A. Freitas '16

- Complete NNLO corrections (Δr, $\sin^2\theta^{\ell}_{\rm eff}$) — Freitas, Hollik, Walter, Weiglein '00; Awramik, Czakon '02; Onishchenko, Veretin '02; Awramik, Czakon, Freitas, Weiglein '04; Awramik, Czakon, Freitas '06; Hollik, Meier, Uccirati '05,07; Degrassi, Gambino, Giardino '14
- "Fermionic" NNLO corrections (g_{Vf}, g_{Af}) — Czarnecki, Kühn '96; Harlander, Seidensticker, Steinhauser '98; Freitas '13,14
- Partial 3/4-loop corrections to ρ/T-parameter
  $\mathcal{O}(\alpha_{\rm t}\alpha_{\rm s}^2)$, $\mathcal{O}(\alpha_{\rm t}^2\alpha_{\rm s})$, $\mathcal{O}(\alpha_{\rm t}\alpha_{\rm s}^3)$ — Chetyrkin, Kühn, Steinhauser '95; Faisst, Kühn, Seidensticker, Veretin '03; Boughezal, Tausk, v. d. Bij '05; Schröder, Steinhauser '05; Chetyrkin et al. '06; Boughezal, Czakon '06

  $(\alpha_{\rm t} \equiv \frac{y_{\rm t}^2}{4\pi})$

Z-decay, etc

✓ Status of intrinsic uncertainties for EW precision observables

From: S. Heinemeyer '17

Quantity	FCC-ee	Current intrinsic unc.		Projected unc.
M_W [MeV]	1	4	$(\alpha^3, \alpha^2\alpha_s)$	1
$\sin^2\theta^\ell_{\text{eff}}$ [10^{-5}]	0.6	4.5	$(\alpha^3, \alpha^2\alpha_s)$	1.5
Γ_Z [MeV]	0.1	0.5	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s, \alpha\alpha_s^2)$	0.2
R_b [10^{-5}]	6	15	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s)$	7
R_l [10^{-3}]	1	5	$(\alpha^2_{\text{bos}}, \alpha^3, \alpha^2\alpha_s)$	1.5

These calculations are required for the projection:

– complete $\mathcal{O}\left(\alpha\alpha_s^2\right)$ corrections

– fermionic $\mathcal{O}\left(\alpha^2\alpha_s\right)$ corrections

– double-fermionic $\mathcal{O}\left(\alpha^3\right)$ corrections

– leading four-loop corrections enhanced by the top Yukawa coupling

– the $\mathcal{O}\left(\alpha^2_{\text{bos}}\right)$ corrections are not the leading uncertainties now

Event Generators

NLO event generators

- ✓ LHC advances can also be put to work for e^+e^-
  - ✓ (almost) Everything today can be computed at NLO with out of the box programs!
- ✓ aMC@NLO: full NLO QCD + EW interfaced to parton showers. Actively developed for e^+e^-

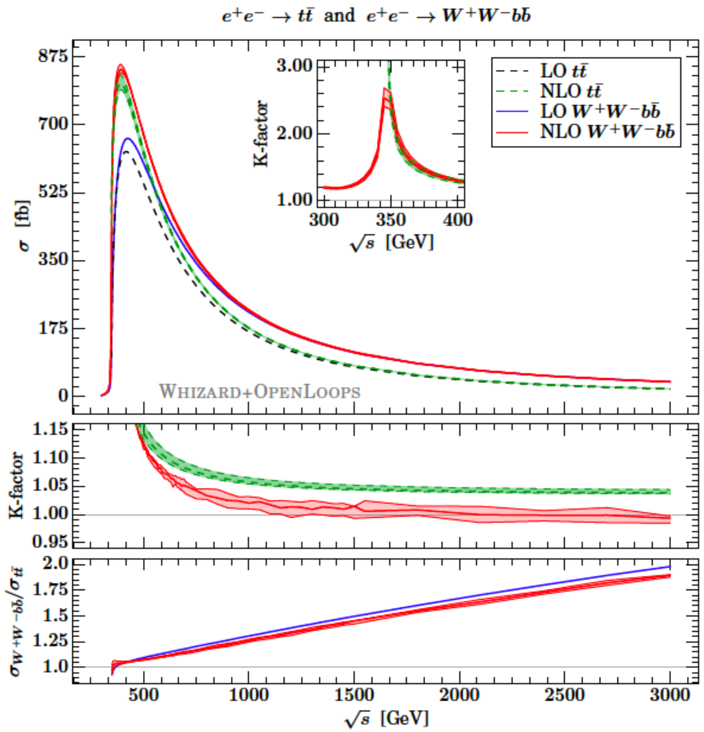
See talk by Shao-Feng Ge

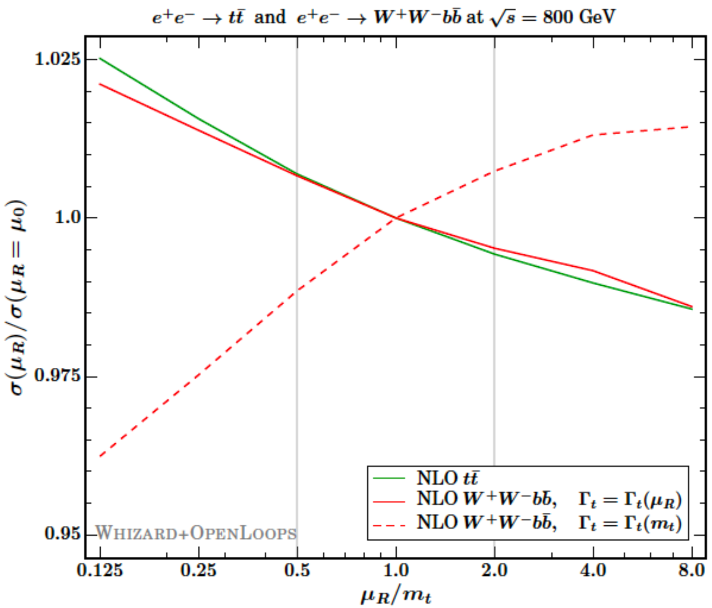
- ✓ WHIZARD

Nejad, Kilian, Lindert, Pozzorini, Reuter, Weiss '16

See talk by Jürgen Reuter

  - ✓ Matching to showers
  - ✓ Matching continuum and threshold production





More on event generators: the future is bright

- ✓ Ongoing are very significant developments regarding event generators at the LHC
- ✓ The long reign of LL parton showers is slowly coming to an end
- ✓ Very intense work underway on extending showers to full NLL accuracy

Hoeche, Prestel, Krauss '16
Others…

  - ✓ Basically, the singularities inside the shower would match the ones of a generic NNLO QCD calculation

- ✓ Such a change will have profound implication for showers since
  - ✓ They will have to be re-tuned from scratch from LEP data.

GigaZ-like physics option may be needed!

- ✓ Basically, the Event generators then will be much more sophisticated than today.
- ✓ Matching of showers to any then-existing NNLO calculation should be assumed
- ✓ In other words, we can assume MC@NNLO with improved tuning from, possibly, future data
- ✓ Showers may become more accurate also because in e^+e^- collisions they do not need to deal with "dirty" hadron physics present at the LHC.

Conclusions

- ✓ There are extensive theory developments that cover both regimes:
  - ✓ Threshold production
  - ✓ Continuum production
- ✓ The currently available results and tools are adequate for
  - ✓ Computing (almost) everything at NLO is now possible with public tool like aMC@NLO, WHIZARD etc.
- ✓ In the future, in time for data taking at CLIC, significant progress compared to today at the LHC can be expected
  - ✓ MC@NNLO style generators with NLL showers. GigaZ-like option will be beneficial.
  - ✓ NNLO calculations for small multiplicities (in fact, $e^+e^- \rightarrow ttH$ at NNLO is not unthinkable for today)
- ✓ These should allow for 1MeV for W mass; %-level for top width; 50MeV precision for m_{top}
- ✓ 3-4 %-level determination of the top-Yukawa coupling
  - ✓ compare to 10% at HL-LHC but 1% at Fcc-hh. Perhaps there is an opportunity for further study here?
- ✓ Precision EW observables and fits benefit from very precise theory and will likely play prominent role in the future.