LC Theory Calculations:
Status and Prospects

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Outline

- Introduction
- Precision observables
- Cross section calculations, Higgs
- Parametric Uncertainties
- Conclusions

Apologies for mostly covering SM calculations and problems.

Apologies for being even very selective for SM calculations.

Apologies for not providing all citations and appraising many developments

. . . due to lack of time

See also 1504.01726: “Physics at the e^+e^- Linear Collider”

Introduction

ILC / CLIC / FCC-ee / CEPC: (note: LC = “Lepton Collider”)

- Non-QCD initial state (less QCD issues in general)
- Collision energy tunable
- Polarization of e^+ / e^- (very powerful when combined with polarization/spin measurements)
- Less background (although not background-free)
- (Lower energy reach)
- In general higher precision than at LHC – IF a measurement is possible.

⇨ Distinctly different from LHC
More powerful in higher precision of measurements (for indirect BSM search)
Smaller reach in direct search reach

- Requirements for theoretical particle physics more focused on precision to get more (or most?) out of experimental data → urge to reduce uncertainties in predictions of known quantities.
- Rewarding for theorist because there is a well-defined problem to tackle mathematically.

⇨ LC not necessarily an easier environment to work, since there are also brick walls that are not necessarily easier to deal with than at the LHC. They just look different.
Sometimes problems known from LHC and not expected at lepton collider reappear.
… hard work in any case …

Introduction

General requirements (everyone knows):

- More higher order perturbative loop calculations
- Higher precision for theoretical input parameters (couplings, masses)

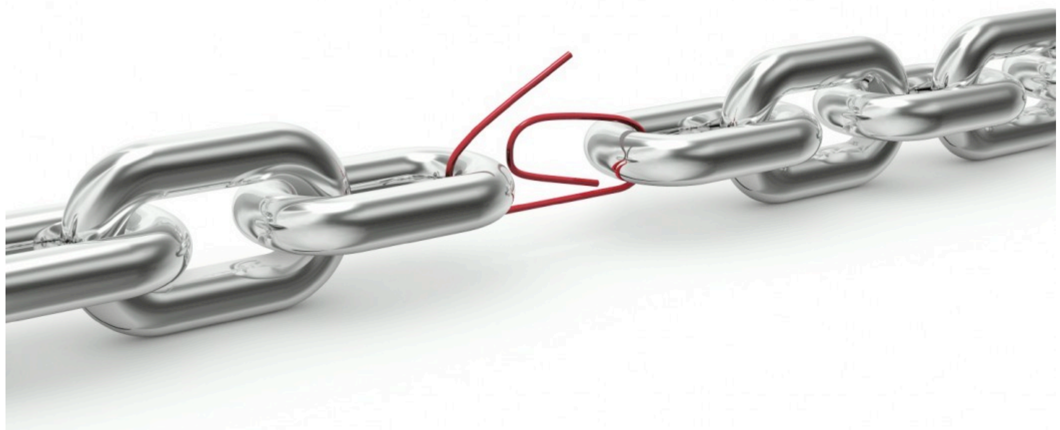
But also:

- Fully differential cross sections
- Automatic N^kLO calculations
- Model independent parametrization of BSM physics
- Beyond on-shell or narrow width approximation for unstable particles
- Better understanding of non-perturbative effects
- Improvements in MC event generators
- Improved jet algorithms / jet finding

And even (for some measurements):

- Beam effects and interference with ISR
- Development of completely new theoretical methods

⇨ A lot of profit for LC physics from work being invested already at LHC
Many issues, however, unique to lepton colliders.
The more precision required, the more involved the theoretical description.



The chain is only as strong as weakest link.

Be aware: not every theorist has the same standards

Experimental Uncertainties ⟷ Theoretical Uncertainties

Parametric Uncertainties

Precision Observables

Precision Observables:

- Can be measured very precisely
- Can be calculated very precisely at quantum level

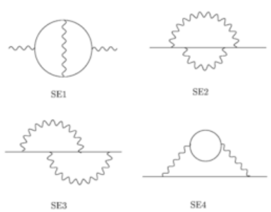
$M_W, \sin^2\theta_{\rm eff}, a_\mu, M_h, \ldots$

Rare B decays, …

Experiment

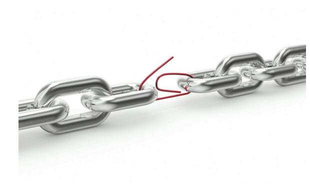
Theory model (SM, MSSM,..)

Through loop calculations sensitive to many other (eventually all) parameters of the theory



- Test of consistency of theory model with experimental data
- Can constrain parameter space of theory model
- Can falsify a theory model

Experimental precision and theoretical precision (often = number of loops calculated) have to match.



Precision Observables

Examples:

W boson mass: Theoretical prediction for M_W in terms of $M_Z, \alpha, G_\mu, \Delta r$:

$$\boxed{M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\,\alpha}{\sqrt{2}\,G_\mu}}(1+\Delta r)$$

Tree level

Loop corrections

One-loop result for M_W in the SM:

[A. Sirlin '80] , [W. Marciano, A. Sirlin '80]

$$\Delta r_{1-\text{loop}} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{\text{rem}}(M_H)$$

$$\sim \log\frac{M_Z}{m_f} \qquad \sim m_t^2 \qquad \log(M_H/M_W)$$

$$\sim 6\% \qquad \sim 3.3\% \qquad \sim 1\%$$

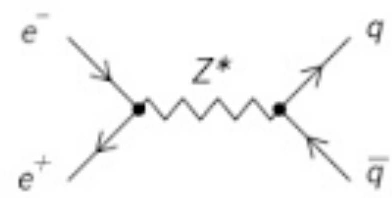
Sensitivity to: gauge couplings, fermion masses, gauge boson masses, Higgs mass

Precision Observables

Examples:

Effective mixing angles: Parametrizes relative strength of V and AV couplings and their loop corrections in

$e^+e^- \to Z^* \to f\bar{f}$ at the Z pole



$$\sin^2\theta_{\text{eff}} = \frac{1}{4\,|Q_f|}\left(1 - \frac{\text{Re}\, g_V^f}{\text{Re}\, g_A^f}\right)$$

Higher order contributions:

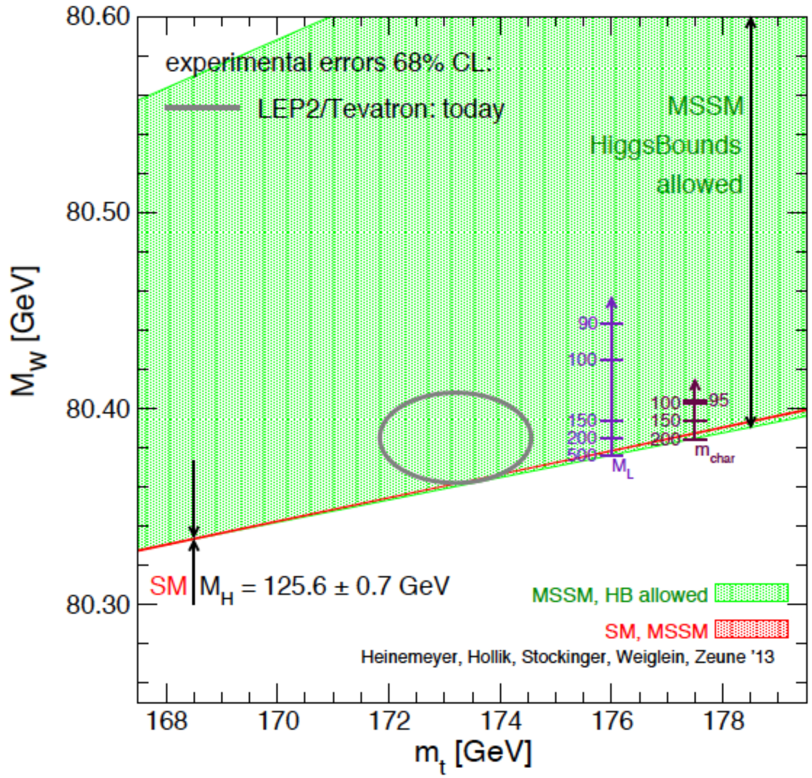
$$g_V^f \to g_V^f + \Delta g_V^f, \quad g_A^f \to g_A^f + \Delta g_A^f$$

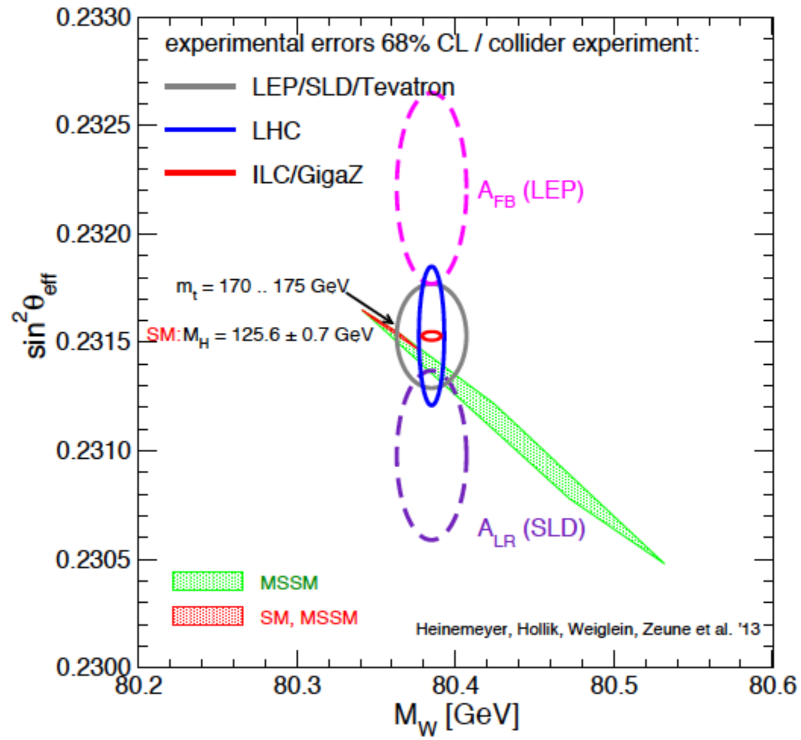
Polarization of beams crucial to get high experimental precision!

Extensively studied in the SM and the MSSM

Precision Observables

Extensively studied in the SM and the MSSM (Gfitter, Zfitter, …)





Precision Observables

The W boson mass

Experimental accuracy:

Today: LEP2, Tevatron: $M_W^{\rm exp} = 80.385 \pm 0.015$ GeV

ILC/FCC-ee: – polarized threshold scan
– kinematic reconstruction of W^+W^- [G. Wilson '13]
– hadronic mass (single W)

$$\delta M_W^{\rm exp,ILC(FCC-ee)} \lesssim 3\,(1)\ {\rm MeV}\ \text{(from thr. scan)} \qquad \Leftarrow \text{TU neglected}$$

Theoretical accuracies:

intrinsic today: $\delta M_W^{\rm SM,theo} = 4$ MeV, $\delta M_W^{\rm MSSM,today} = 5 - 10$ MeV

intrinsic future: $\delta M_W^{\rm SM,theo,fut} = 1$ MeV, $\delta M_W^{\rm MSSM,fut} = 2 - 4$ MeV

parametric today: $\delta m_t = 0.9$ GeV, $\delta(\Delta\alpha_{\rm had}) = 10^{-4}$, $\delta M_Z = 2.1$ MeV

$$\delta M_W^{{\rm para},m_t} = 5.5\ {\rm MeV}, \quad \delta M_W^{{\rm para},\Delta\alpha_{\rm had}} = 2\ {\rm MeV}, \quad \delta M_W^{{\rm para},M_Z} = 2.5\ {\rm MeV}$$

parametric future: $\delta m_t^{\rm fut} = 0.05$ GeV, $\delta(\Delta\alpha_{\rm had})^{\rm fut} = 5 \times 10^{-5}$, $\delta M_Z^{\rm ILC/FCC-ee} = 1/0.1$ MeV

$$\Delta M_W^{{\rm para,fut},m_t} = 0.5\ {\rm MeV},\ \Delta M_W^{{\rm para,fut},\Delta\alpha_{\rm had}} = 1\ {\rm MeV},\ \Delta M_W^{{\rm para,fut},M_Z} = 0.2/0.02\ {\rm MeV}$$

Precision Observables

The effective weak leptonic mixing angle: $\sin^2\theta_{\rm eff}$

Experimental accuracy:

Today: LEP, SLD: $\sin^2\theta_{\rm eff}^{\rm exp} = 0.23153 \pm 0.00016$

GigaZ/TeraZ: both beams polarized, Blondel scheme

$$\delta\sin^2\theta_{\rm eff}^{\rm exp,ILC(FCC-ee)} = 13\,(3) \times 10^{-6} \qquad \Leftarrow \text{TU neglected}$$

Theoretical accuracies: $[10^{-6}]$

intrinsic today: $\delta\sin^2\theta_{\rm eff}^{\rm SM,theo} = 47 \quad \delta\sin^2\theta_{\rm eff}^{\rm MSSM,today} = 50 - 70$

intrinsic future: $\delta\sin^2\theta_{\rm eff}^{\rm SM,theo,fut} = 15 \quad \delta\sin^2\theta_{\rm eff}^{\rm MSSM,fut} = 25 - 35$

parametric today: $\delta m_t = 0.9$ GeV, $\delta(\Delta\alpha_{\rm had}) = 10^{-4}$, $\delta M_Z = 2.1$ MeV

$$\delta\sin^2\theta_{\rm eff}^{{\rm para},m_t} = 30, \quad \delta\sin^2\theta_{\rm eff}^{{\rm para},\Delta\alpha_{\rm had}} = 36, \quad \delta\sin^2\theta_{\rm eff}^{{\rm para},M_Z} = 14$$

parametric future: $\delta m_t^{\rm fut} = 0.05$ GeV, $\delta(\Delta\alpha_{\rm had})^{\rm fut} = 5 \times 10^{-5}$, $\delta M_Z^{\rm ILC/FCC-ee} = 1/0.1$ MeV

$$\Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},m_t} = 2, \; \Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},\Delta\alpha_{\rm had}} = 18, \; \Delta\sin^2\theta_{\rm eff}^{{\rm para,fut},M_Z} = 6.5/0.7$$

Precision Observables

Current uncertainties for EWPOs

[from A. Freitas '16]

	Experiment	Theory error	Main source
M_W	80.385 ± 0.015 MeV	4 MeV	α^3, $\alpha^2\alpha_s$
Γ_Z	2495.2 ± 2.3 MeV	0.5 MeV	α^2_{bos}, α^3, $\alpha^2\alpha_s$, $\alpha\alpha_s^2$
σ^0_{had}	41540 ± 37 pb	6 pb	α^2_{bos}, α^3, $\alpha^2\alpha_s$
$R_b \equiv \Gamma^b_Z/\Gamma^{had}_Z$	0.21629 ± 0.00066	0.00015	α^2_{bos}, α^3, $\alpha^2\alpha_s$
$\sin^2\theta^\ell_{eff}$	0.23153 ± 0.00016	4.5×10^{-5}	α^3, $\alpha^2\alpha_s$

Extrapolation to future:

Parametric inputs:

* **ILC:** $\delta m_t = 100$ MeV, $\delta\alpha_s = 0.001$, $\delta M_Z = 2.1$ MeV

****FCC-ee:** $\delta m_t = 50$ MeV, $\delta\alpha_s = 0.0001$, $\delta M_Z = 0.1$ MeV

also: $\delta(\Delta\alpha) \sim 5 \times 10^{-5}$

	ILC	FCC-ee	perturb. error with 3-loop†	Param. error ILC*	Param. error FCC-ee**
M_W [MeV]	3–5	~ 1	1	2.6	1
Γ_Z [MeV]	~ 1	~ 0.1	$\lesssim 0.2$	0.5	0.06
R_b [10^{-5}]	15	$\lesssim 5$	5–10	< 1	< 1
$\sin^2\theta^\ell_{eff}$ [10^{-5}]	1.3	0.6	1.5	2	2

† **Theory scenario:** $\mathcal{O}(\alpha\alpha_s^2)$, $\mathcal{O}(N_f\alpha^2\alpha_s)$, $\mathcal{O}(N_f^2\alpha^2\alpha_s)$

(N_f^n = at least n closed fermion loops)

VERY CHALLENGING

Assumed: all next order missing corrections calculated. (2-loop ew)

universität wien

Cross Section Calculations

General Situation / Demands:

- Problem of fully differential NLO (QCD + ew) calculations in principle solved[1]: virtual + real radiation
- Limitations due to technical complexity and manpower (e.g. number of external legs, BSM models)
- Resulting typical precision away from extrem kinematical regions of phase space:

  $\mathcal{O}$(few %) for electroweak (α_{em} ~ 0.01)

  $\mathcal{O}$(10 %) for QCD (α_S ~ 0.1)
- NNLO QCD effects desirable in general to reach close to $\mathcal{O}$(few %),
  but hard and can only be expected for very important processes (likely with in approximations and fully differential only in exceptional cases)
- NNLO electroweak corrections desirable for few high-precision observables (e.g. W pair threshold)
  but even harder and only achievable with very high motivation and for inclusive/global observables.
- QED effects a different issue: (ISR, beam effects → "The PDF problem of Lepton Colliders"

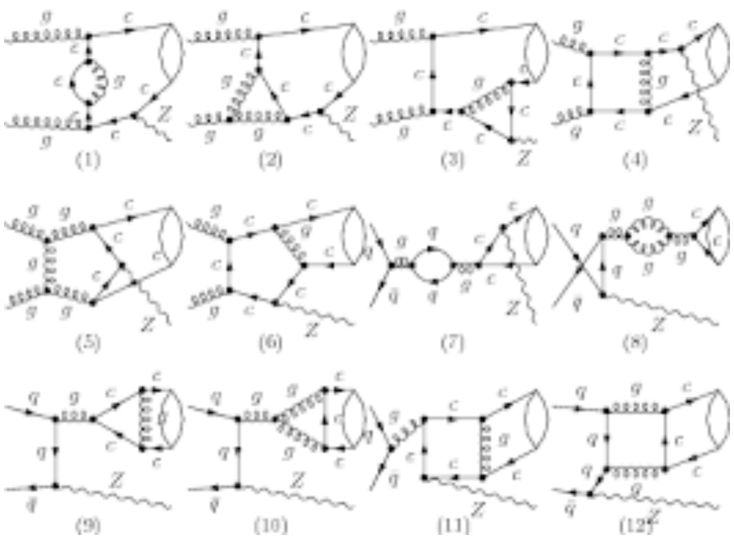
  "QED theory" still at level of LEP and needs to be improved to higher precision for many obs.

- A lot of profit from work that already goes into LHC (in principle immediately available for LC), but there are a number of observables that are very special for Lepton Colliders and require own dedicated methods.

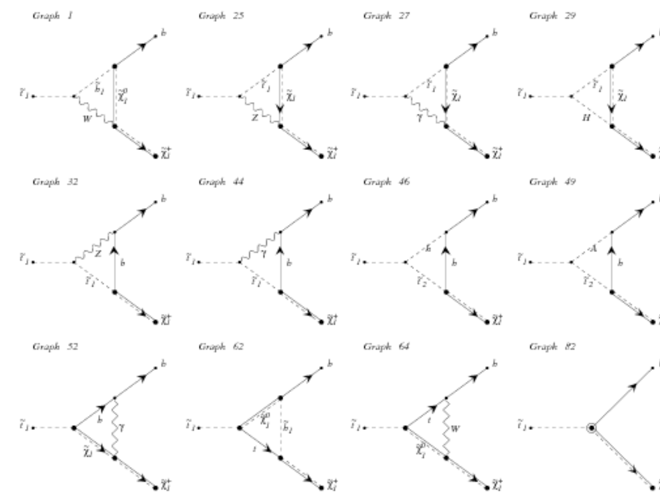
[1] Many processes and NLO corrections already available in automatized MC event generators: Madgraph, Whizard, …
or as dedicated special computer codes.

Cross Section Calculations

QCD/QED Loops

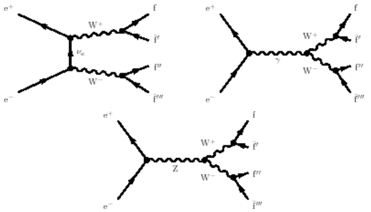


Elektroweak Loops



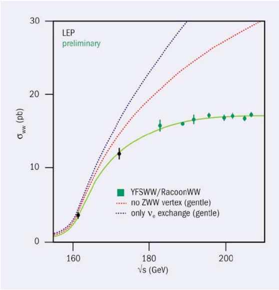
- QCD loops have more lines with zero mass particles (“more mass scales”).
- Can lead to more singularities, but simplifies computations enormously.

Pure Electroweak Process: WW Threshold



W mass measurement:

- Full final state process $e^+e^- \rightarrow 4$ f (incl. non-W) needed
- Full NLO corrections $2 \rightarrow 4$ (RACOONxx) Denner, Dittmaier, Roth, Wackeroth, 99-02
  + QED-ISR
  $\Rightarrow$ Theoretical error on M_W: $\delta^{th} M_W \sim M_W \alpha^2 \sim 5$ MeV
- Expected experimental LC errors: 5 MeV (or even 1 MeV ?)
  (from statistical+systematical+beam errors)
- Full NNLO calculation would resolve all forseen theory uncertainties



- Theory approximations to NNLO and higher orders maybe reach 1 MeV:
  - Finite W lifetime corrections: unstable particle effective methods
  - Nonrelativistic Coulomb effects (QED)
  - Sudakov log summation (all for total cross section only)

Actis, Beneke, Falgari, Schwinn, 08

Overall, experimental and theoretical precision match well, but
higher precision possible with more efforts:
Overall desired precision aim: $\delta^{full} M_W \sim 1$ MeV

QCD Processes: Massless Quarks

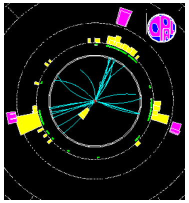
R-ratio / Z-width (inclusive):

- Four-loop corrections known (theory error gone)
- Precision $\delta\alpha_S(M_Z)$~0.003 for error $\delta R/R$~0.001
- More useful for hadronic τ decays.

$$\Gamma_Z = \frac{G_F M_Z^3}{24\pi\sqrt{2}} R^{nc}$$

Baikov etal. '12

$$\begin{aligned} R^{nc} &= 20.1945 + 20.1945\, a_s \qquad a_s = \alpha_s(M_Z)/\pi \\ &+ (28.4587 - 13.0575 + 0)\, a_s^2 \\ &+ (-257.825 - 52.8736 - 2.12068)\, a_s^3 \\ &+ (-1615.17 + 262.656 - 25.5814)\, a_s^4 \end{aligned}$$



3-jet production ($e^+e^- \to qqg+X$):

- Much higher sensitivity to α_S already as leading order.
- NNLO $\mathcal{O}(\alpha_S^3)$ fully differential cross section (up to 5 partons in final state)

Gehrmann etal. '07
Weinzierl '08

- Applications for event shape distributions (thrust, C=parameter) + NNLL resummation of logs + power correction using dispersion approach + LEP data: $\delta\alpha_S(M_Z)$~0.003 (dominated by theory error)

Gehrmann etal. '09

- SCET-EFT factorization + NNNLL resummation of logs + shape funct + analysis of thrust and C-parameter LEP data : $\delta\alpha_S(M_Z)$~0.0015 (theory)

Abbate etal. '10
Hoang etal. '15

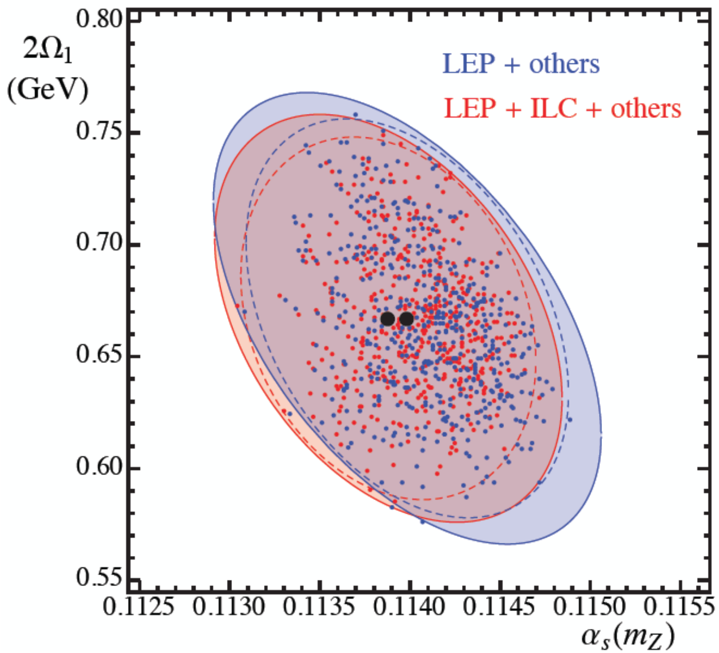
Prospects to improve theory:

- NNNLO perturbative corrections: technology breakthrough needed, many years !
- Improved subleading SCET factorization: studied and complicated. Useful ?

QCD Processes: Massless Quarks

What would a precise measurement of event shapes at Q=500 GeV with current QCD calculations contribute?

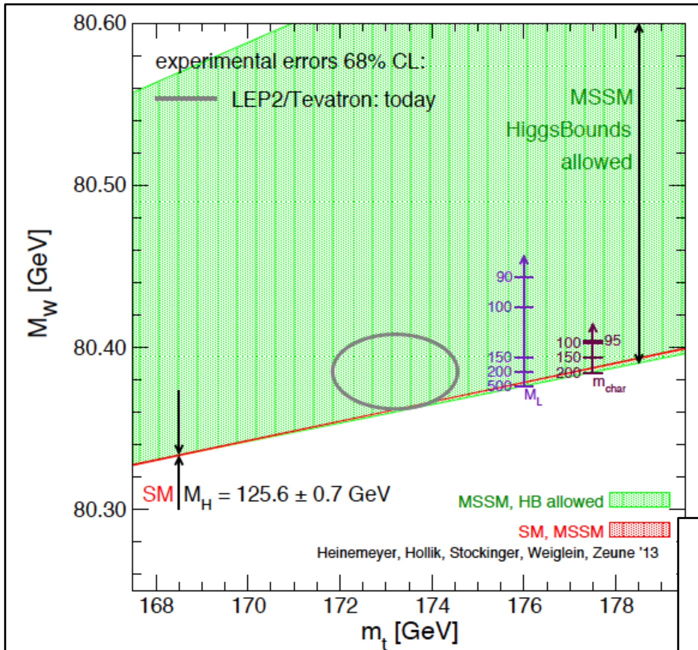
Exercise: Make up fictitious ILC data at 500 GeV, with assumed 1% statistical and 1% systematical uncertainties. Repeat fits.

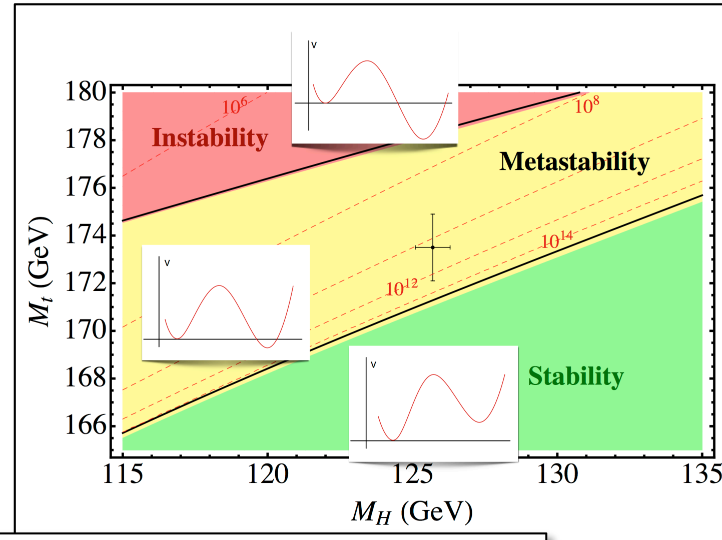


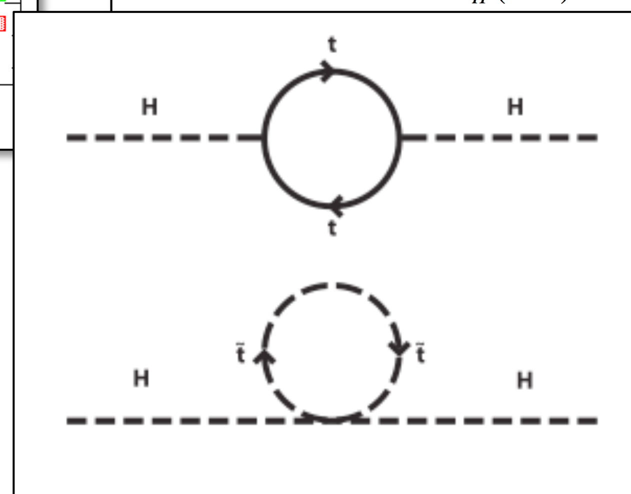
- Limited impact on precision of α_S because even small high-energy uncertainties blown up in the evolution to Z mass
- Nevertheless, would be very important consistency test of our understanding of QCD: α_S determinations.

Dedicated jet program at LC still very important.

QCD Processes: Top Quark







QCD Processes: Top Quark

Continuum ($Q > 2\ m_t$):

- Same situation as for massless quarks, but just one order less!
- Everything done for LHC in principle available for LC (great profit):
  - $\mathcal{O}(\alpha_S^2)$ fully differential stable top cross section — Czakon, Fiedler etal '13-16; Alioli, Fernandes, etal '13
  - $\mathcal{O}(\alpha_S)$ fully differential unstable top NW approx — Bernreuther, Si '10; Melnikov, Schulze '09; Campbell, Ellis '15
  - $\mathcal{O}(\alpha_S)$ fully differential unstable top (Wb) — Denner etal '12; Bavilequa etal '11; Heinrich etal '14
  - $\mathcal{O}(\alpha_S)$ top pair spin density matrix — Bernreuther, Si '13 - 15
  - . . . .

Top mass determination:

- Top mass reconstruction + template fits
- Endpoint / lepton moment methods
- . . .

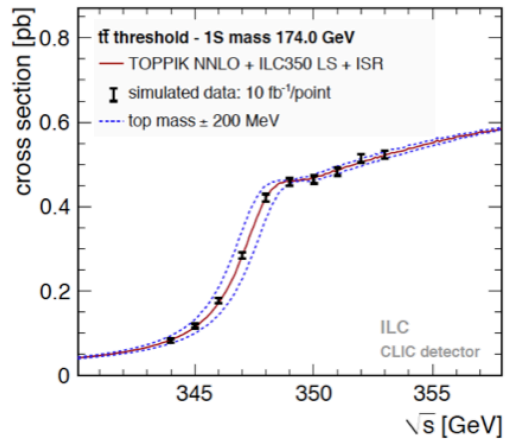
Wanted: Theory how masses are related to field theory masses (MSbar)

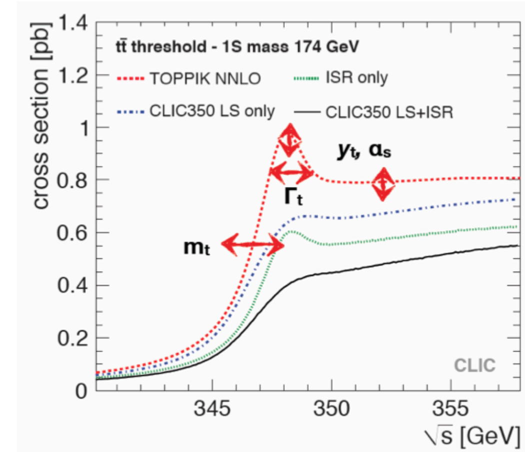
Wanted: $\mathcal{O}(\alpha_S^2)$ precision for essentially all calculations to have $\mathcal{O}(\%)$ theory precision for measurements (anomalous couplings, spin correlations,…)

QCD Processes: Top Quark

Threshold Scan (Q ~ 2 m_t):

- Would-be toponium threshold
- Total cross section: no hadronization corrections.
- Very sensitive to the top mass
- Also important for tth at 500 GeV





$$(\delta m_t^{1S})^{\rm exp,beam} \sim 30\ {\rm MeV} \qquad (\delta m_t^{1S})^{\rm exp,rest} \sim 20\ {\rm MeV} \qquad (\delta m_t^{1S})^{\rm th} \sim 45\ {\rm MeV}$$

(based on regular MC's)

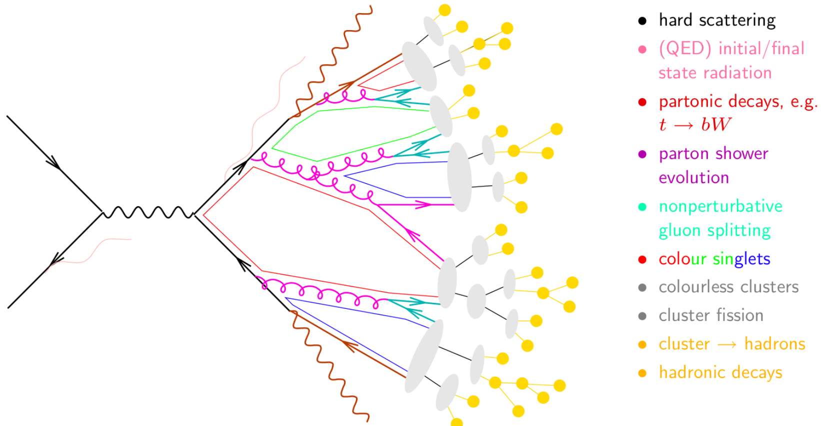
- Total cross section results (σ_{tot}):
  - NNNLO QCD "fixed order" (10 years)
  - NNLL log(v) renormalization group improved (8 years)
  - NNLO electroweak and finite lifetime effects ($e^+e^- \rightarrow WWbb$)

Beneke etal '15
Hoang, Stahlhofen'13
Hoang, Reisser, Ruiz '08
Beneke, Jantzen, Ruiz '10

Desired:

- QCD Next-order total cross section → very hard
- Elektroweak, finite lifetime next order → doable
- Threshold Monte-Carlo (crucial) (NLO/NLL) → talk by Bijan Choukufe
- Modern treatment of ISR / beam (crucial) → doable

Just to mention it: Monte Carlo Generators



- Full simulation of all processes (all experimental aspects accessible)
- QCD-inspired: partly first principles QCD ⇔ partly model (observable-dependent)
- Description power of data better than intrinsic theory accuracy.
- Top quark: treated like a real particle ($m_t^{MC} \approx m_t^{pole}$ +?).

  But pole mass ambiguous by O(1 GeV) due to confinement.

  Better mass definition needed.

Uncertainty (a): But how precise is modelling? ⟶ Part of exp. Analyses

Unvertainty (b): What is the meaning of MC QCD parameters? ⟶

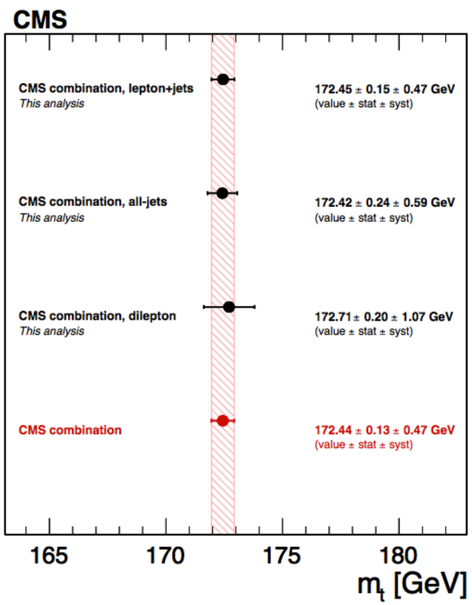
Depends strictly speaking on the observable, because of model character of MCs !

Must be adressed for each type of observable (until we have better MCs).

Just to mention it: MC Improvements

CMS, 1509.04044

Top mass from reconstruction 7+8 TeV combination



Combined m_t result	δm_t(GeV)
Experimental uncertainties	
Method calibration	0.03
Jet energy corrections	
– JEC: Intercalibration	0.01
– JEC: In situ calibration	0.12
– JEC: Uncorrelated non-pileup	0.10
Lepton energy scale	0.01
E_T^{miss} scale	0.03
Jet energy resolution	0.03
b tagging	0.05
Pileup	0.06
Backgrounds	0.04
Trigger	<0.01
Modeling of hadronization	
JEC: Flavor	0.33
b jet modeling	0.14
Modeling of perturbative QCD	
PDF	0.04
Ren. and fact. scales	0.10
ME-PS matching threshold	0.08
ME generator	0.11
Top quark p_T	0.02
Modeling of soft QCD	
Underlying event	0.11
Color reconnection modeling	0.10
Total systematic	0.47
Statistical	0.13
Total Uncertainty	0.48

LC: Seidel etal, 1303.3758
Experimental uncertainties below 100 MeV possible

← Biggest experimental errror

← Monte-Carlo uncertainties

⊕

How is the relation of the MC top quark mass to field theory masses ?

- MC modeling uncertainties usually considered as experimental issues.
- But they are actually theoretical uncertainties that need dedicated conceptual work to be resolved (e.g. LO+NLO parton shower)

MC top mass calibration for LC:
→ Talk by Vicent Mateu

Calibration of the MC Top Mass

Butenschön, Dehnadi, AHH, Mateu, Stewart w.i.p.

Method:

✓ 1) Strongly mass-sensitive hadron level observable (as closely as possible related to reconstructed invariant mass distribution !)

✓ 2) Accurate analytic hadron level QCD predictions at ≧ NLL/NLO with full control over the quark mass scheme dependence.

✓ 3) QCD masses as function of m_t^{MC} from fits of observable.

4) Cross check observable independence

$$m_t^{\rm MC} = m_t^{\rm MSR}(R=1~{\rm GeV}) + \Delta_{t,\rm MC}(R=1~{\rm GeV})$$

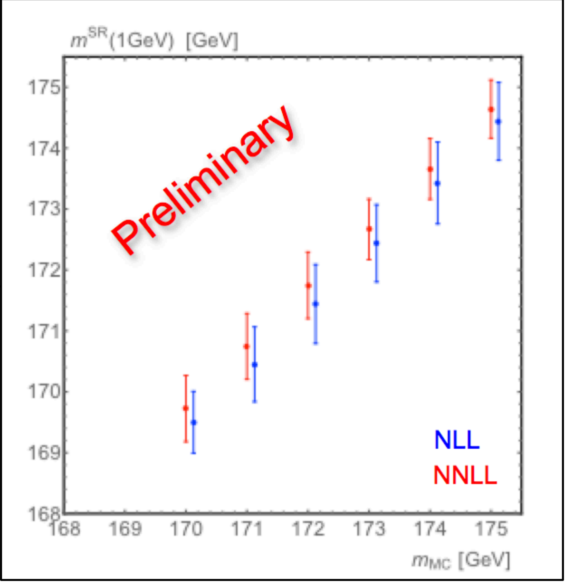
$$\Delta_{t,\rm MC}(1~{\rm GeV}) = \bar{\Delta} + \delta\Delta_{\rm MC} + \delta\Delta_{\rm pQCD} + \delta\Delta_{\rm param}$$

Monte Carlo errors:
- different tunings
- parton showers
- color reconstruction
- Intrinsic error, …

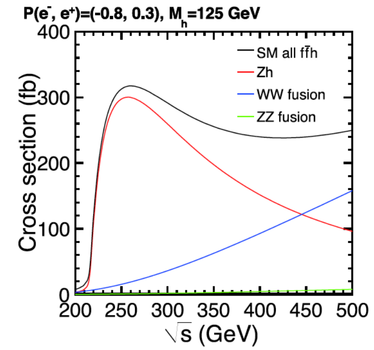
QCD errors:
- perturbative error
- scale uncertainties
- electroweak effects

Parametric errors:
- strong coupling α_s
- Non-perturbative parameters

NLO+NNLL hadron level QCD calculation of the 2-jetiness distribution for $e^+e^- \to tt+X$



Higgs Precision Physics



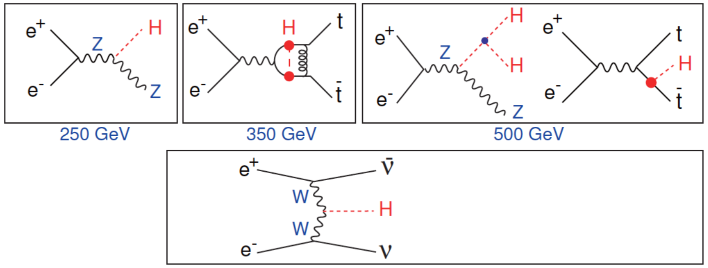
Issues to clarity:

- Couplings to all SM particles: SM Higgs or not?
- Higgs properties: Consistent with SM or inconsistencies?
- Higgs self coupling consistent with SM Higgs potential?
- Are there more than one?

Production mechanisms:

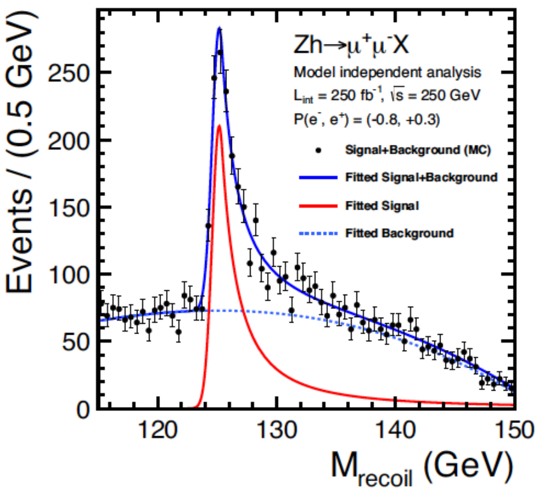
$$\text{Higgs-strahlung} : e^+e^- \to Z + H$$

$$\text{W-boson fusion} : e^+e^- \to \bar{\nu}_e \nu_e + H$$

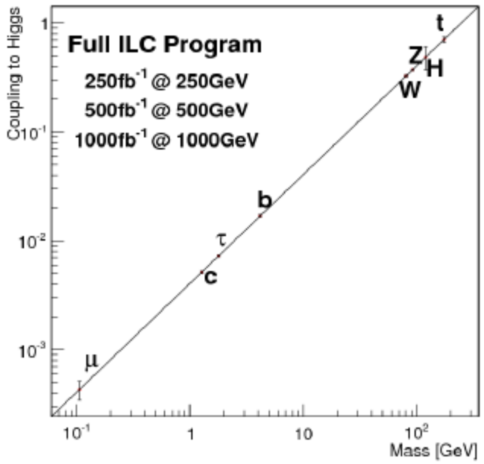


LC special capabilities:

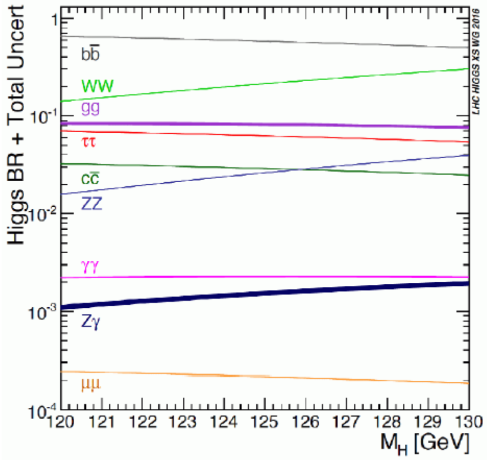
- Model-independent measurements of hZZ coupling, total width, branching ratios, couplings, total cross section, spin +CP quantum numbers (250 GeV)
- Self coupling and top Yukawa coupling measurements above 500 GeV through $e^+e^- \to Zhh$
- Cross section measurements (recoil method)



Higgs Precision Physics



Coupling	LHC	HL-LHC	LC	HL-LHC + LC
HWW	4-6%	2-5%	0.3%	0.1%
HZZ	4-6%	2-4%	0.5%	0.3%
Htt	14-15%	7-10%	1.3%	1.3%
Hbb	10-13%	4-7%	0.6%	0.6%
$H\tau\tau$	6-8%	2-5%	1.3%	1.2%
$H\gamma\gamma$	5-7%	2-5%	3.8%	3.0%
Hgg	6-8%	3-5%	1.2%	1.1%
Hinvis	—	—	0.9%	0.9%



- Higgs physical properties become new precision observables that have to be matched by theoretical calculations: cross sections, partial widths → lot of work to do
- SM perturbative calculations at least 2 loop will become mandatory (particular when QCD corrections important):
  → Already an industry at LHC with tremendous successes (e.g. Higgs production at NNNLO). I'm rather optimistic here
- Automatization for BSM models (NLO for sure): Hdecay, Prphecy4f NNLO (electroweak) very hard, but at least approximation might be possible

Higgs Precision Physics

Higgs branching fractions / couplings / partial widths:

Current theoretical uncertainties: [LHCHXSWG BR group '15]

Partial Width	QCD	Electroweak	Total
$H \to b\bar{b}/c\bar{c}$	$\sim 0.2\%$	$\sim 0.5\%$ for $M_H \lesssim 500$ GeV	$\sim 0.5\%$
$H \to \tau^+\tau^-/\mu^+\mu^-$		$\sim 0.5\%$ for $M_H \lesssim 500$ GeV	$\sim 0.5\%$
$H \to t\bar{t}$	$\lesssim 5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 5\%$
$H \to gg$	$\sim 3\%$	$\sim 1\%$	$\sim 3\%$
$H \to \gamma\gamma$	$< 1\%$	$< 1\%$	$\sim 1\%$
$H \to Z\gamma$	$< 1\%$	$\sim 5\%$	$\sim 5\%$
$H \to WW/ZZ \to 4f$	$< 0.5\%$	$\sim 0.5\%$ for $M_H < 500$ GeV	$\sim 0.5\%$

- QCD corrections: scale change by factor 2 and 1/2
- EW corrections: missing HO estimation based on the known structure and size of the NLO corrections
- Different uncertainties on a given channel added linearly

$\Rightarrow$ Strong improvement in ~ 20 years possible, but . . .
. . . they have to be consistently implemented into codes!
$\Rightarrow$ intrinsic uncertainty can/will be sufficiently under control?!

[one of Sven's slides]

Higgs Precision Physics

Higgs branching fractions / couplings / partial widths:

[LHCHXSWG YR3]

$M_H = 126$ GeV			
Decay	TU [%]	PU [%]	Total [%]
$H \to \gamma\gamma$	± 2.7	± 2.2	± 4.9
$H \to b\bar{b}$	± 1.5	± 1.9	± 3.3
$H \to \tau\tau$	± 3.5	± 2.1	± 5.6
$H \to WW$	± 2.0	± 2.2	± 4.1
$H \to ZZ$	± 2.0	± 2.2	± 4.2

↑ Theory uncertainty (TU) ↑ Parametric uncertainty (PU)

Higgs Precision Physics

Parametric uncertainties: What about those?

Current uncertainties on decay widths: [LHCHXSWG YR4]

Channel	Γ [MeV]	$\Delta\alpha_s$	Δm_b	Δm_c	Δm_t	THU
$H \to b\bar{b}$	2.38	−1.4% +1.4%	+1.7% −1.7%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
$H \to \tau^+\tau^-$	$2.56{\cdot}10^{-1}$	+0.0% +0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.1% −0.1%	+0.5% −0.5%
$H \to \mu^+\mu^-$	$8.90{\cdot}10^{-4}$	+0.0% +0.0%	+0.0% −0.0%	−0.1% −0.0%	+0.0% −0.1%	+0.5% −0.5%
$H \to c\bar{c}$	$1.18{\cdot}10^{-1}$	−1.9% +1.9%	−0.0% −0.0%	+5.3% −5.2%	+0.0% −0.0%	+0.5% −0.5%
$H \to gg$	$3.35{\cdot}10^{-1}$	+3.0% −3.0%	−0.1% +0.1%	+0.0% −0.0%	−0.1% +0.1%	+3.2% −3.2%
$H \to \gamma\gamma$	$9.28{\cdot}10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+1.0% −1.0%
$H \to Z\gamma$	$6.27{\cdot}10^{-3}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.1%	+0.0% −0.1%	+5.0% −5.0%
$H \to WW^*$	$8.74{\cdot}10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%
$H \to ZZ^*$	$1.07{\cdot}10^{-1}$	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.0% −0.0%	+0.5% −0.5%

Data available for $M_H = 124$ GeV, 125 GeV, 126 GeV

$\Rightarrow$ substantially larger than κ precision at ILC/FCC-ee

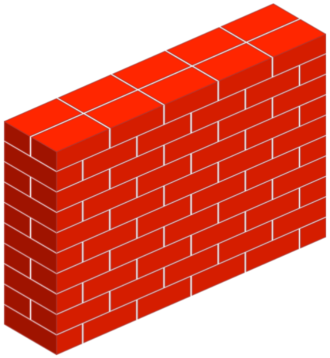
[one of Sven's slides]

Higgs Precision Physics

Parametric uncertainties: Seem to be a brickwall

Parameter	Central value	$\overline{\text{MS}}$ masses	Uncertainty
$\alpha_s(M_Z)$	0.118		±0.0015
m_c	1.403 GeV	$m_c(3\text{ GeV}) = 0.986\text{ GeV}$	±0.026 GeV
m_b	4.505 GeV	$m_b(m_b) = 4.18\text{ GeV}$	±0.03 GeV
m_t	172.5 GeV	$m_t(m_t) = 162.7\text{ GeV}$	±0.8 GeV

Basically follow the PDG averages

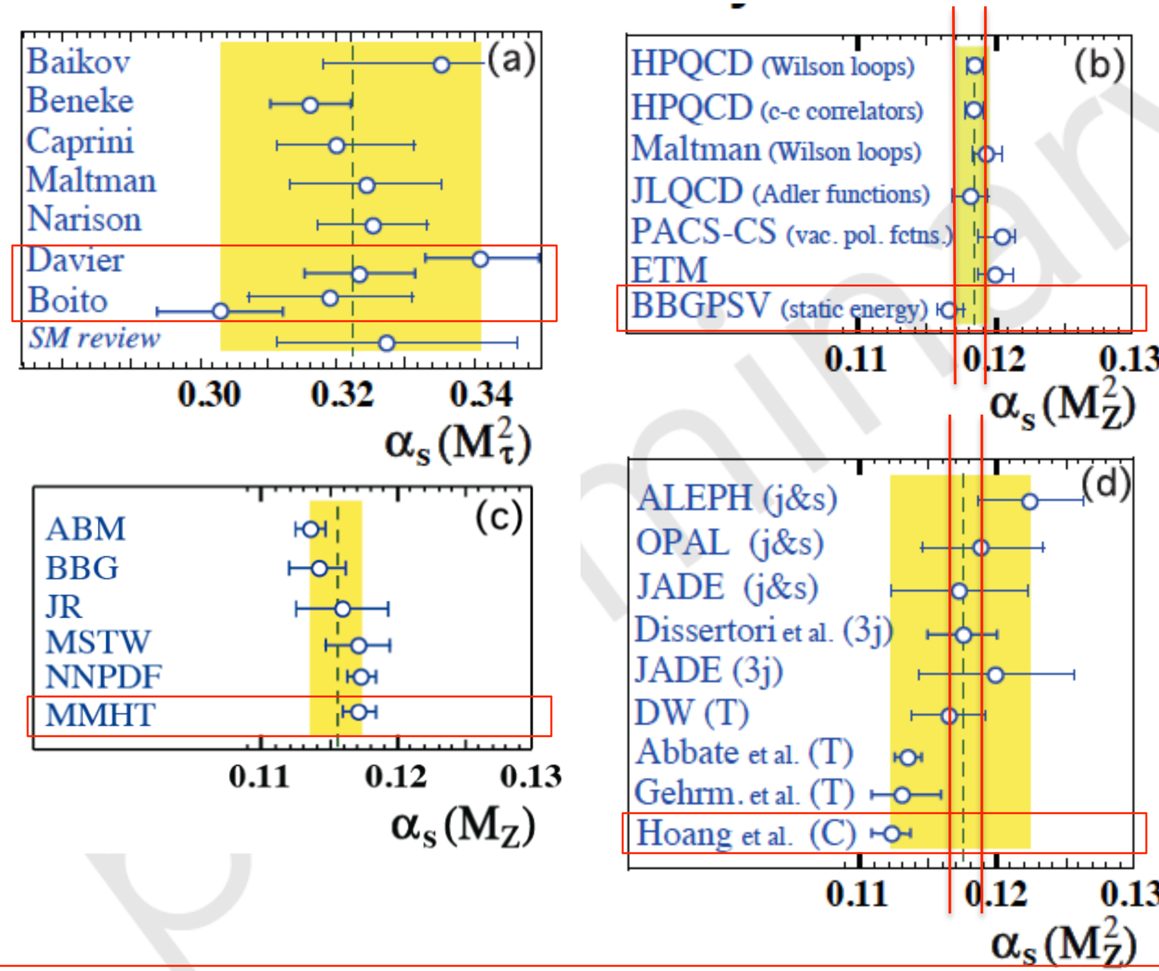


Are the error too conservative or even too optimistic?

Some breakthrough needed: situation deadlocked.

At this time there is NO argument that justifies changing the parameter uncertainties.

Strong Coupling Story



(e) hadron collider (ttbar): $\alpha_s(M_Z) = 0.1151^{+0.0033}_{-0.0032}$

(f) e.w. precision fit (GFitter): $\alpha_s(M_Z) = 0.1196 \pm 0.0030$

[red box] = new

2015 World Average:

- New available results were contradicting and lead for the first time to an increase in the world average
- Quoted error in strong contradiction to some high precision analyses.
- Who is wrong?
- Or have we been a bit too optimistic in the past?
- We have to first understand $\delta\alpha_S$~0.001 before going for $\delta\alpha_S$~0.0001

$\alpha_s(M_Z) = 0.1185 \pm 0.0006$ (2013)

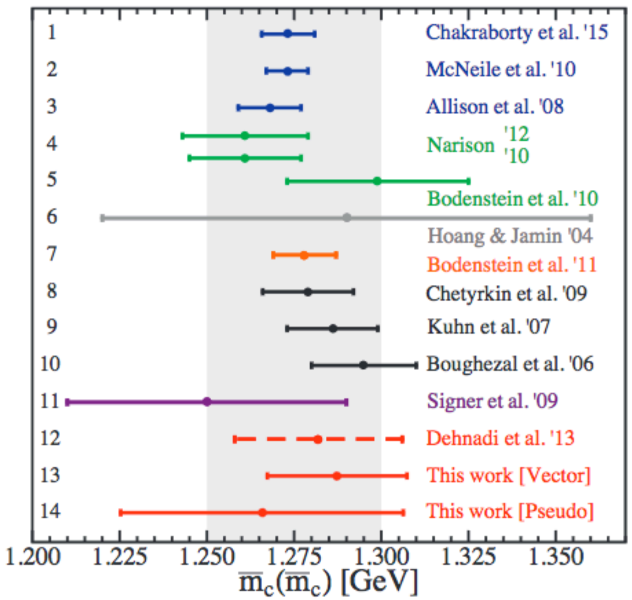
⇩

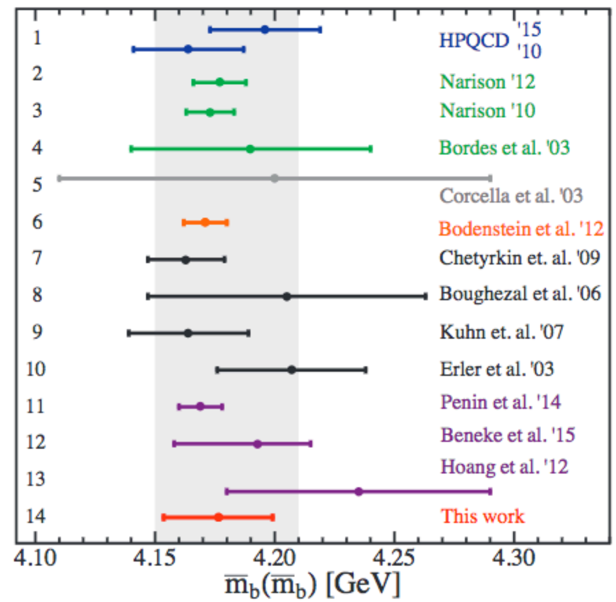
$\alpha_s(M_Z) = 0.1177 \pm 0.0013$ (2015)

Charm and Bottom Quark Mass Story

Most precise methods based on QCD sum rules:

Moments on current-current correlator (3-loops) vs. Data on hadronic R-ratio





Dehnadi etal, 1504.07638

- Most recent analysis with same theory input leading to larger theory uncertainties.
- Maybe go on as before: ask for better data, ask for one more loop?

$$\overline{m}_c(\overline{m}_c) = 1.288 \pm (0.006)_{\rm stat} \pm (0.009)_{\rm syst} \pm (0.014)_{\rm pert} \pm (0.010)_{\alpha_s} \pm (0.002)_{\langle GG \rangle}\ {\rm GeV}\,,$$

$$\overline{m}_b(\overline{m}_b) = 4.176 \pm (0.004)_{\rm stat} \pm (0.019)_{\rm syst} \pm (0.010)_{\rm pert} \pm (0.007)_{\alpha_s} \pm (0.0001)_{\langle GG \rangle}\ {\rm GeV}\,.$$

Dehnadi etal, 1504.07638

Summary

- Lots of progress in theory calculations motivated by LHC physics that can be recycled for LC
  - NLO calculations for in principle any (not too complicated) process possible in automatized manner (numerical, computer intensive)
  - NNLO QCD calculations are desired for essentially all processes, but are only available for specific processes
  - Multileg methods very impressive (limited use for LC)
  - Conceptual developments: factorization, resummation of corrections, parton shower matching to NLO results, …
- NNLO electroweak calculations desired for many processes: systematic tackle of this problem somewhat dormant, but momentum should pick up once LC becomes reality. (Well known what to do in principle)
- LC-specific processes (e.g. top pair threshold) which are very theory demanding and still require many more developments.

- Almost all next big steps (e.g. next order) involve breakthrough developments that appear not easy.
- Parametric uncertainties (α_S, m_c, m_b, $\alpha(Q)$,..) reflect overall consensus of many different independent methods: No obvious path what to do next

  (Maybe the real ultimate precision of QCD?)