Precision Calculations for Higgs Processes

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Americas Workshop on Linear Colliders 2020

Zoom, October 22, 2020

Outline

Theoretical precision for:

- Higgs production in e^+e^-
  - Higgs strahlung
  - Vector boson fusion
- Higgs decays
  - branching ratios
  - differential distributions

$\Rightarrow$ current status and error estimates

$\Rightarrow$ future prospects

Higgs resonance

Higgs width extremely small:

- $\Gamma_{\rm H}/M_{\rm H} \sim 3 \cdot 10^{-5}$

  (compare to $\Gamma_{\rm Z}/M_{\rm Z} \sim 3 \cdot 10^{-2}$)
- narrow-width approximation almost exact (for on-shell studies)
- treat production and decay seperately

Error estimates

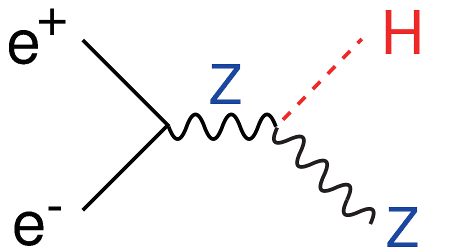
Error sources:

- missing higher orders
- parametric uncertainties $(\alpha_s, m_b, m_c) \rightarrow$ H decays

Estimate of missing higher orders:

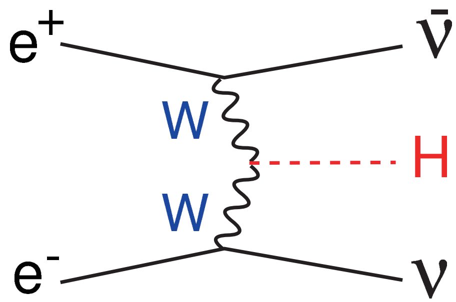
- difficult to know the unknown
- LHC: QCD errors $\Leftrightarrow$ scale variation
- ILC: EW errors not so straight forward
    - perturbation series as geometric series
    - exploit the known structure of corrections

Higgs production in e^+e^-



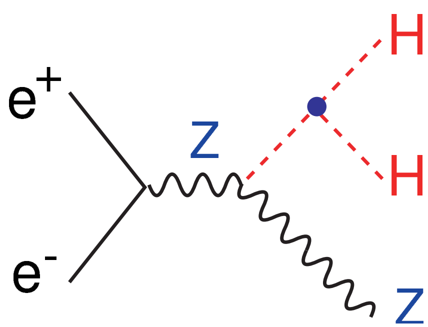
Higgs strahlung

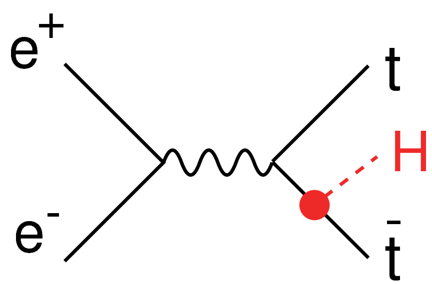
- $e^+e^- \to \mathrm{Z}(\to l^+l^-)\mathrm{H}$
- dominates near threshold



Vector boson fusion

- $e^+e^- \to \nu\bar{\nu}\mathrm{H}$
- dominates at large $\sqrt{s}$



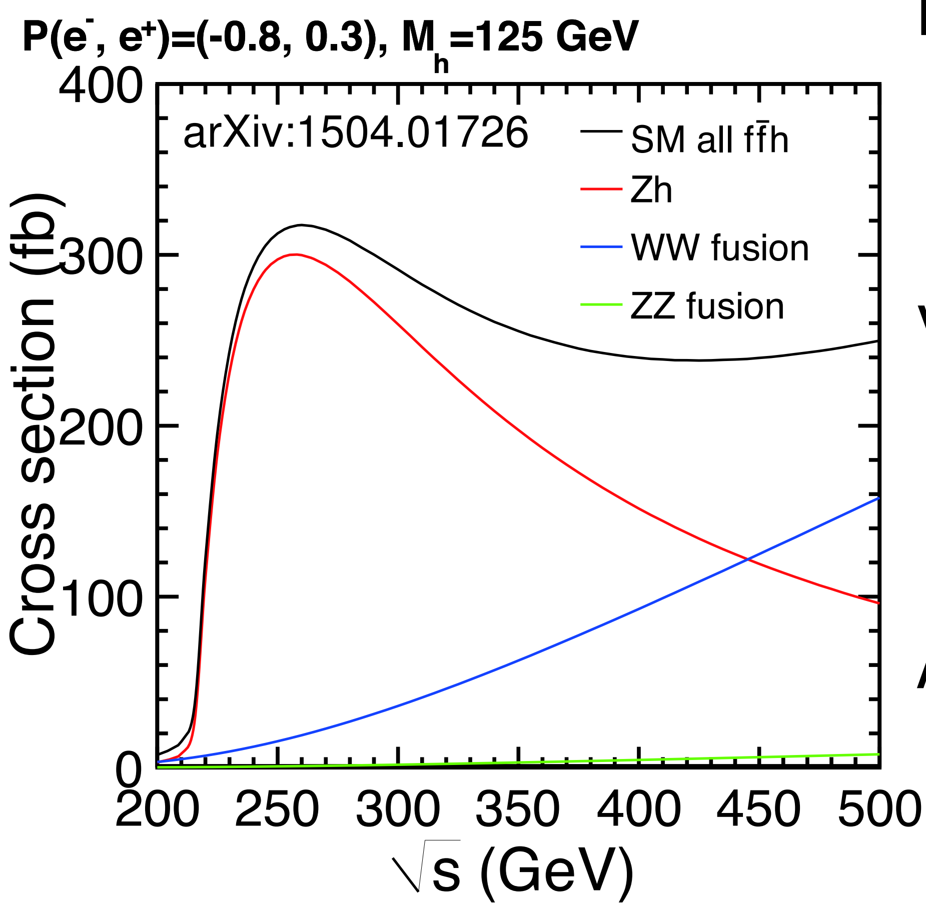


Above $\sqrt{s} \sim 500$ GeV

- $t\bar{t}\,\mathrm{H}$
- HHZ and $\nu\bar{\nu}\mathrm{HH}$

become available

Higgs production in e^+e^-



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Status

Higgs strahlung: $e^+e^- \to \mathrm{ZH}$

- NLO EW

Fleischer, Jegerlehner ['83], Kniehl ['92], Denner et al. ['92]
Denner et al. [hep-ph/0301189]

- mixed QCD-EW corrections $\mathcal{O}(\alpha\alpha_s)$

Gong et al. [1609.03955]

Vector boson fusion: $e^+e^- \to \nu\bar{\nu}\mathrm{H}$

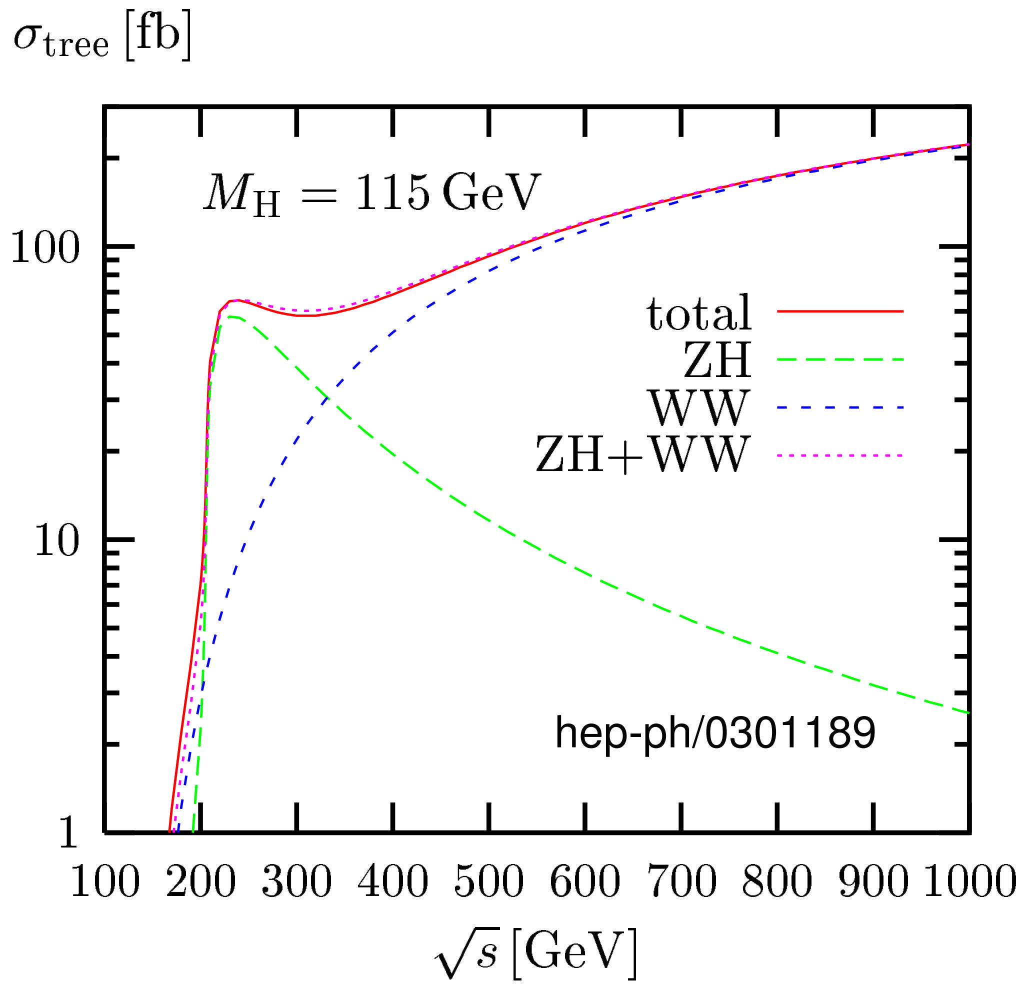
- NLO EW

Belanger et al. [hep-ph/0212261], Denner et al. [hep-ph/0301189]

Today:

- NLO EW completely standard with modern techniques

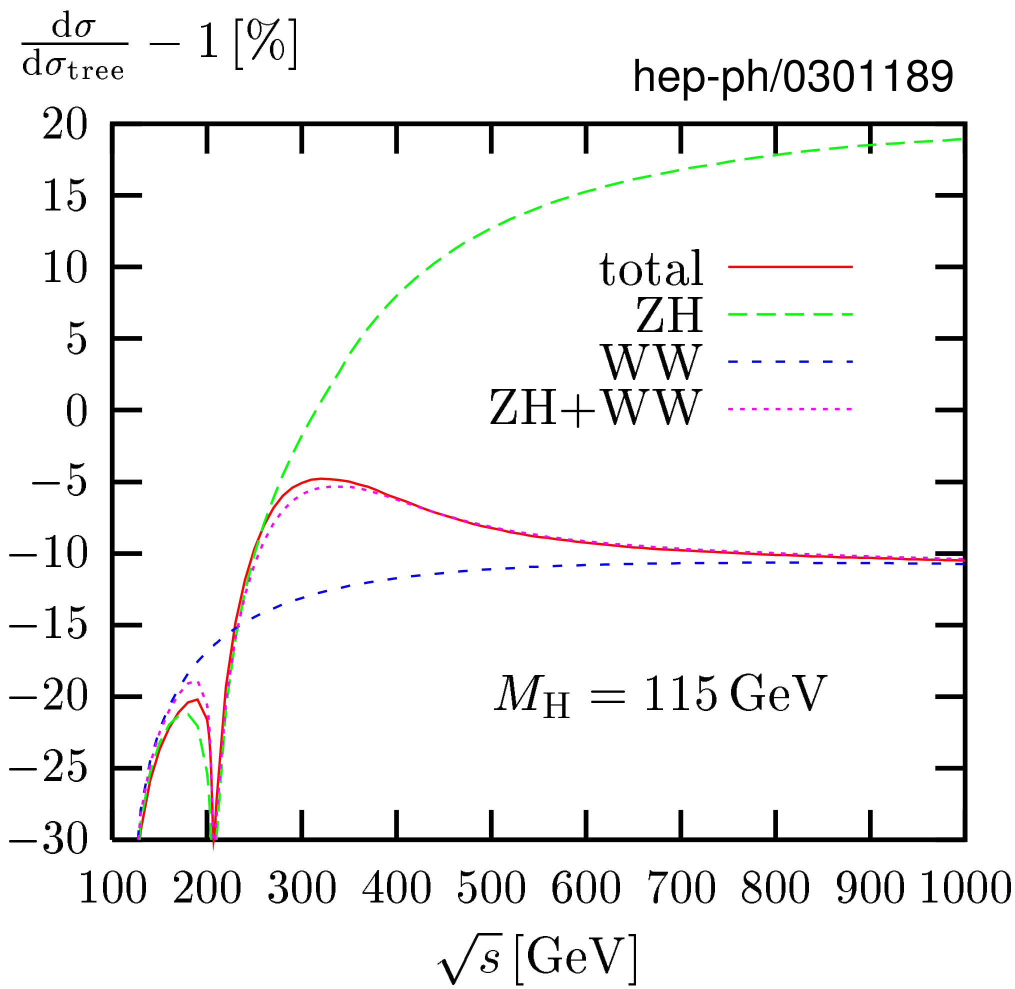
EW corrections



LO for $e^+e^- \to \nu\bar{\nu}\mathrm{H}$:

- $\mathrm{Z}(\to \nu\bar{\nu})\mathrm{H}$
- genuine WW fusion
- interference is small
- EW corr. similar for $\mathrm{Z}(\to \nu\bar{\nu})\mathrm{H}$ and $\mathrm{Z}(\to l^+l^-)\mathrm{H}$

EW corrections

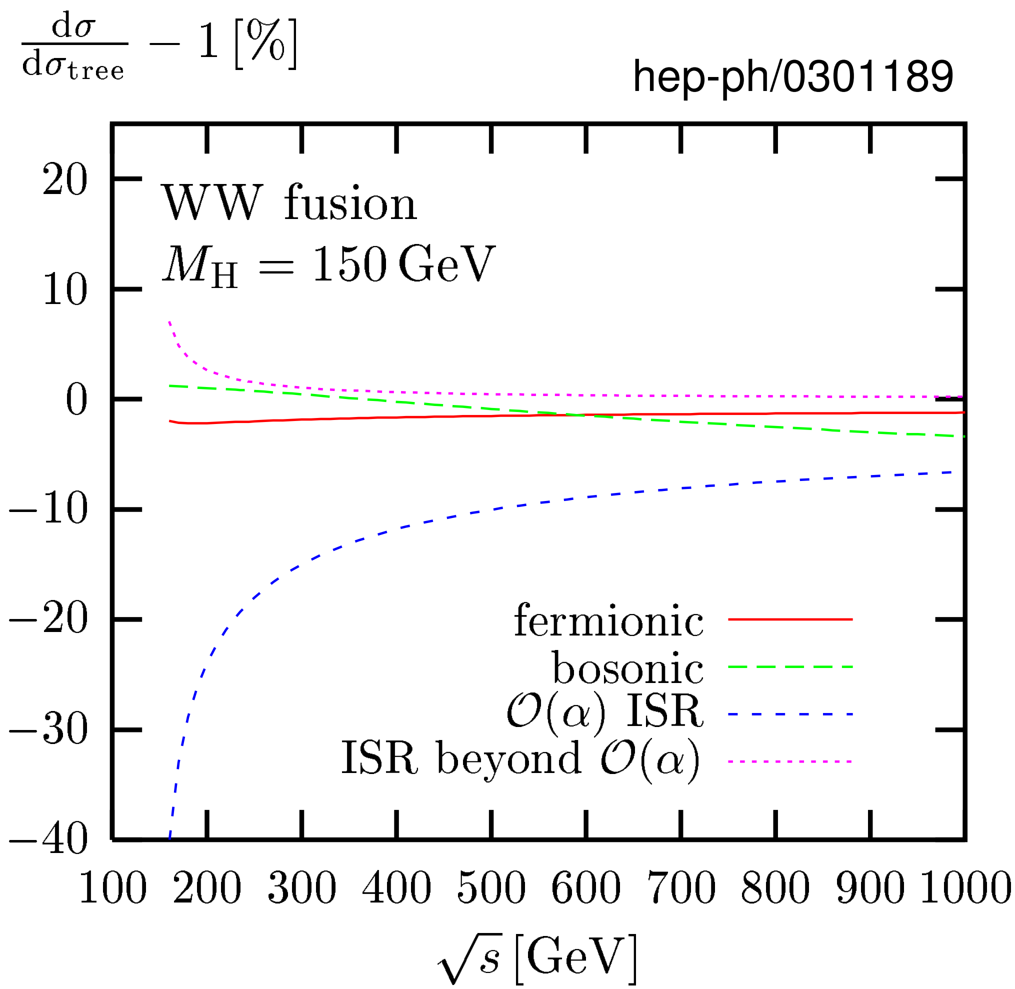


NLO EW for $e^+e^- \to \nu\bar{\nu}\mathrm{H}$:

- G_μ scheme
- large corrections
- mainly ISR

Gong etal. [1609.05379]

EW corrections



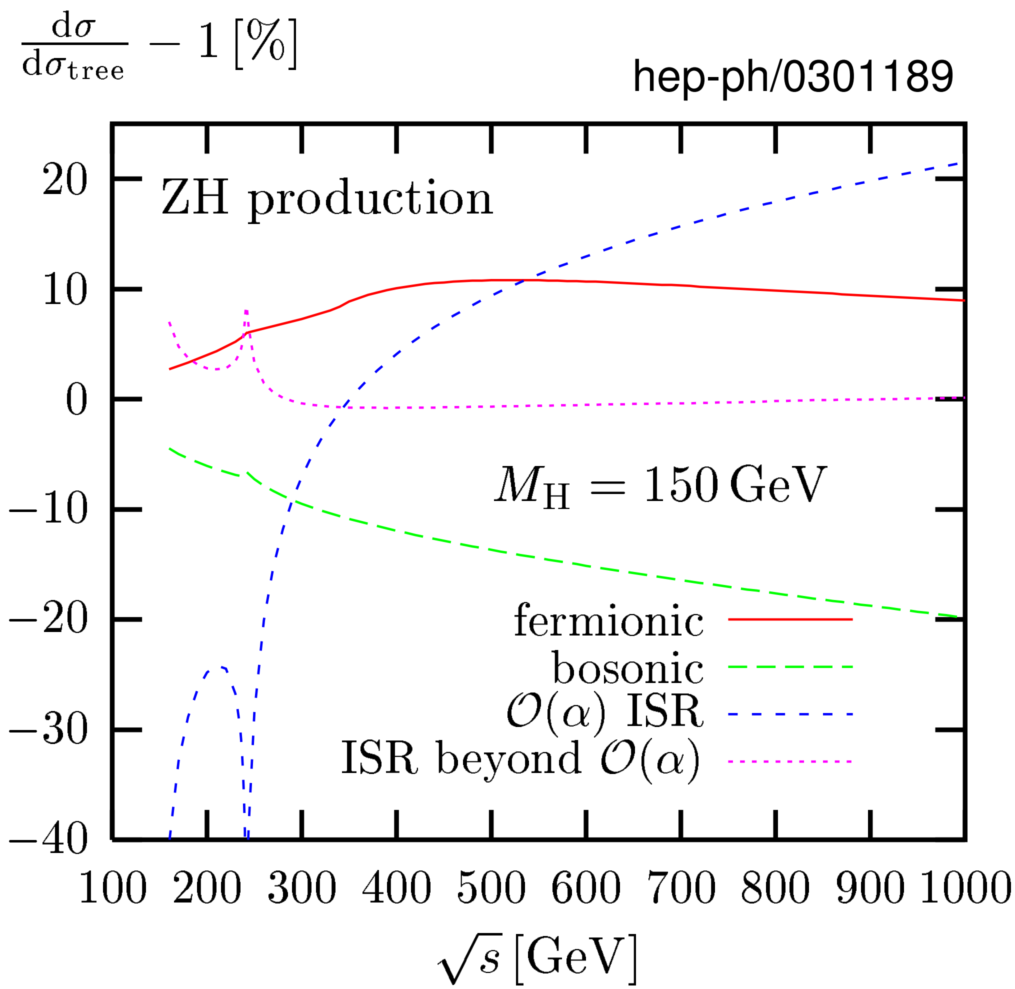
NLO EW for $e^+e^- \to \nu\bar{\nu}H$:

- G_μ scheme
- large corrections
- mainly ISR
- beyond ISR:

  WW fusion: $\mathcal{O}(1\%)$

Gong etal. [1609.05379]

EW corrections



NLO EW for $e^+e^- \to \nu\bar{\nu}\text{H}$:

- G_μ scheme
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- mainly ISR
- beyond ISR:

  WW fusion: $\mathcal{O}$(1%)

  ZH: $\mathcal{O}$(5%-10%)

  1.3% from $\mathcal{O}(\alpha\alpha_s)$

  Gong etal. [1609.05379]

Need for Precision

experimental accuracy at ILC: a few per mille!

theory error on ZH: $\mathcal{O}(1\%)$ Freitas et al. [1906.05379]

- full two-loop EW required
- not out-of reach for $2 \to 2$ process...

...but tough

- LHC:
  - NNLO QCD is state-of the art for $2 \to 2$
  - mixed NLO-EW 2-loop is active field for Drell-Yan

Need for Precision

experimental accuracy at ILC: a few per mille!

theory error on WW fusion: $< 1\%$

- full two-loop EW to be persued
- much tougher for $2 \to 3$ process
- LHC:
  - N^3LO only for structure function approx.
  - full NNLO QCD for vector-boson is out-of-reach today
- need for advances in loop technology
- or clever approximations

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Higgs pairs and $t\bar{t}$ H

State of the art:

- ZHH at NLO EW — Belanger et al. [hep-ph/0309010]
- $\nu\bar{\nu}$HH at NLO EW — Belanger et al. [hep-ph/0510184]
- $t\bar{t}$ H
  - NLO QCD — Dittmaier et al. [hep-ph/9808433] Dawson, Reina [hep-ph/9808443]
  - NLO EW — Belanger et al. [hep-ph/0307029] Denner et al. [hep-ph/0309274]
  - NLL resummation for $t\bar{t}$ threshold — Farrell,Hoang [hep-ph/0604166]
  - NLO QCD for off-shell tops — Nejad et al. [arXiv:1609.03390]

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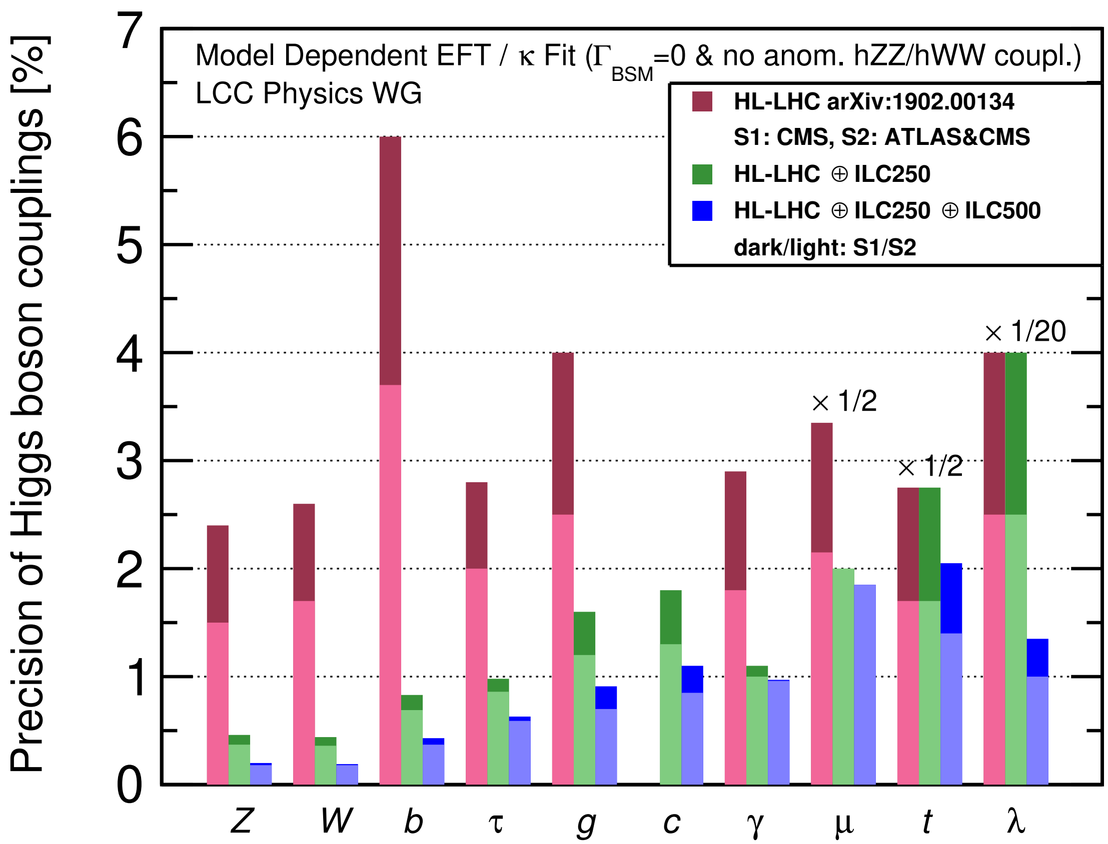
Higgs decays

Higgs partial widths

- crucial for coupling determinations
- parametric errors and missing higher orders important
- not collider specific
- at the LHC
  - coordinated by the LHC H(XS)WG
  - tools: Hdecay and Prophecy4f
  - conservative error estimates (ok for LHC)
  - not all decay channels equally important

ILC will push for per mille level accuracy!

ILC sensitivity



Bambade et al. [1903.01629]

Parametric uncertainties

Impact on coupling determination:

Lepage et al. [1404.0319]

- $\delta_b = \delta m_b$ and $\delta_b = -0.28\ \delta\alpha_s$
- $\delta_c = \delta m_c$ and $\delta_b = -0.80\ \delta\alpha_s$
- $\delta_g = 1.2\ \delta\alpha_s$

Ultimate ILC goals:

Peskin [1312.4947]

- $\delta_b \sim 0.3\%$, $\delta_c \sim 0.7\%$, and $\delta_g \sim 0.6\%$

PDG 2020:	lattice	continuum
$\bar{m}_b(\bar{m}_b)$	$= 4.198(12) \rightarrow 0.3\%$	$4.18(3) \rightarrow 0.7\%$
$\bar{m}_c(\bar{m}_c)$	$= 1.280(13) \rightarrow 1.0\%$	$1.280(25) \rightarrow 2.0\%$
$\alpha_s(M_Z^2)$	$= 0.1182(8) \rightarrow 0.7\%$	$0.1176(11) \rightarrow 1.0\%$

$\rightarrow$ lattice can be improved in the future Lepage et al. [1404.0319]

$H \to b\bar{b}/c\bar{c}$ partial width

State of the art and error estimates:

Freitas et al. [1906.05379]

- N^{4}LO QCD $\to 0.2\%$ (pert. series converges well)
- NLO EW and $\mathcal{O}(\alpha\alpha_s) \to 0.3 - 0.5\%$
- total error: $0.4 - 0.5\%$ (compare to $\delta_b \sim 0.3\%$ as ILC goal)
- ILC will push for improvements

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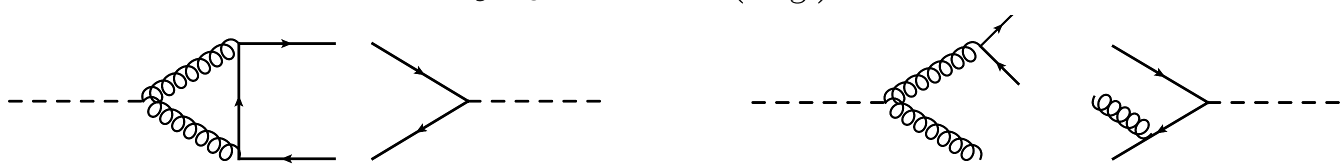
- differential predictions:
  - N^{3}LO — Mondini et al. [1904.08960]
  - resummed predictions — Alioli et al. [2009.13533]
  - contamination by y_t at $\mathcal{O}(\alpha_s^3)$ — Mondini et al. [2006.03563]



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  $\mathcal{O}(1\%/10\%)$ for $b\bar{b}/c\bar{c}$

  $\Rightarrow$ suppress by dedicated phase-space selection

$H \to gg$ partial width

State of the art and error estimates:

Freitas et al. [1906.05379]

- N^{3}LO QCD in heavy top limit and NNLO including top mass effects
  $\to 3\%$ (pert. series converges slowly) (compare to $\delta_g \sim 0.6\%$ as ILC goal)
- NLO EW $\to 1\%$ (5% NLO corections, $N_f \alpha$ suppression expected at NNLO)
- ILC will definitely push for improvements
- full NNLO mass dependence (e.g. for b-loop contributions) already within reach
  $\to$ 3-loop form factor Czakon, Niggetiedt [2001.03008]

$H \to \mathrm{ZZ/WW}$ partial width

$H \to \mathrm{ZZ/WW}$

- fully differential NLO EW/QCD (3-10% correction)
- leading 2-loop for improved born approximation (IBA)

  $\to$ 0.5% (compare to $\delta_\tau \sim 0.2\%$ as ILC goal)

- full NNLO EW not within reach today ($\Leftrightarrow e^+e^- \to \nu\bar{\nu}\mathrm{H}$)
- sensitivity to the Higgs mass ($\delta_\mathrm{W} = 6.9 \cdot \delta m_\mathrm{H},\ \delta_\mathrm{Z} = 7.2 \cdot \delta m_\mathrm{H}$)

  $\Delta m_\mathrm{H} = 30\mathrm{MeV} \to 0.2\%$ error on partial width

More H partial width

$H \to \tau^+\tau^-/\mu^+\mu^-$

- NLO EW $\to 0.3 - 0.5\%$ (compare to $\delta_\tau \sim 0.7\%$ as ILC goal)

$H \to \gamma\gamma$

- NLO EW and NNLO QCD $\to 1\%$
  (compare to $\delta_\gamma \sim 0.8\%$ as ILC goal)

$H \to \mathrm{Z}\gamma/\mathrm{Z}^*\gamma$

- LO only $\to 5\%$
- define the Dalitz decay phase-space

Perspectives

remember the LHC NLO wishlist:

- NLO QCD for multileg processes
- early 2000s none available, some skepticism
- NLO revolution solved the problem

$\Rightarrow$ establish an ILC wish list for Higgs physics

Summary/Outlook

- precision calculation already available in the SM
  - production in e^+e^-
  - decay (overlap with LHC programme)
- ILC will need more
- NNLO EW to be provided for most processes
- include SMEFT or HEFT