Reconstruction Aspects of Focus Topics Related to W-Physics

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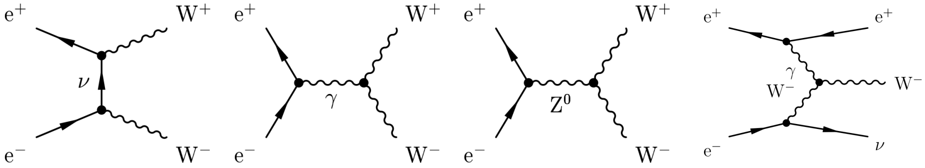


W^+W^- production

Single W

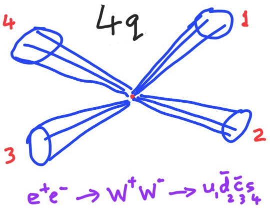
Focus Topics Considered

		HTOSS [HTE]	$e^+e^- \to Zh$ with $h \to s\bar{s}$
		ZHANG [HTE (GLOB)]	$e^+e^- \to Zh$ and reconstruction of decay angles
		HSELF [GLOB]	Higgs self-coupling
Main focus topics considered in this talk (* = "expert" team member)	*	WMASS [PREC]	W mass from W^+W^- threshold and continuum
		WWDIFF [GLOB]	Studies of W^+W^- and $e\nu W$
		TTTHRES [GLOB (HTE)]	Top threshold scan
	*	LUMI [PREC]	Precision luminosity measurement — Especially demanding at the Z
		EXSCALAR [SRCH]	New exotic scalars (typically $e^+e^- \to Z\phi$
		LLPS [SRCH]	Long-lived particles
		EXTT [SRCH]	Exotic top decays
WW XS and BFs		CKMWW [FLAV]	CKM matrix elements from W decays (V_{cs}, V_{cb} ...)
		BKTAUTAU [FLAV]	$B^0 \to K^{*0}\tau^+\tau^-$ (or similar)
		TWOF [HTE]	2-fermion final states at $\sqrt{s} = M_Z$ and beyond: $b\bar{b}$, $c\bar{c}$, $s\bar{s}$, $\tau^+\tau^-$ ...
Hadronization systematics in general important for mW (not just HF)		BCFRAG [FLAV (PREC)]	b and c fragmentation functions
		GSPLIT [PREC (FLAV)]	Gluon splitting to $b\bar{b}$ and $c\bar{c}$, separating gluons from Higgs.

Will emphasize reconstruction themes of: e/gamma separation, electron reconstruction, energy/momentum scale calibration, acceptances.
Also highly relevant: constrained fits, alignment, pile-up mitigation, L,E,P measurements, jet-charge, tau reconstruction, hermeticity etc.

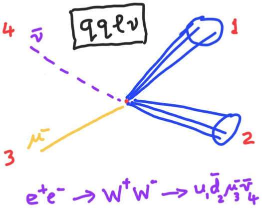
WW Topologies

fully hadronic $q\bar{q}q\bar{q}$



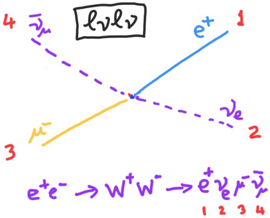
$B_h^2 = 45.4\%$

semi-leptonic $q\bar{q}\ell\nu_\ell$



$6B_\ell B_h = 43.9\%$

fully leptonic $\ell\nu_\ell\ell'\bar{\nu}_{\ell'}$



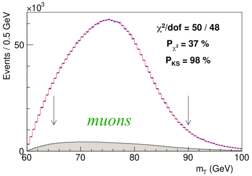
$9B_\ell^2 = 10.6\%$

- Here we take $\ell = e, \mu, \tau$. Events with τ leptons are of some use even for m_{W}.
- 100% of the WW final states are potentially useful for m_{W} in $\mathrm{e^+e^-}$ collisions.
- In hadron collider experiments only single W production and W decay to stable leptons is used (just 22% (or 11%)).
- Much of the power of an $\mathrm{e^+e^-}$ collider is that one measures the **mass** of the W decay products either directly or by imposing kinematic constraints.
- Can target precision at the MeV level.

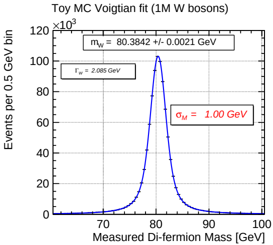
Hadron colliders rely on the $m_T(\ell,\nu)$ and $p_T(\ell)$ in leptonic decays of singly produced W bosons. In contrast, $\mathrm{e}^+\mathrm{e}^-$ colliders can reconstruct the mass of the W boson decay products: measure directly $(m_{\mathrm{W}}, \Gamma_{\mathrm{W}})$ from the B-W lineshape.

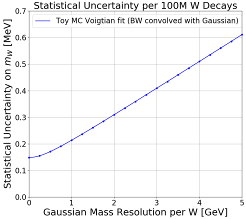
CDF Run II

2.4M $W \to \mu\nu_\mu$ decays



$m_{\mathrm{W}} = 80\,446.1 \pm 9.2 \pm 7.3$ MeV





Fit with Breit-Wigner $\otimes$ Gaussian

Ultimate sensitivity of a future $\mathrm{e}^+\mathrm{e}^-$ collider depends on the techniques, channels, mass resolution, and statistics. Could achieve the same m_{W} stat. sensitivity as this CDF plot with **only** 2.2% of the W decays for $\sigma_M = 1.0$ GeV (optimistic).

Detector design + **Reconstruction algorithms** = ultimate mass resolution

W Mass

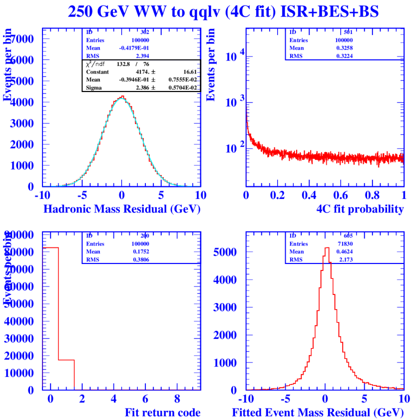
m_{W} is an experimental challenge. Especially so for hadron colliders.

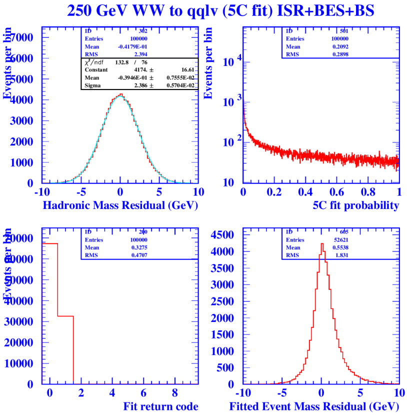
Several promising approaches at an $\mathrm{e}^+\mathrm{e}^-$ collider:

1. Constrained Reconstruction Kinematically-constrained reconstruction of $\mathrm{W}^+\mathrm{W}^-$ using constraints from **4-momentum conservation** and optionally mass-equality: the LEP2 work-horse. Primarily using $q\bar{q}\ell\nu_\ell$ events. Color reconnection disfavors use of $q\bar{q}q\bar{q}$ channel. Use E_{b} constraint for $q\bar{q}\tau\nu_\tau$.
2. Hadronic Mass Direct measurement of the **hadronic mass**. This can be applied particularly to single-W events decaying hadronically or to the hadronic system in semi-leptonic $\mathrm{W}^+\mathrm{W}^-$ events (especially for $q\bar{q}\tau\nu_\tau$).
3. Lepton Endpoints The 2-body decay of each W leads to endpoints in the lepton (or jet) **energy** at $E_\ell = E_{\mathrm{b}}(1 \pm \beta)/2$ where β is the W velocity. These can be used to infer m_{W}. Can use for WW events with ≥ 1 prompt lepton.
4. Fully Leptonic Reconstruction **Pseudomass** method (Apply 5 constraints).
5. Threshold Scan Measurement of the $\mathrm{W}^+\mathrm{W}^-$ cross-section near **threshold**. Uses all final states. Requires dedicated luminosity well below Higgs threshold and good control of background. ILC benefits from longitudinal polarization for background control. See also recent talk by P. Azzurri.

Toy fit of $q\bar{q}\ell\nu_\ell$ $(\ell = e, \mu)$ with ILC beam effects

Successful fits defined as converging and having $p_{\rm fit} > 0.02$
(Residual $= m_{\rm estimate} - m_{\rm generator}$)



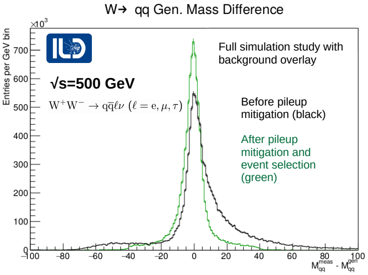


$\varepsilon_{\rm fit} = 72\%$, “$\sigma$”$=2.17$ GeV

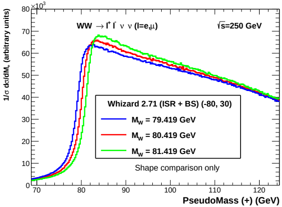
$\varepsilon_{\rm fit} = 55\%$, “$\sigma$”$=1.83$ GeV

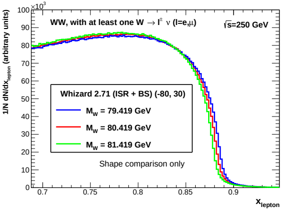
On average, the fit improves a bit over the hadronic mass resolution (2.39 GeV)

m_{W}, Γ_{W} measurements concurrent with Higgs program



- **Hadronic mass study**, J. Anguiano (KU).
- Stat. $\Delta m_{\mathrm{W}} = 2.4$ MeV for $1.6\ \mathrm{ab}^{-1}$ (-80%, +30%).
- Can be improved, but m_{had}-only measurement likely limited by JES systematic
- Expect improvements with **constrained fit** and $\sqrt{s} = 250$ GeV data set

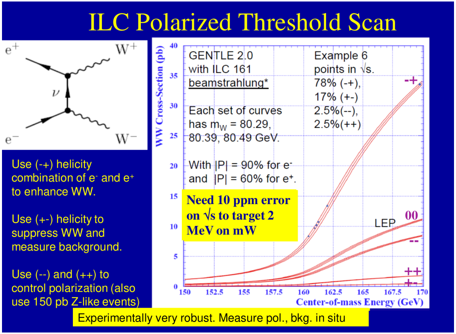


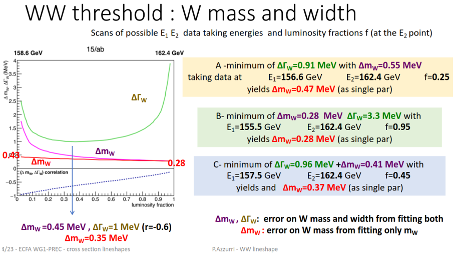


Sensitivity to m_{W} with lepton distributions: **dilepton pseudomasses**, lepton **endpoints**

- Stat. $\Delta m_{\mathrm{W}} = 4.4$ MeV for $2\ \mathrm{ab}^{-1}$ (45,45,5,5) at $\sqrt{s} = 250$ GeV
- **Leptonic observables** (shape-only): M_+, M_-, $x_\ell \equiv E_\ell / E_{\mathrm{b}}$. Exptl. systematics small.

Wmass: m_W from threshold





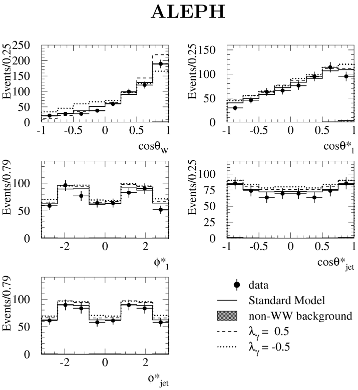
Can also measure W width

- Adequate theory important/essential.
- Big advantage: an inclusive measurement.
- Highest priority: fully hadronic event selection and background systematics.

WW Differential Cross-Sections: TGCs & Polarization

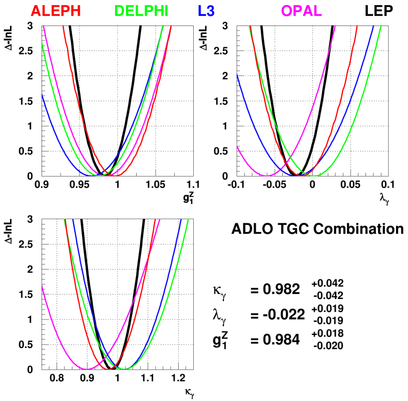
In general WWγ and WWZ coupling described by 14 independent complex couplings usually called triple-gauge-couplings (TGCs). See Hagiwara et al (1987) for details.

- LEP2 analyses focused on 3 TGC couplings (assumed real): g_1^Z, λ_γ and κ_γ.
- Main sensitivity from WW. Mostly $q\bar{q}\ell\nu_\ell$ but also $q\bar{q}q\bar{q}$ and $\ell\nu_\ell\ell'\bar{\nu}_{\ell'}$.
- $q\bar{q}\ell\nu_\ell$ has the advantage that except for the jet-charge ambiguity, all 5 angles can be determined.
- Benefits from fully differential measurements.

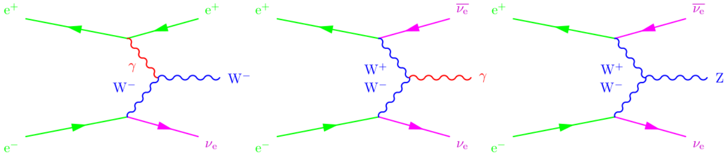


WW $\rightarrow q\bar{q}\ell\nu_\ell$ ($\ell = e, \mu$ channels)

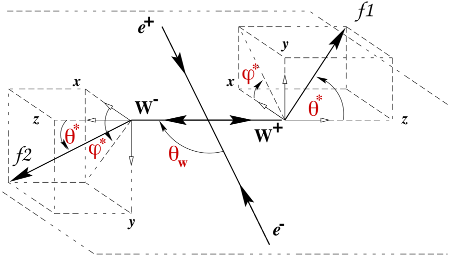
Triple Gauge Couplings



- LEP2 - only about 10,000 WW events per experiment with unpolarized beams.
- Future colliders - expect $10^4 - 10^6$ times more WW events. So typical few% precision of LEP2 translates to few 10^{-4} in the future.
- Higher $\sqrt{s}$ and polarization very helpful.
- In addition to WW, TGC-induced single W, γ, Z relevant too.
- ILC studies emphasize simultaneous measurement of TGC parameters and luminosity-weighted beam polarization using several processes.

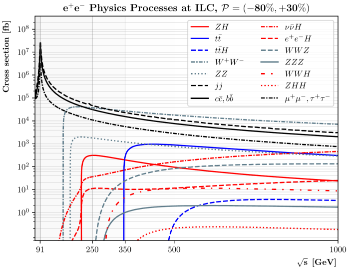


Fully differential WW reconstruction



- Best prospects to reconstruct all 5 angles in WW $\rightarrow q\bar{q}\ell\nu_\ell$ ($\ell = e, \mu$ channels) including applying a constrained fit.
- Jet-charge measurement or jet-flavor tag could help with the quark/anti-quark ambiguity.
- Much of the power is simply in measuring θ_W (for the W^-). Here $q\bar{q}\tau\nu_\tau$ is fine too if the τ lepton charge is well measured.
- Very forward leptons. Privilege correct charge ID of close to beam energy low-angle leptons.
- Events with neutrinos. Hermeticity important.

LUMI: Targets for Absolute Luminosity Precision



- The standard process used for **absolute** luminosity at LEP is small-angle **Bhabha** scattering, $e^+e^- \to e^+e^-$ (high statistics).
- This will be important for **relative** luminosity and could still lead in absolute precision.
- The pure QED process, $e^+e^- \to \gamma\gamma$, is now also considered very seriously for **absolute** luminosity, for both experimental and theoretical reasons.
- It emphasizes reconstruction (rejection) of high energy photons (electrons) over most of the detector's solid angle.

- Ideally match/exceed stat. precision of the accelerator. Denominator normalizing processes should have cross-sections exceeding the numerator.
- Example 1 (ILC): WW at 250 GeV. With 0.9 ab^{-1} (LR) $\to$ 1.7 $\times$ 10^{-4}.
- Example 2 (10^{12} Z with FCC) $\to$ 1.0 $\times$ 10^{-6}.

What is realistically achievable in terms of systematics is another matter. For now the assumption is to target 10^{-4}.

LUMI: $\mathrm{e^+e^-} \rightarrow \gamma\gamma$ for absolute luminosity

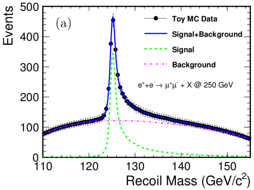
Targeting 10^{-4} precision. Cross-sections (and ratios) at $\sqrt{s} = 161$ GeV.

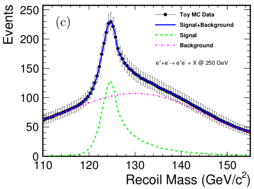
$\theta_{\min}$ ($^\circ$)	$\sigma_{\gamma\gamma}$ (pb)	$\Delta\sigma/\sigma$ (10 μrad)	$\sigma(ee)/\sigma(\gamma\gamma)$
45	5.3	2.0×10^{-5}	6.1
20	12.7	2.2×10^{-5}	22
15	15.5	2.4×10^{-5}	35
10	19.5	2.9×10^{-5}	68
6	24.6	3.9×10^{-5}	155
2	35.7	8.1×10^{-5}	974

- Unpolarized Born cross-sections. $\pm 24\%$ for (80%/30%) longitudinal beam polarization. Typical HO effects: + 5 to 10%.
  Counting statistics adequate for $\sqrt{s} \gg m_{\mathrm{Z}}$. Note: Use **whole** detector.
- For comparison, 10μrad knowledge for OPAL small-angle **Bhabha** lumi acceptance, corresponds to uncertainty of 100×10^{-5}.
  $\gamma\gamma$ has "relaxed" fiducial acceptance tolerances compared to Bhabhas.
- Bhabha rejection (e/γ discrimination) important. May be aided by much better azimuthal measurements given electron bending in the B-field.
  FoM: $B\, z_{LCAL}$. ILD has 7.7 Tm. FCC about 2.2 Tm. OPAL was 1.04 Tm.
  Adequate rejection feasible within tracker acceptance? / challenging below.

Electron Reconstruction

Electron reconstruction is as or more important than muon reconstruction, (t-channel processes), but the performance is typically worrisomely inferior.





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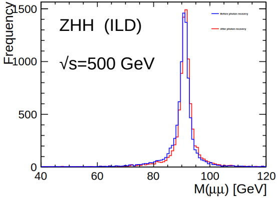
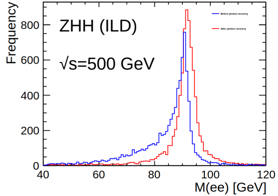


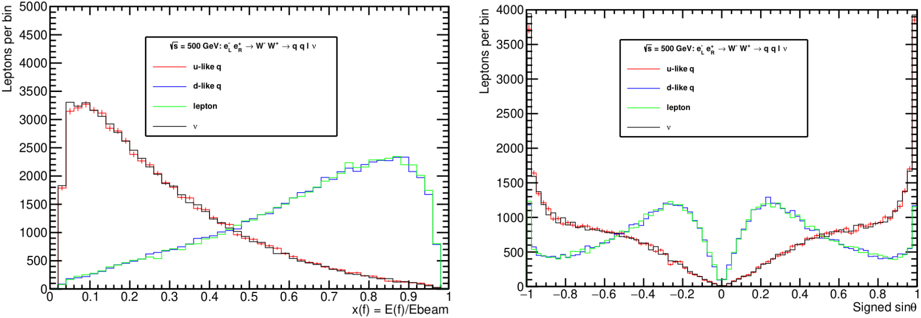


Julie Torndahl

- Given excellent muon momentum resolution, can we do better with electron-oriented track reconstruction and/or photon reconstruction.
- Should look more carefully at electron charge mis-ID and forward electron resolution and supposed uncertainties (for WWdiff and Wmass).

WW Acceptance Considerations

Generator level distributions for the dominant initial-state helicity configuration for $q\bar{q}\ell\nu_\ell$ at $\sqrt{s} = 500$ GeV.



$\sin\theta$ used to visualize the θ acceptance at small angles ($\sin\theta = 0.2 \approx \theta = 0.2$ rad)

- The charged lepton and the down-like quark tends to be energetic (follows the W)
- The charged lepton and the down-like quark jet are very forward (and more so as $\sqrt{s}$ increases).
- The neutrino and the up-like quark tend to be more central and of lower energy.

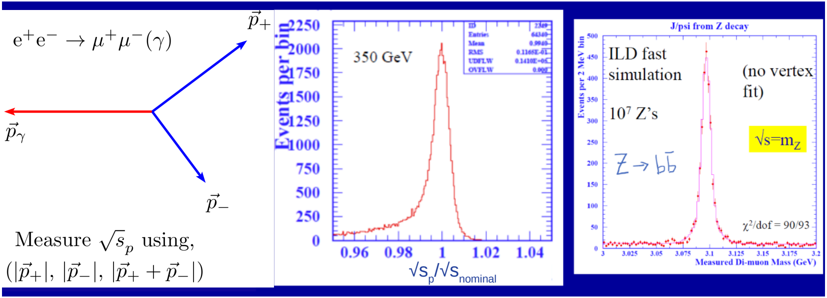
L.E.P.: Measuring Initial Conditions

A common theme for WG1-PREC topics is the measurement of the initial conditions and understanding of the systematic uncertainties.
L.E.P. = Luminosity, Energy and Polarization.
All three feature both experiment-defined and accelerator-based measurement methods. We already discussed Luminosity and Polarization.

- A key ingredient for fits with kinematic constraints or cross-section lineshape measurements is knowledge of the initial-state 4-vector, especially the center-of-mass **energy**, but also the net boost from energy spread and beam-beam energy losses (beamstrahlung), and the luminosity spectrum.
- For such measurements, the dilepton processes, $\mathrm{e}^+\mathrm{e}^- \to \mu^+\mu^-$ and $\mathrm{e}^+\mathrm{e}^- \to \mathrm{e}^+\mathrm{e}^-$ play a very important role. Studies so far have emphasized track-based measurements of muons and calorimeter-based measurements of electrons. **Better electron reconstruction** would help a lot.
- As outlined in 2209.03281 (Madison, Wilson) and references therein, this puts a premium on excellent momentum resolution and calibration of the **absolute momentum scale**, assumed for now to be done with known standard candles. Current target precision is of order 5 ppm (good enough for m_{W}).
- Obviously absolute momentum, implies excellent knowledge of material, B-field, alignment etc, and a comprehensive strategy.

$\sqrt{s_p}$ Method for Absolute Center-of-Mass Energy

Use dilepton **momenta**, with $\sqrt{s_p} \equiv E_+ + E_- + |\vec{p}_{+-}|$ as $\sqrt{s}$ estimator.



Tie detector p-scale to particle masses (know J/ψ, π^+, p to 1.9, 1.3, 0.006 ppm)

Measure $< \sqrt{s} >$ and luminosity spectrum with same events. Expect statistical uncertainty of 1.0 ppm on p-scale per 1.2M $J/\psi \to \mu^+\mu^-$ (4×10^9 hadronic Z's).

- excellent tracker momentum resolution - can resolve beam energy spread.
- feasible for $\mu^+\mu^-$ and e^+e^- (and ... 4l etc).
- relies on excellent modeling of QED effects (**ISR** and FSR)

Concrete Plans/Projects/Outlook

1. $e^+e^- \to \gamma\gamma$ is a promising "new" direction for absolute luminosity for FCC-ee and ILC that requires an all-detector reconstruction (and design?) approach.
2. The $q\bar{q}\ell\nu_\ell$ channels should be the work-horses for WWdiff and Wmass studies. Many different sub-topics related to reconstruction are important: lepton ID, jet-energy-scale, kinematic fits, pile-up mitigation, lepton reconstruction, center-of-mass energy measurement, lepton energy scale, tau ID, vertexing. Can build on past event selection/reconstruction work by I. Marchesini, A. Rosca, J. Anguiano for ILC at 500 GeV.
3. For Wmass, considerable interest in threshold scan based measurement. This needs to become more realistic with relevant simulation studies (eg. 4f contributions) and appropriate event selections accounting for backgrounds especially in the $q\bar{q}\tau\nu_\tau$ and $q\bar{q}q\bar{q}$ channels.
4. Much work to do on improving hadronization modeling/measurements for techniques that rely on the W hadronic mass.
5. Alignment and momentum-scale strategy are large-scope issues for reconstruction.
6. Finally Wmass, LUMI, and Wdiff topics rely partly on improved theoretical calculations and frameworks.

Acknowledgments

- WG1-PREC conveners:
  Adrian Irles, Ayres Freitas, Andreas Meyer, Paolo Azzurri
- Jorge de Blas
- Jenny List, Mogens Dam
- Julie Torndahl
- Justin Anguiano
- Work on developing the various tools over the years.