Theory perspective on future electroweak measurements

A. Freitas
University of Pittsburgh

Lepton-Photon 2017

1. Electroweak precision observables

2. Electroweak showers

3. X-plosion

Electroweak precision observables:

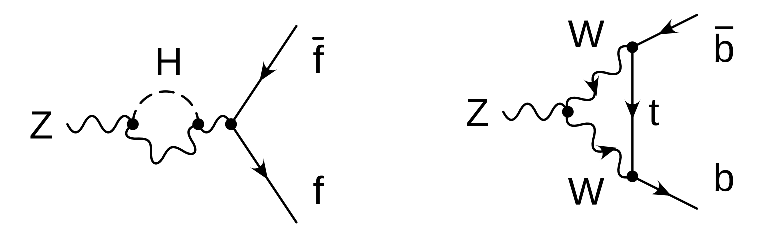
Going after large masses with one weak boson

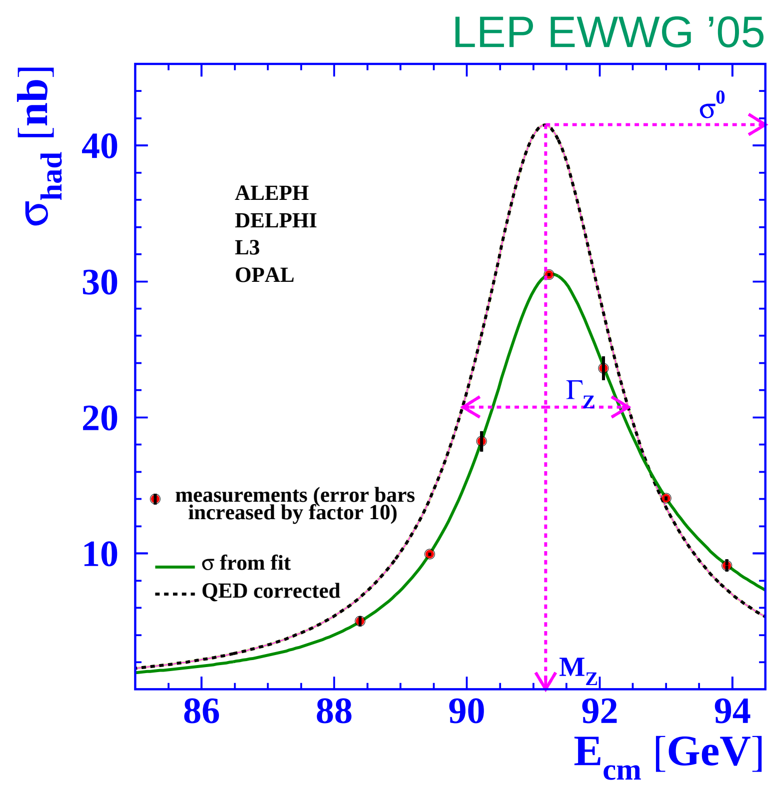
Weak scale observables

Indirect sensitivity to **top**, **Higgs**, and **new physics** through quantum corrections

- W-boson mass M_{W} (from τ_μ)
- Z-boson width Γ_{Z}
- Z-pole cross-section $\sigma^0[e^+e^- \to (Z) \to f\bar{f}]$
- Effective weak mixing angle $\sin^2\theta^f_{\mathrm{eff}}$ from Z asymmetries (A_{LR}, A^f_{FB})

$$\sin^2\theta^f_{\mathrm{eff}} = \frac{1}{2|Q_f|}\,\mathrm{Re}\left\{\frac{g_R^{\mathrm{eff}}}{g_R^{\mathrm{eff}} - g_L^{\mathrm{eff}}}\right\}$$





Current uncertainties

Most important quantities:

	Exp. error	Th. error
$M_{\rm W}$	15 MeV	4 MeV
Γ_Z	2.3 MeV	0.5 MeV
$\sigma^0_{\rm had} = \sigma[e^+e^- \to Z \to \text{had.}]$	37 pb	6 pb
$R_b = \Gamma[Z \to b\bar{b}]/\Gamma[Z \to \text{had.}]$	6.6×10^{-4}	1.5×10^{-4}
$\sin^2\theta^\ell_{\rm eff}$ (from $A_{\rm LR}$ and $A_{\rm FB}$)	1.6×10^{-4}	0.5×10^{-4}

- Complete NNLO or *fermionic* NNLO corrections known

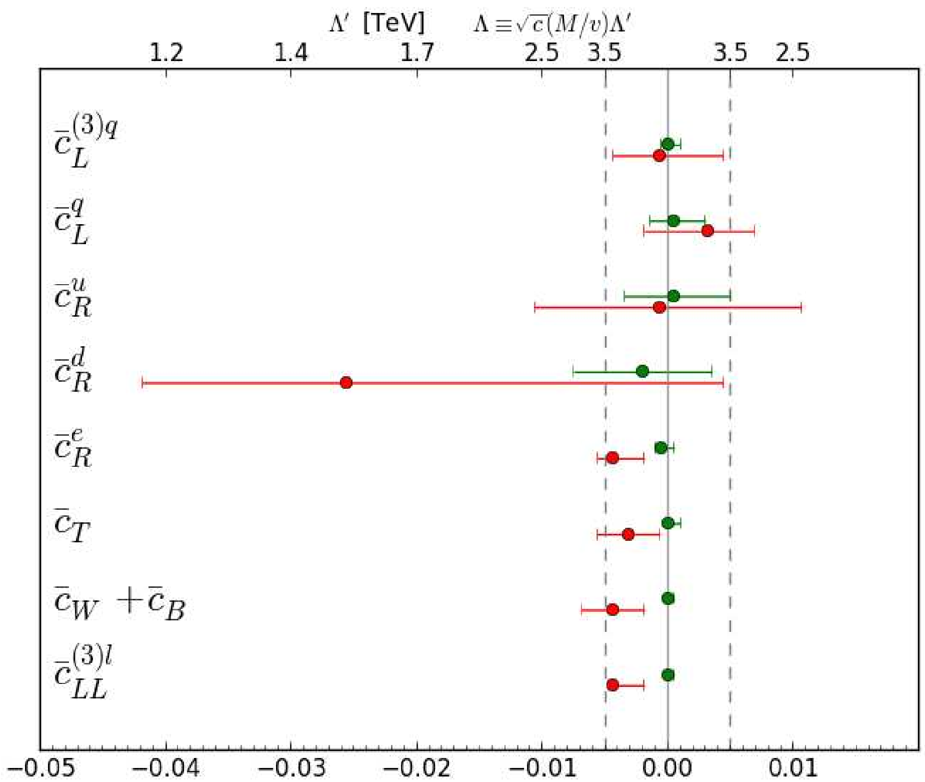
  Freitas, Hollik, Walter, Weiglein '00; Awramik, Czakon '02; Onishchenko, Veretin '02
  Awramik, Czakon, Freitas, Weiglein '04; Awramik, Czakon, Freitas '06
  Hollik, Meier, Uccirati '05,07; Freitas '13,14; Dubovyk, Freitas, Gluza, Riemann, Usovitsch '16

- Partial 3/4-loop corrections

  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

Constraints on new physics in effective theory framework

Assuming flavor universality: $\mathcal{L} = \sum_i \frac{c_i}{\Lambda^2}\mathcal{O}_i + \mathcal{O}(\Lambda^{-3}) \qquad (\Lambda \gg M_Z)$



$$\mathcal{O}_{\phi 1} = (D_\mu \Phi)^\dagger \Phi\, \Phi^\dagger (D^\mu \Phi)$$

$$\mathcal{O}_{\mathrm{BW}} = \Phi^\dagger B_{\mu\nu} W^{\mu\nu} \Phi$$

$$O_{\mathrm{LL}}^{(3)e} = (\bar{L}_{\mathrm{L}}^e \sigma^a \gamma_\mu L_{\mathrm{L}}^e)(\bar{L}_{\mathrm{L}}^e \sigma^a \gamma^\mu L_{\mathrm{L}}^e)$$

$$O_{\mathrm{R}}^{f} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{f}_{\mathrm{R}} \gamma^\mu f_{\mathrm{R}})$$

$$O_{\mathrm{L}}^{F} = i(\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{F}_{\mathrm{L}} \gamma^\mu F_{\mathrm{L}})$$

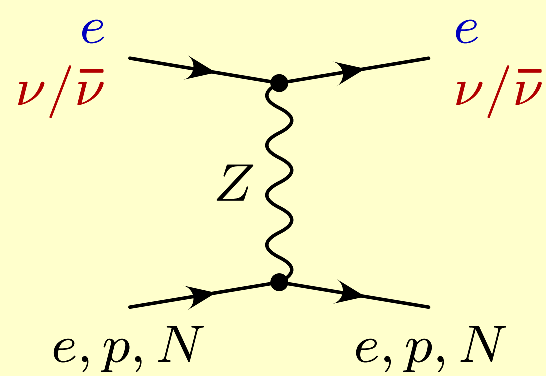
$$O_{\mathrm{L}}^{(3)F} = i(\Phi^\dagger \overleftrightarrow{D}_\mu^a \Phi)(\bar{F}_{\mathrm{L}} \sigma_a \gamma^\mu F_{\mathrm{L}})$$

Pomaral, Riva ’13
Ellis, Sanz, You ’14

Low-energy electroweak observables

- Polarized $ee,\ ep,\ ed$ scattering ($Q_W(e)$, $Q_W(p)$, eDIS)
  E158 '05; Qweak '13; JLab Hall A '13
- $\nu N/\bar{\nu} N$ scattering NuTeV '02
- Atomic parity violation ($Q_W(^{133}\text{Cs})$) Wood et al. '97
  Guéna, Lintz, Bouchiat '05

$\longrightarrow$ Test of running $\overline{\text{MS}}$ weak mixing angle $\sin^2\bar{\theta}(\mu)$



$$g_{\text{AV}}^{ef}\,[\bar{e}\gamma^\mu\gamma_5 e]\,[\bar{f}\gamma_\mu f]$$
$$g_{\text{VA}}^{ef}\,[\bar{e}\gamma^\mu e]\,[\bar{f}\gamma_\mu\gamma_5 f]$$

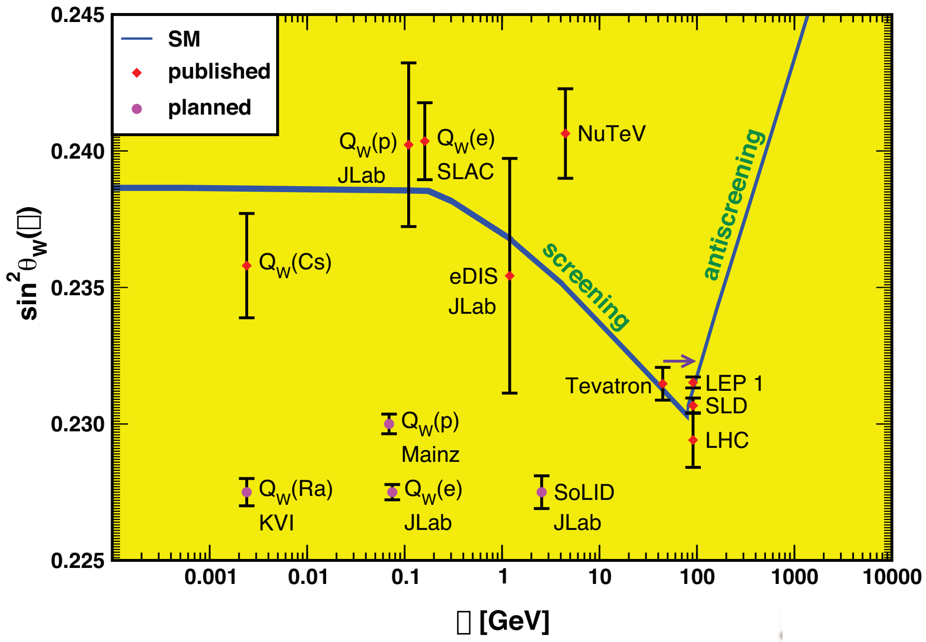
$$g_{\text{AV}}^{ef} = \frac{1}{2} - 2|Q_f|\sin^2\bar{\theta}(\mu)$$
$$g_{\text{VA}}^{ef} = \frac{1}{2} - 2\sin^2\bar{\theta}(\mu)$$

Low-energy electroweak observables

- Polarized ee, ep, ed scattering ($Q_W(e)$, $Q_W(p)$, eDIS)
  E158 '05; Qweak '13; JLab Hall A '13
- $\nu N/\bar{\nu} N$ scattering NuTeV '02
- Atomic parity violation ($Q_W(^{133}\text{Cs})$) Wood et al. '97
  Guéna, Lintz, Bouchiat '05

$\longrightarrow$ Test of running $\overline{\text{MS}}$ weak mixing angle $\sin^2\bar{\theta}(\mu)$

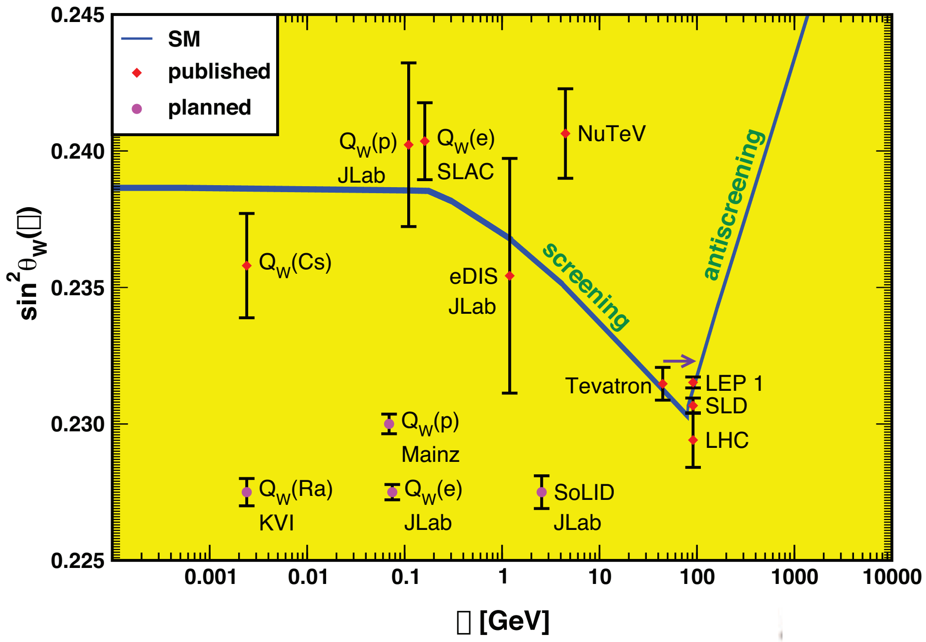
Erler '14



Low-energy electroweak observables

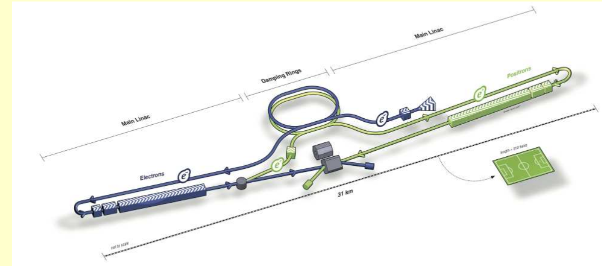
- Polarized ee, ep, ed scattering ($Q_W(e)$, $Q_W(p)$, eDIS)
  E158 '05; Qweak '13; JLab Hall A '13
- $\nu N/\bar{\nu} N$ scattering NuTeV '02
- Atomic parity violation ($Q_W(^{133}\text{Cs})$) Wood et al. '97
  Guéna, Lintz, Bouchiat '05
- Future experiments:
  MOLLER (ee), P2, SoLID (ep), Atomic PV in radium

Erler '14

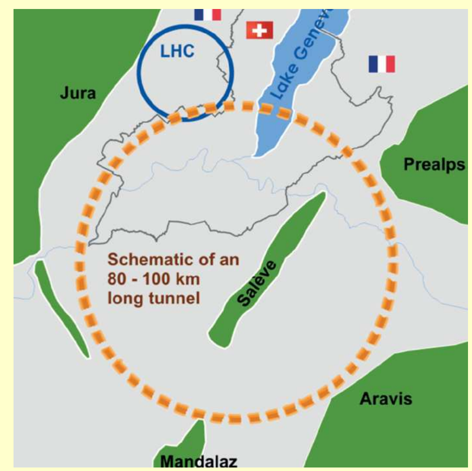


Future high-energy e^+e^- colliders

- International Linear Collider (ILC)
  Int. lumi at $\sqrt{s} \sim M_Z$: 50–100 fb^{-1}



- Circular Electron-Positron Collider (CEPC)
  Int. lumi at $\sqrt{s} \sim M_Z$: 2×150 fb^{-1}



- Future Circular Collider (FCC-ee)
  Int. lumi at $\sqrt{s} \sim M_Z$: $> 2 \times 30$ ab^{-1}

Future projections

	Measurement error				Intrinsic theory	
	Current	ILC	CEPC	FCC-ee	Current	Future†
M_{W} [MeV]	15	3–4	3	1	4	1
Γ_Z [MeV]	2.3	0.8	0.5	0.1	0.5	0.2
R_b [10^{-5}]	66	14	17	6	15	7
$\sin^2\theta^{\ell}_{\text{eff}}$ [10^{-5}]	16	1	2.3	0.6	4.5	1.5

$\longrightarrow$ Existing theoretical calculations adequate for LEP/SLC/LHC, but not ILC/CEPC/FCC-ee!

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

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

Future projections

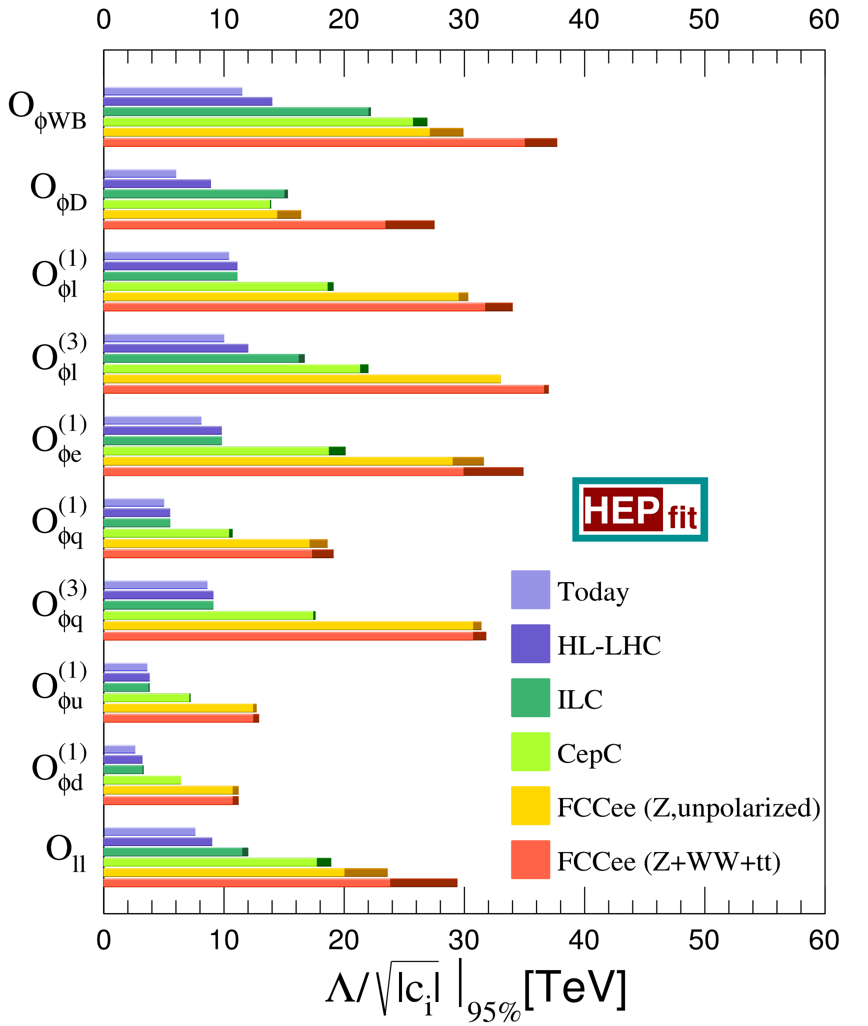
	Measurement		Intrinsic theory		Parametric	
	ILC	FCC-ee	Current	Future	ILC	FCC-ee
M_{W} [MeV]	3–4	1	4	1	2.6	0.6–1
Γ_Z [MeV]	0.8	0.1	0.5	0.2	0.5	0.1
R_b [10^{-5}]	14	6	15	7	< 1	< 1
$\sin^2 \theta^{\ell}_{\mathrm{eff}}$ [10^{-5}]	1	2.3	4.5	1.5	2	1–2

Projected parameter measurements:

	δm_t	$\delta \alpha_{\mathrm{s}}$	δM_{Z}	$\delta(\Delta\alpha)$
ILC:	50 MeV	0.001	2.1 MeV	5×10^{-5}
FCC-ee:	50 MeV	0.0002	0.1 MeV	$3\text{–}5 \times 10^{-5}$

Sensitivity to new physics

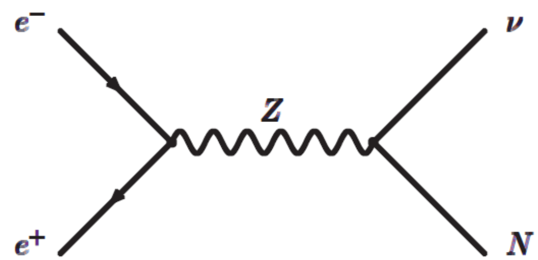
Heavy new physics:

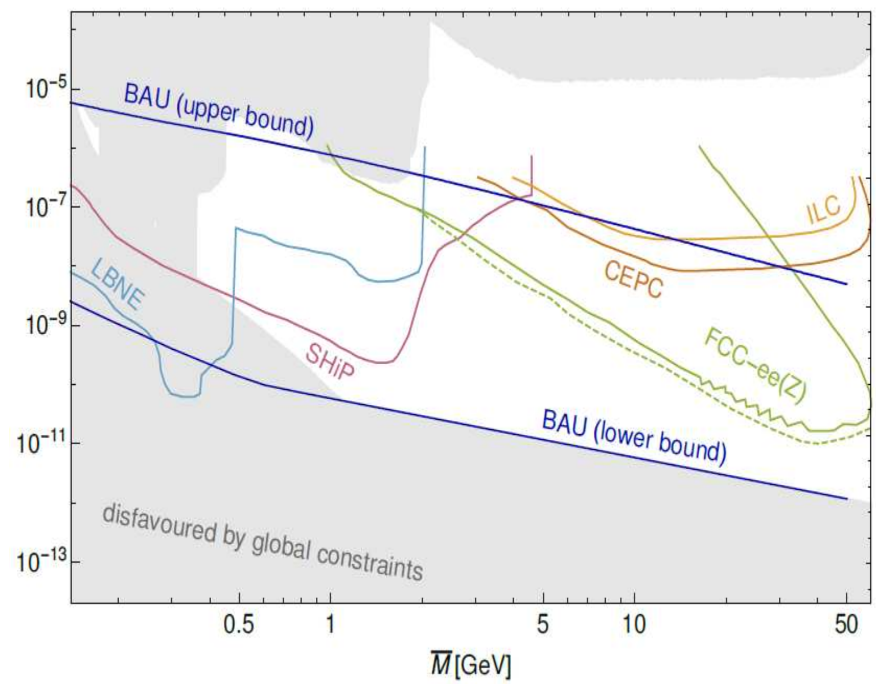


(one op. at a time)

de Blas et al. '16

Light new physics: sterile neutrinos



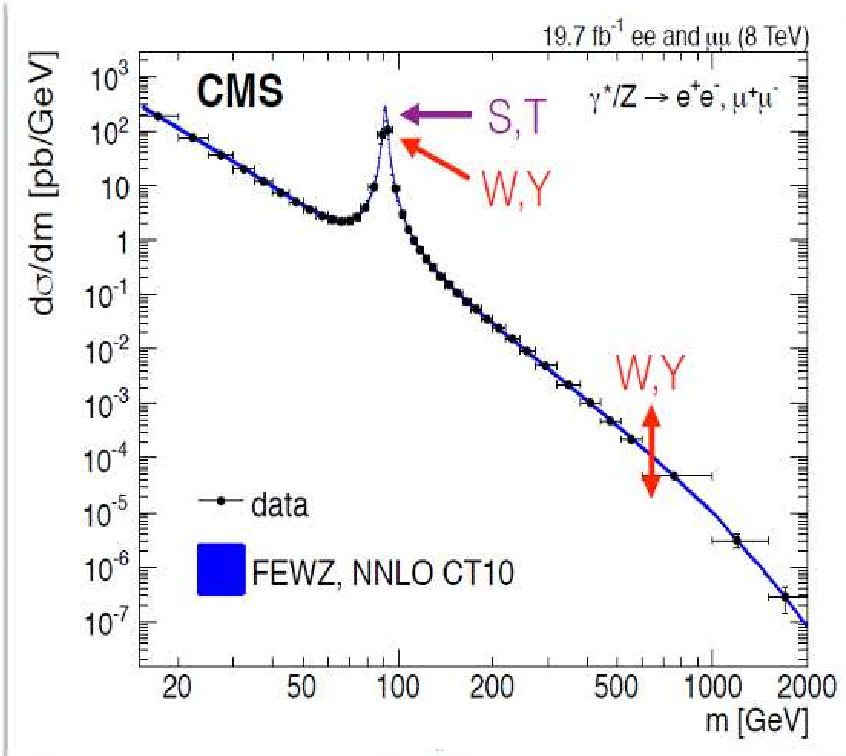


Antusch, Gazzato, Fischer '16

Drewes, Garbrecht, Gueter, Klaric '16

Probes of EWPO with high-mass DY @ 100 TeV

Trade extreme precision for dynamical range, in pursuit of high-scale sensitivity



	universal form factor ($\mathcal{L}$)
W	$-\frac{W}{4m_W^2}(D_\rho W^a_{\mu\nu})^2$
Y	$-\frac{Y}{4m_W^2}(\partial_\rho B_{\mu\nu})^2$

Farina et al. '16
J. Ruderman, FCC physics wshop '17
M. Mangano, FCC week '17

FCC-pp

		LEP	ATLAS 8	CMS 8	LHC 13		100 TeV	ILC	TLEP	ILC 500 GeV
luminosity		$2 \times 10^7\, Z$	$19.7\, \text{fb}^{-1}$	$20.3\, \text{fb}^{-1}$	$0.3\, \text{ab}^{-1}$	$3\, \text{ab}^{-1}$	$10\, \text{ab}^{-1}$	$10^9\, Z$	$10^{12}\, Z$	$3\, \text{ab}^{-1}$
NC	$W \times 10^4$	$[-19, 3]$	$[-3, 15]$	$[-5, 22]$	± 1.5	± 0.8	± 0.04	± 3	± 0.7	± 0.3
	$Y \times 10^4$	$[-17, 4]$	$[-4, 24]$	$[-7, 41]$	± 2.3	± 1.2	± 0.06	± 4	± 1	± 0.2
CC	$W \times 10^4$	—	± 3.9		± 0.7	± 0.45	± 0.02	—	—	—

FCC-ee

assumed syst's at 100 TeV:

- neutral: $\delta_{cor} = \delta_{unc} = 2\%$
- charged: $\delta_{cor} = \delta_{unc} = 5\%$

58

Electroweak showers:

Large scales obscured by many weak bosons

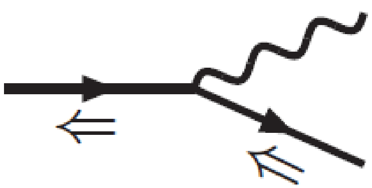
Electroweak showers: massless

EW physics at future pp collider:

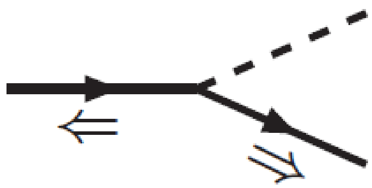
- W/Z bosons can be copiously produced at multi-TeV pp collider
- Enhancement $\sim \log^2(E/M_W)$ for near-collinear emission
- Approximate description through parton shower

Ciafaloni, Ciafaloni, Comelli ’00
Ciafaloni, Comelli ’05; Bell, Kühn, Rittinger ’10
Christensen, Sjöstrand ’14; Krauss, Petrov, Schoenherr, Spannowsky ’14
Bauer, Ferland ’16; Chen, Han, Tweedie ’16

Presence of scalar fields (Higgs/longitudinal gauge bosons):



$$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{1+\bar{z}^2}{z}\right)$$

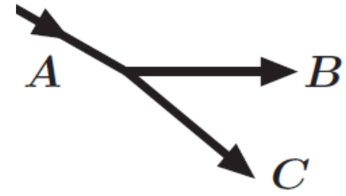


$$\frac{1}{8\pi^2}\frac{1}{k_T^2}\left(\frac{z}{2}\right)$$

Chen, Han, Tweedie ’16

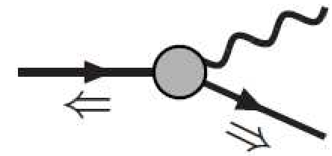
Electroweak showers: massive

Effect of masses / EWSB:



- Kinematics: $k_T^2 \to k_T^2 + \bar{z}m_B^2 + zm_C^2 - z\bar{z}m_A^2$

- Helicity-flipping ("ultra-collinear") splitting functions



$$\frac{1}{16\pi^2}\frac{v^2}{\tilde{k}_T^4}$$

- Complication from gauge artifacts $\propto E/M_{\mathrm{W}}$
  $\longrightarrow$ Remove with convenient gauge choice

$$\mathcal{L}_{\mathrm{gf}} = -\frac{1}{2\xi}\left[n^\mu W_\mu(k)\right]\left[n^\nu W_\nu(-k)\right] \qquad (\xi \to \infty)$$

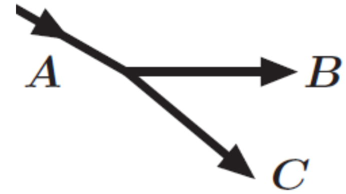
$$n^\mu = (1, -\hat{k})$$

  $\longrightarrow$ Smoothly interpolates to Goldstone equivalence of unbroken gauge at high energies

Chen, Han, Tweedie '16

Electroweak showers: massive

Effect of masses / EWSB:



- Kinematics: $k_T^2 \to k_T^2 + \bar{z}m_B^2 + zm_C^2 - z\bar{z}m_A^2$

- Helicity-flipping ("ultra-collinear") splitting functions

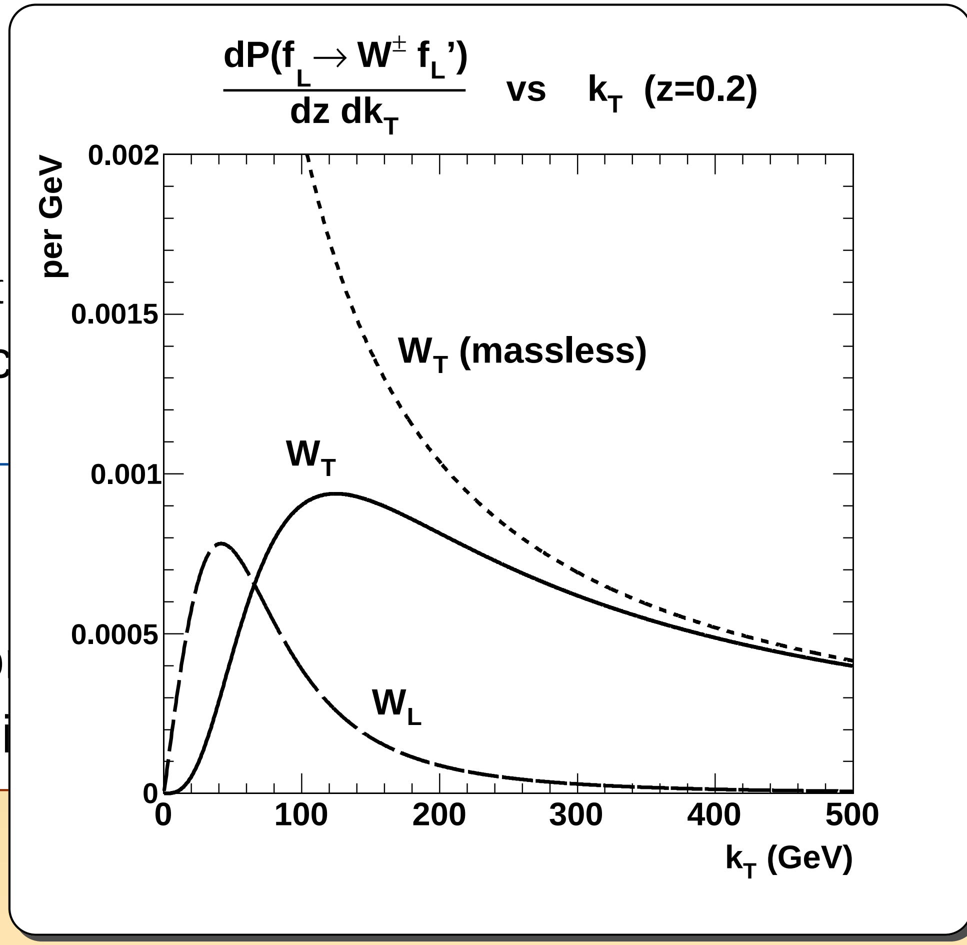
- Complication from gauge artifacts $\propto$

  $\longrightarrow$ Remove with convenient gauge c

  $$\mathcal{L}_{\mathrm{gf}} = -\frac{1}{2\xi}\left[n^\mu W_\mu(k)\right]\left[n^\nu W_\nu(-$$

  $$n^\mu = (1, -\hat{k})$$

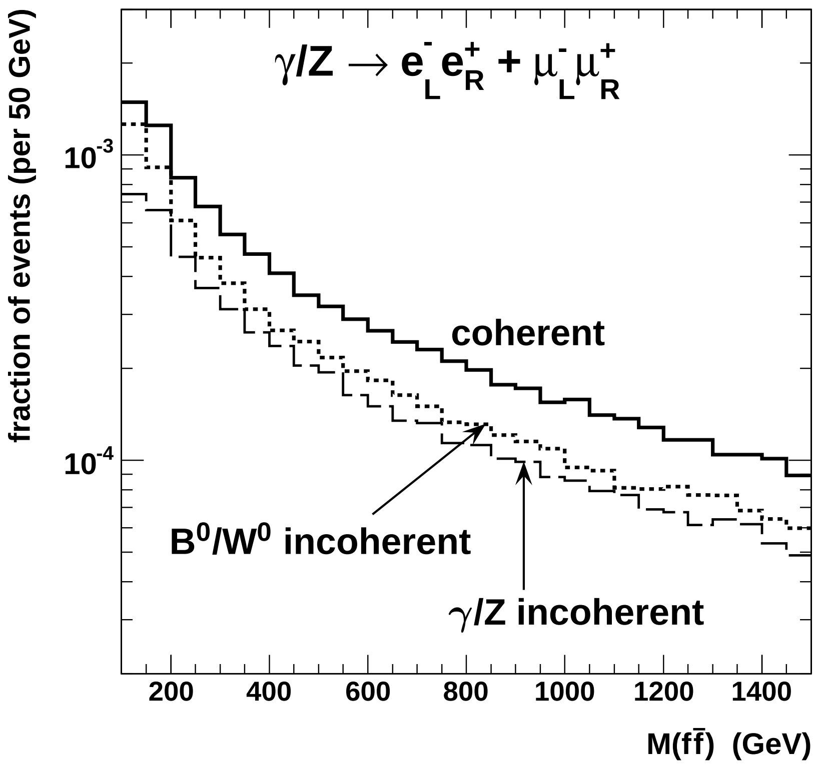
  $\longrightarrow$ Smoothly interpolates to Goldsto of unbroken gauge at high energi



Electroweak showers: mixing and PDFs

γ/Z_T and h/Z_L mixing:

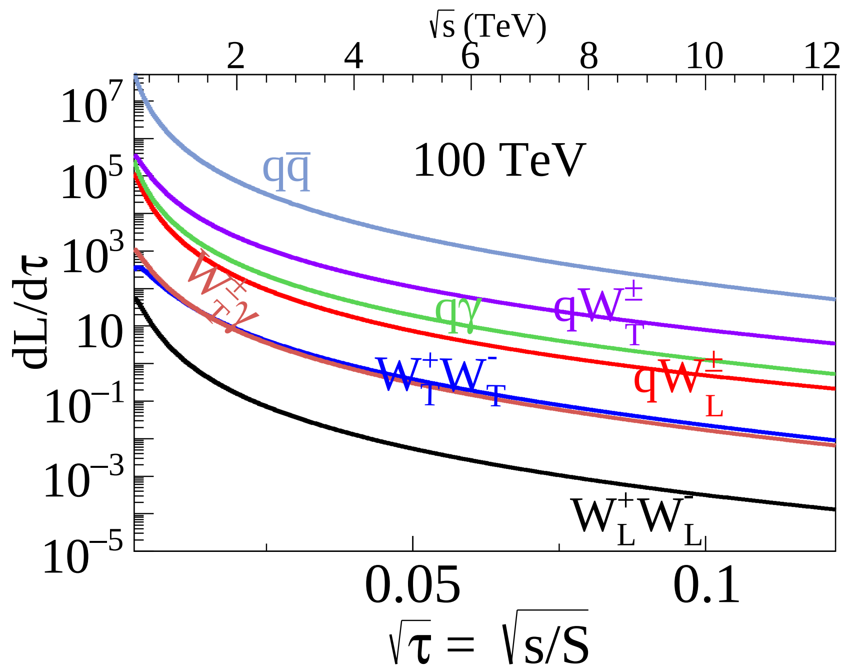
Sudakov evolution with density matrix



Electroweak PDFs:

$$f_V(z) \approx \int dk_T^2 \int \frac{dz'}{z'} \frac{dP_{q\to Vq^{(\prime)}}}{dz' dk_T^2} f_q(z/z')$$

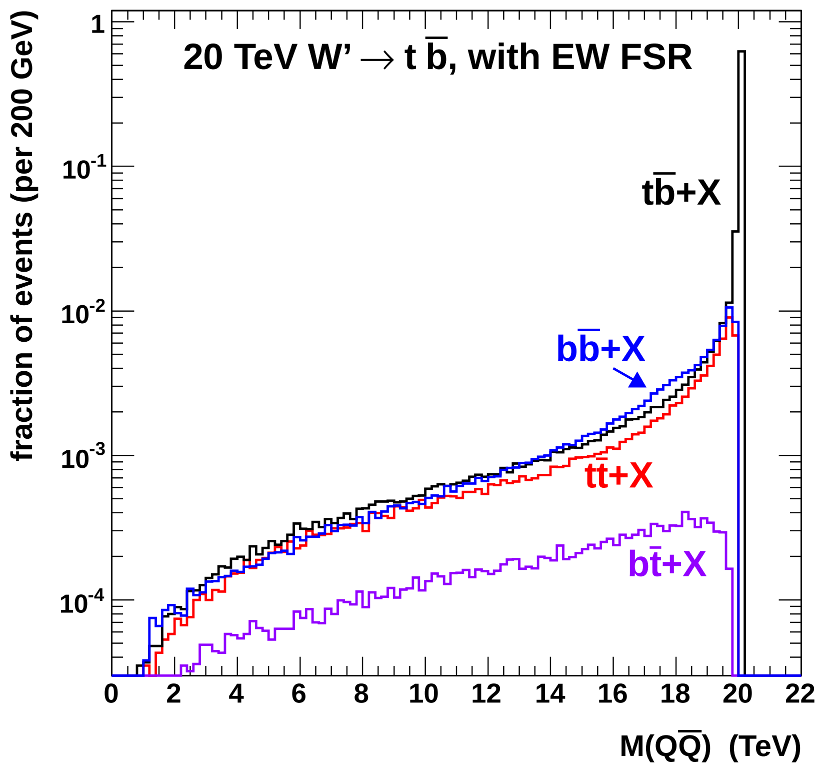
Kane, Repko, Rolnick '84; Dawson '85



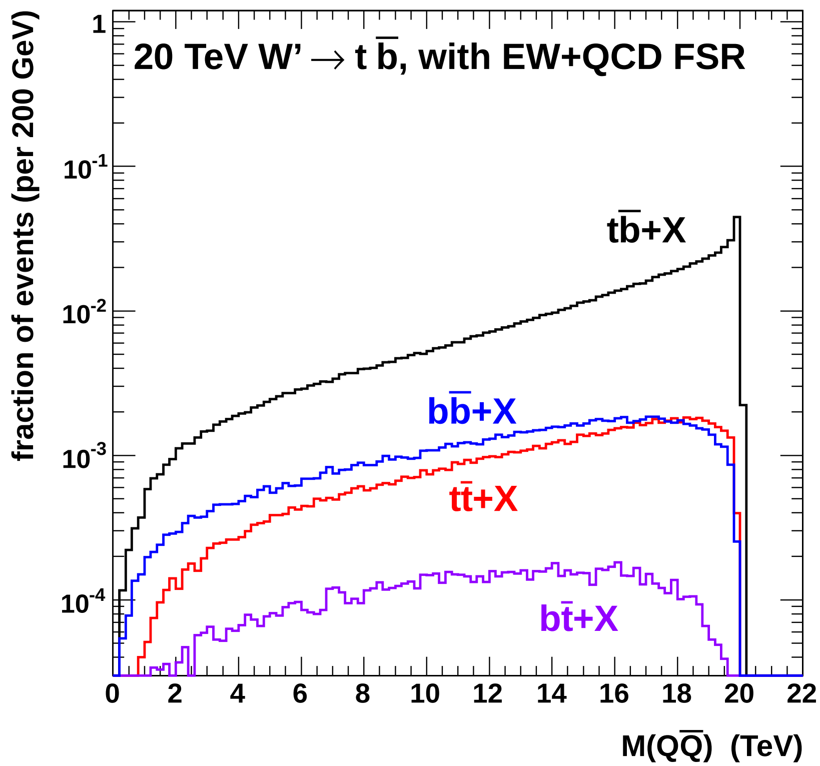
Chen, Han, Tweedie '16

Decay of W' with $m_{W'} = 20$ TeV into heavy quarks:

with EW shower:



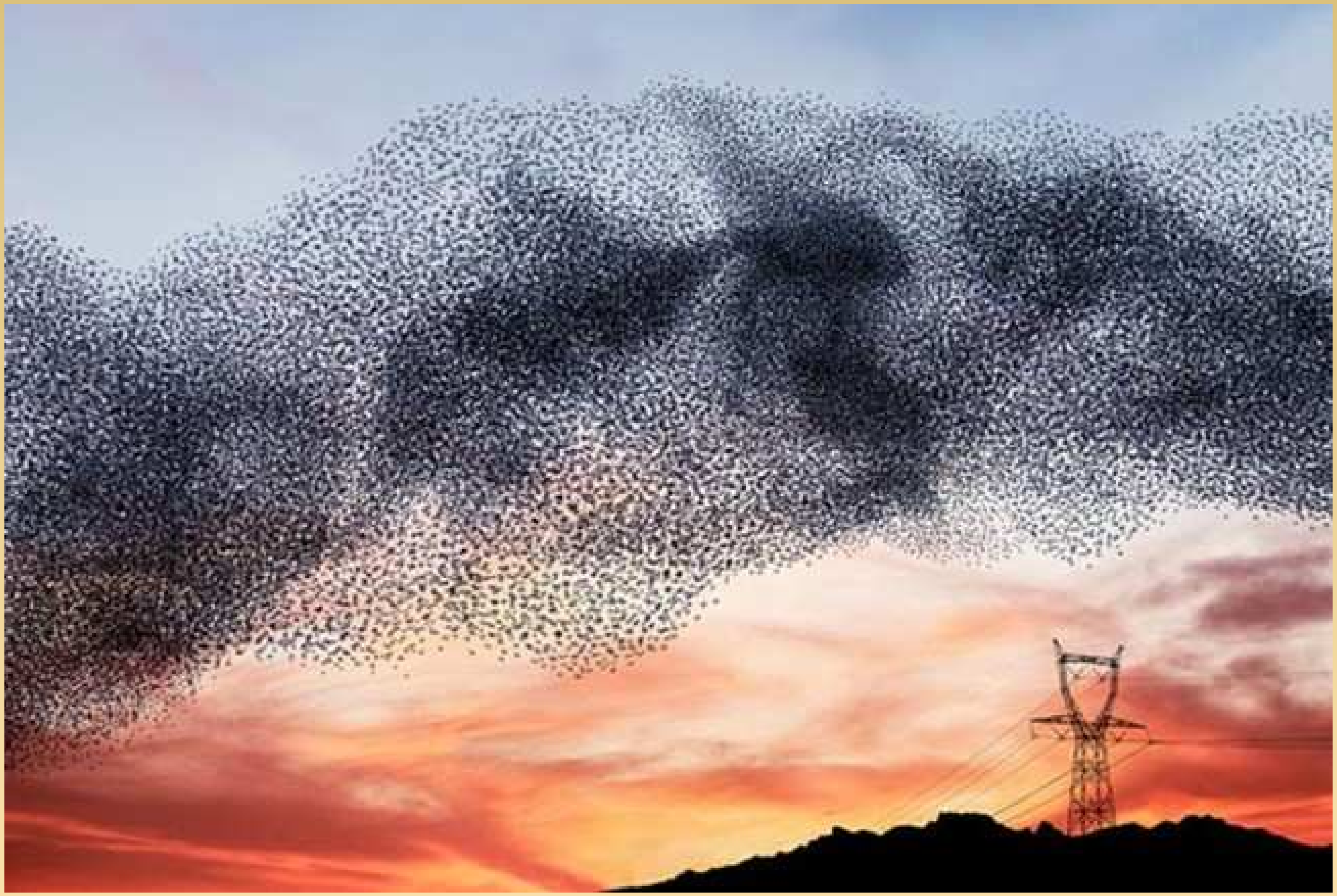
with EW+QCD shower:



Chen, Han, Tweedie '16

X-plosion:

Strength in numbers



Weak amplitudes at high energies

Higgs-plosion:

- $\phi^* \to n\phi$ in ϕ^4 theory: number of diagrams grows factorially

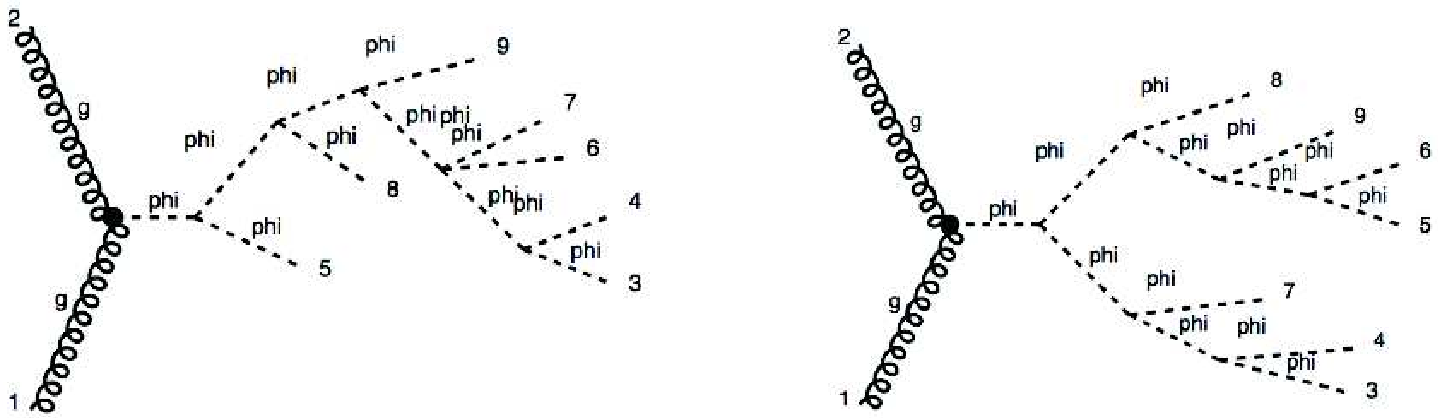
  Result at threshold: $$A_n = n! \left(\frac{\lambda}{2m^2}\right)^{(n-1)/2} \left[1 + n(n-1)\frac{\sqrt{3}\lambda}{8\pi}\right]$$

  Voloshin '92; Argyres, Kleiss, Papadopoulos '92; Brown '92; Smith '92

- $n!$ eventually overcomes $\lambda^{n/2}$ yielding large cross-section

  Libanov, Rubakov, Son, Troitsky '94; Son '95

Khoze '15



Weak amplitudes at high energies

Higgs-plosion:

- $\phi^* \to n\phi$ in ϕ^4 theory: number of diagrams grows factorially

  Result at threshold: $$A_n = n! \left(\frac{\lambda}{2m^2}\right)^{(n-1)/2} \left[1 + n(n-1)\frac{\sqrt{3}\lambda}{8\pi}\right]$$

  Voloshin '92; Argyres, Kleiss, Papadopoulos '92; Brown '92; Smith '92

- $n!$ eventually overcomes $\lambda^{n/2}$ yielding large cross-section

  Libanov, Rubakov, Son, Troitsky '94; Son '95

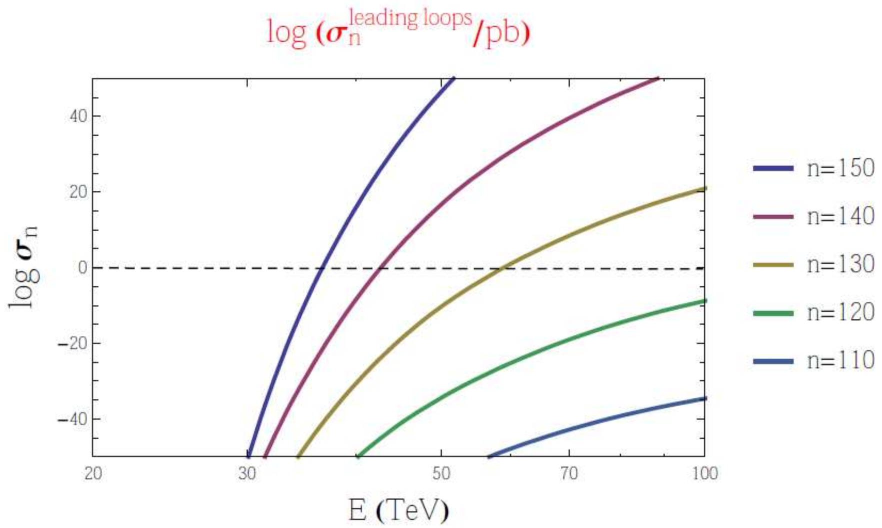
W/Z-plosion:

Khoze '14,15

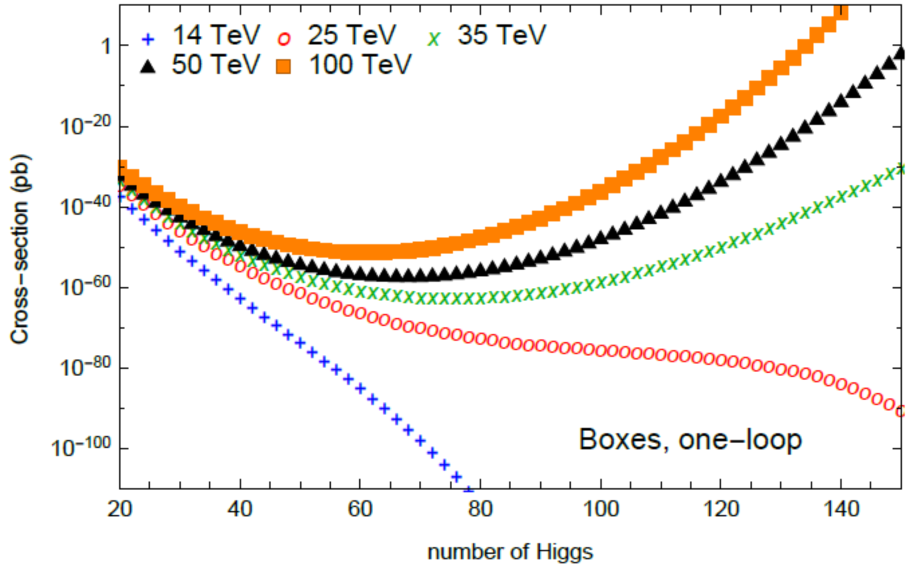
- Similar effect in SM for (longitudinal) SU(2) gauge bosons:
  $A[nh + mZ_L] \sim n!m!$
- Techniques:
  - recursion relations
  - classical solutions
  - extrapolation from MadGraph

Cross-sections at high energies

Partonic cross-section:



pp cross-section:

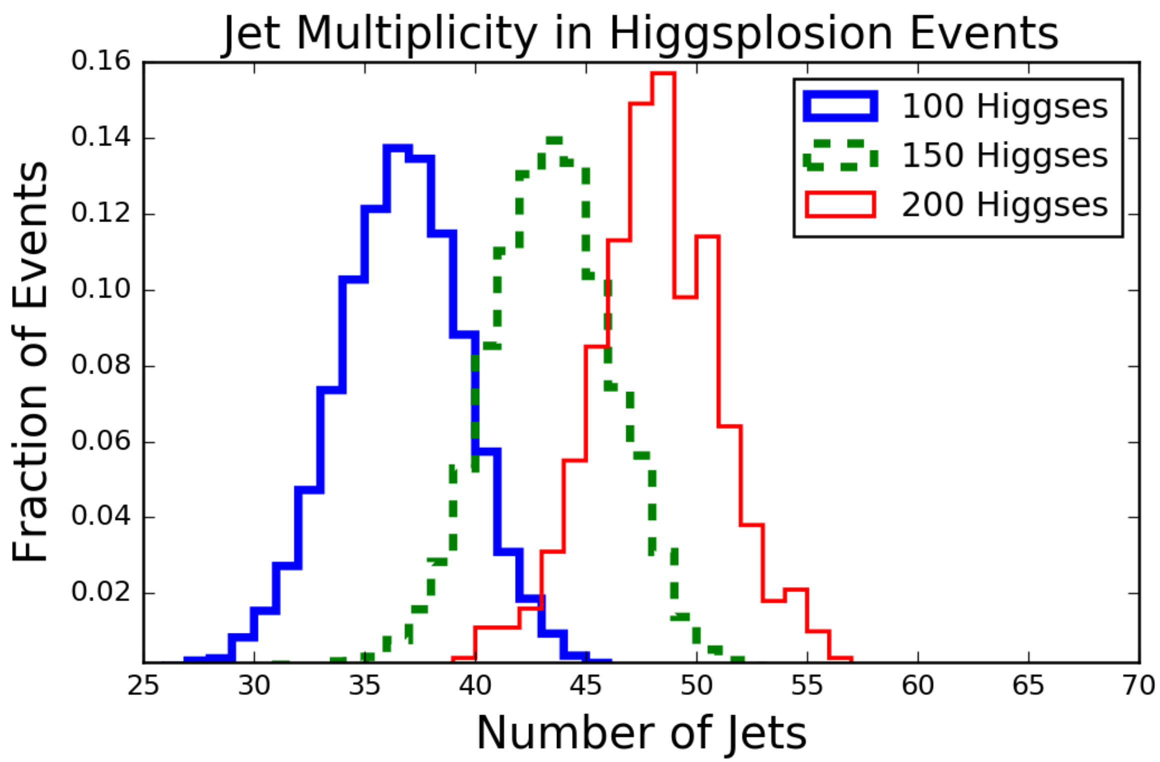


- Unitarity limit: $\sqrt{s_{\text{part}}} \lesssim 800$ TeV
- Non-perturbative limit: $\sqrt{s_{\text{part}}} \lesssim 300$ TeV

Khoze, Jaeckel '14

X-plosion: Observation

- Experimental search is simple (background free)



$\sqrt{S} = 100$ TeV

$p_{T,j} > 50$ GeV

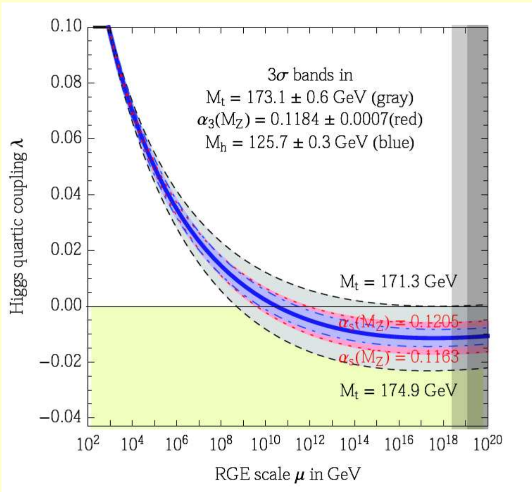
$\Delta R > 0.4$

Gainer '17

X-plosion: Interpretation

- Large cross-section σ_n for $n > 100$ H/W/Z bosons at 100-TeV collider?
- σ_n may be tamed by higher-order corrections
- $n > 100$ corresponds to $\mathcal{O}(\alpha^n)$ amplitude
  $\longrightarrow$ Perturbative expansion diverges, but non-perturbative $\sigma_n \ll$ unitarity limit

- Imaginary part of self-energies will dominate propagators for $p^2 \gg m^2$
  $\longrightarrow$ Damping of cross-section — Khoze, Spannowsky '17
- Fermion loops can cancel boson loops — Voloshin '17
- Higgs self-coupling runs to zero at large energies



Degrassi et al. '12

Summary: Electroweak physics at future colliders

Multi-faceted and possibly surprising insights:

- Indirect sensitivity to high scales at high-lumi e^+e^- colliders
- Direct access to multi-boson interactions at pp colliders

Summary: Electroweak physics at future colliders

Multi-faceted and possibly surprising insights:

- Indirect sensitivity to high scales at high-lumi e^+e^- colliders
- Direct access to multi-boson interactions at pp colliders

Theory description is challenging and requires new methods:

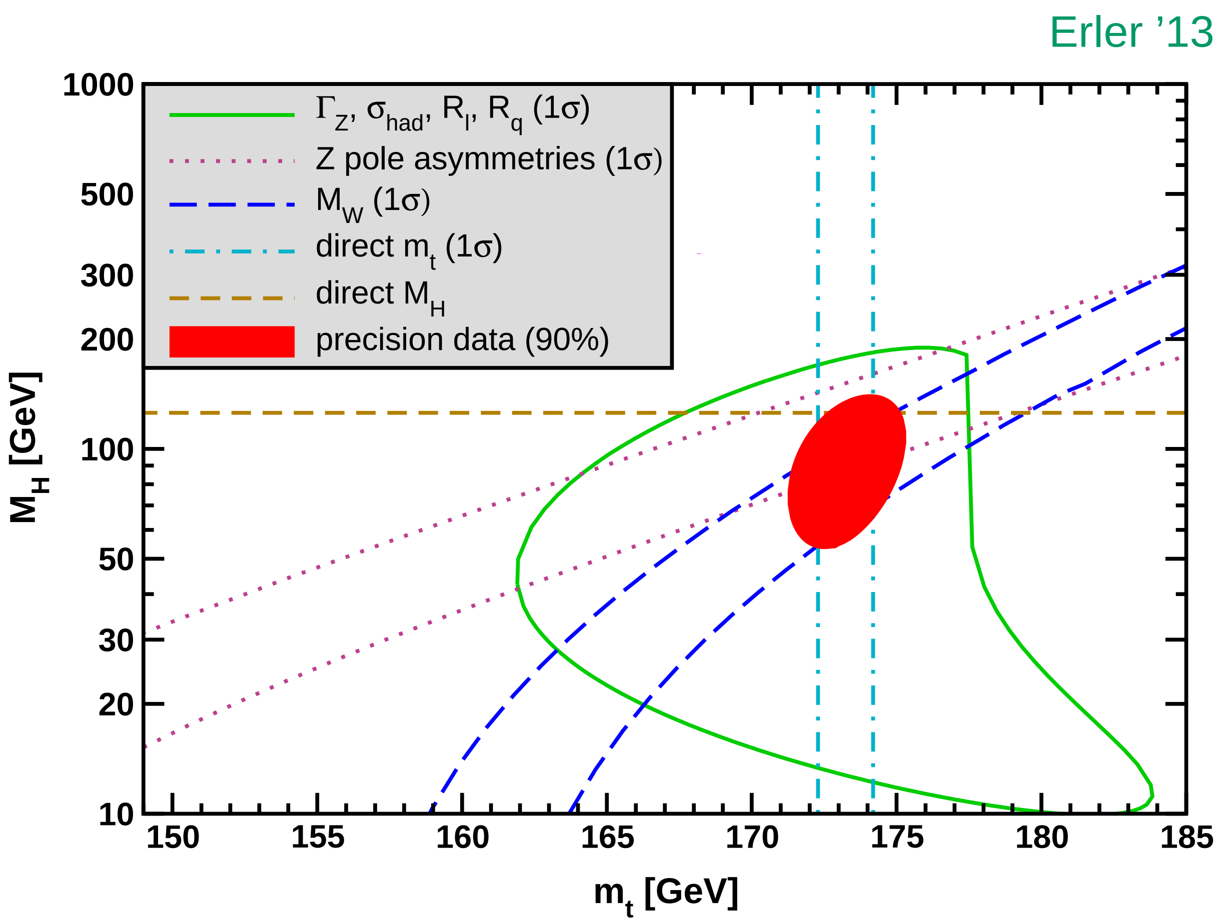
- Multi-loop (3,4,...) corrections for EWPO
- Electroweak parton showers, matching and merging
- Non-perturbative (?) description of multi-boson production

Backup slides

Current status of electroweak precision tests

Standard Model after Higgs discovery:

- Good agreement between measured mass and indirect prediction
- Very good agreement over large number of observables



Direct measurements:

$M_{\rm H} = 125.6 \pm 0.4$ GeV

$m_{\rm t} = 173.24 \pm 0.95$ GeV

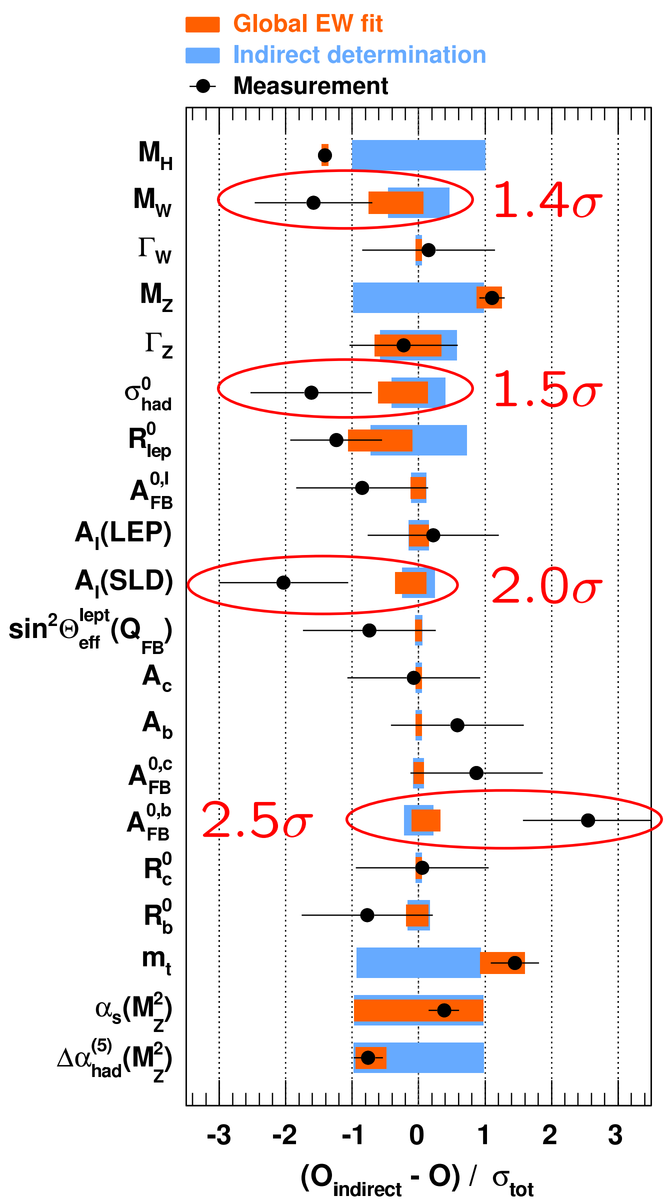
Indirect prediction:

$M_{\rm H} = 123.7 \pm 2.3$ GeV (with LHC BRs)

$M_{\rm H} = 89^{+22}_{-18}$ GeV (w/o LHC data)

$m_{\rm t} = 177.0 \pm 2.1$ GeV

Current status of electroweak precision tests



Surprisingly good agreement:
χ^2/d.o.f. $= 18.1/14$ ($p = 20\%$)

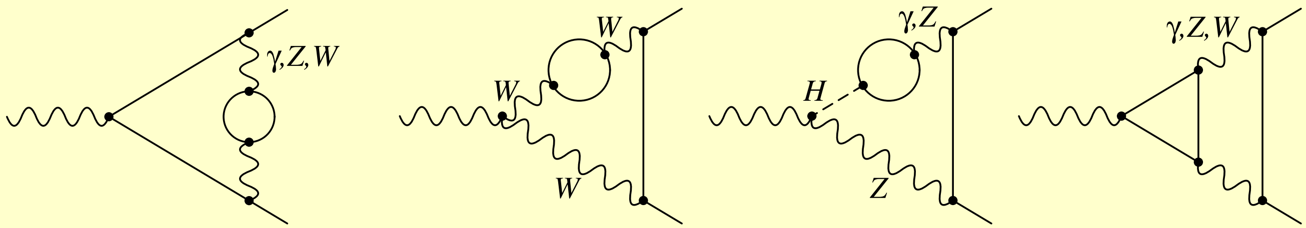
Most quantities measured with 1%–0.1% precision

A few interesting deviations:

M_W	$(\sim 1.4\sigma)$
σ^0_{had}	$(\sim 1.5\sigma)$
A_ℓ(SLD)	$(\sim 2\sigma)$
A^b_{FB}	$(\sim 2.5\sigma)$
$(g_\mu - 2)$	$(\sim 3\sigma)$

GFitter coll. '14

Current status of SM loop results



- Complete NNLO corrections (Δr, $\sin^2\theta^f_{\rm eff}$) 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
  Dubovyk, Freitas, Gluza, Riemann, Usovitsch '16

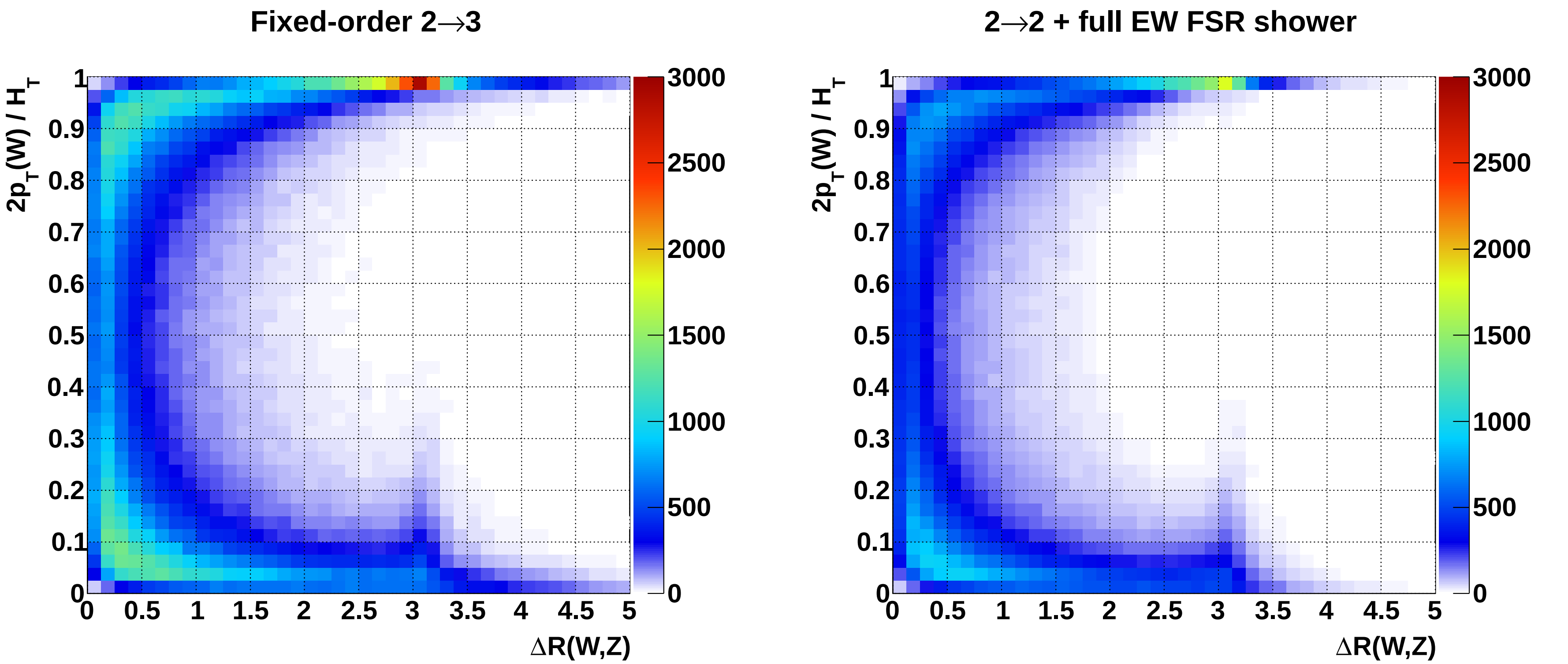
- "Fermionic" NNLO corrections ($\overline{\Gamma}_Z$, $\sigma^0_{\rm had}$, R_f) Czarnecki, Kühn '96
  Harlander, Seidensticker, Steinhauser '98
  Freitas '13,14

- Partial 3/4-loop corrections to ρ/T-parameter
  $\mathcal{O}(\alpha_t\alpha_s^2)$, $\mathcal{O}(\alpha_t^2\alpha_s)$, $\mathcal{O}(\alpha_t\alpha_s^3)$ 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

$(\alpha_t \equiv \frac{y_t^2}{4\pi})$

Electroweak showers vs. fixed order

Phase-space population for $WZ + j$ production: $(pp, \sqrt{S} = 100$ TeV$)$



Chen, Han, Tweedie '16