Summary of the Mini-Workshop "Physics Behind Precision"

Fulvio Piccinini (INFN Pavia)

CERN, 2-3 February 2016

Organizers: P. Azzi, F. Blekman, E. Locci, F.P., and R. Tenchini

Covered topics

- Historical perspective and motivations for the future

  P. Langacker

- Precision
  - Electroweak physics at the Z peak

    A. Freitas, F. Jegerlehner, P. Janot, S. Jadach
  - Top quark physics (in particular at $t\bar{t}$ threshold)

    G. Corcella, N. Foppiani, M. Steinhauser, M. Vos, C. Zhang
  - W boson physics at WW threshold

    P. Azzurri, G. Wilson

- Event generator developments

  I. Helenius (PYTHIA), J. Reuters (WHIZARD)

- Behind Precision

  S. De Curtis, J. Erler, B. Mele

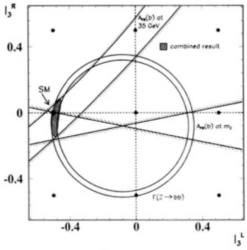
Thanks to all the speakers!

We benefitted also from two sessions of academic training lectures

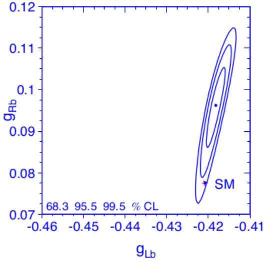
Few highlights in the following slides

Precision: where we come from and where we are

$(-\frac{1}{2}, 0)$, SM
$(0, -\frac{1}{2})$, mirror
$(0, 0)$, topless
$(-\frac{1}{2}, -\frac{1}{2})$, vector doublet



Schaile and Zerwas, Phys.Rev. D45 (1992)

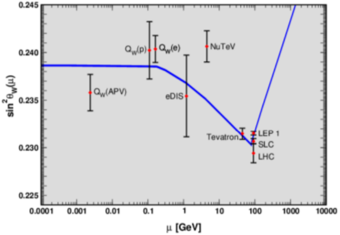


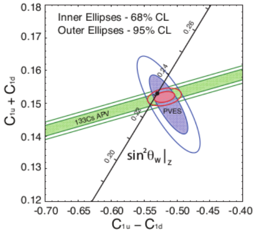
LEPEWWG

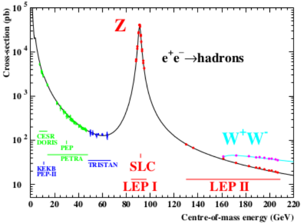
Physics Behind Precision, CERN (2/2/16)

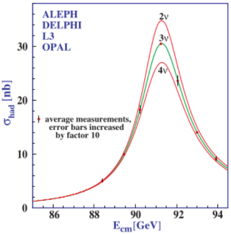
Paul Langacker (IAS)

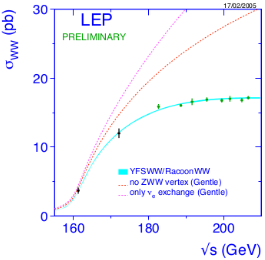
Summary after > 20 years of collider physics (high and lower energies)



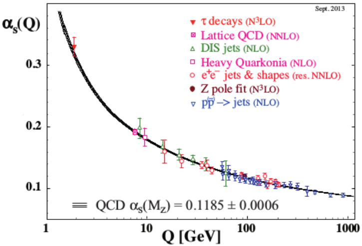




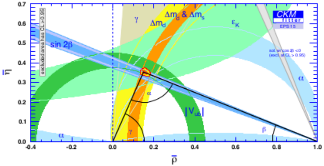




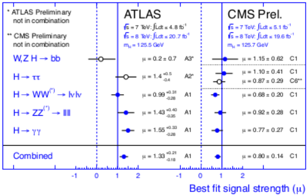
LEP
PRELIMINARY
17/02/2005
σWW (pb)
√s (GeV)
YFSWW/RacoonWW
no ZWW vertex (Gentle)
only νe exchange (Gentle)



αs(Q)
Sept. 2013
τ decays (N3LO)
Lattice QCD (NNLO)
DIS jets (NLO)
Heavy Quarkonia (NLO)
e+e– jets & shapes (res. NNLO)
Z pole fit (N3LO)
pp –> jets (NLO)
QCD αs(MZ) = 0.1185 ± 0.0006
Q [GeV]



CKM fitter
EPS 15
sin 2β
Δmd & Δms
Δmd
εK
|Vub|
α
β
γ
η̄
ρ̄



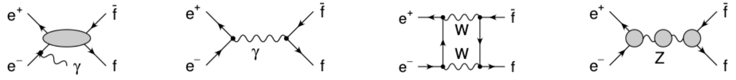
* ATLAS Preliminary not in combination
** CMS Preliminary not in combination
ATLAS
CMS Prel.
W,Z H → bb
H → ττ
H → WW(*) → lνlν
H → ZZ(*) → llll
H → γγ
Combined
Best fit signal strength (μ)

LEP: from data to primary observables (A. Freitas)

Tools for electroweak precision observables

"Analytical" tools for $e^+e^- \to f\bar{f}$

- State of the art: `Zfitter 6.42` — Bardin et al. '99, Arbuzov et al. '05
  Older code: `TOPAZ0` — Montagna, Nicrosini, Passarino, Piccinini '98,01
- Describes true observables ($\sigma_{e^+e^-\to f\bar{f}}(s)$, etc.)
  and pseudo-observables (Γ_Z, $\sigma^0_{\rm had}$, $\mathcal{A}_f$, etc.)
- Final-state QED and QCD corrections at $\mathcal{O}(\alpha^2)$, $\mathcal{O}(\alpha\alpha_s)$, $\mathcal{O}(\alpha_s^3)$
- Deconvolution of initial-state and initial-final QED radiation
  at $\mathcal{O}(\alpha)$, $\mathcal{O}(\alpha^2 L)$ and $\mathcal{O}(\alpha^3 L^2)$ ($L \equiv \log(s/m_e^2)$)
- Full NLO electroweak corrections for $e^+e^- \to f\bar{f}$
- Partial $\mathcal{O}(\alpha^2)$ and higher-order electroweak corrections



From primary observables to EWPOs

Z-pole observables

- Deconvolution of initial-state QED radiation:

$$\sigma[e^+e^- \to f\bar{f}] = \mathcal{R}_{\text{ini}}(s,s') \otimes \sigma_{\text{hard}}(s')$$

- Subtraction of γ-exchange, γ–Z interference, box contributions:

$$\sigma_{\text{hard}} = \sigma_{\text{Z}} + \sigma_\gamma + \sigma_{\gamma\text{Z}} + \sigma_{\text{box}}$$

- Z-pole contribution:

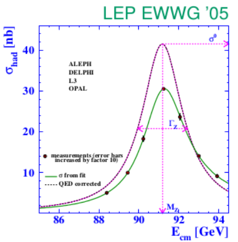
$$\sigma_{\text{Z}} = \frac{R}{(s-\overline{M}_{\text{Z}}^2)^2 + \overline{M}_{\text{Z}}^2\overline{\Gamma}_{\text{Z}}^2} + \sigma_{\text{non-res}}$$

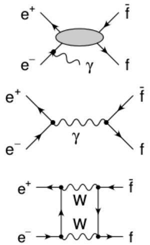
- In experimental analyses:

$$\sigma \sim \frac{1}{(s-M_{\text{Z}}^2)^2 + s^2\Gamma_{\text{Z}}^2/M_{\text{Z}}^2}$$

$$\overline{M}_{\text{Z}} = M_{\text{Z}}\Big/\sqrt{1+\Gamma_{\text{Z}}^2/M_{\text{Z}}^2} \approx M_{\text{Z}} - 34\ \text{MeV}$$

$$\overline{\Gamma}_{\text{Z}} = \Gamma_{\text{Z}}\Big/\sqrt{1+\Gamma_{\text{Z}}^2/M_{\text{Z}}^2} \approx \Gamma_{\text{Z}} - 0.9\ \text{MeV}$$





"Analytical" tools for $e^+e^- \to f\bar{f}$

Drawbacks:

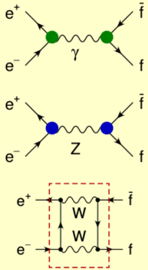
- Not all available NNLO and higher-order corrections implemented (code structure makes implementation difficult)
- For consistent treatment beyond NLO, need expansion of $\mathcal{A}[e^+e^- \to \mu^+\mu^-]$ about $s_0 = M_Z^2 - iM_Z\Gamma_Z$:

$$\mathcal{A}[e^+e^- \to f\bar{f}] = \frac{R}{s-s_0} + S + (s-s_0)T + \ldots$$

$$R = g_Z^e(s_0)g_Z^f(s_0)$$

$$S = \left[\frac{1}{M_Z^2} g_\gamma^e g_\gamma^f + g_Z^e g_Z^{f\,\prime} + g_Z^{e\,\prime} g_Z^f + S_{\rm box}\right]_{s=s_0}$$

$g_V^f(s)$: effective $Vf\bar{f}$ couplings



At NNLO: Need R at $\mathcal{O}(\alpha^2)$, S at $\mathcal{O}(\alpha)$, etc.

Conclusions

EWPOs:

- FCC-ee will reduce exp. error by factor $\gtrsim 10$ compared to LEP/SLC
  - $\longrightarrow$ Current SM theory calculations not sufficient
  - $\longrightarrow$ 3-loop and partial 4-loop (5-loop?) corrections needed!
- Good control over input parameters m_{t}, M_{W}, α_{s} and $\Delta\alpha_{\mathrm{had}}$ is crucial
  - $\longrightarrow$ New ideas may be helpful
  - $\longrightarrow$ Probably limited by theory uncertainties!
- Need for new/improved computer tools:
  - $\longrightarrow$ Monte-Carlo methods for multiple photon corrections
  - $\longrightarrow$ Consistent complex pole expansion for electroweak part

2. $\alpha(M_Z^2)$ in precision physics (precision physics limitations)

Uncertainties of hadronic contributions to effective α are a problem for electroweak precision physics:

α , G_μ, M_Z **most precise input parameters** $\Rightarrow$ **precision predictions**

50% non-perturbative $\qquad \sin^2\Theta_f, v_f, a_f, M_W, \Gamma_Z, \Gamma_W, \cdots$

$\alpha(M_Z), G_\mu, M_Z$ **best effective input parameters for VB physics (Z,W) etc.**

$\frac{\delta\alpha}{\alpha}$	$\sim$	3.6	$\times$	10^{-9}	
$\frac{\delta G_\mu}{G_\mu}$	$\sim$	8.6	$\times$	10^{-6}	
$\frac{\delta M_Z}{M_Z}$	$\sim$	2.4	$\times$	10^{-5}	
$\frac{\delta\alpha(M_Z)}{\alpha(M_Z)}$	$\sim$	$0.9 \div 1.6$	$\times$	10^{-4}	(present : lost 10^5 in precision!)
$\frac{\delta\alpha(M_Z)}{\alpha(M_Z)}$	$\sim$	5.3	$\times$	10^{-5}	(ILC requirement)

LEP/SLD: $\sin^2\Theta_{\rm eff} = (1 - g_{Vl}/g_{Al})/4 = 0.23148 \pm$ 0.00017

$$\delta\Delta\alpha(M_Z) = 0.00020 \qquad \Rightarrow \qquad \delta\sin^2\Theta_{\rm eff} = 0.00007$$

affects Higgs mass bounds, precision tests and new physics searches!!!

For pQCD contributions very crucial: precise QCD parameters $\alpha_s,\ m_c,\ m_b,\ m_t \Rightarrow$ Lattice-QCD

3. Evaluation of $\alpha(M_Z^2)$

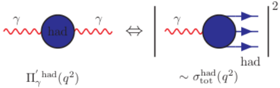
Non-perturbative hadronic contributions $\Delta\alpha^{(5)}_{\rm had}(s) = -\left(\Pi'_\gamma(s) - \Pi'_\gamma(0)\right)$ **can be evaluated in terms of** $\sigma(e^+e^- \to \text{hadrons})$ **data via dispersion integral:**

$$\Delta\alpha^{(5)}_{\rm had}(s) = -\frac{\alpha\, s}{3\pi}\left(\oint_{4m_\pi^2}^{E^2_{\rm cut}} ds' \frac{R^{\rm data}_\gamma(s')}{s'(s'-s)} + \oint_{E^2_{\rm cut}}^{\infty} ds' \frac{R^{\rm pQCD}_\gamma(s')}{s'(s'-s)} \right)$$

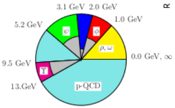
Compilation: FJ 15

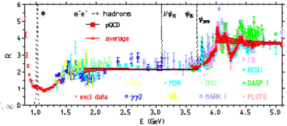
Theory = pQCD: Gorishny et al. 91, Chetyrkin et al. 97...09

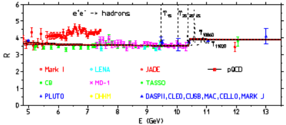
where $R_\gamma(s) \equiv \frac{\sigma^{(0)}(e^+e^- \to \gamma^* \to \text{hadrons})}{\frac{4\pi\alpha^2}{3s}}$



hadronic vacuum polarization







$$\alpha(s) = \frac{\alpha}{1-\Delta\alpha(s)}\ ; \quad \Delta\alpha(s) = \Delta\alpha_{\rm lep}(s) + \Delta\alpha^{(5)}_{\rm had}(s) + \Delta\alpha_{\rm top}(s)$$

History and recent

- big progress in data CMD-2, SND, BESII, KLOE, BaBar, ···
- progress in pQCD [..., Chetyrkin, Kühn et al. ...], by far more progressive use of pQCD

4. Reducing uncertainties via the Euclidean split trick: Adler function controlled pQCD

- experiment side: new more precise measurements of $R(s)$
- future direct measurements Talk Patrick Janot
- theory side: $\alpha_{\rm em}(M_Z^2)$ by the "Adler function controlled" approach

$$\alpha(M_Z^2) \quad = \quad \alpha^{\rm data}(-s_0) + \left[\alpha(-M_Z^2) - \alpha(-s_0)\right]^{\rm pQCD} + \left[\alpha(M_Z^2) - \alpha(-M_Z^2)\right]^{\rm pQCD}$$

where the space-like $-s_0$ is chosen such that pQCD is well under control for $-s < -s_0$. The monitor to control the applicability of pQCD is the Adler function

$$D(Q^2 = -s) = \frac{3\pi}{\alpha} s \frac{d}{{\rm d}s} \Delta\alpha_{\rm had}(s) = -(12\pi^2)\, s\, \frac{{\rm d}\Pi'_\gamma(s)}{{\rm d}s} = Q^2 \int_{4m_\pi^2}^{\infty} \frac{R(s)}{(s+Q^2)^2}$$

which also is determined by $R(s)$ and can be evaluated in terms of experimental e^+e^-–data. Perturbative QCD tail: $D(Q^2) \to N_c \sum_f Q_f^2\, (1 + O(\alpha_s))$ as $Q^2 \to \infty$.

Future: **ILC/FCC-ee requirement: improve by factor 10 in accuracy**

- **direct integration of data: 46% from data 54% p-QCD**

$$\Delta\alpha^{(5)\,\mathrm{data}}_{\mathrm{had}} \times 10^4 = 126.86 \pm 1.78 \text{ (1.4\%)}$$

1% overall accuracy ± 1.27

1% accuracy for each region (divided up as in table)

added in quadrature: ± 0.40

Data: [1.78] vs. [0.40] $\Rightarrow$ **improvement factor 4.5**

$$\Delta\alpha^{(5)\,\mathrm{pQCD}}_{\mathrm{had}} \times 10^4 = 149.57 \pm 0.05 \text{ (0.0\%)}$$

Theory: no improvement needed !

- **integration via Adler function: 22% from data 78% p-QCD**

$$\Delta\alpha^{(5)\,\mathrm{data}}_{\mathrm{had}} \times 10^4 = 060.49 \pm 0.66 \text{ (1.1\%)}$$

1% overall accuracy ± 0.60

1% accuracy in region 1.0 to 2.5 GeV

added in quadrature: ± 0.28

Data: [1.19] vs. [1.03,0.57,0.37] $\Rightarrow$ **improvement factor 2.1-3.2 (Adler vs Adler)**

[1.78] vs. [1.03,0.57,0.37] $\Rightarrow$ **improvement factor 3.1-4.8 (Standard vs Adler)**

$$\Delta\alpha^{(5)\,\mathrm{pQCD}}_{\mathrm{had}} \times 10^4 = 214.48 \pm 1.00 \text{ (0.05\%)}$$

Theory: massive 4-loop needed and more accurate m_c, m_b and α_s!

- **direct measurement (near/off Z peak)** **Patrick Janot's talk**

Proposal by P. Janot: direct measurement of $\alpha(M_Z^2)$

Sensitivity of $e^+e^- \to \mu^+\mu^-$ to $\alpha_{QED}(m_Z^2)$

- The $e^+e^- \to \mu^+\mu^-$ angular distribution
  - Absolute cross section measurement might be challenging to the required precision
    - Uncertainty of the integrated luminosity determination
  - Rely of a self-normalizing quantity, the forward-backward asymmetry $A_{\rm FB}^{\mu\mu} = \dfrac{\sigma_{\mu\mu}^{\rm F} - \sigma_{\mu\mu}^{\rm B}}{\sigma_{\mu\mu}^{\rm F} + \sigma_{\mu\mu}^{\rm B}}$,

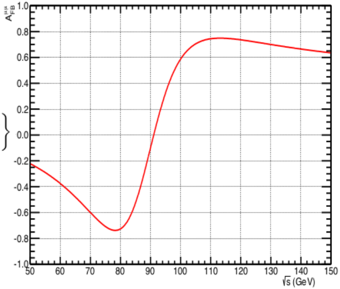
$$\frac{d\sigma_{\mu\mu}}{d\cos\theta}(s) \propto G_1(s) \times (1+\cos^2\theta) + G_3(s) \times 2\cos\theta,$$

$$A_{\rm FB}^{\mu\mu}(s) = \frac{3}{4}\frac{G_3(s)}{G_1(s)}.$$

$$G_1(s) = \mathcal{G} + \mathcal{I} + \mathcal{Z} \quad \text{and} \quad G_3(s) = \frac{a^2}{v^2}\left\{\mathcal{I} + \frac{4v^4/a^4}{(1+v^2/a^2)^2}\mathcal{Z}\right\}$$

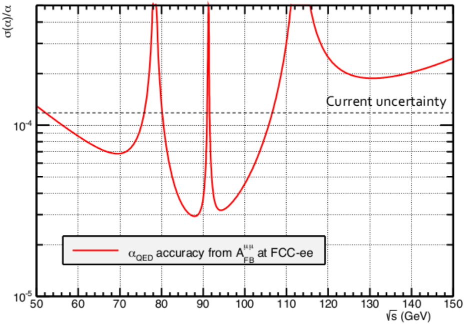
$$A_{\rm FB}^{\mu\mu} = A_{\rm FB,0}^{\mu\mu} + \frac{3}{4}\frac{a^2}{v^2}\frac{\mathcal{I}}{\mathcal{G}+\mathcal{Z}}.$$

$$A_{\rm FB,0}^{\mu\mu} = (3/4) \times 4v^2a^2/(a^2+v^2)^2 \simeq 0.016.$$



Sensitivity of $e^+e^- \rightarrow \mu^+\mu^-$ to $\alpha_{QED}(m_Z^2)$

- Turning the previous plot in a $\sigma(\alpha)/\alpha$ plot, for a year of running at any $\sqrt{s}$



- Optimal centre-of-mass energies for a 3×10^{-5} uncertainty on α_{QED}
  - One year at $\sqrt{s_-}$ = 87.9 GeV or one year at $\sqrt{s_+}$ = 94.3 GeV
  - Even better: six months at $\sqrt{s_-}$ and six months at $\sqrt{s_+}$

Systematic uncertainties

- Summary of the study

Type	Source	Uncertainty
Experimental	$E_{\rm beam}$ calibration	1×10^{-5}
	$E_{\rm beam}$ spread	$< 10^{-7}$
	Acceptance and efficiency	negl.
	Charge inversion	negl.
	Backgrounds	negl.
Parametric	m_Z and Γ_Z	1×10^{-6}
	$\sin^2\theta_W$	5×10^{-6}
	G_F	5×10^{-7}
(IFI to be numerically checked) Theoretical	QED (ISR, FSR, IFI)	$< 10^{-6}$
	Missing EW higher orders	few 10^{-4}
	New physics in the running	0.0
Total (except missing EW higher orders)	Systematics	1.2×10^{-5}
	Statistics	3×10^{-5}

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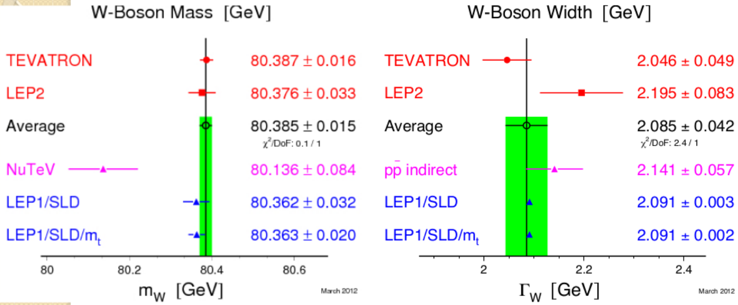
- detailed analysis of QED higher order corrections by S. Jadach

WW theshold (G. Wilson and P. Azzurri)

m_W & Γ_W status



direct measurements from W (transverse) mass distribution

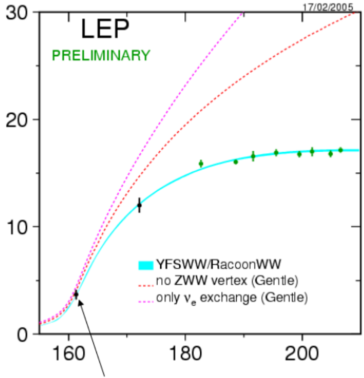
Outline

follow up of first presentation 26/10/15

https://indico.cern.ch/event/446552/contribution/2/attachments/1176747/1701589/eeWWthr.pdf

- revisit the WW threshold
- m_W & Γ_W dependence and measure
- optimal data taking configurations
- first look at effects of limiting syst and correlated uncertainties

Lep2 WW



$$\sigma(m_W, E)$$

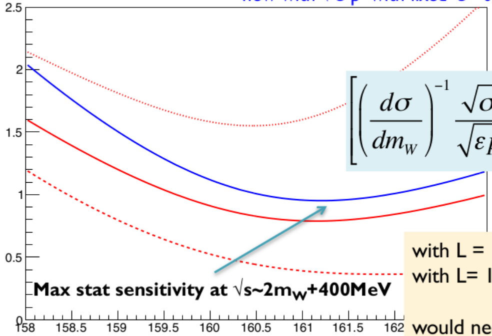
$$m_W = \sigma^{-1}(E)$$

$$\Delta m_W = \left(\frac{d\sigma}{dm_W}\right)^{-1} \Delta\sigma$$

$$m_W = 80.40 \pm 0.21\,\mathrm{GeV}/c^2$$

m_W from σ_{WW}

now with $\sqrt{\varepsilon p}$ with fixed ε =0.75 and σ_B=0.3pb



$$\left[\left(\frac{d\sigma}{dm_W}\right)^{-1}\frac{\sqrt{\sigma}}{\sqrt{\varepsilon p}}\right]_{min}\approx 0.95\frac{GeV}{pb^{1/2}}$$

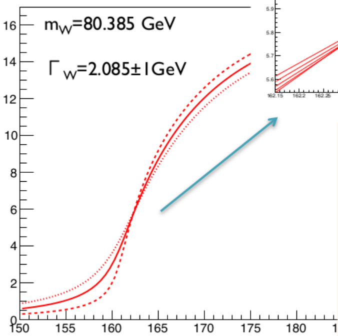
↓

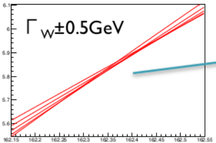
$2m_W$

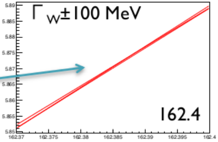
with L = 11/pb ➔ Δ mw≈380MeV
with L= 15/ab ➔ Δ mw≈0.25 MeV

would need
Δ E(beam)<0.25 MeV (3x10-6)
Δ ε / ε , Δ L/L < 10-4
Δ σ_B<0.5 fb (10-3)

Γ_W from σ_{WW}







Measure σ_{WW} in two energy points E_1, E_2 with a fraction f of lumi in E_1
➔ determine both m_W & Γ_W

Determine f, E_1, E_2 such to mimimise ($\Delta\Gamma_W$, Δm_W) with some target

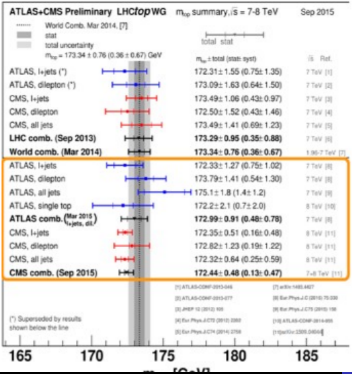
Evaluate loss of Δm_W precision in the single parameter (m_W) determination wrt scenario of running only at an optimal E_0=161 point

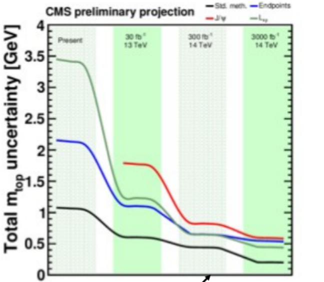
Current status: Top Mass

Hadron colliders (LHC and Tevatron) achieved a precision in the measurement of the top mass of ~ **0.76 GeV in March 2014** arXiv:1403.4427

Combination of consistent set of measurements from 4 experiments (ATLAS, CMS, CDF and D0)

New results from CMS even more precise
~ **0.5 GeV September 2015**





LHC already **exceeding prospects**

CMS expects 200 MeV after 3000 fb^{-1} (conventional method, *CMS-FTR-13-017-PAS)* based on "*assumptions [that] are optimistic but not unrealistic*"

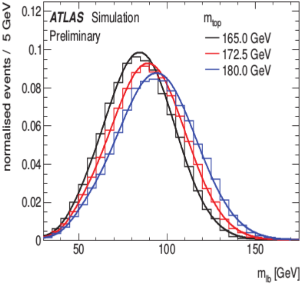
Issues with interpretation not accounted for.

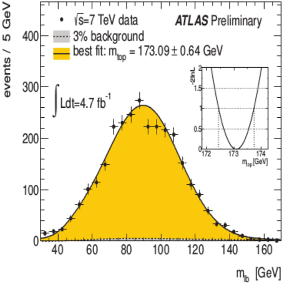
Top measurements compare data with theory: m_t is the parameter in the prediction

Standard reconstruction: template, ideogram and matrix-element methods

Alternatives: $t\bar{t}(j)$ cross section, endpoint, $m_{b\ell}$, J/ψ, b-jet energy, leptonic observables

Example: data vs MC templates and m_t ('Monte Carlo' mass) minimizes the χ^2





Standard generators: LO hard scattering; (N)LL parton showers; hadronization models

POWHEG and aMC@NLO: NLO $t\bar{t}$ and single top production

aMC@NLO includes off-shell and non-resonant effects, not yet NLO decays

Improvement in POWHEG: NLO top decays and approximate treatment of top width

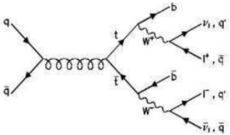
Top-mass definitions depend on subtraction of the UV divergences in self energy $\Sigma(p)$

$$\Sigma = \left[\frac{1}{\epsilon} - \gamma + \ln 4\pi - \ln\frac{m_0^2}{\mu^2} + A\right] \not p - \left[4\left(\frac{1}{\epsilon} - \gamma + \ln 4\pi - \ln\frac{m_0^2}{\mu^2}\right) + B\right] m_0$$

$$S^R(p) = -\frac{i}{\not p - m_0 + \Sigma^R(p, m_0, \mu)} \Rightarrow S^R_{o.s.}(p) \sim \frac{i}{\not p - m_{\rm pole}} \;\; ; \;\; S^R_{\overline{\rm MS}} \sim \frac{i}{\not p - m_{\overline{\rm MS}} - (A-B) m_{\overline{\rm MS}}}$$

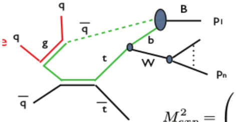
Pole mass is the pole of the propagator; $\overline{\rm MS}$ mass is quite far from the pole

Measurements relying on (on-shell) top decays must yield a mass close to $m_{\rm pole}$

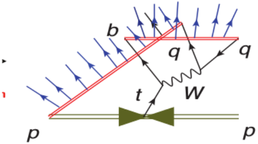


$$\frac{1}{[(p_W + p_b)^2 - m_t^2]^2 + m_t^2\Gamma_t^2} \sim \frac{1}{\pi}\,\delta[(p_W + p_b)^2 - m_t^2] \;\text{for}\; \Gamma_t \ll m_t$$

Width and colour-reconnection effects can spoil this picture

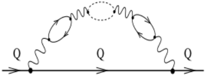


$$M^2_{exp} = \left(\sum_{i=1,\dots,n} p_i\right)^2$$



Left: M.L.Mangano, TOP 2013 workshop, Right: S.Argyropoulos, LNF'15 workshop

Higher-order corrections to the self energy: renormalon ambiguity



$$\Sigma(m,m) \sim m \sum_n \alpha_S^n \, (2b_0)^n \, n!$$

$$\delta m_{\rm pole} \approx \mathcal{O}(\Lambda) \approx \mathcal{O}(100 \text{ MeV})$$

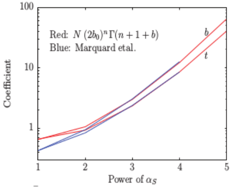
Pole vs $\overline{\rm MS}$ mass at 4 loops $[\bar{m} = \bar{m}(\bar{m})]$ (P.Marquard et al, PRL'15, talk by M.Steinhauser)

$m_{\rm pole} = \bar{m}[1 + 0.42\,\alpha_S + 0.83\,\alpha_S^2 + 2.38\,\alpha_S^3 + (8.49 \pm 0.25)\,\alpha_S^4]$; $\Delta m_{\rm pole,MS} \simeq 195$ MeV

Renormalon calculation (Beneke,'94) - large-n expansion:

$$m_{\rm pole} = \bar{m} \times \left(1 + \sum_{n=0}^{\infty} r_n \alpha_S^{n+1}\right) \; ; \; r_n \to N(2b_0)^n \Gamma\left(n + 1 + \frac{b_1}{b_0^2}\right)\left(1 + \sum_{k=1}^{\infty} \frac{s_k}{n^k}\right)$$

Fitting N: $N \simeq 0.726$

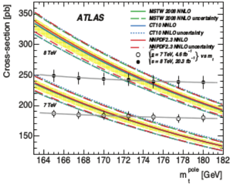


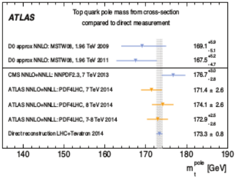
Can be used to predict higher-order terms:

$$m_{\rm pole} = (163.63 + 7.56 + 1.62 + 0.50 + 0.19 + 0.10 + \dots) \text{ GeV}$$

Minimum for $n \sim$ 8-9: $\Delta m \approx |r_8 \alpha_S^8 - r_9 \alpha_S^9| \approx 68$ MeV (P.Nason, summary talk at TOP 2015)

Pole mass from total NNLO+NNLL $t\bar{t}$ cross section (Czakon, Fielder and Mitov, '13):

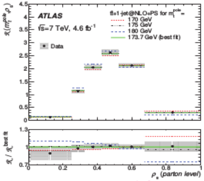


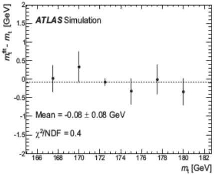


Recent extension to NNLO differential distributions (M.Czakon, D.Heymes and A.Mitov,1511.00549)

NLO calculation of $t\bar{t}$+jet cross section with the pole mass (S.Alioli et al.,'13)

POWHEG+PYTHIA, unfolding shower, hadronization and detector to recover $t\bar{t}j$





$m_t^{\rm pole} = [173.1 \pm 1.5({\rm stat}) \pm 1.4({\rm syst})^{+1.0}_{-0.5}({\rm theo})]$ GeV

Errors are expected to become smaller (~ 1 GeV) thanks to higher statistics

Lepton colliders: top production at threshold in NRQCD: $e^+e^- \to t\bar{t}$, $\sqrt{s} \sim 2m_t$

Strongly-ordered scales (hard, soft, ultrasoft): $mv^2 \ll mv \ll m$, $v \ll 1$

$$R = \frac{\sigma_{t\bar{t}}}{\sigma_{\mu^+\mu^-}} = v \sum_k \left(\frac{\alpha_S}{v}\right)^k \sum_i (\alpha_S \ln v)^i \left\{1(\mathrm{LL}); \alpha_S, v(\mathrm{NLL}); \alpha_S^2, \alpha_S v, v^2(\mathrm{NNLL})\right\}$$

Fixed-order N^{k}LO ($k = 0, 1, 2, \dots$) resums terms $\alpha_S^m v^n$, with $m + n = 1, \dots k + 1$

Resummation of $\alpha_s^k \ln^k v$ (LL) $\alpha_S^{k+1} \ln^k v$, $v\alpha_S^k \ln^k v$ (NLL) ... $v \sim \alpha_S \ll 1$, $\alpha_S \ln v \sim 1$

State of the art NNNLO (Beneke et al,'15) and NNLL (Hoang, Stahlhofen,'14)

Pole mass is not adequate; $1S$ and potential-subtracted are suitable threshold masses

$$m_{1S} = \frac{1}{2} \left\{m\left[\Upsilon(1S)_{t\bar{t}}\right]\right\} \;\; ; \;\; m_{\mathrm{PS}}(\mu_F) = m_{\mathrm{pole}} - \frac{1}{2}\int_{|q|<\mu_F} \frac{d^3q}{(2\pi)^3}\tilde{V}(q)$$

Relating 1S and PS masses to $\overline{\mathrm{MS}}$ mass:

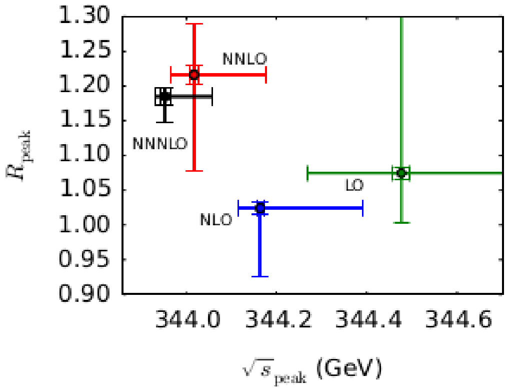
4-loop impact: 44 MeV (PS), 8 MeV (1S)

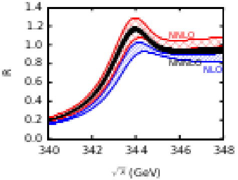
Overall uncertainty on $\overline{\mathrm{MS}}$ mass conversion:

23 MeV (PS); 7 MeV (1S)

input #loops	$m^{\mathrm{PS}} =$ 171.792	$m^{\mathrm{1S}} =$ 172.227
1	165.097	165.045
2	163.943	163.861
3	163.687	163.651
4	163.643	163.643
4 (×1.03)	163.637	163.637

$R_{\rm peak}$ vs $\sqrt{s_{\rm peak}}$

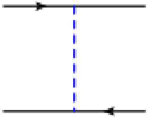




N^{3}LO: $\delta(\sqrt{s_{\rm peak}}) \approx \pm 60$ MeV

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

Beyond-QCD effects

- $v^2 \sim \alpha_s^2 \sim y_t^2 \sim \alpha$
- Higgs: potential  $\delta V_H = -\frac{y_t^2}{2m_H^2}$

[Eiras,Steinhauser'06; Beneke,Maier,Piclum,Rauh'15]

production current  ⇨ c_v, $\mathcal{O}(y_t^2)$ and $\mathcal{O}(\alpha_s y_t^2)$

[Grzadkowski,Kühn,Krawczyk,Stuart'86; Guth,Kühn'91; Hoang,Reißer'06; Eiras,Steinhauser'06]

- Non-resonant production: $e^+e^- \to W^+W^-b\bar{b}$
  NLO [Hoang,Reißer'06; Beneke,Jantzen,Ruiz-Femenia'10; Penin,Piclum'12]
  NNLO not complete [Penin,Piclum'12; Jantzen,Ruiz-Femenia'13; Ruiz-Femenia'14]
- $\delta V_{\rm QED} = -\frac{4\pi\alpha Q_t^2}{|\vec{q}|^2}$
- P wave production ($\gamma^\mu\gamma^5$ coupling of Z boson)

[Penin,Pivovarov'99; Beneke,Piclum,Rauh'13]

Conclusions $e^+e^- \to t\bar{t}$

- N^{3}LO QCD corrections stabilize perturbation theory uncertainty $\approx 3\%$
- Beyond QCD effects (Higgs, non-resonant, QED, P wave) under control
- top quark mass determination with $\delta m_t = \pm 50$ MeV feasible

---

- Convert threshold mass to $\overline{\rm MS}$ mass:
  PS mass: $m_t^{\overline{\rm MS}} = 168.20 - 3.89 - 0.60 - 0.09$ GeV
  LO NLO NNLO
  1S mass: $m_t^{\overline{\rm MS}} = 172.23 - 7.18 - 1.18 - 0.21$ GeV
  ➪ uncertainties are too big
  ➪ N^{3}LO term in conversion formula needed
  ➪ requires: 4-loop $\overline{\rm MS}$-on-shell top mass relation

Composite Higgs models $\Longleftrightarrow$ Top physics (S. De Curtis)

☑ The Higgs at 125 GeV opened up the stage of particle property determination and made the **physics case for future accelerators** stronger than ever

☑ Theoretical arguments supporting the importance of **sub-percent Higgs coupling precision** continue to grow, especially to find hints for non-SM Higgs **(how can we decide if it is the elementary SM Higgs or a composite state from a strong dynamics?)**

☑ An **e+e- collider** could help in detecting **deviations in the cross sections for single, double Higgs production**, but it will also have a **great potential on top physics**: mass, width and precise coupling determination, very important for NP (for ex. indirect probe of partial compositeness)

☑ The study of top quark is often considered a part of precision QCD (top quark mass, width, $t\bar{t}$ threshold scan) but also .... **precise measurements of top properties and interactions provide sensitivities to New Physics** ⟶ Couplings to photon/Z-boson, top Yukawa coupling

TOP physics is an important sector of EWSB studies complementary to HIGGS measurements

2

Wednesday, February 3, 2016

☑ The very accurate measurements at an e+e- collider of the top quark form factors will improve the precision of our knowledge over what will be possible at the HL-LHC

Why is it important to do this?

☑ The top quark is the heaviest particle of the SM and its coupling to the Higgs is the largest of any particle. In the SM there is no explanation for it as there is no explanation for EWSB (it is put in by hand!)

Can we find an explanation outside the SM?

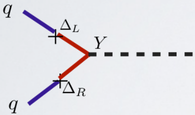
☑ The idea that remains attractive is that the Higgs boson is composite. New interactions at the TeV scale bind the Higgs constituents and are responsible for EWSB. This is compatible with a Higgs light and weakly coupled if the Higgs is a pseudo Nambu-Goldstone Boson

☑ Compositeness of the Higgs can bring compositeness of the top quark and the prediction of new particles: vector-like tops T (needed to give a finite and calculable theory of the Higgs mass), new vector resonances Z',W' (contributing to the EW top axial and vector-axial coupling modification)

Explicit Models in 4D

Elementary Sector		**Strong Sector**
$A_\mu, \psi \in SU(2) \times U(1)_Y$	$\mathcal{L}_{\text{mix}} = g_0 A_\mu J^\mu_\rho + \Delta \bar{\psi} \Psi$	$\rho_\mu, \Psi \in G_{\text{strong}}$
$g_0 < 1$		$m_\rho,\ 1 < g_\rho < 4\pi$

Linear elementary-composite couplings (partial compositeness)



$$\Delta_R \bar{q}_R \mathcal{O}_L \ + \ \Delta_L \bar{q}_L \mathcal{O}_R \ + Y \bar{\mathcal{O}}_L H \mathcal{O}_R$$

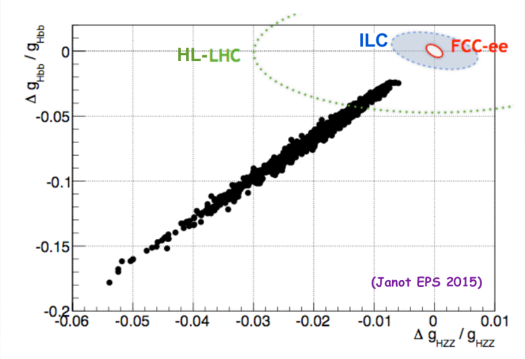
$$y_{SM} = \epsilon_L \cdot Y \cdot \epsilon_R \qquad \epsilon = \frac{\Delta}{m_Q}$$

SM hierarchies are generated by the mixings:
light quarks elementary, b and t partially composite

$$m_t \sim \frac{v}{\sqrt{2}} \frac{\Delta_{t_L}}{m_\psi} \frac{\Delta_{t_R}}{m_\chi} \frac{Y_T}{f}$$

top Yukawa coupling generated by the elementary-composite couplings

4DCHM : deconstruction of the minimal SO(5)/SO(4) 5D model, truncated to describe the composite degrees of freedom accessible to the LHC (DC,Redi,Tesi 1110.1613)



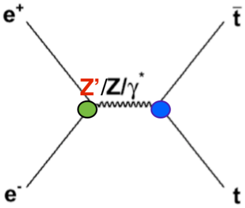
Deviations expected for HZZ and Hbb couplings in the 4DCHM compared with the relative precision expected at HL-LHC, ILC, FCC-ee

4DCHM black points: $M_{Z'} \sim f g_\rho > 2$ TeV and M_T >800GeV, $M_{5/3}$ >900GeV

(CMS PAS B2G-15-006)

FCC-ee will be able to discover CHMs with a 10σ significance !!

Top quark precision physics at an e+e- collider



The CHM modifications of the process arise via 3 effects:

- ☑ modification of the Zee coupling (negligible)
- ☑ modification of the Ztt coupling from: mixing between top and extra fermions (partial compositeness), mixing between Z and Z's
- ☑ the s-channel exchange of the new Z's (interference) - commonly neglected BUT can be very important also for large $M_{Z'}$

$e^+e^- \to$ tt production is one of the most prominent 6f process, strong sensitivity also to new particles. Asymmetries O(1)

Observables:
- Total cross-section $\sigma(e^+e^- \to t\bar{t})$
- Forward-Backward Asymmetry A_{FB}
- Single and Double Spin Asymmetries A_L , A_{LL}

Born approximation - QCD and EW corrections not included
ISR and beamstrhalung included but not important when considering $\mathcal{O}/\mathcal{O}_{\rm SM}$

Top-quark EW coupling determination at the FCC-ee

the lack of initial polarization is compensated by the presence of substantial final state polarization and by a larger integrated luminosity

- At FCC-ee, the final state top quarks are produced with non-zero polarization (ttZ)
  - The top polarization (and the total rate) depend on the ttZ/γ couplings
  - The top polarization is maximally transferred to the top decay products $t \to Wb$
    - ➨ Affect the energy and angular distributions of these decay product

      Similar to τ polarization in $Z \to \tau^+\tau^-$ events at LEP

$$t\bar{t} \to (bW^+)(\bar{b}W^-) \to (bqq')(\bar{b}l\nu)$$

Optimal-observable analysis of lepton angular and energy distributions from top-quark pair production with semi-leptonic decays is used to predict the sensitivity to the EW top-quark couplings at FCC-ee with 360 GeV and 2.6/ab (3years)

(Janot 1503.01325, HEP-EPS 2015)

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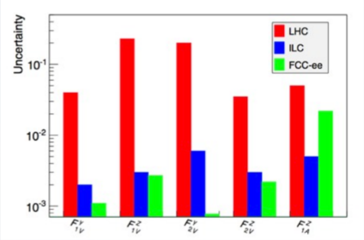
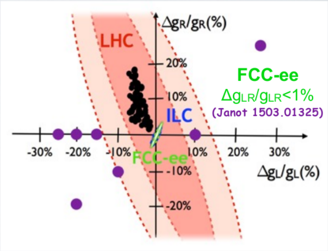
Top-quark EW coupling determination at the FCC-ee

Optimal-observable analysis of lepton angular and energy distributions from top-quark pair production with semi-leptonic decays at FCC-ee with 360 GeV and 2.6 ab^{-1}





LHC (14 TeV, 300 fb^{-1})
ILC(500GeV, 500 fb^{-1}) with polarized beams
(ILC-TDR 1306.6352; Amjad et al. 1505.06020)
FCC-ee (360GeV, 2.6 ab^{-1}) from lepton angular and energy distributions
(Janot 1503.01325)

continuous(dashed): from angular and energy distributions of leptons (b-quarks)
(Janot, EPS HEP 2015, WhatNext White paper of CSN1)

total x-section predicted with a 2% precision
warning: large QCD corr. near threshold, possible underestimation of x-section error

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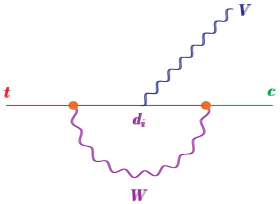
- see also talk by N. Foppiani for a complete simulation

FCNC top (really rare !) decays in the SM : NOT measurable !



GIM-suppressed by $\left(\frac{m_b}{M_W}\right)^4$

+ MFV (CKM matrix)

$\mathrm{BR}(t \to c\gamma) \simeq 5 \times 10^{-14}$

$\mathrm{BR}(t \to cg) \simeq 5 \times 10^{-12}$

$\mathrm{BR}(t \to cZ) \simeq 1 \times 10^{-14}$

$\mathrm{BR}(t \to ch) \simeq 3 \times 10^{-15}$

$(t \to ux)/(t \to cx) \simeq |V_{ub}/V_{cb}|^2 \simeq 0.008$

$\mathrm{BR}(t \to u\gamma) \simeq 4 \times 10^{-16}$

$\mathrm{BR}(t \to ug) \simeq 4 \times 10^{-14}$

$\mathrm{BR}(t \to uZ) \simeq 8 \times 10^{-17}$

$\mathrm{BR}(t \to uh) \simeq 2 \times 10^{-17}$

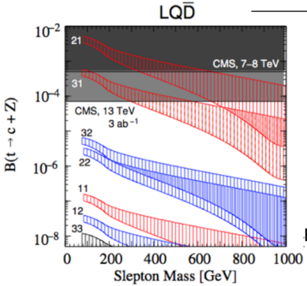
(Aguilar-Saavedra hep-ph/0409342)

New Physics can hugely enhance predictions !

Pattern of enhancements is model dependent !

	2HDM	MSSM	RS
$t \to cZ$	$\lesssim 10^{-6}$	$\lesssim 10^{-7}$	$\lesssim 10^{-5}$
$t \to c\gamma$	$\lesssim 10^{-7}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$
$t \to cg$	$\lesssim 10^{-5}$	$\lesssim 10^{-7}$	$\lesssim 10^{-10}$
$t \to ch$	$\lesssim 10^{-2}$	$\lesssim 10^{-5}$	$\lesssim 10^{-4}$

Snowmass Top Quark Working Group Report 1311.2028



Bardhan et al., arXiv:1601.04165

most general effective Lagrangian for FC tqV(H) interactions with terms up to dim 5

$$
\begin{aligned}
-\mathcal{L}^{\rm eff} \;=\;& \frac{g}{2c_W} X_{qt}\, \bar{q}\gamma_\mu (x^L_{qt} P_L + x^R_{qt} P_R) t Z^\mu + \frac{g}{2c_W} \kappa_{qt}\, \bar{q}(\kappa^v_{qt} + \kappa^a_{qt}\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t} t Z^\mu \\
&+ e\lambda_{qt}\, \bar{q}(\lambda^v_{qt} + \lambda^a_{qt}\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t} t A^\mu + g_s \zeta_{qt}\, \bar{q}(\zeta^v_{tq} + \zeta^a_{qt}\gamma_5)\frac{i\sigma_{\mu\nu}q^\nu}{m_t} T^a q G^{a\mu} \\
&+ \frac{g}{2\sqrt{2}} g_{qt}\, \bar{q}(g^v_{qt} + g^a_{qt}\gamma_5) t H + \text{H.c.}\,,
\end{aligned}
$$

$\sigma_{\mu\nu}$ terms grow with V^μ momentum q^{nu}

$$
\begin{aligned}
\text{Br}(t \to qZ)_\gamma &= 0.472\, X^2_{qt}, \\
\text{Br}(t \to qZ)_\sigma &= 0.367\, \kappa^2_{qt}, \\
\text{Br}(t \to q\gamma) &= 0.428\, \lambda^2_{qt}, \\
\text{Br}(t \to qg) &= 7.93\, \zeta^2_{qt}, \\
\text{Br}(t \to qH) &= 3.88 \times 10^{-2}\, g^2_{qt}
\end{aligned}
$$

(Aguilar-Saavedra hep-ph/0409342)

bounds on tqZ and $tq\gamma$

ILC versus full LHC

Process	Br Limit	Search	Dataset
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV
$t \to Zq$	$5\,(2) \times 10^{-4}$ *	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1} 250 GeV
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1} 500 GeV
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1} 500 GeV
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV
$t \to \gamma q$	6×10^{-5} *	ILC single top	500 fb^{-1} 250 GeV
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1} 500 GeV
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1} 500 GeV

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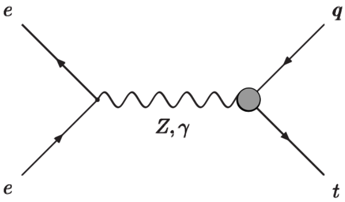
* extrapolated

$\sigma_{\mu\nu}$ terms grow with V^μ momentum q^{mu} **(~ √S in single top)**

$\Rightarrow$ $e^+e^- \to \gamma, Z(q^\mu) \to tq$ *at ILC, most sensitive channel (!)*

$$e^+e^- \to \gamma, Z(q^\mu) \to tq$$



(LEP2 and ILC)

Han and Hewett 9811237

Bar-Shalom, Wudka 9905407

Aguilar-Saavedra, Riemann 0102197

(FCC-ee, leptonic top $t \to b\ell\nu$)

Khanpour at al. 1408.2090

main background from W j j

√S= 240 GeV ***(large cross section and large lumi at FCC-ee)***

versus

√S= 350, 500 GeV **(lower bckgd and more sensitive to $\sigma_{\mu\nu}$ terms)**

√S = 240 GeV

x-sections (fb)

γ	4811.7	$\lvert\lambda_{qt}\rvert^2$
Z, γ_μ	2057.4	$\lvert\mathcal{X}_{qt}\rvert^2$
$Z, \sigma_{\mu\nu}$	3218.0	$\lvert\kappa_{qt}\rvert^2$

New Analysis :

FCC-ee, Hadronic top $t \to bjj$ **(Biswas, Margaroli, BM)**

hadronic top twice as sensitive to $BR(top)^{FCNC}$ as leptonic top

(leptonic channel) $(100\ fb^{-1})$ (hadronic)

$\sqrt{s}$ (GeV)	240	(hadronic)
$Br(t \to q\gamma)$	5.9×10^{-4}	3.3×10^{-4}
$Br(t \to qZ)$ $(\sigma_{\mu\nu})$	8.8×10^{-4}	4.3×10^{-4}
$Br(t \to qZ)$ (γ_μ)	1.4×10^{-3}	8.8×10^{-4}

Khanpour at al. 1408.2090

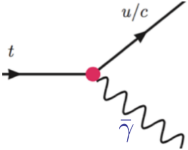
a little stronger bounds expected at $E_{cm}(e+e-) \sim 350$ GeV

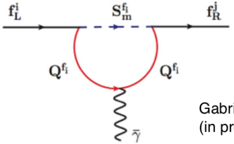
FCNC's mediated by Dark Photons

$t \to q\,\bar{\gamma}$

$b \to s\,\bar{\gamma}$

$\ell \to \ell'\,\bar{\gamma}$





Gabrielli, BM, Raidal, Venturini
(in preparation)

- Based on NP Model explaining Yukawa hierarchy via a Hidden Sector (HS) with extra unbroken Dark $U(1)_F$ (➜ massless dark photon)

(Gabrielli, Raidal, arXiv:1310.1090; Ma, arXiv:1311.3213)

- HS contains N_f heavy fermions (Df=Dark Matter ?) charged under Dark $U(1)_F$
- Chiral Simmetry spont. broken in HS via non-perturbative effects (higher-derivative in DP field ~ $1/\Lambda$ ➜ Lee-Wick ghosts)

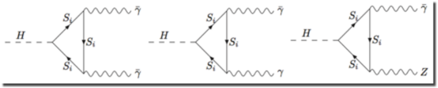
  ➜ Dark fermions get M_{Df} masses depending on their $U(1)_F$ charge q_{Df} ➜ exponentially-spread Df spectrum (for integer charges q_{Df}=1, 2, 3, 4...)
- Flavor and Chiral Sym Breaking transferred to (radiative) Yukawa couplings at one-loop via (heavy) squark/slepton-like scalar messangers

  ➜ Yukawa hierarchy appears in visible sector, too !

→ plenty of new signatures at colliders involving stable dark photons ← (invisible and massless)

(exploration just started !)

- in decays : $H \to \gamma\bar{\gamma}$

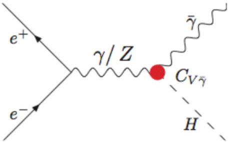


mono-photon resonant signature

Higgs non-decoupling effects (just as in SM) can enhance BR

Gabrielli, Heikinheimo, BM, Raidal, arXiv:1405.5196

- in production :



Higgs momentum balanced by a massless invisible system

Biswas, Gabrielli, Heikinheimo, BM, 1503.05836