Precision Measurements in the CLIC CDR

André H. Hoang, Klaus Mönig

Outline

① Introduction

② Gauge boson self couplings

③ Two fermion final states

④ Top production

⑤ QCD studies, event shapes

- Subject
- Physics interest (why interesting?)
- Processes
- Limits, comments
- Necessity for CLIC simulations

Introduction

- Basic strong points of e+e- collisions
  - Q variable (line shapes, threshold vs. continuum)
  - Polarization (e- standard, e+ maybe, modify handedness of initial state)
  - Relative easy to make theory progress (higher order calculations)
  - Norm measurements possible (absolute scales)
  - e-e- and ϒϒ options
- Major issues to consider
  - Beamstrahlung (scary!)
  - Accuracy of Q, Lumi spectrum, reconstruction of c.m. frame
  - Backgrounds
  - Reliable rules for upscaling of ILC results (or new analyses?)
  - “Precision” studies are time consuming (theory + experimental input)
- Complementary to LHC
  - LHC results/hints trigger optimized e+e- strategies (model-independent limits worse)
  - CLIC covers LHC ranges
- General comments
  - Dedicated CLIC studies not yet available, resource: ILC studies
  - Conclusions of upscaling can be case/model dependent
  - Conclusions on necessity case/model dependent
  - Full potential might not be uncovered

Gauge Boson Self Couplings

- Physics interest
  - VVV, VVVV couplings (longitudinal modes) very sensitive to SSB mechanism
  - Accurate measurements, relations of couplings and masses allow for conclusions on mechanism
  - Only way to learn about SSB if Higgs is not found

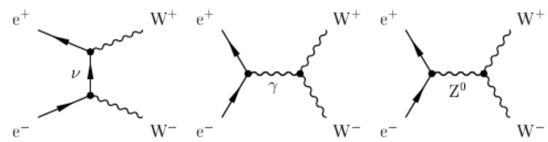
- Triple (VVV) couplings
- Quartic (VVVV) couplings

VVV Triple Gauge Couplings

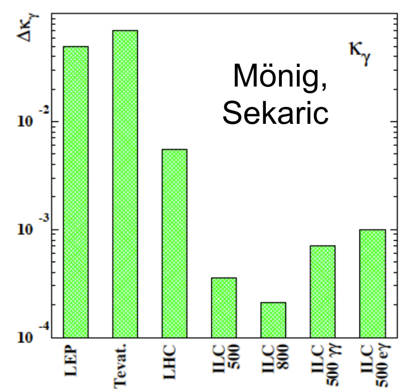
$$\mathcal{L}_{WWV} = g_{WWV}\Big[ig_1^V V_\mu\left(W_\nu^- W_{\mu\nu}^+ - W_{\mu\nu}^- W_\nu^+\right) + i\kappa_V W_\mu^- W_\nu^+ V_{\mu\nu} + i\frac{\lambda_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ V_{\nu\lambda}$$
$$+ g_4^V W_\mu^- W_\nu^+ \left(\partial_\mu V_\nu + \partial_\nu V_\mu\right) + g_5^V \epsilon_{\mu\nu\lambda\rho}\left(W_\mu^- \partial_\lambda W_\nu^+ - \partial_\lambda W_\mu^- W_\nu^+\right) V_\rho$$
$$+ i\tilde{\kappa}_V W_\mu^- W_\nu^+ \tilde{V}_{\mu\nu} + i\frac{\tilde{\lambda}_V}{M_W^2} W_{\lambda\mu}^- W_{\mu\nu}^+ \tilde{V}_{\nu\lambda}\Big],$$

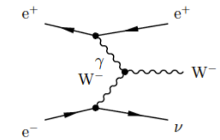
SM: $g_1^V = \kappa_V = 1$

$e^+e^- \to W^+W^-$



$e^+e^- \to \ell\ell' W^-$





- LEP, Tevatron limits are typically few$\times 10^{-2}$
- ILC can improve them to few$\times 10^{-4}$
- CLIC should be able to go below 10^{-4}

  Gauge cancellations grow with Q, statistics, use polarization

- Preliminary calculations show that e.g. SUSY loop corrections are well above 10^{-4}

- VV resonances should be visible as the J/Ψ is seen in e^+e^-

CLIC simulations desirable to obtain more reliable numbers (selection efficiencies, S/B, full correlation)

Corresponding theory analyses also desirable.

Analysis: Anyone out there?

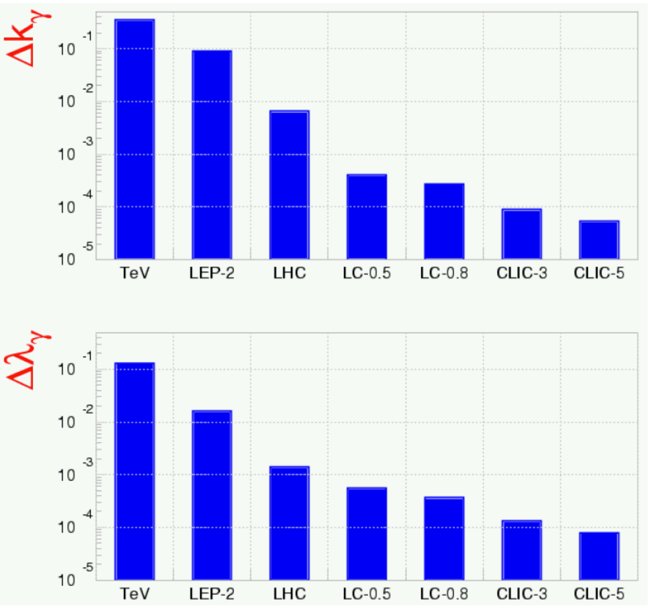
$\mathcal{P}_{e^-} = 80\%$ and $\mathcal{P}_{e^+} = 60\%$

$\mathcal{L} = 500\ \text{fb}^{-1}$ $\mathcal{L} = 1000\ \text{fb}^{-1}$

coupling	error $\times 10^{-4}$	
	$\sqrt{s} = 500$ GeV	$\sqrt{s} = 800$ GeV
Δg_1^Z	15.5	12.6
$\Delta\kappa_\gamma$	3.3	1.9
λ_γ	5.9	3.3
$\Delta\kappa_Z$	3.2	1.9
λ_Z	6.7	3.0
g_5^Z	16.5	14.4
g_4^Z	45.9	18.3
$\tilde{\kappa}_Z$	39.0	14.3
$\tilde{\lambda}_Z$	7.5	3.0

Menges

VVV Triple Gauge Couplings



$\sqrt{s}$ (GeV)	Re Δg_1^L	Re $\Delta\kappa_L$	Re λ_L	Re g_5^L	Re Δg_1^R	Re $\Delta\kappa_R$	Re λ_R	Re g_5^R
500	2.6	0.85	0.59	2.0	10	2.4	3.6	6.7
800	1.6	0.35	0.24	1.4	6.2	0.92	1.8	4.8
3000	0.93	0.051	0.036	0.88	3.1	0.12	0.36	3.2

$\sqrt{s}$ (GeV)	Re Δg_4^L	Re $\tilde{\lambda}_L$	Re $\tilde{\kappa}_L$	Re Δg_4^R	Re $\tilde{\lambda}_R$	Re $\tilde{\kappa}_R$
500	2.5	0.60	2.7	10	3.8	11
800	1.7	0.24	1.8	6.5	1.8	6.8
3000	0.90	0.036	0.97	3.4	0.36	3.2

CLIC: hep-ph/0412251

Statistical only,
but full correlation accounted for

VVVV Quartic Gauge Couplings

- Quartic couplings parametrised in effective Lagrangian (model-independent, Higgs and no-Higgs)

$$L_4 = \alpha_4 \, \mathrm{tr}\left(V_\mu V_\nu\right) \mathrm{tr}\left(V^\mu V^\nu\right) \,, \quad L_5 = \alpha_5 \, \mathrm{tr}\left(V_\mu V^\mu\right) \mathrm{tr}\left(V_\nu V^\nu\right)$$

- Processes: $e^+e^- \to VVV \qquad e^+e^- \to \ell_1 \ell_2 VV$

- No-Higgs scenario @ 1 TeV:

Sensitivity to strong resonances up to 2 TeV.

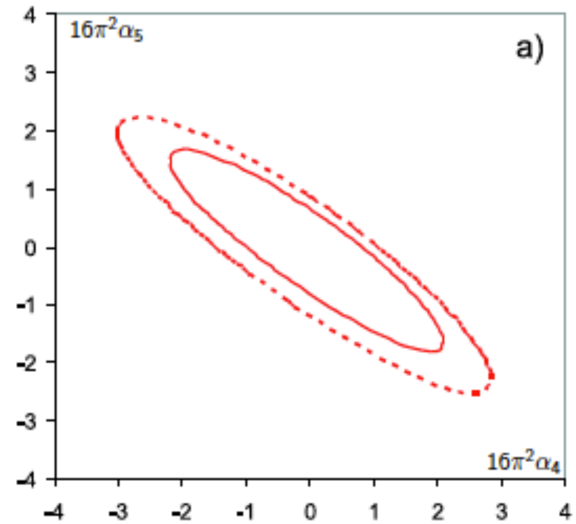
Sensitivity at the level of natural size of couplings. Marginal !

CLIC should be better at least by a factor 2.

Dedicated simulations analysis definitely needed.

Analysis: Moenig, Kilian, Reuter (confirmed)

$1000 \ \mathrm{fb}^{-1}$ at $\sqrt{s} = 1 \, \mathrm{TeV}$



Beyer, Kilian, Krstonosic, Mönig, Reuter, Schmidt, Schröder

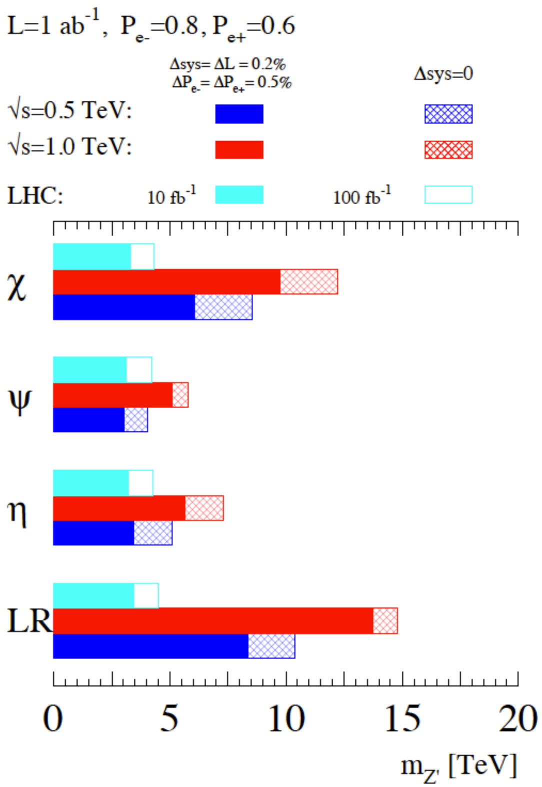
Two-Fermion Final States

- Physics interest $e^+e^- \xrightarrow{\gamma, Z, Z'} f\bar{f}$
  - Well understood final states
  - Very sensitive to any kind of new neutral weak gauge boson (GUTs, extra dimensions, Z‘, ...) through **interference**
- Observables: total rates, angular distributions, F-B asym., polarization needed
- Impressive ILC prospects:

Z’ mass reach: $\mathcal{O}(10\,Q)$

Any final state useful.

Z’ spin from polarization dependence. (J. Hewett)



S. Riemann

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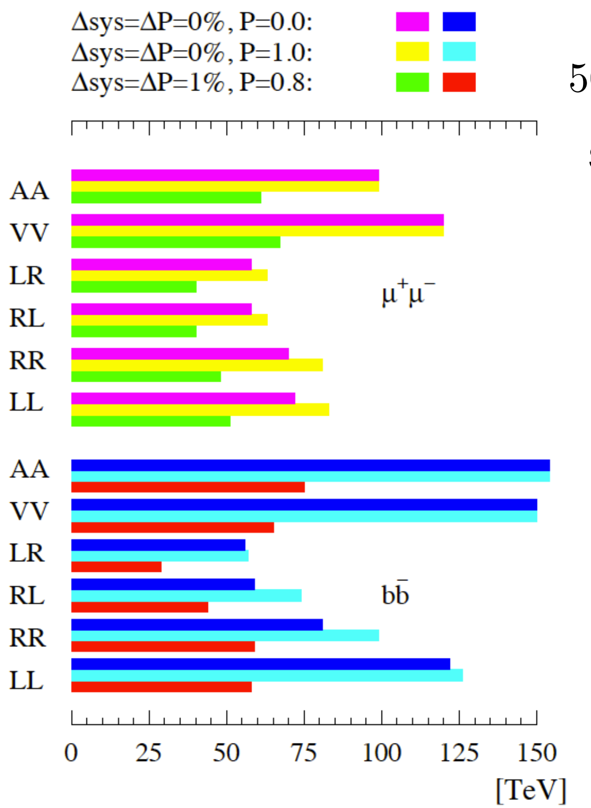
Effective contact interactions

$$\mathcal{L}_{\rm eff} = \sum_{i,j=L,R} \eta_{ij} \frac{4\pi}{\Lambda_{ij}^2} \bar{e}_i \gamma^\mu e_i \cdot \bar{f}_j \gamma_\mu f_j$$

$$\frac{1}{\Lambda^2} \sim \frac{g_X^2}{M_X^2}$$

$$\frac{g_X}{M_X} \sim \sqrt{\Delta\sigma_{\rm stat}} \sim (L_{\rm int} Q^2)^{1/4}$$



$500\ \mathrm{GeV}, 500\ \mathrm{fb}^{-1}$

S. Riemann

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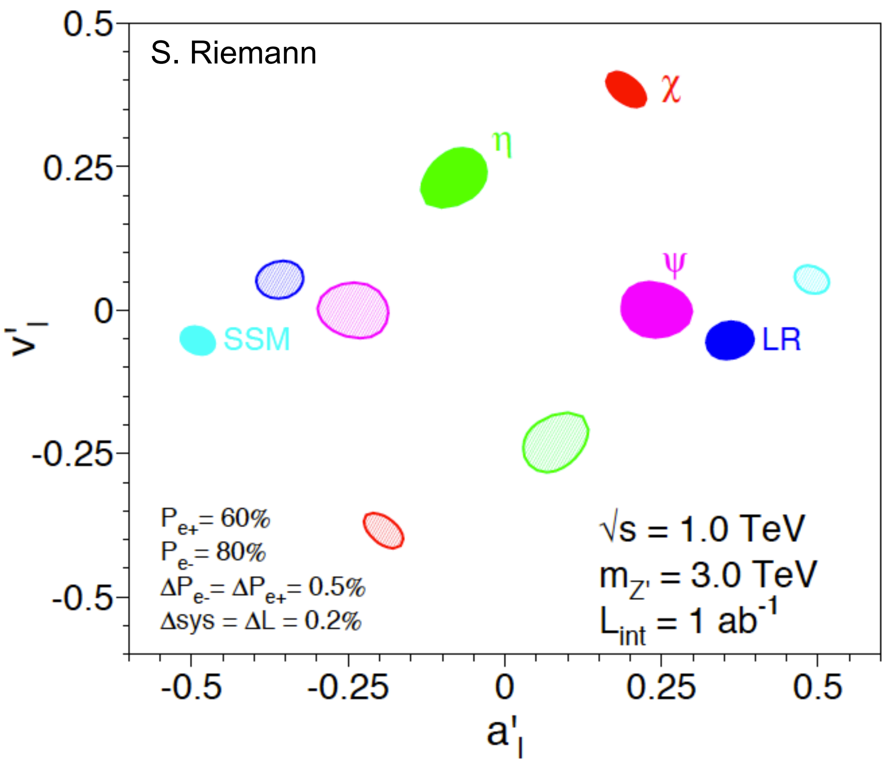
CLIC covers full LHC discovery range.
LHC – CLIC interplay.

Insane not to do a dedicated CLIC simulation. Machinery well in place.

Analysis: S. Riemann ?



Top Production

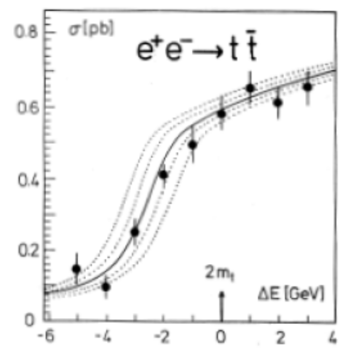
- Physics interest
  - Heaviest known particle with mass generated by SSB
  - top = top(SM) ?
  - mass input parameter for many other observables (SM+new physics)
  - Couplings can have large non-SM contributions
  - Study case for any heavy colored fermion (partly also scalar)

- Top Threshold (reminder)

Threshold scan: mass, width, Yukawa

Study case for other NP thresholds
(S- vs. P-wave).

Theory very well known.



ILC reach

$\rightarrow \delta m_t^{\rm exp} \simeq 50$ MeV

$\rightarrow \delta m_t^{\rm th} \simeq 100$ MeV

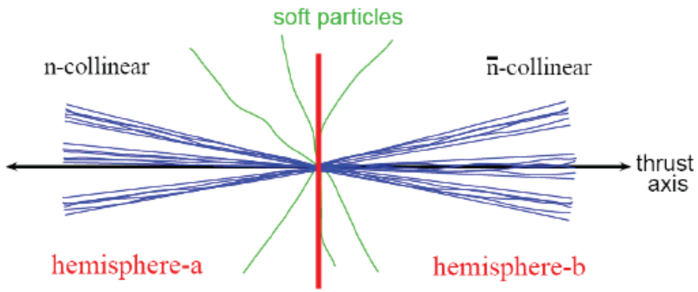
Beamstrahlung(CLIC) >> Beamstrahlung(ILC)
Shape information lost.
Can CLIC do a Q scans in the first place?

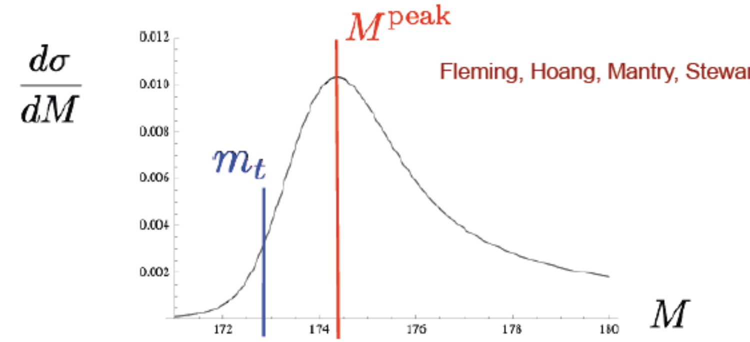
Precision mass measurement more difficult than for ILC !

Analysis: How much sensitivity for CLIC ?

Top Production

- Top Invariant Mass Reconstruction
  - New theory approach (SCET): rigorous factorization involving heavy particles
  - Hemisphere invariant mass distribution
  - Event shapes (thrust, jet mass)
  - Expansion: m/Q << 1 (CLIC ideal)
  - Short-distance top mass measurement





$$M_{\rm peak} = m_t^{\rm jet} + \Delta M_{\rm pert} + \Delta M_{\rm non-pert.}$$

Dedicated simulation analyses very desirable.
(background, beam effects)

On the way (detector performance group): **mass reconstruction** (Pythia mass)
CLIC @ 500 GeV → 1-3 TeV

Analysis: F. Simon, K. Seidel, ...

Top Production

- Neutral current anomalous couplings

$$\Gamma^{\mu}_{t\bar{t}(\gamma,Z)} = i\,e\left\{\gamma^{\mu}\left[F^{\gamma,Z}_{1V} + F^{\gamma,Z}_{1A}\,\gamma^{5}\right] + \frac{(p_t - p_{\bar{t}})^{\mu}}{2\,m_t}\left[F^{\gamma,Z}_{2V} + F^{\gamma,Z}_{2A}\,\gamma^{5}\right]\right\}$$

SM: $F^{\gamma}_{1V} = \frac{2}{3}\,,\; F^{Z}_{1V} = \frac{1}{4\sin\theta_W\cos\theta_W}\left(1-\frac{8}{3}\sin^2\theta_W\right)\,,\; F^{Z}_{1A} = -\frac{1}{4\sin\theta_W\cos\theta_W}$

$$e^+e^- \to t\bar{t} \to \ell + \text{jet} + X$$

Angular distr., F-B asym., p_T distribution., polarization

ILC: 0.01 precision

CLIC: similar expectations

(but coupling at higher scale)

Dedicated simulation desirable (with polarization).

Theory input desirable (QCD corrections).

Analysis: ?.

Comparison: lepton + jets, p_T-distribution (1σ limits)

coupling	LHC (300 fb^{-1})	e^+e^- (snowmass)
$\Delta\widetilde{F}^{\gamma}_{1V}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, 200 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{1A}$	$^{+0.051}_{-0.048}$	$^{+0.011}_{-0.011}$, 100 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{2V}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, 200 fb^{-1}
$\Delta\widetilde{F}^{\gamma}_{2A}$	$^{+0.16}_{-0.17}$	$^{+0.014}_{-0.014}$, 100 fb^{-1}
$\Delta\widetilde{F}^{Z}_{1V}$	$^{+0.34}_{-0.72}$	$^{+0.012}_{-0.012}$, 200 fb^{-1}
$\Delta\widetilde{F}^{Z}_{1A}$	$^{+0.079}_{-0.091}$	$^{+0.013}_{-0.013}$, 100 fb^{-1}
$\Delta\widetilde{F}^{Z}_{2V}$	$^{+0.26}_{-0.34}$	$^{+0.009}_{-0.009}$, 200 fb^{-1}
$\Delta\widetilde{F}^{Z}_{2A}$	$^{+0.35}_{-0.35}$	$^{+0.052}_{-0.052}$, 100 fb^{-1}

U. Bauer †

Top Production

- Charged current couplings

$$\Gamma^{\mu}_{tbW} = -\frac{g}{\sqrt{2}} V_{tb} \left\{ \gamma^{\mu} \; [f_1^L P_L + f_1^R P_R] - \frac{i\,\sigma^{\mu\nu}}{M_W} (p_t - p_b)_{\nu} \; [f_2^L P_L + f_2^R P_R] \right\}$$

In top decays

ILC: 0.01 precision for f_2^R

CLIC: similar expectations (?)

Theory input desirable (QCD corrections).

Analysis: ?.

- Top FCNC's
  - Very sensitive to new physics.
  - Seems promising to optimized strategies (correlations)

$\sqrt{s} = 500$ GeV	SM	2HDM-III	MSSM	TC2
$\sigma(\gamma\gamma \to t\bar{c})$[fb]	$\mathcal{O}(10^{-8})$	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10^{-1})$	$\mathcal{O}(10)$
$\sigma(e\gamma \to et\bar{c})$[fb]	$\mathcal{O}(10^{-9})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(1)$
$\sigma(e^+e^- \to t\bar{c})$[fb]	$\mathcal{O}(10^{-10})$	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-2})$	$\mathcal{O}(10^{-1})$
$Br(t \to cg)$	$\mathcal{O}(10^{-11})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-5})$	$\mathcal{O}(10^{-4})$
$Br(t \to cZ)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-6})$	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-4})$
$Br(t \to c\gamma)$	$\mathcal{O}(10^{-13})$	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-7})$	$\mathcal{O}(10^{-6})$
$Br(t \to cH)$	$< 10^{-13}$	$\mathcal{O}(10^{-3})$	$\mathcal{O}(10^{-4})$	$\mathcal{O}(10^{-1})$

Yang, hep-ph/0409351

Aguilar-Saavedra, hep-ph/0409342

$t \to qZ, q\gamma \quad \mathcal{O}(10^{-6} - 10^{-5})$

ILC: from single-top w. polarization

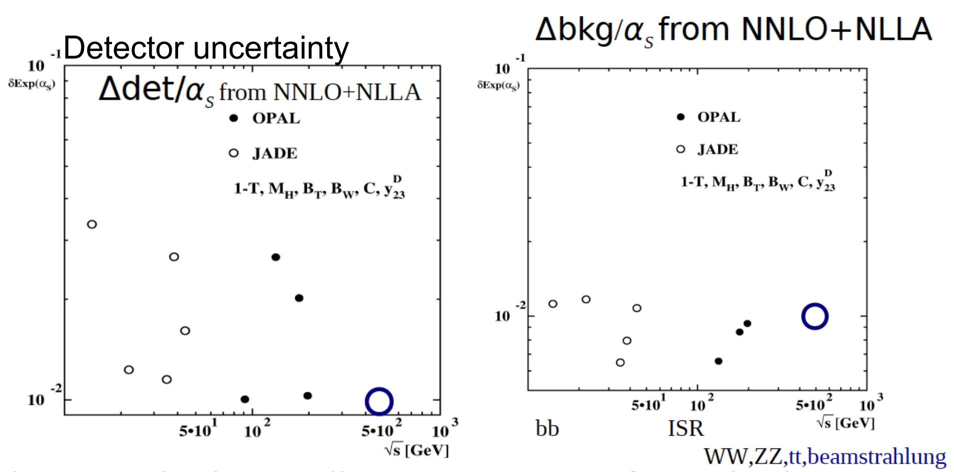
Dedicated simulation desirable.

Analysis: ?.

QCD Studies, Jets

- Physics interest
  - Check for theory understanding of QCD
  - Also top quarks can be studied
  - Probes different scales (Q, Λ_{QCD}, $\sqrt{Q\,\Lambda_{QCD}}$, ...) → nontrivial check of evolution
  - Strong coupling measurement
  - Non-perturbative effects small
  - Theory precision high (NNLO (classic), NNNLL (SCET)), certainly some further improvements

- Experimental issues
  - Background (WW)
  - Detector
  - Beam effects (particularly for event shapes, c.m. frame reconstruction)



C. Pahl, ILCWS 2010 (from event shapes @ 500 GeV)

Errors from beam effects ?
→ work under way

CLIC study very desirable.

Analysis: S. Kluth, C. Pahl, …