(Non)Perturbative QCD at the Linear Collider

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ILC Physics in Florence

GGI – 13/09/07

Outline

QCD@ILC

- Like LEP before it, ILC will be a *wonderful machine* for *precision QCD* studies
  - Precision meaurements of α_s
  - Event shape distributions, jets.
  - Hadronization effects
  - Heavy quarks
- Precision QCD is *necessary* for many *new physics* studies (and for precise determinations of m_{top}, m_{W})
- Our understanding of QCD is *incomplete*, new studies and more data are *important*
  - LEP unfinished jobs $\longrightarrow$ GigaZ
  - *Hadronization* beyond modelling
  - Universality of *power corrections*, shape functions

QCD for new physics: Grand Unification

(from: P. Zerwas)

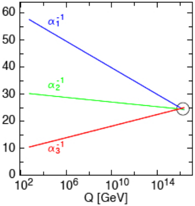
GAUGE COUPLINGS 17

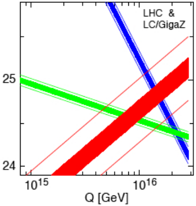
Evolution: present elw/strong gauge couplings
$\oplus$ SUSY threshold corr $\sim$ LHC

GigaZ : $\Delta s_W^2/\alpha_s \leq 10^{-5/-3}$
$\oplus$ ILC completed

Grand Unification : $\sim 2\sigma$ / g^U : 2%

Δ_3 at 8σ level : high sc phys





	Present/"LHC"	GigaZ/"LHC+LC"
M_U α_U^{-1}	$(2.36 \pm 0.06) \cdot 10^{16}$ GeV 24.19 ± 0.10	$(2.360 \pm 0.016) \cdot 10^{16}$ GeV 24.19 ± 0.05
$\alpha_3^{-1} - \alpha_U^{-1}$	0.97 ± 0.45	0.95 ± 0.12

Controlling QCD effects for SM/BSM physics

- Multijet final states are *commonplace*
  - *Trilinear* Higgs coupling via $e^+e^- \to HHZ$ (up to 6 jets)
  - Top *Yukawa coupling* via $e^+e^- \to t\bar{t}H$
  - *SUSY* final states ($\tilde{t}\bar{\tilde{t}} \to \mathrm{jets} + \mathrm{missing\,energy}$)
- Understanding *jet definition* and *dynamics* is *necessary*
  - Jet *algorithm*, *size* dependence, *hadronization* corrections.
  - Flavor *tagging* crucial $\leftrightarrow$ *Define* jet flavor (Banfi *et al.*)
- Precision observables *require* refined *QCD analysis*: resummations, effective theories
  - M_{top} from *threshold scan* (see A. Hoang)
  - M_W from WW production (see G. Zanderighi)

(Non)Perturbative QCD after LEP/SLC

- *Theoretical progress* in QCD has *continued* after LEP/SLC.
  - Achieved: NNLO event shape *distributions*, *jet* cross sections
  - QCD models: *non-perturbative* corrections to event shape *distributions*, shape functions
- *Experimental analysis* has almost *stopped* (LHC beckons ...)
  - Existing data *not fully exploited*
  - More precise *future data* (GigaZ?)
    $\longrightarrow$ *powerful constraints* on hadronization models
- Do we need *power corrections* at ILC?

$$\left(\frac{\alpha_s(500\,\mathrm{GeV})}{\pi}\right)^2 \simeq 0.00093\ , \quad \frac{\Lambda_{QCD}}{500\,\mathrm{GeV}} \simeq 0.0005.$$

  - For *permille* accuracy: *we do.*
  - *Much larger impact* in selected regions in phase space

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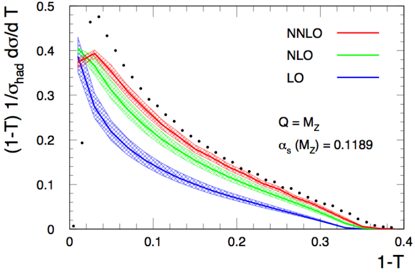
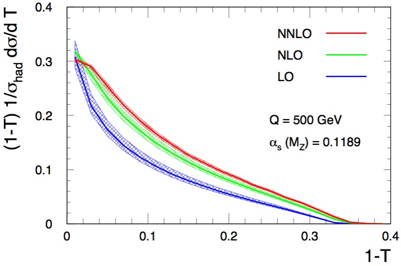
NNLO event shape distributions

(from: T. Gehrmann *et al.*, `arXiv:0709.1608`)



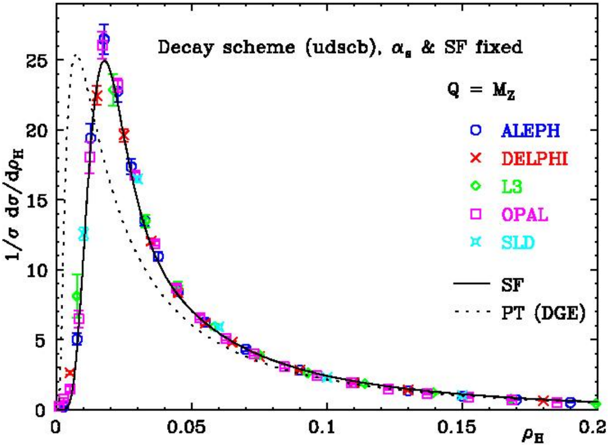
The perturbative thrust distribution vs. LEP data



The perturbative thrust distribution at ILC

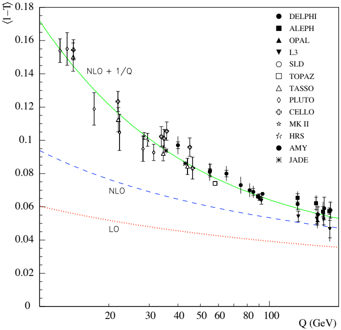
Resummation and power correction effects

A fit of LEP data for the *heavy jet mass* distribution with a *shape function* from thrust (Gardi, Rathsman).

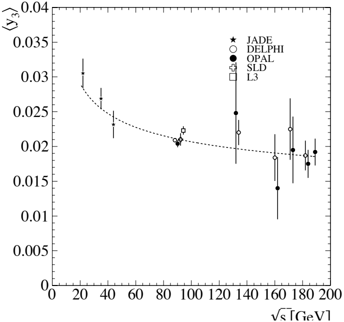


Impact of nonperturbative corrections

Different observables behave *differently*, understanding *necessary* (M. Dasgupta, G. Salam).



Data for the average thrust vs. QCD predictions



Data for the average Durham jet resolution parameter y_{23} vs. NLO QCD

On event shape distributions

Examples

- Thrust: $T = \max_{\hat{n}} \frac{\sum_i |\vec{p}_i \cdot \hat{n}|}{\sum_i |\vec{p}_i|}$; $\tau = 1 - T$.

  $\longrightarrow$ $\hat{n}$ is used to define several *other shape variables*.

- C-parameter: $C = 3 - \frac{3}{2} \sum_{i,j} \frac{(p_i \cdot p_j)^2}{(p_i \cdot q)\,(p_j \cdot q)}$.

  $\longrightarrow$ does *not require maximization* procedures.

- Broadening: $B_{\ell,r} = \frac{\sum_{i \in \mathcal{H}_{\ell,r}} |\vec{p}_i \times \hat{n}|}{2 \sum_i |\vec{p}_i|}$

  $\longrightarrow$ *select* or *combine* hemispheres.

- Angularity: $\tau_a = \frac{1}{Q} \sum_i (p_\perp)_i \mathrm{e}^{-|\eta_i|(1-a)}$.

  $\longrightarrow$ recently introduced, *one-parameter* family.

Angularities

- *Definition:* $\tau_a = \frac{1}{Q} \sum_i (p_\perp)_i \, \mathrm{e}^{-|\eta_i|(1-a)}$.

  Also: $\tau_a = \frac{1}{Q} \sum_i \omega_i \, (\sin\theta_i)^a \, (1 - |\cos\theta_i|)^{1-a}$,
- *Some properties*
  - $\tau_0 = 1 - T \, ; \; \tau_1 = B$.
  - $a < 2$ for IR safety.
  - $a < 1$ for simplicity of resummation (*recoil* negligible).
- For *negative* a, high rapidity particles (*w.r.t.* the thrust axis) are weighted less: *better* collinear behavior.
- At *one loop*, with the thrust axis given by particle i,

$$\tau_a = \frac{(1-x_i)^{1-a/2}}{x_i} \left[(1-x_j)^{1-a/2} (1-x_k)^{a/2} + (j \leftrightarrow k) \right] .$$

Resumming Sudakov logarithms

Infrared and collinear emission dominates the two-jet limit

- Large *double* logarithms of the variable vanishing in the two-jet limit $(L = \log\tau\ ; L = \log C\ ; \ldots)$ enhance finite orders $\rightarrow$ *need to resum*.
- A pattern of *exponentiation* emerges

$$\sum_k \alpha_s^k \sum_p^{2k} c_{kp} L^p \rightarrow \exp\left[L g_1(\alpha_s L) + g_2(\alpha_s L) + \alpha_s g_3(\alpha_s L) + \ldots\right]$$

- In general the *Laplace transform* exponentiates. For thrust

$$\int_0^\infty d\,\tau\, \mathrm{e}^{-\nu\tau} \frac{1}{\sigma}\frac{d\sigma}{d\tau} = \exp\left[\int_0^1 \frac{du}{u}\left(\mathrm{e}^{-u\nu} - 1\right)\left(B\left(\alpha_s\left(uQ^2\right)\right) + 2\int_{u^2Q^2}^{uQ^2} \frac{dq^2}{q^2} A\left(\alpha_s(q^2)\right)\right)\right].$$

Resummation for angularities

- Sudakov logs at one loop have *simple scaling* with a.

$$\left.\frac{d\sigma}{d\tau_a}\right|_{\log}^{(1)} = \frac{2}{2-a}\,\frac{2}{\tau_a} C_F \frac{\alpha_s}{\pi} \ln\left(\frac{1}{\tau_a}\right) = \frac{2}{2-a}\,\left.\frac{d\sigma}{d\tau}\right|_{\log}^{(1)} .$$

- Resummation is *intricate*. To *NLL* accuracy

$$\tilde{\sigma}_a\left(\nu\right) = \exp\left\{2\int_0^1 \frac{du}{u}\left[\int_{u^2Q^2}^{uQ^2} \frac{dq^2}{q^2} A\left(\alpha_s(q^2)\right)\left(\mathrm{e}^{-u^{1-a}\nu(q/Q)^a} - 1\right)\right.\right.$$

$$\left.\left. + \frac{1}{2} B\left(\alpha_s(u\,Q^2)\right)\left(\mathrm{e}^{-u\,\nu^{2/(2-a)}} - 1\right)\right]\right\}.$$

- General a-dependence of Sudakov logs is *nontrivial*.

$$g_1(x,a) = -\frac{4}{\beta_0}\,\frac{2-a}{1-a}\,\frac{A^{(1)}}{x}\left[\frac{1-x}{2-a}\ln\left(1-x\right)\right.$$

$$\left. - \left(1 - \frac{x}{2-a}\right)\ln\left(1 - \frac{x}{2-a}\right)\right].$$

Scaling for the shape function

An analysis of power corrections for angularities using the *shape function* approach (Berger, Sterman) shows a remarkable *scaling*.

- As done for *thrust*, focus on *small* τ_a, *large* ν, set IR factorization scale μ, expand in powers of ν/Q (soft), *neglecting* ν/Q^2 (collinear). In this case

$$S_{\rm NP}^{(a)}(\nu/Q,\mu) \;=\; 2\int_0^{\mu^2}\frac{dq^2}{q^2}A\left(\alpha_s(q^2)\right)\int_{q^2/Q^2}^{q/Q}\frac{du}{u}\left({\rm e}^{-u^{1-a}\nu(q/Q)^a}-1\right)$$
$$\simeq\;\frac{1}{1-a}\sum_{n=1}^{\infty}\frac{1}{n!}\left(-\frac{\nu}{Q}\right)^n\lambda_n(\mu^2)\;,$$

- The *full result* suggested by the resummation can be expressed in terms of *two* shape functions

$$\tilde\sigma_a\left(\nu\right)=\tilde\sigma_{a,{\rm PT}}\left(\nu,\mu\right)\,\tilde f_{a,{\rm NP}}\left(\frac{\nu}{Q},\mu\right)\,\tilde g_{a,{\rm NP}}\left(\frac{\nu}{Q^{2-a}},\mu\right)\;,$$

- *Leading* power corrections are described by $\tilde{f}_{a,\mathrm{NP}}$ and obey

$$\tilde{f}_{a,\mathrm{NP}}\left(\frac{\nu}{Q},\mu\right)=\left[\tilde{f}_{0,\mathrm{NP}}\left(\frac{\nu}{Q},\mu\right)\right]^{1/(1-a)}\quad .$$

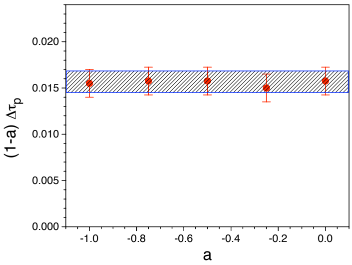
- *Scaling* can be traced to *boost invariance* in the eikonal limit. A *renormalon* calculation breaks boost invariance but *scaling survives* in the Sudakov limit. *DGE* (Berger, LM) yields

$$B_a^{\mathrm{soft}}(\nu,u)=\frac{1}{1-a}\left[2\,\mathrm{e}^{5u/3}\,\frac{\sin\pi u}{\pi u}\,\Gamma(-2u)\left(\nu^{2u}-1\right)\frac{2}{u}\right]$$

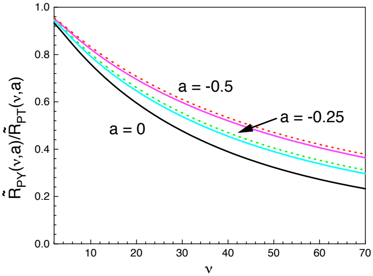
- *Collinear* contribution shows an *intricate* structure of *fractional* power corrections in DGE, but they are suppressed by ν/Q^{2-a}, consistent with resummation.
- *Scaling* is a *testable prediction* with *existing* LEP data. ILC, GigaZ provide *lever arm*, *precision*.

Testing the scaling rule

The scaling rule is a *prediction* waiting for data *analysis* ... in the meantime, it can be compared with PYTHIA output (Berger).



Shift in the position of the peak of τ_a distribution, between NLL result and PYTHIA, after rescaling by $1 - a$, vs. shift for $a = 0$ computed from data.



The leading shape function for different a, PYTHIA output (solid) vs. scaled result (dashed).

Hadronization for jets, in hadron collisions

M. Cacciari, M. Dasgupta, LM, G. Salam

- *Consider* the single inclusive distribution for a jet observable $O(y, p_T, R)$, with an effective *jet radius* $R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.
- *Measure* the effect on the distribution of *single soft gluon* emission by each *hard dipole* at power accuracy.
- *Define* R-dependent power correction

$$\Delta O_{ij}^{\pm}(R) \equiv \int_{\pm} d\eta \frac{d\phi}{2\pi} \int_{\mu_c}^{\mu_f} d\kappa_T^{(ij)} \, \alpha_s\left(\kappa_T^{(ij)}\right) k_T \left|\frac{\partial k_T}{\partial \kappa_T^{(ij)}}\right| \frac{p_i \cdot p_j}{p_i \cdot k \, p_j \cdot k} \, \delta O^{\pm}\left(k_T, \eta, \phi\right) \; .$$

- *Express* leading power R dependence in terms of (*universal?*) moment of coupling $\mathcal{A}$

$$\mathcal{A}\left(\mu_f\right) = \int_0^{\mu_f} \frac{dk_\perp}{k_\perp} \alpha_s(k_\perp) \cdot k_\perp$$

- `Note:` only the *final state* dipole would contribute in e^+e^- annihilation

Radius dependence: p_T distribution

Let $O = \xi_T \equiv 1 - 2p_T/\sqrt{S}$. In this case

- *In-In dipole*

$$\Delta\xi_{T,12}(R) = \frac{-4}{\sqrt{S}} \int_{+} d\eta \frac{d\phi}{2\pi} \alpha_s(k_t) \frac{dk_t}{k_t} k_t \cos\phi = -\frac{4}{\sqrt{S}} \mathcal{A}(\mu_f) \left(\frac{R^2}{2} - \frac{R^4}{16} + \frac{R^6}{384} + \ldots \right).$$

- *In-Jet dipoles*

$$\begin{aligned} \Delta\xi_{T,1j}(R) &= -\sqrt{\frac{2}{S}} \int_{\eta^2+\phi^2<R^2} d\eta \frac{d\phi}{2\pi} \alpha_s(\kappa_t) \frac{d\kappa_t}{\kappa_t} \kappa_t \frac{\cos\phi \, e^{\frac{3\eta}{2}}}{(\cosh\eta - \cos\phi)^{\frac{3}{2}}} \\ &= \frac{2}{\sqrt{S}} \mathcal{A}(\mu_f) \left(\frac{2}{R} - \frac{5}{8} R + \frac{23}{1536} R^3 + \ldots \right) \end{aligned}$$

- *Jet-Recoil dipole*

$$\Delta\xi_{T,jr}(R) = \frac{2}{\sqrt{S}} \mathcal{A}(\mu_f) \left(\frac{2}{R} + \frac{1}{2} R + \frac{1}{96} R^3 + \ldots \right)$$

- *In-Recoil dipoles*

$$\Delta\xi_{T,1r}(R) = -\frac{2}{\sqrt{S}} \mathcal{A}(\mu_f) \left(\frac{1}{8} R^2 - \frac{9}{512} R^4 - \frac{73}{24576} R^6 + \ldots \right)$$

Radius dependence: mass distribution

For comparison, let $O = \nu_J \equiv M_J^2/S$. Now only gluons *recombined* with the jet contribute, and one finds *nonsingular* R dependence.

- *In-In dipole*

$$\Delta\nu_{J,12}(R) = \frac{1}{\sqrt{S}}\mathcal{A}(\mu_f)\left(\frac{1}{4}R^4 + \frac{1}{4608}R^8 + \mathcal{O}\left(R^{12}\right)\right) ,$$

- *In-Jet dipoles*

$$\Delta\nu_{J,1j}(R) = \frac{1}{\sqrt{S}}\mathcal{A}(\mu_f)\left(R + \frac{3}{16}R^3 + \frac{125}{9216}R^5 + \frac{7}{16384}R^7 + \mathcal{O}\left(R^9\right)\right) ,$$

- *Jet-Recoil dipole*

$$\Delta\nu_{J,jr}(R) = \frac{1}{\sqrt{S}}\mathcal{A}(\mu_f)\left(R + \frac{5}{576}R^5 + \mathcal{O}\left(R^9\right)\right) ,$$

- *In-Recoil dipoles*

$$\Delta\nu_{J,1r}(R) = \frac{1}{\sqrt{S}}\mathcal{A}(\mu_f)\left(\frac{1}{32}R^4 + \frac{3}{256}R^6 + \frac{169}{589824}R^8 + \mathcal{O}\left(R^{10}\right)\right) .$$

Power corrections by MonteCarlo

The *analytical* estimate of power corrections provided by resummation is valid *near threshold*. It can be compared with *numerical* estimates from QCD-inspired *MonteCarlo models* of hadronization.

- *Run* MC at *parton level* (p), *hadron level without UE* (h) and finally *with UE* (u)
- *Select* events with hardest jet in chosen p_T range, *identify* two hardest jets, *define* for each hadron level

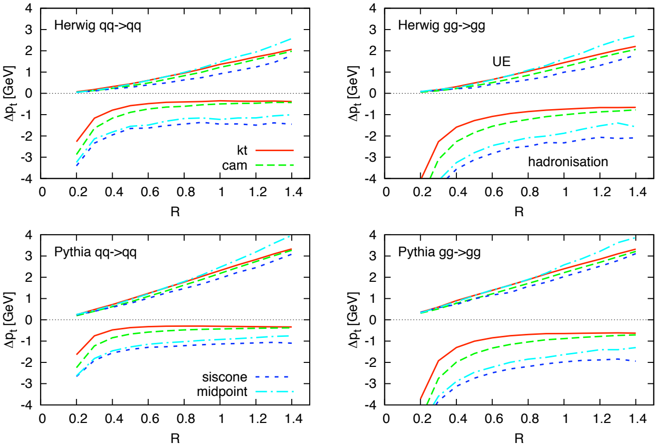
$$\Delta p_T^{(h/u)} = \frac{1}{2}\left(p_{T,1}^{(h/u)} + p_{T,2}^{(h/u)} - p_{T,1}^{(p)} - p_{T,2}^{(p)}\right) .$$

$$\Delta p_T^{(u-h)} = \Delta p_T^{(u)} - \Delta p_T^{(h)} .$$

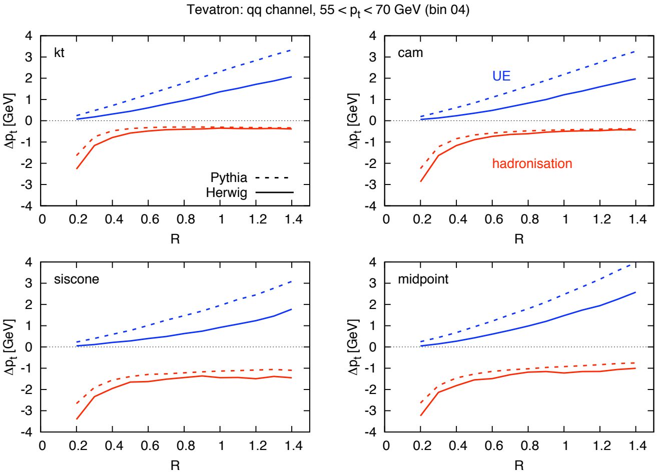
- *Compare* results for different *jet algorithms*, *hadronization models*, *parton channels*.

MC power corrections: comparing jet algorithms

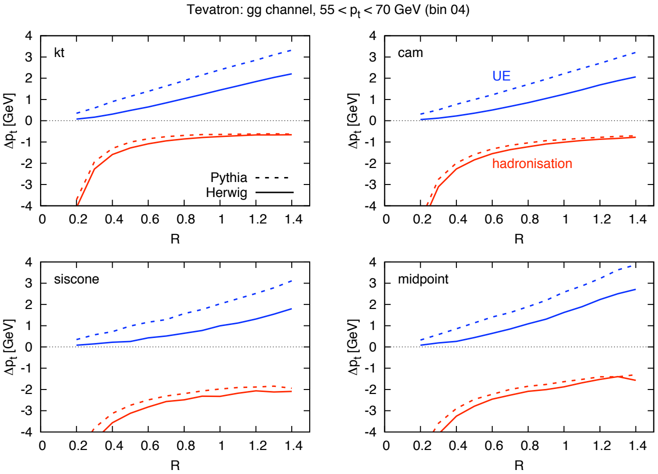
Tevatron: $55 < p_t < 70$ GeV (bin 04)



MC power corrections: quark channel



MC power corrections: gluon channel



Perspective

- ILC is *very useful* for QCD (even more so in GigaZ mode)
- QCD is *a necessary tool* for ILC
- *Hadronization* matters even at large $\sqrt{s}$
- LEP left *unfinished work*: analytic hadronization models make *testable predictions*.
  - *Scaling rule* for shape function for *angularities*
  - Singular *R-dependence* of hadronization corrections for *jets*
- We should be *ready* to take *full advantage* of a wonderful *precision machine* for both SM and BSM physics.

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