Top Quark Mass from Top Jets

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Goal: measure the top mass as accurately as possible!

- What makes for a good top quark mass observable?

  Well defined relation to a short distance mass

  Good signal to background ratio

- Threshold scan: $\delta m_t^{th} \sim 100 MeV$

  (Peskin & Strassler; Hoang, Manohar, Stewart, Teubner,...)

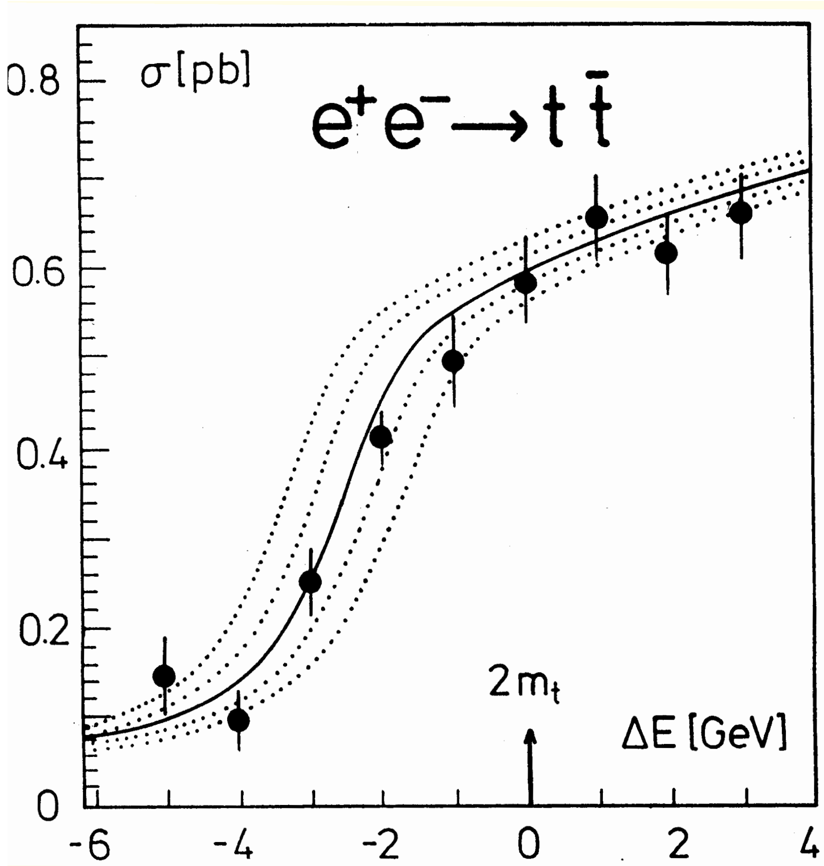
  ▷ count number of $t\bar{t}$ events

  ▷ color singlet state

  ▷ background is non-resonant

  ▷ physics well understood

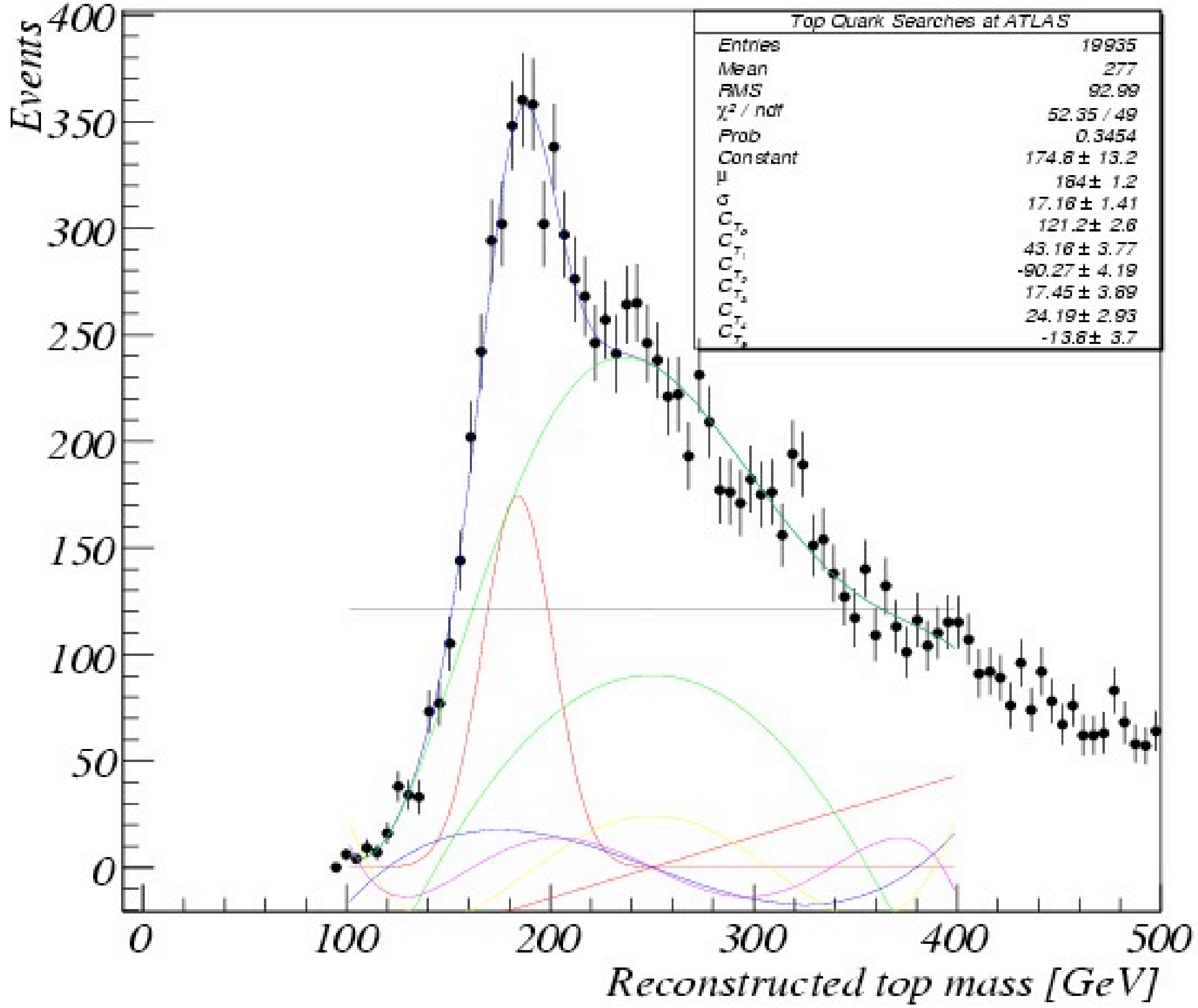
  (renormalons, summations)



Top quark mass observable at the LHC - Jet Reconstruction

- Expt. Issues:

1) Determining parton momentum
2) Combinatorics
3) Jet energy scale
4) Underlying events
5) Initial & Final state radiation
6) b-Jets, b-fragmentation
7) MC dependence
8) b-tagging efficiency
9) Background & Statistics



Top quark mass observable at the LHC - Jet Reconstruction

- Th. Issues:

1) Definition of jet observable with a clear relation to the Lagrangian mass
2) Color reconnection and soft gluon interactions
3) Summing large logs: $Q \gg m_t \gg \Gamma_t$
4) Final state radiation
5) Parton Distribution Functions
6) Beam remenant
7) Initial state radiation
8) Underlying events

These effects can be studied in: $e^+e^- \to t\bar{t} + X$ for $Q \gg m_t$

Pair Production of Top Jets

$$e^+e^- \longrightarrow t\bar{t} \qquad pp \longrightarrow t\bar{t}X$$

LC

LHC

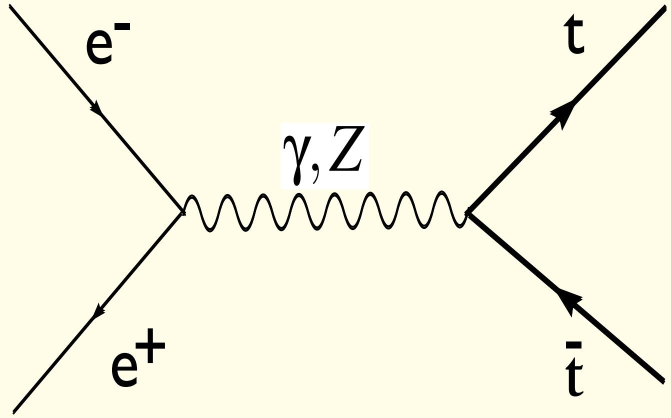
Focus of this talk

Goals for our Analysis

- relate top jet observables with a given Lagrangian mass (define suitable short-distance mass with good convergence properties → What mass is measured?)
- proof of factorization of dynamics at different length scales (→ What has to be computed by theorists ?)
- combined treatement of top production & decay
- separate perturbative from non-perturbative effects
- hopefully better understand & reduce theoretical & experimental uncertainties

Sequence of Effective Field Theories

Jet Observable Sensitive to Top Mass



- Focus on the dijet region where the top and antitop jets have invariant masses close to the top mass.

- The top and antitop jets are defined to have the invariant masses:

$$M_t\,,\ M_{\bar t}$$

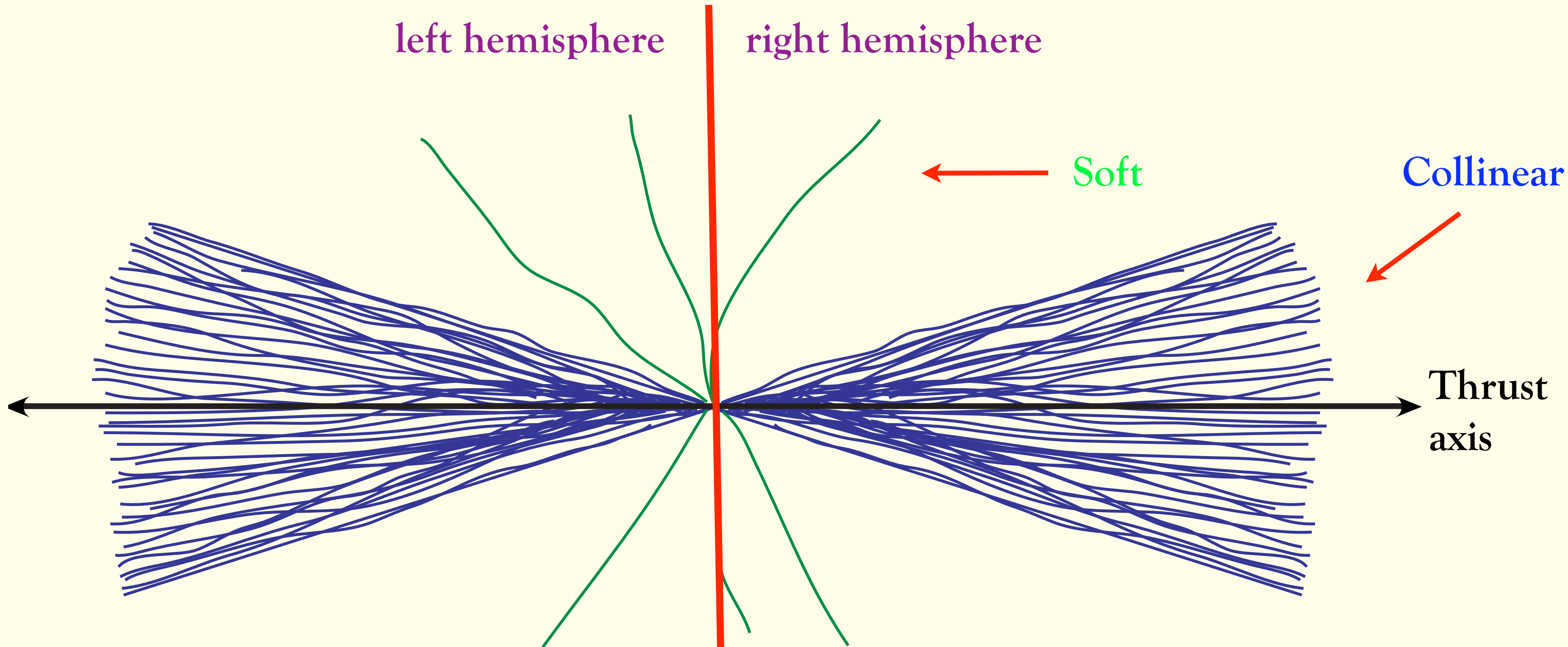
- The jet invariant mass condition is characterized as:

$$\hat{s}_{t,\bar t} \equiv \frac{s_{t,\bar t}}{m} \equiv \frac{M^2_{t,\bar t} - m^2}{m} \sim \Gamma \ll m$$

- The jet observable of interest is the double differential jet invariant mass distribution:

$$\frac{d\sigma}{dM_t^2\, dM_{\bar t}^2}$$

Hemisphere invariant mass distribution



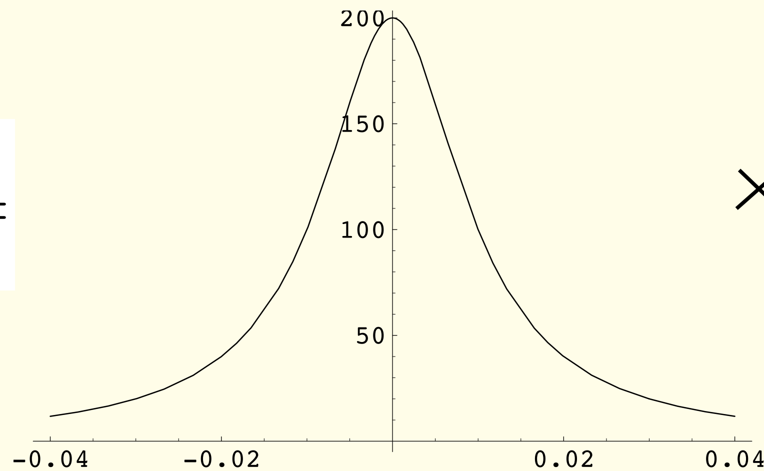
$$M_{\bar{t}}^2 - m^2 \sim m\Gamma \qquad\qquad M_t^2 - m^2 \sim m\Gamma$$

Expected Result

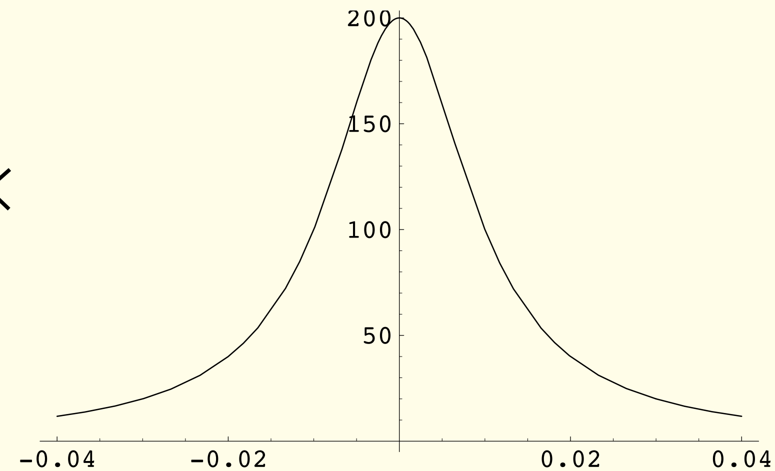
Tree Level Breit Wigner Curves?

- A first guess might be that the distribution is a product of Breit Wigner curves.

$$\left.\frac{d^2\sigma}{ds_t\, ds_{\bar{t}}}\right|_{\text{tree level}} =$$



$\times$



This is not correct even at tree level!

Relevant Energy Scales

- Center of mass energy $Q \sim 1\text{TeV}$
- Top quark mass $m \sim 174\text{GeV}$
- Top quark width $\Gamma \sim 2\text{GeV}$
- Confinement Scale $\Lambda \sim 500MeV$

Disparate energy scales $\longrightarrow$ Effective Field Theory!

Group Photo of Effective Field Theories

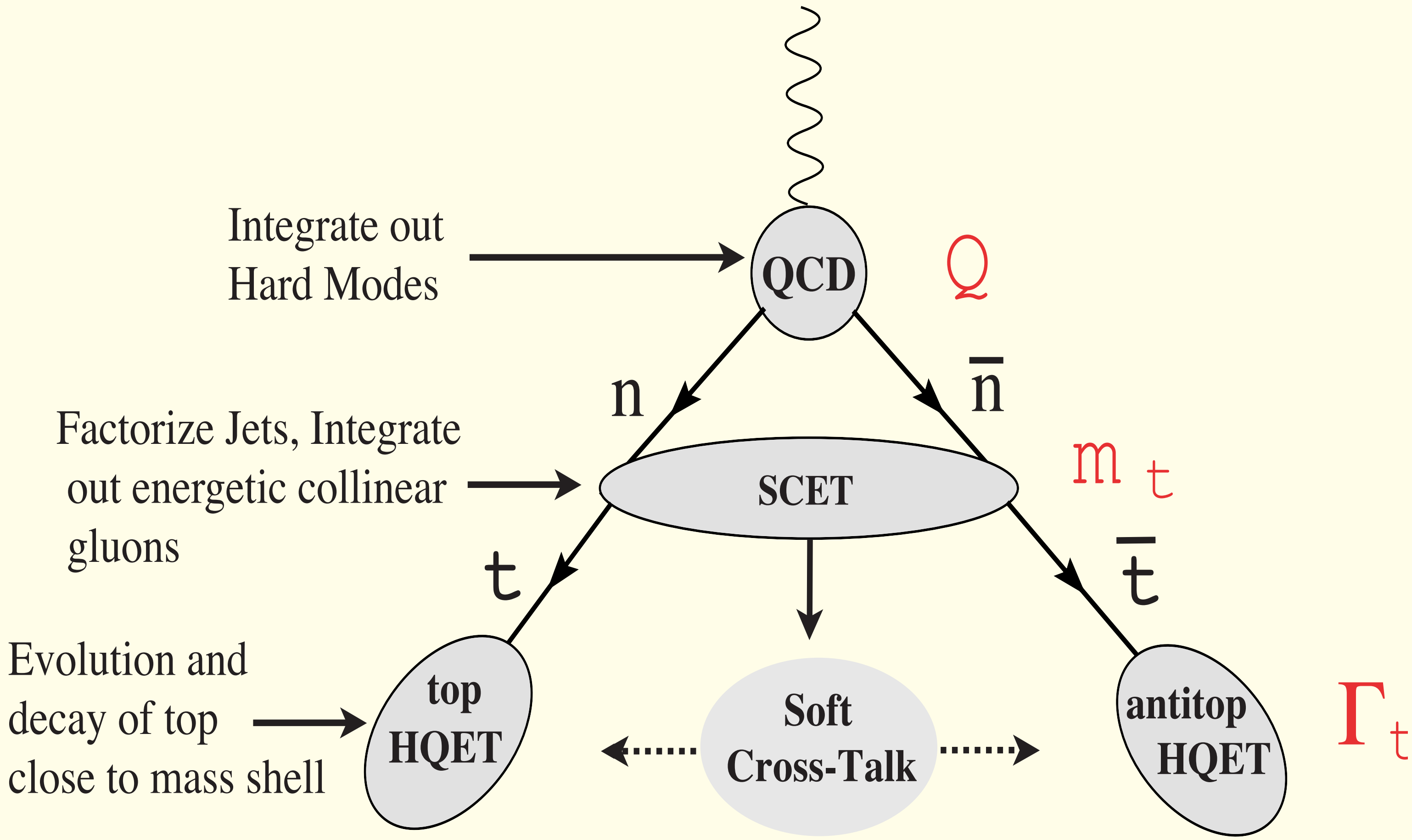
QCD Q

↓

SCET m

↓

HQET Γ



SCET Cross-section

- In the hemisphere scenario the SCET cross section takes the form:

$$\frac{d^2\sigma}{dM_t^2\, dM_{\bar t}^2} = \sigma_0\, H_Q(Q,\mu) \int_{-\infty}^{\infty} d\ell^+ d\ell^-\, J_n(s_t - Q\ell^+, \mu) J_{\bar n}(s_{\bar t} - Q\ell^-, \mu) S_{\text{hemi}}(\ell^+, \ell^-, \mu)$$

Hard Wilson Coefficient

Top Jet Function

Anti-Top Jet Function

Soft Cross Talk Function

Calculable perturbative top and antitop jet functions

$$J_n(Qr_n^+ - m^2) = \frac{-1}{2\pi Q} \int d^4x\, e^{ir_n\cdot x}\, \text{Disc}\, \langle 0|\text{T}\{\overline{\chi}_{n,Q}(0) \bar{\not{n}} \chi_n(x)\}|0\rangle$$

$$J_{\bar n}(Qr_{\bar n}^- - m^2) = \frac{1}{2\pi Q} \int d^4x\, e^{ir_{\bar n}\cdot x}\, \text{Disc}\, \langle 0|\text{T}\{\bar\chi_{\bar n}(x) \not{n} \chi_{\bar n,-Q}(0)\}|0\rangle$$

Universal nonperturbative soft function

$$S_{\text{hemi}}(\ell^+, \ell^-, \mu) = \frac{1}{N_c} \sum_{X_s} \delta(\ell^+ - k_s^{+a}) \delta(\ell^- - k_s^{-b}) \langle 0|\overline{Y}_{\bar n}\, Y_n(0)|X_s\rangle \langle X_s|Y_n^\dagger\, \overline{Y}_{\bar n}^\dagger(0)|0\rangle$$

- The same soft function appears in massless dijets *(Korchemsky & Sterman; Bauer, Lee, Manohar, Wise)*.

Final Factorized form of the Cross-Section

Integrate out the top quark mass by matching the jet functions from SCET onto HQET:

$$J_n(m\hat{s},\Gamma,\mu_m) = T_+(m,\mu_m)\, B_+(\hat{s},\Gamma,\mu_m)$$
$$J_{\bar{n}}(m\hat{s},\Gamma,\mu_m) = T_-(m,\mu_m)\, B_-(\hat{s},\Gamma,\mu_m)$$

Hard Production modes integrated out

"Hard" collinear gluons integrated out

Evolution and decay of top quark close to mass shell

Non-perturbative Cross talk

$$\left(\frac{d^2\sigma}{dM_t^2\, dM_{\bar{t}}^2}\right)_{\rm hemi} = \sigma_0\, H_Q(Q,\mu_m) H_m\left(m,\frac{Q}{m},\mu_m,\mu\right)$$
$$\times \int_{-\infty}^{\infty} d\ell^+ d\ell^-\, B_+\left(\hat{s}_t - \frac{Q\ell^+}{m},\Gamma,\mu\right) B_-\left(\hat{s}_{\bar{t}} - \frac{Q\ell^-}{m},\Gamma,\mu\right) S_{\rm hemi}(\ell^+,\ell^-,\mu)$$

$$B_\pm(\hat{s},\Gamma_t) = \frac{1}{\pi m_t}\frac{\Gamma_t}{\hat{s}^2+\Gamma_t^2}$$

LO Analysis: Soft Effects

$$\left(\frac{d^2\sigma}{dM_t^2\,dM_{\bar t}^2}\right)_{\rm hemi} = \sigma_0\, H_Q(Q,\mu_m) H_m\left(m, \frac{Q}{m}, \mu_m, \mu\right) \times \int_{-\infty}^{\infty} d\ell^+ d\ell^-\, B_+\left(\hat{s}_t - \frac{Q\ell^+}{m}, \Gamma, \mu\right) B_-\left(\hat{s}_{\bar t} - \frac{Q\ell^-}{m}, \Gamma, \mu\right) S_{\rm hemi}(\ell^+, \ell^-, \mu)$$

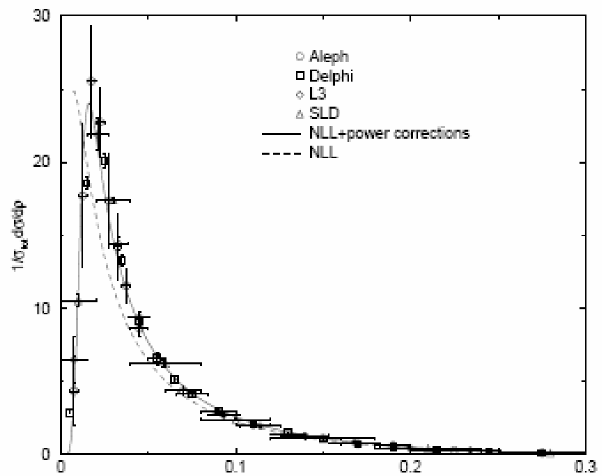
Jet functions:

$$B_\pm(\hat{s}, \Gamma_t) = \frac{1}{\pi m_t} \frac{\Gamma_t}{\hat{s}^2 + \Gamma_t^2}$$

Soft function:

$$S_{\rm hemi}^{\rm M1}(\ell^+, \ell^-) = \theta(\ell^+)\theta(\ell^-) \frac{\mathcal{N}(a,b)}{\Lambda^2} \left(\frac{\ell^+\ell^-}{\Lambda^2}\right)^{a-1} \exp\left(\frac{-(\ell^+)^2 - (\ell^-)^2 - 2b\ell^+\ell^-}{\Lambda^2}\right)$$

$$a = 2\,, \quad b = -0.4$$
$$\Lambda = 0.55 \text{ GeV}$$



Fit to heavy jet mass distribution

Korchemsky, Tafat
hep-ph/0007005

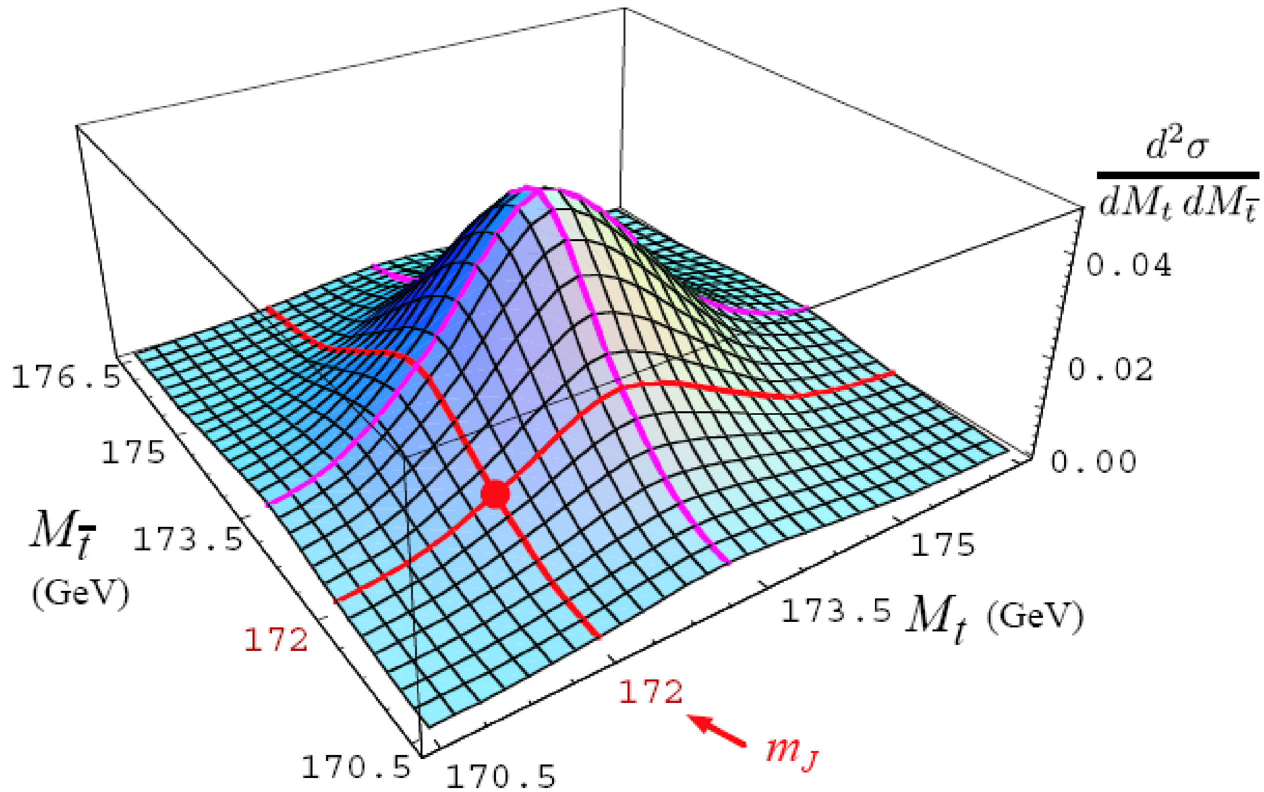
LO Analysis: Soft Effects

Double differential invariant mass distribution:

$Q = 745$ GeV

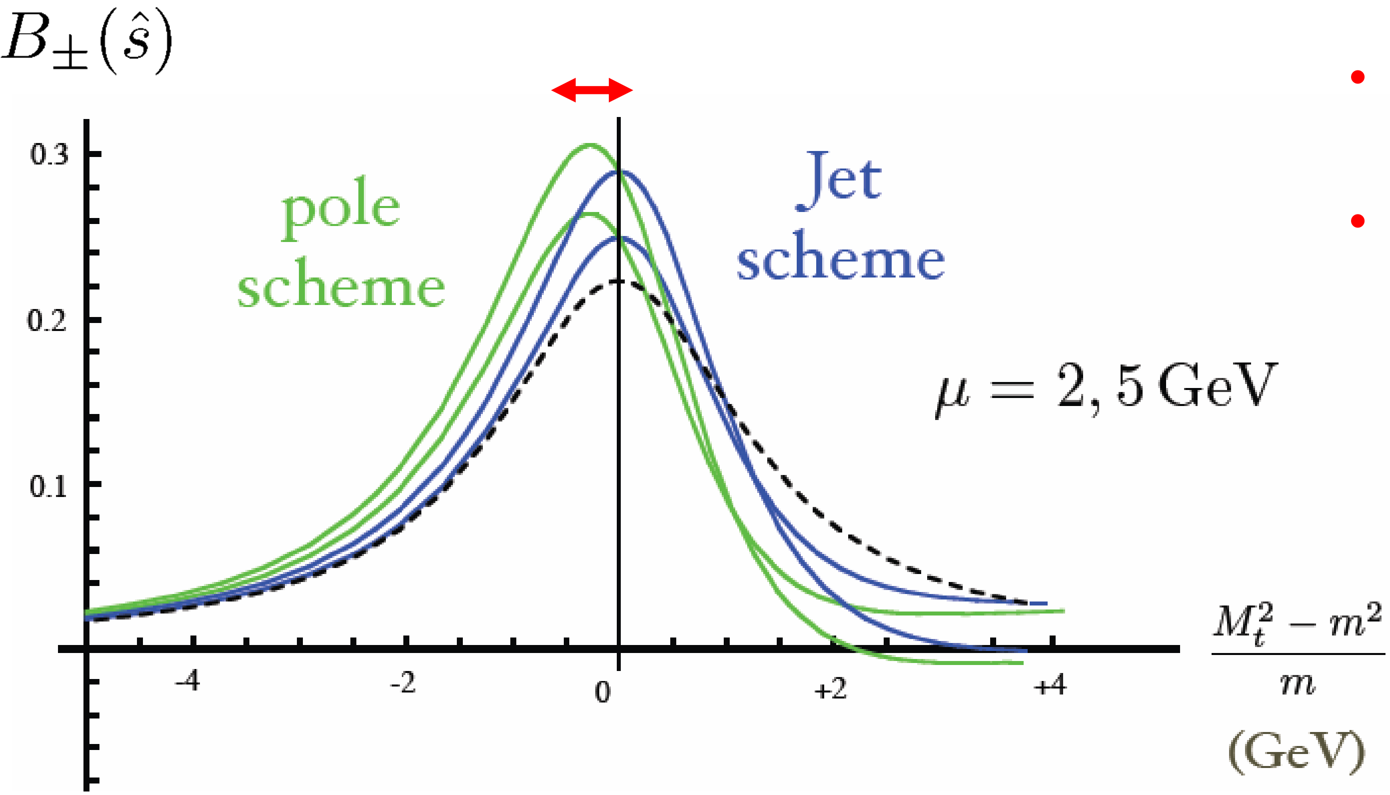
$\Gamma = 1.43$ GeV

$m_J = 172$ GeV



Non-perturbative effects shift the peak to higher energies and broaden the distribution.

Analysis of Short Distance Mass in the Jet Function



- **One-loop: shift in the pole scheme 300 MeV**
- **shift in the pole scheme contains $\mathcal{O}(\Lambda_{\text{QCD}})$ renormalon**

Define a short-distance "jet" mass:

$$\left.\frac{dB_+(\hat{s},\mu,\delta m_J)}{d\hat{s}}\right|_{\hat{s}=0} = 0$$

$$m_J(\mu) = m_{\text{pole}} - \Gamma\frac{\alpha_s(\mu)}{3}\left[\ln\left(\frac{\mu}{\Gamma}\right) + \frac{3}{2}\right]$$

Summary & Outlook

- Analysis of Spectrum based on EFT
  - Factorization
    - Well defined characterization of non-perturbative effects
  - Power corrections well defined
  - Systematic summation of logarithms (Analysis in Progress)
- Exact & Systematic relation of peak to Lagrangian mass
  - Jet mass
- Mass peak shifted by non-perturbative physics
- Extension planned: $pp \to t\bar{t} + X_{\mathrm{soft}}$ (Large Pt)

  $pp \to t\bar{t} + \mathrm{jet} + X_{\mathrm{soft}}$