Recent advances at the top threshold: summation of logs and finite lifetime effects

André H. Hoang

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Based on work with:

C. Farrell, A. Manohar, Ch. Reisser, P. Ruiz-Femenia, M. Stahlhofen, I. Stewart, T. Teubner,

Outline

- Physics at the Top Pair Threshold
    - Measurements, experimental issues
    - Theory issues
- Effective Theory (A): stable top quarks
- Effective Theory (B): unstable particle EFT
    - Finite lifetime effects
    - Interference effects
    - Phase space UV-divergences, summation of logs
    - Phase space matching
- Applications:
    - $e^+e^- \to t\bar{t}$ at NNLL
    - $e^+e^- \to t\bar{t}\,H$ at NLL
    - squark pair production → **A. Sopczak's talk**

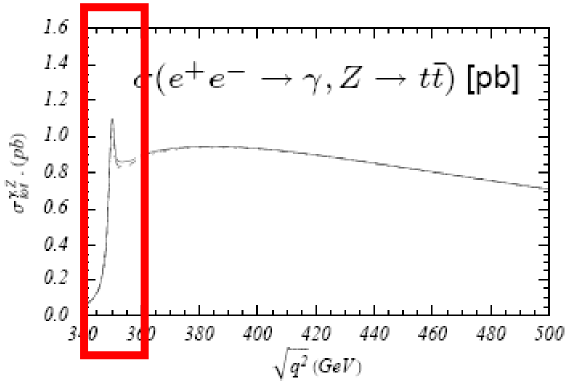
Top Physics and the ILC

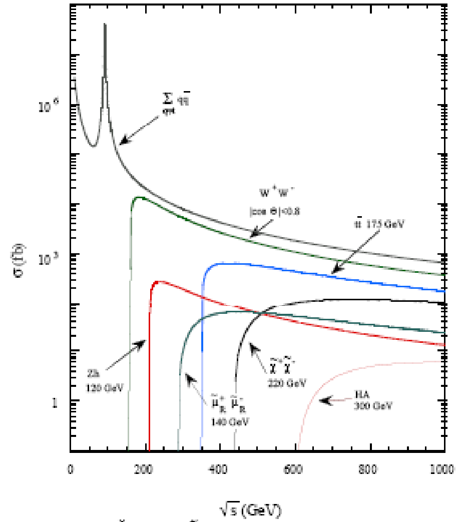
- e^+e^- collider: $E_{\rm cm} = 350$ GeV – 1 TeV
- Luminosity: 10^{34}–$10^{35}\,{\rm cm}^{-2}{\rm s}^{-1} \rightarrow 100$–$1000\,{\rm fb}^{-1}$/year

  LC $\sim 10^5$ $t\bar{t}$ pairs $\quad [\sigma_{\rm tot} < 1\,{\rm pb}]\ (e^+e^- \rightarrow t\bar{t})$

  LHC $\sim 10^8$ $t\bar{t}$ pairs $\quad [\sigma_{\rm tot} \approx 850\,{\rm pb}]\ (gg \rightarrow t\bar{t})$

- Initial state tunable and very well known $\rightarrow$ threshold & continuum
  - Centre of mass energy variable





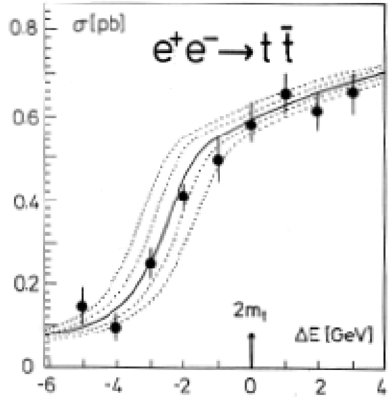
  - $e^\pm$ beam polarization: $P_{e^-} \sim 80\%$, $P_{e^+} \sim 60\%$
  - $\gamma\gamma$, γe options: $e^+e^- \rightarrow t\bar{t}\,(^3S_1)$, $\quad \gamma\gamma \rightarrow t\bar{t}\,(^1S_0)$

Threshold Measurements

Threshold Scan: $\sqrt{s} \simeq 350$ GeV (Phase I)

- ▷ count number of $t\bar{t}$ events
- ▷ color singlet state
- ▷ background is non-resonant
- ▷ physics well understood

  (renormalons, summations)



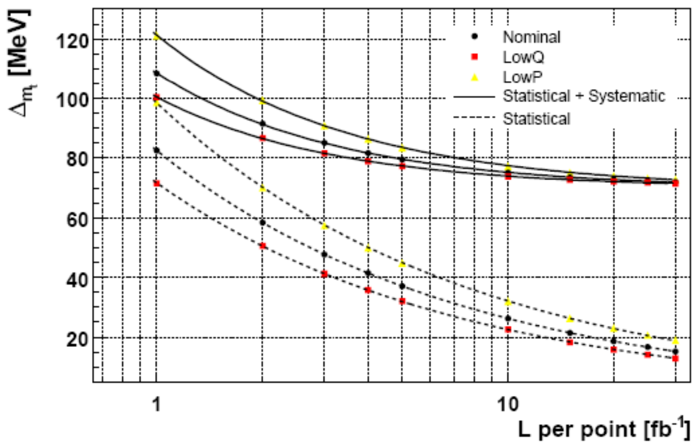
$\rightarrow \delta m_t^{\rm exp} \simeq 50$ MeV

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

What mass?

$\sqrt{s}_{\rm rise} \sim 2m_t^{\rm thr}$ + pert.series

(short distance mass: 1S $\leftrightarrow$ $\overline{\rm MS}$)



Boogert, Gounaris 2007
9+1 scan points

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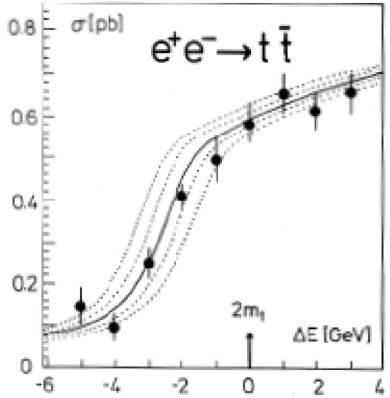

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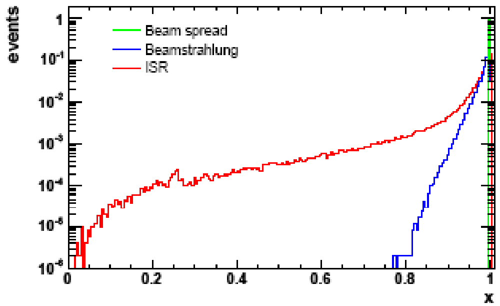
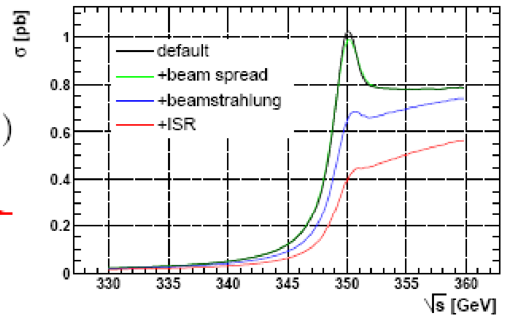
Simulations — Influence of Luminosity spectrum (LO QED effect!) — Boogert , Gounaris



$$\sigma(s) = \int_0^1 dx L(x) \sigma^0(x^2 s)$$



Threshold Measurements

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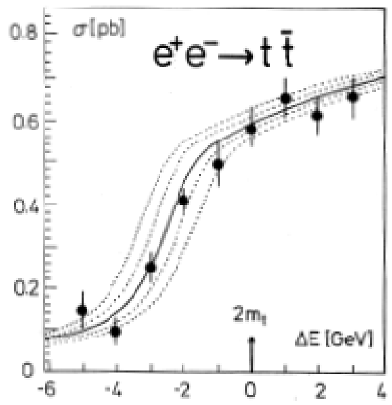


$\to \delta m_t^{\rm exp} \simeq 50$ MeV

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

What mass?

$\sqrt{s}_{\rm rise} \sim 2m_t^{\rm thr}$ + pert.series

(short distance mass: 1S $\leftrightarrow \overline{\rm MS}$)

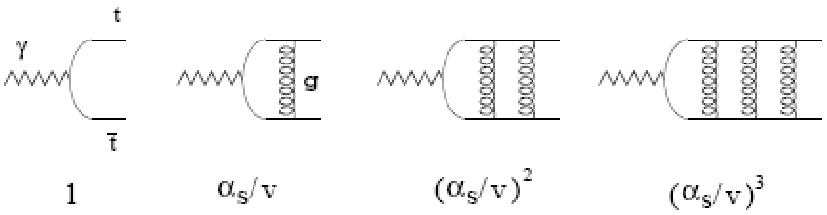
Simulations 300 fb^{-1}, 9+1 scan points → goal: $(\delta\sigma/\sigma)^{\rm theo} \leq 3\,\%$

$(\delta m_t)^{\rm stat} \sim 20$ MeV	$(\delta m_t)^{\rm syst} = 50$ MeV	$(\delta m_t)^{\rm theo} \simeq 100$ MeV
$(\delta\lambda_t/\lambda_t)^{\rm stat} = 15 - 50\%$	$(\delta\lambda_t/\lambda_t)^{\rm syst} = ?$	$(\delta\lambda_t/\lambda_t)^{\rm theo} \sim ?$
$(\delta\alpha_s(M_Z))^{\rm stat} = 0.001$	$(\delta\alpha_s(M_Z))^{\rm syst} = 0.002$	$(\delta\alpha_s(M_Z))^{\rm theo} \sim ?$
$(\delta\Gamma_t)^{\rm stat} = 50$ MeV	$(\delta\Gamma_t)^{\rm syst} = 15$ MeV	$(\delta\Gamma_t)^{\rm theo} \sim ?$

Theory Issues

m_t (hard) $\gg$ $\mathbf{p} \sim m_t v$ (soft) $\gg$ $E \sim m_t v^2$ (ultrasoft)

- perturbation theory in α_s breaks down $(\alpha_s/v)^n$



"Coulombsingularities"

$\rightarrow$ Schrödinger Equation

- perturbation theory in α_s breaks down $\rightarrow$ large logs $(\alpha_s \ln v)^n$

$m_t = 175$ GeV, $\mathbf{p} \sim 25$ GeV, $E \sim 4$ GeV $\Rightarrow \ln\left(\frac{m_t^2}{E^2}\right) = 8$ $\rightarrow$ RGE's

"multi-scale problem"

Theory Issues

- $\boxed{\Gamma_t \approx 1.5\,\text{GeV} \gg \Lambda_{\rm QCD}}$ $\Rightarrow$ $v = \sqrt{\frac{E}{m}} \rightarrow v_{\rm eff} = \sqrt{\frac{E+i\Gamma_t}{m}}$

  (Fadin,Khoze)

  $\Rightarrow m_t \gg p = m v_{\rm eff} \gg E = m v_{\rm eff}^2 \gtrsim \Lambda_{\rm QCD}$ always true !

  $\Rightarrow$ top threshold entirely perturbative ! $\longrightarrow$ "Schrödinger theory"

- $\boxed{E \sim \Gamma_t:}$ top quarks are always produced off-shell !

  $\longrightarrow$ methods for on-shell production do not apply for

  - theoretical computations
  - experimental analysis $\longrightarrow$ dependence on exp. cuts

"theory for unstable particles"

EFT – Shopping List

$$\sigma_{t\bar{t}} \sim v \sum_{n,m} \left(\frac{\alpha_s}{v}\right)^n \left(\alpha_s \ln v\right)^m \left[1,\ \{v, \alpha_s\},\ \{v^2, \alpha_s v, \alpha_s^2\},\ \ldots\right]$$

LL NLL NNLL

- Action from Lagrangian in terms of field operators
  - ▷ Manifest power counting in v at all times
    consistently obeye $E \ll p \ll m$ and $\Gamma_t \sim E \sim p^2/m$
  - ▷ Symmetries: gauge, spin, . . .
  - ▷ Regulator independence $\rightarrow$ matching in different schemes
- Renormalization of the theory $\rightarrow$ anomalous dimensions, summation of $(\alpha_s \ln v)^m$
- Dimensional regularization

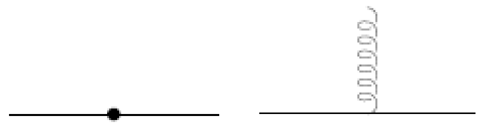
vNRQCD (stable quarks)

$\underline{\mathcal{L} = \mathcal{L}_{\text{usoft}} + \mathcal{L}_{\text{potential}} + \mathcal{L}_{\text{soft}}}$

Luke, Manohar, Rothstein, Stewart, A.H.

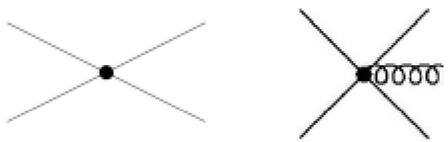
$$D^\mu = \partial^\mu + i\mu_U^\epsilon g_s(m\nu^2)A^\mu$$

$\mathcal{L}_{\text{usoft}}$:



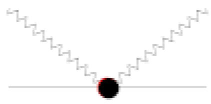
$$\psi_{\mathbf{p}}^\dagger(x)\left\{iD^0 - \frac{(\mathbf{p}-i\mathbf{D})^2}{2m_t} - \delta m_t\right\}\psi_{\mathbf{p}}(x)$$

$\mathcal{L}_{\text{potential}}$:



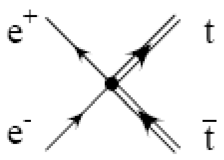
$$\mu_S^{2\epsilon}\, V(\nu)\, \psi_{\mathbf{p}'}^\dagger \psi_{\mathbf{p}} \chi_{-\mathbf{p}'}^\dagger \chi_{-\mathbf{p}}$$

$\mathcal{L}_{\text{soft}}$:



$$\mu_S^{2\epsilon}\, U_{\mu\nu}(\nu)\; \psi_{\mathbf{p}'}^\dagger A_q^\mu A_{q'}^\nu \psi_{\mathbf{p}}$$

<u>external currents:</u> (production & annihilation)



$$\mathbf{O}_{\mathbf{p}} = C_{V,A}(\nu)\cdot[\bar{e}\gamma^i(\gamma_5)e][\psi_{\mathbf{p}}^\dagger\, \boldsymbol{\sigma}^i\, \tilde{\chi}_{-\mathbf{p}}^*] + \cdots \qquad t\bar{t}\;(^3S_1)$$

Cross Section at NNLL Order

Schematic:

$$\sigma_{\mathrm{tot}} \propto \mathrm{Im}\left[\int d^4x\, e^{-i\hat{q}x} \left\langle 0 \left| T\, \mathbf{O}^\dagger_{\mathbf{p}}(0)\, \mathbf{O}_{\mathbf{p}'}(x) \right| 0 \right\rangle \right]$$

$$\propto \mathrm{Im}\left[(C_A(\nu)^2 + C_V(\nu)^2)\, G(0,0,\sqrt{s})\right]$$

$$\left(-\frac{\nabla^2}{m} - \frac{\nabla^4}{4m^3} + V(\mathbf{r}) - (\sqrt{s} - 2m - 2\delta m) - i\Gamma_t\right) G(\mathbf{r},\mathbf{r}') = \delta^{(3)}(\mathbf{r}-\mathbf{r}')$$

fully known

at NNLL order ✓

Manohar,Stewart; AH '99-'03
Pineda,Soto '00-'01
Peter '94, Schröder '98

NLL ✓

NNLL (matching) ✓ Benke etal; Czarnecki etal '99

NNLL (non-mixing) ✓ AH '03

NNLL (mixing)

spin-dependent (soft) Penin etal. '04

usoft $1/m^2$ Stahlhofen, AH '05

Cross Section at NNLL Order

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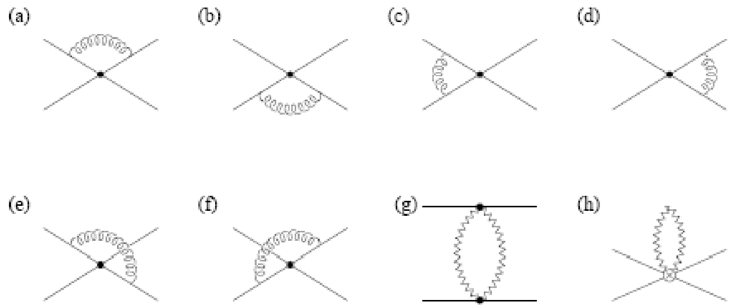
LL running of $V_{1/m^2}(\nu)$



$$\frac{\mathcal{V}_r(\nu)(\mathbf{p}^2+\mathbf{p}'^2)}{2m^2\mathbf{k}^2} + \frac{\mathcal{V}_2(\nu)}{m^2} + \frac{\mathcal{V}_s(\nu)}{m^2}\mathbf{S}^2 + \frac{\mathcal{V}_\Lambda(\nu)}{m^2}\Lambda + \frac{\mathcal{V}_t(\nu)}{m^2}T$$

Cross Section at NNLL Order

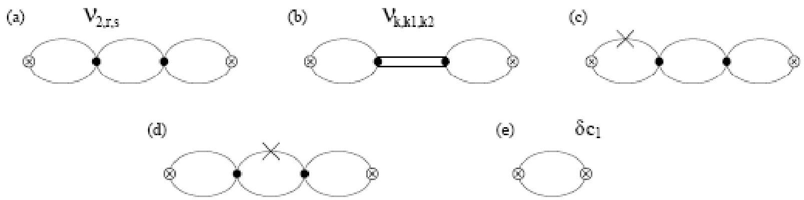
Schematic:

$$\sigma_{\rm tot} \;\propto\; {\rm Im}\left[\int {\rm d}^4{\rm x}\, {\rm e}^{-{\rm i}\hat{q}{\rm x}} \left\langle 0 \left| {\rm T}\, \mathbf{O}^\dagger_{\mathbf{p}}(0)\, \mathbf{O}_{\mathbf{p}'}({\rm x}) \right| 0 \right\rangle\right]$$

$$\propto\; {\rm Im}\left[({\rm C_A}(\nu)^2 + {\rm C_V}(\nu)^2)\, {\rm G}(0,0,\sqrt{\rm s})\right]$$

$$\left(-\frac{\nabla^2}{m} - \frac{\nabla^4}{4m^3} + V(\mathbf{r}) - (\sqrt{s} - 2m - 2\delta m) - i\Gamma_t\right) G(\mathbf{r},\mathbf{r}') = \delta^{(3)}(\mathbf{r}-\mathbf{r}')$$

NLL running of $C(\nu)$



$$\frac{d}{d\ln\nu}\ln C(\nu) = -\frac{\mathcal{V}_c(\nu)}{16\pi^2}\left(\frac{\mathcal{V}_c(\nu)}{4} + \mathcal{V}_2(\nu) + \mathcal{V}_r(\nu) + \mathbf{S}^2\mathcal{V}_s(\nu)\right) + \frac{\mathcal{V}_k(\nu)}{2}$$

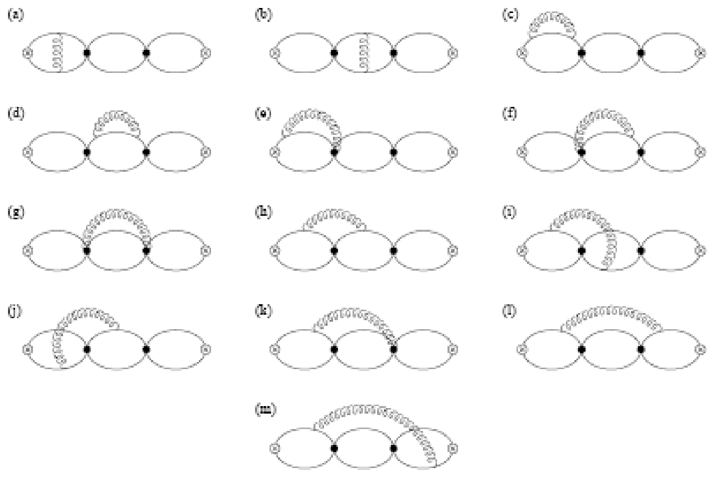
Luke,Manohar,Rothstein '99, Pineda '01
Stewart,AHH '02

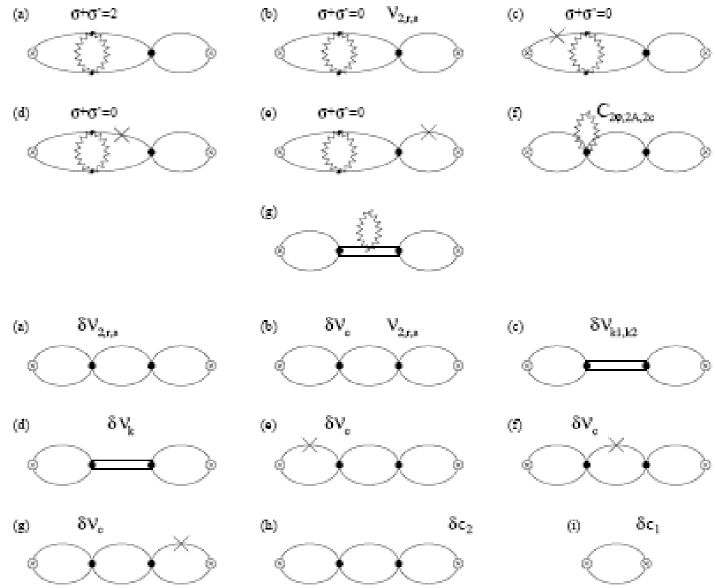
Cross Section at NNLL Order

NNLL running of $C(\nu)$

(a) next-order running of couplings in NLL anom. dim. $\longrightarrow$ w.i.p.

(b) genuine 3-loop anomalous dimension AHH '03





ultrasoft corrections
dominate by factor 10

Cross Section at NNLL Order

NNLL running of $C(\nu)$

(a) next-order running of couplings in NLL anom. dim. $\rightarrow$ w.i.p.

(b) genuine 3-loop anomalous dimension AHH '03

$$\frac{\delta z_c^{\rm NNLL,1}}{\epsilon} = \frac{\rm const}{\epsilon} + \frac{\rm const}{\epsilon} \times \ln\left(\frac{m_t\,\mu_U}{\mu_S^2}\right)$$

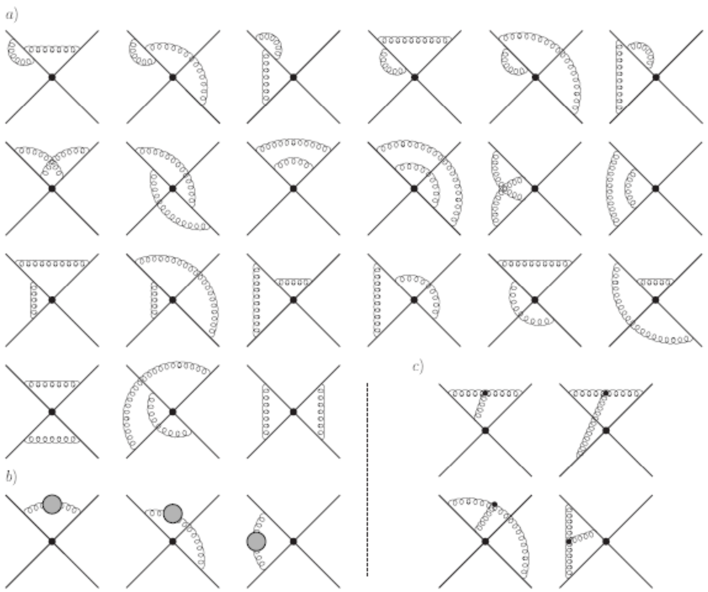
$\Rightarrow$ consistency under renormalization requires:

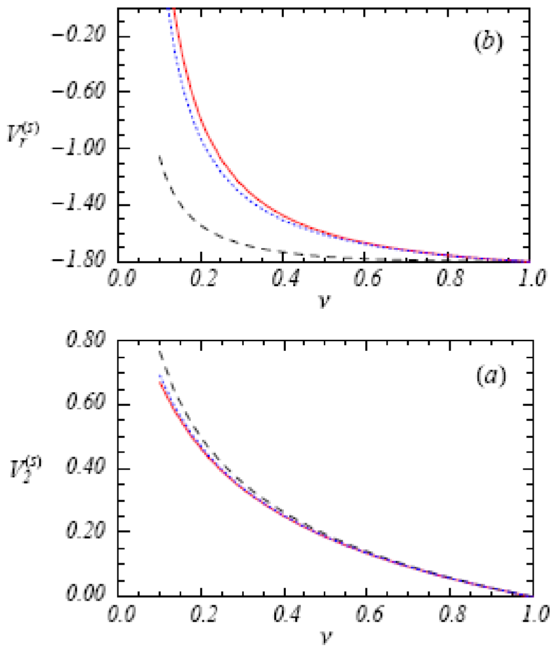
scale correlation: $\mu_U \propto \mu_S^2/m_t$

Cross Section at NNLL Order

NNLL <u>usoft</u> running of $C(\nu)$ (mixing contributions) **Stahlhofen, AH 2006**

→ **spin-independent $\mathcal{O}(1/m^2)$ potentials**



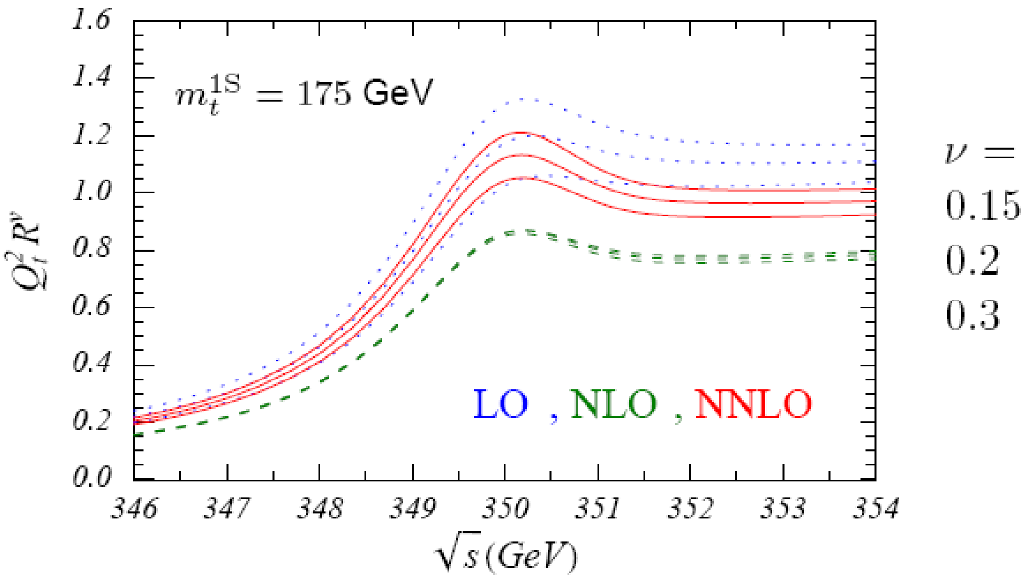


→ **spin-independent $\mathcal{O}(1/m|\vec{k}|)$ potentials w.i.p.**

Cross Section at NNLO Order

1S mass - fixed order approach

Teubner,AH; Melnikov, Yelkovski;Yakovlev; Beneke,Signer,Smirnov; Sumino, Kiyo



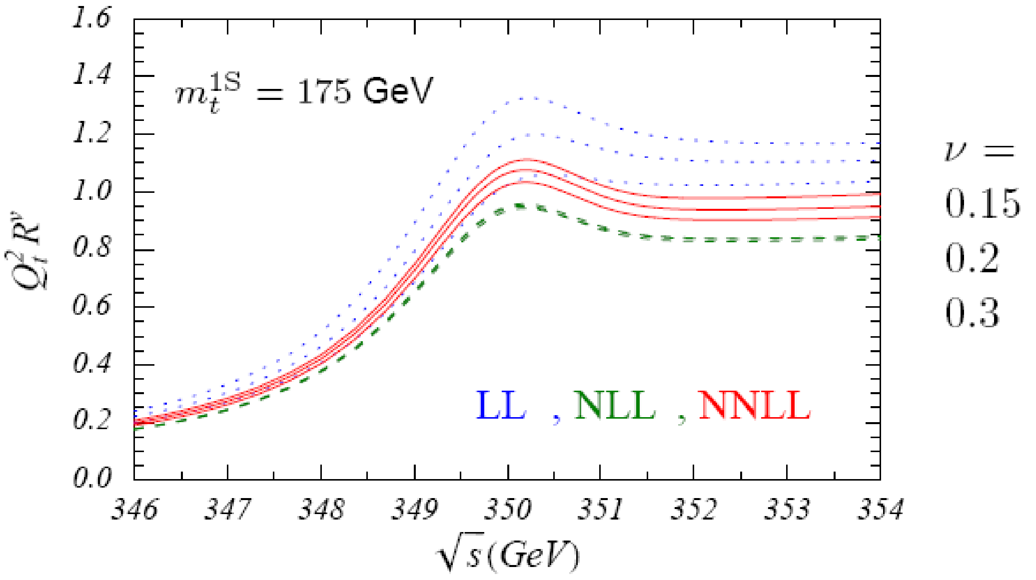
- peak position stable (threshold masses: 1S, PS, . . .)
- large sensitivity to factorization/renormalization scale setting
- NNNLO partial results: Penin etal. '02 '05, Beneke etal. '05, Eiras etal. '05**, '06**
  Marquard, Steinhauser etal '06

→ **talk by Y. Kiyo**

Cross Section at NNLL Order

1S mass - RG-improved, with NNLL non-mixing terms

Manohar,Stewart,Teubner,AH

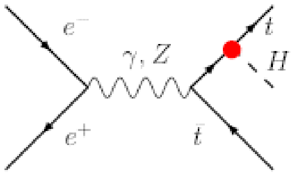


- RGI expansion shows better convergence
- theory error: $\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim \pm 6\%$ goal: 3%

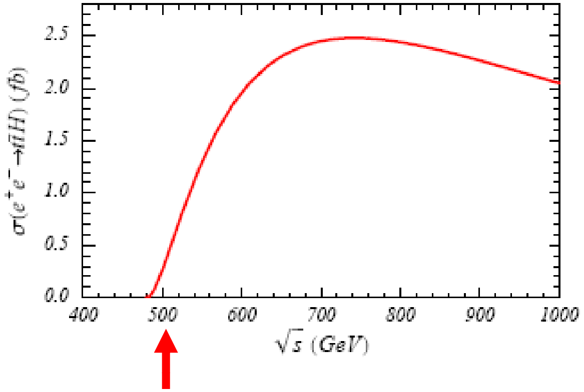
$\rightarrow$ full NNLL (mixing) running of $C(\nu)$ required $\rightarrow$ w.i.p.

Reminder: ttH Production

$e^+e^- \to t\bar{t}H$ $\longrightarrow$ top-Yukawa coupling



- Theory Status: $\sigma(e^+e^- \to t\bar{t}H)$
  Born ✓ [Gaemers et al., Djouadi et al.]
  1-loop ew. ✓ [Denner et al., Belanger et al., You et al.]
  $\mathcal{O}(\alpha_s)$ fixed-order ✓ [Dittmaier et al., Dawson et al.]
  NLL large-E_H QCD endpoint corrections ✓ [C. Farrell, AHH]

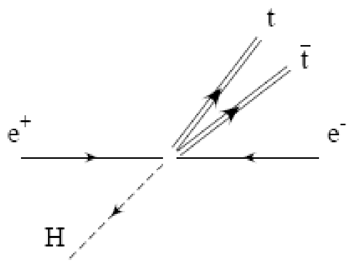


- tiny cross section for $\sqrt{s} = 500$ GeV
- measurement of Yukawa coupling difficult
- $\delta Y_t/Y_t \sim 30\%$ feasible at $\sqrt{s} = 500$ GeV
  [A. Juste, 2002]

Reminder: ttH Production

Farrell, AH 2006

➡ region of large Higgs energy

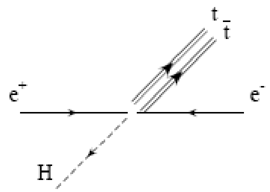


$\rightarrow$ $t\bar{t}$ collinear

$\rightarrow$ QCD effects localized in $t\bar{t}$ system

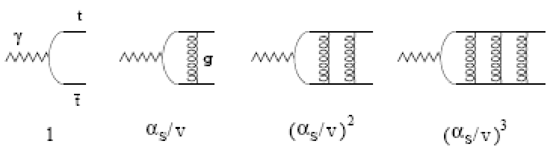
$\Rightarrow$ $t\bar{t}$ dynamics non-relativistic

➡ $$\left(\frac{d\sigma}{dE_H}\right)_{\mathrm{E_H \approx E_H^{max}}} \sim C^2(\mu, \sqrt{s}, m_t, m_H) \times \mathrm{Im}[G(0,0,v,\mu)]$$



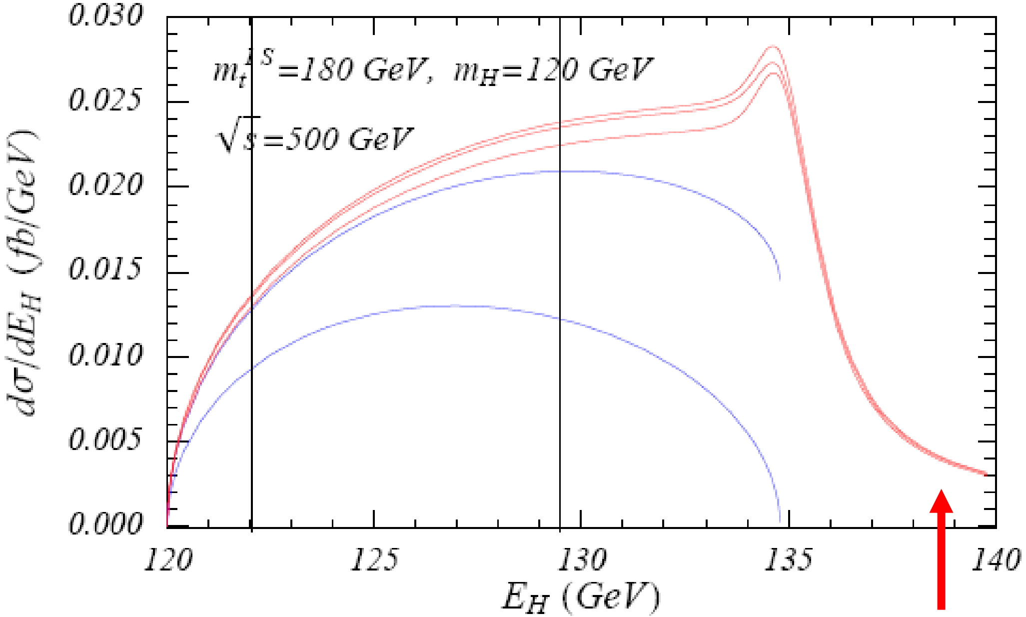
+ hard QCD corrections

soft & ultrasoft QCD corrections



Reminder: ttH Production

$e^+e^- \to t\bar{t}H$ → NLL Higgs energy spectrum



Farrell, AHH

Current work:

NLL finite lifetime effects

500 GeV:

- factor 2 enhancement over tree level from summation of $(\alpha_s/v)^n$, $(\alpha_s \ln v)^n$ terms
- essential for realistic studies for ILC (phase I) Juste '02, '06

$\Rightarrow$ $(\delta\lambda_t/\lambda_t)^{\rm ILC}_{500\,\rm GeV} \sim 30\% \quad \stackrel{\sim}{\longrightarrow} \quad 10-15\%$

NRQCD (unstable quarks)

"inclusive treatment"

⇒ Optical Theory: effective complex indices of refraction for absorptive processes

⇒ NRQCD: contributions from real Wb final states included in EFT matching conditions to QCD+ew. theory (=SM)

- complex matching conditions & anomalous dimensions
- effective Lagrangian non-hermitian
- total rates through the optical theorem
- phase space matching
- power counting maintained

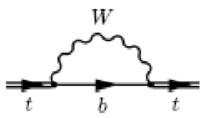
Christoph Reisser, AH; Phys. Rev. D 71, 074022 (2005)
Christoph Reisser, AH; hep-ph/0604104

NRQCD (unstable quarks)

quark bilinears: $(\rightarrow \mathcal{L}_{\text{usoft}})$

time dilatation correction

$$\mathrm{Im}\Sigma_t = \tfrac{1}{2}\Gamma_t$$



$$= i\Sigma_t \qquad \Longrightarrow \qquad \delta\mathcal{L} = \psi_{\mathbf{p}}^{\dagger}\left[i\frac{\Gamma_t}{2}\left(1 - \frac{\mathbf{p}^2}{2m_t^2}\right)\right]\psi_{\mathbf{p}}$$

- power counting: $\Gamma_t \propto m_t g^2 \sim m_t v^2 \quad \Rightarrow \quad \boxed{g \sim g' \sim v \sim \alpha_s}$
- finite lifetime is LL order, $E \rightarrow E + i\Gamma_t$ Fadin,Khoze
- NNLL time dilatiation effect
- $E \rightarrow E + i\Gamma_t$ prescription does not work beyond LL order

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time dilatation correction

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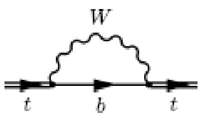
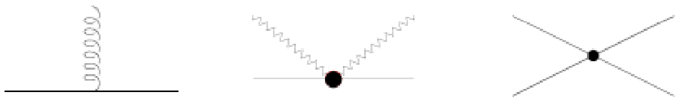
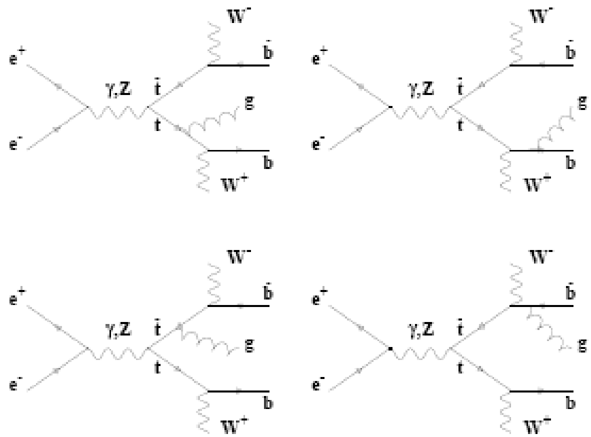


$$= i\Sigma_t \quad \Longrightarrow \quad \delta\mathcal{L} = \psi_{\mathbf{p}}^\dagger \left[i\frac{\Gamma_t}{2}\left(1-\frac{\mathbf{p}^2}{2m_t^2}\right)\right]\psi_{\mathbf{p}}$$

gluon interactions & potentials:





- electroweak corrections either beyond NNLL order or vanish due to gauge cancellations

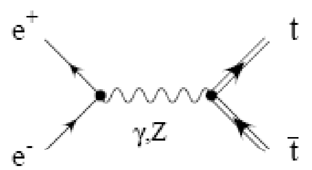
→ ultrasoft gluon interference effects vanish at NLL and NNLL order (new !) [Khoze etal., Melnikov etal.]

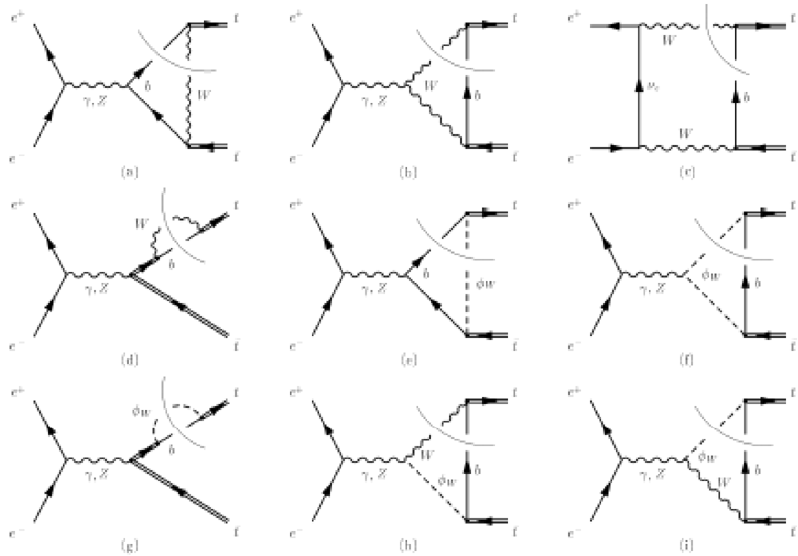
Requirement: inclusive with respect to top and antitop decay products

NRQCD (unstable quarks)

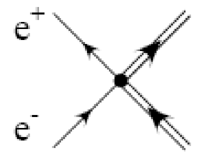
Currents:

- only bW-cuts included
- bW-cuts gauge invariant
- W treated as stable particle





$$\mathbf{O_p} = \left[C^{\mathrm{LL}} + C^{\mathrm{NLL}} + C^{\mathrm{NNLL}} + iC^{\mathrm{NNLL}}_{\mathrm{abs}} \cdots \right] \cdot \left(\quad \right) + \cdots$$



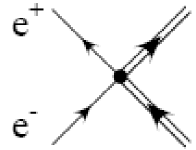
Re$[C^{\mathrm{NNLL}}_{\mathrm{ew}}]$ $\longrightarrow$ weak contributions: C. Reisser, AH, hep-ph/0604104

Guth, Kühn 1992

NRQCD (unstable quarks)

Currents:

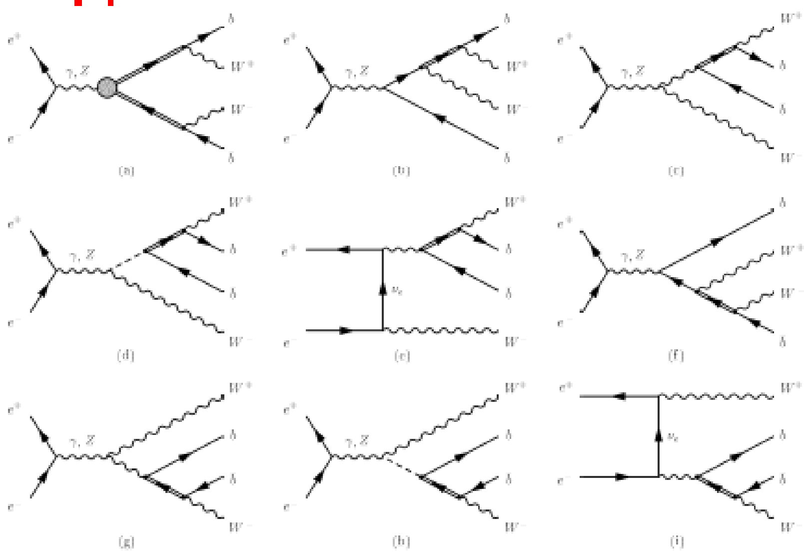
$$\mathbf{O_p} = \left[C^{\rm LL} + C^{\rm NLL} + C^{\rm NNLL} + iC^{\rm NNLL}_{\rm abs} \dots \right] \cdot \left(\quad \right) + \cdots$$



$$\sigma_{\rm tot} \propto \mathrm{Im}\left[\mathrm{C}(\nu)^2\, \mathrm{G}(0,0,\sqrt{\mathrm{s}}+\mathrm{i}\Gamma_{\rm t})\right]$$

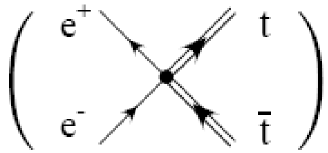
- accounts for irreducible interference contributions:

  resonant ↔ non-resonant $W^+W^-b\bar{b}$ final states



NRQCD (unstable quarks)

Currents:

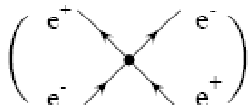
$$\mathbf{O_p} = \left[C^{\rm LL} + C^{\rm NLL} + C^{\rm NNLL} + iC^{\rm NNLL}_{\rm abs} \cdots \right] \cdot$$ 

$$+ \cdots$$

$$\sigma_{\rm tot} \propto \mathrm{Im}\left[\mathrm{C}(\nu)^2\, \mathrm{G}(0,0,\sqrt{\mathrm{s}}+\mathrm{i}\Gamma_{\rm t})\right]$$

$\mathcal{O}(v^3) \sim \mathcal{O}(\alpha_s^3)$

- $(\Delta\sigma^{\Gamma}_{\rm tot}) \sim \alpha_s \Gamma_t \frac{1}{\epsilon}$ ⇒ NNLL logarithmic phase space UV divergences

→ NLL anom. dim. for $(e^+e^-)(e^+e^-)$ operator → $iC(\nu) \cdot$ 

✓

→ matching for $iC(\nu)$:

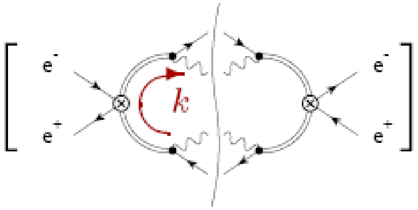
- physical $W^+W^-b\bar{b}$ phase space → "Phase Space Matching" w.i.p.

Phase Space Matching

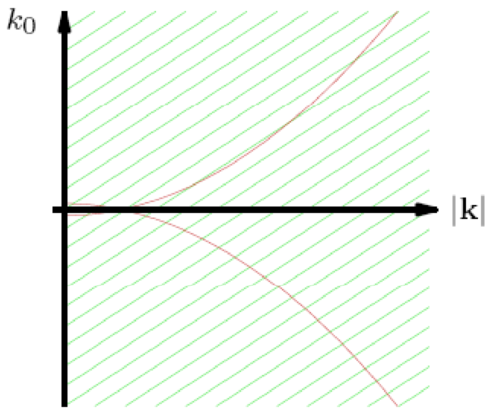
Reisser, Ruiz-Femenia, AH **w.i.p.**

- required for $\sigma_{\rm tot}$ from optical theorem in EFT
- finite imaginary matching conditions for <u>all</u> EFT operators

  $\rightarrow$ removal of unphysical EFT phase space contributions (violate unitarity)

$\sigma_{\rm tot} \sim$ 

$$\int_{-\infty}^{+\infty} dk_0 \int_0^{+\infty} d|\mathbf{k}| \, \frac{|\mathbf{k}|^2\, \Gamma_t^2}{|k_0 - \frac{\mathbf{k}^2}{2m_t^2} + i\Gamma_t|^2 \, |-k_0 - \frac{\mathbf{k}^2}{2m_t^2} + i\Gamma_t|^2}$$



Phase Space Matching

Reisser, Ruiz-Femenia, AH **w.i.p.**

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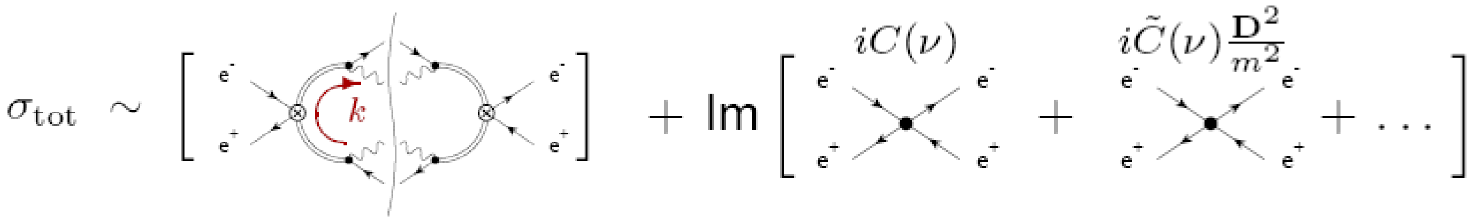

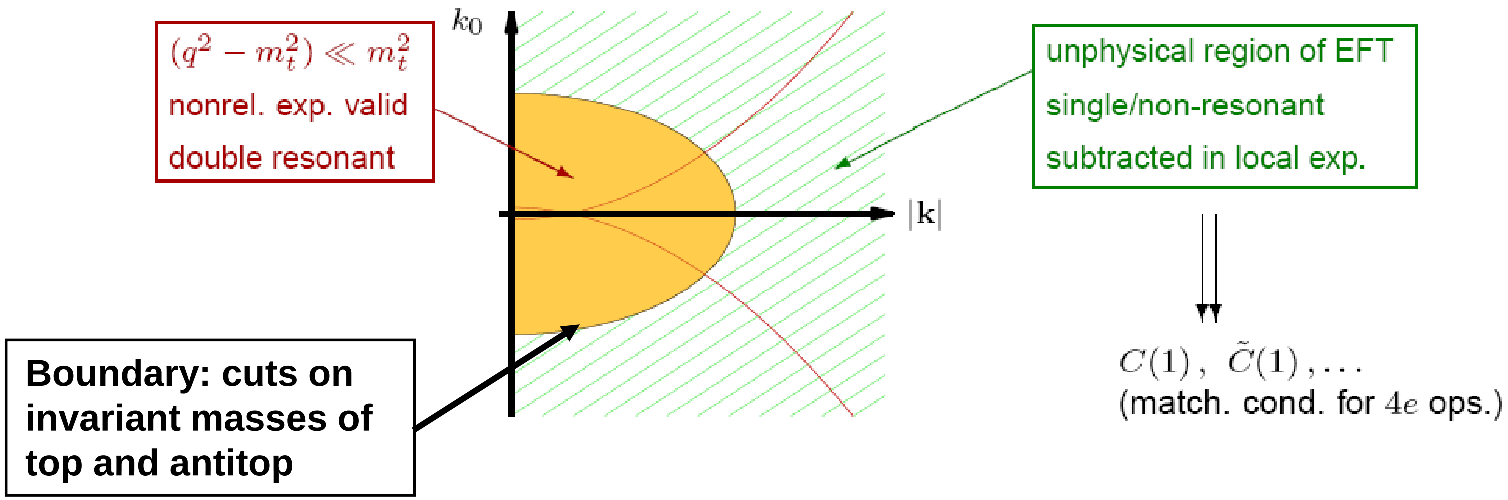

Phase Space Matching

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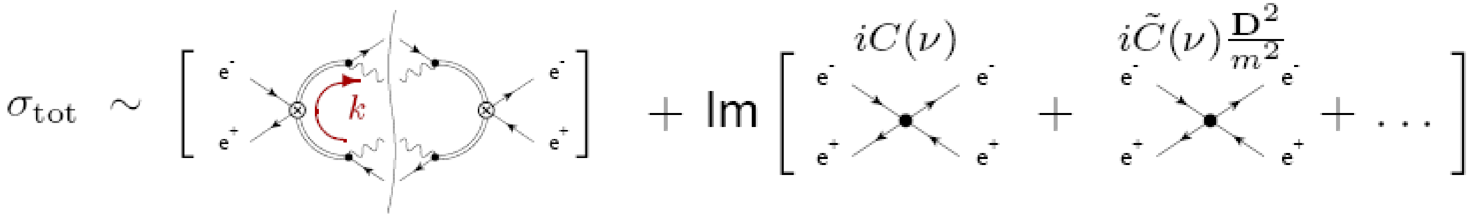
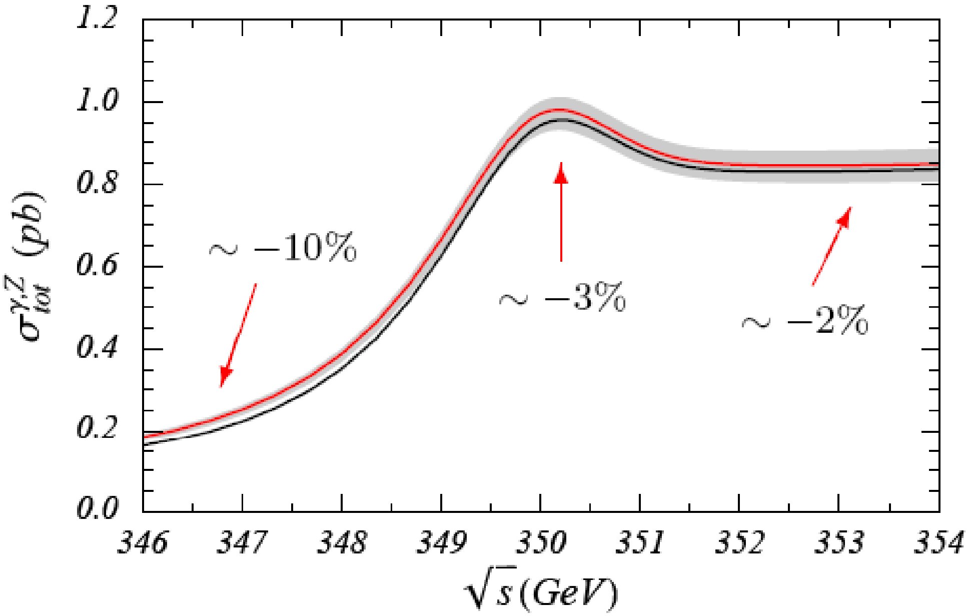


- "mild" powercounting breaking through use of momentum cuts
- mandatory for consistent predictions for P-, D-, etc. wave production (e.g. squark pairs) even at LO

Current work:

- phase space matching at NLL and NNLL for S-wave production (NNLL insertions + ultrasoft gluon effects)
- P- and higher partial waves

Effect for Total Cross Section



Reisser, AHH **'05**

- phase space logs & time-dilatation corrections
- finite lifetime corrections comparable to NNLL QCD corrections
- shift in the peak position: $30 - 50$ MeV $\quad (\delta m_t^{ex} \approx 50$ MeV)

Conclusions & Outlook

- Status for total cross section (with invariant mass cuts):
  - LL (QCD+ew): ok
  - NLL (QCD): ok
  - NLL (ew): completed soon (affect line-shape)
  - NNLL (QCD): ok, except for prod. current (abolutely crucial for coupling measurements) dom. ultrasoft contributions completed soon
  - NNLL (ew): partially known, could be relevant in the off-shell region below Q=2m

  - LO (QCD+ew): ok
  - NLO (QCD): ok
  - NNLO (QCD): ok
  - NNLO (QCD): completed soon

  Combination

- Total cross section depends on experimental selection cuts: formally a NLL effect. (But numerical size depends on cuts.)
- EW+finite lifetime effects generally small where cross section ist large, but important for the Q<2m tail region. (Could slightly affect mass determination. ⟷ Luminosity spectrum).
- More differential predictions are needed for more sophisticated selection cuts where additional theory input is required (e.g. contributions to distributions that cancel in the total cross section and are therefore usually neglected.

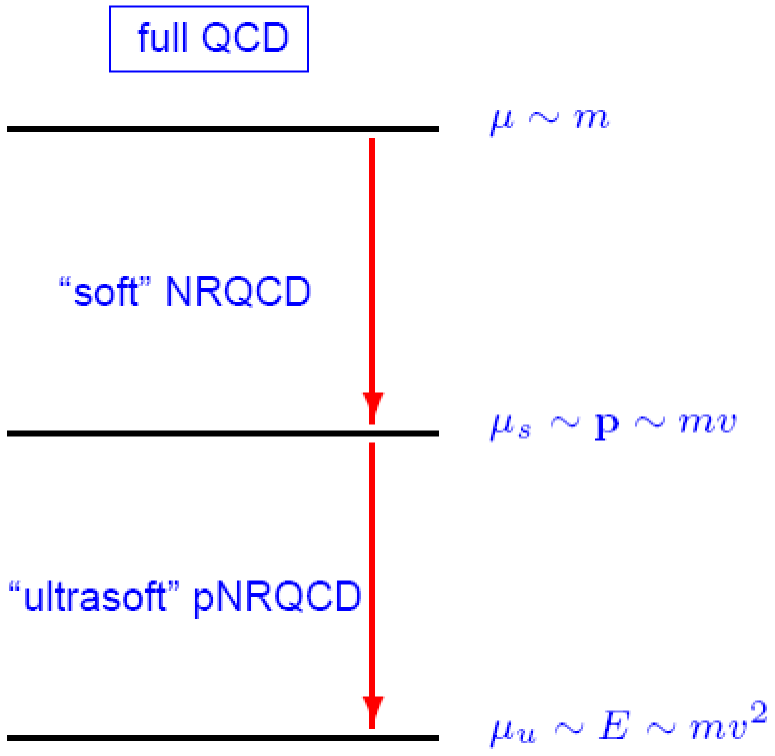
Backup Slides

Degrees of Freedom

pNRQCD:

$m_t \gg \mathbf{p} \gg E$

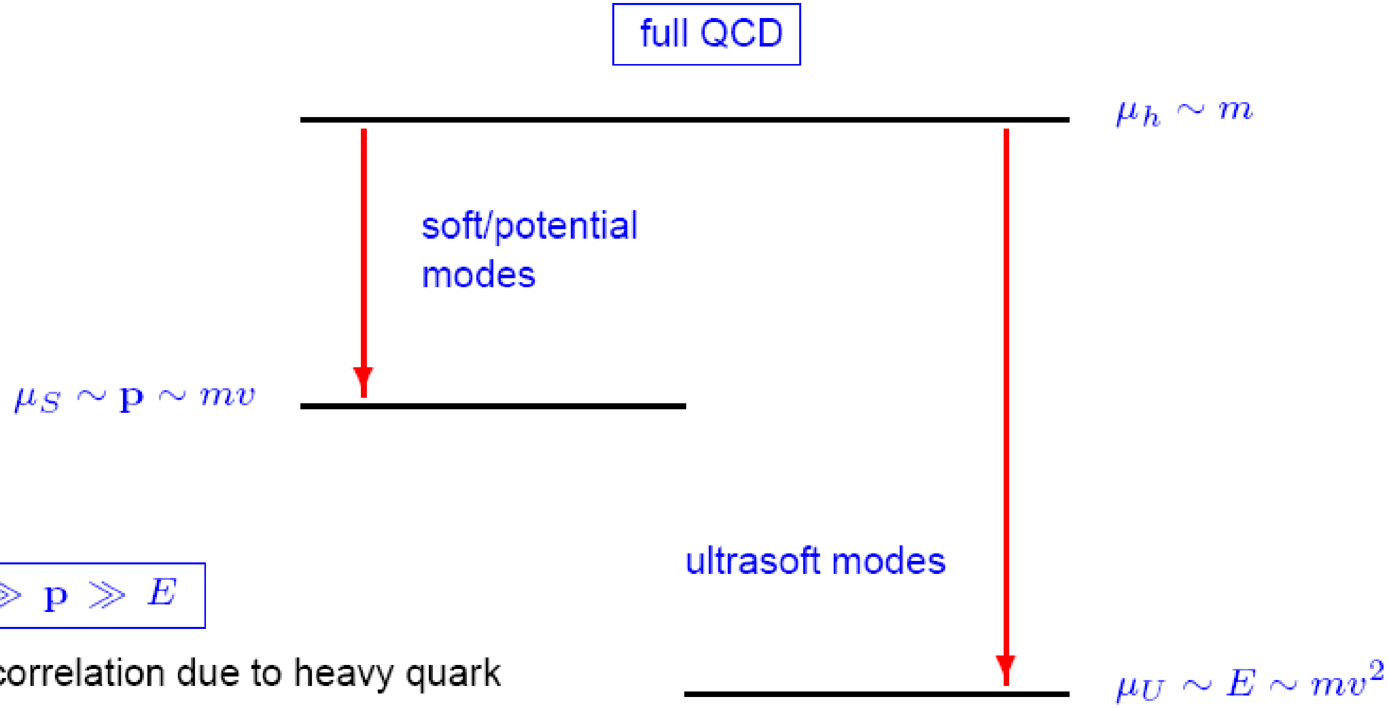
- sucessively integrated out d.o.f.'s
- sequence of effective theories
- soft matching scale (mv) and ultrasoft scale (mv^2) independent
- appropriate setup for static quarks
- top threshold:
  correlate $\mu_u = \mu_s^2/m$ by hand
  $\longrightarrow$ large logs for matching at μ_s



Pineda, Soto, Brambilla, Vairo

Degrees of Freedom

vNRQCD:



$m_t \gg \mathbf{p} \gg E$

and scale correlation due to heavy quark equation of motion: $E = \mathbf{p}^2/m$

Luke, Manohar, Rothstein, Stewart, A.H.

- soft and ultrasoft modes exist at the same time
- $\mu_U = \mu_S^2/m \quad \rightarrow \quad \mu_S = m\nu\,,\ \ \mu_U = m\nu^2$