Topics in Heavy Quark Physics

André H. Hoang

Project Review

Max-Planck-Institute for Physics

December 19-20, 2005

Group at the MPI

Postdocal researcher:

Pedro Ruiz-Femenia — chiral resonance theory; squark production at threshold

Doctoral students:

Cailin Farrell — $e^+e^- \to t\bar{t}H$ at the ILC
Christoph Reisser — unstable nonrelativistic particles
Maximilian Stahlhofen — NNLL renormalization of NRQCD

Diploma students:

Michael Fickinger — e^+e^- dijet event shapes in SCET
Alexander Laschka

Humboldt awardee: (March - August 2005)

Prof. Aneesh Manohar (UC San Diego)

charm mass determination from $B \to X_c l\nu$
V_{ub} determ. from $B \to X_u l\nu$ and $B \to X_s\gamma$

Group at the MPI

Postdocal researcher:

Pedro Ruiz-Femenia — chiral resonance theory; squark production at threshold

Doctoral students:

Cailin Farrell
Christoph Reisser
Maximilian Stahlhofen

$e^+e^- \to t\bar{t}H$ at the ILC
unstable nonrelativistic particles
NNLL renormalization of NRQCD

Threshold Physics

Diploma students:

Michael Fickinger
Alexander Laschka

e^+e^- dijet event shapes in SCET

Humboldt awardee: (March - August 2005)

Prof. Aneesh Manohar (UC San Diego)

charm mass determination from $B \to X_c l\nu$
V_{ub} determ. from $B \to X_u l\nu$ and $B \to X_s\gamma$

Threshold Physics: Outline

- Threshold Physics at the ILC
- Top Pair Threshold
- Effective Theory: stable top quarks
- Effective Theory: unstable top quarks
- Other Applications:
  - $e^+e^- \to t\bar{t}H$
  - $e^+e^- \to \tilde{q}\bar{\tilde{q}}$

Top Physics and the ILC

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

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

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

Top Physics and the ILC

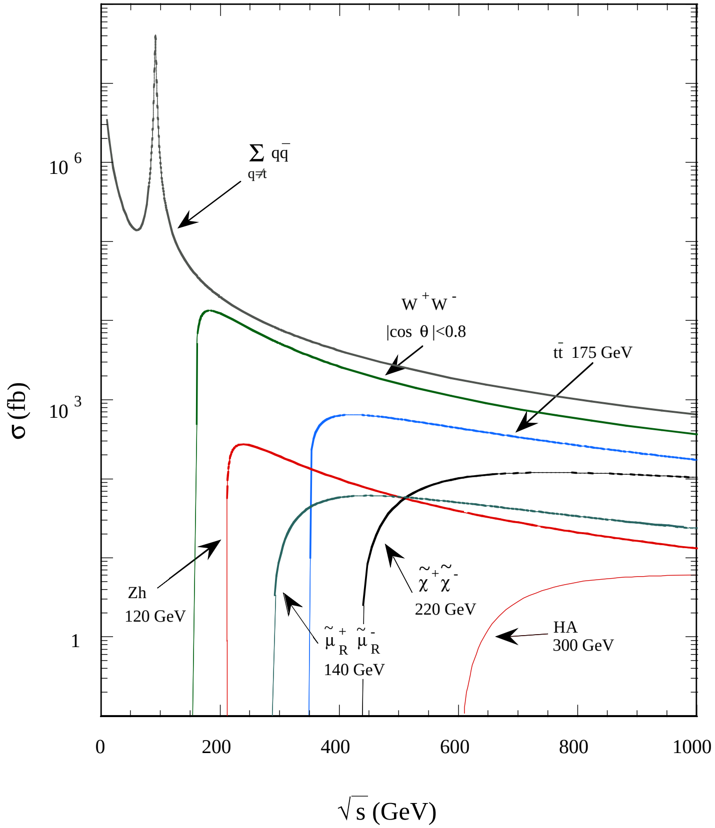
- e^+e^- collider: $E_{\rm cm} = 350$ GeV – 1 TeV
- Luminosity: 10^{34}–$10^{35}\,{\rm cm}^{-2}{\rm s}^{-1}$ $\rightarrow$ 100–$1000\,{\rm fb}^{-1}$/year

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

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

- Initial state tunable and very well known
  - Centre of mass energy variable

    $\rightarrow$ threshold & continuum



Top Physics and the ILC

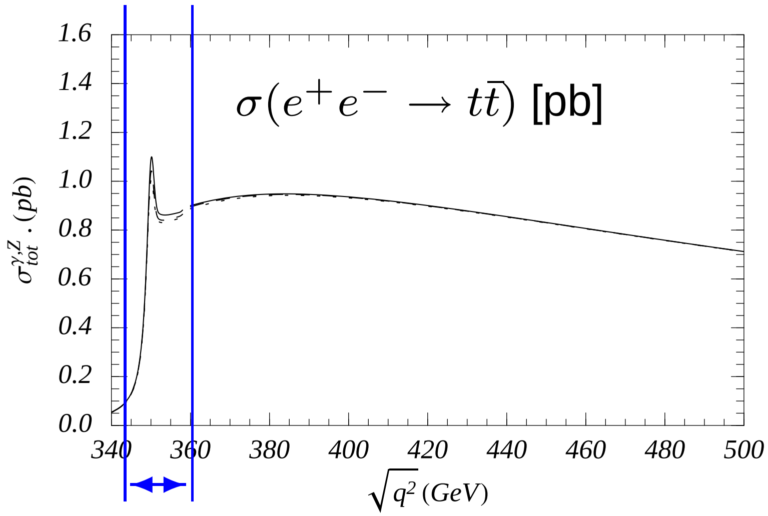
- e^+e^- collider: $E_{\rm cm} = 350$ GeV – 1 TeV
- Luminosity: 10^{34}–$10^{35}\,{\rm cm}^{-2}{\rm s}^{-1} \rightarrow 100$–$1000\,{\rm fb}^{-1}$/year

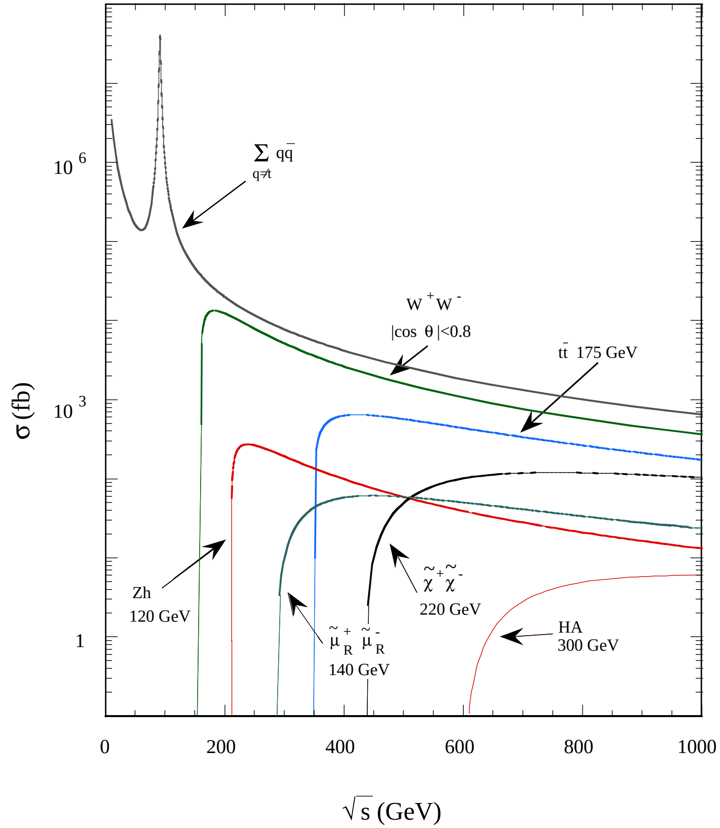
  LC $\sim 10^5$ $t\bar{t}$ pairs $[\sigma_{\rm tot} < 1\,{\rm pb}]$ $(e^+e^- \rightarrow t\bar{t})$

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

- Initial state tunable and very well known
  - Centre of mass energy variable

    $\rightarrow$ threshold & continuum

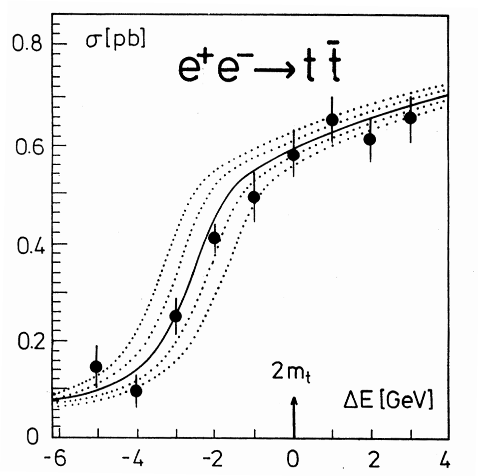




Threshold Measurements

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)



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

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

What mass?

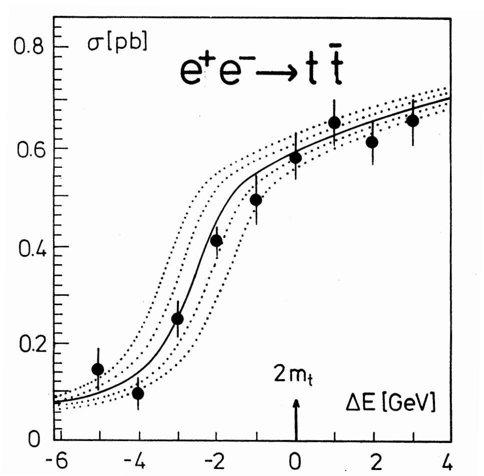
$\sqrt{s}_{\rm rise} \sim 2 m_t^{\rm thr} +$ pert.series

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

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)



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

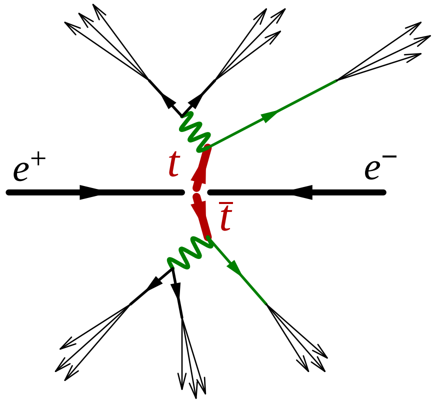
$\longrightarrow \delta m_t^{\rm th} \simeq 100$ MeV

What mass?

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

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

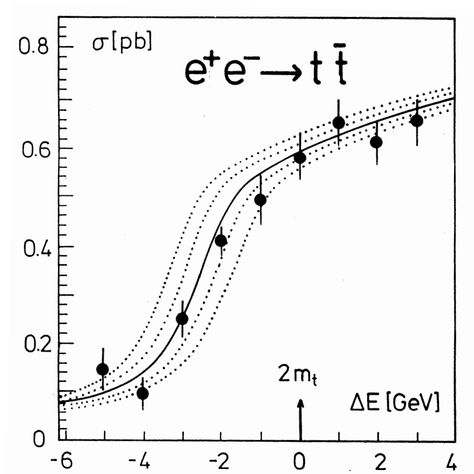
Reconstruction: any $\sqrt{s}$ (LHC & ILC)



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?

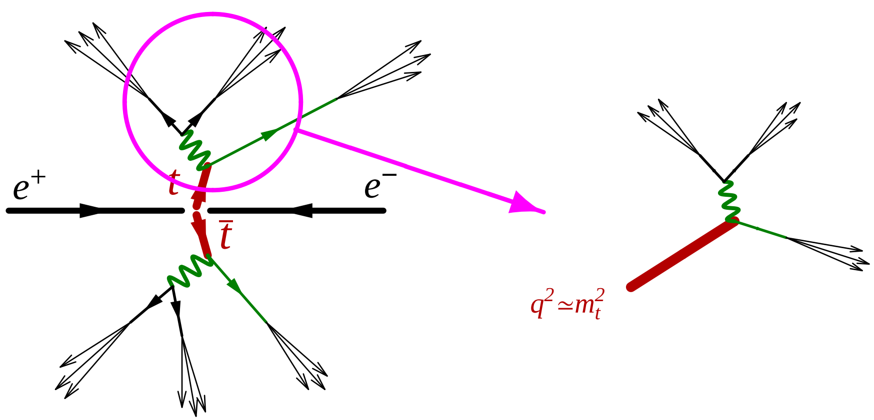
$\sqrt{s}_{\rm rise} \sim 2m_t^{\rm thr}$ + pert.series

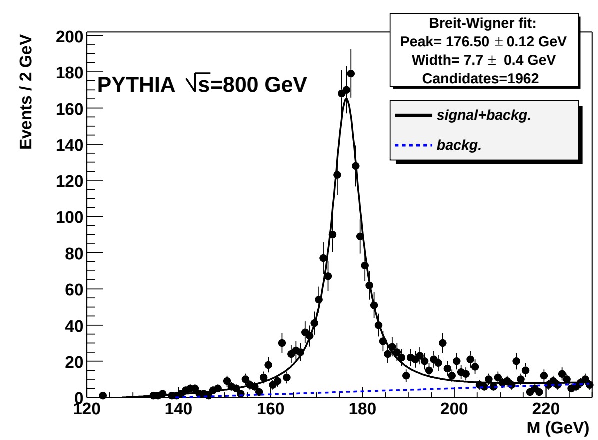
(short distance mass: 1S $\leftrightarrow$ $\overline{\rm MS}$)

Reconstruction: any $\sqrt{s}$ (LHC & ILC)

$\rightarrow \delta m_{t,\rm ILC}^{\rm ex,stat} \simeq 100$ MeV

$\rightarrow \delta m_{t,\rm IHC}^{\rm ex,stat} \simeq 1.5$ GeV

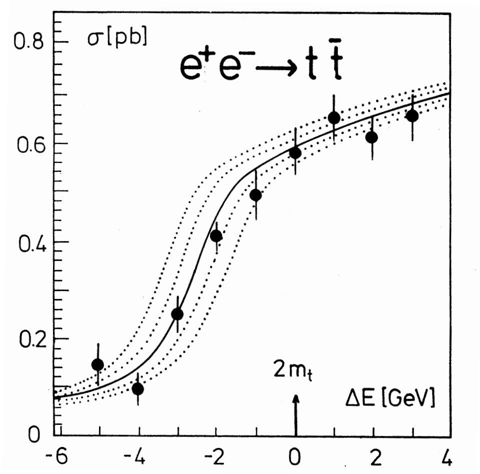




Threshold Measurements

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)



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

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

What mass?

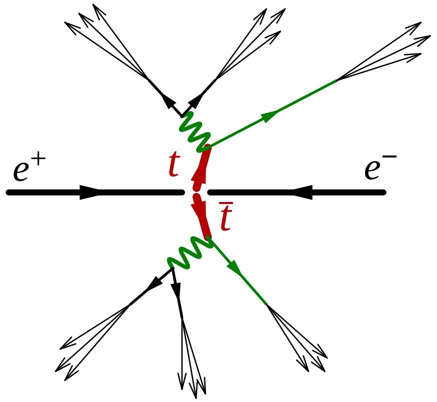
$\sqrt{s}_{\rm rise} \sim 2m_t^{\rm thr} +$ pert.series

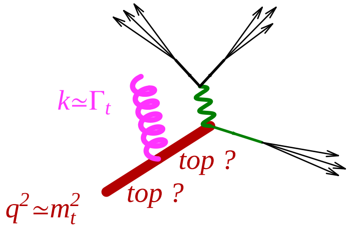
(short distance mass: 1S $\leftrightarrow$ $\overline{\rm MS}$)

Reconstruction: any $\sqrt{s}$ (LHC & ILC)

$\to \delta m_{t,\rm ILC}^{\rm ex,stat} \simeq 100$ MeV

$\to \delta m_{t,\rm IHC}^{\rm ex,stat} \simeq 1.5$ GeV





What mass?

Pole Mass ?

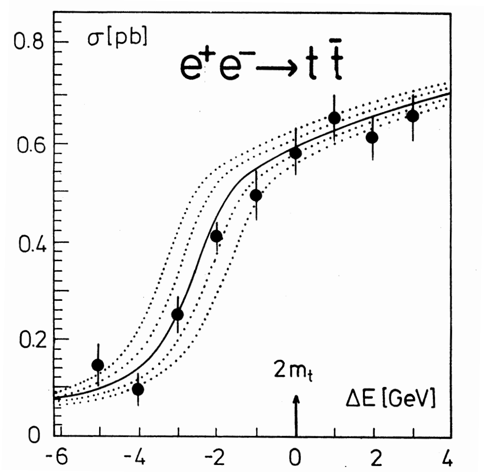
ambiguity: $\Delta m_t \sim \Lambda_{\rm QCD}$

$\Delta m_t \sim \alpha_s(\Gamma_t)\,\Gamma_t$

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)



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

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

What mass?

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

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

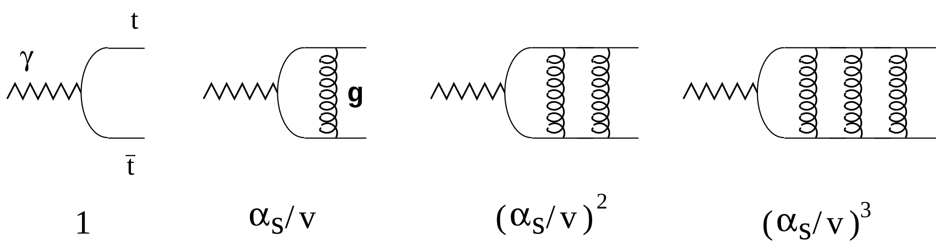
Simulations $\Longrightarrow$ theory goal: $(\delta\sigma/\sigma)^{\rm theo} \le 3\,\%$

$(\delta m_t)^{\rm stat} \sim 20$ MeV	$(\delta m_t)^{\rm syst} = 50$ MeV	$(\delta m_t)^{\rm theo} = 100$ 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 ! $\rightarrow$ “Schrödinger theory”

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

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

  - theoretical computations
  - experimental analysis

“theory for unstable particles”

Degrees of Freedom

proper picture:

full QCD

$\mu_h \sim m$

$\mu_S \sim \mathbf{p} \sim mv$

soft/potential modes

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

and scale correlation due to heavy quark

equation of motion: $E = \mathbf{p}^2/m$

ultrasoft modes

$\mu_U \sim E \sim mv^2$

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

Degrees of Freedom

proper picture:

full QCD

$\mu_h \sim m$

$\mu_S \sim \mathbf{p} \sim mv$ soft/potential modes

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

and scale correlation due to heavy quark

equation of motion: $E = \mathbf{p}^2/m$

ultrasoft modes $\mu_U \sim E \sim mv^2$

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

Degrees of Freedom

proper picture:

full QCD

$\mu_h \sim m$

$\mu_S \sim \mathbf{p} \sim mv$ soft/potential modes

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

ultrasoft modes $\mu_U \sim E \sim mv^2$

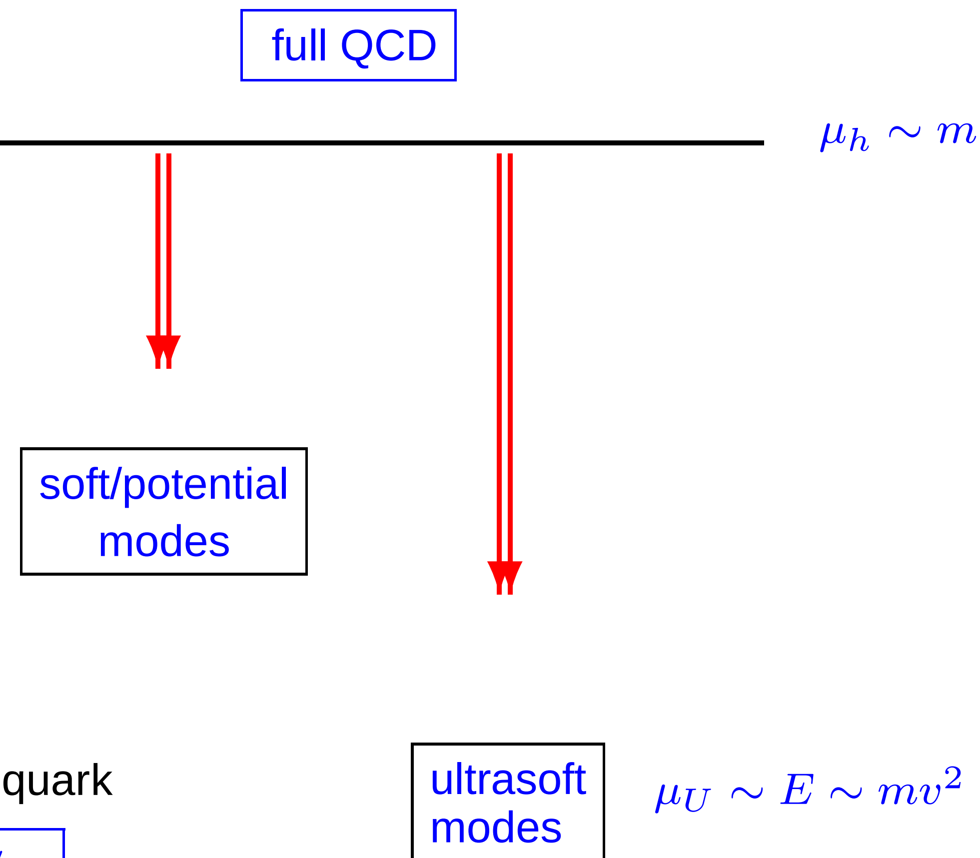
and scale correlation due to heavy quark

equation of motion: $E = \mathbf{p}^2/m$

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

Degrees of Freedom

proper picture:



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

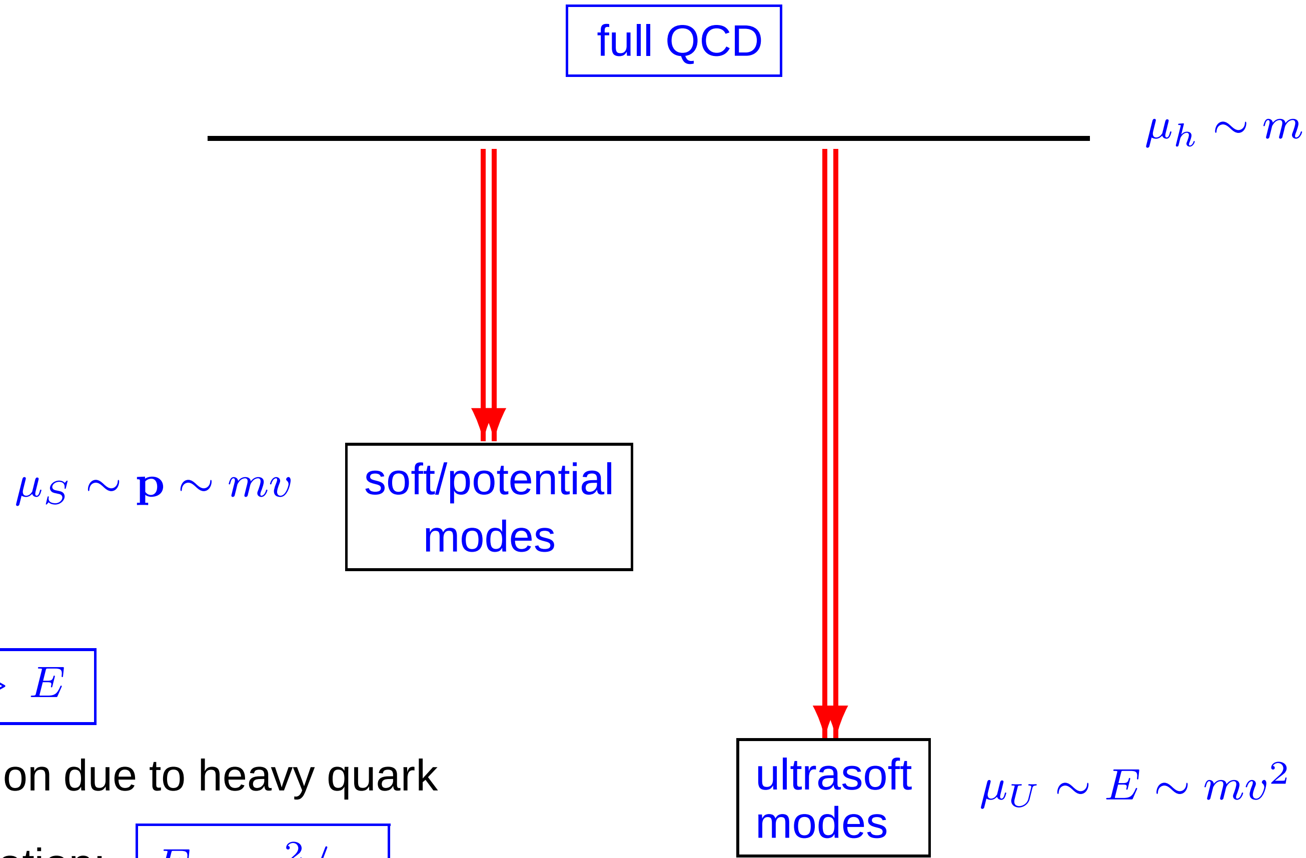
and scale correlation due to heavy quark

equation of motion: $E = \mathbf{p}^2/m$

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

Degrees of Freedom

proper picture:



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

and scale correlation due to heavy quark

equation of motion: $E = \mathbf{p}^2/m$

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

Degrees of Freedom

- fields for degrees of freedom that can resonate for the quark-antiquark system

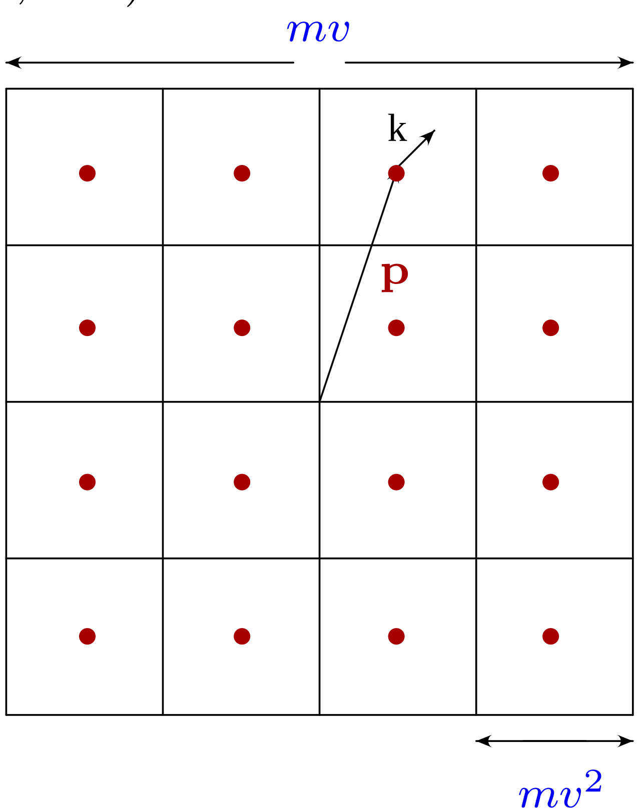
potential quarks	ψ_p, χ_p:	$(k_0, \mathbf{k}) \sim (mv^2, mv)$
soft gluons	$A_q{}^{\mu}$:	$(k_0, \mathbf{k}) \sim (mv, mv)$
ultrasoft gluons	A^{μ}:	$(k_0, \mathbf{k}) \sim (mv^2, mv^2)$

- vNRQCD label formalism:

$$(P^0, \mathbf{P}) = (0, \mathbf{p}) + (k^0, \mathbf{k})$$

soft component label — ultrasoft component dynamic variable

$$\psi_{\rm QCD}(x) \to \sum_{\mathbf{p}} e^{i\mathbf{p}.\mathbf{x}}\, \psi_{\mathbf{p}}(x)$$



vNRQCD (stable quarks)

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

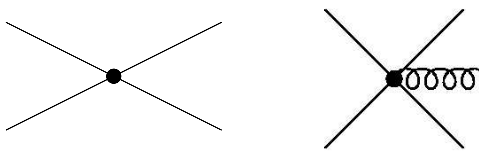
Luke, Manohar, Rothstein, Stewart, A.H.

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

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

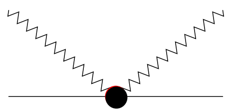
$$\psi_{\mathbf{p}}^\dagger(x)\left\{iD^0 - \frac{(\mathbf{p}-i\mathbf{D})^2}{2m_t} - \delta m_t\right\}\psi_{\mathbf{p}}(x)$$

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



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

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



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

$$V = \left[\frac{\mathcal{V}_c(\nu)}{\mathbf{k}^2} + \frac{\mathcal{V}_k(\nu)\pi^2}{m|\mathbf{k}|} + \frac{\mathcal{V}_r(\nu)(\mathbf{p}^2+\mathbf{p}'^2)}{2m^2\mathbf{k}^2} + \frac{\mathcal{V}_2(\nu)}{m^2} + \frac{\mathcal{V}_s(\nu)}{m^2}\mathbf{S}^2 + \frac{\mathcal{V}_\Lambda(\nu)}{m^2}\Lambda + \frac{\mathcal{V}_t(\nu)}{m^2}T\right]$$

$$\mathbf{k} \equiv \mathbf{p} - \mathbf{p}'$$

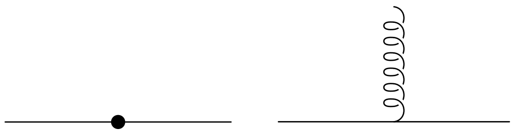
vNRQCD (stable quarks)

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

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

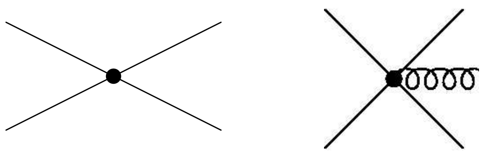
$$D^\mu = \partial^\mu + i\mu_U^\epsilon g_s(m\nu^2)A^\mu$$

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



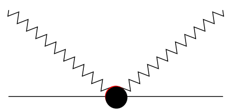
$$\psi_{\mathbf{p}}^\dagger(x)\left\{iD^0 - \frac{(\mathbf{p}-i\mathbf{D})^2}{2m_t} - \delta m_t\right\}\psi_{\mathbf{p}}(x)$$

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



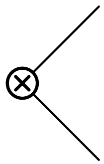
$$\mu_S^{2\epsilon}\,V(\nu)\,\psi_{\mathbf{p}'}^\dagger\psi_{\mathbf{p}}\chi_{-\mathbf{p}'}^\dagger\chi_{-\mathbf{p}}$$

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



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

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



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

Cross Section at NNLL Order

Schematic:

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

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

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

Cross Section at NNLL Order

Schematic:

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

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

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

fully known
at NNLL order ✓

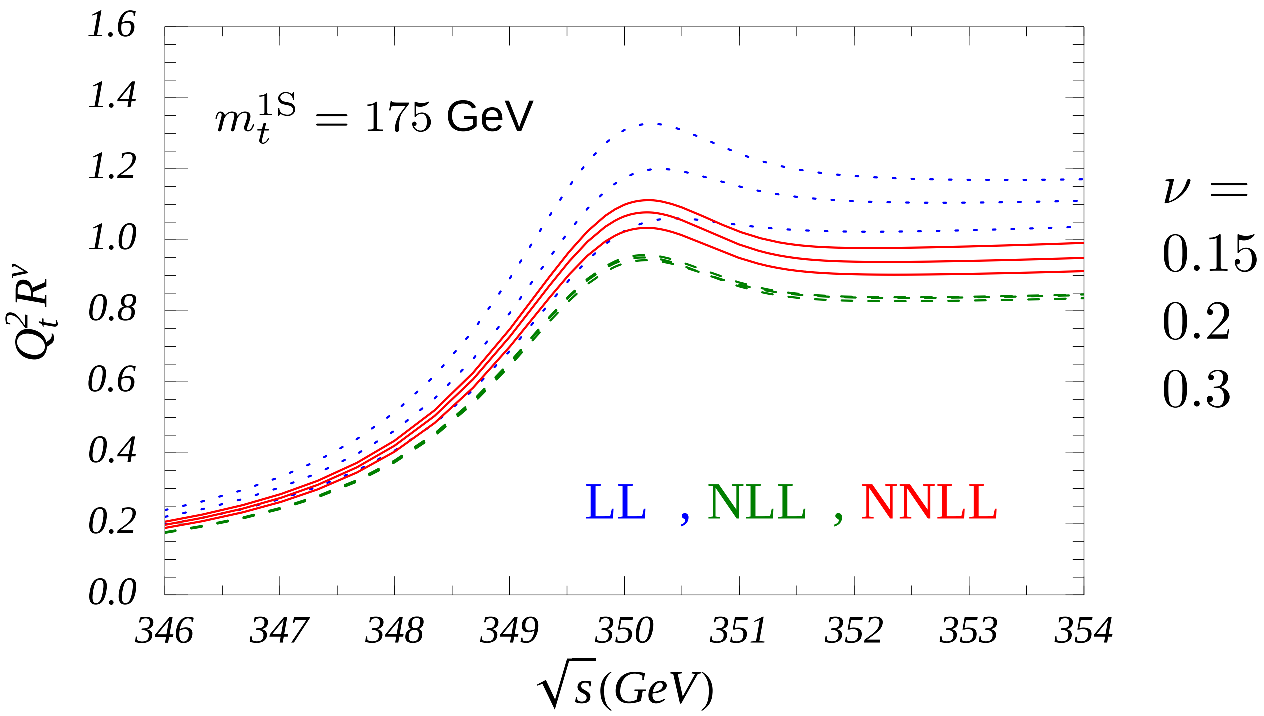
NLL ✓
NNLL (non-mixing) ✓
NNLL (mixing) unknown

Manohar,Stewart; AHH ’99-’03
Pineda,Soto ’00-’01

Cross Section at NNLL Order

AHH 2003

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



- very good stability of peak position
- theory error: $\delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}} \sim \pm 6\%$

$\longrightarrow$ full NNLL (mixing) evolution of $C(\nu)$ required

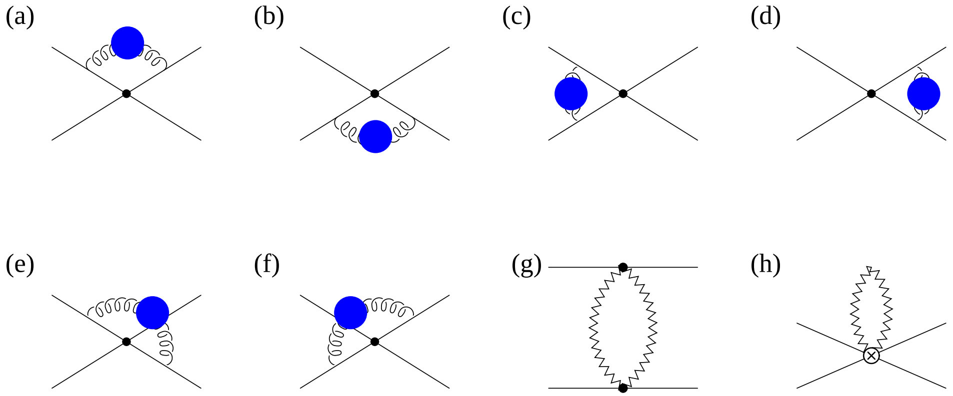
Cross Section at NNLL Order

NNLL running of $C(\nu)$

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

status: “ultrasoft n_f corrections” Maxi Stahlhofen

NLL ultrasoft n_f running of $V_{1/m^2}(\nu)$



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

vNRQCD (unstable quarks)

"inclusive treatment"

$\Rightarrow$ Optical Theory: effective complex indices of refraction for absorptive processes

$\Rightarrow$ vNRQCD: contributions from real Wb final states included in EFT matching conditions to QCD+ew. theory (=SM)

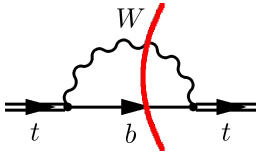
- complex matching conditions
- effective Lagrangian non-hermitian
- total rates through the optical theorem

Christoph Reisser, AH; Phys. Rev. D 71, 074022 (2005)

vNRQCD (unstable quarks)

time dilatation correction

quark bilinears:

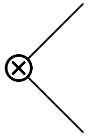


$$iD^0 - \frac{\mathbf{p}^2}{2m_t} + \delta m_t \quad\Longrightarrow\quad iD^0 - \frac{\mathbf{p}^2}{2m_t} + \delta m_t + i\frac{\Gamma_t}{2}\left(1 - \frac{\mathbf{p}^2}{2m_t^2}\right)$$

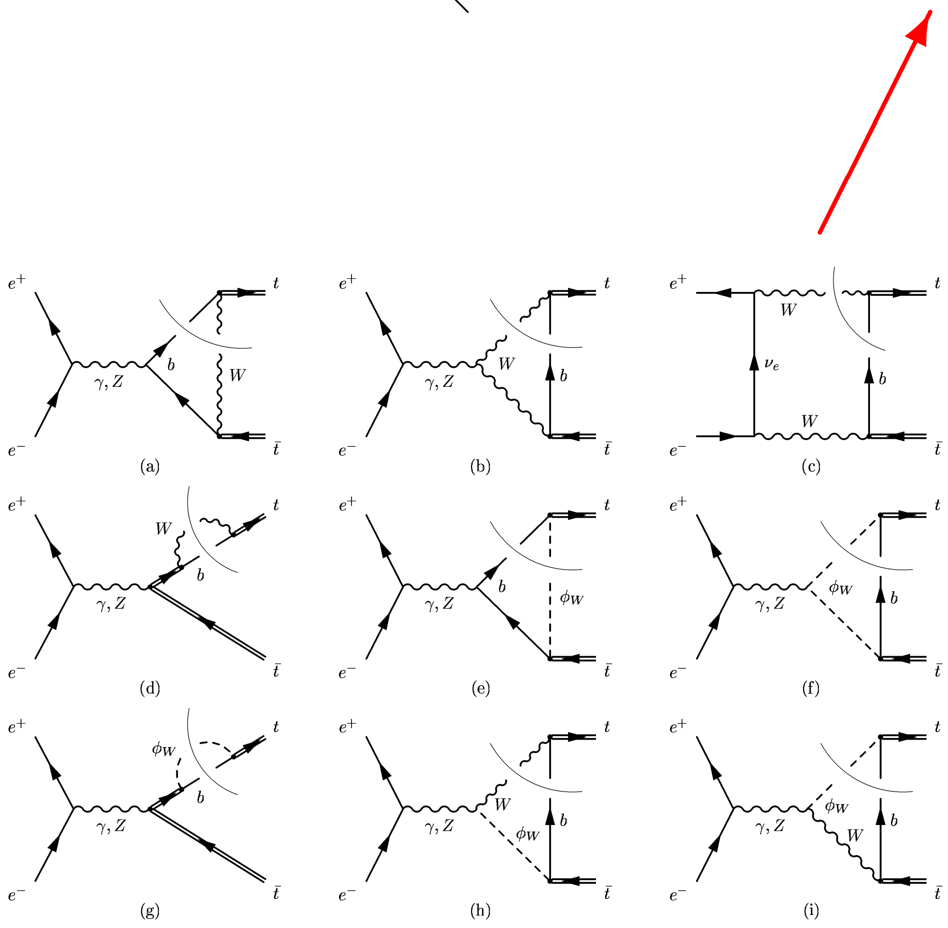
- power counting: $\Gamma_t \propto m_t g^2 \sim m_t v^2 \quad \Rightarrow \quad \boxed{g \sim g' \sim v \sim \alpha_s}$ $\rightarrow$ gauge invariance

vNRQCD (unstable quarks)

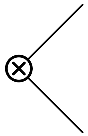
<u>external currents:</u>



$$= (C_{\rm real}(\nu) + iC_{\rm abs}(\nu)) \cdot (\psi_{\mathbf p}^\dagger \, \boldsymbol\sigma \, \tilde\chi^*_{-\mathbf p})$$



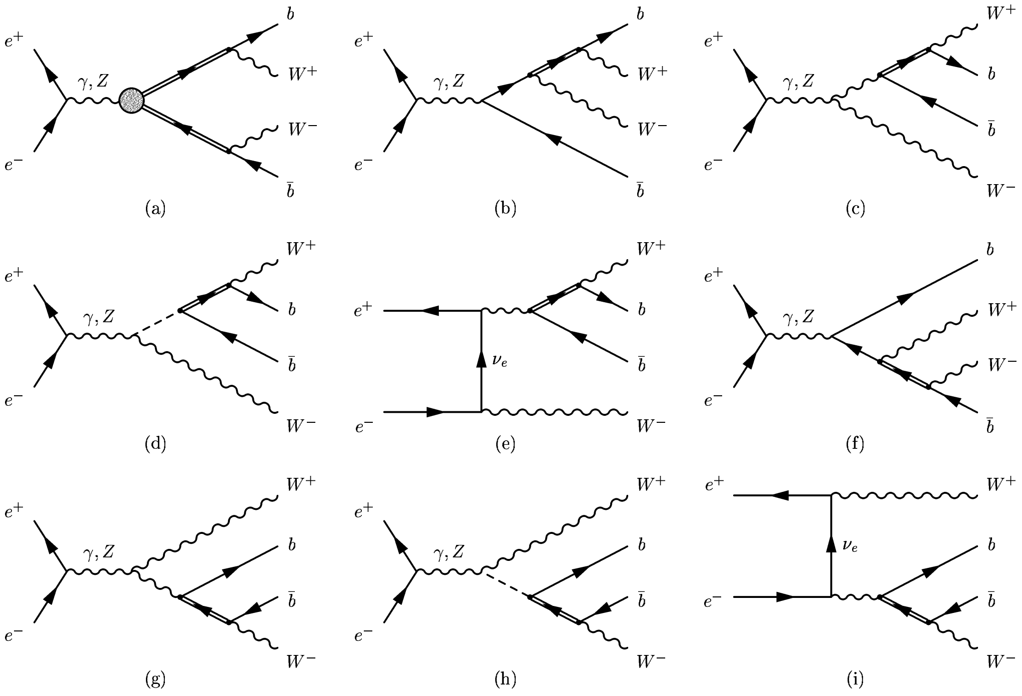
vNRQCD (unstable quarks)

external currents:  $= (C_{\rm real}(\nu) + iC_{\rm abs}(\nu)) \cdot (\psi_{\mathbf{p}}^\dagger \, \boldsymbol{\sigma} \, \tilde{\chi}^*_{-\mathbf{p}})$

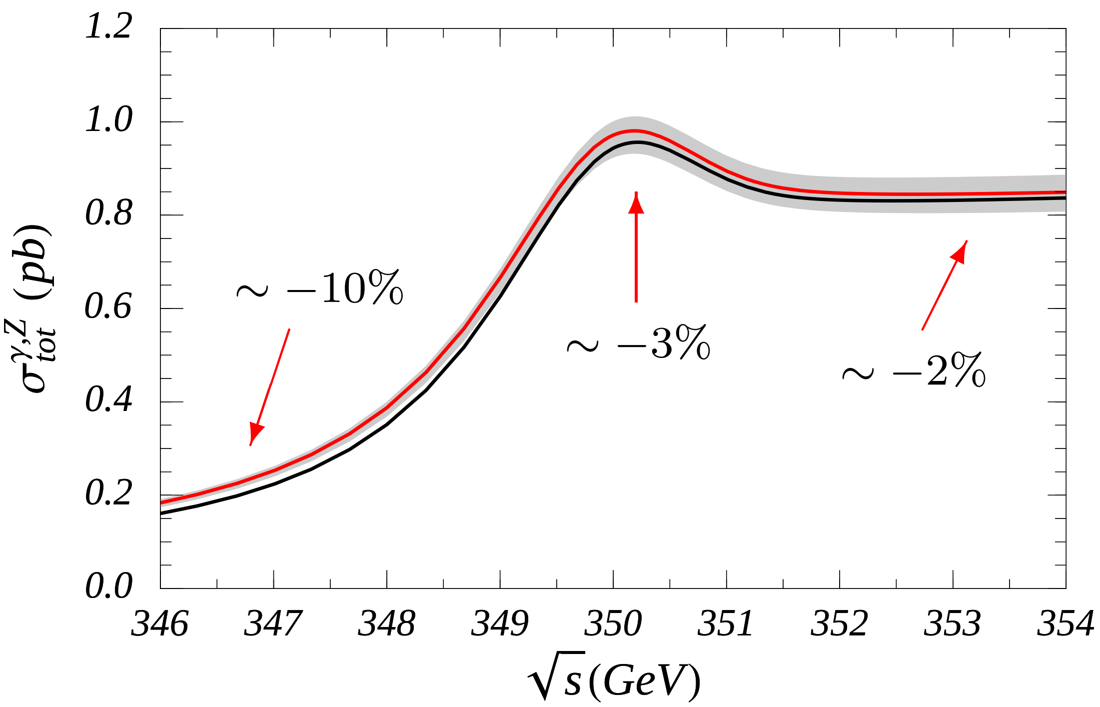
cross section: $\sigma_{\rm tot} \propto \text{Im}[\, C^2(\nu)\, G(0,0,\sqrt{s}+i\Gamma_t)\,]$

- accounts for irreducible interference terms

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



Total Cross Section

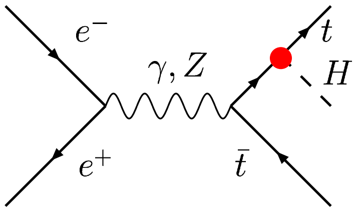


C. Reisser, AH

- corrections comparable to NNLL QCD corrections
- shift in the peak position: $30 - 50$ MeV ($\delta m_t^{\rm ex} \approx 50$ MeV)

Other Applications

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



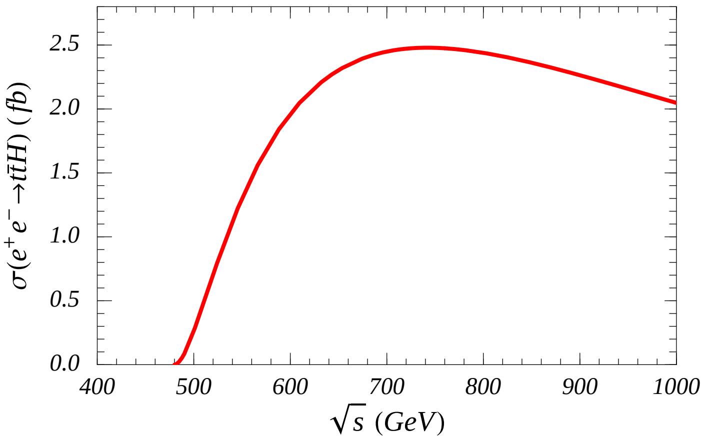
- Theory Status: $\sigma(e^+e^- \to t\bar{t}H)$

  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 ✓ [Cailin Farrell, AHH]

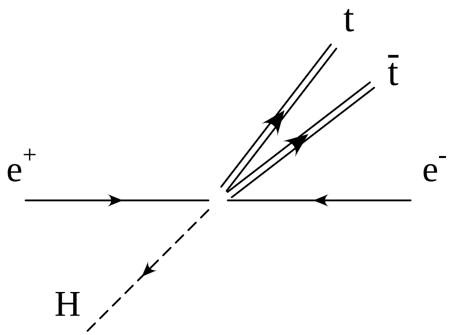


- tiny cross section for $\sqrt{s} = 500$ GeV
- measurement of Yukawa coupling difficult

Other Applications

$e^+e^- \longrightarrow t\bar{t}H$

$\longrightarrow$ region of large Higgs energy



$\longrightarrow t\bar{t}$ collinear

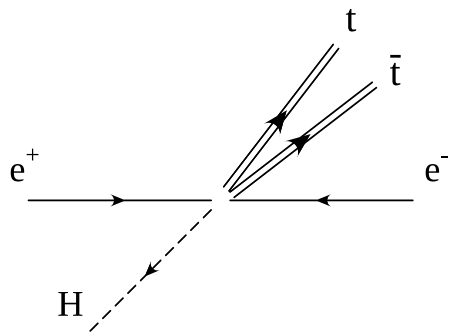
$\longrightarrow$ QCD effects localized in $t\bar{t}$ system

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

Other Applications

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

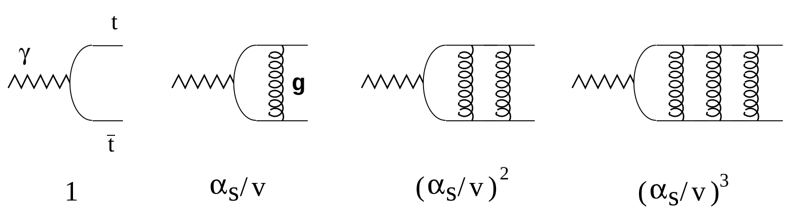
$\longrightarrow$ region of large Higgs energy

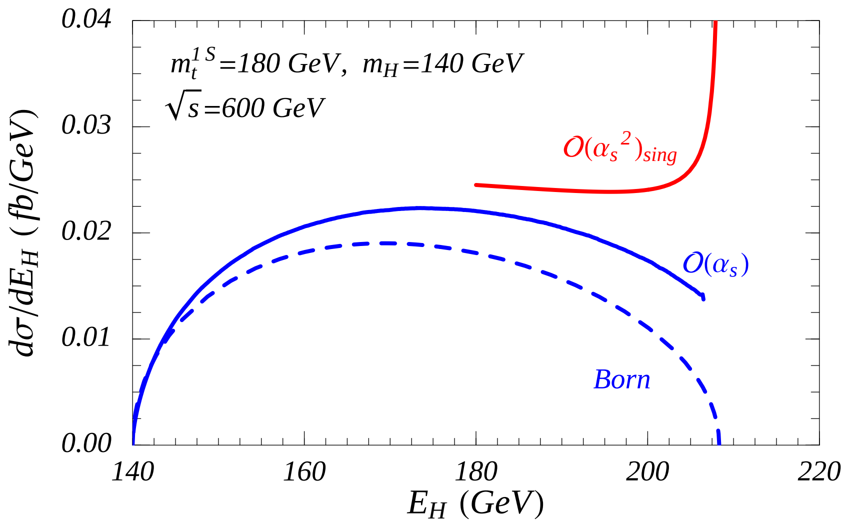


$\longrightarrow$ $t\bar{t}$ collinear

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

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





$\longrightarrow$ singularities: $\sim (\alpha_s/v)^n$,

$\sim (\alpha_s \ln v)^n$

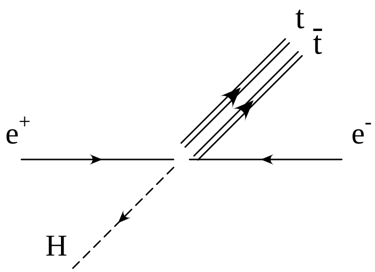
$\longrightarrow$ fixed order expansion breaks down

$\Rightarrow$ summation of singular terms

Other Applications

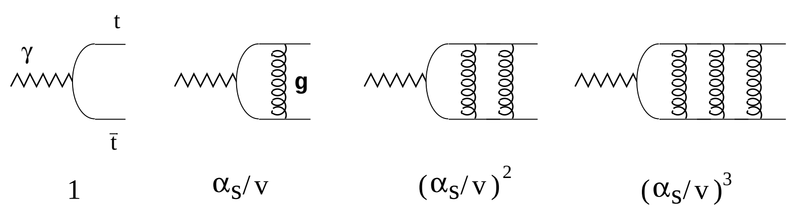
$e^+e^- \longrightarrow t\bar{t}H$ $\longrightarrow$ factorization formula

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



$+$ hard QCD corrections

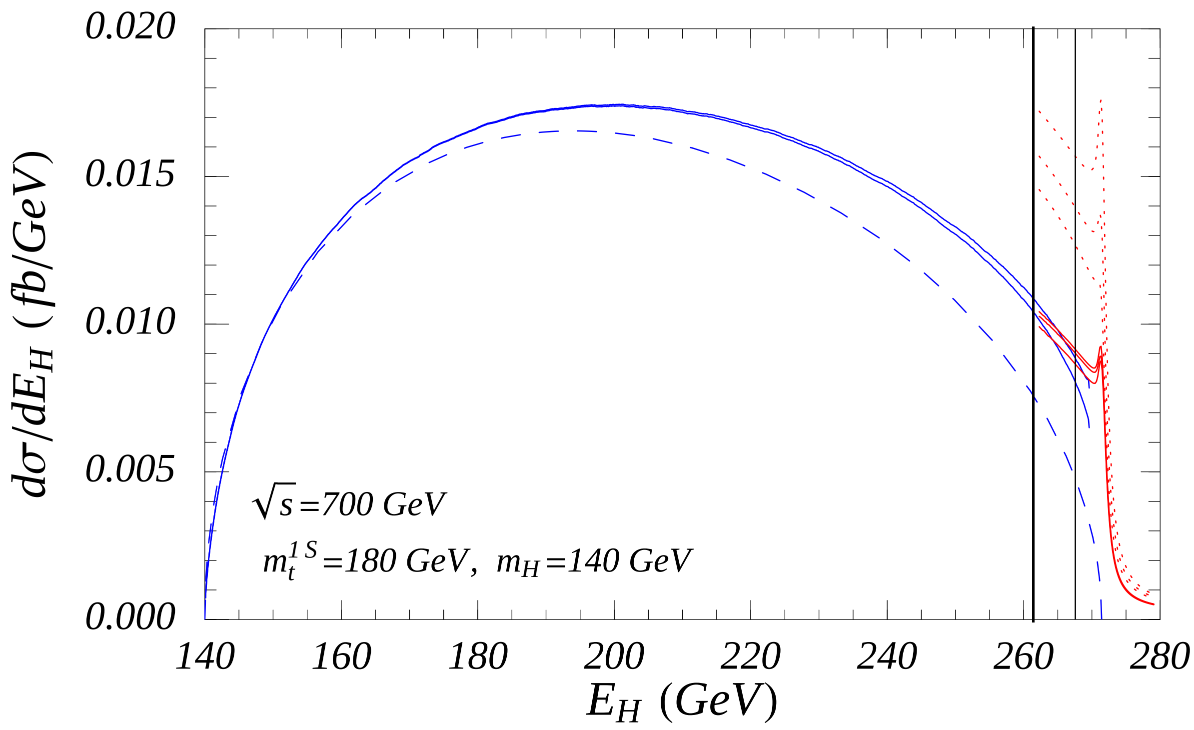
soft & ultrasoft QCD corrections



NLL formalism: Cailin Farrell, AHH; Phys.Rev.D72,014007 (2005)

Other Applications

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

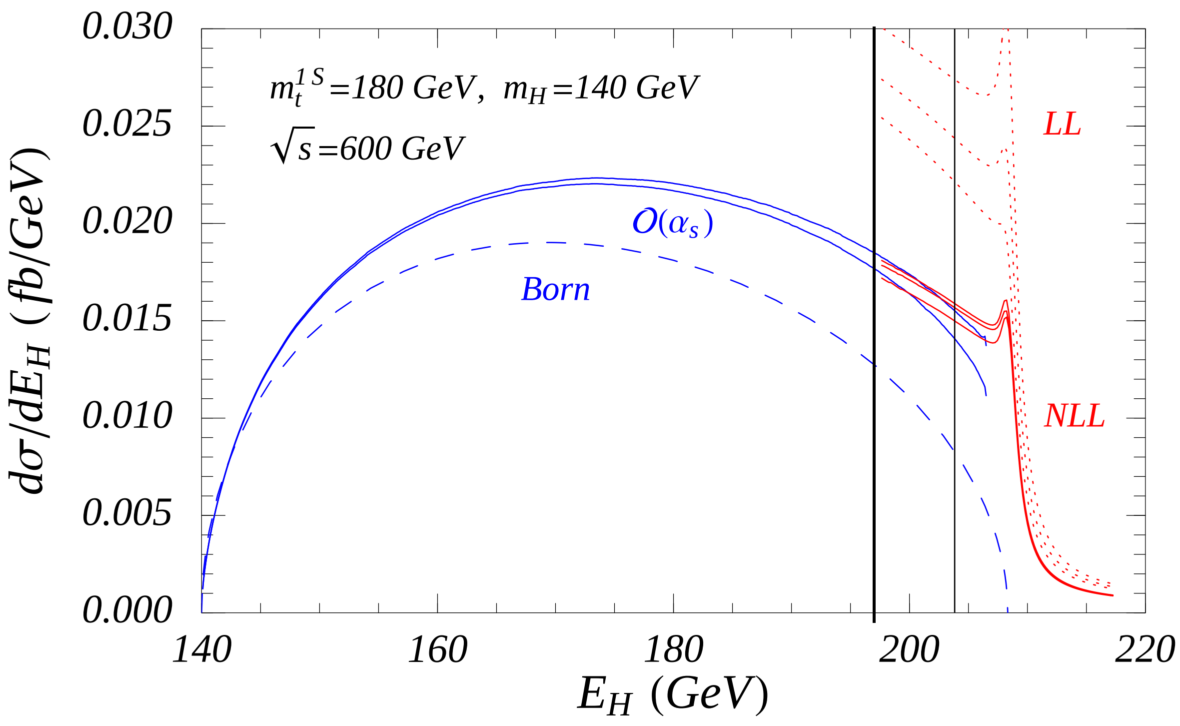


Farrell, AHH

- large E_H endpoint regions increases for smaller $\sqrt{s}$ / larger m_H

Other Applications

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

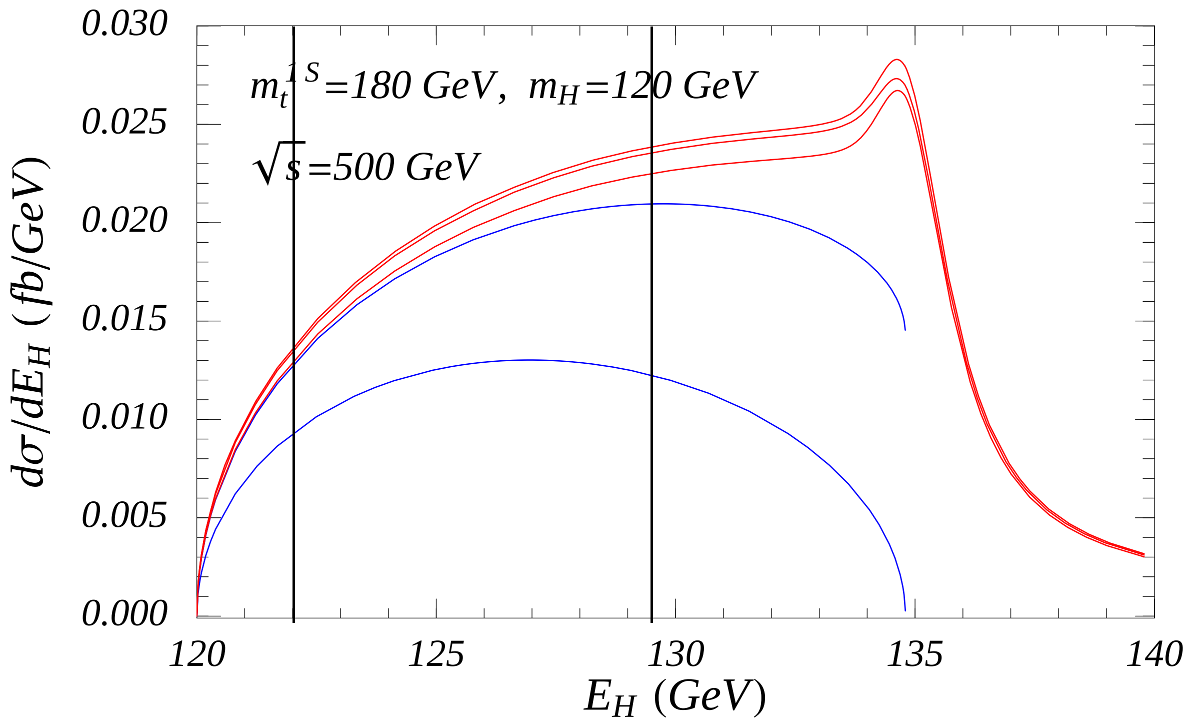


Farrell, AHH

- large E_H endpoint regions increases for smaller $\sqrt{s}$ / larger m_H

Other Applications

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

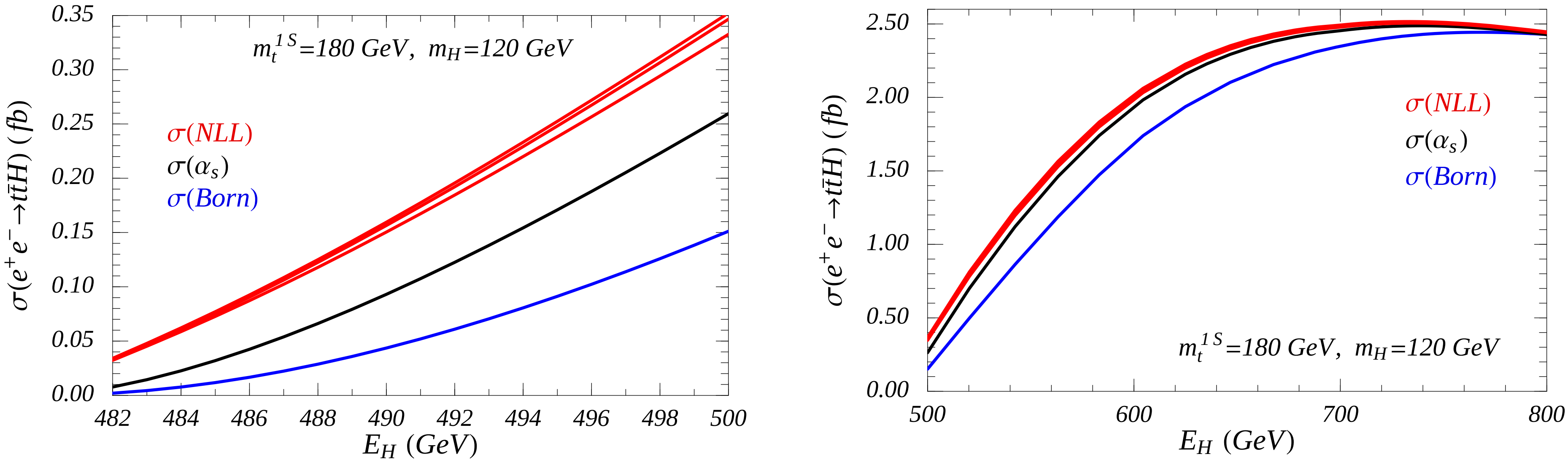


Farrell, AHH

- large E_H endpoint regions increases for smaller $\sqrt{s}$ / larger m_H

Other Applications

$e^+e^- \to t\bar{t}H$ $\to$ total cross section



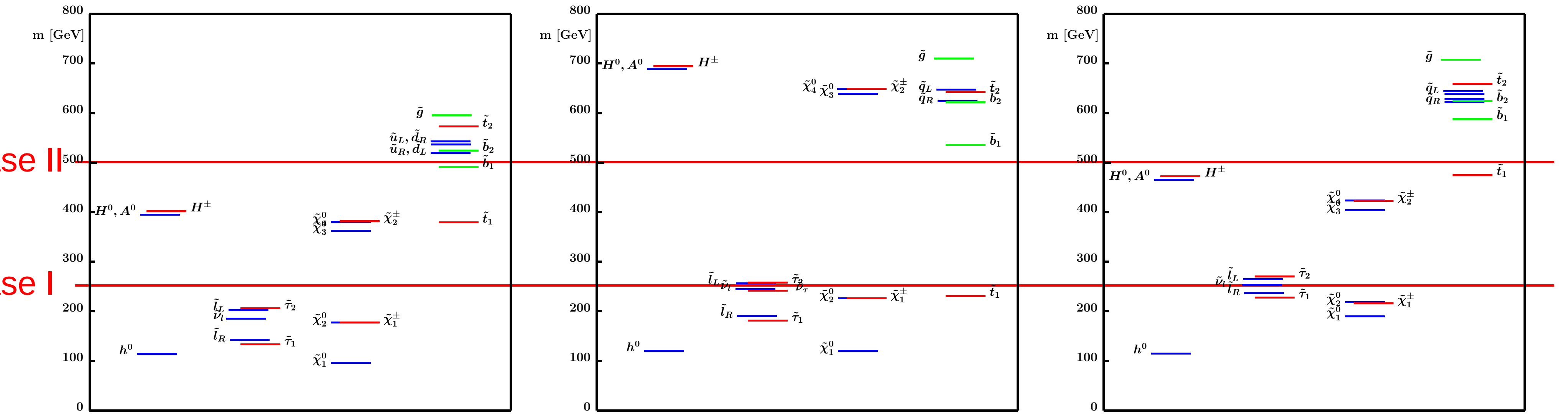
- significant enhancement from summation of $(\alpha_s/v)^n$, $(\alpha_s \ln v)^n$ singularities
- essential for realistic studies for ILC (phase I)
- another factor of 2 enhancement for $P_- = -80\%$, $P_+ = +60\%$

Other Applications

$e^+e^- \to \tilde{q}\bar{\tilde{q}}$

- in many models for SUSY breaking squark pair production is possible at the ILC

SPS 1a SPS 5 SPS 6



SPS 1a	SPS 5	SPS 6
$m_{\tilde{t}_1} = 396$ GeV	$m_{\tilde{t}_1} = 240$ GeV	$m_{\tilde{t}_1} \simeq 490$ GeV
$\tilde{t}_1 \to b\chi_1^+, \ldots$	$\tilde{t}_1 \to b\chi_1^+, c\chi_1^0$	$\tilde{t}_1 \to b\chi_1^+, \ldots$
$\Gamma_{\tilde{t}_1} = 1.92$ GeV	$\Gamma_{\tilde{t}_1} = 0.04$ GeV	$\Gamma_{\tilde{t}_1} \simeq 3.2$ GeV

Other Applications

$e^+e^- \to \tilde{q}\bar{\tilde{q}}$ $\to$ scalar vNRQCD

squarks:

- no spin-dependent interactions
- P-wave production
- full NLL QCD running completed

Pedro Ruiz-Femenia, AHH [hep-ph/0511102]

$$V = \left[\frac{\mathcal{V}_c(\nu)}{\mathbf{k}^2} + \frac{\mathcal{V}_k(\nu)\pi^2}{m|\mathbf{k}|} + \frac{\mathcal{V}_r(\nu)(\mathbf{p}^2 + \mathbf{p}'^2)}{2m^2\mathbf{k}^2} + \frac{\mathcal{V}_2(\nu)}{m^2} \right]$$

$$\frac{d}{d\ln\nu} \ln C_{^1P_1}(\nu) = -\frac{\mathcal{V}_c(\nu)}{48\pi^2} \left(\frac{\mathcal{V}_c(\nu)}{4} + \mathcal{V}_2(\nu) + \mathcal{V}_r(\nu) \right) + \frac{\mathcal{V}_k(\nu)}{6}$$

$$C_{^1P_1}(\nu = 1) = 1 - \frac{4}{3} \frac{\alpha_s(m_t)}{\pi}$$

Conclusion

- Top pair total rate predictions become more and more realistic
  - full set of electroweak corrections (w.i.p)
  - full NNLL QCD corrections (w.i.p.) $\rightarrow d\sigma/\sigma \lesssim 3\%$
- reaching goals like $\delta m_t \sim 100$ MeV is no (totally) free lunch

  prospects are very good

  (all remaining problems appear controllable)
- Many interesting applications of threshold physics exist.

Colors

This is blue

This is red

This is brown

This is magenta

This is Dark Green

This is Dark Blue

This is Green

This is Cyan

Test how this color looks

Test how this color looks

Test how this color looks

Test how this color looks

Test how this color looks