Electroweak Effects in Boosted Top Jet Production

in collaboration with A. H. Hoang and M. Procura

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universität wien

$\int dk \Pi$ Doktoratskolleg Particles and Interactions

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Top quark mass determinations from $t\bar{t}$-production

- Top group @ Uni Wien: precision top mass determinations
- Top pair-production: precision studies at future linear colliders
  - Threshold scans -> *non-relativistic tops*
  - Direct reconstruction from top decay products -> *boosted tops*
- Usual tools:
  - Multipurpose Monte Carlo (MMC)
  - Perturbative fixed-order (FO)
- Our work: focus on analytic calculations in factorization approaches
  - Systematically improvable (order and/or expansion/logarithmic accuracy)
  - Controlled uncertainities
  - Analytic resummation of large logarithms

$$m_t^{\text{pole}} = 172.5 \pm 0.7\,\text{GeV} \quad \text{(cross section)}$$
$$m_t^{\text{MC}} = 172.76 \pm 0.30\,\text{GeV} \quad \text{(direct reconstruction)}$$

[PDG, 20]

$$\Delta m_t = 50\,\text{MeV} \quad \text{(threshold scan)}$$
$$\Delta m_t = 100\,\text{MeV} \quad \text{(direct reconstruction)}$$

Projected uncertainties for ILC500 [Zarnecki et al, 11]

- $t\bar{t}$ (stable): $\text{QCD}^{\text{NNLL}}_{\text{NNLO}} + \text{EW}_{\text{NLO}}$
  [Czakon et al, 16, 17, 18]
- $t\bar{t} \times$ top decay (NWA): $\text{QCD}_{\text{NNLO}} + \text{EW}_{\text{NLO}}$
  [Gao et al, 13, 17]
- $bW^+(\nu l^+)\bar{b}W^-(\bar{\nu} l^-)$: $\text{QCD}_{\text{NLO}} + \text{EW}_{\text{NLO}}$
  [Heinrich et al, 14] [Denner et al, 18]

Top physics group @ Uni Wien

Threshold
Boosted tops

supported by
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MC/Parton shower aspects


D. Samitz

- Shower effects in m_t^{MC} vs. m_t^{QFT}
- Soft and hadronization impact on m_t^{MC}
- Single-purpose MC for $e^+e^- \to t\bar{t}$


S. Plätzer


C. Regner

Top production at threshold


A. Widl

- Implementation of MSR mass scheme
- Improving interpolation between kinematic regimes


A.H. Hoang

Differential top


I. Ruffa

- Top decay-sensitive observables
- Unstable W
- Lepton spectra and (b-)jet observables
- QCD corrections in differential distributions

Electroweak effects

- Systematic inclusion of EW effects
- Coherent resummation of EW and QCD logs
- Finite-lifetime effects


M. Procura


D. Lechner

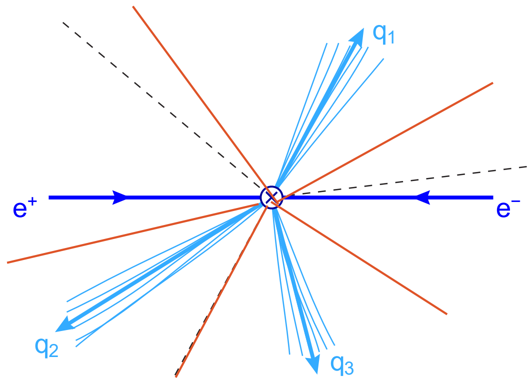
2-jettiness: a case study

- *N-jettiness τ_N* [Stewart et al, 10]
  - ➢ Field-theoretically well-defined
  - ➢ Simple, yet general in its IR-structure
  - ➢ Top mass-sensitive !

Jet directions (pre-determined)

Particle momenta

$$\tau_N \equiv \sum_k \min_i \frac{2q_i \cdot p_k}{Q_i}$$



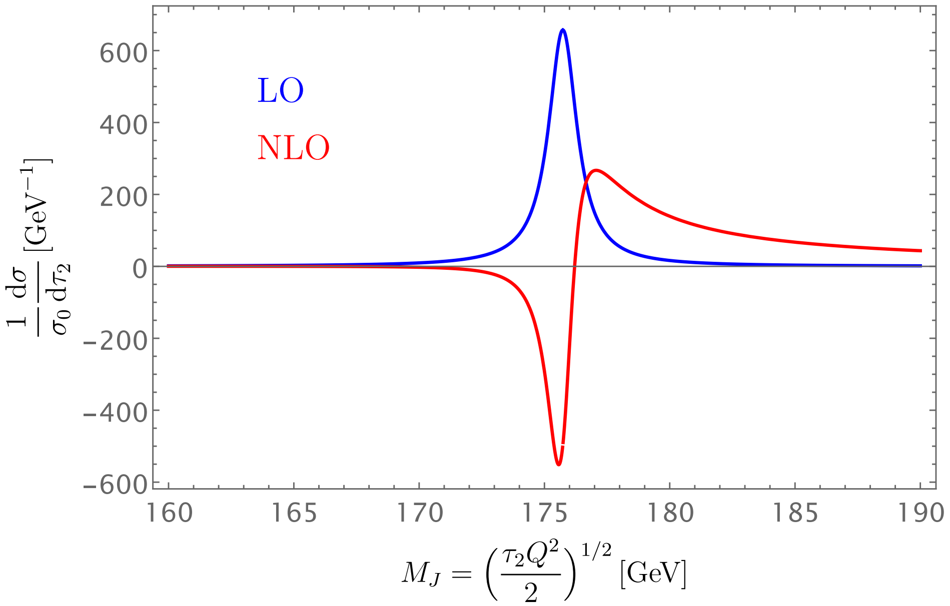
Jet sector boundaries without/with beam

- Important:
  - ➢ Treating EW (QED!) effects necessitates including the beam (jets)
  - ➢ Not very realistic concerning beam treatment
  - ➢ Important future direction: more differential observables!

- Tree-level: Breit-Wigner

$$\frac{1}{\sigma_0}\left(\frac{d\sigma}{d\tau_2}\right)^{(0)} = f_{\mathrm{BW}}\left(\tau_2 - \tau_{\min}, \frac{2\Gamma_t}{Q\varrho_t}\right)$$

$$\begin{aligned} Q &= \sqrt{\hat{s}} && \text{... CM energy} \\ \varrho_t &= Q/m_t && \text{... boost factor} \\ \beta_t &= \sqrt{1 - 4/\varrho_t} && \text{... quark velocity} \\ \tau_{\min} &= 1 - \beta_t && \text{... stable threshold} \end{aligned}$$



- Radiative corrections (QCD NLO and beyond) sizable

Radiative corrections to 2-jettiness for $t\bar{t}$ production

- Of interest: boosted jet regime: $E_{jet}^2 \gg p_{jet}^2 \sim m_t^2$, i.e. small τ_2
- Complex beyond LO because of multiple scales
- Due to scale separation, e.g. in the peak region

$$Q^2 \gg m_t^2 \gg Q^2\tau_2 - m_t^2 \gtrsim m_t\Gamma_t \gg \varrho_t^{-1} m_t\Gamma_t \gtrsim \Lambda_{\mathrm{QCD}}$$

scale	magnitude [GeV]
Q	1000
m_t	173
Γ_t	1.4
Λ_{QCD}	< 1

Top physics = multiscale problem

- Large QCD/QED logs: $\alpha_s^n \ln^k \tau_2$, $\alpha_{em}^n \ln^k \tau_2$
- (EW) Sudakov logs: $\alpha_s^n \ln^k Q/m_t$, $\alpha_w^n \ln^k Q/M_w$

$\Longrightarrow$ Resummation necessary

- Factorization properties of *N*-jettiness:

$$\hat{\tau}_2 = \hat{\tau}_c + \hat{\tau}_s + \mathcal{O}(\tau_2)$$

← Indicates power-suppressed/ non-singular terms

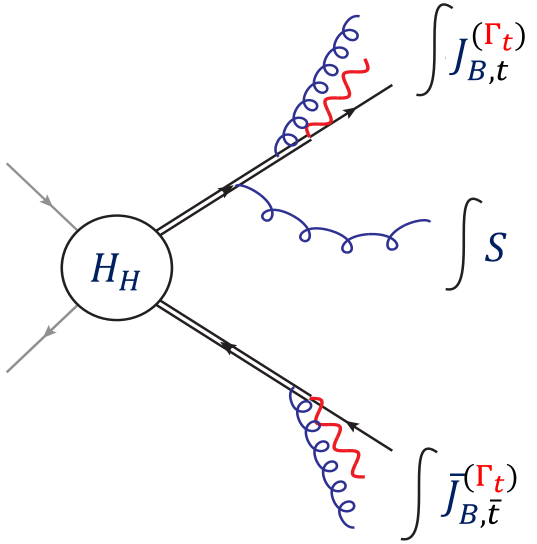
- Effective Field Theory (EFT) approach:
  - Soft-Collinear Effective Theory (SCET) [Stewart et al, 01]
  - boosted Heavy Quark Effective Theory (bHQET) [Fleming et al, 07]

Factorization for 2-jettiness in pure QCD

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau_2} = H_Q(Q,\mu) \times H_M(\varrho_t, m_t, \mu)$$

[Fleming et al, 07]

$$\times J_{B,t}^{(\Gamma_t)}(Q^2\tau_2, m_t, \mu) \otimes \bar{J}_{B,\bar{t}}^{(\Gamma_t)}(Q^2\tau_2, m_t, \mu) \otimes S(Q\tau_2, \mu) + \mathcal{O}\left(\lambda, \varrho_t^{-1}, \frac{\Gamma_t}{m_t}\right)$$



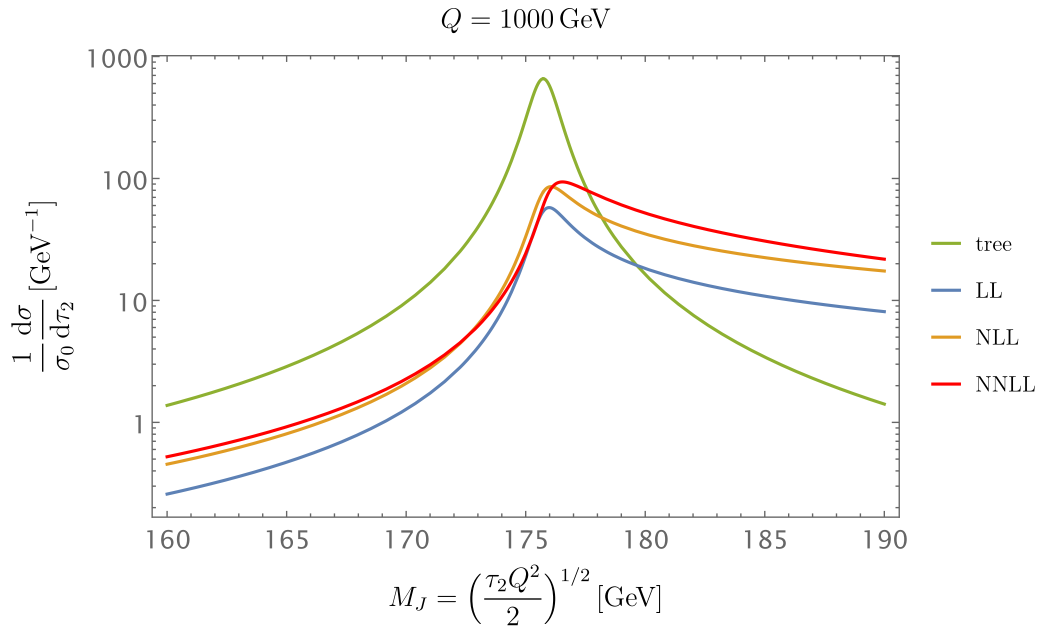
- Factorization ≡ product × or convolution ⊗
- EFTs provide the possibility to resum large logarithmic corrections by renormalization group evolution

$$\mu\frac{d}{d\mu}F(t,\mu) = \gamma_F(t,\mu)\,F(t,\mu)$$

$$\gamma_F(t,\mu) = \Gamma_{\text{cusp}}[\alpha_s]\,\ln(i\mu e^{\gamma_E}t) + \gamma[\alpha_s]$$

- Formalism can be extended to resum electroweak Sudakov logarithms consistently with QCD logs

[Chiu et al, 07, 08, 09]



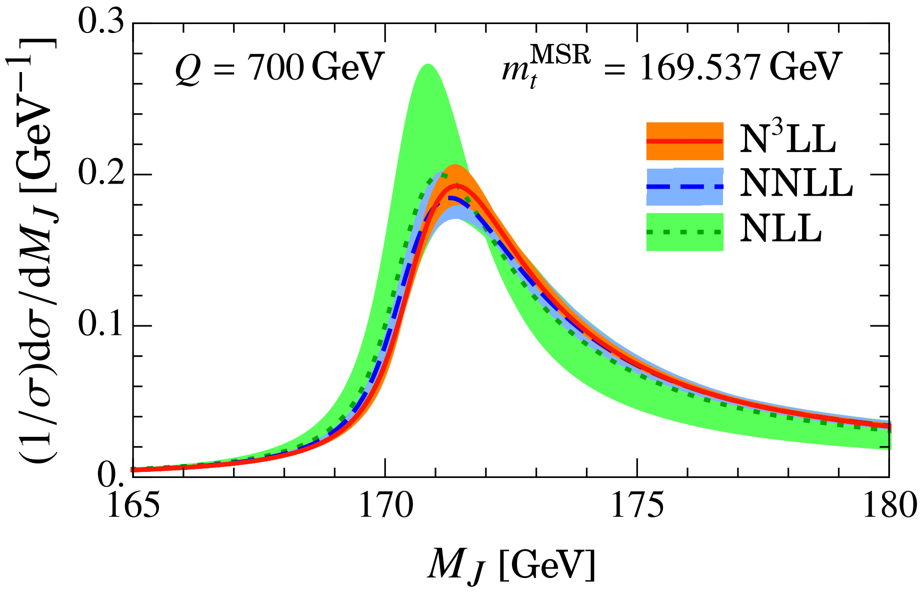
QCD state-of-the-art (peak region)

$$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau_2} = H_Q(Q,\mu) \times H_M(\varrho_t, m_t, \mu)$$
$$\times J_{B,t}^{(\Gamma_t)}(Q^2\tau_2, m_t, \mu) \otimes \bar{J}_{B,\bar{t}}^{(\Gamma_t)}(Q^2\tau_2, m_t, \mu) \otimes S(Q\tau_2, \mu) + \mathcal{O}\left(\lambda, \varrho_t^{-1}, \frac{\Gamma_t}{m_t}\right)$$

	$F(\mu_F)$	$\Gamma_{\text{cusp}}, \beta$	γ
LL	0	1	0
NLL	0	2	1
NLL'	1	2	1
N^2LL	1	3	2
N^3LL	2	4	3

Loop-orders of resummation ingredients

- State-of-the-art QCD:
  - NLL QCD + LO EW (width Γ_t in peak region) [Fleming et al, 07, 08]
  - 2-loop bHQET jet function [Stewart et al, 08]
  - 2-loop SCET-bHQET current matching [Pathak et al, 15]
  - N^3LL-study (peak region) [Hoang et al, 20]
  - 2-loop SCET massive jet function [Lepenik et al, 18]
- QCD field-theoretic subtleties:
  - Non-perturbative corrections, Renormalons
  - Top mass schemes (MSR mass)
  - …
- EW only LO so far
- Extend formalism: systematically incorporate subleading EW effects



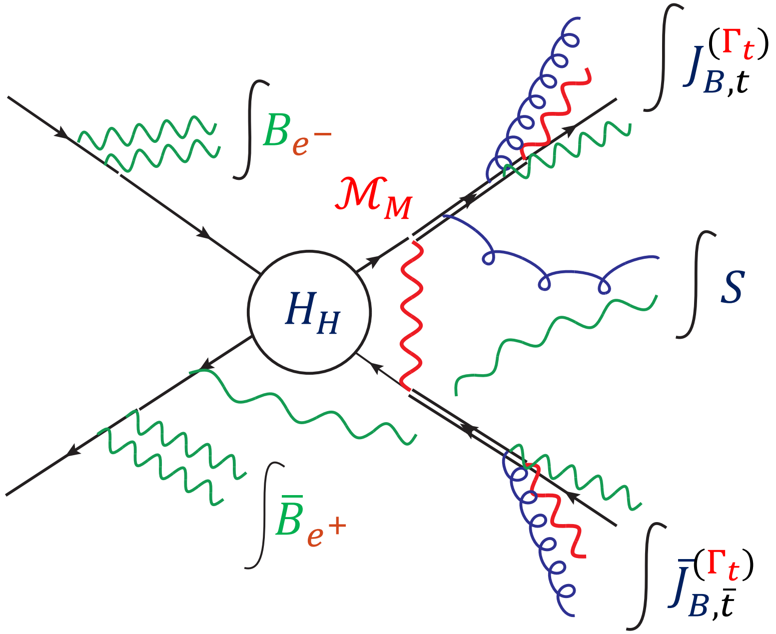
[Hoang et al, 20]

Master formula (double-resonant case)

Formalism extension of [Chiu et al, 07, 08, 09]

$$\frac{\mathrm{d}\sigma_{e^+e^-t\bar{t}}(P_-,P_+)}{\mathrm{d}\tau_2\,\mathrm{d}\Phi_2} = \sum_{\kappa,\rho} \frac{K_\Phi^{\kappa\rho}}{\mathcal{F}}\,\mathrm{Tr}\big[\rho_{e^+e^-t\bar{t}}\,\mathcal{M}_M H_H \mathcal{M}_M^\dagger\big]^{\kappa\rho} * J_{B,t}^{(\Gamma_t)} \otimes \bar{J}_{B,t}^{(\Gamma_t)} \otimes B_{e^-}^{\kappa|P_-} \otimes B_{e^+}^{\kappa|P_+} \otimes S_{e^+e^-t\bar{t}}$$

Hard phase space — Beam polarizations, $P_i \in [-1,1]$ — Hard kinematics + flux



- Lepton chirality $\kappa = \pm 1$, quark chirality $\rho = \pm 1$
- Isospin density matrix (in isospin space):

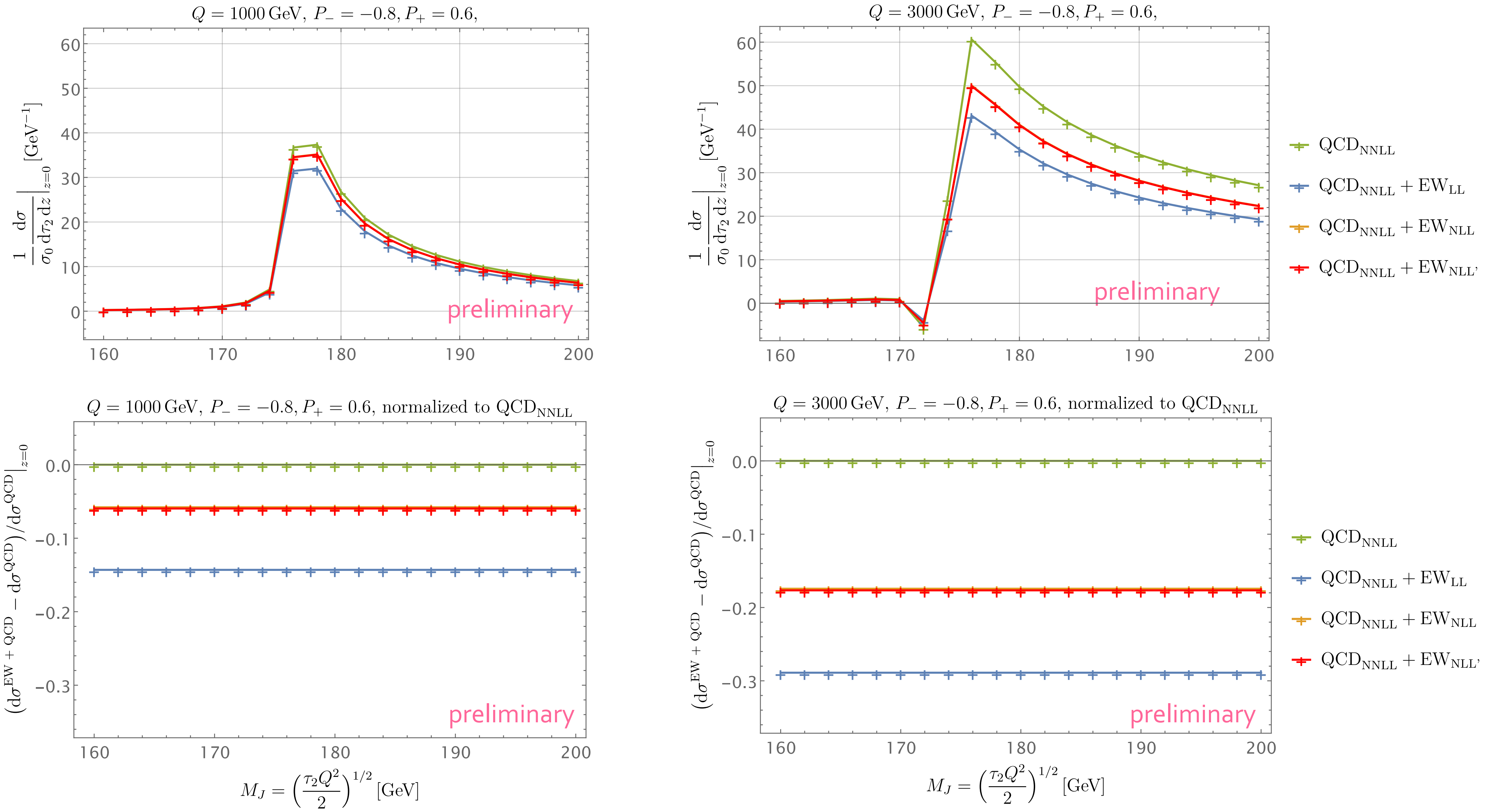
$$\rho_{e^+e^-t\bar{t}} = \mathrm{diag}(0,0,1,0,0,0)$$

$$i \sim \begin{pmatrix} (\bar{\nu}\nu)(\bar{u}u) \\ (\bar{\nu}\nu)(\bar{d}d) \\ (\bar{e}e)(\bar{u}u) \\ (\bar{e}e)(\bar{d}d) \\ (\bar{e}\nu)(\bar{u}d) \\ (\bar{\nu}e)(\bar{d}u) \end{pmatrix}$$

- Switching off QED below electroweak scale:

$$\frac{\mathrm{d}\sigma_{e^+e^-t\bar{t}}(P_-,P_+)}{\mathrm{d}\tau_2\,\mathrm{d}z} = \sum_{\kappa,\rho} \frac{K_\Phi^{\kappa\rho}\,\phi^\kappa(P_-,P_+)}{\mathcal{F}}\,\mathrm{Tr}\big[\rho_{e^+e^-t\bar{t}}\,\mathcal{M}_M H_Q \mathcal{M}_M^\dagger\big]^{\kappa\rho} * J_{B,t}^{(\Gamma_t)} \otimes \bar{J}_{B,t}^{(\Gamma_t)} \otimes S_{e^+e^-t\bar{t}}$$

CM frame now: $z = \cos\theta_*$ — Beam polarization function



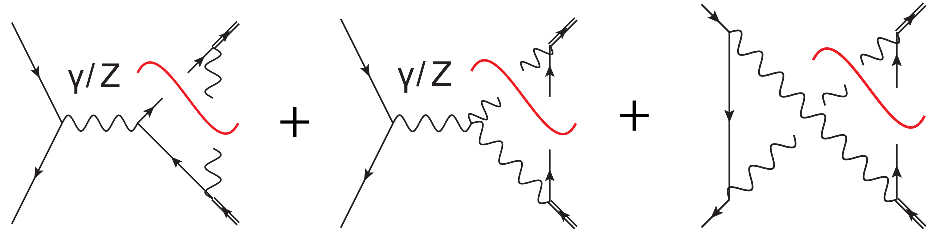
$Q = 1000\,\mathrm{GeV},\ P_- = -0.8, P_+ = 0.6,$
$\frac{1}{\sigma_0}\frac{d\sigma}{d\tau_2\,dz}\Big|_{z=0}\,[\mathrm{GeV}^{-1}]$
preliminary
$Q = 3000\,\mathrm{GeV},\ P_- = -0.8, P_+ = 0.6,$
preliminary
$\mathrm{QCD_{NNLL}}$
$\mathrm{QCD_{NNLL} + EW_{LL}}$
$\mathrm{QCD_{NNLL} + EW_{NLL}}$
$\mathrm{QCD_{NNLL} + EW_{NLL'}}$
$Q = 1000\,\mathrm{GeV},\ P_- = -0.8, P_+ = 0.6,$ normalized to $\mathrm{QCD_{NNLL}}$
$\left(d\sigma^{\mathrm{EW+QCD}} - d\sigma^{\mathrm{QCD}}\right)/d\sigma^{\mathrm{QCD}}\big|_{z=0}$
preliminary
$M_J = \left(\frac{\tau_2 Q^2}{2}\right)^{1/2}\,[\mathrm{GeV}]$
$Q = 3000\,\mathrm{GeV},\ P_- = -0.8, P_+ = 0.6,$ normalized to $\mathrm{QCD_{NNLL}}$
preliminary
$M_J = \left(\frac{\tau_2 Q^2}{2}\right)^{1/2}\,[\mathrm{GeV}]$

Single-resonant case

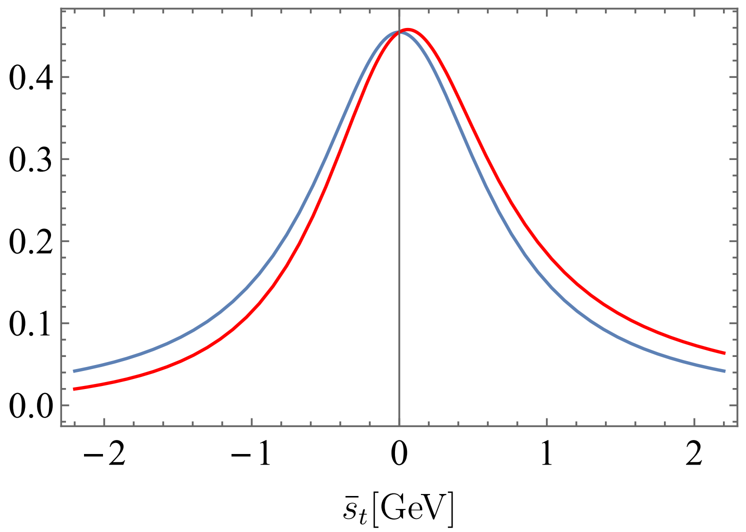
$$\frac{d\sigma_{e^+e^-t\bar{t}}(P_-,P_+)}{d\tau_2\,dz} = \sum_{\kappa,\rho} \frac{K_\Phi^{\kappa\rho}\,\phi^\kappa(P_-,P_+)}{\mathcal{F}} \mathrm{Tr}\left[\rho_{e^+e^-t\bar{t}}\,\mathcal{M}_c\,\mathcal{M}_s H_Q \mathcal{M}_s^\dagger \mathcal{M}_c^\dagger\right]^{\kappa\rho} * J_{B,t}^{(\Gamma_t)} \otimes \bar{J}_{B,t}^{(\Gamma_t)} \otimes S_{e^+e^-t\bar{t}}$$

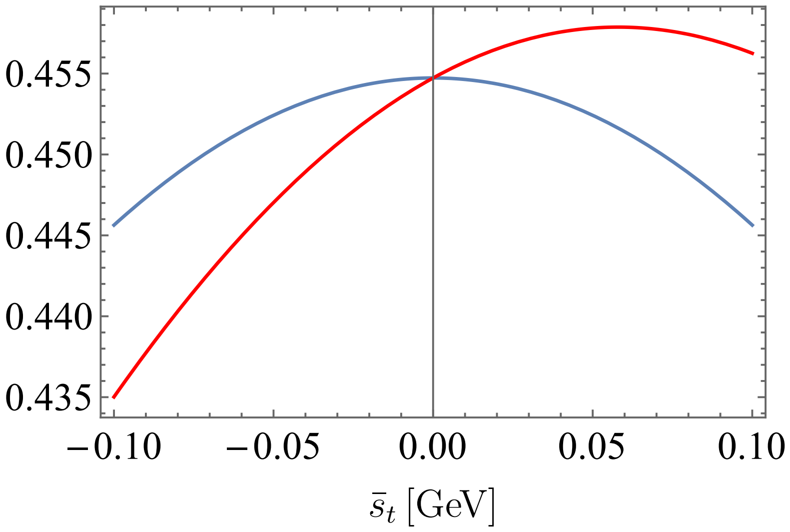
- There are imaginary parts in $\mathcal{M}_c$ due to *bW*-cuts
- Resonant/non-resonant interference contributions are obtained by keeping these imaginary parts

  [Hoang, Reisser, 04]

$\mathcal{M}_c \sim$ 

- Leads to peak shift O(30-50 MeV)
- WIP: including QCD logs





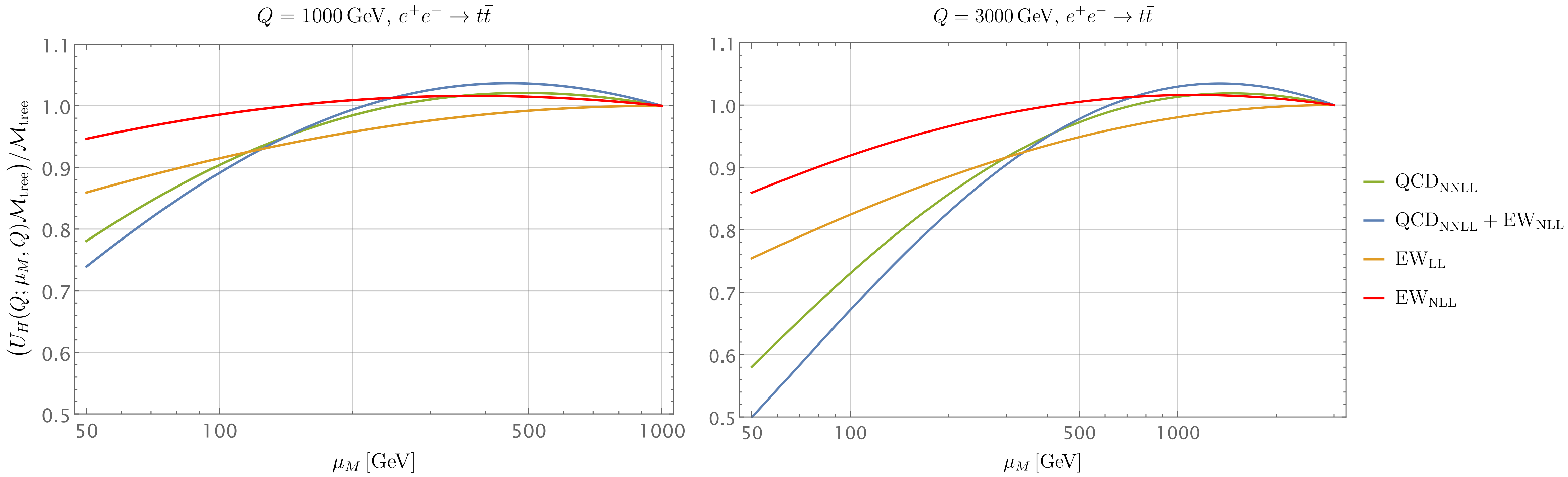
Summary and outlook

- Summary:
  - Extension of QCD factorization formalism to systematic inclusion of subleading EW effects for inclusive boosted top jet pair-production
  - Coherent resummation of QCD logs and EW Sudakov logarithms
  - 2-jettiness double-resonant cross section (NNLL QCD + NLL' EW) for linear collider environment (including beam polarization effects)
  - Resonant/non-resonant interference

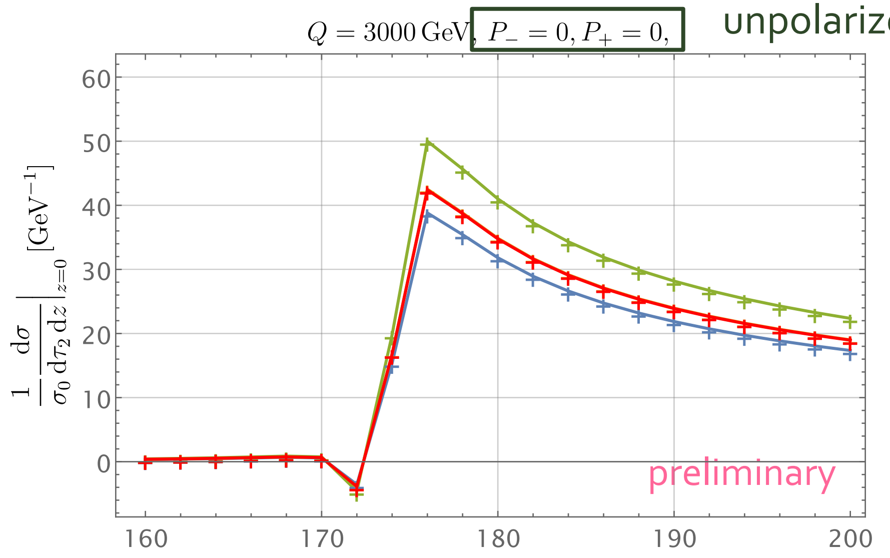
- Outlook:
  - Coherent treatment of resonant/non-resonant interference and QCD effects
  - QED below electroweak scale
  - Realistic beam treatment (QED! Weak?!)
  - Extend factorization formalism to more differential final-state
    - Top decay-sensitive observables
    - Fragmentation
    - ...
  - Extension of the formalism to LHC observables

Backup

Sudakov evolution



Chirality of operators shown: left-left (for right-left and left-right: SU(2)-parts roughly half the size) unpolarized



ILC polarization