Including Coulomb corrections $t\bar{t}$ production

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Plan

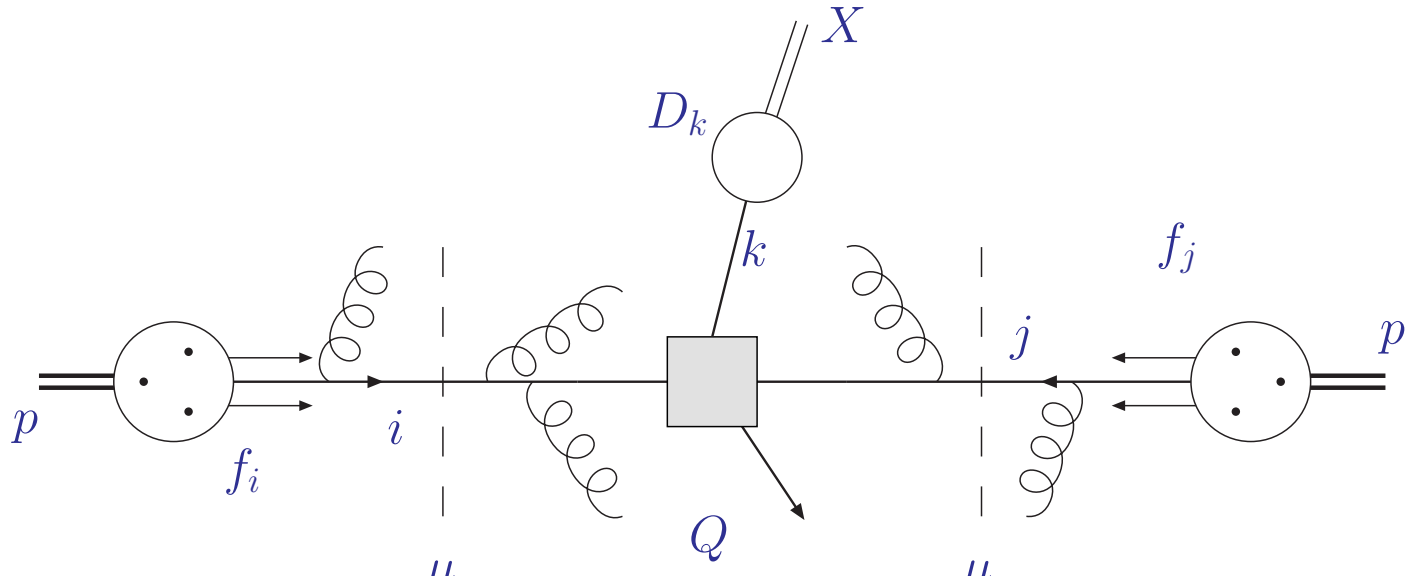
Coulomb corrections

- *Top-quark pair production near threshold at LHC*
  Y. Kiyo, J. H. Kühn, S. M., M. Steinhauser and P. Uwer arXiv:0812.0919

Phenomenology update

- Work in progress
  M.V. Garzelli, G. Limatola, S. M., M. Steinhauser and S. Zenaiev

QCD factorization



$$\sigma_{pp\to X} = \sum_{ij} f_i(\mu^2) \otimes f_j(\mu^2) \otimes \hat{\sigma}_{ij\to X}\left(\alpha_s(\mu^2), Q^2, \mu^2, m_X^2\right)$$

- Factorization at scale μ
  - separation of sensitivity to dynamics from long and short distances
- Hard parton cross section $\hat{\sigma}_{ij\to X}$ calculable in perturbation theory
  - cross section $\hat{\sigma}_{ij\to k}$ for parton types i, j and hadronic final state X
- Non-perturbative parameters: parton distribution functions f_i, strong coupling α_s, particle masses m_X
  - known from global fits to exp. data, lattice computations, . . .

Progress in theory

Challenge

- Improve theory predictions and reduce theoretical uncertainty
  - hard scattering cross section $\hat{\sigma}_{ij\to X}$
- Beyond (N)NLO focus on kinematical limits
  - high energy (boosted) regime
  - soft and collinear kinematics
  - Coulomb corrections

Threshold logarithms

- Sudakov logarithms in velocity $\beta_{t\bar{t}} = \sqrt{1-4m^2/s}$ of heavy quarks
  - all order resummation of large logarithms $\alpha_s^n \ln^{2n}(\beta) \longleftrightarrow \alpha_s^n \ln^{2n}(N)$ in Mellin space (renormalization group equation) Kidonakis, Sterman '97; Bonciani, Catani, Mangano, Nason '98; Kidonakis, Laenen, S.M., Vogt '01; ...

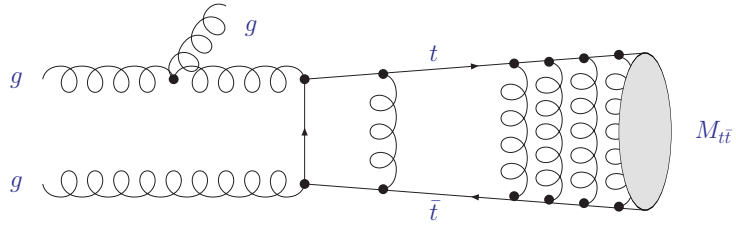
Coulomb corrections

- Singular contributions in $(\alpha_s/\beta_{t\bar{t}})^n$ at n-loops

Kiyo, Kühn, S.M., Steinhauser, Uwer '08

Coulomb corrections

- Heavy quark production very close to threshold
  - resummation of Coulomb corrections $\sim 1/\beta_{t\bar{t}}$ to all orders
  - factorization in non-relativistic QCD Bodwin, Braaten, Lepage '95
- **ILC**: much work (theory and phenomenology) [many people]
  - fixed center-of-mass energy S allows threshold scan at $\sqrt{S} \sim 2m_t$
  - dominant color-singlet production $\rightarrow t\bar{t}\left({}^3S_1^{[1]}\right)$
- **LHC**: effects on top-mass measurement Hagiwara, Sumino, Yokoya '08
  - complete NLO NRQCD result Petrelli, Cacciari, Greco, Maltoni, Mangano '97 (corrections by Hagiwara, Sumino, Yokoya '08)
  - NLL resummation Cacciari '99
  - detailed study in NRQCD assembling existing knowledge at NLO/NLL Kiyo, Kühn, S.M., Steinhauser, Uwer '08
  - bound-state effects on kinematical distributions Sumino, Yokoya '10

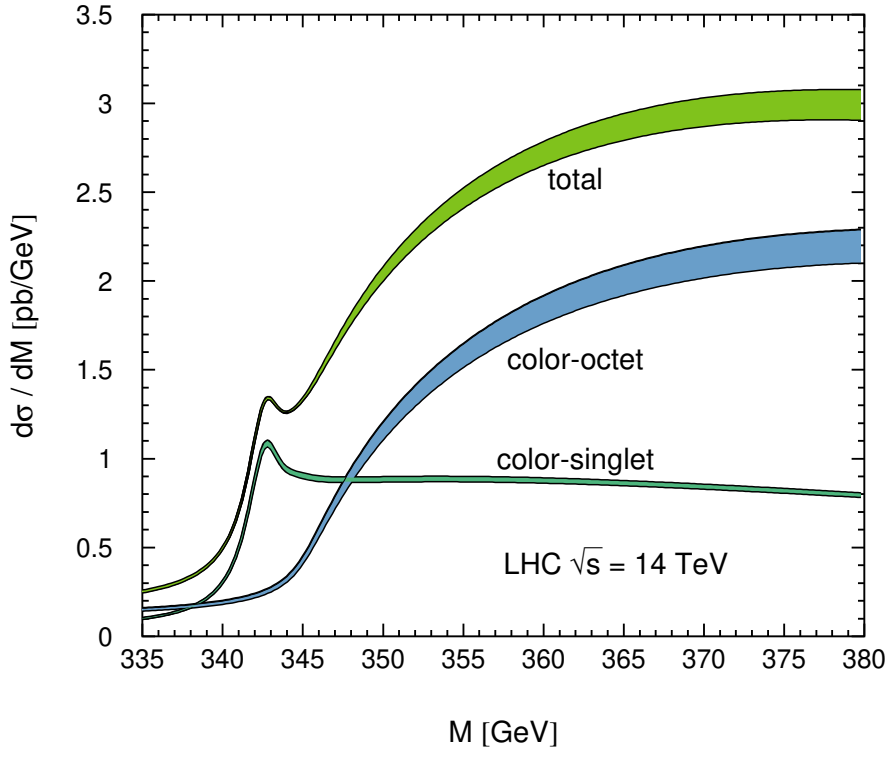


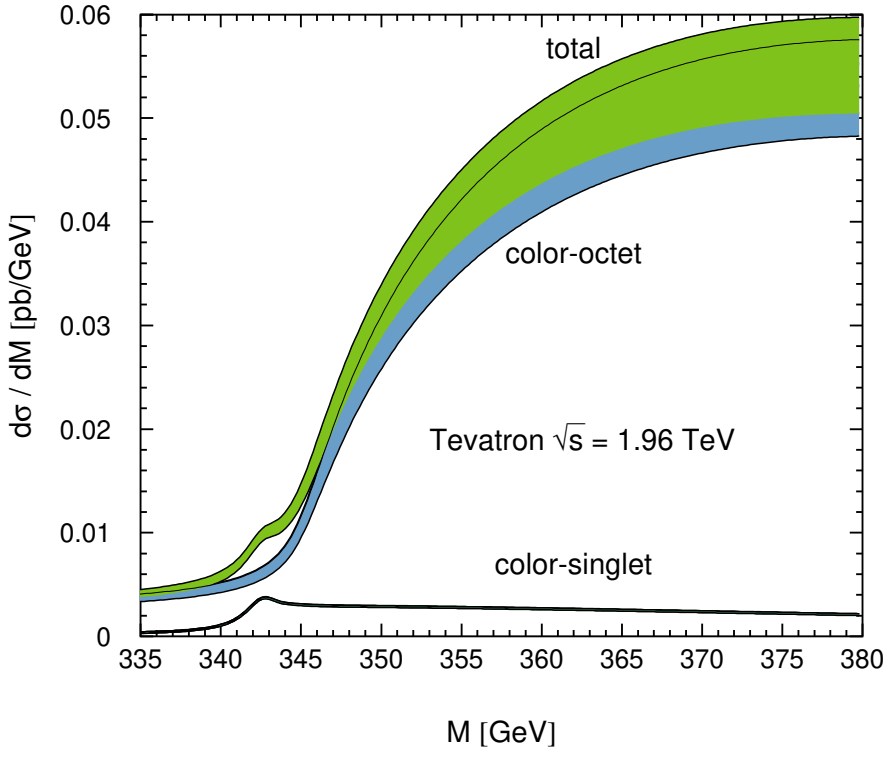
Coulomb corrections

- Recall master equation $\sigma_{pp\to t\bar{t}} = \sum_{ij} f_i \otimes f_j \otimes \hat{\sigma}_{ij\to t\bar{t}}$
- Convolution with PDFs $f_i \otimes f_j$
  - top-quark pairs produced as color-singlets and color-octets $\to t\bar{t}\left({}^{2s+1}S_J^{[1,8]}\right)$
  - threshold at $M_{t\bar{t}} \sim 2m_t$ with $M_{t\bar{t}} = (p_t + p_{\bar{t}})^2$
- NRQCD factorization of partonic cross section into $\hat{\sigma}_{ij\to t\bar{t}} = F_{ij\to T} \otimes G(M_{t\bar{t}})$
  - free $t\bar{t}$ production rate F
  - evolution factor into "boundstate" (Green's function) G
- Differential kinematics $\frac{d\hat{\sigma}_{ij\to t\bar{t}}}{dM_{t\bar{t}}^2} = F_{ij\to T} \times \Im G^{[1,8]}(M_{t\bar{t}})$
  - factorization of soft-collinear dynamics (real emission radiation)
  - matching at NLO and NLL resummation
- Effective theory formulation Beneke, Falgari, Schwinn '09; Beneke, Kiyo, Schuller '13

Invariant mass distristribution

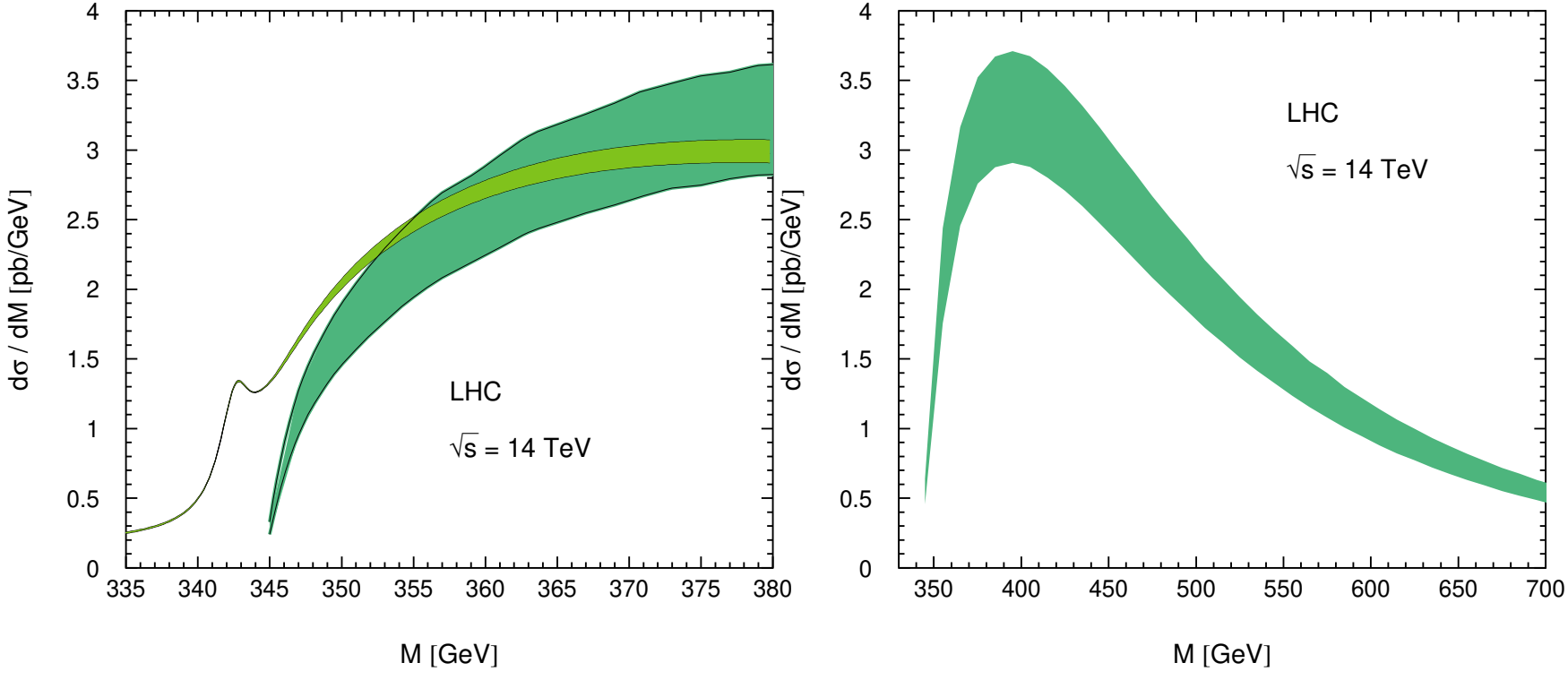
- $d\sigma/dM_{t\bar{t}}$ at LHC driven by large gluon luminosity
  - $gg \to t\bar{t}\left({}^1S_0^{[1]}\right)$ dominates
- $d\sigma/dM_{t\bar{t}}$ at Tevatron with small bound state effects
  - $q\bar{q}$-channel large with only color-octet configurations only
- Validity of Coulomb resummation restricted to $dM_{t\bar{t}} \geq 335$ GeV





Matching to fixed order

- $d\sigma/dM_{t\bar{t}}$ with at LHC
  - compare NLL resummed result in NRQCD with (plain vanilla) NLO (use HVQMNR Mangano, Nason, Ridolfi '92 for matching)
  - consistency check OK
- Resolution of bound state effects in $d\sigma/dM_{t\bar{t}}$ at LHC difficult (requires rather fine binning)



Recent phenomenology

- Resummation (small $\beta_{t\bar{t}}$) in SCET

  Wan-Li Ju, Guoxing Wang, Xing Wang, Xiaofeng Xu, Yongqi Xu,Li Lin Yang '20

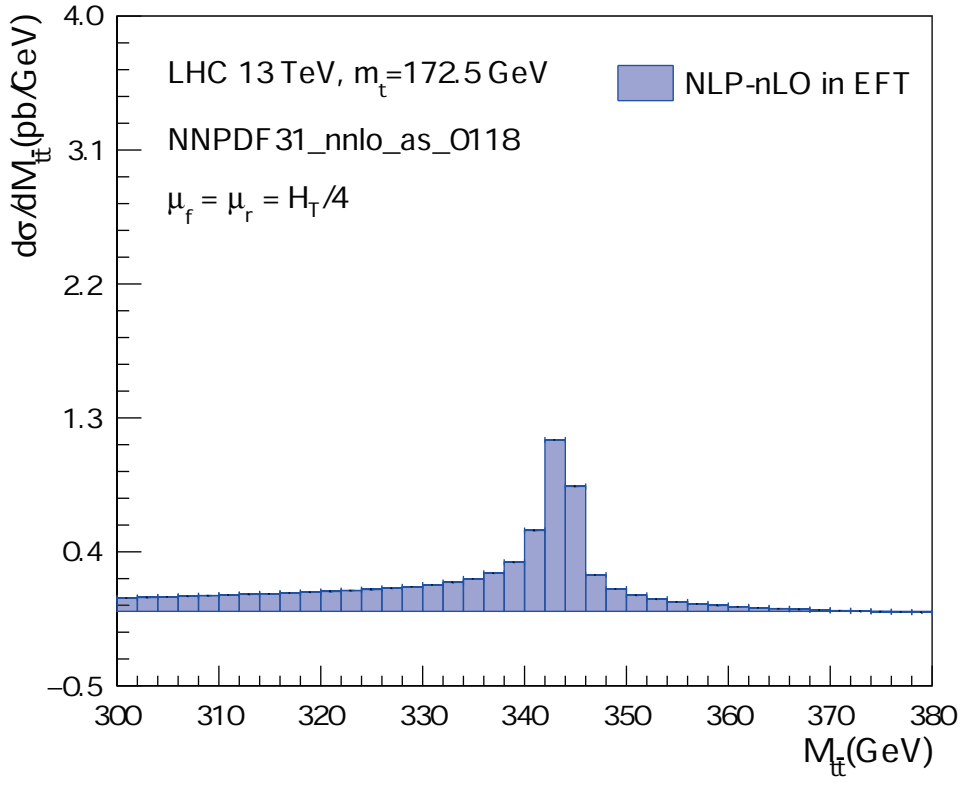
  - double-differential distribution in $M_{t\bar{t}}$ and $y_{t\bar{t}}$
- Signatures of toponium formation Fuks, Hagiwara, Kai Ma, Ya-Juan Zheng '21
  - color-singlet spin-0 toponium bound state η_t of $t\bar{t}$
  - di-lepton decay $gg \to \eta_t \to l\bar{l}b\bar{b}\nu\bar{\nu}$

Comment on 2004.03088

- Resummation effects in top quark mass determination with claimed shift of $m_t \sim 1.4$ GeV

  Wan-Li Ju, Guoxing Wang, Xing Wang, Xiaofeng Xu, Yongqi Xu,Li Lin Yang '20

- Contributions from resummation in region 300 GeV $\leq M_{t\bar{t}} \leq 380$ GeV at the 13 TeV LHC



Comment on 2102.11281

- Signatures of spin-0 toponium bound state η_t decay

  Fuks, Hagiwara, Kai Ma, Ya-Juan Zheng '21

  - theory estimate based on Sumino, Yokoya '10
  - di-lepton decay $gg \to \eta_t \to l\bar{l}b\bar{b}\nu\bar{\nu}$
- Short-comings
  - toponium cross section essentially as integral over $M_{t\bar{t}}$ GeV (way too large range in $M_{t\bar{t}}$ GeV for application of NRQCD)
  - neglect color-octet configurations (no enhancement)
- Published ratios for toponium cross sections σ_{η_t} vs. $\sigma_{t\bar{t}}$ not suitable for re-weighting of MC event samples in experimental analysis

Summary

- Coulomb corrections and their resummation for $t\bar{t} + X$ production
  - update of resummation studies at NLL for upcoming analyses
- Combination with QCD perturbation theory to NNLO for $t\bar{t} + X$ production
  - bin-wise matching