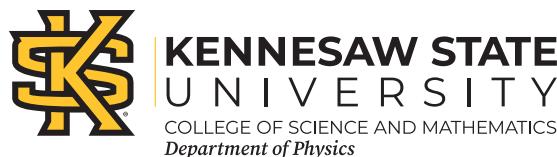


# Top-antitop cross sections at high energies

Nikolaos Kidonakis

- Soft-gluon resummation
- Top-antitop pair production
- aN<sup>3</sup>LO cross sections



DIS2022



## Soft-gluon corrections

partonic processes at LO:  $q\bar{q} \rightarrow t\bar{t}$  and  $gg \rightarrow t\bar{t}$

in 1PI kinematics  $a(p_a) + b(p_b) \rightarrow t(p_t) + X$

we define  $s = (p_a + p_b)^2$ ,  $t = (p_a - p_t)^2$ ,  $u = (p_b - p_t)^2$  and  $s_4 = s + t + u - 2m_t^2$

At partonic threshold  $s_4 \rightarrow 0$

Soft corrections  $\left[ \frac{\ln^k(s_4/m_t^2)}{s_4} \right]_+$  with  $k \leq 2n - 1$  for the order  $\alpha_s^n$  corrections

The soft-gluon corrections are dominant and provide excellent approximations to NLO and NNLO exact results for total cross sections and for single-differential and double-differential top-quark distributions

The approximate NNLO (aN<sup>3</sup>NLO) calculations with soft gluons accurately predicted the later complete NNLO results at Tevatron and LHC energies

Approximation turns out to remain very good even at much higher energies

Best predictions with approximate N<sup>3</sup>LO (aN<sup>3</sup>LO) calculations

## Soft-gluon resummation

Factorization of the cross section under Laplace transforms, and resummation of the soft-gluon corrections

$$d\tilde{\sigma}_{ab \rightarrow t\bar{t}}^{\text{resum}}(N) = \exp \left[ \sum_{i=a,b} E_i(N_i) \right] \exp \left[ \sum_{i=a,b} 2 \int_{\mu_F}^{\sqrt{s}} \frac{d\mu}{\mu} \gamma_{i/i}(N_i) \right]$$

$$\times \text{tr} \left\{ H_{ab \rightarrow t\bar{t}} \left( \alpha_s(\sqrt{s}) \right) \exp \left[ \int_{\sqrt{s}}^{\sqrt{s}/N} \frac{d\mu}{\mu} \Gamma_{S ab \rightarrow t\bar{t}}^\dagger(\alpha_s(\mu)) \right] \tilde{S}_{ab \rightarrow t\bar{t}} \left( \alpha_s \left( \frac{\sqrt{s}}{N} \right) \right) \exp \left[ \int_{\sqrt{s}}^{\sqrt{s}/N} \frac{d\mu}{\mu} \Gamma_{S ab \rightarrow t\bar{t}}(\alpha_s(\mu)) \right] \right\}$$

with  $H_{ab \rightarrow t\bar{t}}$  a hard function and  $\tilde{S}_{ab \rightarrow t\bar{t}}$  a soft function

Soft anomalous dimension  $\Gamma_{S ab \rightarrow t\bar{t}}$  controls the evolution of the soft function

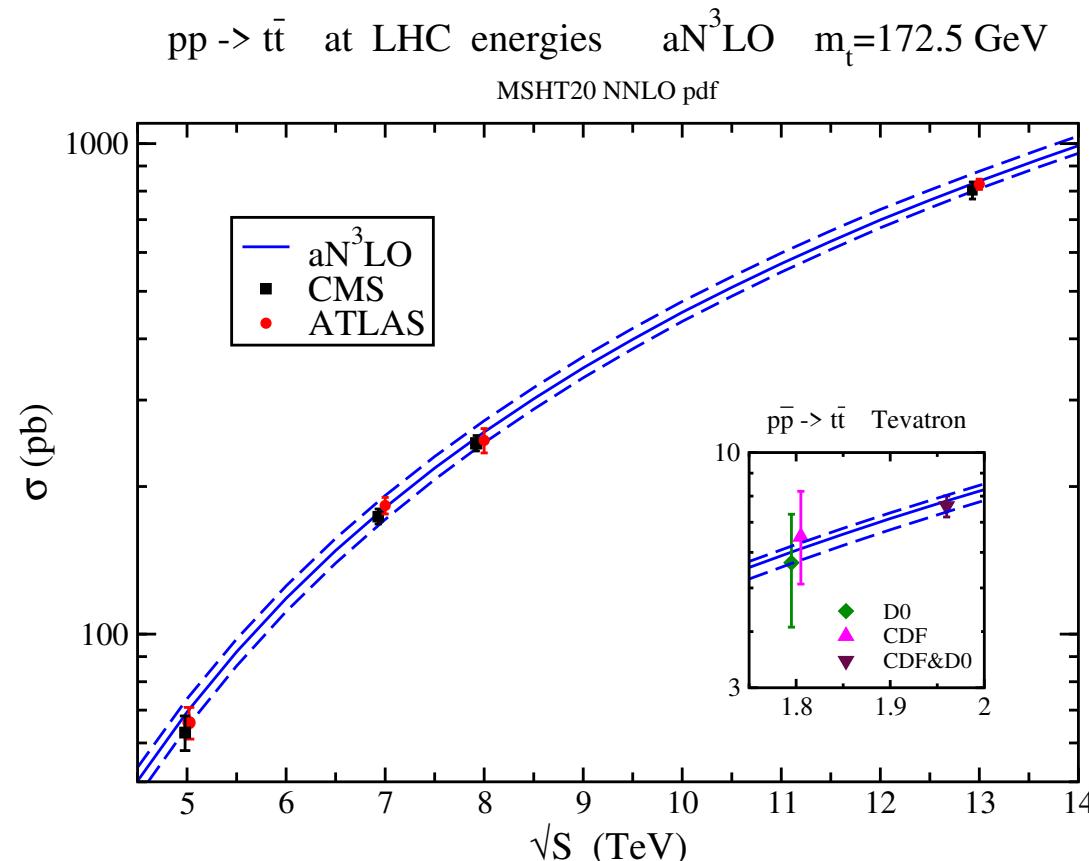
$\Gamma_{S q\bar{q} \rightarrow t\bar{t}}$  is a  $2 \times 2$  matrix

$\Gamma_{S gg \rightarrow t\bar{t}}$  is a  $3 \times 3$  matrix

At NNLL accuracy we need two-loop results for  $\Gamma_{S ab \rightarrow t\bar{t}}$   
partial three-loop results are also known

Finite-order expansions  $\rightarrow$  no prescription needed

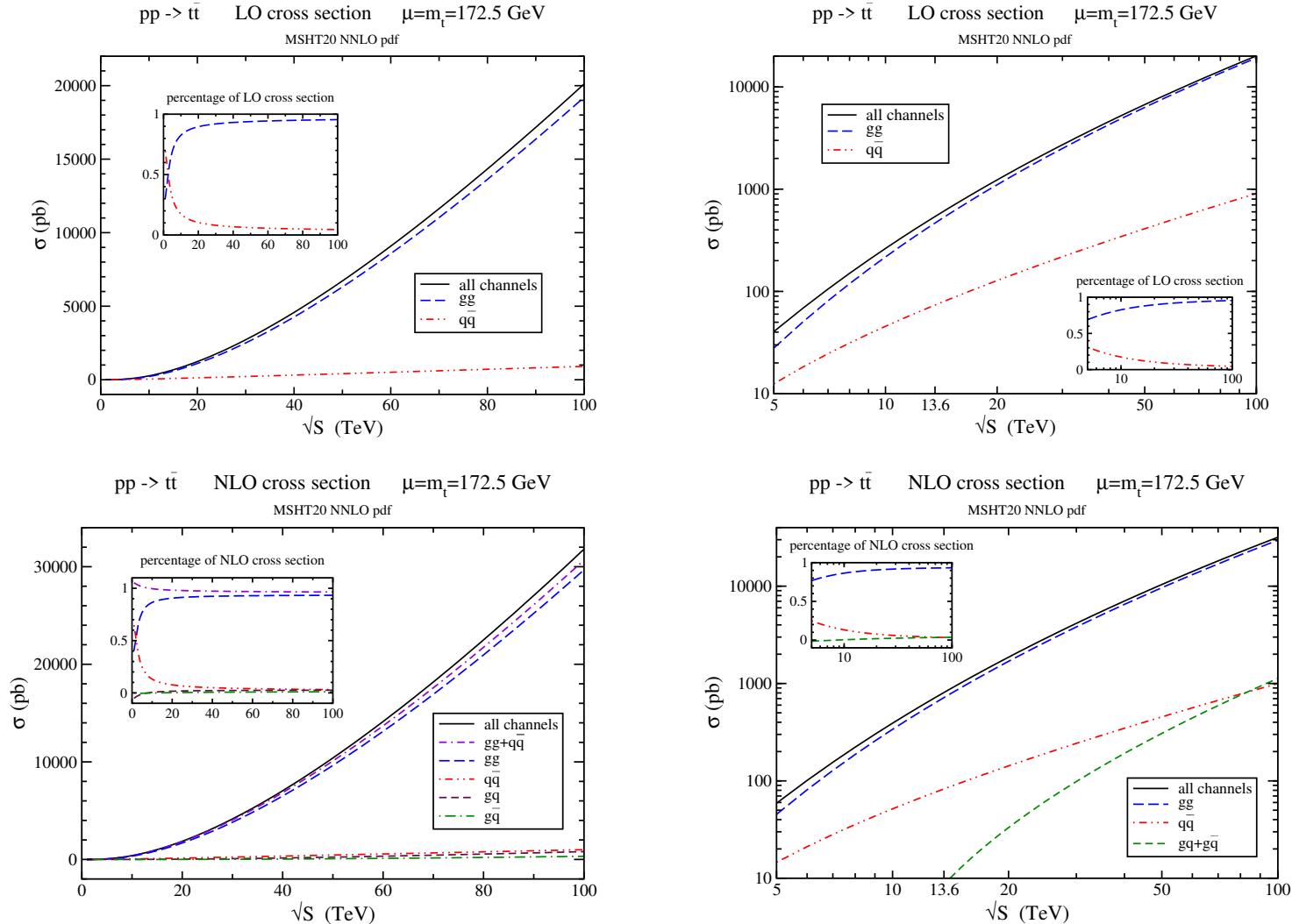
## Top-antitop pair production



$aN^3LO$  cross sections with combined scale and pdf uncertainties

excellent agreement with collider data

# $t\bar{t}$ production at high energies



the  $gg \rightarrow t\bar{t}$  channel is increasingly dominant at higher energies

## $t\bar{t}$ production cross sections

| $t\bar{t}$ cross sections at LHC energies |       |       |        |          |        |
|---|-------|-------|--------|----------|--------|
| $\sigma$ in pb                            | 7 TeV | 8 TeV | 13 TeV | 13.6 TeV | 14 TeV |
| LO  | 106   | 150   | 488    | 540      | 576    |
| NLO                                       | 155   | 222   | 730    | 809      | 864    |
| NNLO                                      | 174   | 249   | 814    | 902      | 963    |
| aN <sup>3</sup> LO                        | 181   | 258   | 839    | 928      | 990    |

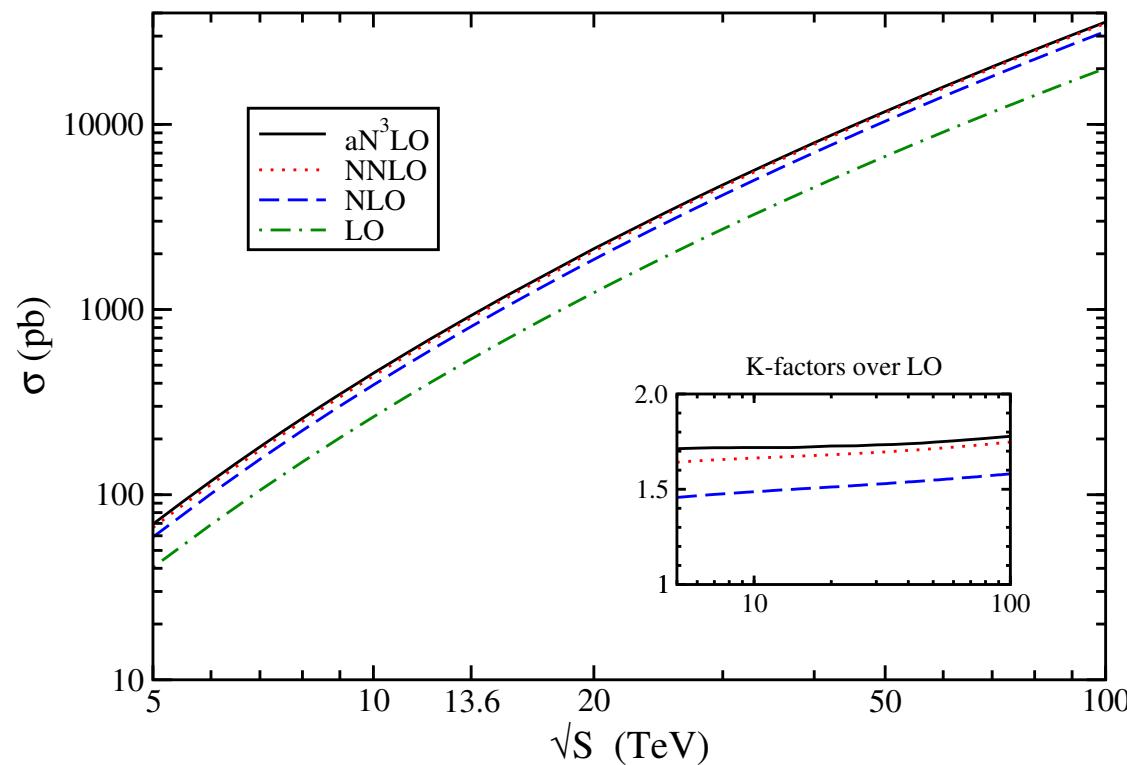
all results with MSHT20 NNLO pdf

$aN^3LO = NNLO + \text{soft-gluon } N^3LO \text{ corrections}$

| $t\bar{t}$ cross sections in high-energy $pp$ collisions |                    |                    |                    |
|--|--------------------|--------------------|--------------------|
| $\sigma$ in pb   | 27 TeV             | 50 TeV             | 100 TeV            |
| LO   | $2.23 \times 10^3$ | $6.72 \times 10^3$ | $20.1 \times 10^3$ |
| NLO  | $3.39 \times 10^3$ | $10.4 \times 10^3$ | $31.8 \times 10^3$ |
| NNLO   | $3.77 \times 10^3$ | $11.5 \times 10^3$ | $35.1 \times 10^3$ |
| aN <sup>3</sup> LO                                       | $3.86 \times 10^3$ | $11.7 \times 10^3$ | $35.8 \times 10^3$ |

## aN<sup>3</sup>LO $t\bar{t}$ cross sections

pp  $\rightarrow t\bar{t}$       cross sections       $\mu=m_t=172.5$  GeV  
 MSHT20 NNLO pdf

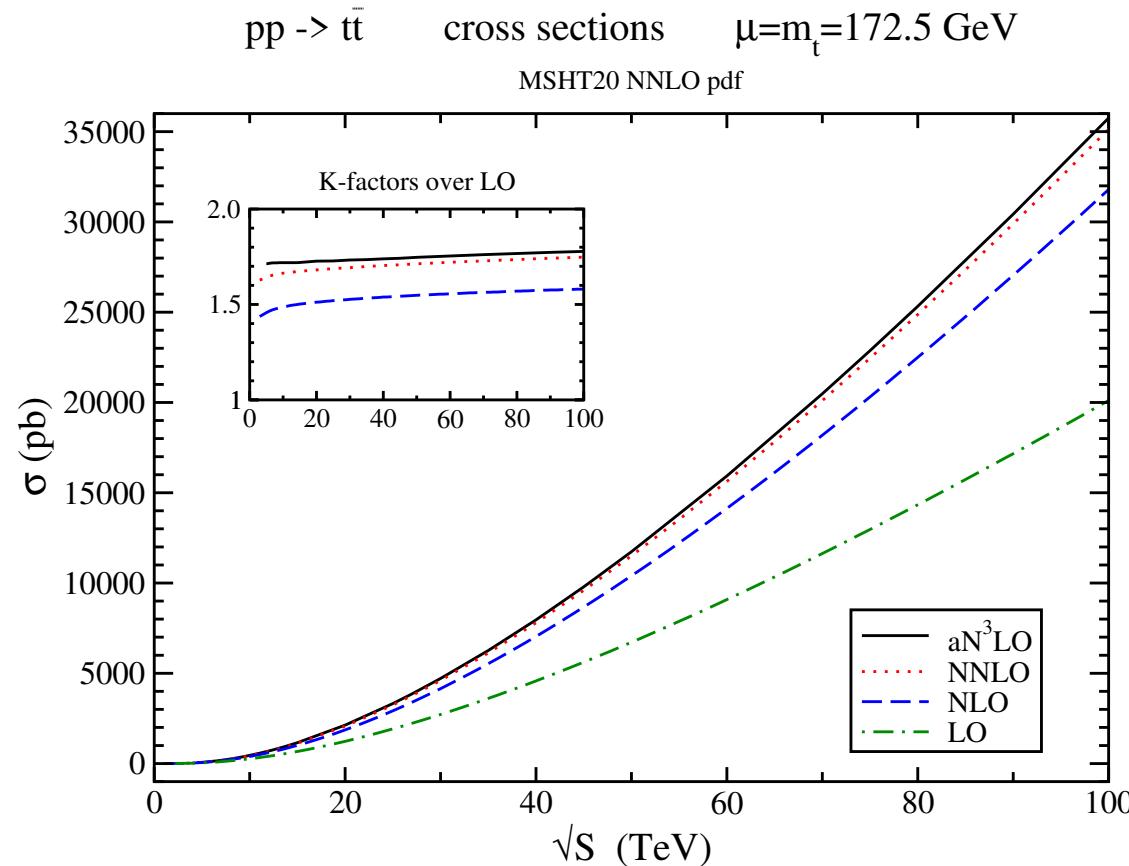


aN<sup>3</sup>LO cross section at 13 TeV  $\rightarrow 839^{+23+17}_{-18-11}$  pb

at 13.6 TeV  $\rightarrow 928^{+25+18}_{-20-12}$  pb

at 14 TeV  $\rightarrow 990^{+27+19}_{-22-13}$  pb

## aN<sup>3</sup>LO $t\bar{t}$ cross sections



The cross section grows by orders of magnitude in the energy range shown and the  $K$ -factors remain consistently large throughout the energy range

## K-factors at LHC and higher energies

| <i>K</i> -factors for $t\bar{t}$ production at LHC energies |       |       |        |          |        |
|---|-------|-------|--------|----------|--------|
| <i>K</i> -factor  | 7 TeV | 8 TeV | 13 TeV | 13.6 TeV | 14 TeV |
| NLO/LO  | 1.47  | 1.48  | 1.50   | 1.50     | 1.50   |
| NNLO/LO   | 1.65  | 1.66  | 1.67   | 1.67     | 1.67   |
| aN <sup>3</sup> LO/LO                                       | 1.72  | 1.72  | 1.72   | 1.72     | 1.72   |
| aNLO/NLO  | 1.01  | 1.00  | 0.99   | 0.99     | 0.99   |
| aNNLO/NNLO  | 1.01  | 1.01  | 1.00   | 1.00     | 1.00   |

$\text{aNLO} = \text{LO} + \text{soft-gluon NLO corrections}$

$\text{aNNLO} = \text{NLO} + \text{soft-gluon NNLO corrections}$

| <i>K</i> -factors for $t\bar{t}$ production in $pp$ collisions |        |        |         |
|--|--------|--------|---------|
| <i>K</i> -factor   | 27 TeV | 50 TeV | 100 TeV |
| NLO/LO   | 1.52   | 1.55   | 1.58    |
| NNLO/LO  | 1.69   | 1.71   | 1.75    |
| aN <sup>3</sup> LO/LO  | 1.73   | 1.75   | 1.78    |
| aNLO/NLO   | 0.97   | 0.95   | 0.92    |
| aNNLO/NNLO   | 1.00   | 0.99   | 0.98    |

The soft-gluon approximation is excellent throughout

## Summary

- top-antitop pair production in high-energy  $pp$  collisions
- quality of soft-gluon approximation is excellent at LHC energies and it remains very good even at much higher energies
- soft-gluon corrections are dominant and they are significant through  $aN^3LO$