Resummation and Scale Study for boosted top pair production @ NNLO+NNLL' in QCD

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1803.07623

In collaboration with M. Czakon, A. Ferroglia, D. Heymes, A. Mitov ,
B. D. Pecjak, D. J. Scott and L.L. Yang

Motivation

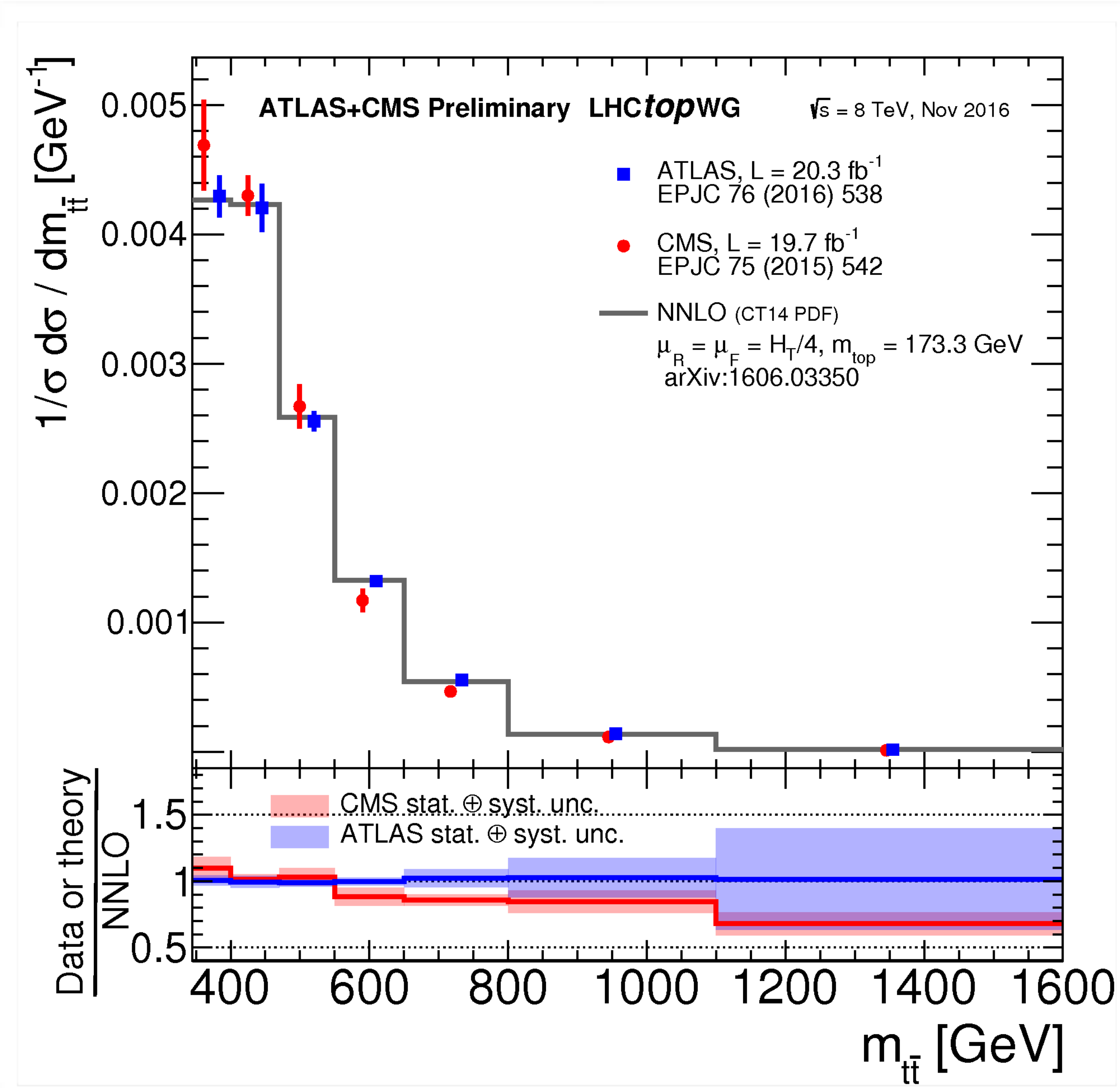
- Heaviest in SM, an important field in SM precision measurements.
- A window to BSM, especially in boosted regions, e.g. invariant mass distribution.
- More and more boosted events.

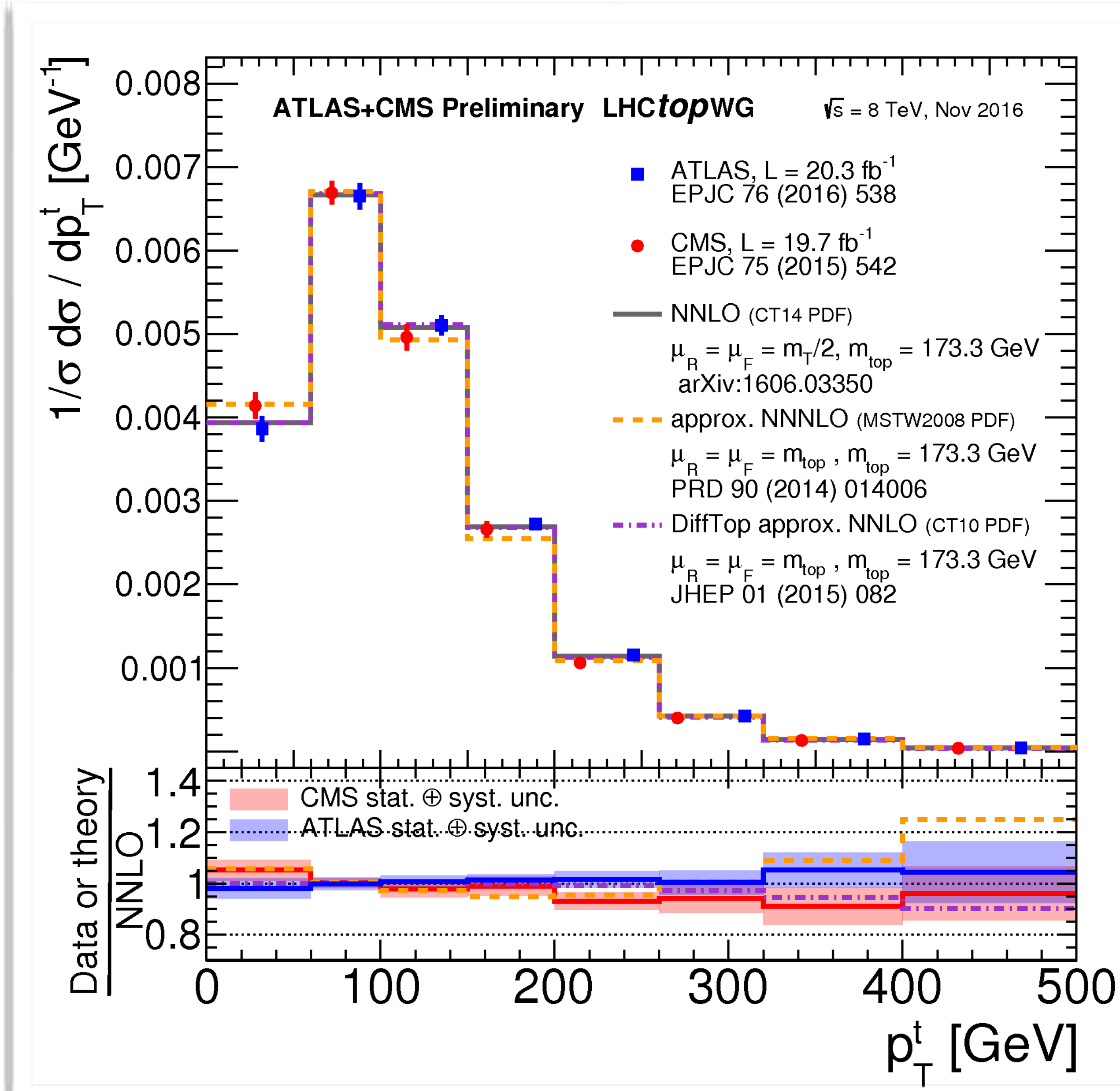
Motivation

Top is more and more important...

- LHC 8 TeV results beginning to probe the "boosted" regions:

ATLAS&CMS Summary



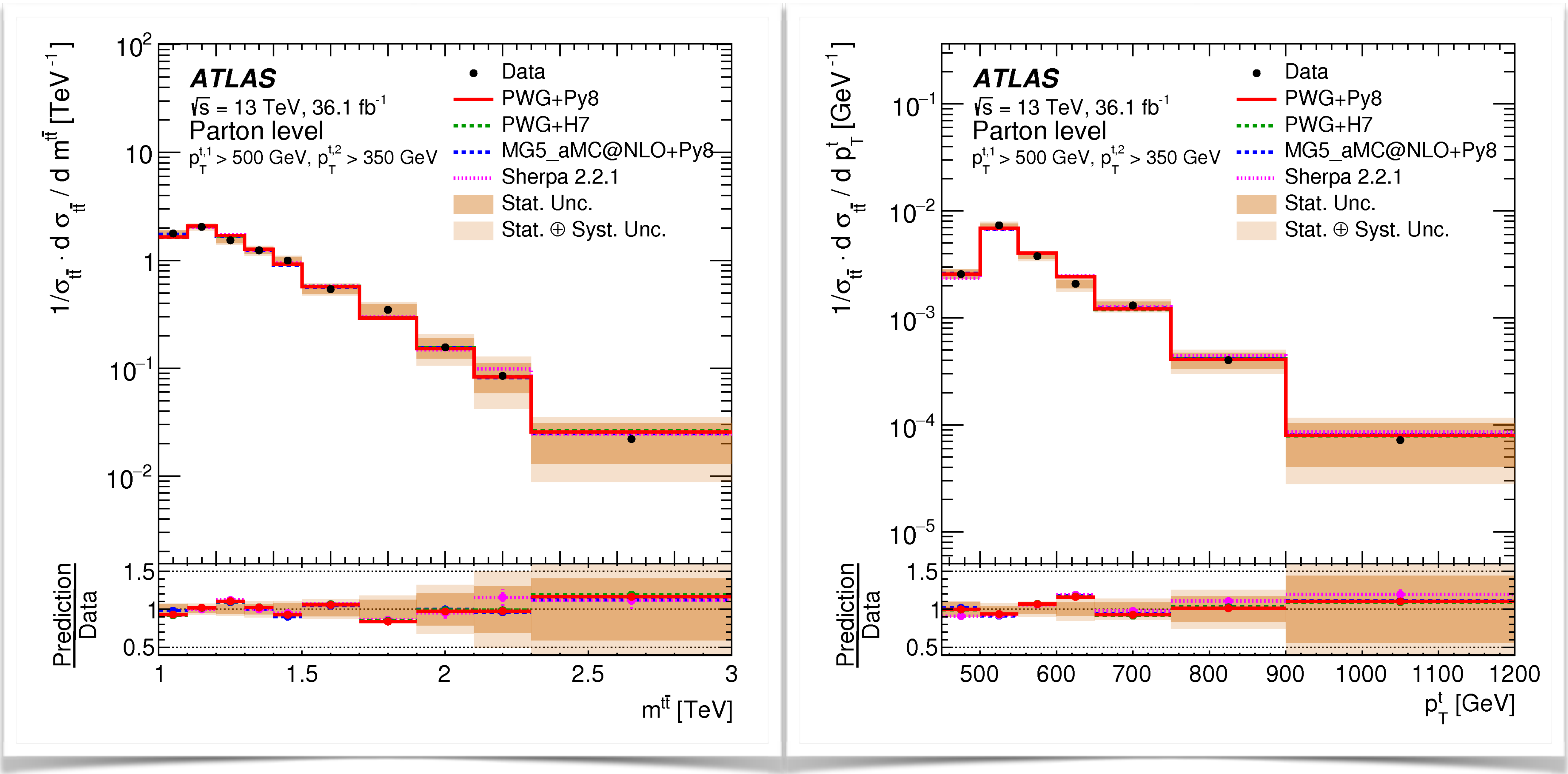


Motivation

Top is more and more important…

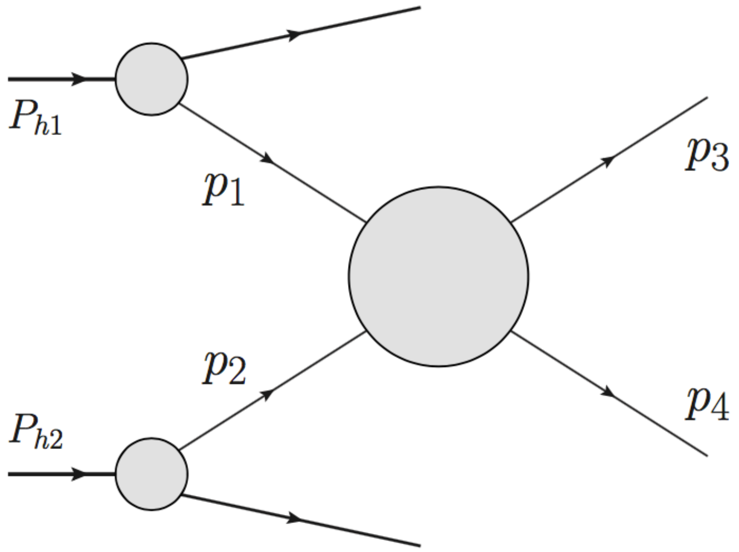
- Expect more boosted data @LHC 13 TeV

ATLAS, arXiv: 1801.02052



Set-up

$$i(p_1) + j(p_2) \to t(p_3) + \bar{t}(p_4) + X(p_X)$$



$$\frac{d^2\sigma(\tau)}{dM\, d\cos\theta} = \frac{8\pi\beta_t}{3sM} \sum_{ij} \int_\tau^1 \frac{dz}{z} \mathcal{L}_{ij}(\tau/z, \mu_f)\, C_{ij}(z, M, m_t, \cos\theta, \mu_f)\,,$$

$$z \to 1$$

is partonic threshold limit(soft)

$$s = (P_1 + P_2)^2, \hat{s} = (p_1 + p_2)^2$$

$$M_{t\bar{t}}^2 = (p_3 + p_4)^2,$$

$$z = M_{t\bar{t}}^2/\hat{s}, \tau = M_{t\bar{t}}^2/s$$

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- Stepping in NNLO era, improving significantly.

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- In boosted regions, two potential large logs arise.

$$\hat{s}, |t_1| \gg m_t^2 \gg \hat{s}(1-z)^2 \gg m_t^2(1-z)^2$$

$$\left[\frac{\log^n(1-z)}{1-z}\right]_+ \qquad\qquad \log^n \frac{m_t}{M_{t\bar{t}}}$$

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$$\log^n N \qquad\qquad \log^n \frac{m_t}{M_{t\bar{t}}}$$

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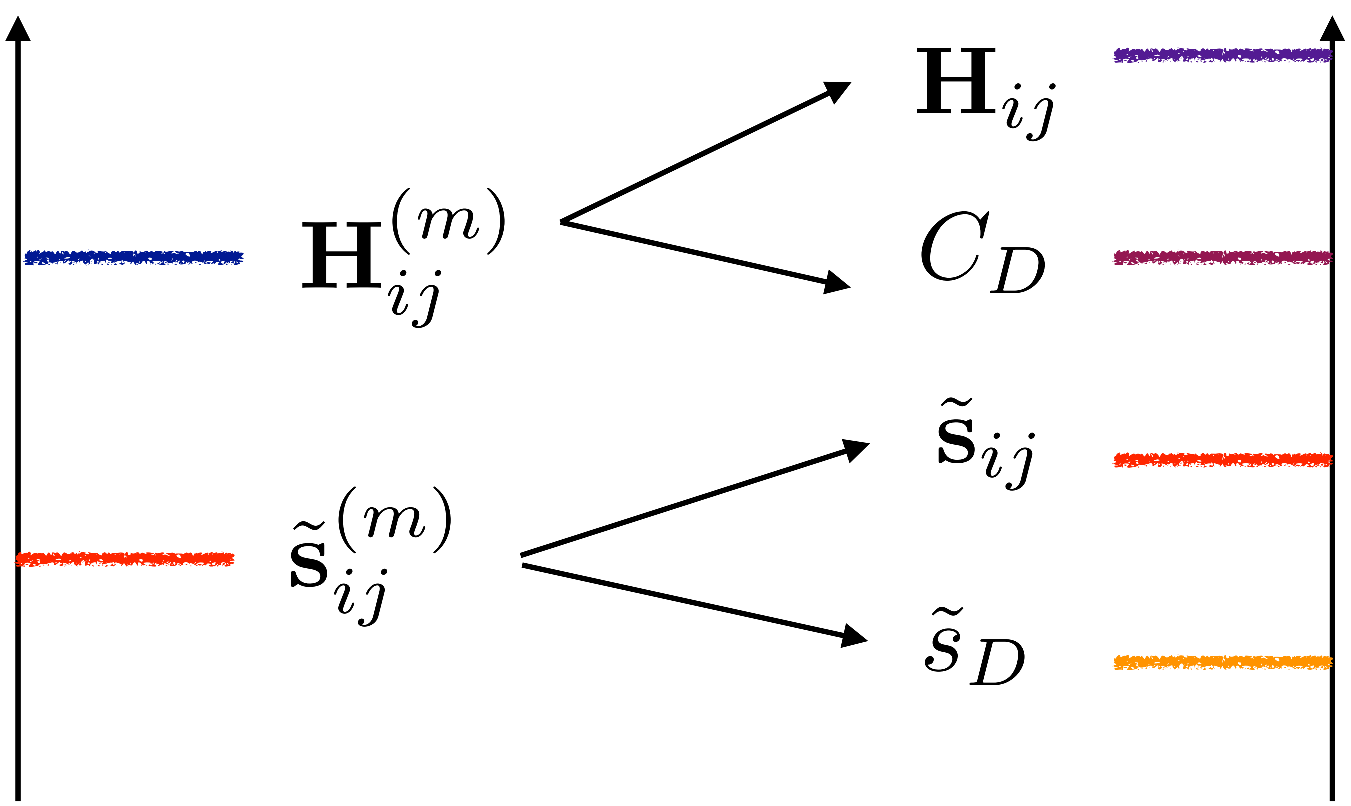
$$\log^n N \qquad \qquad \log^n \frac{m_t}{M_{t\bar{t}}}$$

- Matching FO and Res will give prediction for the wide range of observables and has some interesting feature.

Framework

In soft limit, we can factorize the partonic hard as(Mellin space):

$$\tilde{c}_{ij}(N) = Tr[\mathbf{H}_{ij}^{(m)} \tilde{\mathbf{s}}_{ij}^{(m)}(N)] + \mathcal{O}(1/N)$$



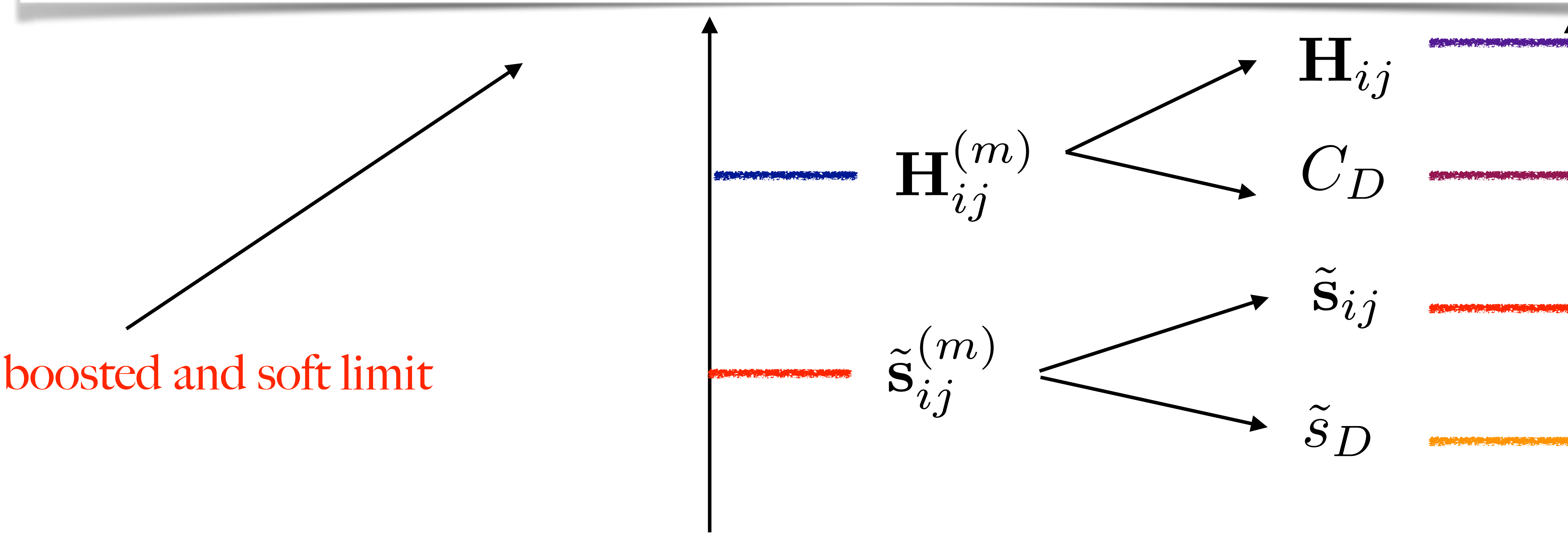
Framework

Two-step factorization

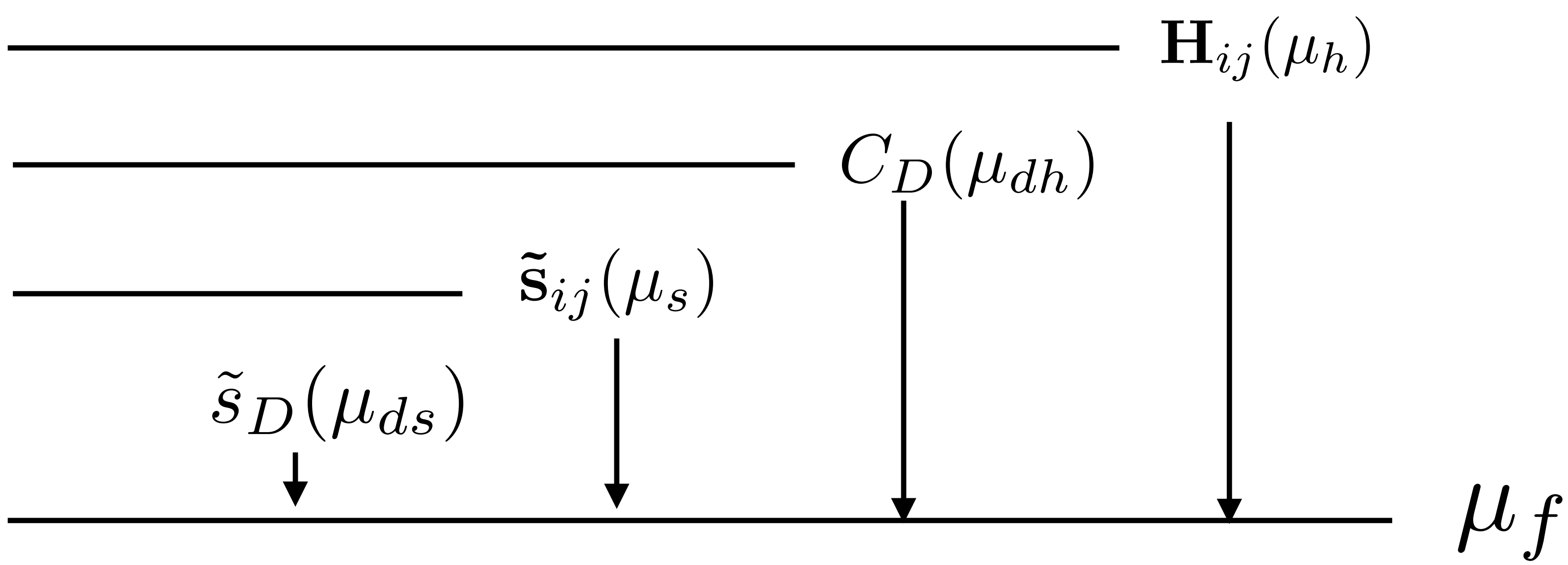
Final collected factorization formula for hard kernel in Mellin-space:

1205.3662 A.Ferroglia, B.Pecjak, L.L.Yang
1601.07020 B.Pecjak, D.Scott, X.Wang, L.L.Yang

$$\widetilde{c}_{ij}(N, M, m_t, \cos\theta, \mu_f) = Tr\left[\mathbf{H}_{ij}(M, \cos\theta, \mu_f)\,\widetilde{\mathbf{s}}_{ij}\left(\ln\frac{M^2}{\bar{N}^2\mu_f^2}, M, \cos\theta, \mu_f\right)\right]$$
$$\times C_D^2(m_t, \mu_f)\,\widetilde{s}_D^2\left(\ln\frac{m_t}{\bar{N}\mu_f}, \mu_f\right) + \mathcal{O}\left(\frac{1}{N}\right) + \mathcal{O}\left(\frac{m_t}{M}\right)$$



Framework



- Use RGEs to resum large logs

$$\widetilde{c}_{ij}(N,\mu_f) = Tr\left[\widetilde{\mathbf{U}}_{ij}(\bar{N},\mu_f,\mu_h,\mu_s)\,\mathbf{H}_{ij}(\mu_h)\,\widetilde{\mathbf{U}}^{\dagger}_{ij}(\bar{N},\mu_f,\mu_h,\mu_s)\widetilde{\mathbf{s}}_{ij}\left(\ln\frac{M^2}{\bar{N}^2\mu_s^2},\mu_s\right)\right]$$
$$\times\, U_D^2(\bar{N},\mu_f,\mu_{dh},\mu_{ds})\,C_D^2(m_t,\mu_{dh})\,\widetilde{s}_D^2\left(\ln\frac{m_t}{\bar{N}\mu_{ds}},\mu_{ds}\right) + \mathcal{O}\left(\frac{1}{N}\right) + \mathcal{O}\left(\frac{m_t}{M}\right)$$

Framework

- To obtain the final result, Mellin inverse is necessary.

$$\frac{d^2\sigma}{dM_{t\bar{t}}\, d\cos\theta} = \frac{8\pi\beta_t}{3sM_{t\bar{t}}} \sum_{ij} \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} dN\, \tau^{-N}\, \widetilde{\mathcal{L}}_{ij}(N,\mu_f)\, \widetilde{c}_{ij}(N, M_{t\bar{t}}, m_t, \cos\theta, \mu_f)$$

$$= \frac{8\pi\beta_t}{3sM_{t\bar{t}}} \sum_{ij} \int_{\tau}^{\infty} \frac{dz}{z}\, \mathcal{L}_{ij}(\tau/z,\mu_f) \frac{1}{2\pi i} \int_{c-i\infty}^{c+i\infty} dN\, z^{-N}\, \widetilde{c}_{ij}(N, M_{t\bar{t}}, m_t, \cos\theta, \mu_f)$$

- Use Chebyshev polynomials to approximate x-space PDFs, then do Mellin transformation.

- Adopt MP to avoid Landau pole.

A. Kulesza, G. F. Sterman and W. Vogelsang, 0202251

M. Bonvini and S. Marzani, 1405.3654

Framework

Framework

- matching with soft-gluon resummation

$$d\sigma^{\mathrm{NNLL}'_{b+m}} = d\sigma^{\mathrm{NNLL}'_b} + (d\sigma^{\mathrm{NNLL}_m} - d\sigma^{\mathrm{NNLL}_m}|_{m_t\to 0})$$

“m” denotes only soft logs resumed, so keeps the full dependence on the top mass.
While “b” means resummation of both mass logs and soft logs.

Framework

- matching with soft-gluon resummation

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- matching with fixed order

$$d\sigma^{\mathrm{(N)NLO+NNLL}'} = d\sigma^{\mathrm{NNLL}'_{b+m}} + (d\sigma^{\mathrm{(N)NLO}} - d\sigma^{\mathrm{NNLL}'_{b+m}}|_{\mathrm{(N)NLO}})$$

"m" denotes only soft logs resumed, so keeps the full dependence on the top mass.
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Main results and scale choice

Notations

In boosted region, it's important that we could have $m_t^2 \ll |t_1| \ll M_{t\bar{t}}^2$

$$x_t = -t_1/M_{t\bar{t}}^2$$

$$\mathcal{H}_{gg}^{\rm LO}\Big|_{t_1 \to 0} \propto 1/x_t$$

$$m_{T,t} + m_{T,\bar{t}} \equiv H_T$$

$\downarrow$ soft limit

$$H_T = 2m_T$$

$$\mathcal{H}_{ij}^{\rm LO} = \mathcal{S}_{ij}^{\rm LO} \equiv {\rm Tr}[\mathbf{H}_{ij}^{\rm LO}\tilde{\mathbf{s}}_{ij}^{\rm LO}]$$

$$\mathcal{H}_{ij}^{N(NLO)} \equiv {\rm Tr}[\mathbf{H}_{ij}^{\rm N(NLO)}\tilde{\mathbf{s}}^{\rm LO}]$$

$$\mathcal{S}_{ij}^{N(NLO)} \equiv {\rm Tr}[\mathbf{H}_{ij}^{\rm LO}\tilde{s}^{\rm (N)NLO}]$$

$M_{t\bar{t}}$ distribution μ_h

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In boosted region, it's important that we could have $m_t^2 \ll |t_1| \ll M_{t\bar{t}}^2$

$$-t_1\big|_{m_t\to 0} \approx \frac{M_{t\bar{t}}^2}{2}(1-\cos\theta) + m_t^2\cos\theta \xrightarrow{\cos\theta\to 1} p_T^2 + m_t^2 \equiv m_T^2\,,$$

$$-u_1\big|_{m_t\to 0} \approx \frac{M_{t\bar{t}}^2}{2}(1+\cos\theta) - m_t^2\cos\theta \xrightarrow{\cos\theta\to -1} m_T^2\,.$$

$$\frac{\mathcal{H}_{gg}^{\rm NLO}(\mu_h)}{\mathcal{H}_{gg}^{\rm LO}(\mu_h)}\bigg|_{t_1\to 0} = 1+\frac{\alpha_s(\mu_h)}{36\pi}\left[-78\ln^2\left(\frac{-t_1}{\mu_h^2}\right)+24\ln\left(\frac{-t_1}{\mu_h^2}\right)(3+2\ln x_t)+37\pi^2-168\right]$$

$$\frac{\mathcal{H}_{gg}^{\rm NNLO}(\mu_h)}{\mathcal{H}_{gg}^{\rm NLO}(\mu_h)}\bigg|_{t_1\to 0} = 1+\left(\frac{\alpha_s(\mu_h)}{4\pi}\right)^2\left[37.6\ln^4\left(\frac{-t_1}{\mu_h^2}\right)-\big(46.2\ln x_t+47.2\big)\ln^3\left(\frac{-t_1}{\mu_h^2}\right)\right.$$
$$+\big(14.2\ln^2 x_t+22.2\ln x_t-248\big)\ln^2\left(\frac{-t_1}{\mu_h^2}\right)$$
$$\left.+\big(154\ln x_t+102\big)\ln\left(\frac{-t_1}{\mu_h^2}\right)+12.7\ln x_t+577\right]+\mathcal{O}(\alpha_s^3)$$

The philosophy is to get rid of large logs as possible as we can!

$M_{t\bar{t}}$ distribution μ_h

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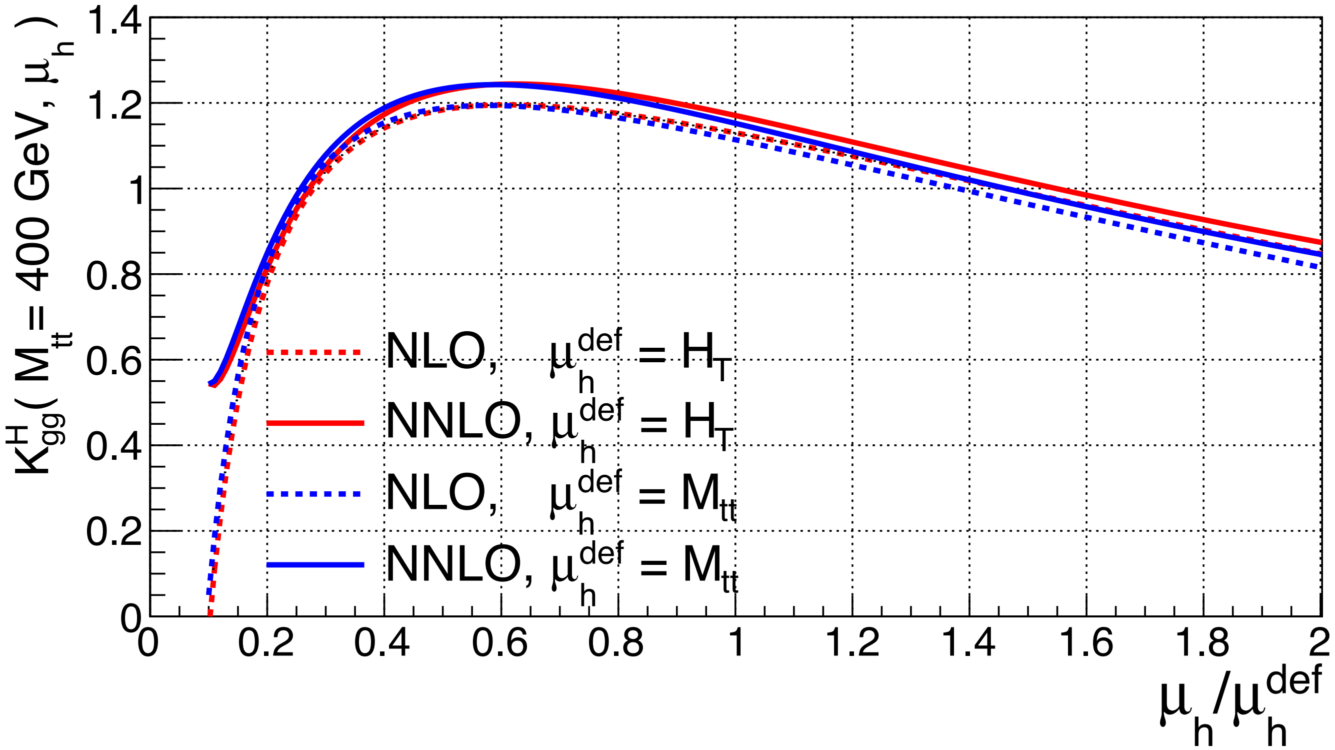
So in boosted region, H_T based hard scale choice is preferred, e.g. $\mu_h \sim H_T/2$
while in not boosted region $M_{t\bar{t}}$ based choice is good.

$M_{t\bar{t}}$ distribution μ_h

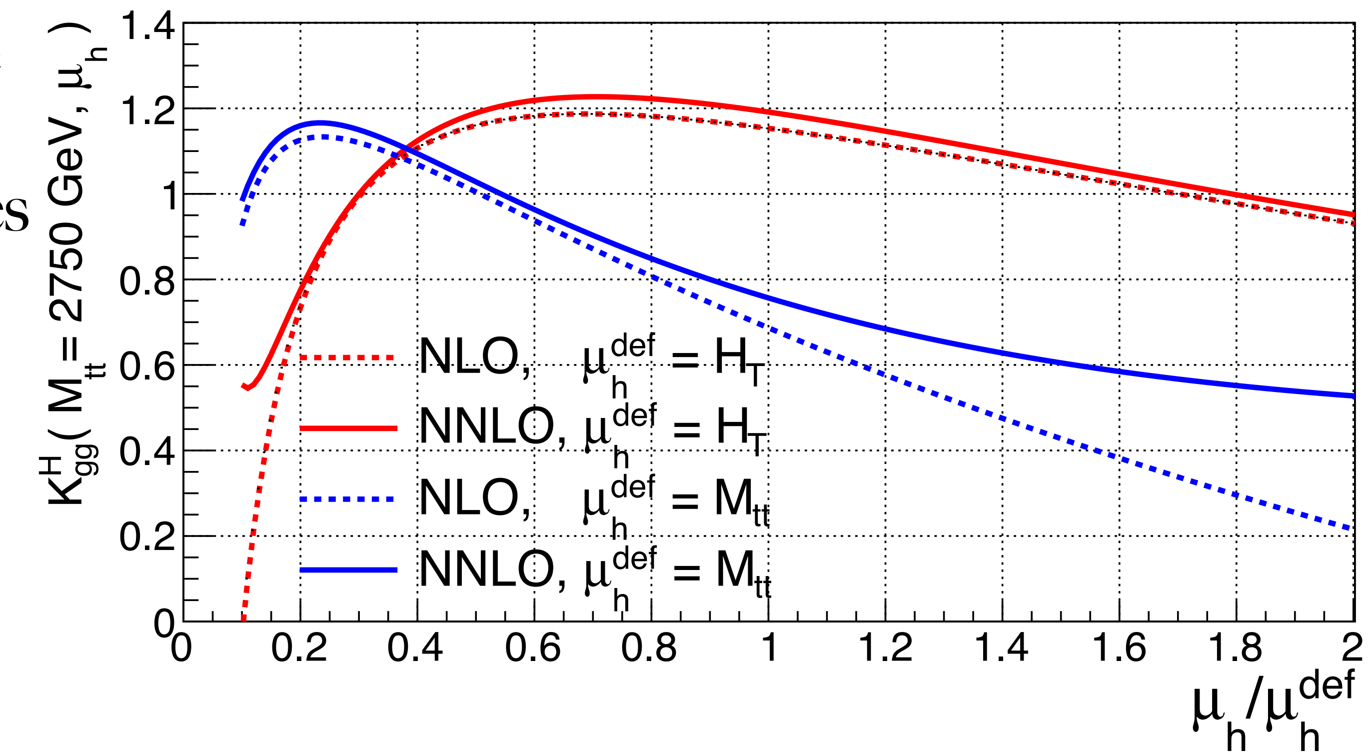


$$\mathrm{K}^{\mathrm{H,N(NLO)}}_{\mathrm{gg}}(M_{t\bar{t}}, \mu_h) \equiv \frac{\int_{-1}^{1} \mathcal{H}^{\mathrm{N(NLO)}}_{ij}(\mu_h) d\cos\theta}{\int_{-1}^{1} \mathcal{H}^{\mathrm{LO}}_{ij}(\mu_h) d\cos\theta}$$

$$\mathcal{H}^{N(NLO)}_{ij} \equiv \mathrm{Tr}[\mathbf{H}^{\mathrm{N(NLO)}}_{ij} \tilde{\mathbf{s}}^{\mathrm{LO}}]$$

- when not boosted, the two kinds of choice don't make any difference.
- But if highly boosted, H_T based one varies gently.

$$\mu_h^{\mathrm{def}} = H_T/2$$



$M_{t\bar{t}}$ distribution μ_s

$$\left.\frac{\mathcal{S}_{gg}^{\text{NLO}}(\mu_s)}{\mathcal{S}_{gg}^{\text{LO}}}\right|_{t_1\to 0} = 1+\frac{\alpha_s(\mu_s)}{36\pi}\left[78\ln^2\left(\frac{-t_1}{\mu_s^2\bar{N}^2}\right) - 48\ln\left(\frac{-t_1}{\mu_s^2\bar{N}^2}\right)\ln x_t + 24\ln^2 x_t + 31\pi^2\right]$$

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$$+ \left(37.3\ln^2 x_t + 20.4\ln x_t + 354\right)\ln^2\left(\frac{-t_1}{\mu_s^2\bar{N}^2}\right)$$

$$- \left(14.2\ln^3 x_t + 20.4\ln^2 x_t + 218\ln x_t + 12.9\right)\ln\left(\frac{-t_1}{\mu_s^2\bar{N}^2}\right)$$

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H_T

$M_{t\bar{t}}$

$M_{t\bar{t}}$ distribution μ_s

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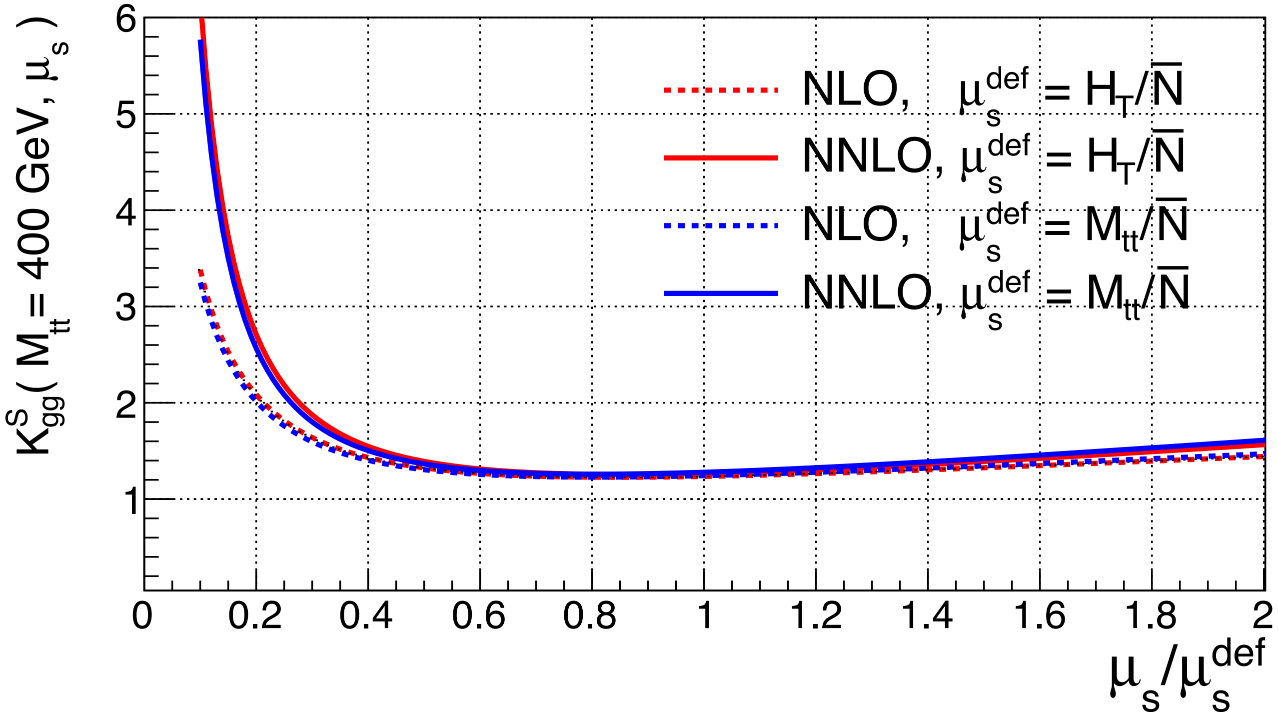
but still need more care numerically

$M_{t\bar{t}}$ distribution μ_s



$$\mathrm{K}_{\mathrm{gg}}^{\mathrm{S,N(NLO)}}(M_{t\bar{t}}, \mu_s) \equiv \frac{\int_{-1}^{1} \mathcal{S}_{ij}^{\mathrm{N(NLO)}}(\mu_s) d\cos\theta}{\int_{-1}^{1} \mathcal{S}_{ij}^{\mathrm{LO}}(\mu_s) d\cos\theta}$$

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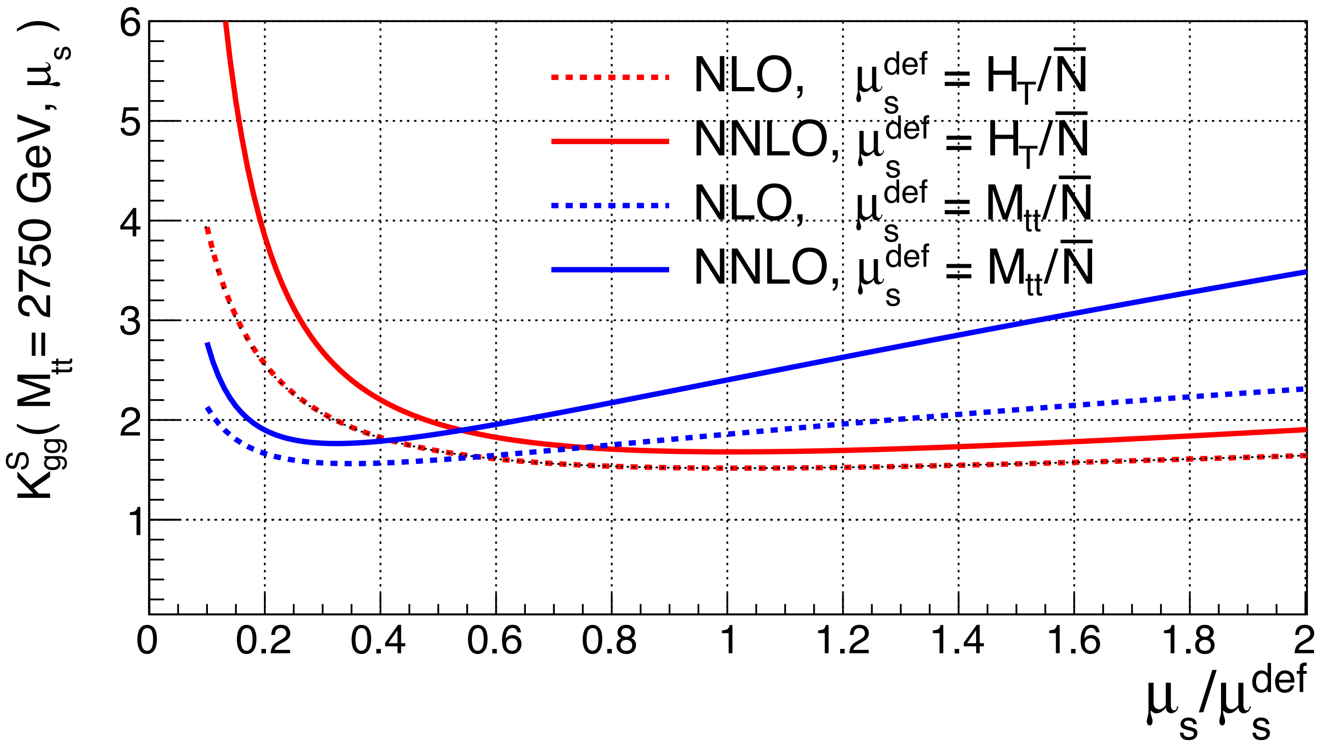
N-space PDFs needed

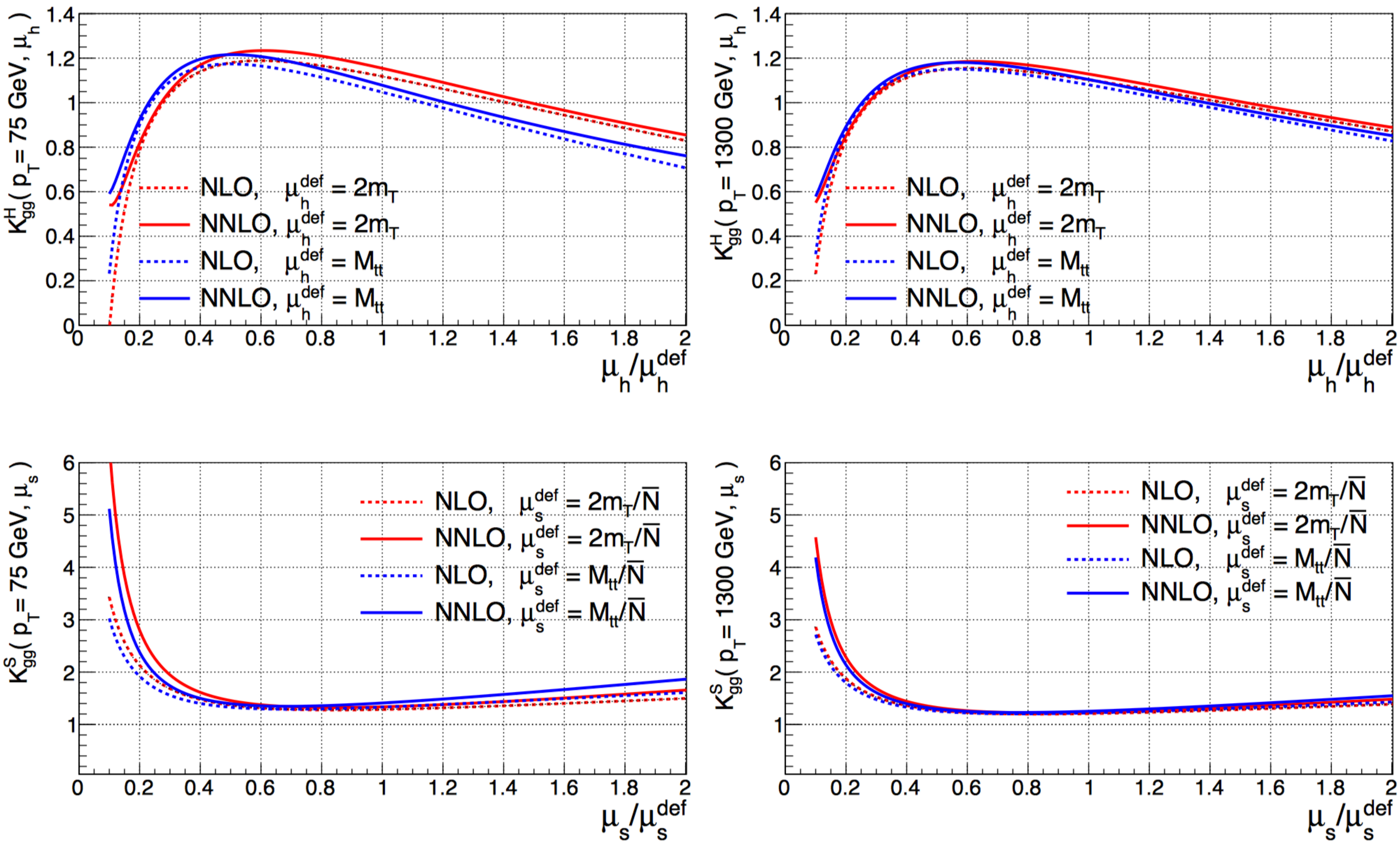
- when not boosted, the two kinds of choice don't make any difference.
- But if highly boosted, H_T based one varies gently.



$$\mu_s^{\mathrm{def}} = H_T/\bar{N}$$

$p_{T,t}$ distribution

μ_h and μ_s



$p_{T,t}$ distribution

μ_h and μ_s

$p_{T,t}$ distribution

Jacobian peak: $2m_T \sim M_{t\bar{t}}$

- fixed the pTt don't indeed constrain much on the pT of anti-top, but rather on the combined pT of anti-top and the radiation.
- in fact, hard radiations contribute a lot.

$p_{T,t}$ distribution

Jacobian peak: $2m_T \sim M_{t\bar{t}}$

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but rather on the combined pT of anti-top and the radiation.

- in fact, hard radiations contribute a lot.

↓

- soft limit is not so good as in Mtt case!
- but still, we can choose in the similar way:

$$\mu_h^{\text{def}} = m_T, \ \mu_s^{\text{def}} = 2m_T/\bar{N}$$

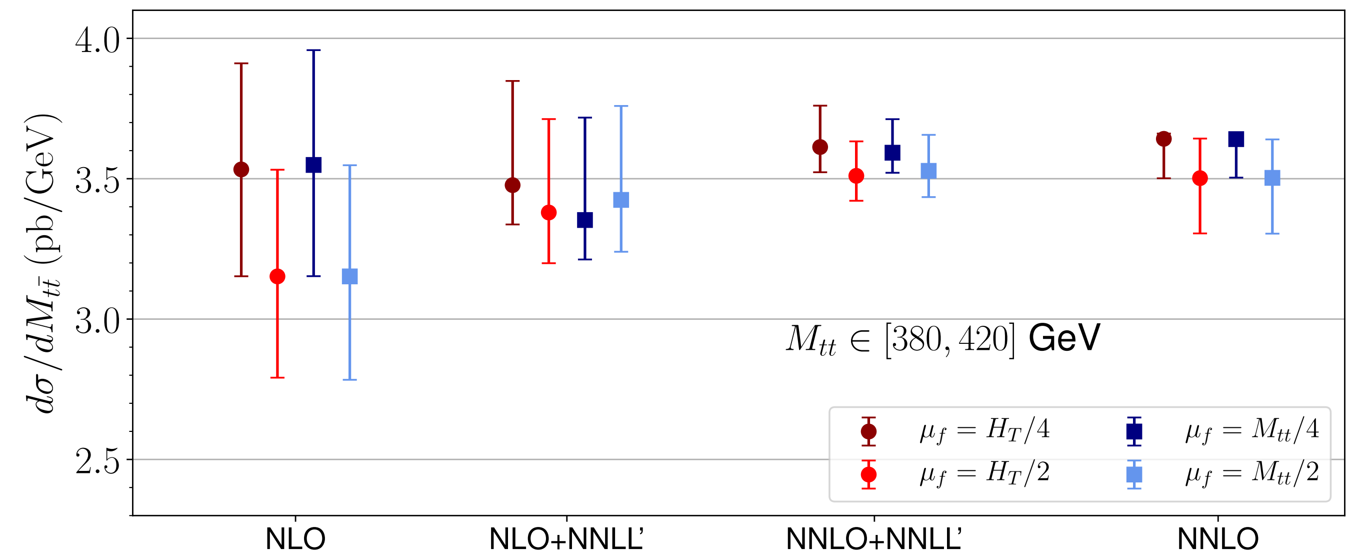
$M_{t\bar{t}}$ and $p_{T,t}$ distribution

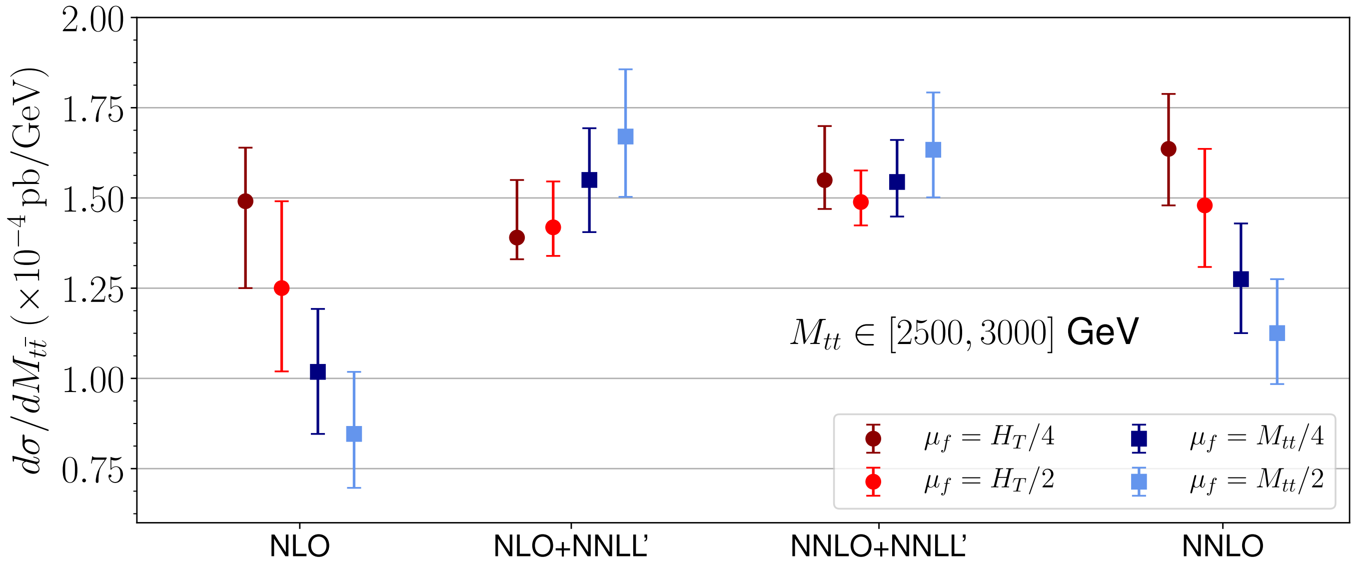
- m_t is fixed, so the natural scale choice for these two matching pieces is straightforward.
- In fact, the numerical dependence on these two scales choice is small.

$$C_D(m_t, \mu_{dh}),\ \ s_D(m_t/\bar{N}, \mu_{ds})$$

$$\mu_{dh}^{\text{def}} = m_t,\ \ \mu_{ds}^{\text{def}} = m_t/\bar{N}$$

$M_{t\bar{t}}$ distribution μ_f





- Resummation is indeed important in high energy tail.
- Resummation improve the convergence.
- Matched results is not sensitive to different choices.

based on perturbative convergence

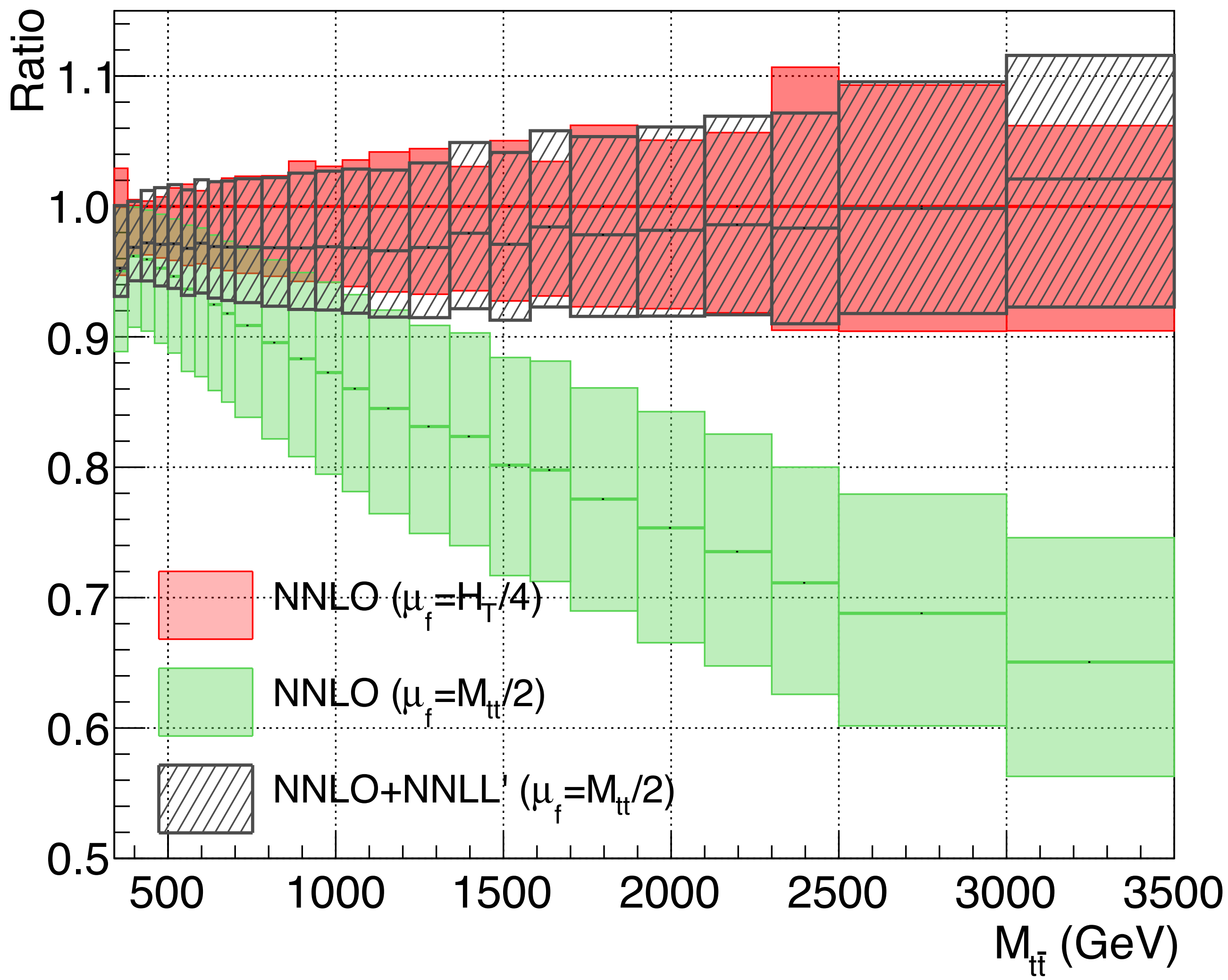
$$\mu_f^{\text{def,NNLO}} = H_T/4$$

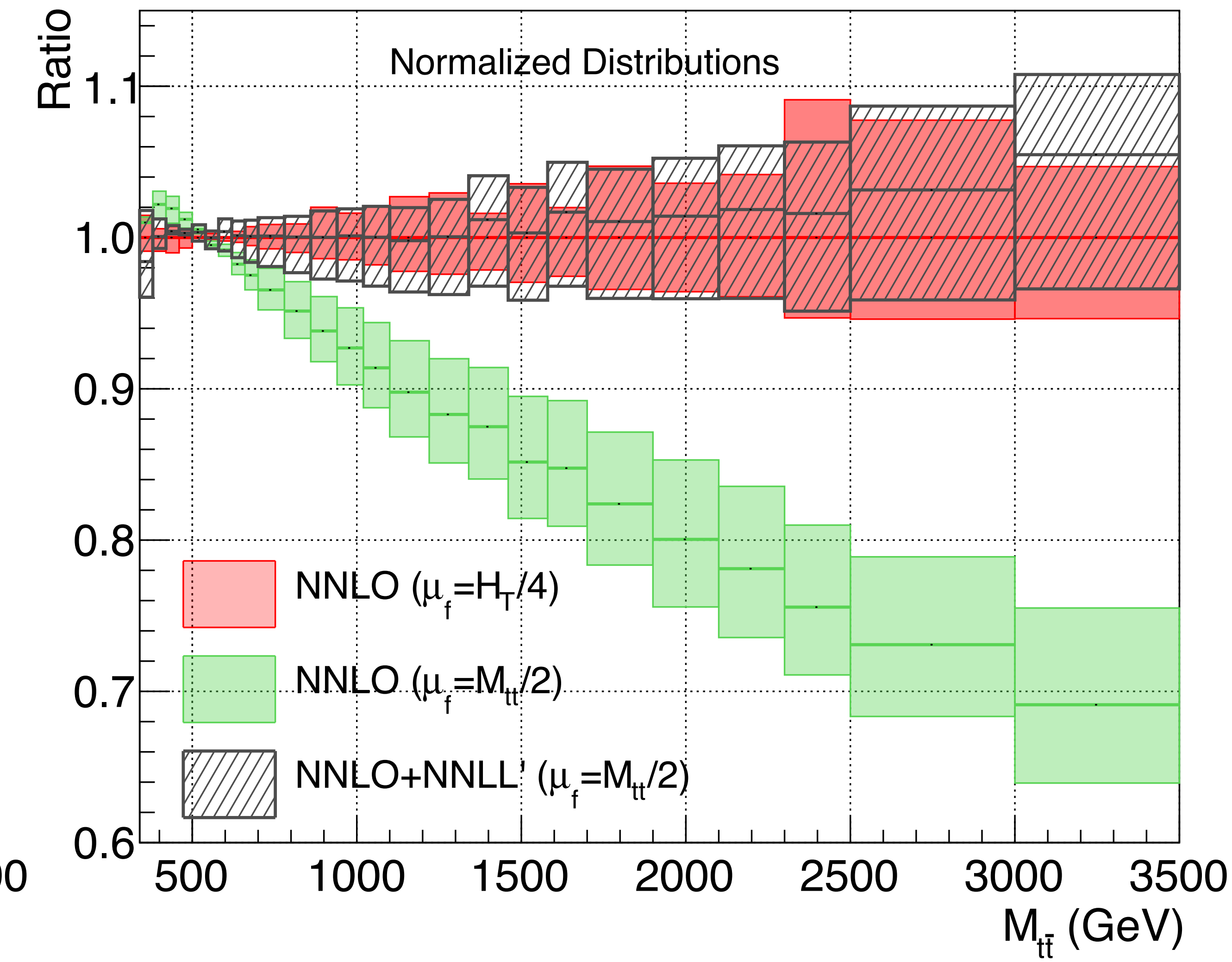
$$\downarrow$$

$$\mu_f^{\text{def,NNLO+NNLL'}} = H_T/4$$

1606.03350 M. Czakon, D. Heymes, A. Mitov

$M_{t\bar{t}}$ distribution μ_f

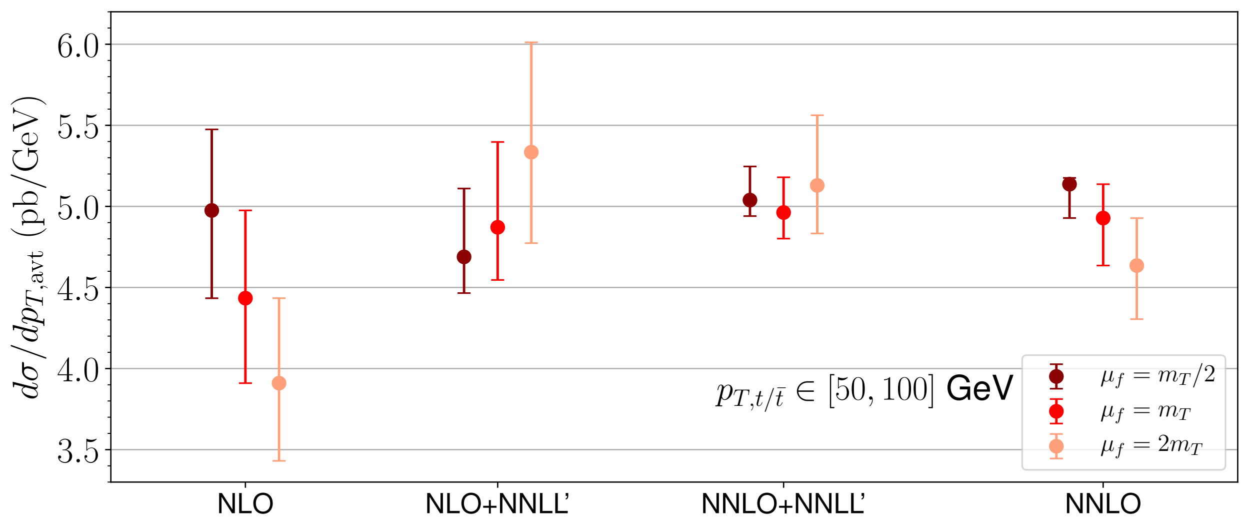


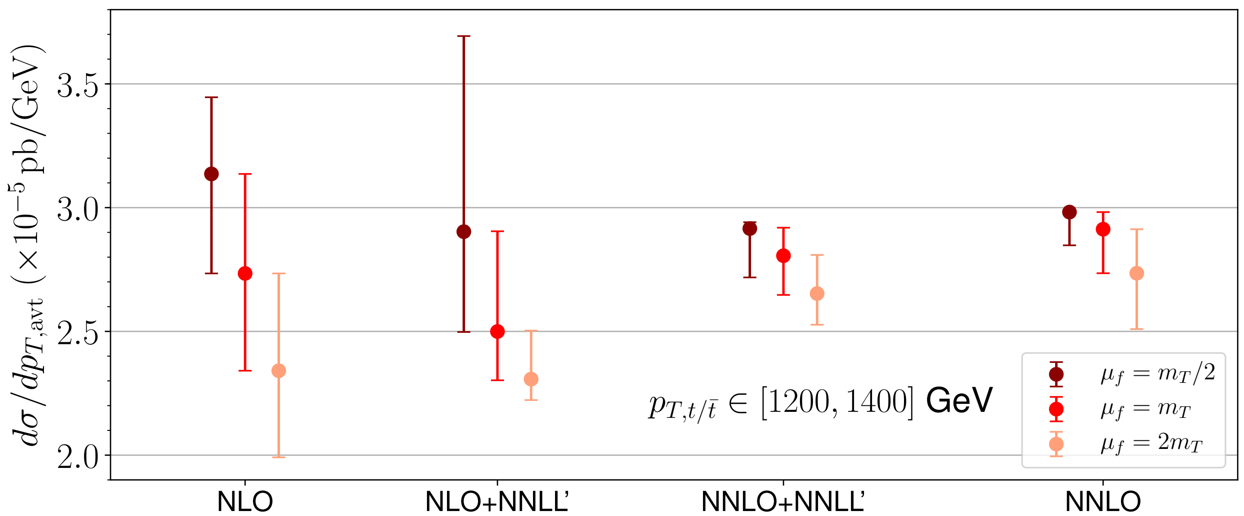


- Resummation make results more stable w.r.t different μ_f choice

$$\text{Ratio} \equiv \frac{d\sigma}{d\sigma^{\text{NNLO}}(\mu_f^{\text{def}} = H_T/4)}$$

$p_{T,t}$ distribution μ_f





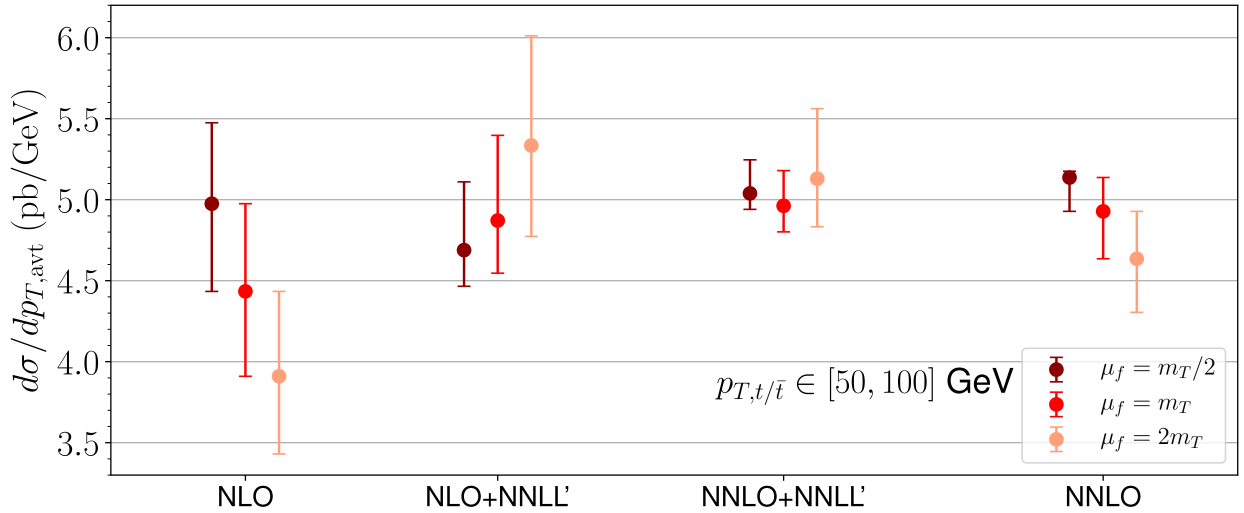
- pT case is very different, while in low energy region, it improve the convergence, in high region it does not.
- It is because of different kinematic limit in pT case.

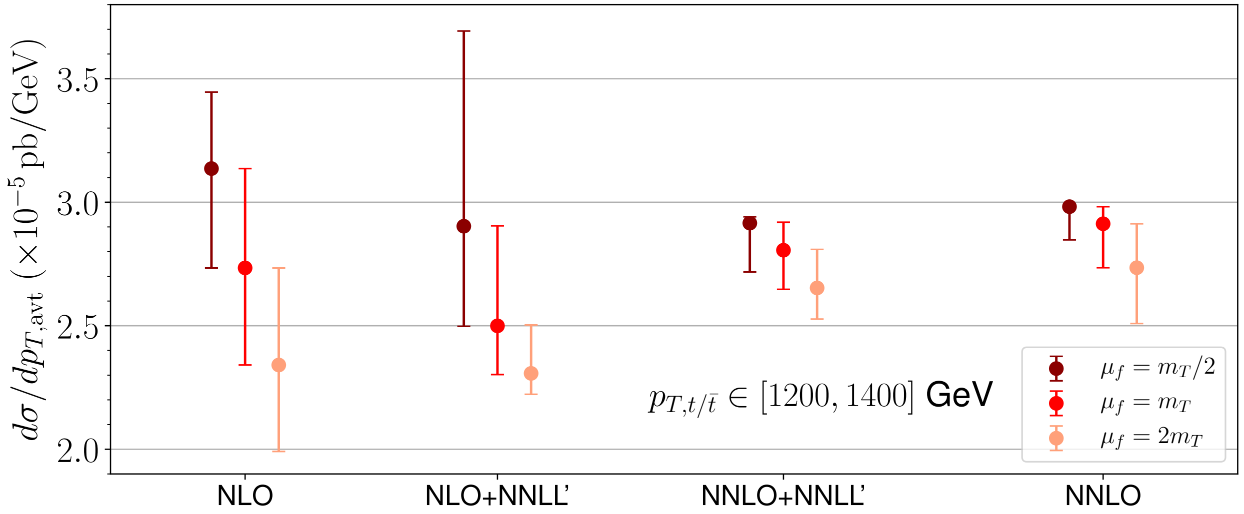
$$\mu_f^{\text{def,NNLO}} = m_T/2$$

$$\downarrow$$

$$\mu_f^{\text{def,NNLO+NNLL'}} = m_T/2$$

$p_{T,t}$ distribution μ_f





- pT case is very different, while in low energy region, it improve the convergence, in high region it does not.
- It is because of different kinematic limit in pT case.

$$\mu_f^{\text{def,NNLO}} = m_T/2$$

$$\downarrow$$

$$\mu_f^{\text{def,NNLO+NNLL'}} = m_T/2$$

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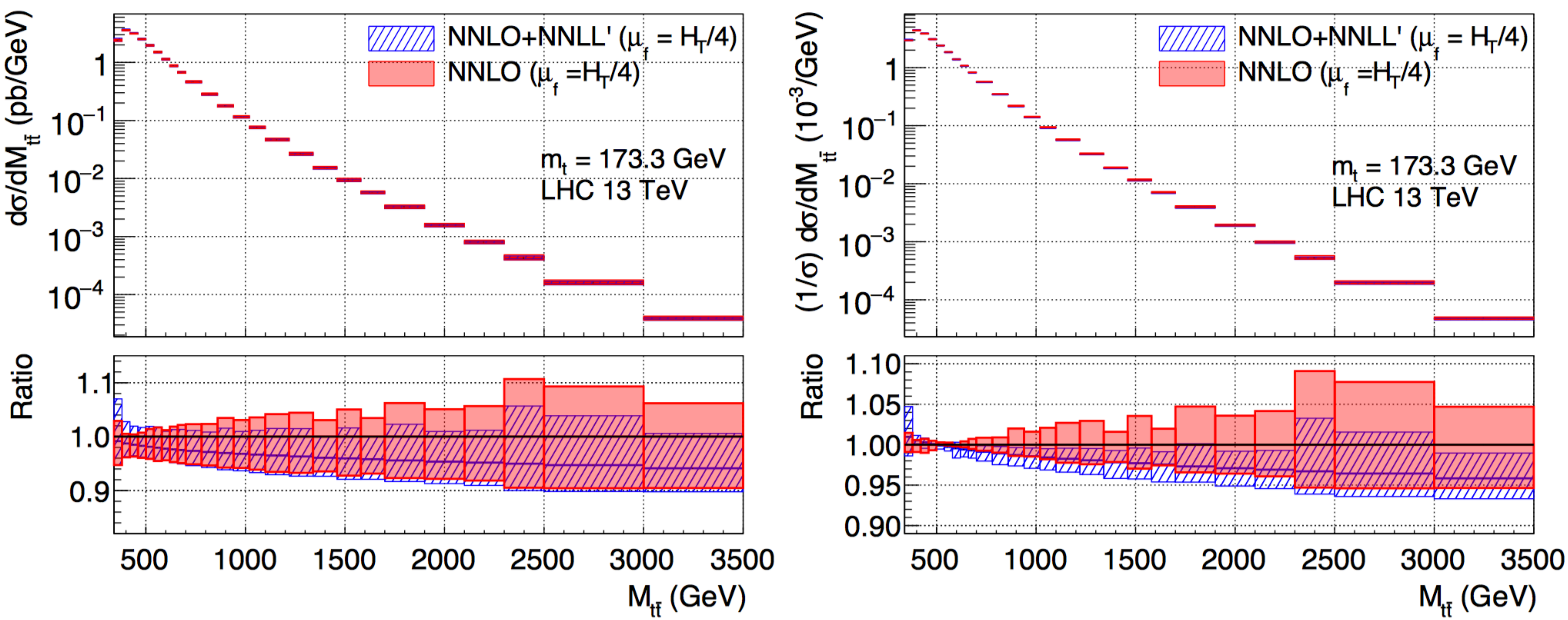
Final results $M_{t\bar{t}}$

$$\mu_f^{\rm def} = H_T/4, \mu_h^{\rm def} = H_T/2, \mu_s^{\rm def} = H_T/\bar{N}$$
$$\mu_{dh}^{\rm def} = m_t, \mu_{ds}^{\rm def} = m_t/\bar{N},$$

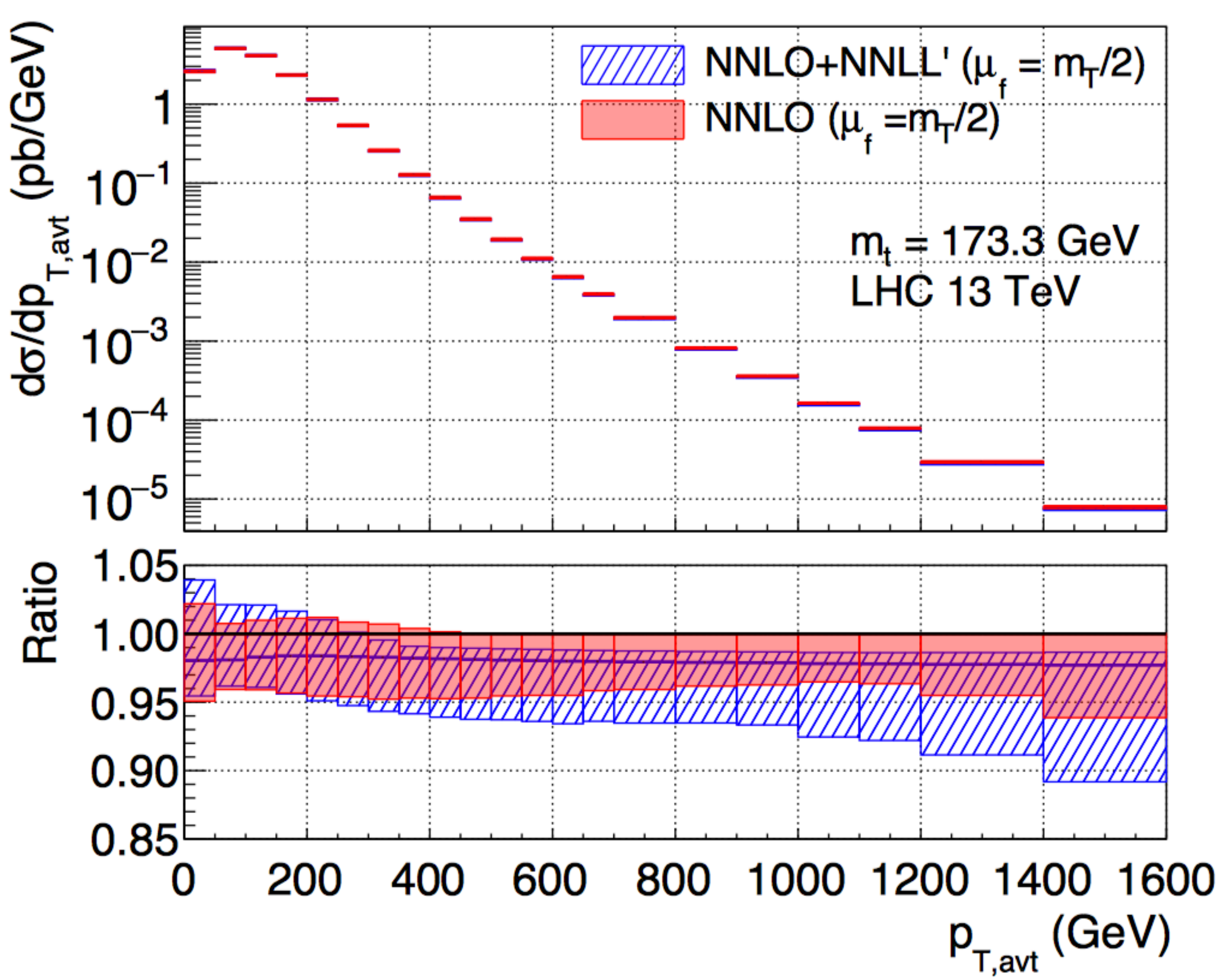


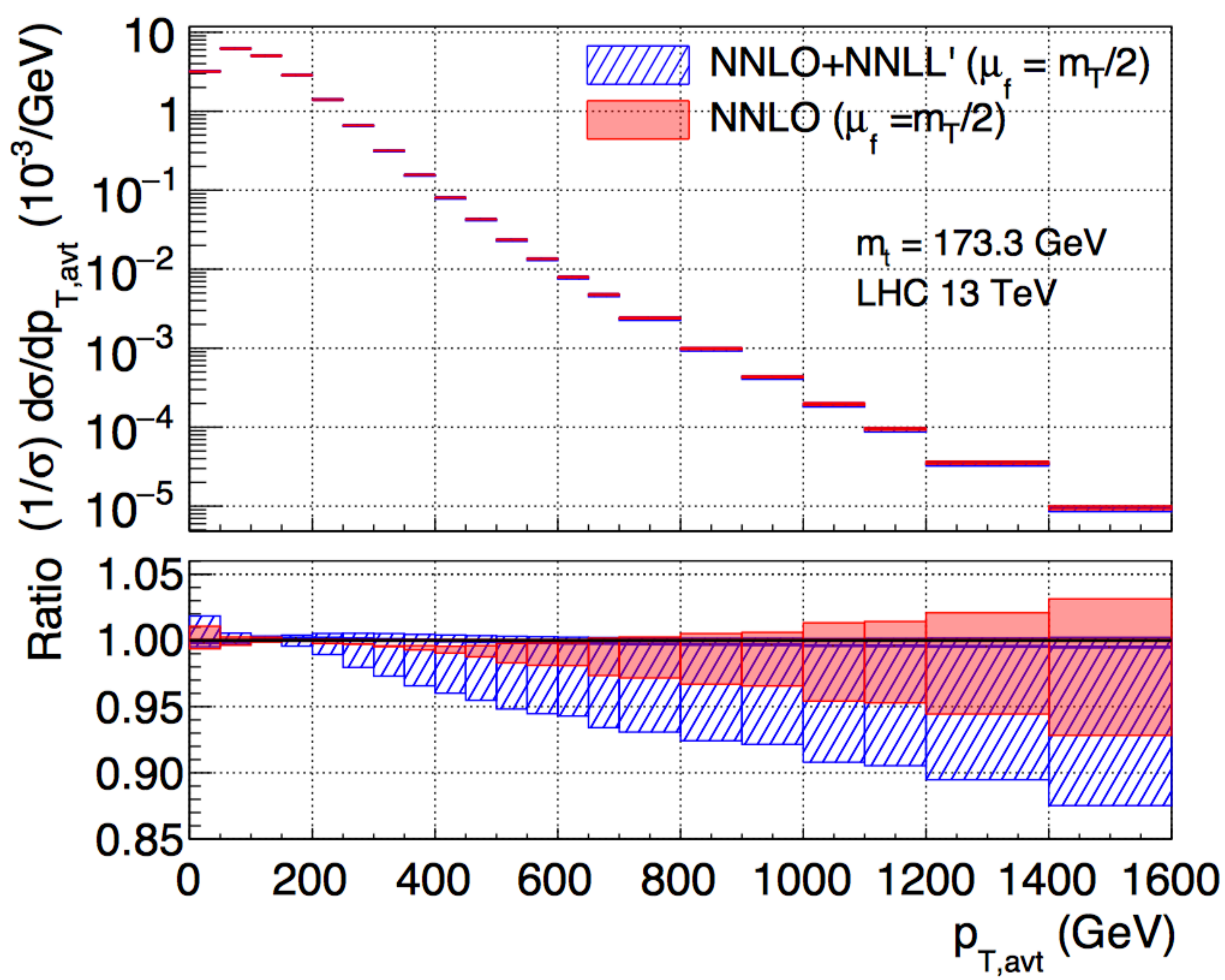
Final results

$p_{T,t}$

$$\mu_f^{\rm def} = m_T/2, \mu_h^{\rm def} = m_T, \mu_s^{\rm def} = 2m_T/\bar{N}$$

$$\mu_{dh}^{\rm def} = m_t, \mu_{ds}^{\rm def} = m_t/\bar{N},$$





Conclusion and Next

- It's the state-of-the-art QCD prediction for top pair differential distribution for the whole phase space.
- After resummation, it is more stable w.r.t different factorization scale choices.
- In boosted region, hard and soft scale have very different behaviors against usually chosen ones.
- $p_{T,t}$ distributions has less of an impact compared with $M_{t\bar{t}}$ ones.
- Especially, with new scale choice, $M_{t\bar{t}}$ distribution's uncertainty is also smaller.
- We will compare with the latest experiment data soon.

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Thank you for the last attention!