$\mathrm{NNLO}_{\mathrm{sing}}$ and $\mathrm{N^3LL}$ for W/Z and Higgs production at large p_T

Thomas Becher
AEC, University of Bern

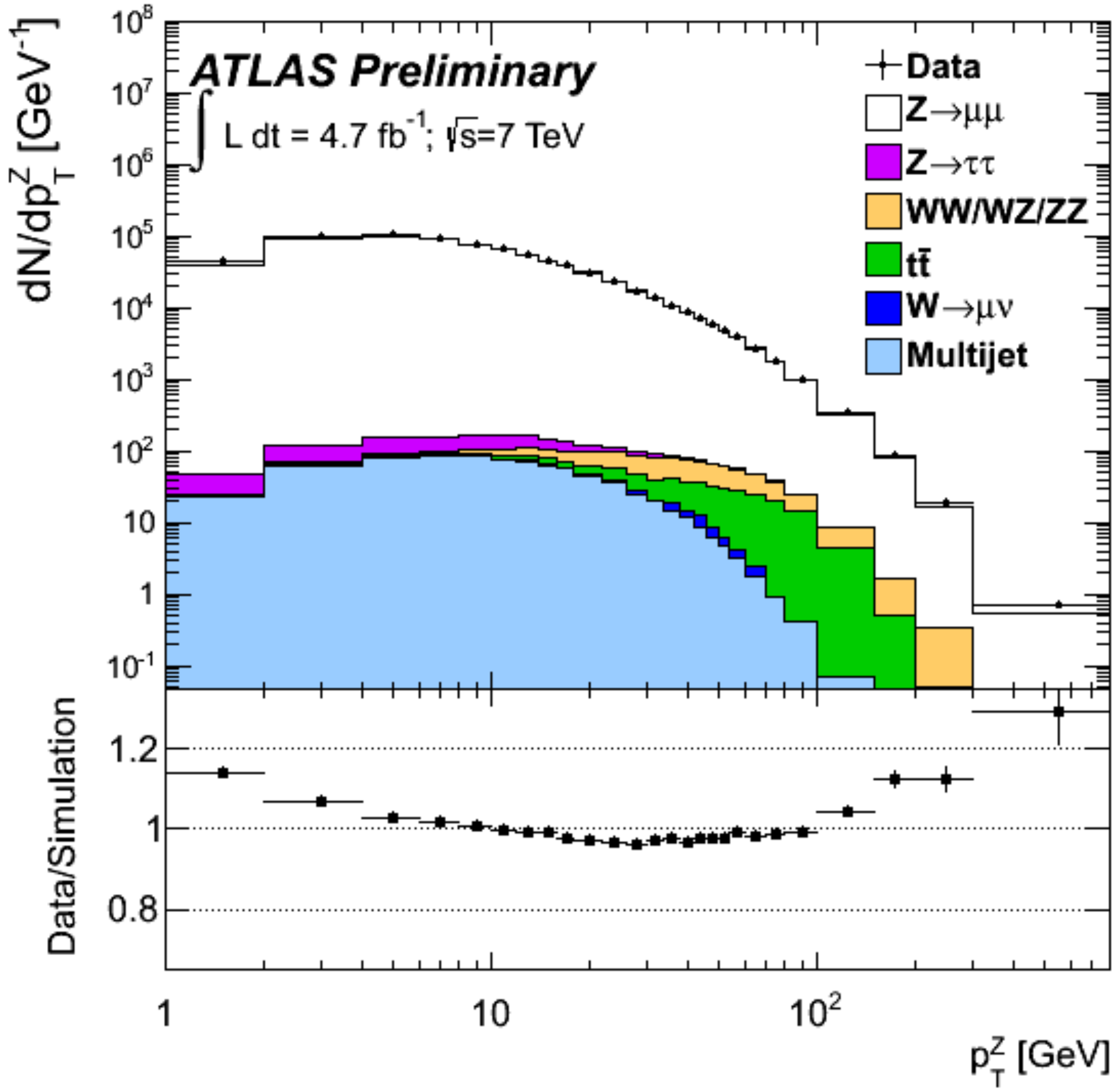
Loopfest XIII, NY City College of Technology
June 18th to 20th, 2014

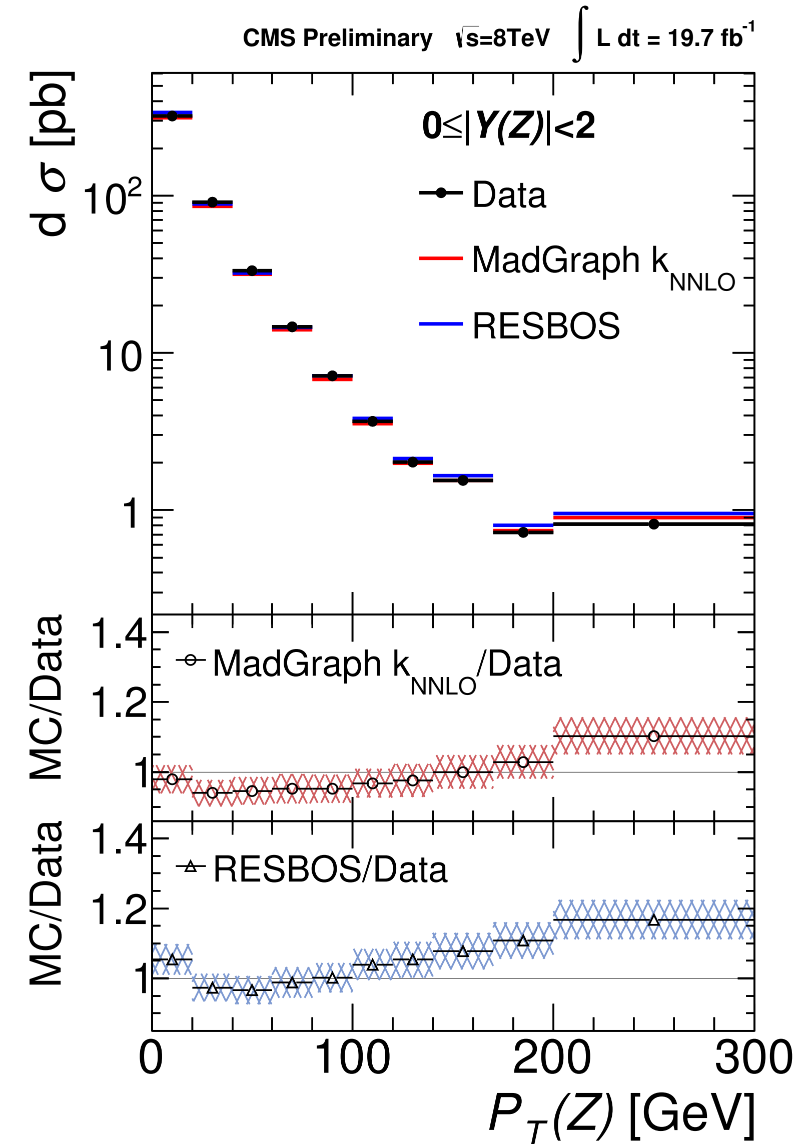
Inclusive production of single, electroweak boson is the most basic hard-scattering process at hadron colliders.

- QCD benchmark
- PDF determination, M_W determination
- Jet-energy calibration
- Search for New Physics
- ...

see Michael Schmitt's Talk

New measurements for Z production





1406.3660

CMS-PAS-SMP-13-013

0.5% Precision at low p_T, few % at higher p_T.

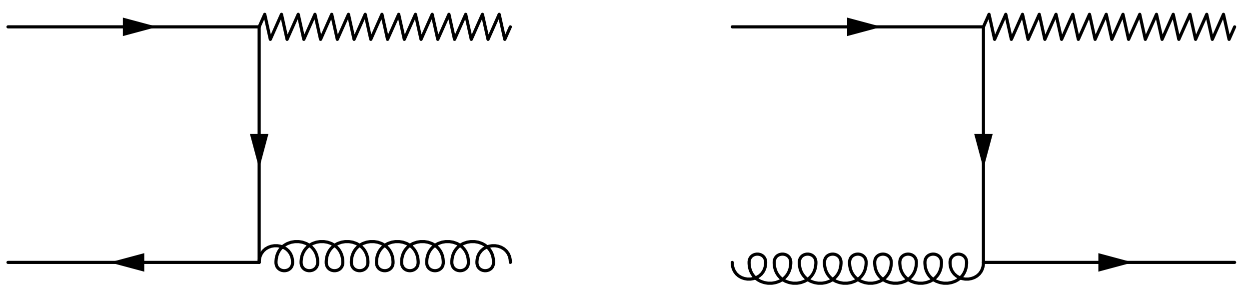
Among the most precise measurements at LHC!

Talk based on

- Factorization theorem, NNLL resummation for photon production TB, Schwartz ’09
- W/Z to $N^3LL_{partial}$+NLO TB, Lorentzen, Schwartz ’12
- Electroweak Sudakov effects TB, Garcia Tormo ’13
- Two-loop jet functions TB Neubert ’06, TB, Bell ’11 two-loop soft function TB, Bell, Marti ’12
- **New:** Two-loop hard function, full N^3LL+NLO for W/Z and Higgs TB, Bell, Lorentzen, Marti ’13
  - First resummation of “3 jet obs.” at this accuracy

Fixed order at $q_T \neq 0$

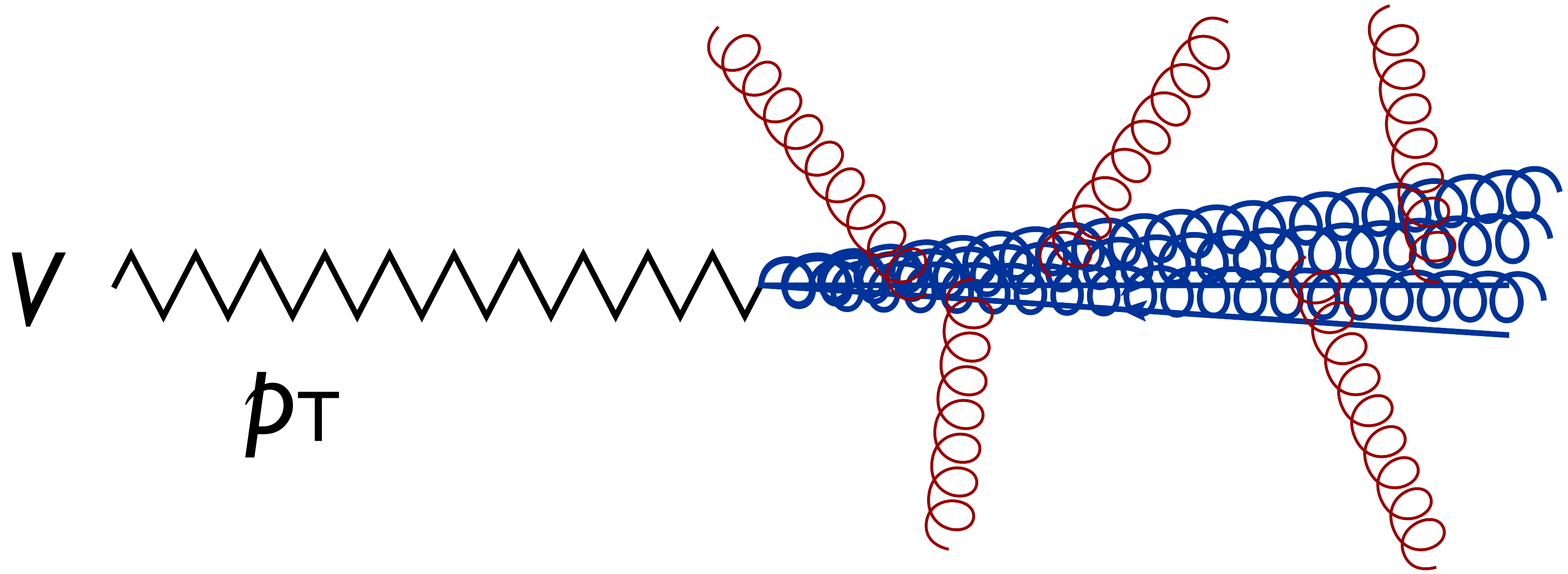
- LO



- NLO known since the 80's. (Ellis, Martinelli, Petronzio'83; Arnold Reno '89; Gonsalves, Pawlowski, Wai '89) Implemented in numerical codes.
- NNLO computations in progress.
  - 2-loop virtual corrections known (Garland, Gehrmann, Glover, Koukoutsakis and Remiddi '01 '02, Gehrmann and Tancredi '11 + Weihs '13; Gehrmann, Jaquier, Glover and Koukoutsakis '11)
  - Difficulty: singularity structure of **real emissions**!
  - First results for $gg \to H + X$ Boughezal et al. '13

update: talks by Fabrizio Caola and Matthieu Jaquier

Simplification near threshold



Real emission simplify drastically near the partonic threshold $m_X^2 \to 0$:

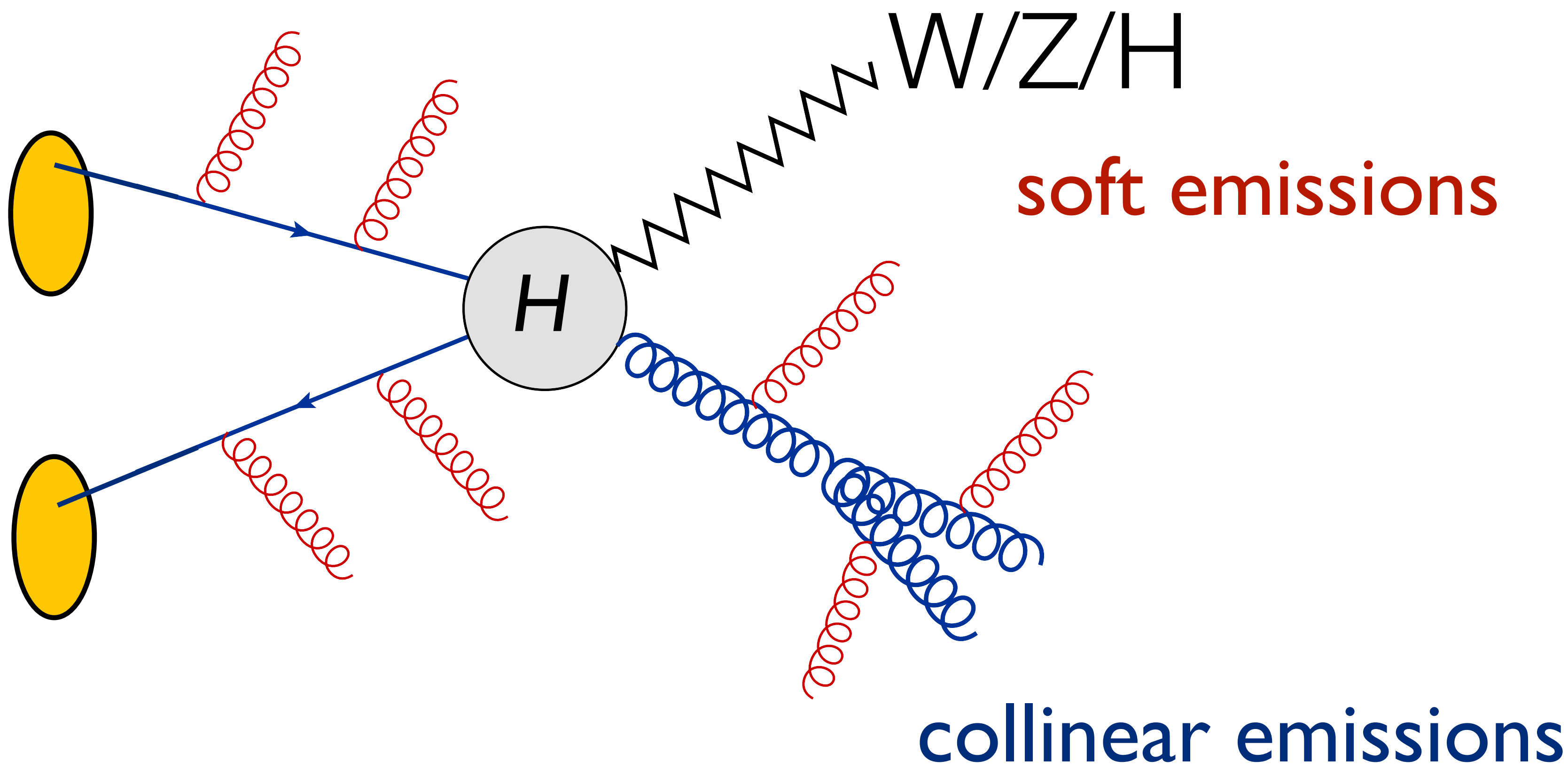
- single, low-mass jet, recoiling against V,
- accompanied by soft radiation

Use SCET to compute real emissions.

Factorization theorem

Cross section at large p_T near the partonic threshold $m_X^2 \to 0$

TB, Schwartz '09

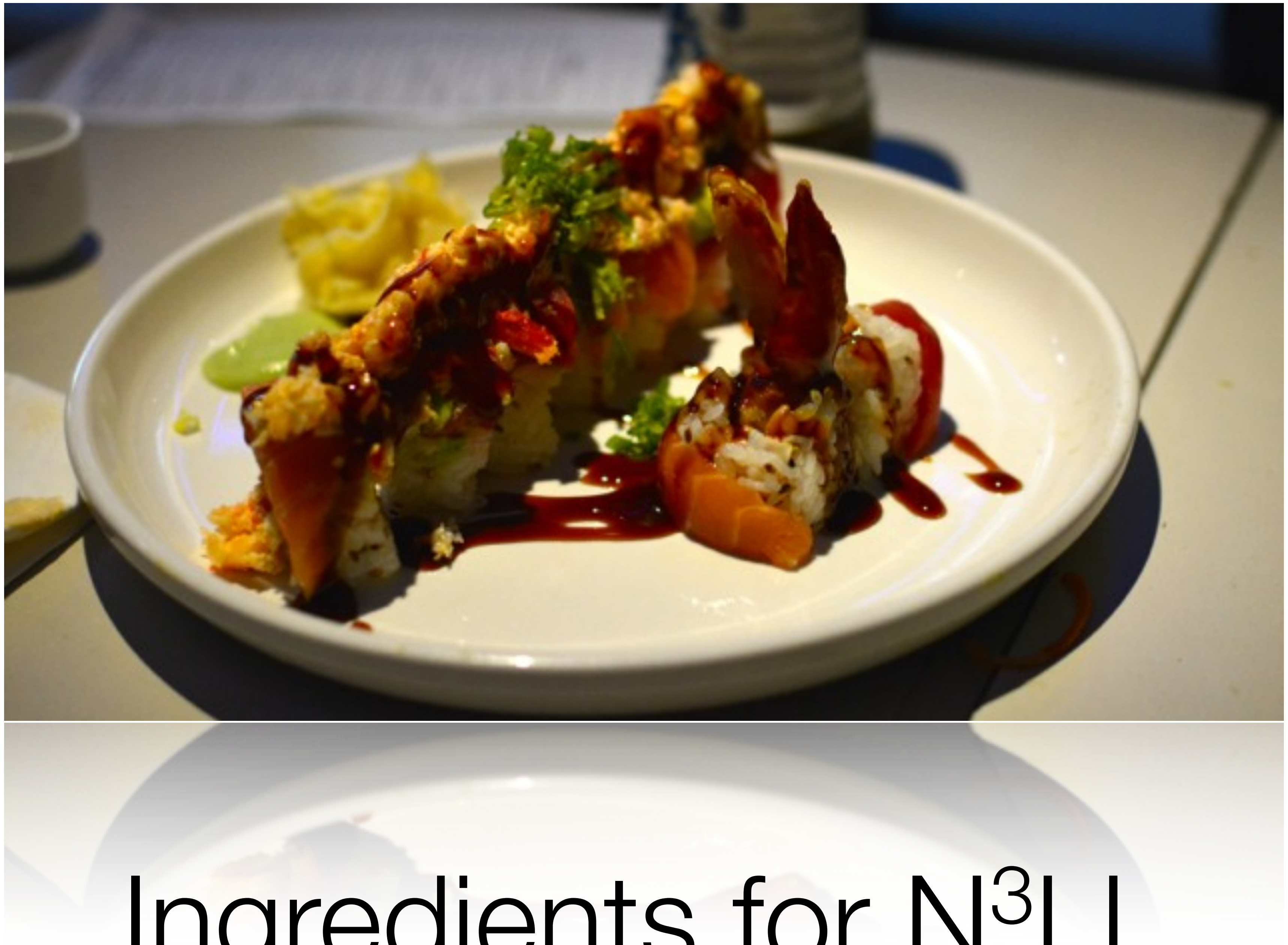


$$\hat{s}\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}\hat{u}\,\mathrm{d}\hat{t}} = H_{ab}(\hat{u},\hat{t})\,(J_c \otimes S_{ab})(m_X^2)$$

Threshold cross section

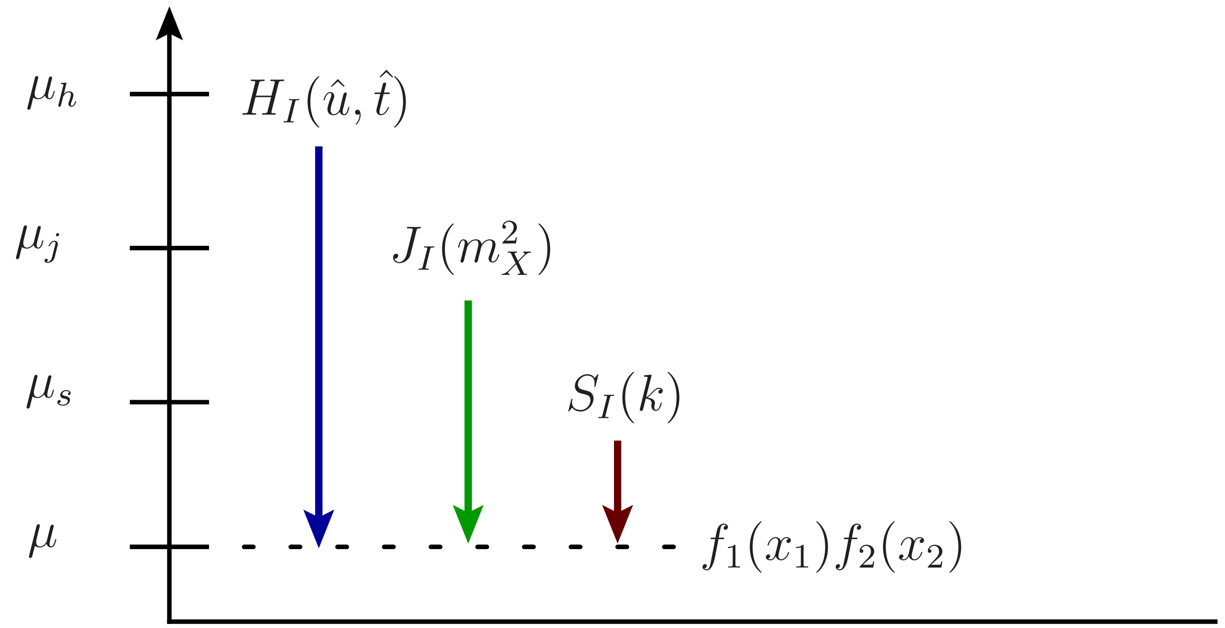
$$\frac{d^2\hat{\sigma}^{\rm sing}}{dy\,dp_T^2} = \hat{\sigma}^{(0)}\Bigg\{\delta(m_X^2) + \frac{\alpha_s}{4\pi}\left[\delta(m_X^2)\left(p_0^{(1)} + h^{(1)}\right) + \left[\frac{1}{m_X^2}\right]_\star p_1^{(1)} + \left[\frac{\ln\frac{m_X^2}{\mu^2}}{m_X^2}\right]_\star p_2^{(1)}\right]$$
$$+\left(\frac{\alpha_s}{4\pi}\right)^2\left[\delta(m_X^2)\left(h^{(2)} + h^{(1)}\cdot p_0^{(1)} + p_0^{(2)}\right) + \left[\frac{1}{m_X^2}\right]_\star\left(h^{(1)}\cdot p_1^{(1)} + p_1^{(2)}\right)\right.$$
$$\left.+\left[\frac{\ln\frac{m_X^2}{\mu^2}}{m_X^2}\right]_\star\left(h^{(1)}\cdot p_2^{(1)} + p_2^{(2)}\right) + \left[\frac{\ln^2\frac{m_X^2}{\mu^2}}{m_X^2}\right]_\star p_3^{(2)} + \left[\frac{\ln^3\frac{m_X^2}{\mu^2}}{m_X^2}\right]_\star p_4^{(2)}\right]\Bigg\}$$

- Theorem gives leading terms for $m_X^2 \to 0$: Singular distributions in m_X^2.
  - Numerically dominant.
- In addition, there are regular contributions. Known at NLO.



Ingredients for N^3LL

Resummation at N^3LL

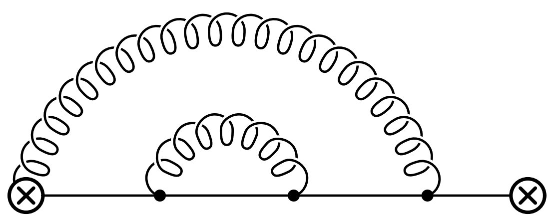


- Two-loop ***H***, ***J***, ***S***
- Three-loop anomalous dimensions γ_H , γ_J, γ_S. All known.
  - γ_H follows from two-jet result using factorization constraints TB, Neubert '09.
- Four-loop $\gamma_{\rm cusp}$
  - Not available, but numerically insignificant, use Padé

Soft and jet functions

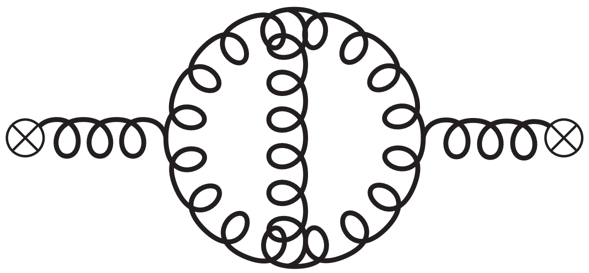
Jet functions (imaginary part of two-point functions)

Quark jet



TB, Neubert ’06

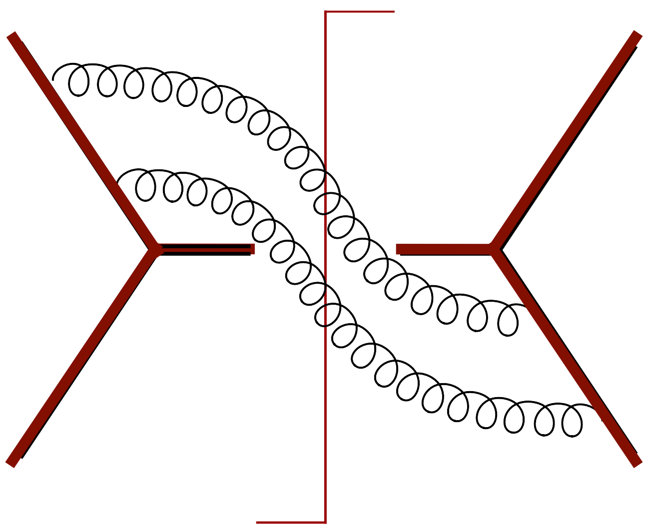
Gluon jet



TB, Bell ’11

Soft function

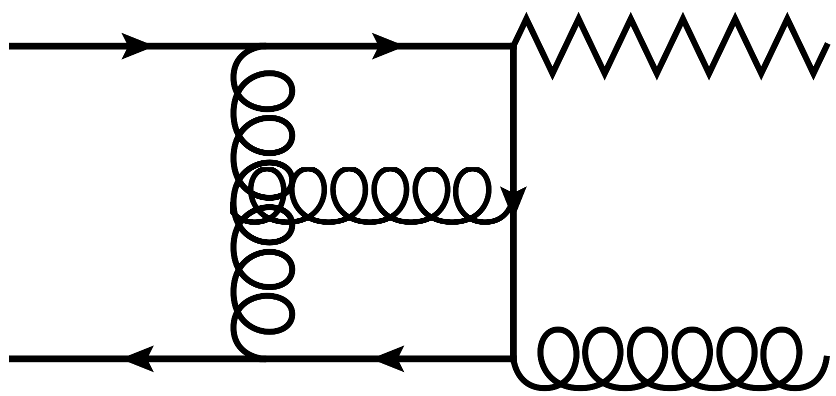
3 Wilson lines



+ ...

TB, Bell, Marti ’12

Hard function



Contains 2-loop virtual corrections. Computed quite some time ago.
Garland, Gehrmann, Glover et al. '02, ...

- Helicity amplitudes, given in electronic form.

Assemble two-loop hard function from two-loop helicity amps.
TB, Bell, Lorentzen, Marti '13

- Use ***C*** and ***P*** and analytic continuation to obtain all helicity amplitudes from minimal set.
- Convert from Catani IR subtraction to $\overline{\text{MS}}$ IR subtraction.

Conversion Catani to $\overline{\text{MS}}$

$\overline{\text{MS}}$ subtraction

H in SCET

poles only

$$|\mathcal{M}^{\text{ren}}(\{p\},\, \mu)\rangle = \lim_{\epsilon \to 0} \boldsymbol{Z}^{-1}(\epsilon,\, \{p\},\, \mu)\, |\mathcal{M}(\epsilon,\, \{p\})\rangle$$

Catani subtraction

$$|\mathcal{M}^{\text{fin}}(\{p\}, \mu)\rangle = \left[1 - \frac{\alpha_s}{2\pi}\boldsymbol{I}^{(1)}(\epsilon) - \left(\frac{\alpha_s}{2\pi}\right)^2 \boldsymbol{I}^{(2)}(\epsilon) + \ldots\right] |\mathcal{M}(\epsilon, \{p\})\rangle$$

given by
Gehrmann et al.

arbitrarily high orders in ε

Result for conversion

$$\mathcal{M}^{(2),\mathrm{ren}} = \mathcal{M}^{(2),\mathrm{fin}} + \boldsymbol{\mathcal{C}_0}\,\mathcal{M}^{(1),\mathrm{fin}} + \left\{ \frac{1}{2}\boldsymbol{\mathcal{C}_0^2} + \frac{\gamma_1^{\mathrm{cusp}}}{8}\left(\boldsymbol{\mathcal{C}_0} + \frac{\pi^2}{128}\Gamma_0'\right) + \frac{\beta_0}{2}\left(\boldsymbol{\mathcal{C}_1} + \frac{\pi^2}{32}\boldsymbol{\Gamma_0} + \frac{7\zeta_3}{96}\Gamma_0'\right) - \frac{1}{8}\left[\boldsymbol{\Gamma_0}, \boldsymbol{\mathcal{C}_1}\right] \right\}\mathcal{M}^{(0)}\,,$$

$\mathcal{C}_0$ and $\mathcal{C}_1$ from ε expansion of $\mathrm{I}^{(1)}(\varepsilon)$

$$\boldsymbol{\mathcal{C}_0} = \sum_{(i,j)} \frac{\boldsymbol{T}_i \cdot \boldsymbol{T}_j}{16}\left[\gamma_0^{\mathrm{cusp}}\,\ln^2\frac{\mu^2}{-s_{ij}} - \frac{4\gamma_0^i}{C_i}\,\ln\frac{\mu^2}{-s_{ij}}\right] - \frac{\pi^2}{96}\Gamma_0'$$

$$\boldsymbol{\mathcal{C}_1} = \sum_{(i,j)} \frac{\boldsymbol{T}_i \cdot \boldsymbol{T}_j}{48}\left[\gamma_0^{\mathrm{cusp}}\,\ln^3\frac{\mu^2}{-s_{ij}} - \frac{6\gamma_0^i}{C_i}\,\ln^2\frac{\mu^2}{-s_{ij}}\right] - \frac{\pi^2}{48}\boldsymbol{\Gamma}_0 - \frac{\zeta_3}{24}\Gamma_0'$$

See 1309.3245 for details.

PeTeR – Hepforge

peter.hepforge.org

hep-ph/recent SPIRES-HEP Search Blogs inspire Readability arXiv hep-ph/new

PeTeR is hosted by Hepforge, IPPP Durham

- Home
- Download
- Manual
- Contact

PeTeR

Resummation for electroweak bosons at large transverse momentum

Christian Lorentzen

This is the development page of the PeTeR project. PeTeR is a C++ code for the computation of the transverse momentum spectrum of the production of an electroweak boson (photon, W, Z, Higgs).

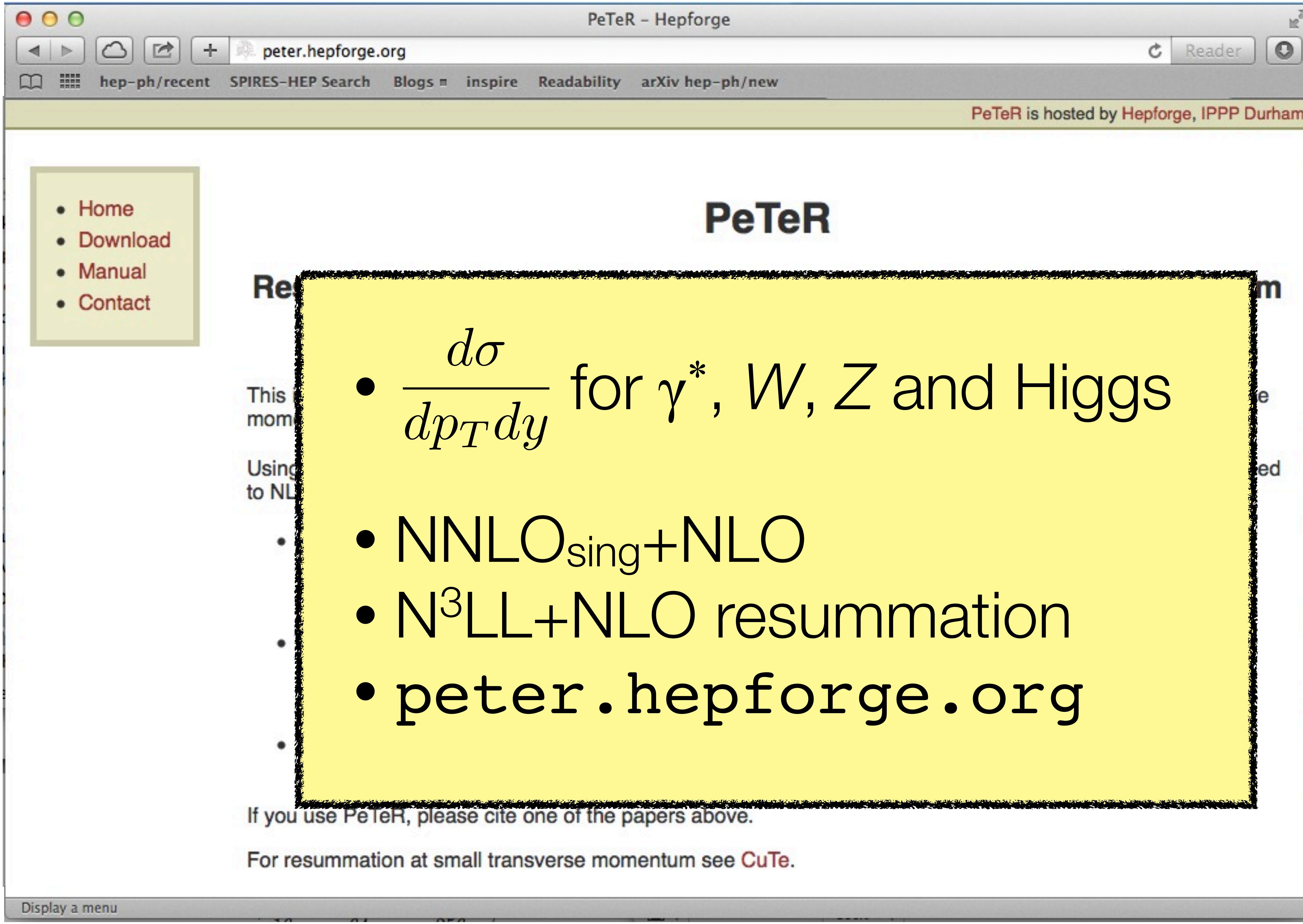
Using the SCET approach, PeTeR is able to perform a threshold resummation for large p_T up to N^3LL matched to NLO. It is based on the following following papers:

- *Resummation for W and Z production at large pT*
  Thomas Becher, Christian Lorentzen and Matthew D. Schwartz, Phys.Rev.Lett. **108** (2012) 012001, arXiv:1106.4310 [hep-ph]
- *Precision Direct Photon and W-Boson Spectra at High p_T and Comparison to LHC Data*
  Thomas Becher, Christian Lorentzen and Matthew D. Schwartz, Phys.Rev. D**86** (2012) 054026, arXiv:1206.6115 [hep-ph]
- *Transverse-momentum spectra of electroweak bosons near threshold at NNLO*
  Thomas Becher, Guido Bell, Christian Lorentzen and Stefanie Marti, (2013), arXiv:1309.3245 [hep-ph]

If you use PeTeR, please cite one of the papers above.

For resummation at small transverse momentum see CuTe.

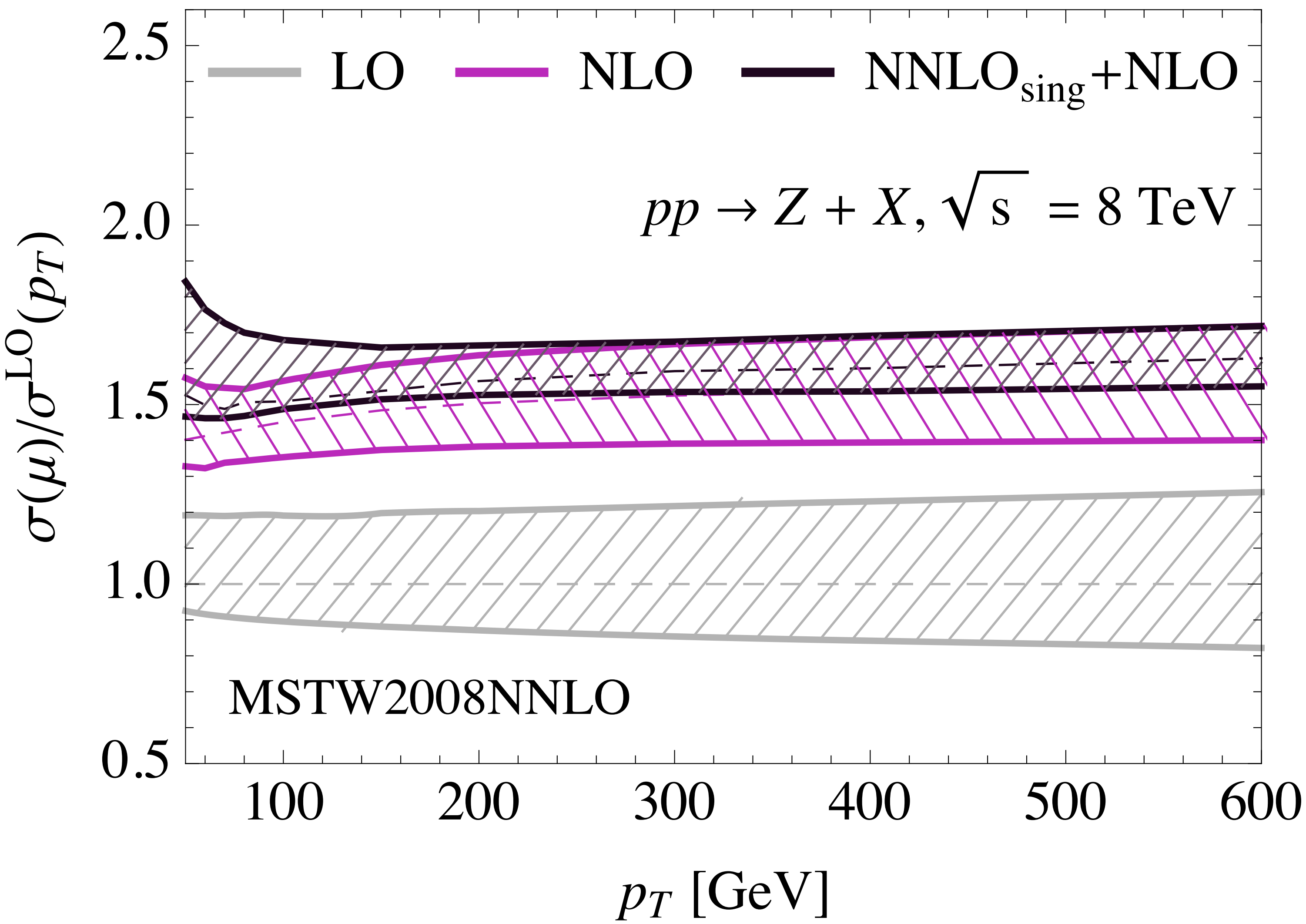
Display a menu



- $\dfrac{d\sigma}{dp_T\,dy}$ for γ^*, W, Z and Higgs
- $\mathrm{NNLO_{sing}}$+NLO
- $\mathrm{N^3LL}$+NLO resummation
- `peter.hepforge.org`

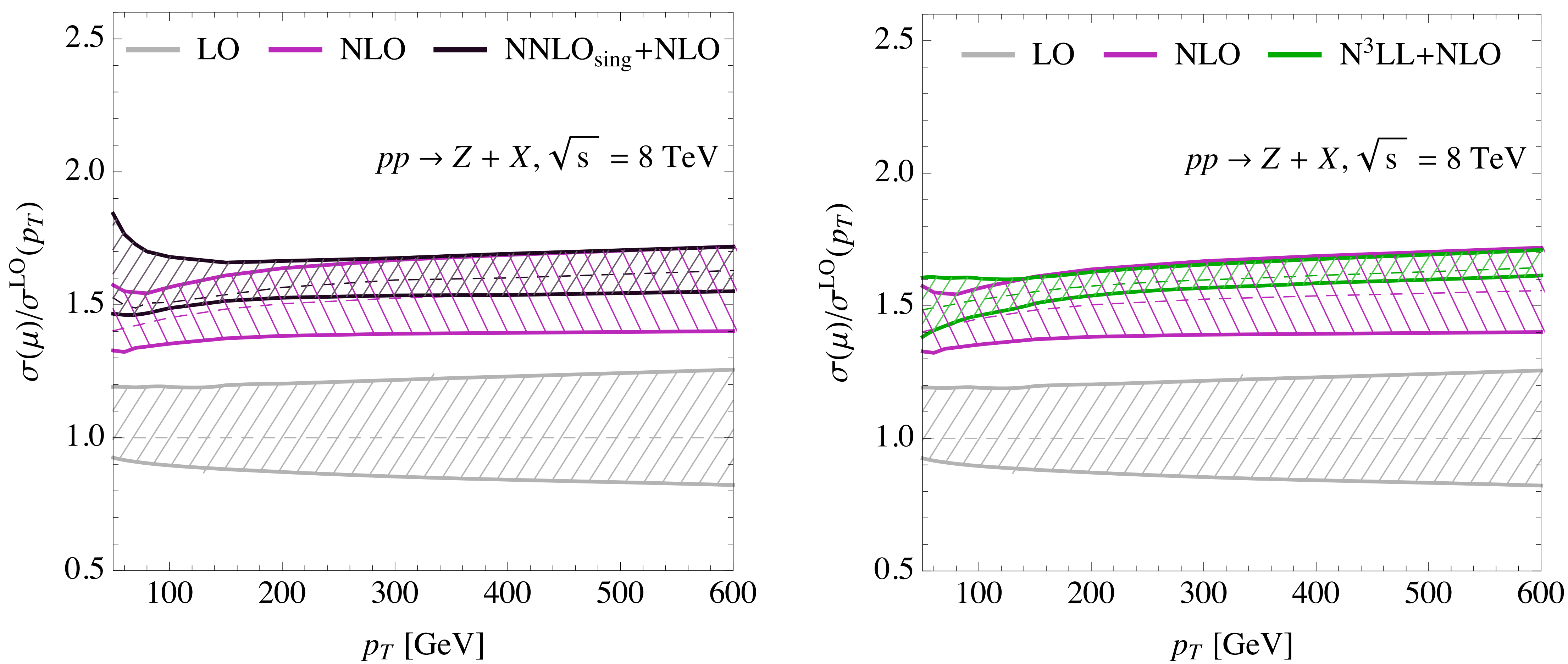
Numerical results: Higgs versus Z

Z production with PeTeR



- Moderate NNLO corrections of O(10%). Vary $\mu = \mu_{\text{h}} = \mu_{\text{j}} = \mu_{\text{s}}$ and μ_{f} independently by a factor of two around $\mu_{\text{f}} = \mu = p_T$.
  - will use the same prescription for Higgs

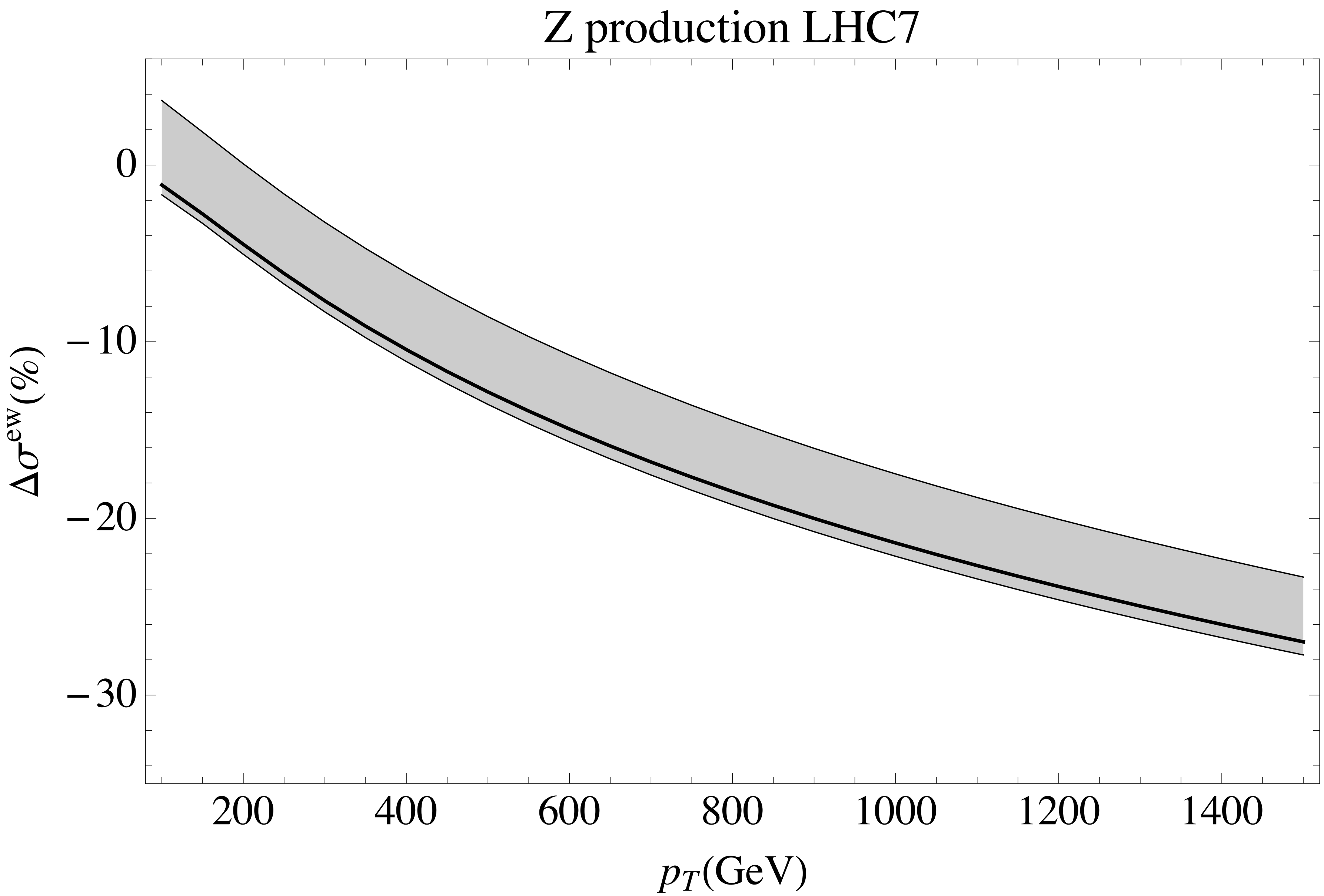
$\text{NNLO}_{\text{sing}}$ versus N^3LL resummation



Resummation reduces scale uncertainty but has small effect on central value. No large logarithms: m_X not dramatically lower than p_T.

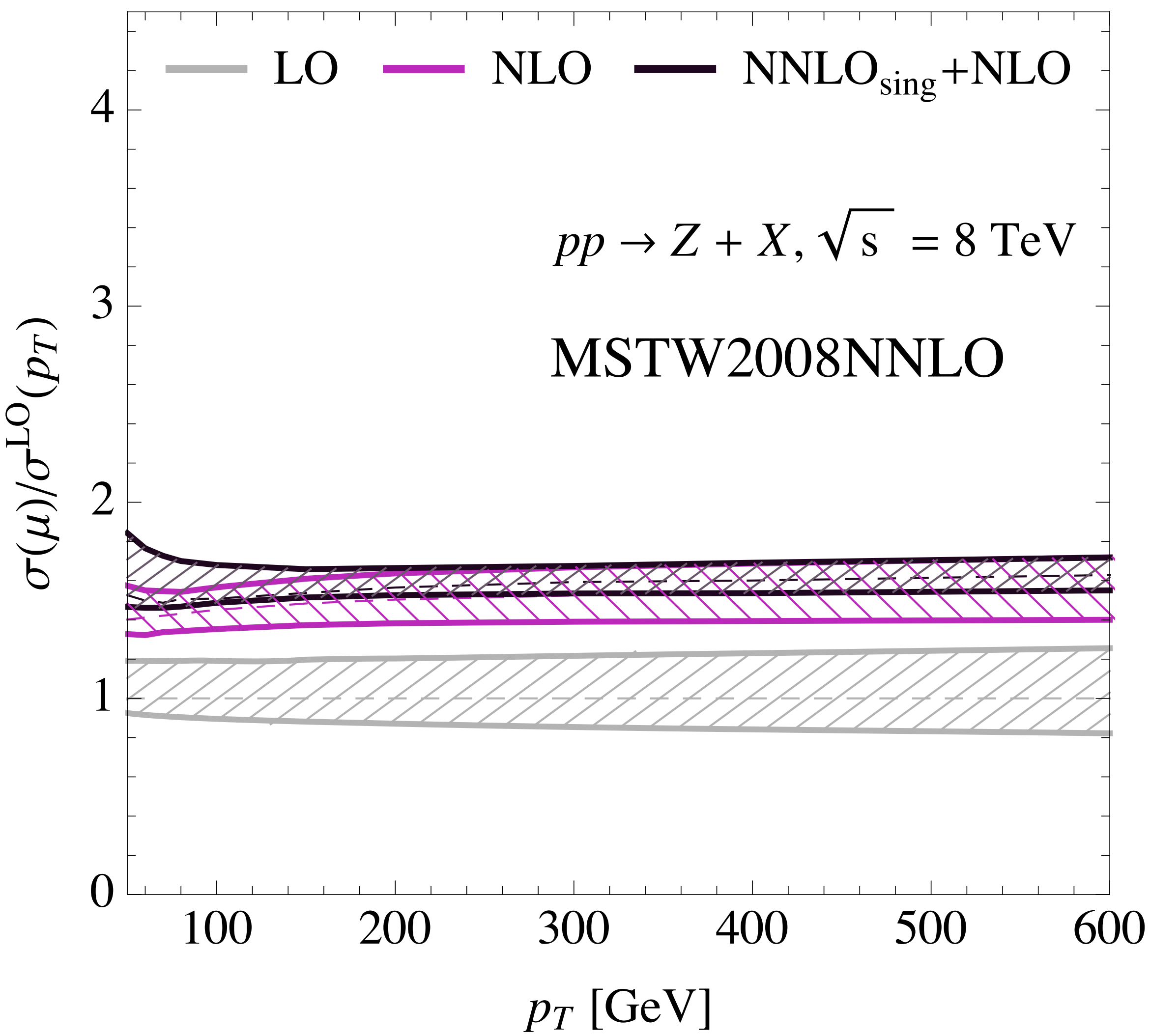
EW corrections

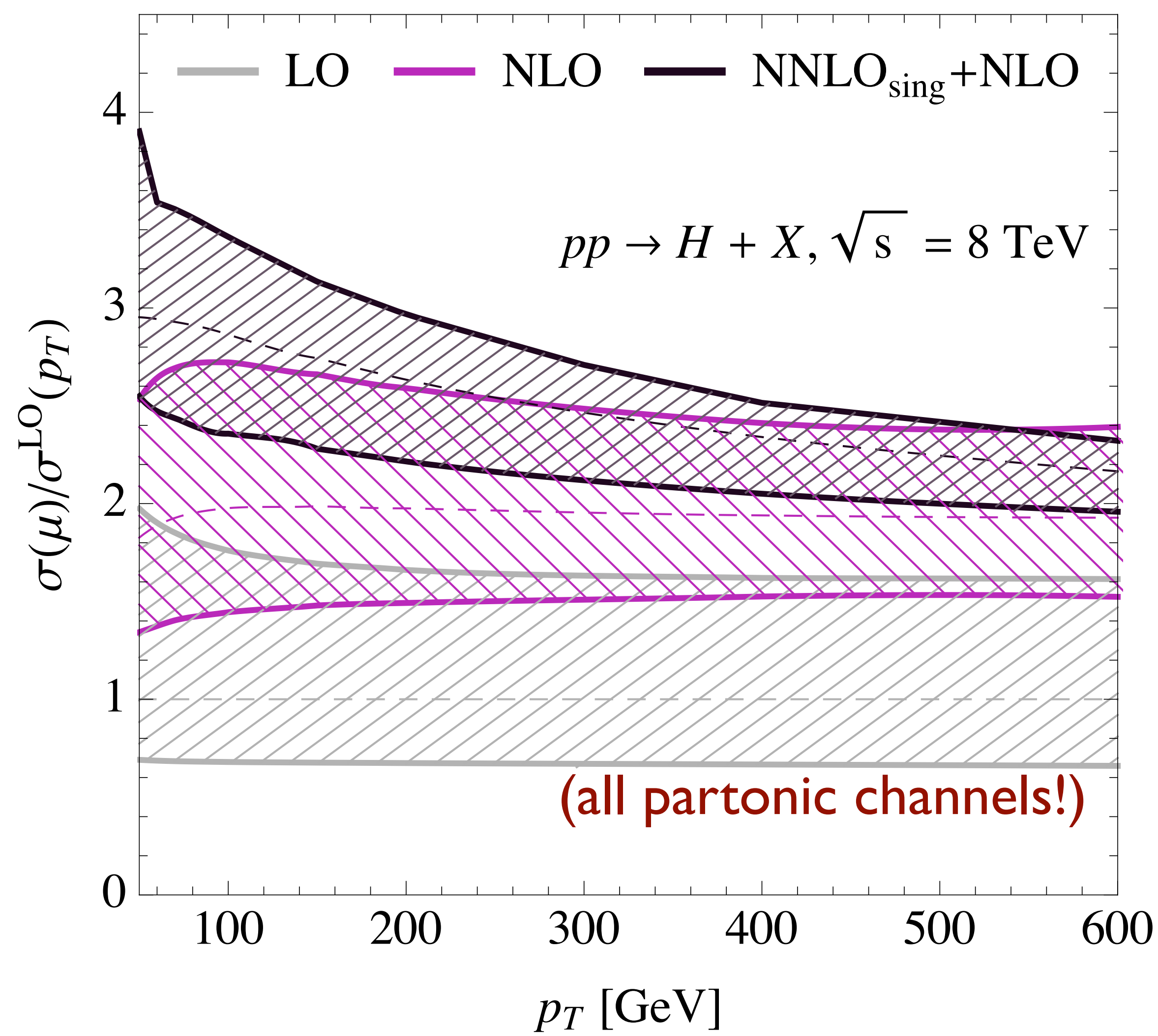
Kühn Kulesza, Pozzorini, Schulze 05; TB, Garcia Tormo ’13



- Resummed simultaneously with QCD corr’ns.
- QCD and EW factorize to good accuracy

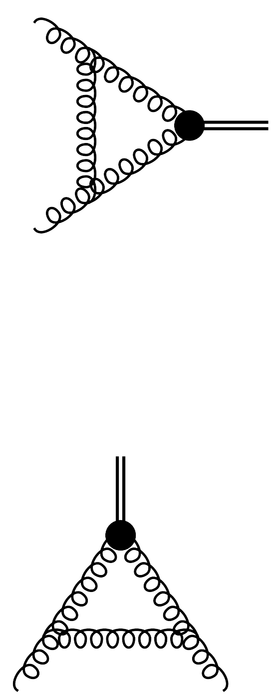
Z-boson versus Higgs

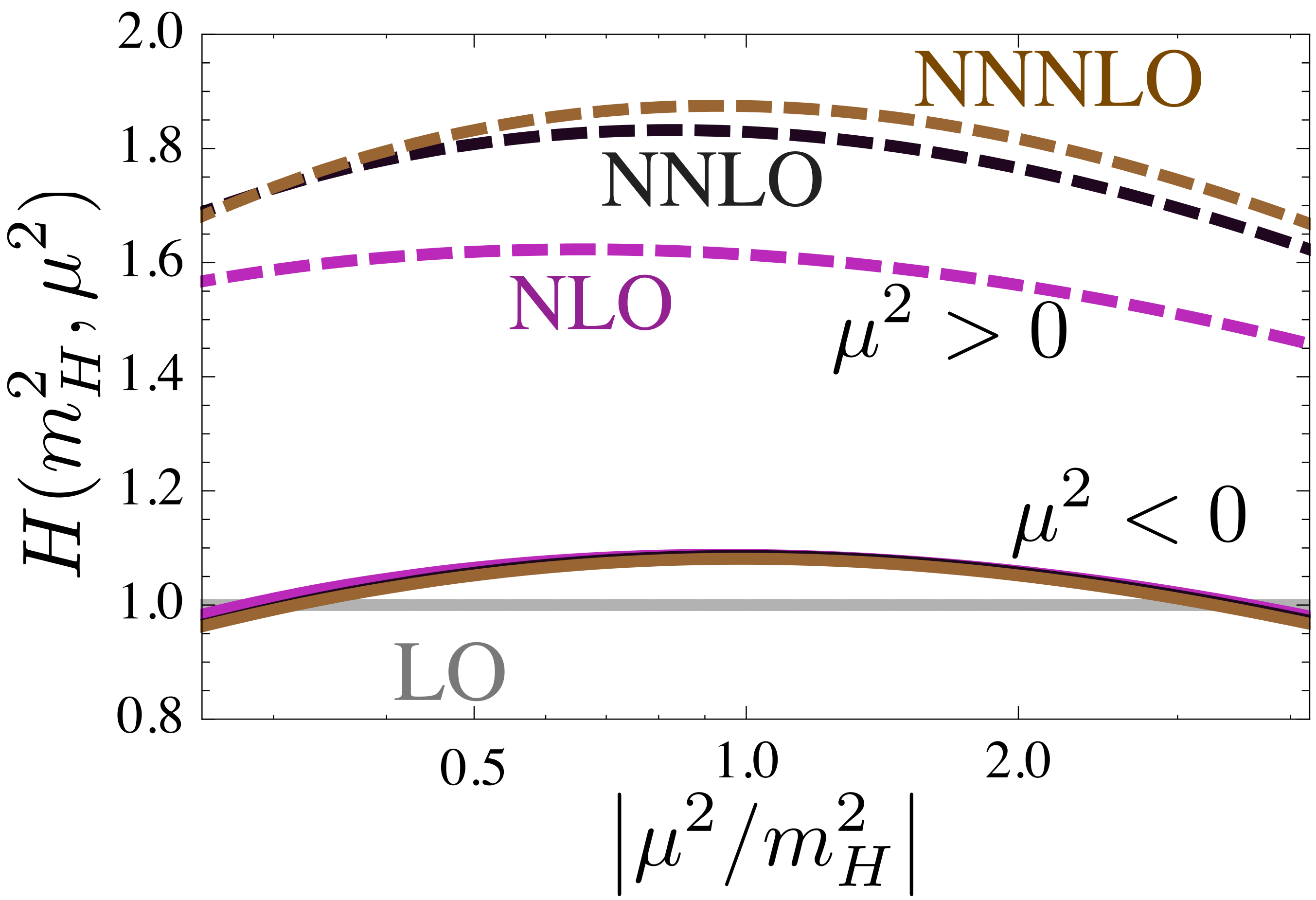




- *Much* larger corrections for Higgs production!
- Real emissions in both cases are described by the same jet and soft functions.
  - Large corrections in hard function $H_{gg\to Hg}$!

Hard function for total rate



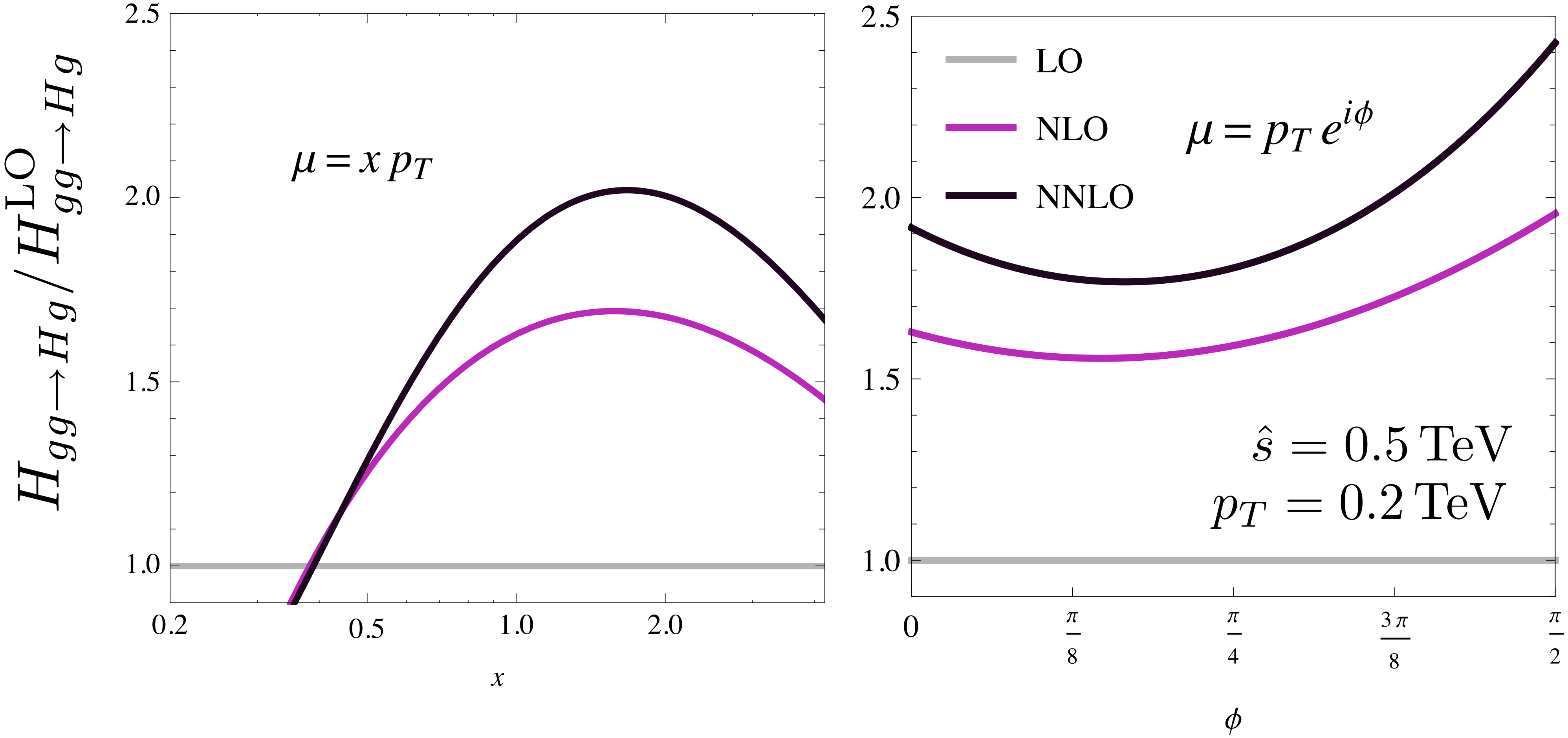


- Hard function for total rate is scalar gluon form factor.
- Convergence much better for $\mu^2 = -m_H^2$. Avoids imaginary parts, corresponds to expansion of space-like form factor.

Ahrens, TB, Neubert, Yang '09

- Same procedure cannot immediately be applied to $H + j$. (Imaginary parts from different channels.)

Hard function for H + jet



- Large corrections, irrespective of $\arg(\mu)$
- Logs from different channels:

$$\alpha_s^n(\mu)\ln^{2n}\frac{-\hat{s}}{\mu^2} \qquad \alpha_s^n(\mu)\ln^{2n}\frac{-\hat{t}}{\mu^2} \qquad \alpha_s^n(\mu)\ln^{2n}\frac{-\hat{u}}{\mu^2}$$

RG-equations

$$H_{gg\to Hg}(\hat{u},\hat{t},\mu) = \sum |\mathcal{M}_{gg\to Hg}(\hat{u},\hat{t},\mu)|^2$$

Renormalized amplitude

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}\mathcal{M}_{gg\to Hg}(\hat{u},\hat{t},\mu) = \left[\frac{C_A}{2}\gamma_{\mathrm{cusp}}(\alpha_s)\left(\ln\frac{-\hat{s}}{\mu^2}+\ln\frac{-\hat{t}}{\mu^2}+\ln\frac{-\hat{u}}{\mu^2}\right)+3\gamma_g(\alpha_s)\right]\mathcal{M}_{gg\to Hg}(\hat{u},\hat{t},\mu)$$

Scalar *gg*→*H* form factor F_S

$$\frac{\mathrm{d}}{\mathrm{d}\ln\mu}F_S(\hat{s},\mu) = \left[C_A\,\gamma_{\mathrm{cusp}}(\alpha_s)\,\ln\frac{-\hat{s}}{\mu^2}+2\gamma_g\right]F_S(\hat{s},\mu)$$

Simple improvement scheme

Define reduced amplitude

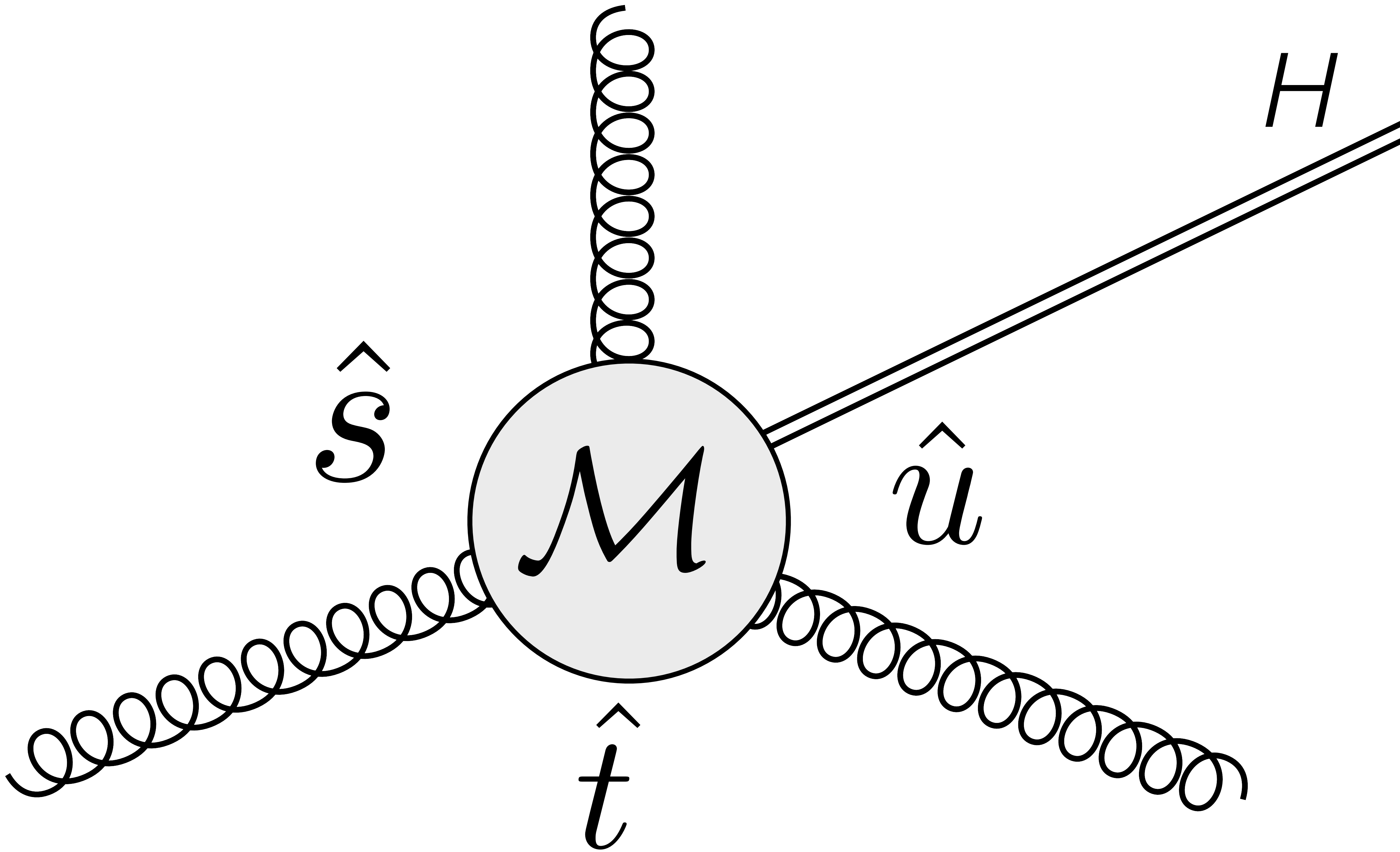
$$\widetilde{\mathcal{M}}_{gg\to Hg}(\hat{u},\hat{t}) = \frac{\mathcal{M}_{gg\to Hg}(\hat{u},\hat{t},\mu)}{\sqrt{F_S(\hat{s},\mu)F_S(\hat{t},\mu)F_S(\hat{u},\mu)}}$$

Then use RG-method to improve formfactor F_S.

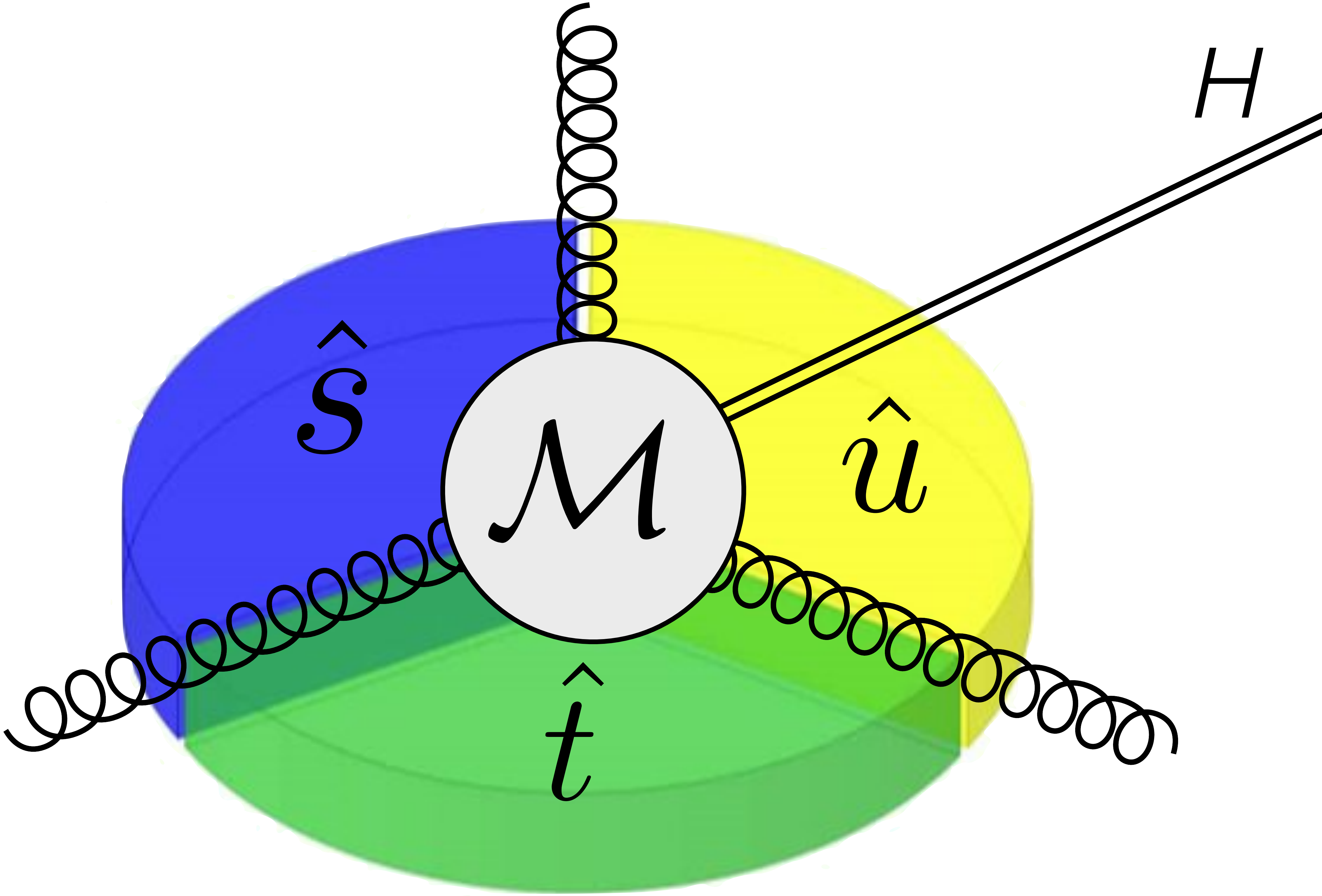
Improved cross section

$$\left(\frac{d\sigma}{dp_T}\right)^{\text{impr.}} = \left|\frac{F_S(\hat{s},\mu_h)U_S(\mu_h,\mu)}{F_S(\hat{s},\mu)}\right| \frac{d\sigma}{dp_T}$$

with evolution U_S from $\mu_h^2 = -\hat{s}$ to $\mu^2 = +\hat{s}$.

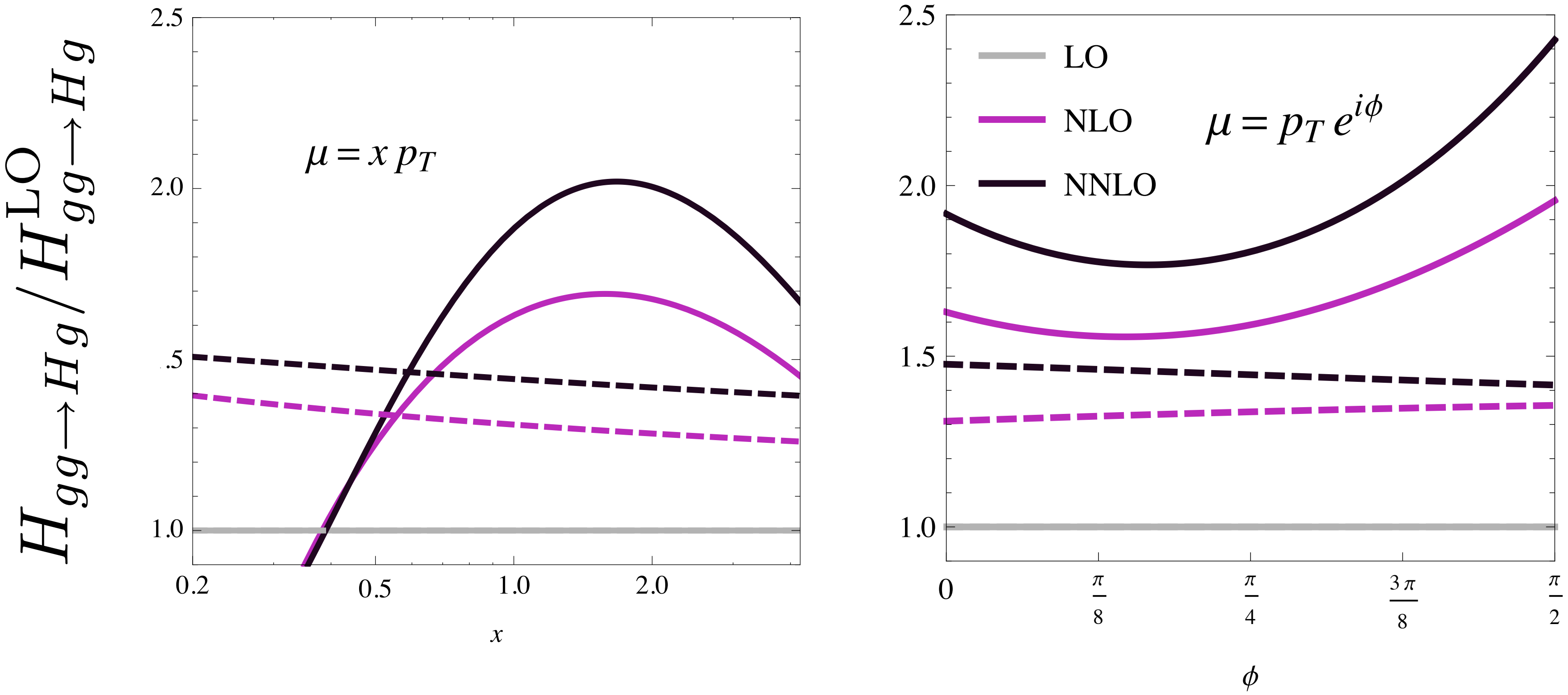


Divide out form factor pieces, use RG to improve them.



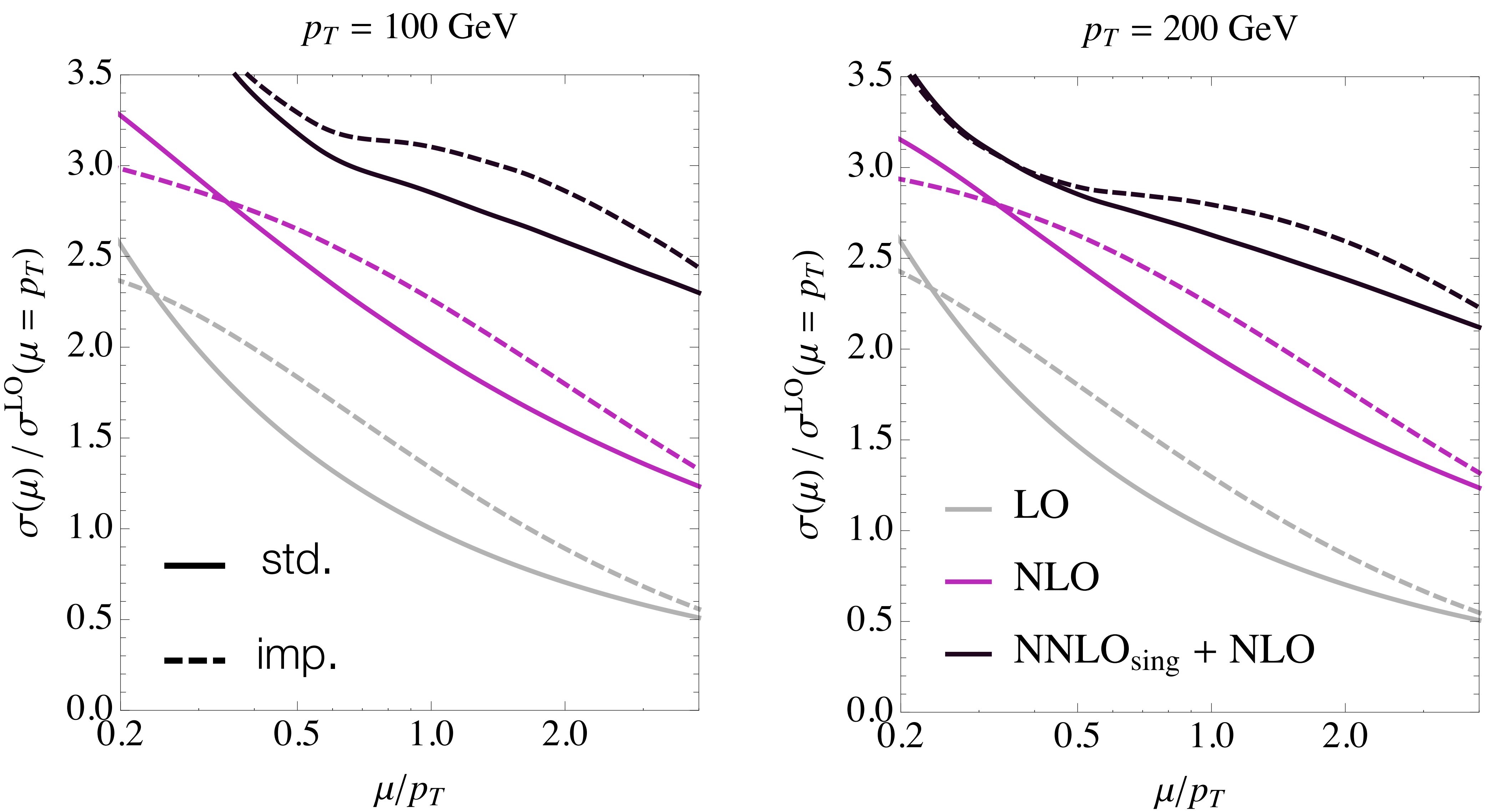
Divide out form factor pieces, use RG to improve them.

Reduced amplitude



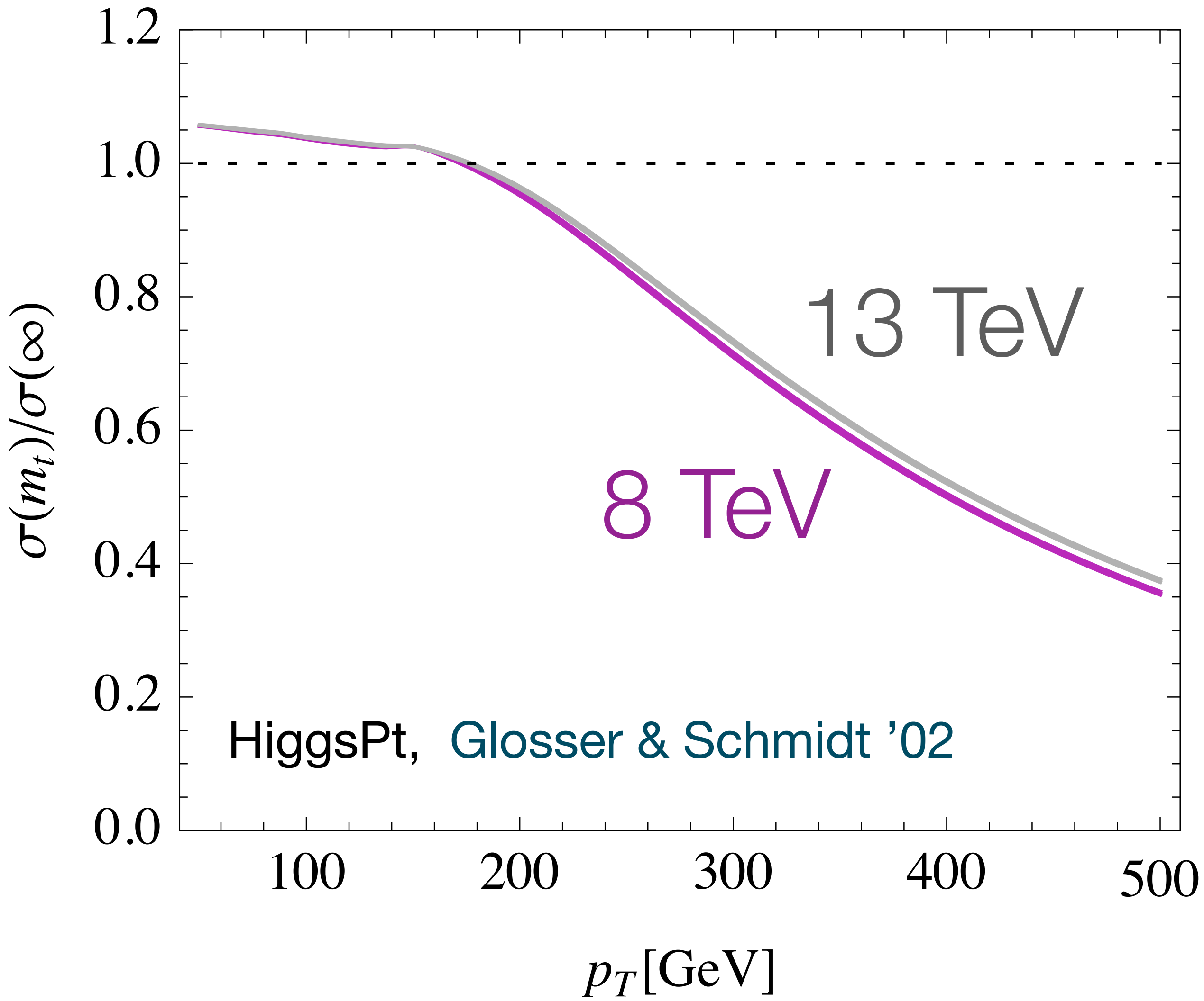
- Reduced hard function (dashed lines) has better perturbative behavior.
- However, at the end of the day, only moderate improvement of cross section.

Improved cross section



- Moderate improvement: corrections larger than those to the form factor.
- Reduced scale unc. at NNLO.

Heavy top approximation



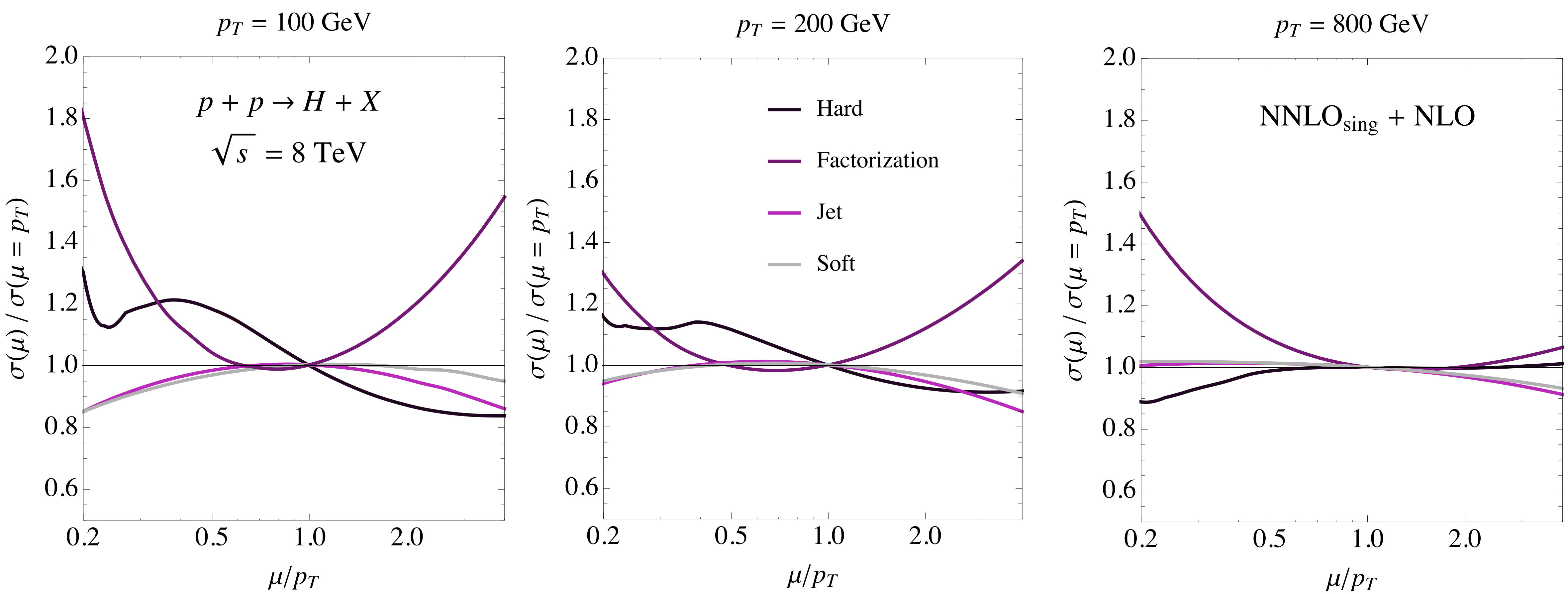
- Finite-m_t result only known at LO. (Approximate NLO: Harlander et al. '12.)
- Small difference below $p_T = 200$ GeV

Summary and outlook

- NNLO$_{\text{sing}}$ / N^{3}LL result for W, Z and Higgs production at large p_{T}.
  - Public code **`PeTeR`**
  - Small NNLO corrections for *W/Z*, large for *H*.
  - Among first hadron collider physics results from 2-loop four-point functions. Same hard function will arise in all resummations for single-jet observables.
  - Nontrivial check on the full NNLO results once they become available, estimate of N^{3}LO.
- Will do phenomenological analysis with QCD and EW, comparison to new *W/Z* measurements by ATLAS and CMS.
- New results at low p_T: Two-loop collinear functions. Gehrmann, Lübbert, Yang '14 Better understanding of NP effects. TB, Bell '14

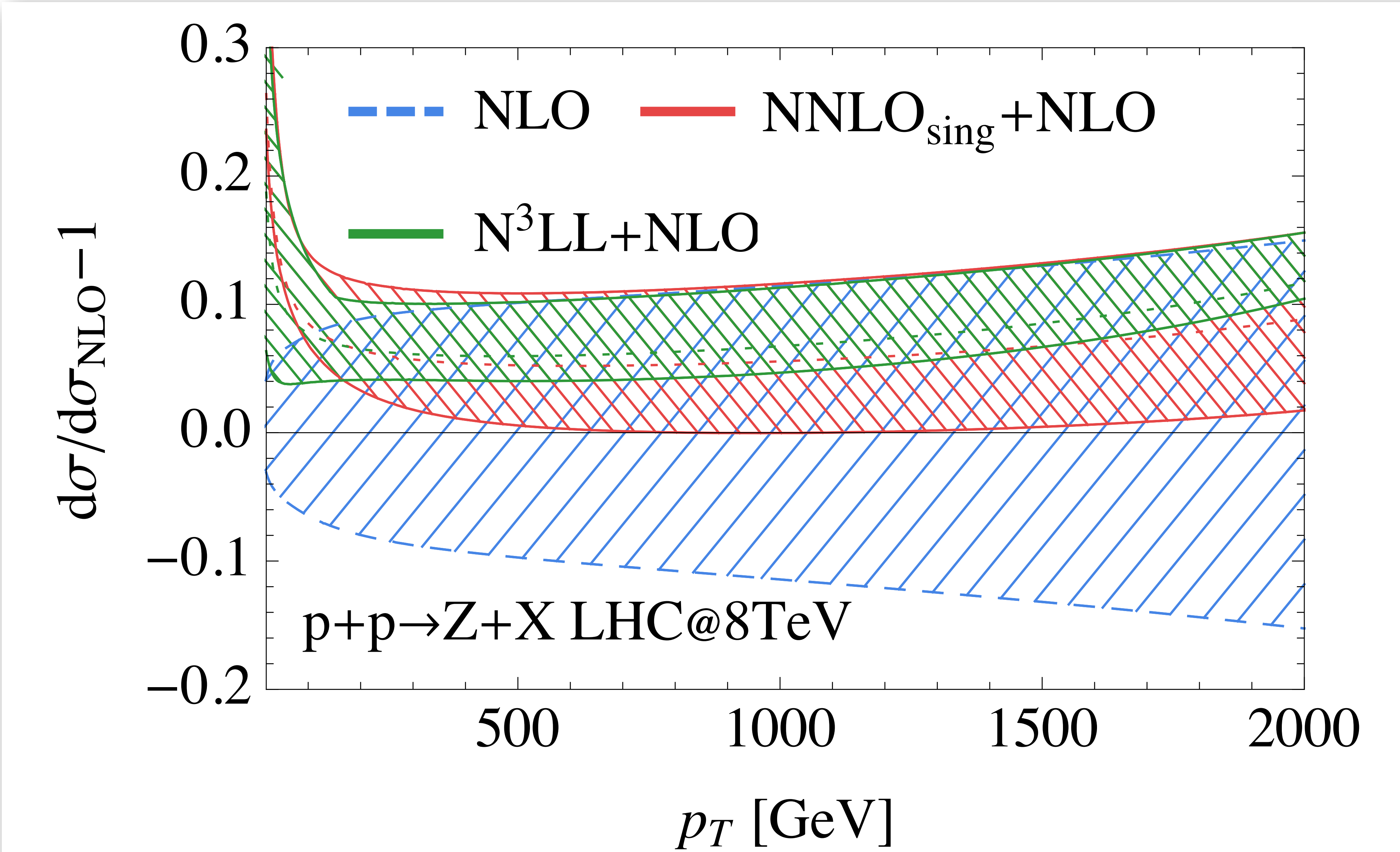
Additional slides

Individual scale variations

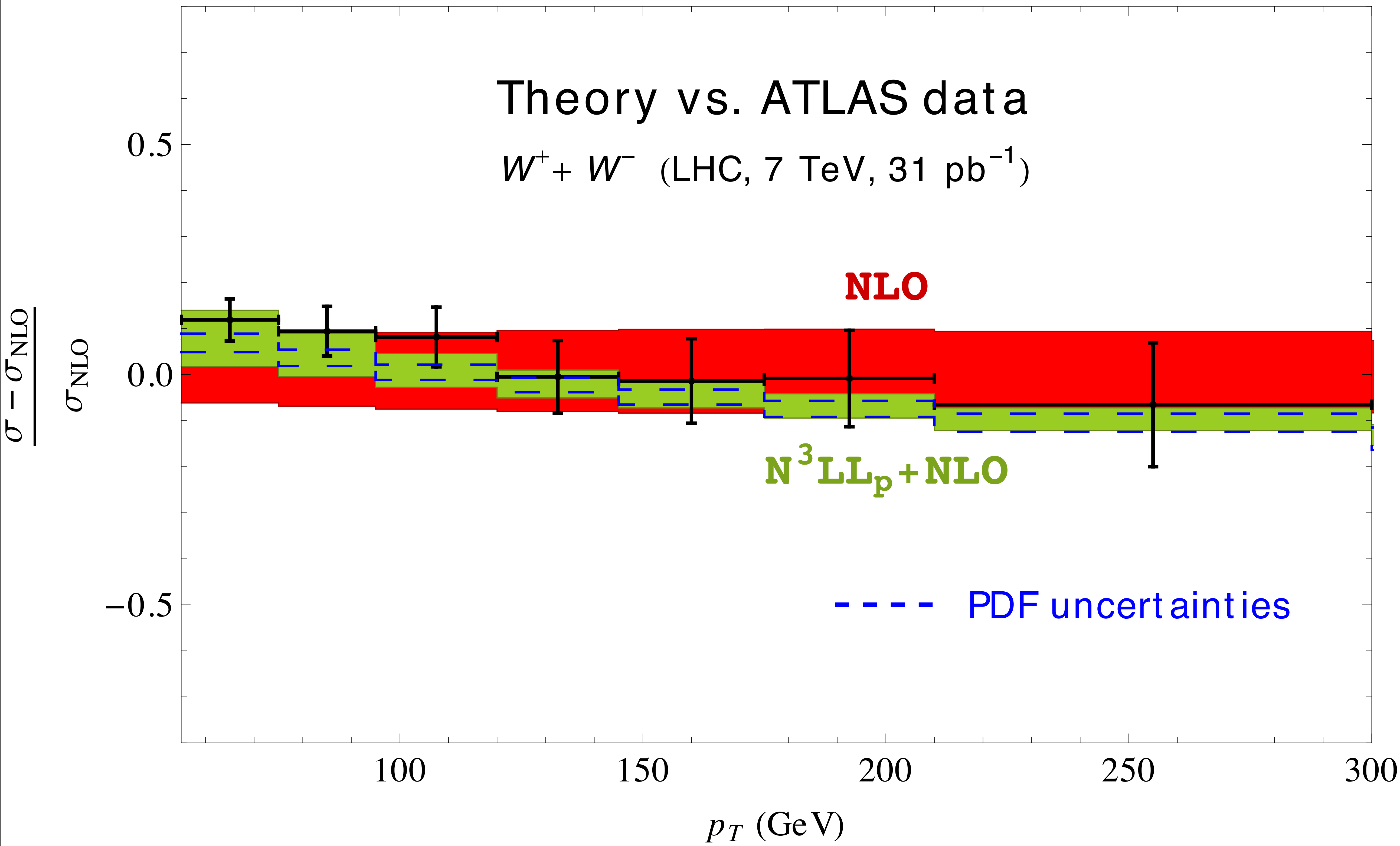


- Dominant uncertainties are from μ_{h} and μ_{f} variation. → Vary those separately.

Resummation for Z-production

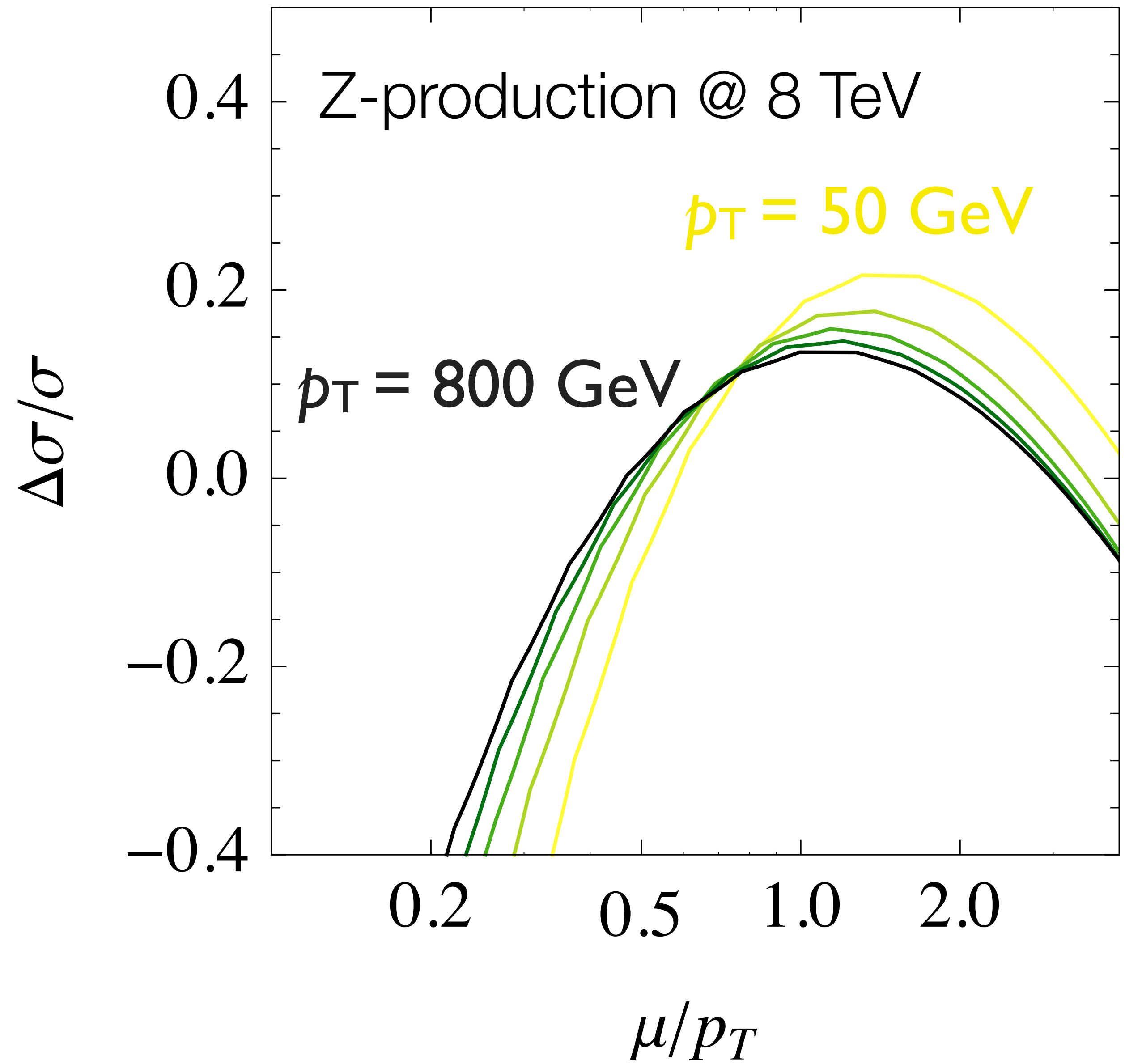


Moderate effect: Difference NNLO$_{sing}$ vs N^{3}LL is $O(\alpha_s^3)$ and logarithms are not very large.



- Numerically N^3LL_p and N^3LL are quite close

NLO correction to hard function:

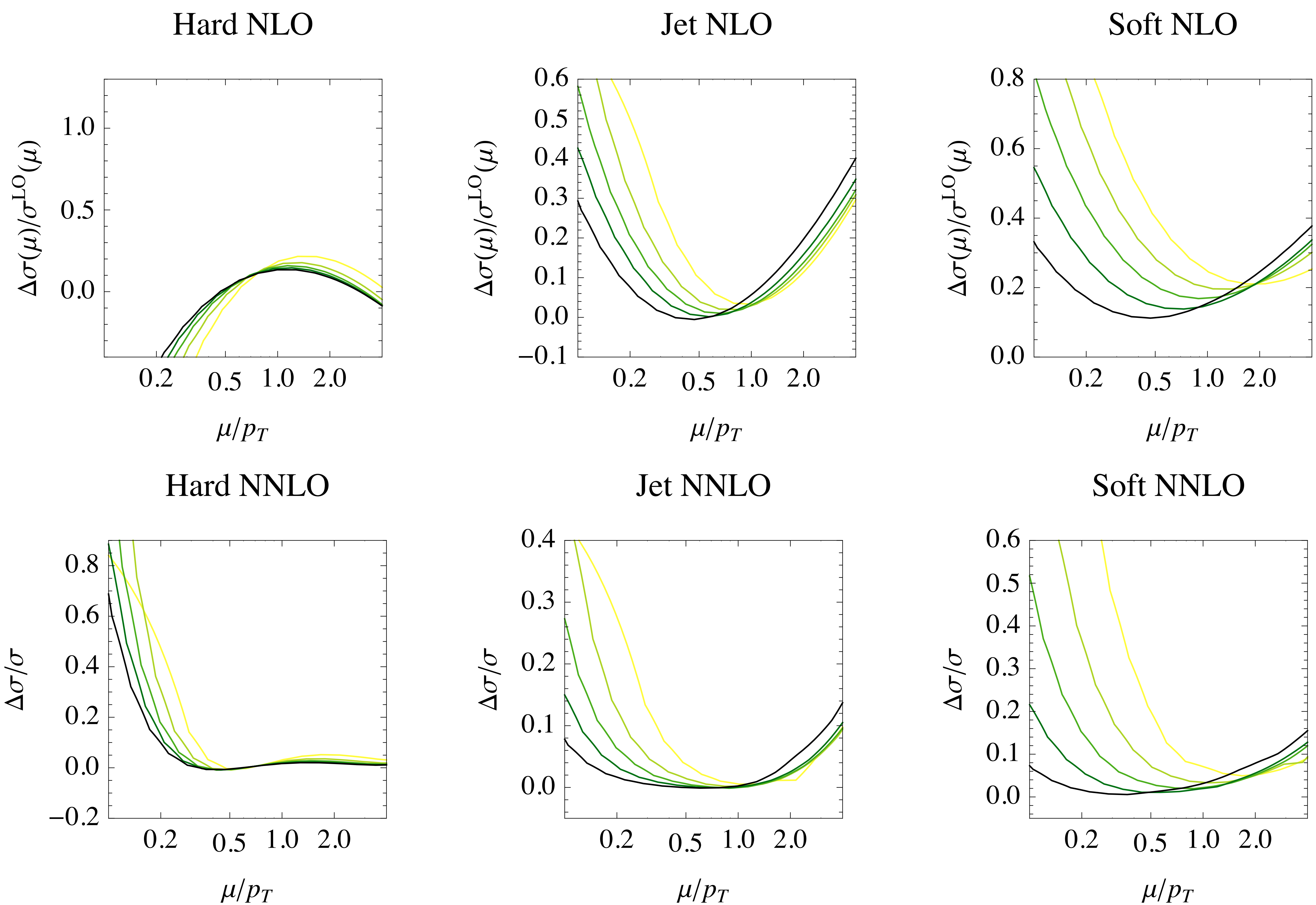


Correction is of the form

$$\alpha(\mu)\left(c_2 L^2 + c_1 L + c_0\right) \qquad\qquad L = \ln(\mu/p_T)$$

Plot shows that $\mu \approx p_T$ is reasonable choice.

Z production



Higgs production