Precision Prediction for Higgs Production at Small Transverse Momentum

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Based on:

Ye Li, D. Neill, HXZ, 1604.00392

Ye Li, HXZ, 1604.01404

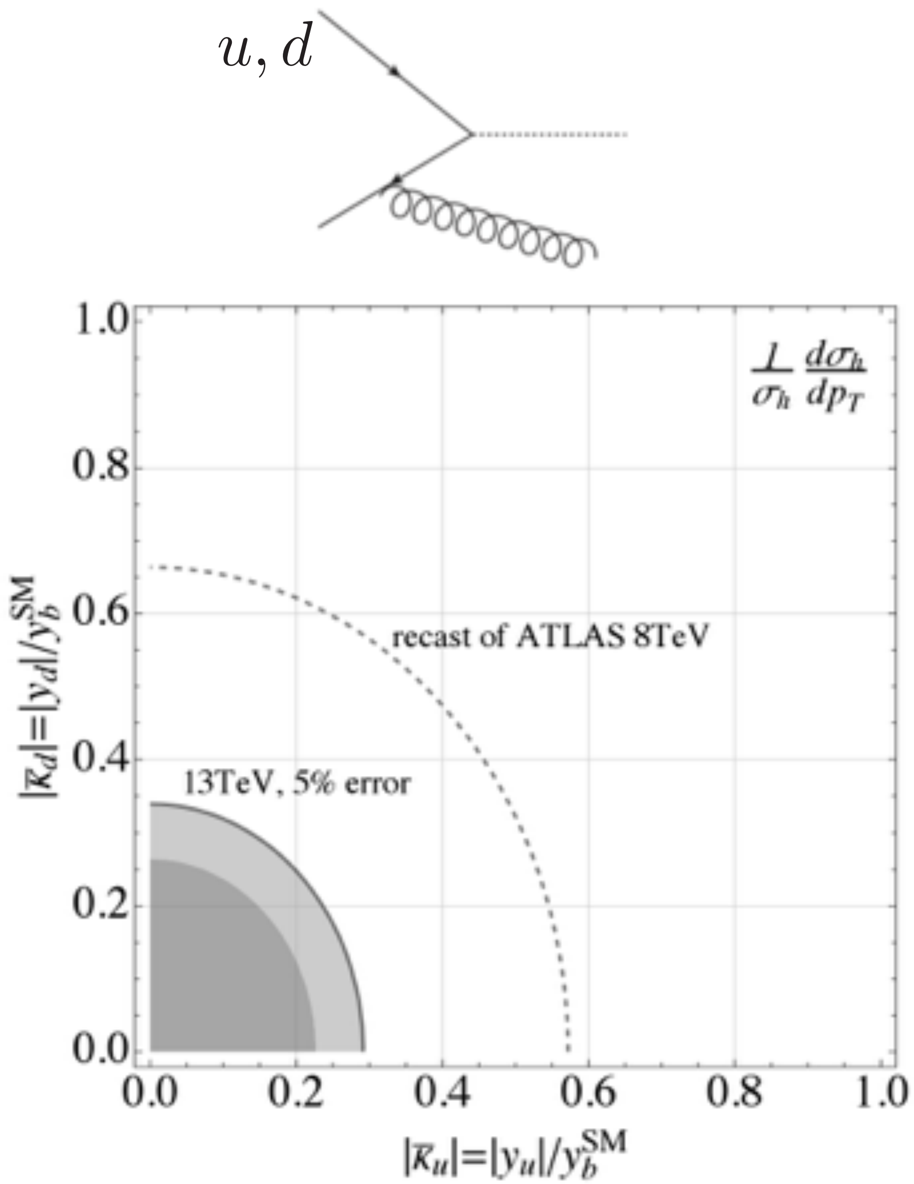
Ye Li, D. Neill, I. Stewart, M. Schulze, HXZ, in preparation

Where do we stand?

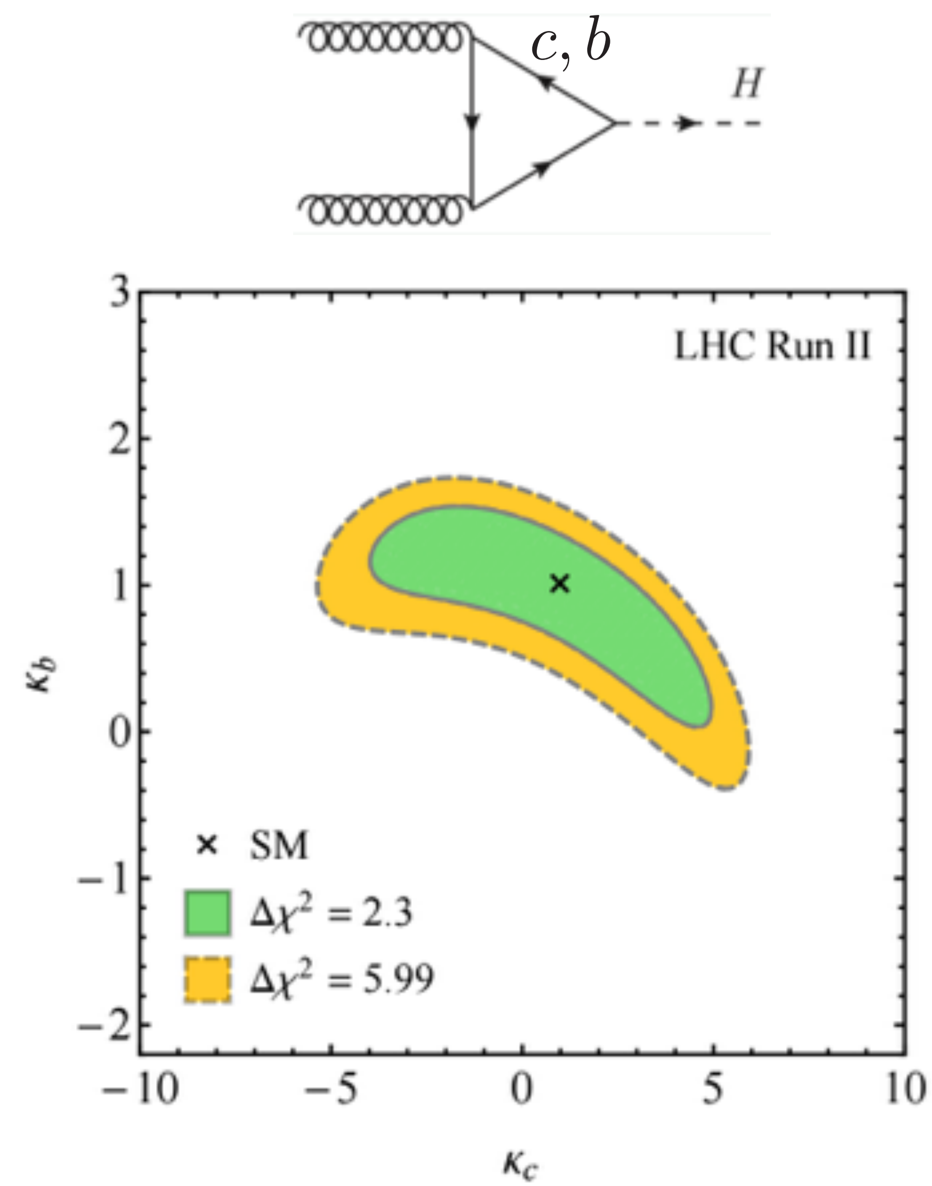
- On July 4th, 2012, the ATLAS and CMS collaborations at CERN announced the observation of a new particle consistent with the Higgs particle in the Standard Model
- This discovery filled the last gap of the SM.
- However, it leaves many important questions open
- If no new physics found at LHC run 2, studying the properties of the Higgs boson in great detail will be of the utmost importance

Bounding light quark Yukawa from Higgs pT

- Precision measurement of Higgs pT can be used to constrain light quark Yukawa



Soreq, Zupan, HXZ, 2016



Bishara, Haisch, Monni, Re, 2016

Previous works on Higgs prod. at low pT

- Accurate description of Higgs pT spectrum requires the resummation of large logarithms $\log(q_T/m_H)$
  - Hinchliffe, Novaes, 1988; Kauffman, 1999; Berger, Qiu, 2002; Gao, Li, Liu, 2005; Idilbi, Ji, Yuan, 2005; Bozzi, Catani, Florian, Grazzini, 2005; Mantry, Petriello, 2009; Becher, Neubert, Wilhelm, 2012; Echevarria, Kasemets, Mulders, Pisano, 2015; Neill, Rothstein, Vaidya, 2015; Bagnaschi,Vicini, 2015; Bagnaschi, Harlander, Mantler,Vicini,Wiesemann, 2015; …
- All the previous works are done at NLL or NNLL accuracy ($\exp(\alpha_s^k \log^n(bm))$, $n \geq k-1$)
- In this talk, a first effort to extend the pT resummation to N3LL (including all the logarithmic singular terms at $O(\alpha_s^3)$)

Review of rapidity RG formalism for pT resummation

Chiu, Jain, Neill, Rothstein, 2012; Neill, Rothstein, Vaidya, 2015

$$p^\mu = (p^+, p^-, p_\perp) = (p_0 + p_z, p_0 - p_z, p_\perp)$$

$$n^\mu = (2,0,0) \quad \bar{n}^\mu = (0,2,0)$$

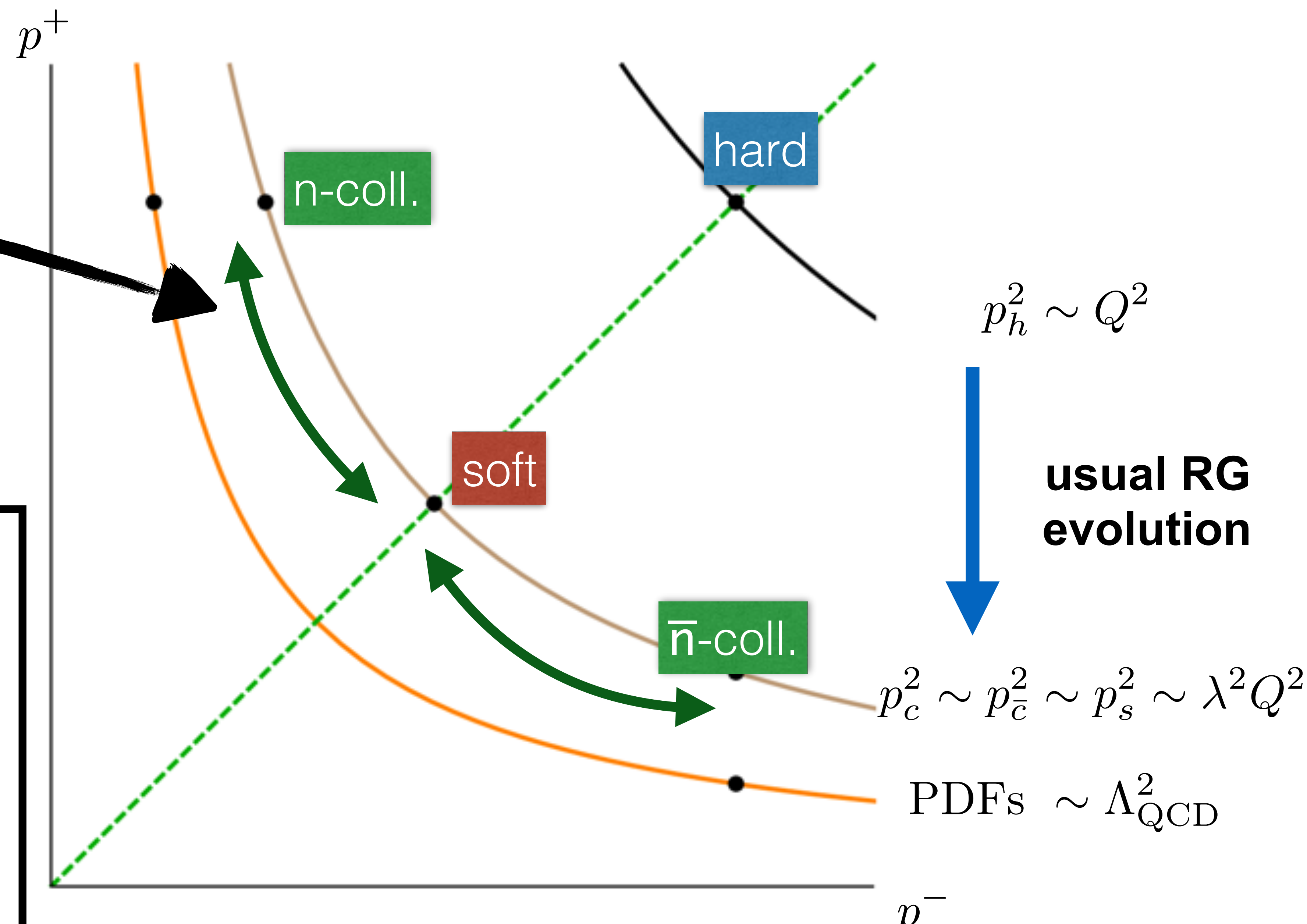
power counting parameter $\lambda \sim \frac{q_\perp}{Q}$

hard: $Q(1,1,1)$

collinear: $Q(1,\lambda^2,\lambda), \quad Q(\lambda^2,1,\lambda)$

soft: $Q(\lambda,\lambda,\lambda)$

Rapidity evolution between soft and collinear/anti-collinear modes



Large logs are resumed by solving usual RG equation and rapidity RG equation

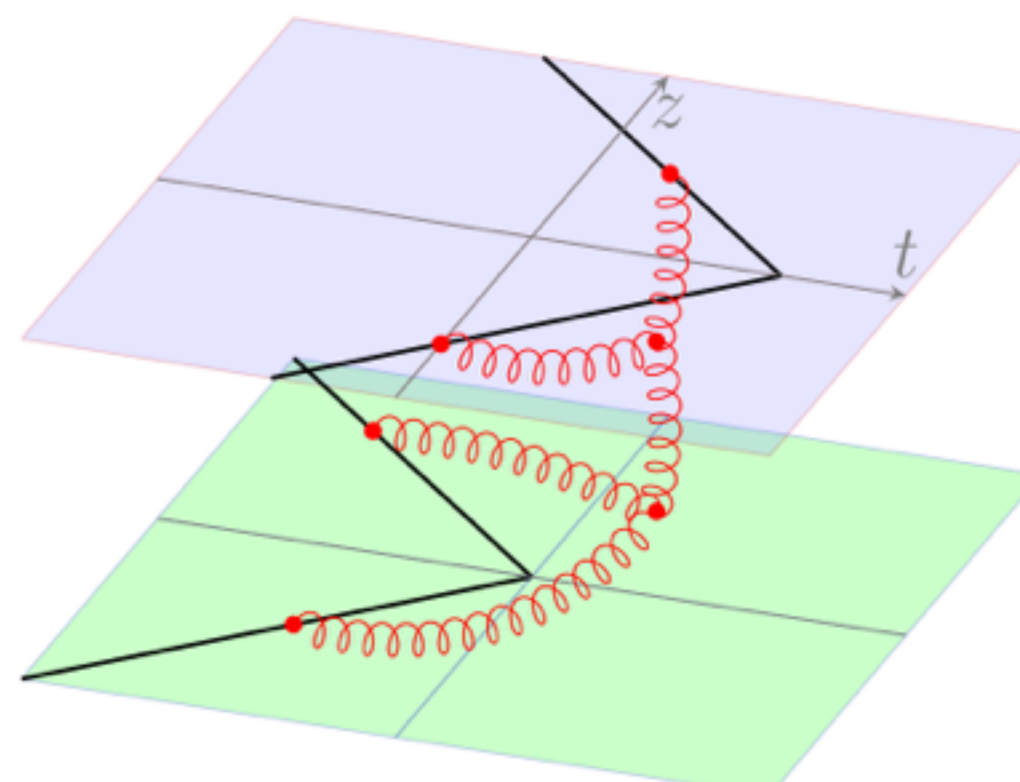
Exponential regulator for rapidity divergence

- Within the Rapidity RG formalism, there is the freedom of choosing different rapidity regulator
- We adopt the recently introduced exponential regulator in our calculation [Ye Li, Neill, HXZ, 2016]

The exponential regulator

$$\frac{d^3\mathbf{p}}{(2\pi)^3 2|\mathbf{p}|} \to \frac{d^3\mathbf{p}}{(2\pi)^3 2|\mathbf{p}|} \exp\left[-2\tau|\mathbf{p}|\right] \qquad \begin{array}{c} \lim \tau \to 0 \\ \nu \equiv 1/\tau \end{array}$$

- The exponential regulator is gauge invariant, preserve non-abelian exponentiation, and has operator definition
- Soft function calculated to three loops with exponential regulator [Ye Li, HXZ, 2016]



The pT resummed formula

Neill, Rothstein, Vaidya, 2015

- The resummation formula in impact parameter space

$$\frac{d^2\sigma}{d^2\vec{Q}_T} = \int x_a \int x_b\, \delta\Big(x_a x_b - \frac{m_H^2}{S}\Big)\sigma_0 \int \frac{d^2\vec{b}}{(2\pi)^2} e^{i\vec{b}\cdot\vec{Q}_T} W\big(x_a, x_b, m_H, \vec{b}, \mu, \nu\big) + \frac{d^2\sigma}{d^2\vec{Q}_T}\Big|_{\text{n.s.}}$$

$$W(x_a, x_b, m_H, \vec{b}, \mu, \nu) = \Big|C_V\big(m_t, m_H, \mu\big)\Big|^2 S(\vec{b}, \mu, \nu) B^{\alpha\beta}_{g/N_1}(x_a, Q, \vec{b}, \mu, \nu) B^{\alpha\beta}_{g/N_2}(x_b, Q, \vec{b}, \mu, \nu)$$

$$C_V(m_t, m_H, \mu) = C_V(m_t, m_H, \mu_H) \exp\left[\frac{1}{2}\int_{\mu_H^2}^{\mu^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\left(\Gamma_{\text{cusp}}[\alpha_s(\bar{\mu})] \ln\frac{M_H^2}{\bar{\mu}^2} + \gamma^V[\alpha_s(\bar{\mu})]\right)\right]$$

$$B^{\alpha\beta}_{g/N}(x, \vec{b}, Q, \mu, \nu) = \frac{g_\perp^{\alpha\beta}}{d-2} B_{g/N}(x, b, Q, \mu, \nu) + \left(\frac{g_\perp^{\alpha\beta}}{d-2} + \frac{b^\alpha b^\beta}{b^2}\right) B'_{g/N}(x, b, Q, \mu, \nu)$$

$$B_{g/N}(x, b, Q, \mu, \nu) = \sum_j \int_x^1 \frac{dz}{z} I_{gj}(z, b, Q, \mu, \nu) f_{j/N}(x/z, \mu) + \ldots$$

$$S_\perp(b, \mu, \nu) = S_\perp(b, \mu_s, \nu_s) \exp\left[\int_{\mu_s^2}^{\mu^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\left(\Gamma_{\text{cusp}}[\alpha_s(\bar{\mu})] \ln\frac{b^2\bar{\mu}^2}{b_0^2} + \gamma^s[\alpha_s(\bar{\mu})]\right) + \ln\frac{\nu^2}{\nu_s^2}\left(-\int_{b_0^2/b^2}^{\mu^2} \frac{d\bar{\mu}^2}{\bar{\mu}^2}\Gamma_{\text{cusp}}[\alpha_s(\bar{\mu})] + \gamma^r[\alpha_s(b_0/b)]\right)\right]$$

Relation to the Colins-Soper-Sterman formula

- The SCET formula can be related to the CSS formula

Identify:

$$C^{\alpha\beta}_{g/N_1}(x_a,\vec{b},m_H) = B^{\alpha\beta}_{g/N_1}\left(x_a,\vec{b},m_H,\mu_B=\frac{b_0}{b},\nu_B=\frac{1}{m_H}\right)\sqrt{S\left(\vec{b},\mu_s=\frac{b_0}{b},\nu_s=\frac{b_0}{b}\right)}$$
$$\cdot\sqrt{|C_V\left(m_t,m_H,\mu_H=m_H\right)|^2}$$

$$A\big[\alpha_S(\bar{\mu})\big] = \Gamma_{\rm cusp}\big[\alpha_S(\bar{\mu})\big] + 2\bar{\mu}\frac{d\gamma^r\left[\alpha_S(\bar{\mu})\right]}{d\bar{\mu}}$$

$$B\big[\alpha_S(\bar{\mu})\big] = \gamma^V\big[\alpha_S(\bar{\mu})\big] - \gamma^r\big[\alpha_S(\bar{\mu})\big]$$

- The resumed component in SCET reduces to

$$W(x_a,x_b,m_H,\vec{b}) = C^{\alpha\beta}_{g/N_1}C^{\alpha\beta}_{g/N_2}\exp\left\{-\int_{b_0^2/b^2}^{m_H^2}\frac{d\bar{\mu}^2}{\bar{\mu}^2}\left[A\big[\alpha_s(\bar{\mu})\big]\ln\frac{m_H^2}{\bar{\mu}^2}+B\big[\alpha_s(\bar{\mu})\big]\right]\right\}$$

Summarize the perturbative ingredients

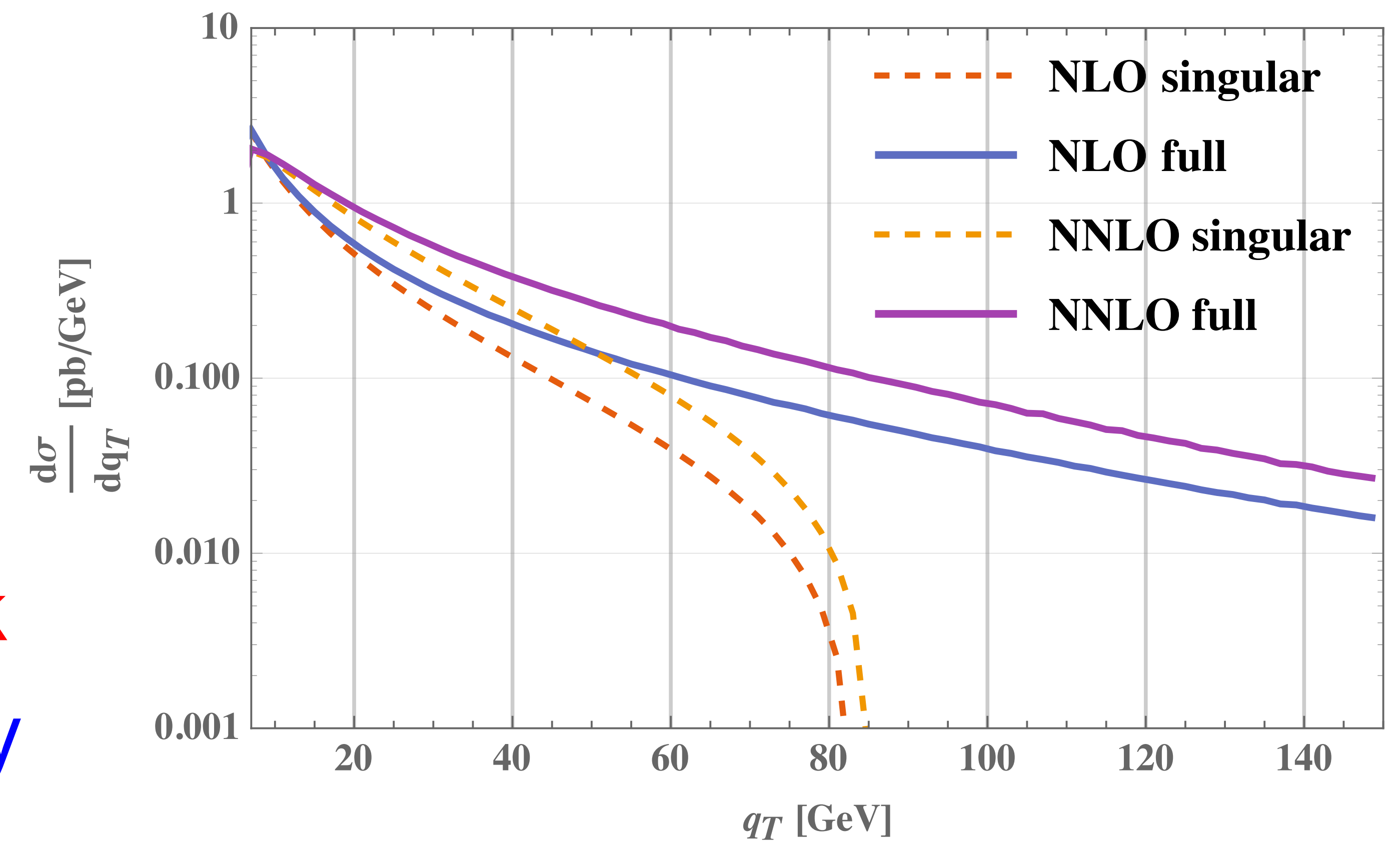
	matching (singular)	nonsingular	γ^x	$\Gamma_{\rm cusp}$	β	PDF
NLO	NLO	NLO	-	-	1-loop	LO
NNLO	NNLO	NNLO	-	-	2-loop	NLO
N3LO	N3LO	N3LO	-	-	3-loop	NNLO
LL	NLO	-	-	1-loop	1-loop	LO
NLL	NLO	-	1-loop	2-loop	2-loop	LO
NNLL	NNLO	-	2-loop	3-loop	3-loop	NLO
NLL′+NLO	NLO	NLO	1-loop	2-loop	2-loop	NLO
NNLL+NNLO	NNLO	NNLO	2-loop	3-loop	3-loop	NNLO
NNLL′+N3LO	N3LO	N3LO	2-loop	3-loop	3-loop	NNLO
N^3LL+N3LO	N3LO	N3LO	3-loop	4-loop	4-loop	NNLO

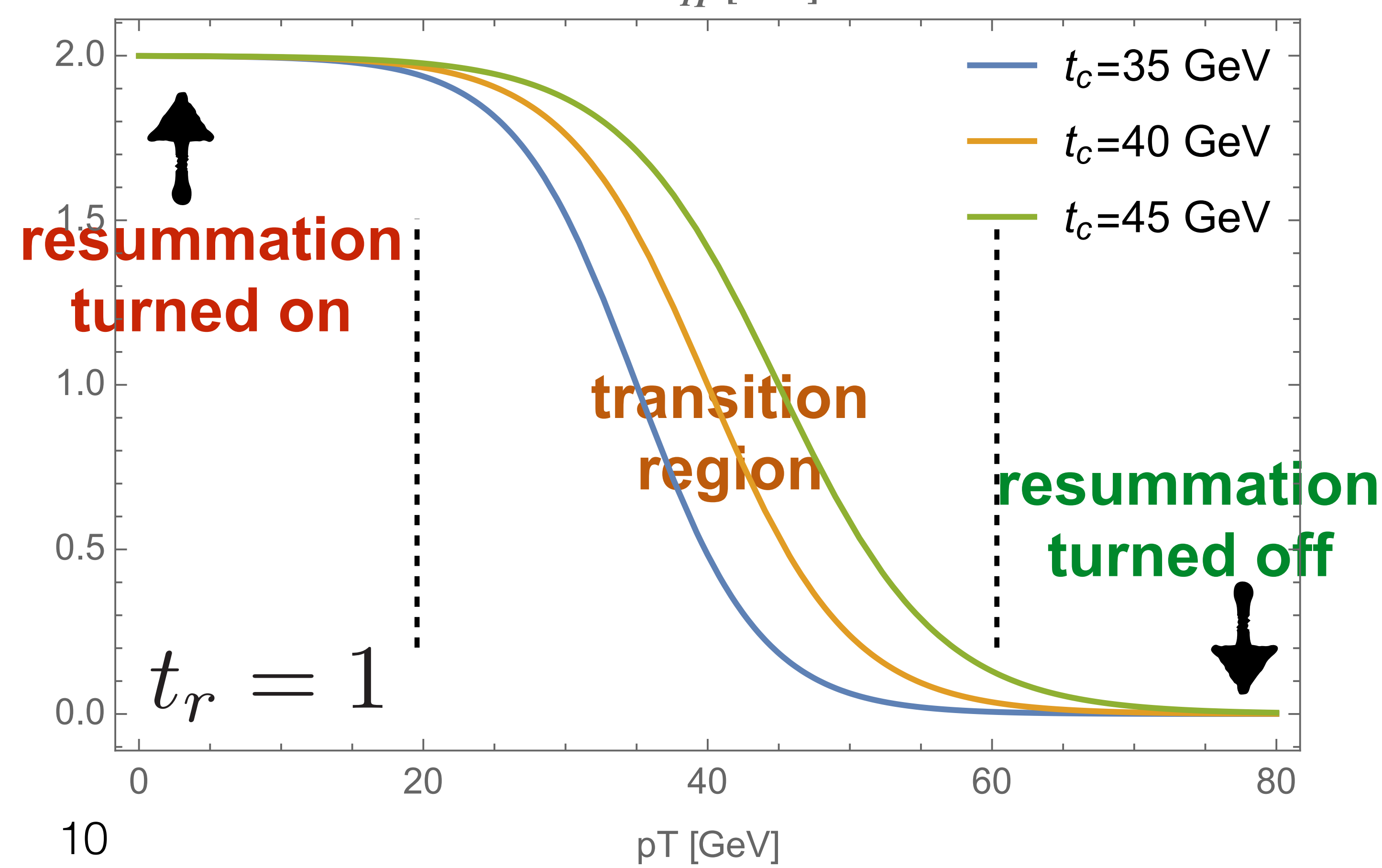
- Perturbative ingredients only available recently
  - Three-loop rapidity anomalous dim. (B_3): [Ye Li, HXZ, 2016]
  - Two-loop TMD beam function: [Gehrmann, Luebert, L.L. Yang, 2014]
  - $O(\alpha_s^3)$ (N3LO) nonsingular remainder (the Y term) [not shown in this talk]
- Only missing ingredient to achieve full N3LL resummation: 4-loop cusp anomalous dim.

Profile scale for switching from resumed to fixed order

- The large logarithms only dominate the cross section at small pT
- Needs to switch to fixed order prediction at large pT. See also Bowen Wang's talk
- Use profile scale to smoothly switch from resumed region to fixed-order region [Tackmann, Ligeti, Stewart '08; Abbate, Fickinger, Mateu, Hoang, Stewart '10]
- pT profile function [Neill, Rothstein, Vaidya, '15]:

$$P(q_T) = 1 - \tanh\left[t_r\left(\frac{4q_T}{t_c} - 4\right)\right]$$



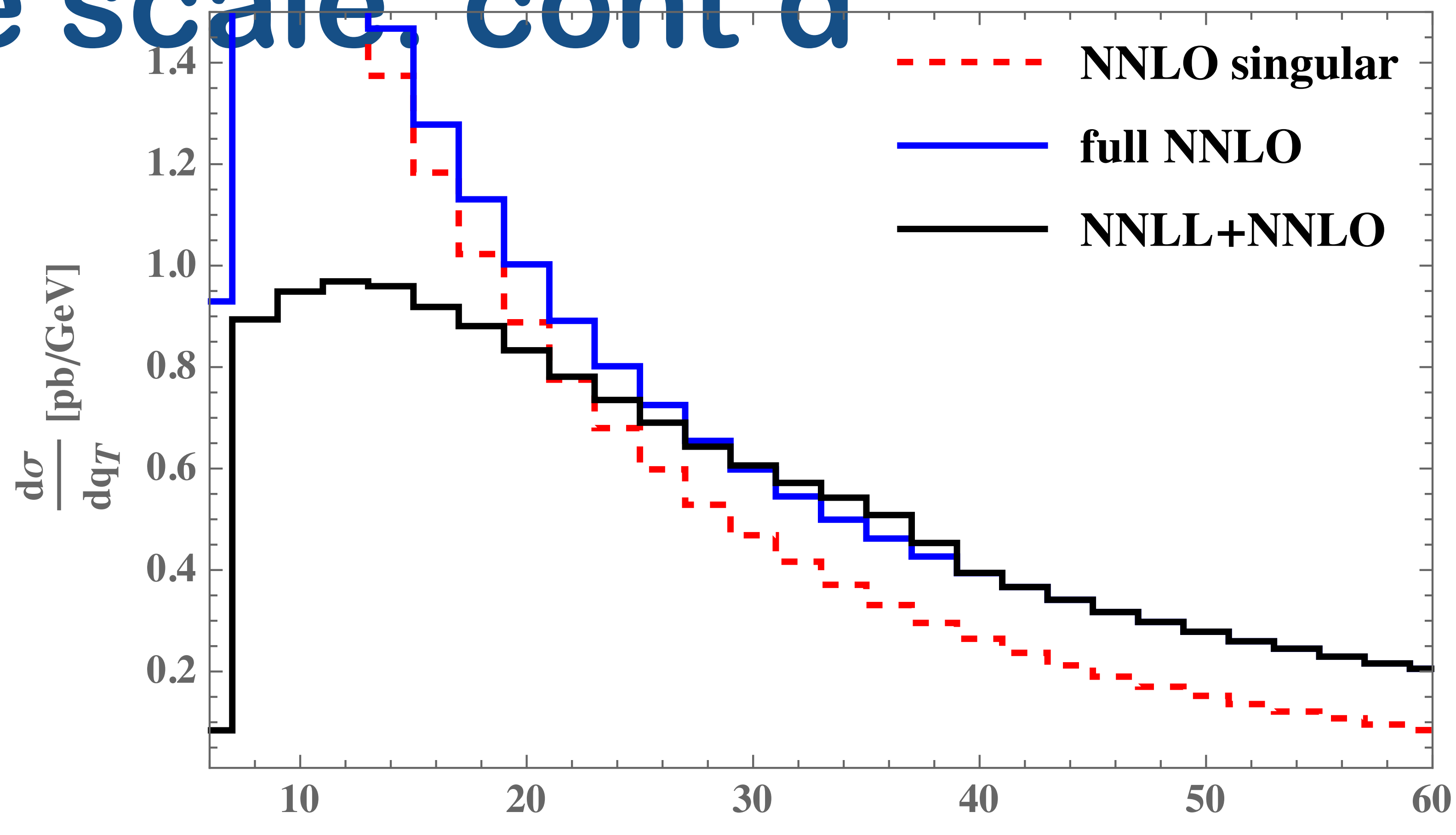


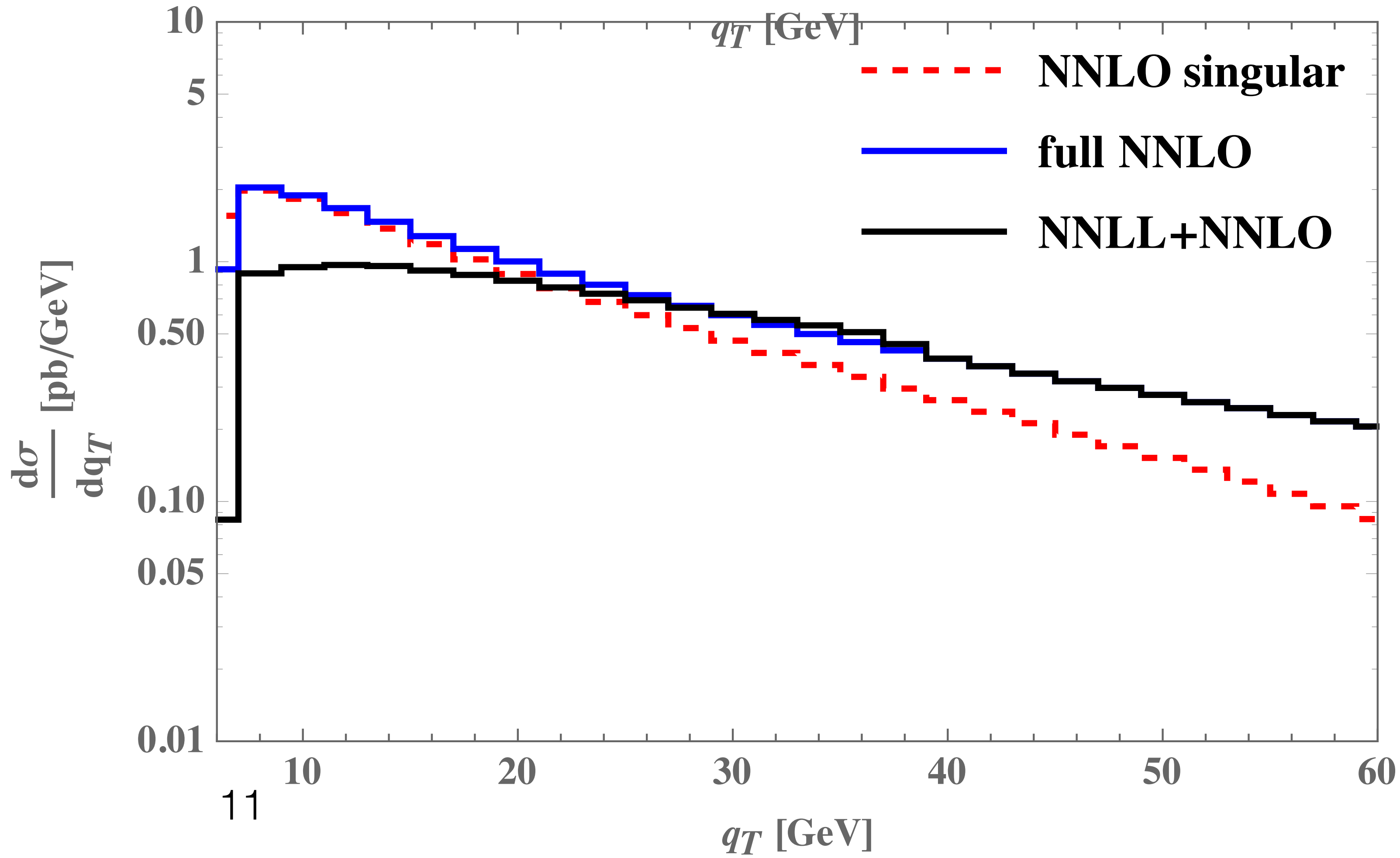
Profile scale: cont'd

$$P(q_T) = 1 - \tanh\left[t_r\left(\frac{4q_T}{t_c} - 4\right)\right]$$

Center of transition: t_c = 35 GeV

Transition rate: t_r = 1





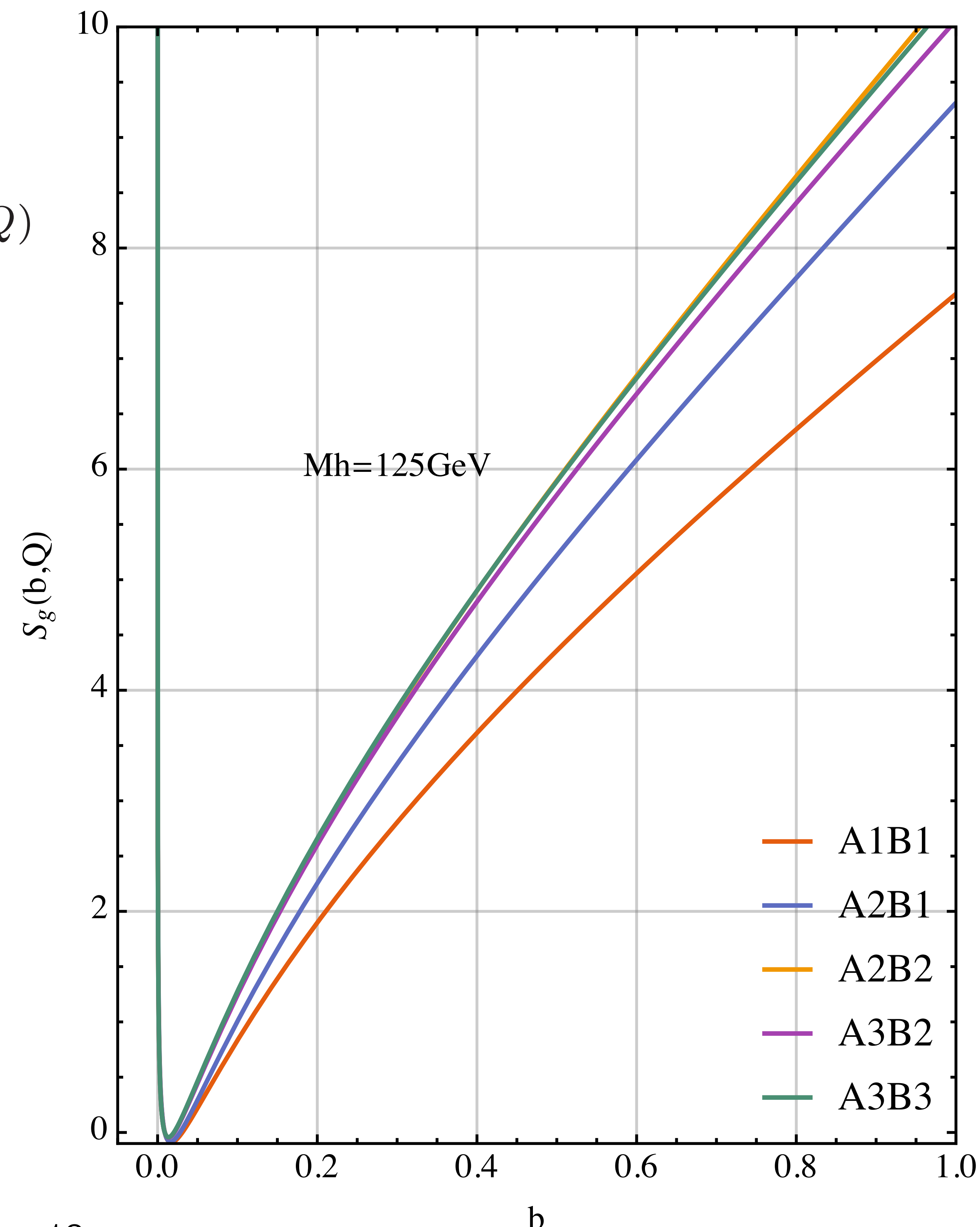
- Upper panel: y-axis in linear scale
- bottom panel: y-axis in logarithmic scale
- With the profile scale, achieve a smooth transition from resumed region to tail region

Suppression of nonperturbative effects

Sudakov factor

$$\sigma \sim \sigma_0 H(f \otimes C) \otimes (f \otimes C) e^{-S_g(b,Q)}$$

- In the b-space resumed formalism, non-perturbative effects enter at large b
- Important effects for Drell-Yan
- Much less important for Higgs production
  - Large Sudakov suppression of integrand at large b [Berger, Qiu, 2002]

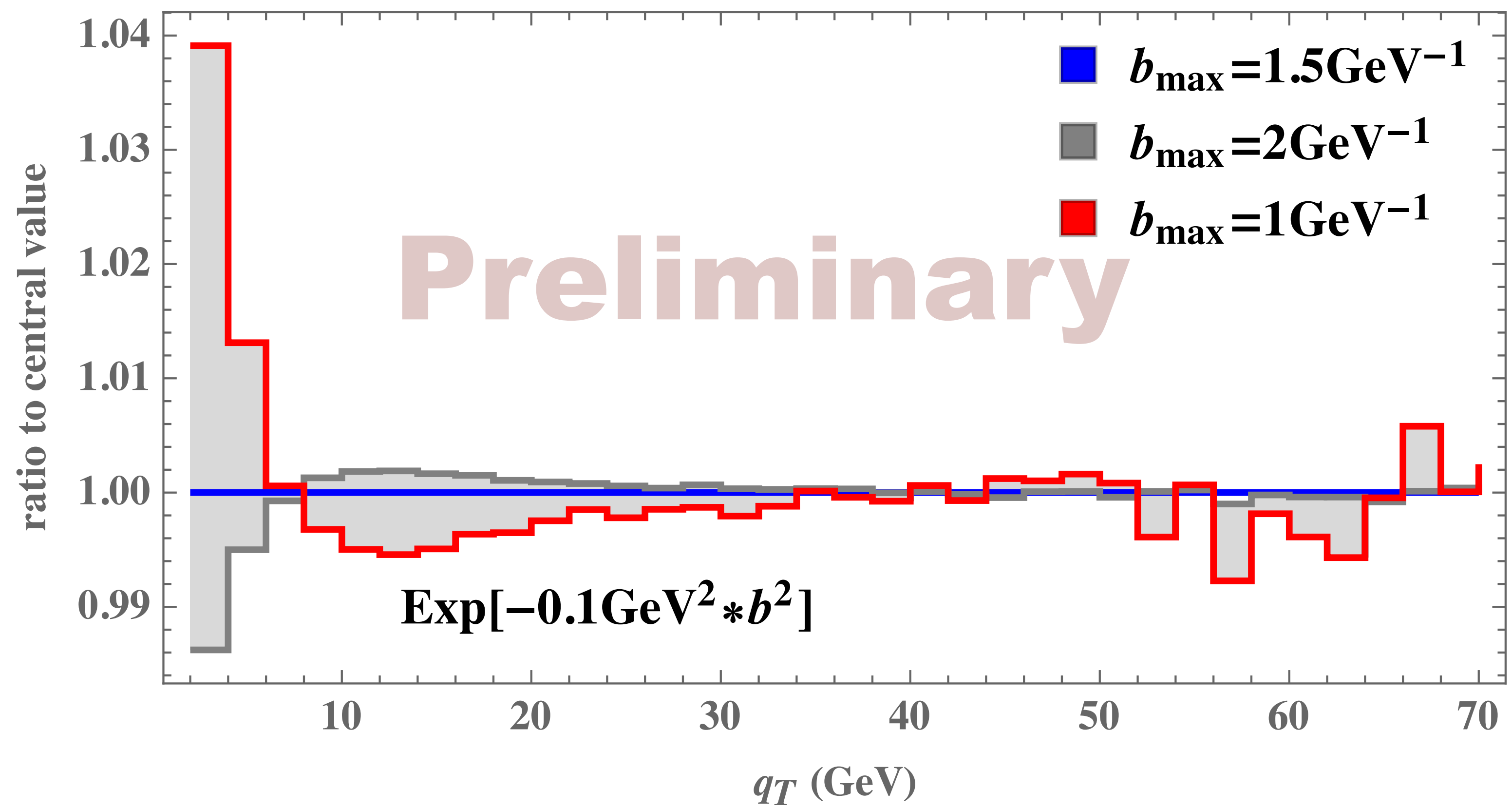


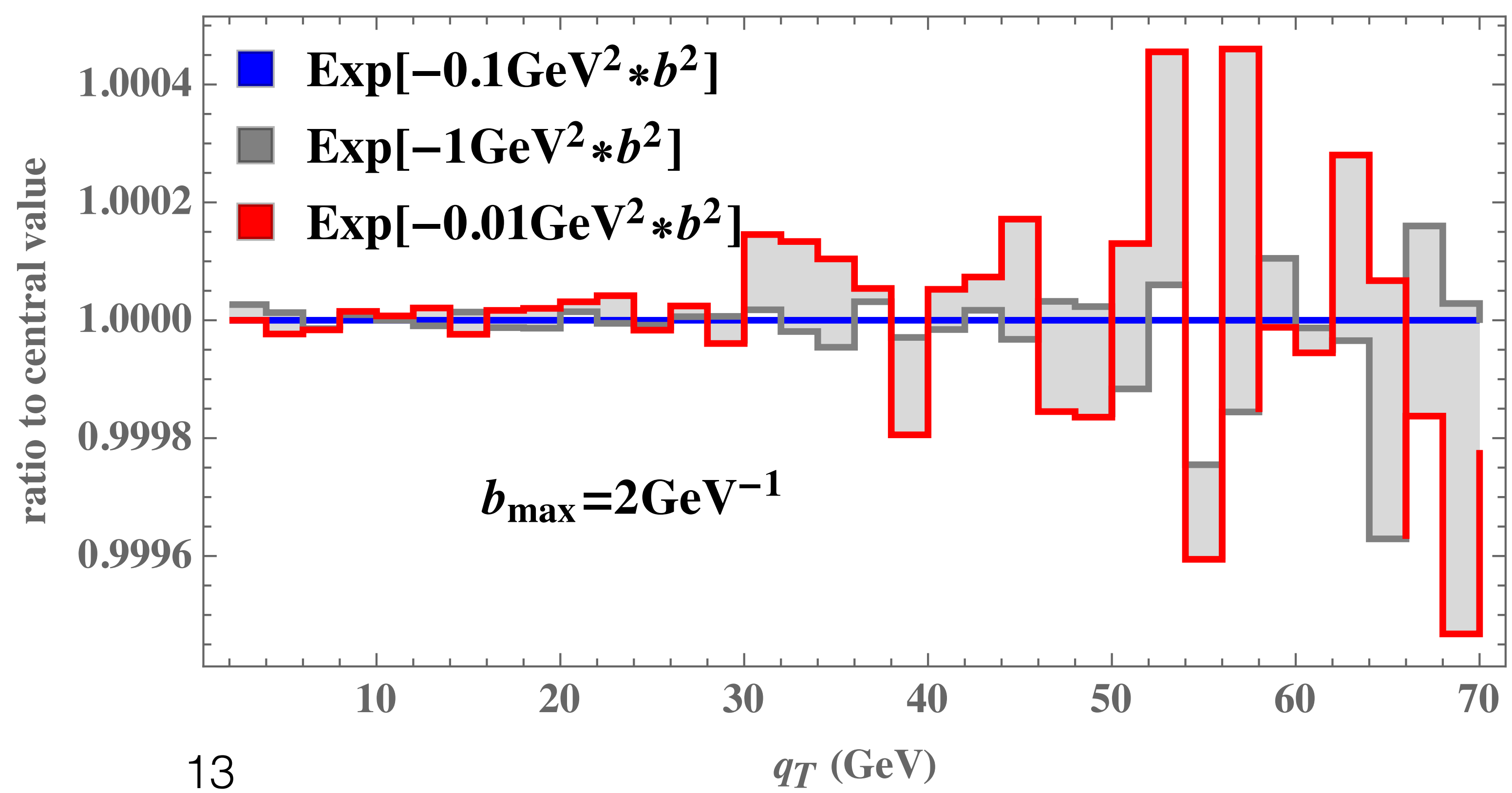
Dependence on nonperturbative parameter

$$b^* = \frac{b}{\sqrt{1 + b^2/b_{\max}^2}}$$

$$e^{-S_g} \to e^{-S_g} \exp\left[-cb^2\right]$$

- b_{max} scheme
- Use a simple exponential function to model N.P. effects
- Varying the N.P. parameter to estimate the N.P. uncertainties
- Higgs pT distribution is insensitive to N.P. corrections: less than 1% at peak region



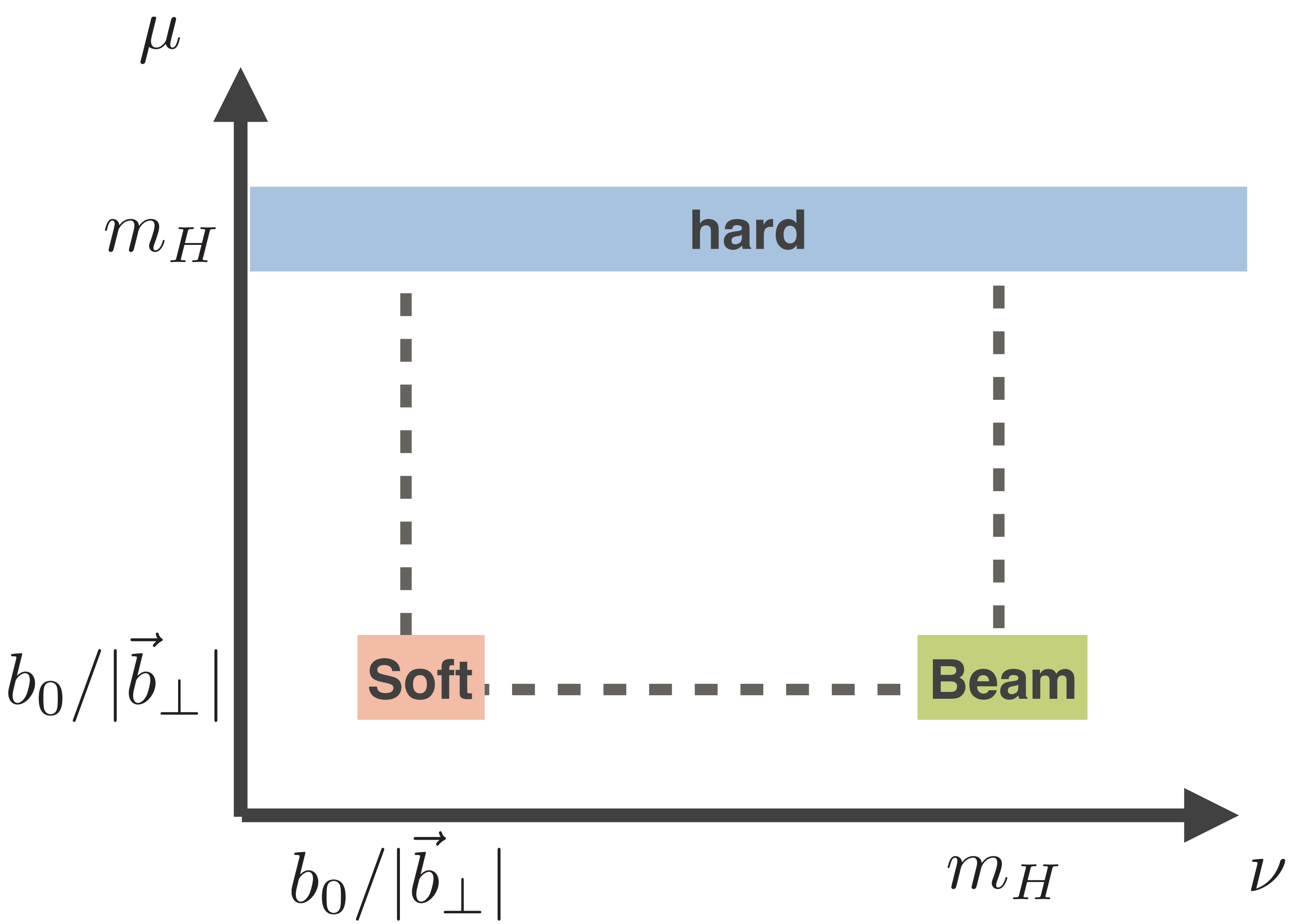


Estimate of uncertainties

- Choose central scales such that large logarithms in the Wilson coefficients for hard, beam, and soft functions are minimized.
- Vary by a factor of two around central scale to estimate theory uncertainties

$$\mu_H \in [\frac{1}{4}m_H, m_H]$$

$$\mu_B = \mu_S \in [\frac{1}{2}\frac{b_0}{b_\perp}, 2\frac{b_0}{b_\perp}]$$

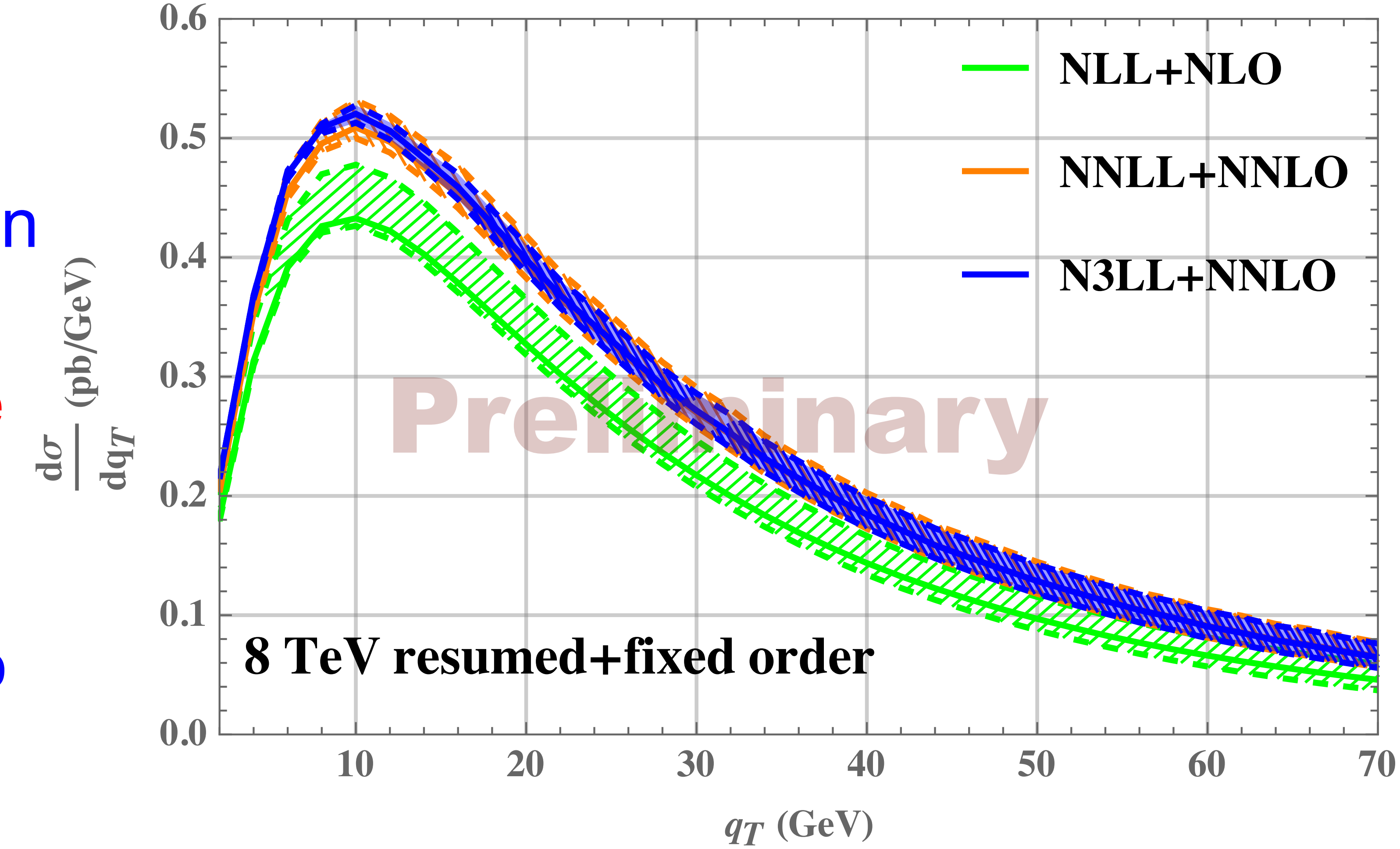


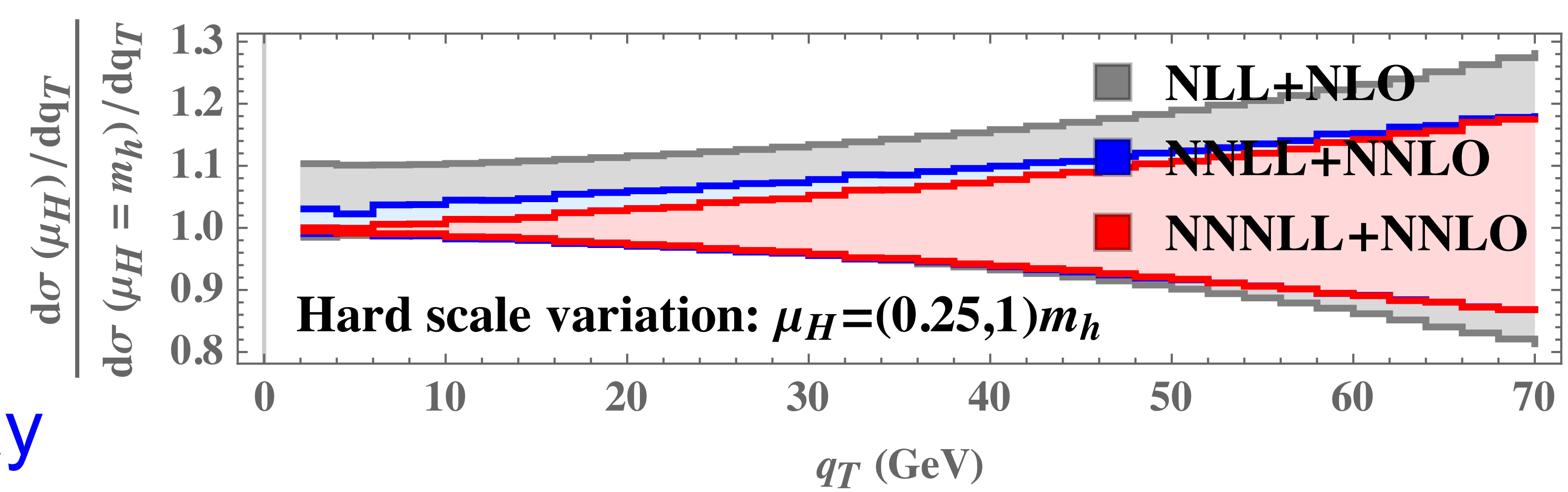
$$\nu_S \in [\frac{1}{2}\frac{b_0}{b_\perp}, 2\frac{b_0}{b_\perp}]$$

$$\nu_B = m_H$$

Uncertainty from hard scale variation

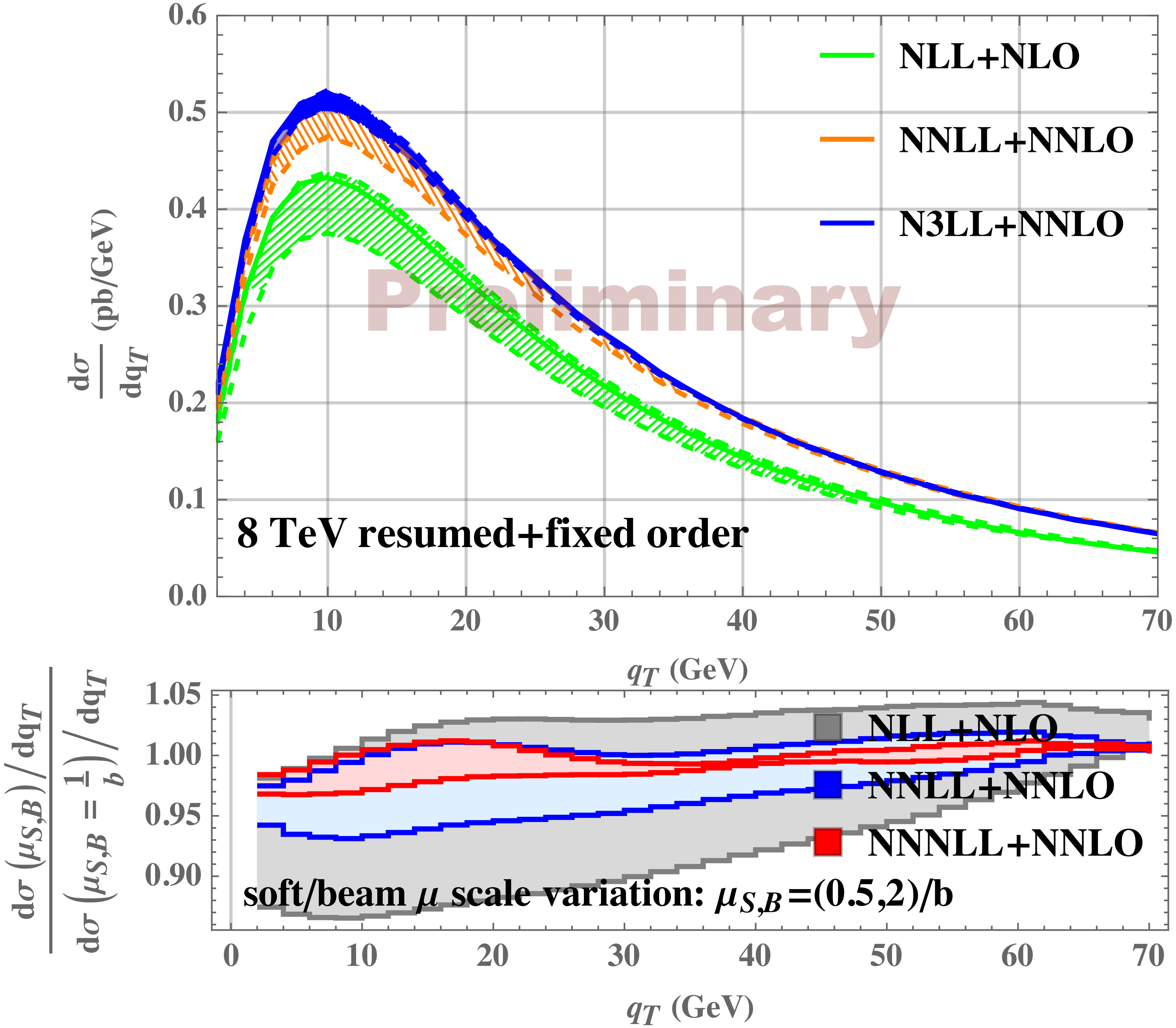
- Central scale for hard function chosen as μ=m_H/2 to minimize large π^2 terms in Wilson coefficient.
- Leads to better perturbative convergence.
- Obvious reduction of scale uncertainty at low pT due to resummation
- At large pT, scale uncertainties dominated by fixed order perturbation theory.
- Implementing N3LO non-singular reminder on the way





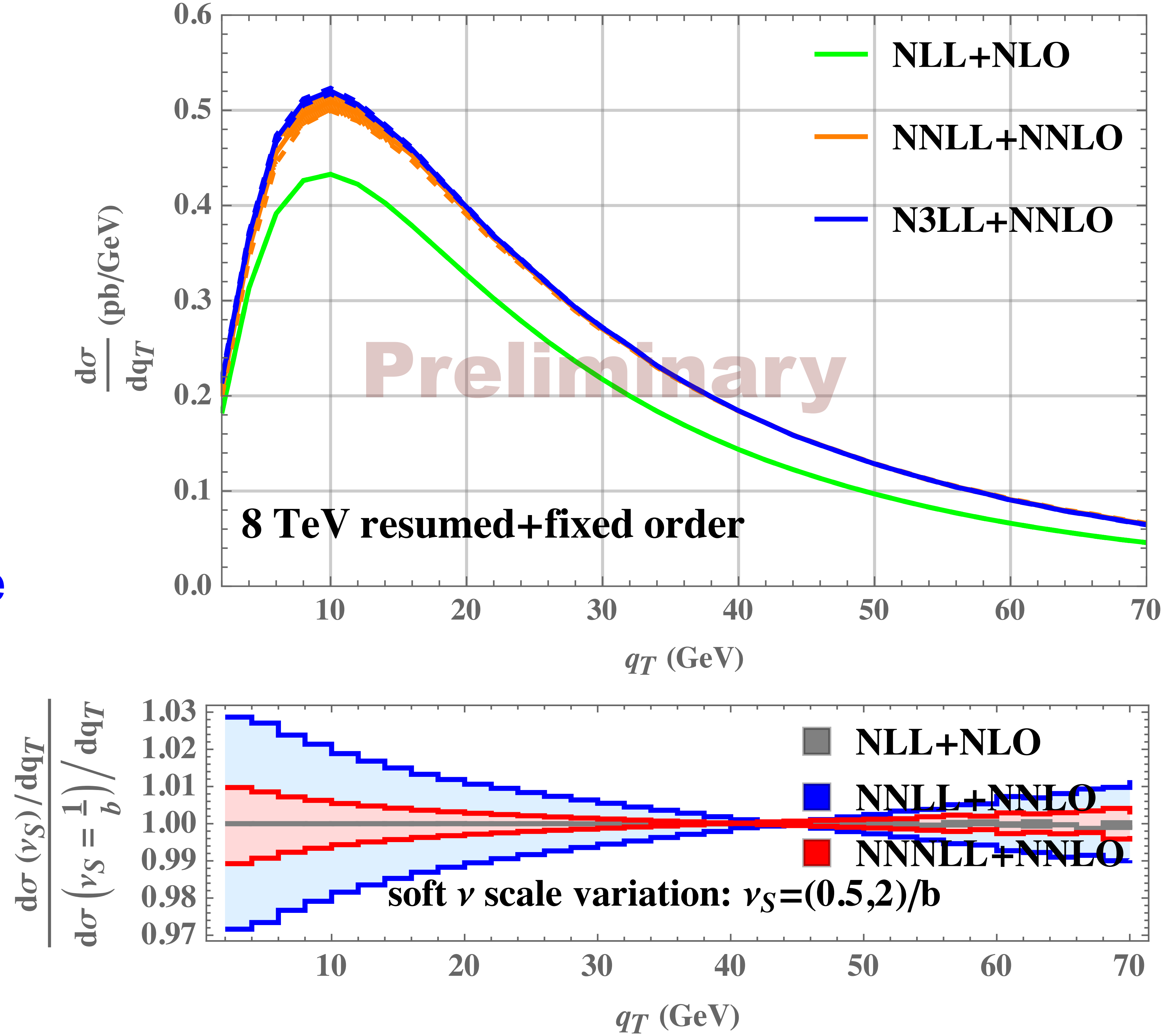
Uncertainty from soft scale variation

- Central soft scale chosen as 1/b
- Large soft scale dependence at low pT, improved order by order in RG improved perturbation theory
- As expected, little soft scale dependence at large pT
- Peaks at about 10 GeV. The typical soft scale far from nonperturbative region



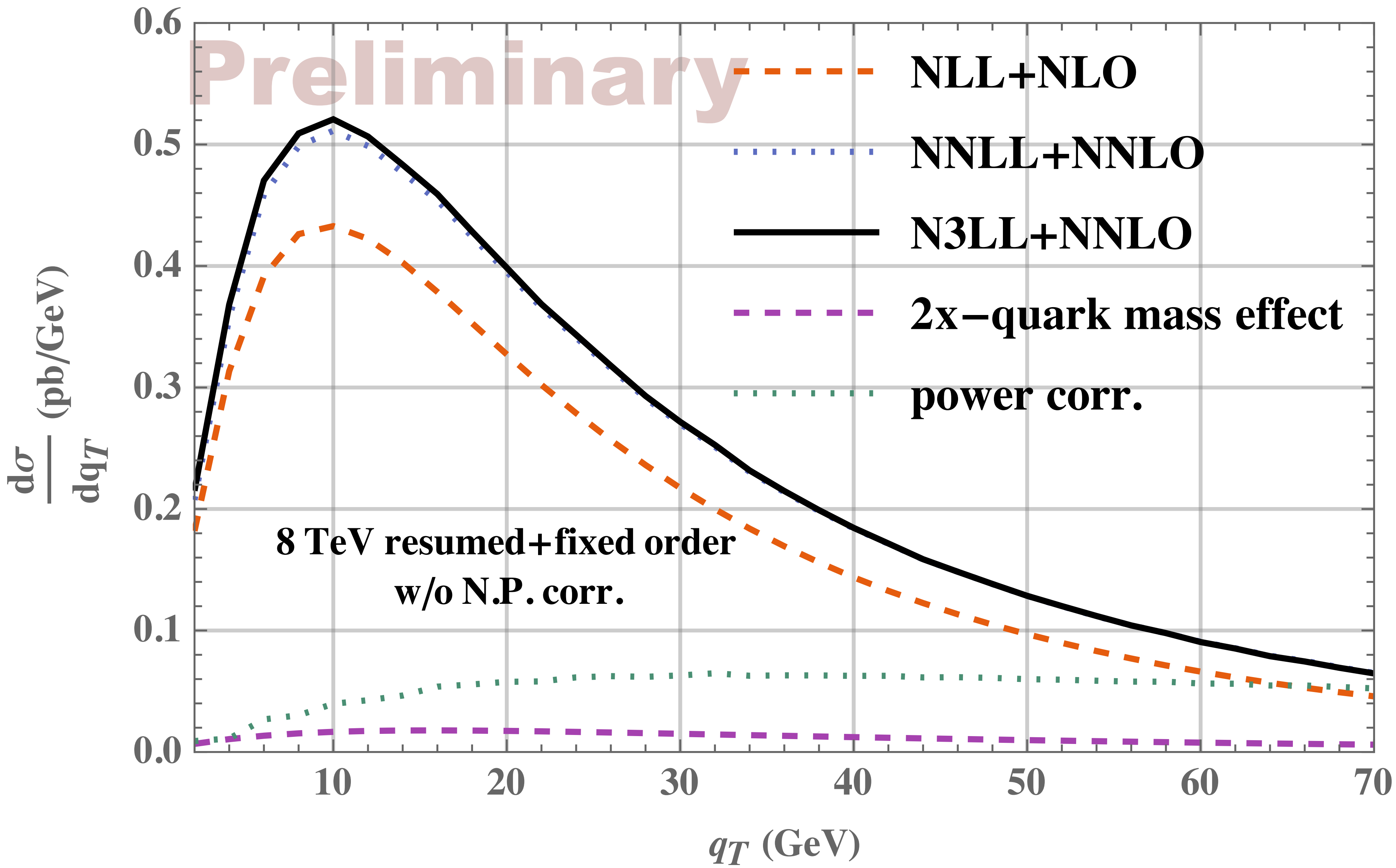
Uncertainty from rapidity scale variation

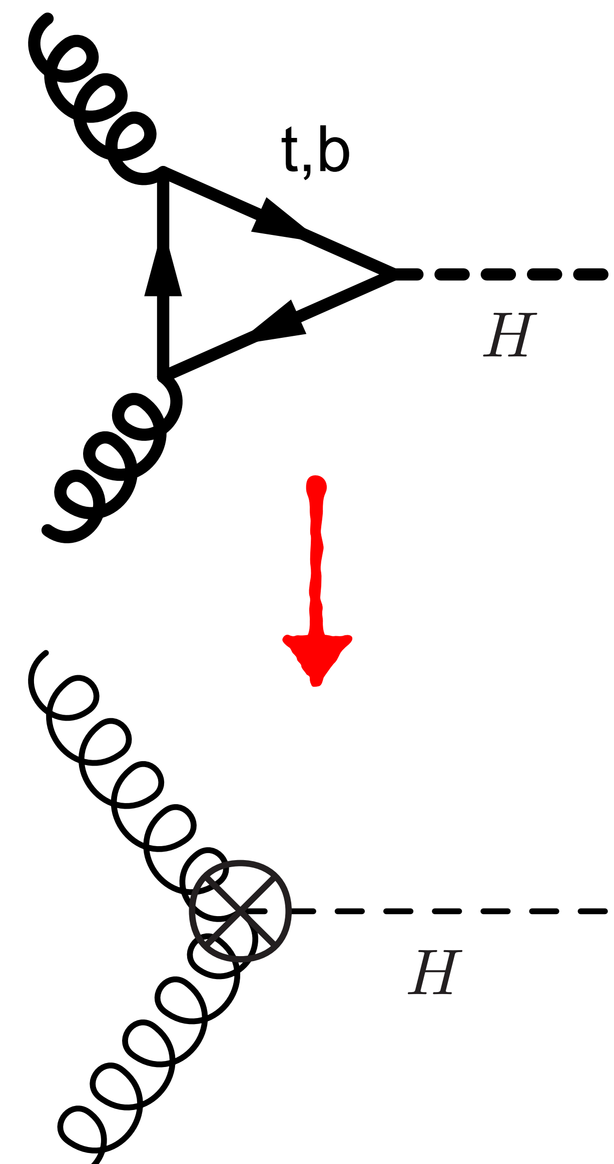
- Central rapidity scale chosen as 1/b
- Absence of rapidity scale dependence at NLL, due to accidental vanishment of rapidity anomalous dim. at this order
- Important to compute higher order rapidity scale variation
- It turns out rapidity uncertainties is in general small in Higgs production



Corrections to the Higgs effective theory

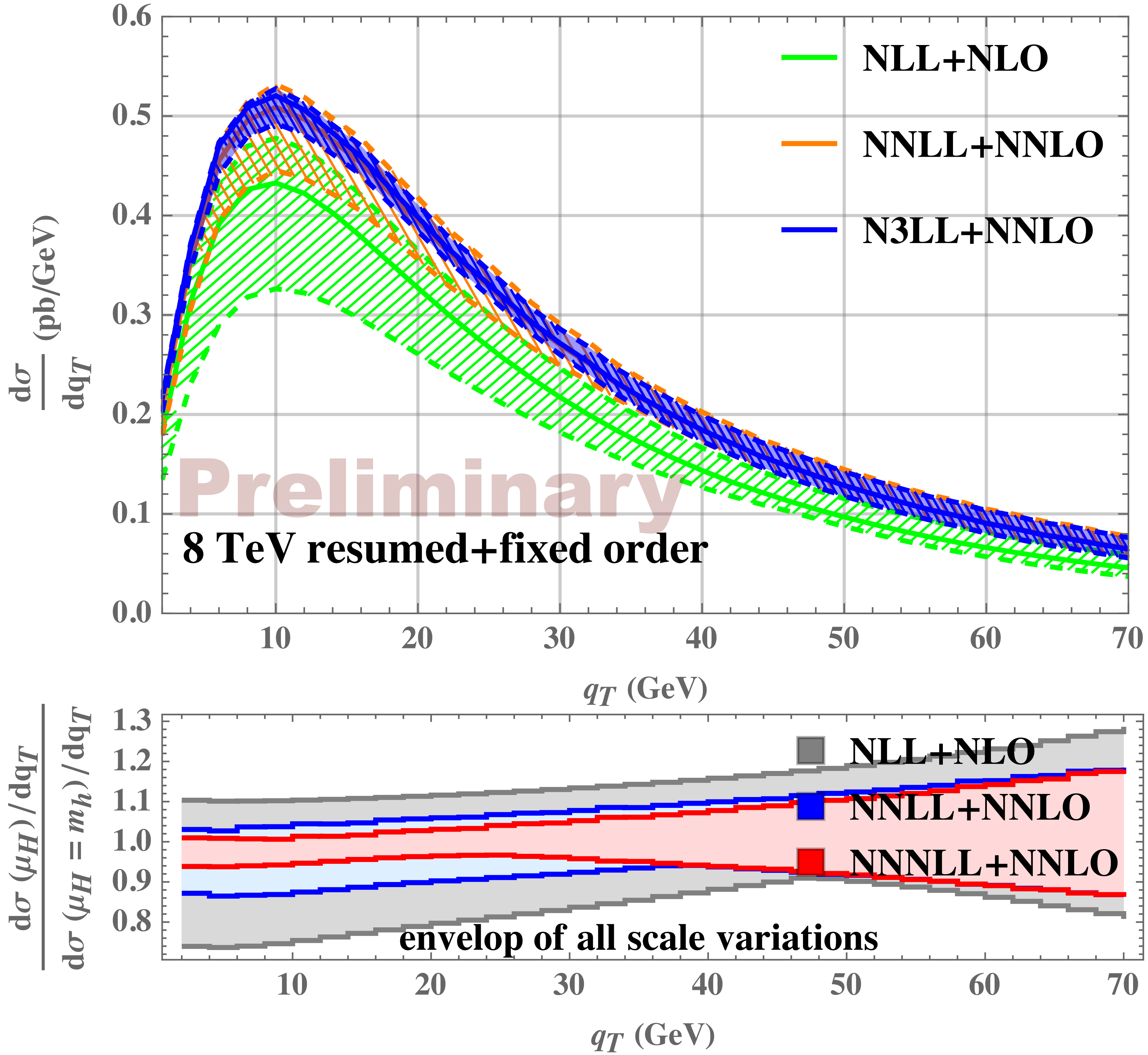
- Our calculation performed in Higgs effective theory, with the quark loop integrated out
- Good approximation for top quark loop at small and moderate pT
- It turns out the full bottom quark loop effects are small at LO





Total N3LL$_{partial}$ uncertainties

- Total scale uncertainties estimated as envelop of individual scale uncertainties
- Order by order reduction of uncertainties. Give confidence in the reliability of RG improved perturbation theory
- Remaining scale uncertainties at the level of < 5%
- Uncertainty due to unknown 4-loop cusp anomalous dim. at comparable level



Summary

- With the discovery of Higgs boson and lack of other new physics, studying its property, like pT distribution, is of great importance
- Recent advance in QCD make possible resummation of Higgs pT distribution at (partial) N3LL level
- Implementing the N3LO nonsingular remainder (Y term) is in progress. Stay tuned
- Ingredients for resumming the large pT logarithms in Drell-Yan production are also available
- Expect larger impact from N3LL corrections to DY distribution

$$\frac{B_3^{DY}(\alpha_s)}{B_2^{DY}(\alpha_s)} \simeq 1.317 \qquad \frac{B_3^{H}(\alpha_s)}{B_2^{H}(\alpha_s)} \simeq 0.109$$

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Thank you for your attention!