Resummation of E_T in Higgs boson production

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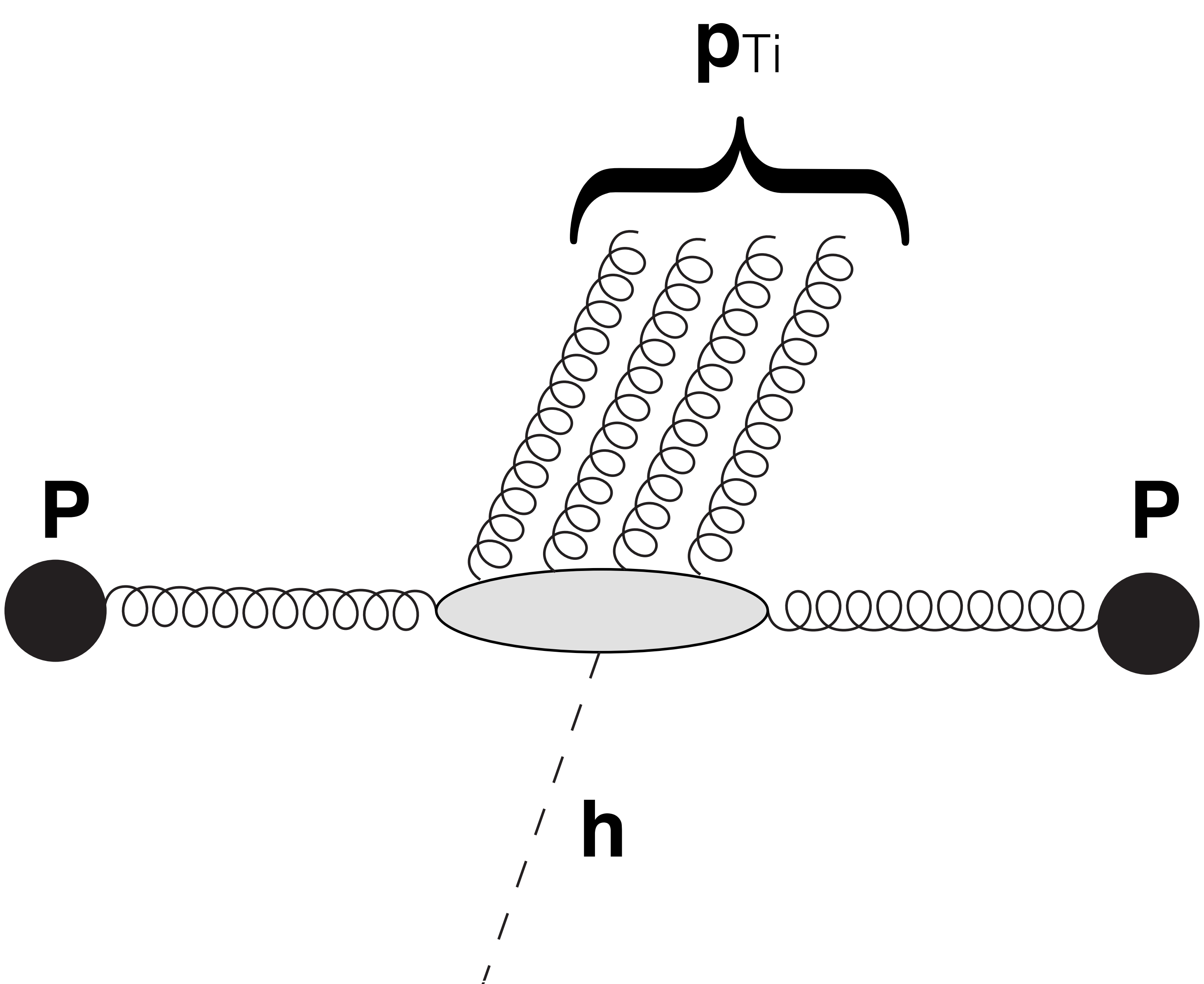
[**1002.4375**, AP, B. R. Webber, J. M., Smillie & **1403.3394**, M.Grazzini, AP, B. R. Webber, J. M., Smillie]

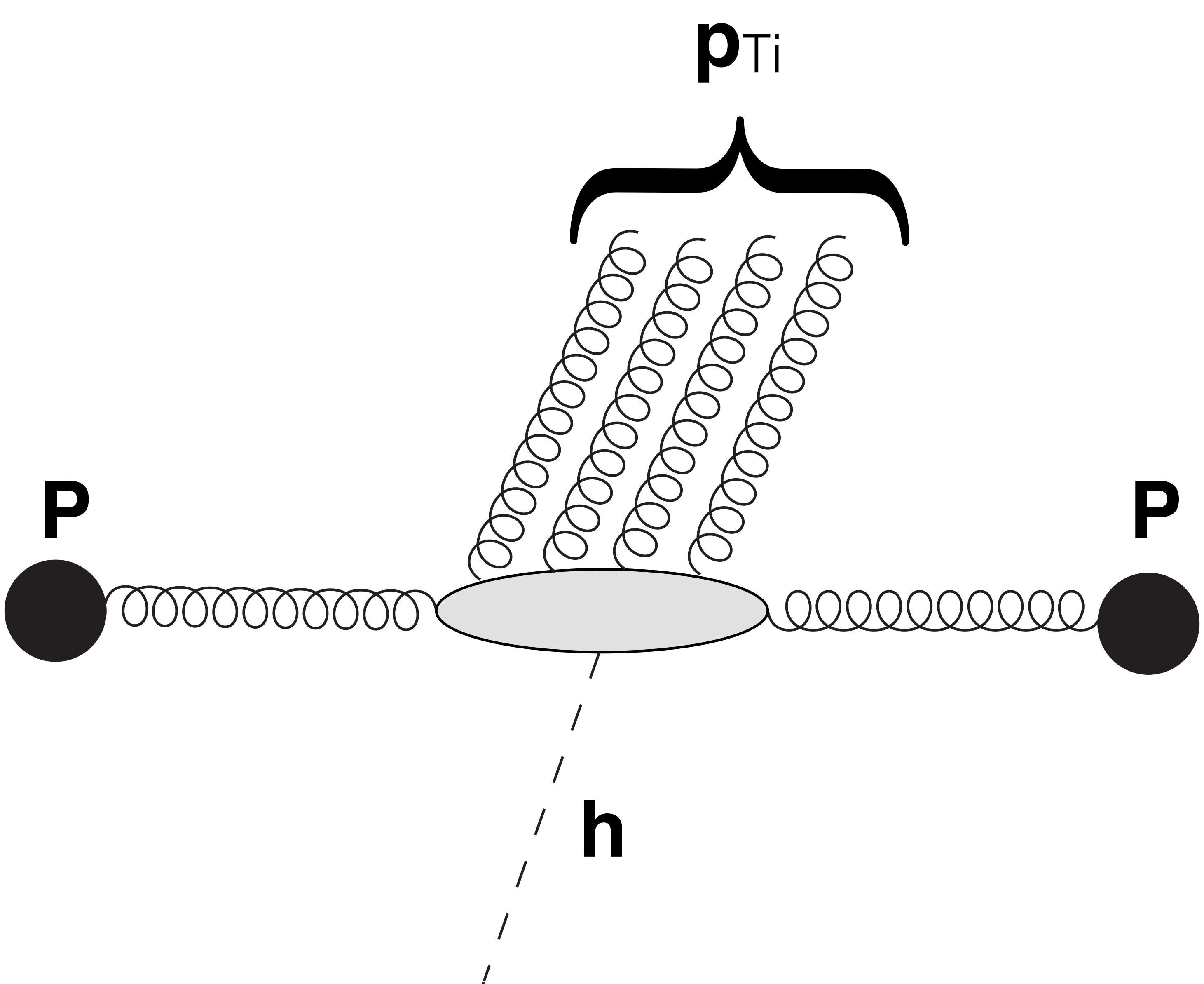
the plan

- definition+motivation.
- from q_T to E_T resummation.
- matching to fixed order.
- Monte Carlo studies.
- conclusions+outlook.

definition

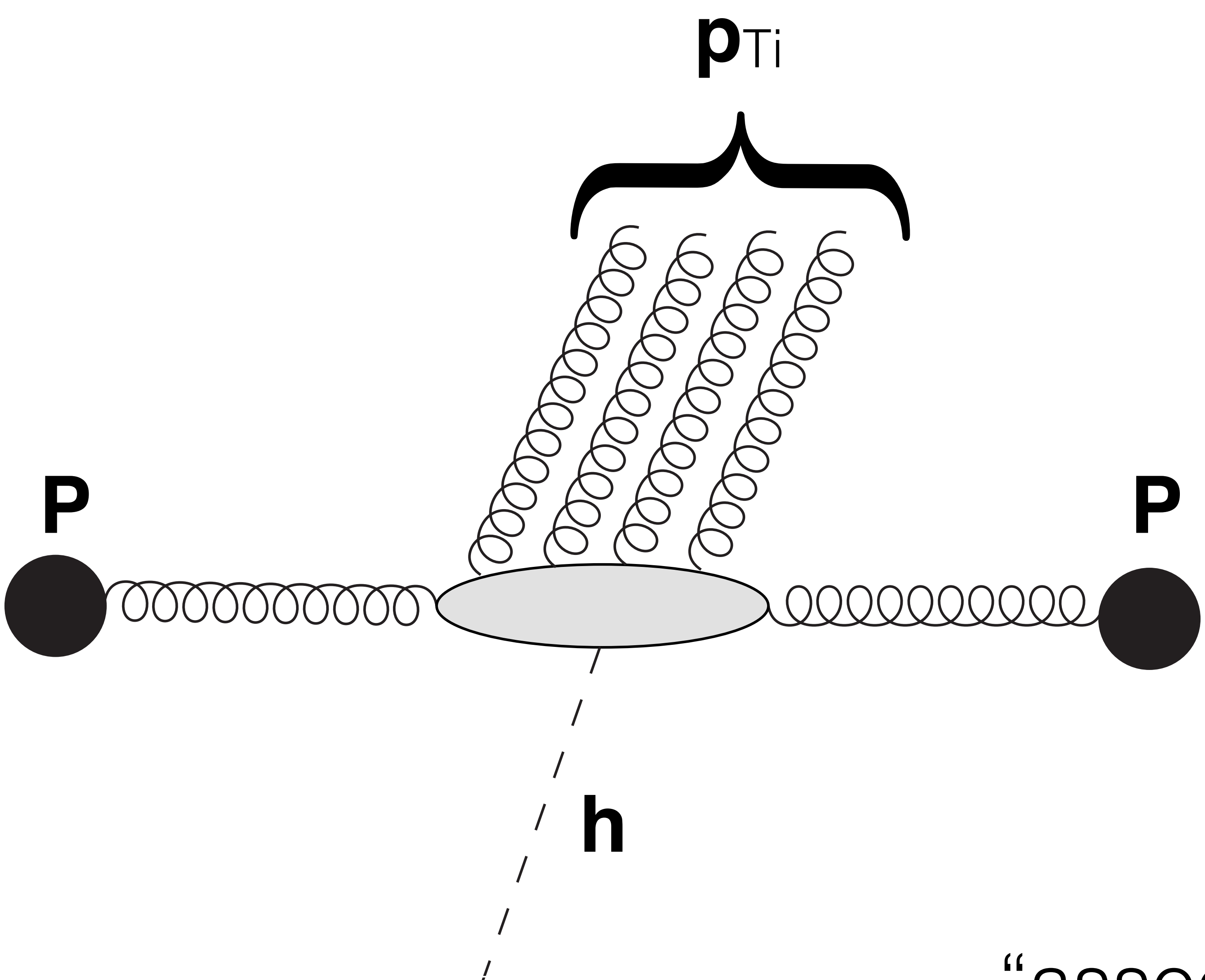


definition



$$\mathbf{q}_T = -\sum_i \mathbf{p}_{Ti}$$

definition



$$\mathbf{q}_T = -\sum_i \mathbf{p}_{Ti}$$

$$E_T = \sum_i |\mathbf{p}_{Ti}|$$

"associated" transverse energy

motivation

- an alternative variable for studying initial-state radiation in Higgs boson production.
- may help separate different production mechanisms (VBF versus ggF).
- sensitive to the underlying event, may help improve its modelling.

q_T resummation

$$\frac{\mathrm{d}\sigma_H}{\mathrm{d}Q^2\ \mathrm{d}q_T^2} = \left[\frac{\mathrm{d}\sigma_H}{\mathrm{d}Q^2\ \mathrm{d}q_T^2}\right]_{\mathrm{res.}} + \left[\frac{\mathrm{d}\sigma_H}{\mathrm{d}Q^2\ \mathrm{d}q_T^2}\right]_{\mathrm{fin.}}$$

[e.g. Catani, de Florian, Grazzini, hep-ph/0008184]

q_T resummation

$$\frac{\mathrm{d}\sigma_H}{\mathrm{d}Q^2\ \mathrm{d}q_T^2} = \underbrace{\left[\frac{\mathrm{d}\sigma_H}{\mathrm{d}Q^2\ \mathrm{d}q_T^2}\right]_{\mathrm{res.}}}_{\substack{\text{contains log-enhanced} \\ \text{contributions} \\ \alpha_S^n \ln^m Q^2/q_T^2}} + \left[\frac{\mathrm{d}\sigma_H}{\mathrm{d}Q^2\ \mathrm{d}q_T^2}\right]_{\mathrm{fin.}}$$

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[e.g. Catani, de Florian, Grazzini, hep-ph/0008184]

resummed component

$$\left[\frac{\mathrm{d}\sigma_H}{\mathrm{d}Q^2\ \mathrm{d}q_T^2}\right]_{\mathrm{res.}} = \sum_{a,b}\int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \int_0^\infty \mathrm{d}b\ \frac{b}{2} J_0(bq_T)\ f_{a/h_1}(x_1,\mu)\ f_{b/h_2}(x_2,\mu)$$

$$\times W_{ab}^H(x_1 x_2 s; Q, b, \mu)$$

- carry out the resummation in **b**-space (transverse momentum conservation).
- W_{ab}^H is the perturbative, process-dependent partonic cross section: embodies all-order resummation of large logs $\ln Q^2 b^2$.
- note: $q_T \ll Q \longleftrightarrow Qb \gg 1$.

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W_{ab}^{H} (resummed partonic cross section)

$$W_{ab}^{H}(s;Q,b,\mu) = \int_0^1 \mathrm{d}z_1 \int_0^1 \mathrm{d}z_2 \; C_{ga}(\alpha_S(\mu),z_1;b,\mu) \; C_{gb}(\alpha_S(\mu),z_2;b,\mu) \; \delta(Q^2 - z_1 z_2 s)$$
$$\times \sigma_{gg}^{H}(Q,\alpha_S(Q)) \; S_g(Q,b)$$

- coefficient functions (**no** ln(Qb) terms):

$$C_{ga}(\alpha_S,z) = \delta_{ga}\delta(1-z) + \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n C_{ga}^{(n)}$$

- σ_{gg}^{H} : partonic ggF Higgs cross section,
- $S_g(Q,b)$: gluon Sudakov form factor.

from q_T to E_T

when performing resummation: sum over multiple emissions, enforcing the relations via δ-functions:

$$\mathbf{q}_T = -\sum_i \mathbf{p}_{Ti}$$

(gives Bessel function)

$$\Rightarrow \delta(\mathbf{q}_T + \sum_i \mathbf{p}_{Ti}) = \frac{1}{(2\pi)^2} \int \mathrm{d}\mathbf{b}\ \mathrm{e}^{i\mathbf{q}_T\cdot\mathbf{b}} \prod_i \mathrm{e}^{i\mathbf{p}_{Ti}\cdot\mathbf{b}}$$

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$$E_T = \sum_i |\mathbf{p}_{Ti}|$$

$$\Rightarrow \delta(E_T - \sum_i |\mathbf{p}_{Ti}|) = \frac{1}{2\pi} \int \mathrm{d}\tau\ \mathrm{e}^{-iE_T\tau} \prod_i \mathrm{e}^{i|\mathbf{p}_{Ti}|\tau}$$

$$\left[\frac{\mathrm{d}\sigma_H}{\mathrm{d}Q^2\ \mathrm{d}q_T^2}\right]_{\mathrm{res.}} = \sum_{a,b}\int_0^1 \mathrm{d}x_1 \int_0^1 \mathrm{d}x_2 \int_0^\infty \mathrm{d}b\ \frac{b}{2} J_0(bq_T)\ f_{a/h_1}(x_1,\mu)\ f_{b/h_2}(x_2,\mu)$$
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resummed partonic cross section:

$$W_{ab}^{H}(s;Q,\tau,\mu) = \int_0^1 \mathrm{d}z_1 \int_0^1 \mathrm{d}z_2\ C_{ga}(\alpha_S(\mu), z_1; \tau, \mu)\ C_{gb}(\alpha_S(\mu), z_2; \tau, \mu)\delta(Q^2 - z_1 z_2 s)$$

$$\times \sigma_{gg}^{H}(Q, \alpha_S(Q)) S_g(Q, \tau)$$

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$$\times \sigma_{gg}^{H}(Q, \alpha_S(Q)) S_g(Q, \tau)$$

form factor:

$$S_g(Q,\tau) = \exp\left\{-2\int_0^Q \frac{\mathrm{d}q}{q}\left[2A_g \ln\frac{Q}{q} + B_g\right](1 - \mathrm{e}^{iq\tau})\right\}$$

the form factor

$$S_g(Q,\tau) = \exp\left\{-2\int_0^Q \frac{\mathrm{d}q}{q}\left[2A_g \ln\frac{Q}{q} + B_g\right]\left(1-\mathrm{e}^{iq\tau}\right)\right\}$$

- A_g, B_g: **no** ln(Qτ) terms:

$$A_g(\alpha_S) = \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n A_g^{(n)}$$

$$B_g(\alpha_S) = \sum_{n=1}^{\infty}\left(\frac{\alpha_S}{\pi}\right)^n B_g^{(n)}$$

perturbative coefficients

- here (i.e. [1403.3394, M.Grazzini, AP, B. R. Webber, J. M., Smillie]), we include:

$$\underbrace{A_g^{(1)}, A_g^{(2)}, B_g^{(1)}}_{*}, B_g^{(2)}, \underbrace{C_{ga}^{(1)}}_{*}$$

*= same as q_T resummation.

$B_g^{(2)}$ is ***not*** necessarily equal! (see few slides later).

turning the handle…

- form factor evaluated analytically using “g-functions”:

$$-2\int_{b_0/b}^{Q}\frac{\mathrm{d}q}{q}\left[2A_g\ln\frac{Q}{q}+B_g\right]=Lg_1(Y)+g_2(Y)+\alpha_R g_3(Y)+...$$

$$L=2\ln(Qb/b_0),\alpha_R=\alpha_S(\mu_R)/\pi,Y=\beta_0\alpha_R L$$

- where this is modified accordingly for E_T:

$$b\to\tau,\ b_0\to\tau_0\equiv\exp(-\gamma_E)$$

(+ modifications in the integrand)

[Bozzi, Catani, de Florian, Grazzini, hep-ph/050868]

$$B_g^{(2)}$$

- may be different in q_T vs E_T resummation.

- expand q_T and E_T resummed predictions to NLO and subtract:

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}E_T} - \frac{\mathrm{d}\sigma}{\mathrm{d}q_T}\right]_{\mathrm{NLO}}\Bigg|_{q_T=E_T} \sim \alpha_R^2 (B_g^{(2)}|_{E_T} - B_g^{(2)}|_{q_T}) + \ldots$$

- fit to HNNLO and extract:

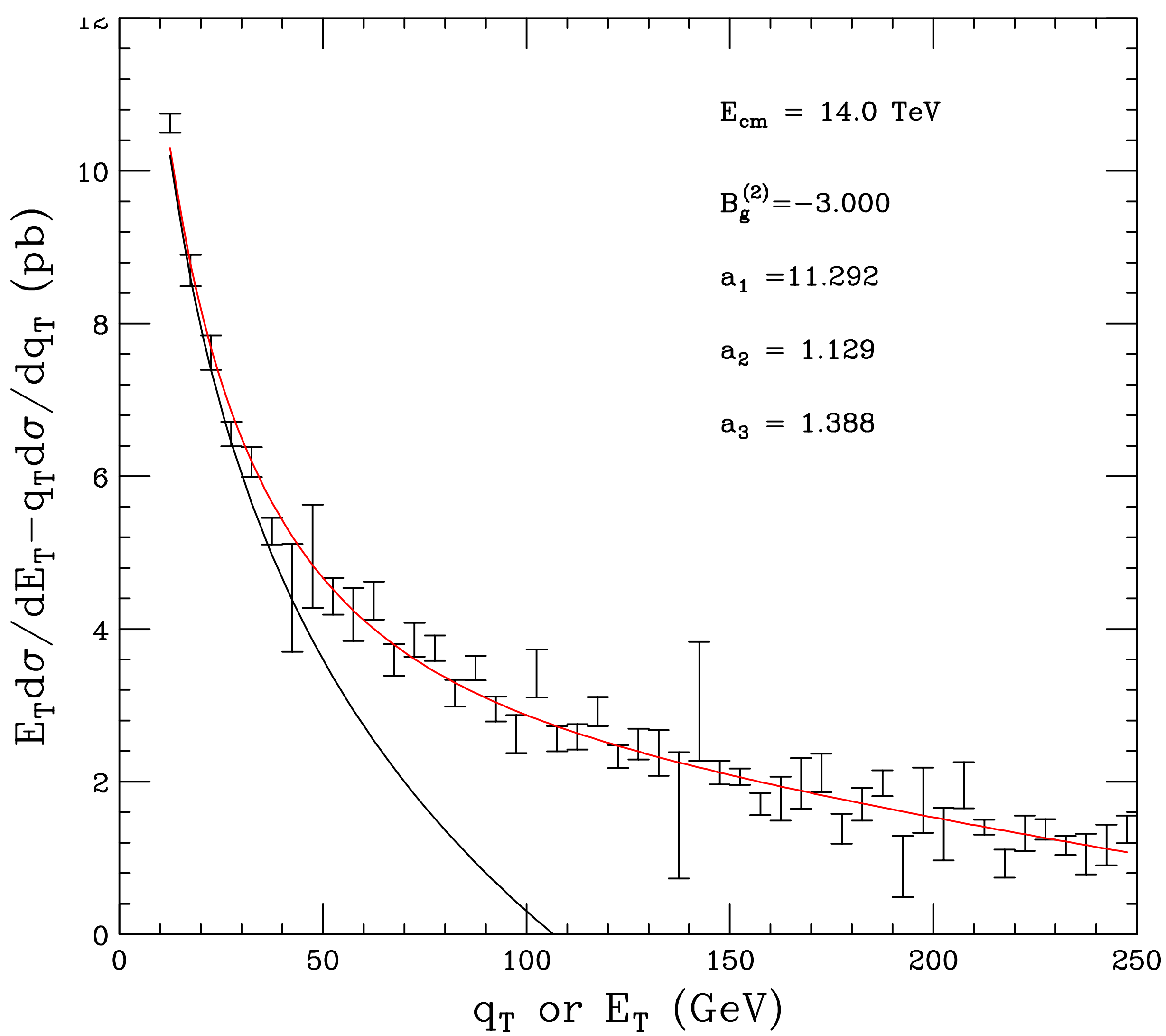
red curve: fit to all terms,

black curve: fit to log terms,

data: HNNLO (at NLO).

$$B_g^{(2)}|_{E_T} = -3.0 \pm 1.4$$

(c.f. $B_g^{(2)}|_{q_T} = 26.8$)

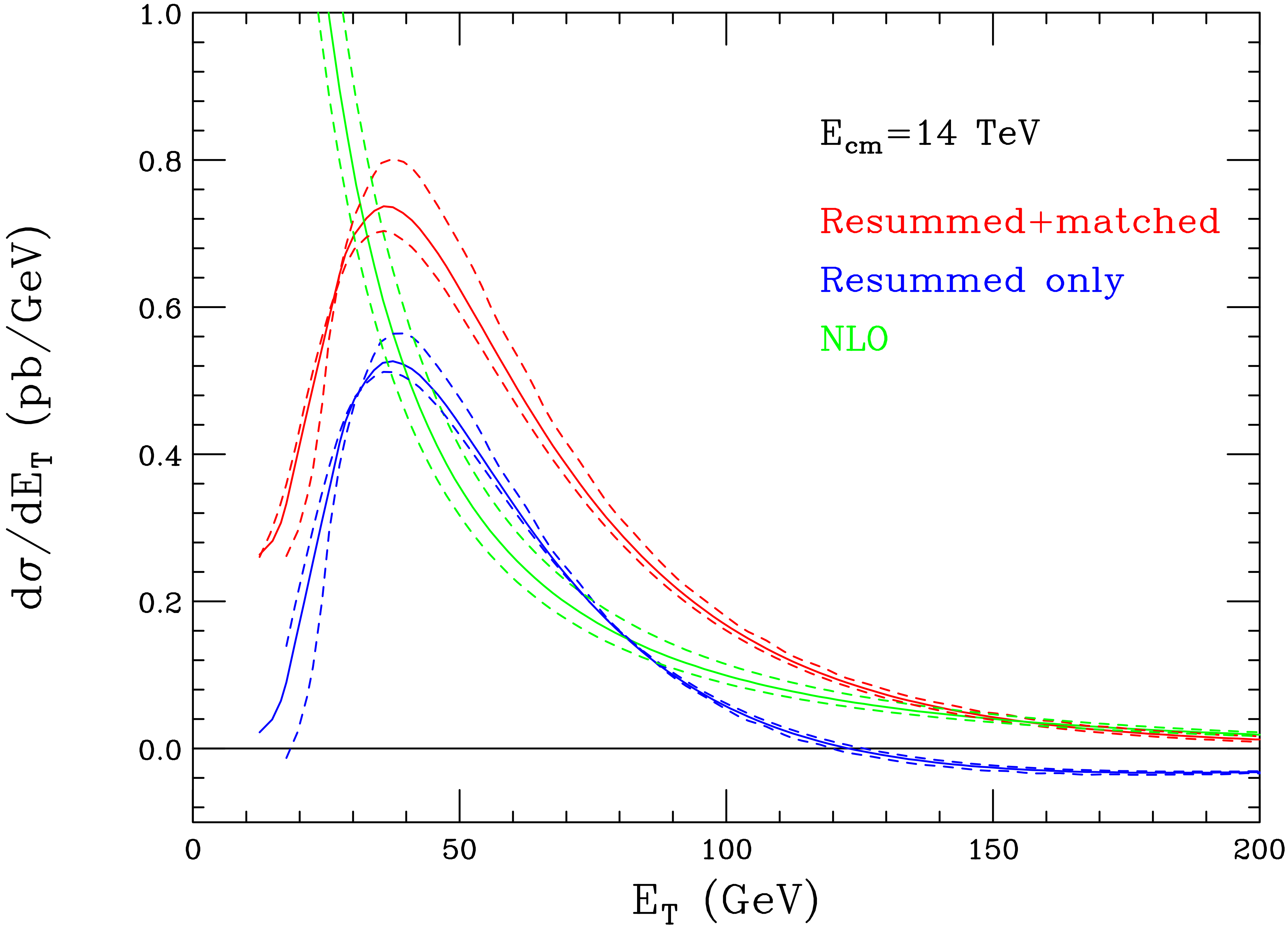


matching to NLO

- to match the resummed and NLO ET distributions:
  - subtract the NLO log terms that are already included in the resummation,
  - replace by full NLO result:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}E_T} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}E_T}\right]_{\mathrm{resum}} - \left[\frac{\mathrm{d}\sigma}{\mathrm{d}E_T}\right]_{\mathrm{resum,\ NLO}} + \left[\frac{\mathrm{d}\sigma}{\mathrm{d}E_T}\right]_{\mathrm{NLO}}$$

results



(dashed: renorm. scale variation)

Monte Carlo studies

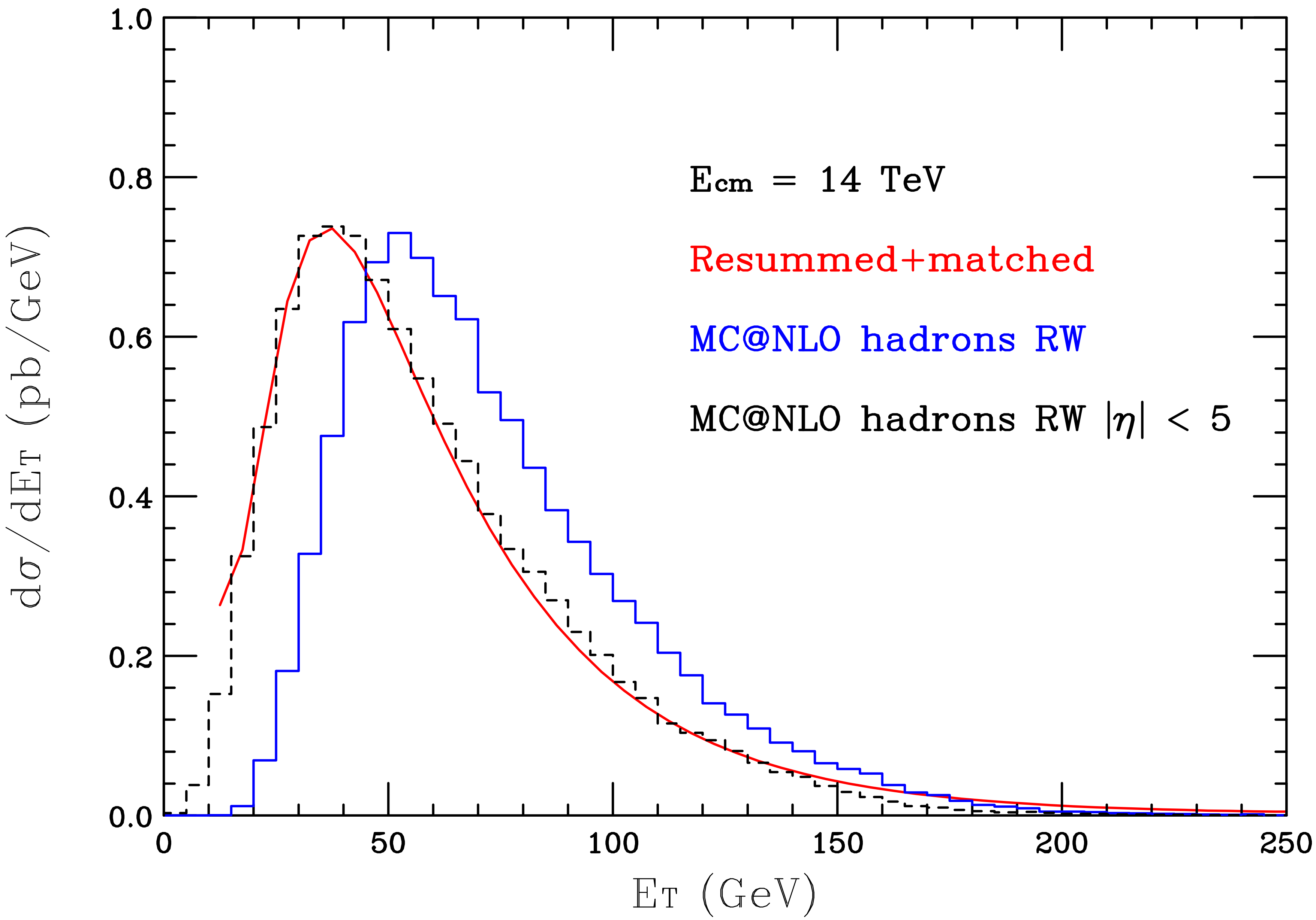
$$E_T = \sum_{\substack{|\eta_i|<\eta^c \\ |\mathbf{p}_{Ti}|>p_T^c}} |\mathbf{p}_{Ti}| \ ,$$

- essential to investigate non-perturbative effects.
- + detector geometry and effects.
- the **underlying event**, thought to originate from secondary parton-parton interactions, seems to be an important contribution.
- (see **Jo Gaunt**'s talk for theoretical issues behind this involving Glauber gluons).
- **reweight** the parton-level MC distribution to match the resummed result.

hadronization

- effect of hadronization can be studied with or without restriction on pseudorapidity of particles

- effect seems to be compensated for **|η| < 5** on particles contributing**.**



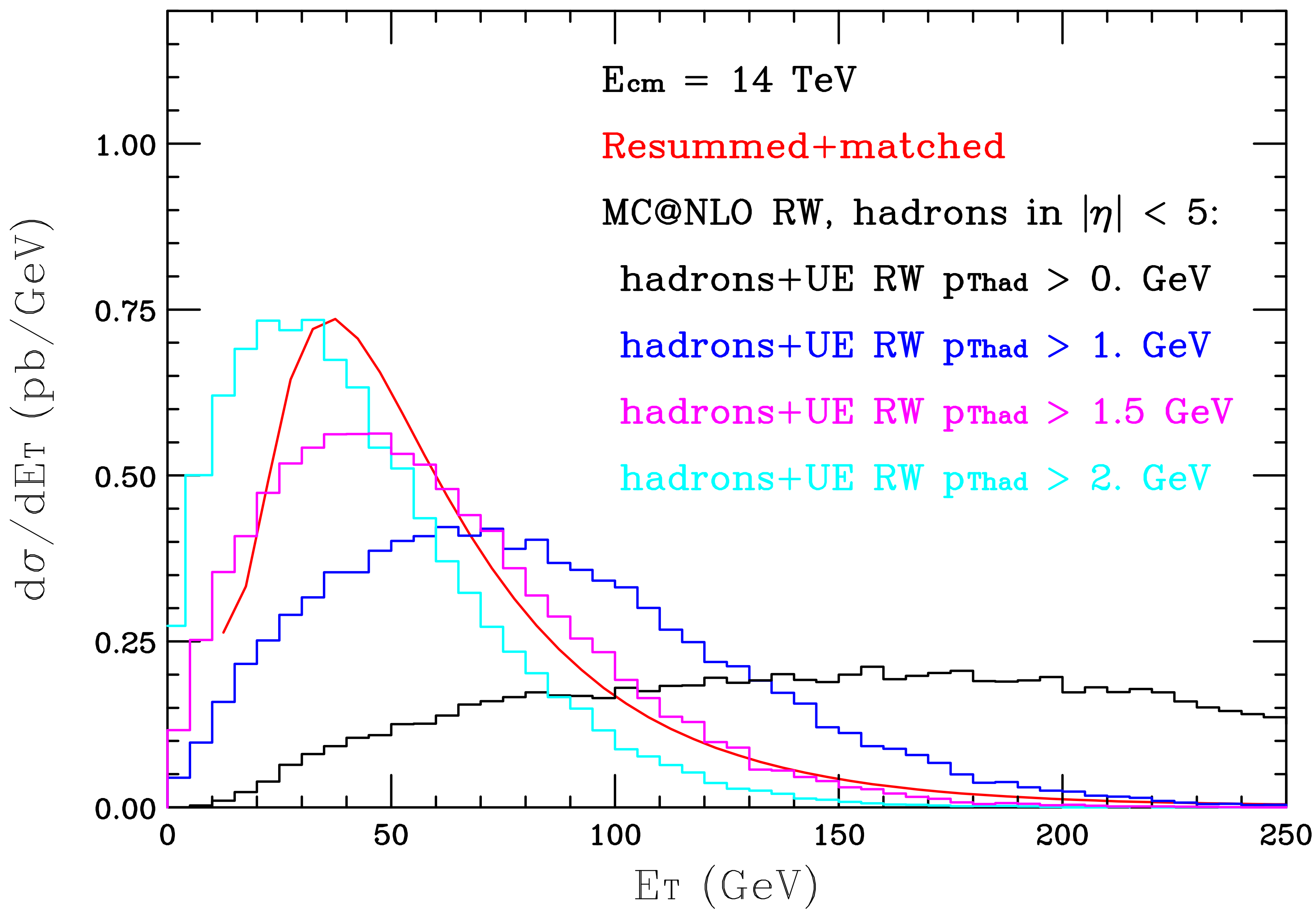
aMC@NLO events.

hadronization+shower:

using **Herwig++**, but similar results with **Pythia 8.**

the underlying event

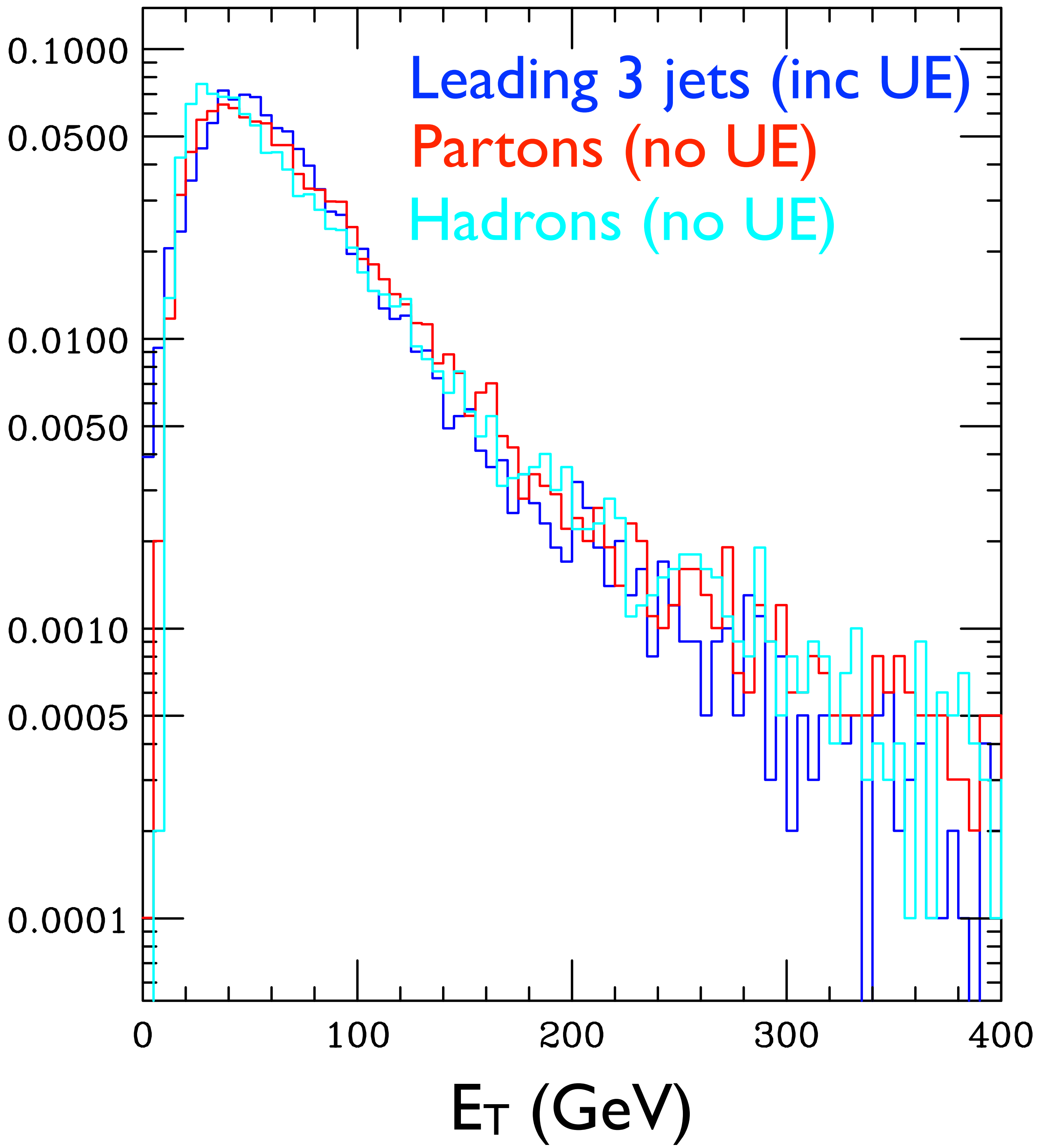
- in Herwig++: simulated as multiple-parton interactions between the interacting protons.



aMC@NLO events, **|η| < 5.**

different p_T cut on hadrons contributing to E_T sum shown.

E_T from jets?



- use jets instead of hadrons.
- anti-k_T, R=0.7.
- parton level ~ E_T of leading n jets.

[preliminary, AP, B.R. Webber, Thanks to G. Salam for suggesting.]

conclusions+outlook

- our resummed+matched calculation includes resummation of NNLL terms (not all) and matched to NLO.
- Monte Carlo studies indicate that non-perturbative effects (hadronization+UE) are significant.
- (using leading jets may help ?).
- future:
    - ✦ direct analytical/numerical calculation of $B_g^{(2)}$.
    - ✦ further investigation of the non-perturbative effects.
    - ✦ experimental data!(?).

Thanks for your attention!

[**1002.4375**, AP, B. R. Webber, J. M., Smillie & **1403.3394**, M.Grazzini, AP, B. R. Webber, J. M., Smillie]

Auxiliary slides

unitarity

- unitarity is enforced to “kill” the logs as:

$$\tau \to 0, \;\; Q \to \infty$$

- via:

$$\lambda \to \tilde{\lambda} = \ln\left(1 + \frac{Q\tau}{i\tau_0}\right)$$

- (and corresponding shift in factorisation scale for PDFs and coefficient functions).

- cross section (after matching) compares well to NNLO inclusive cross section:

	resummed+matched	**NNLO (fixed order)**
$8\ \mathrm{TeV}:$	**18.2 pb**	**18.22 pb**
$14\ \mathrm{TeV}:$	**47.5 pb**	**47.28 pb**

other coefficients ($A^{(3)}$)

- investigate the effect of varying “higher-order” coefficients.

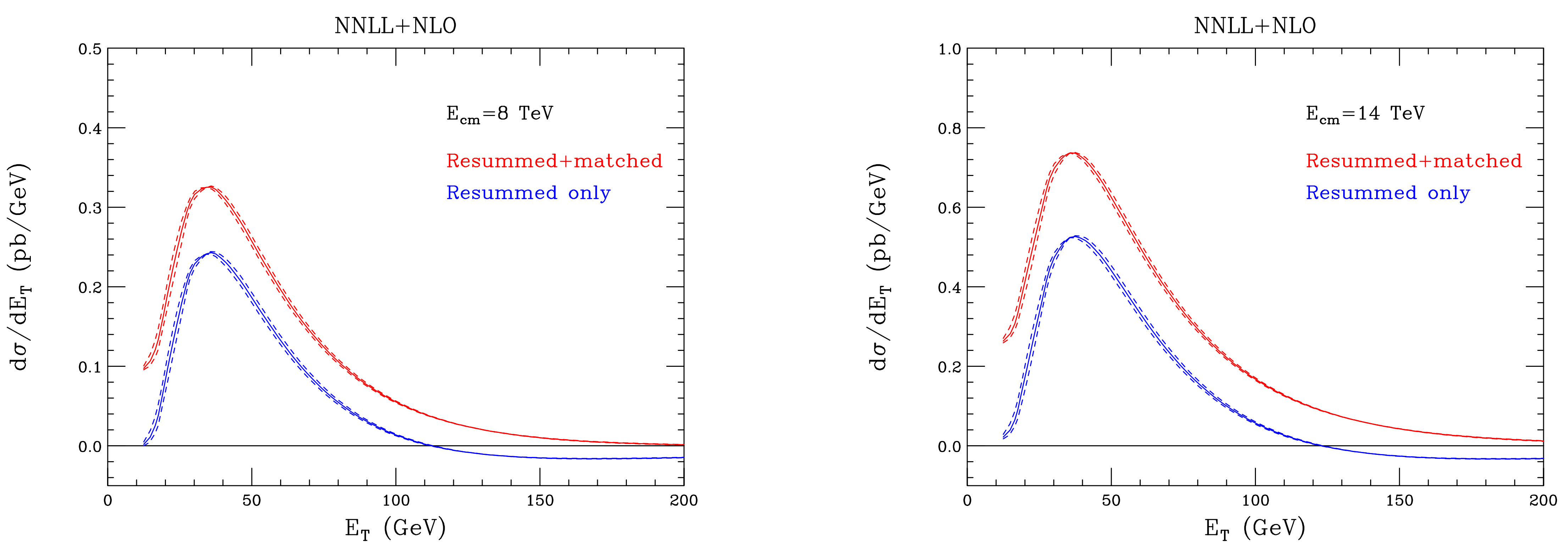


Figure 4: Transverse-energy distribution in Higgs boson production at the LHC at 8 and 14 TeV. Blue: resummed only. Red: resummed and matched to NLO. The solid curves correspond to $A_g^{(3)} = 0$, the dashed to $A_g^{(3)} = \pm 30$.

other coefficients ($C^{(2)}$)

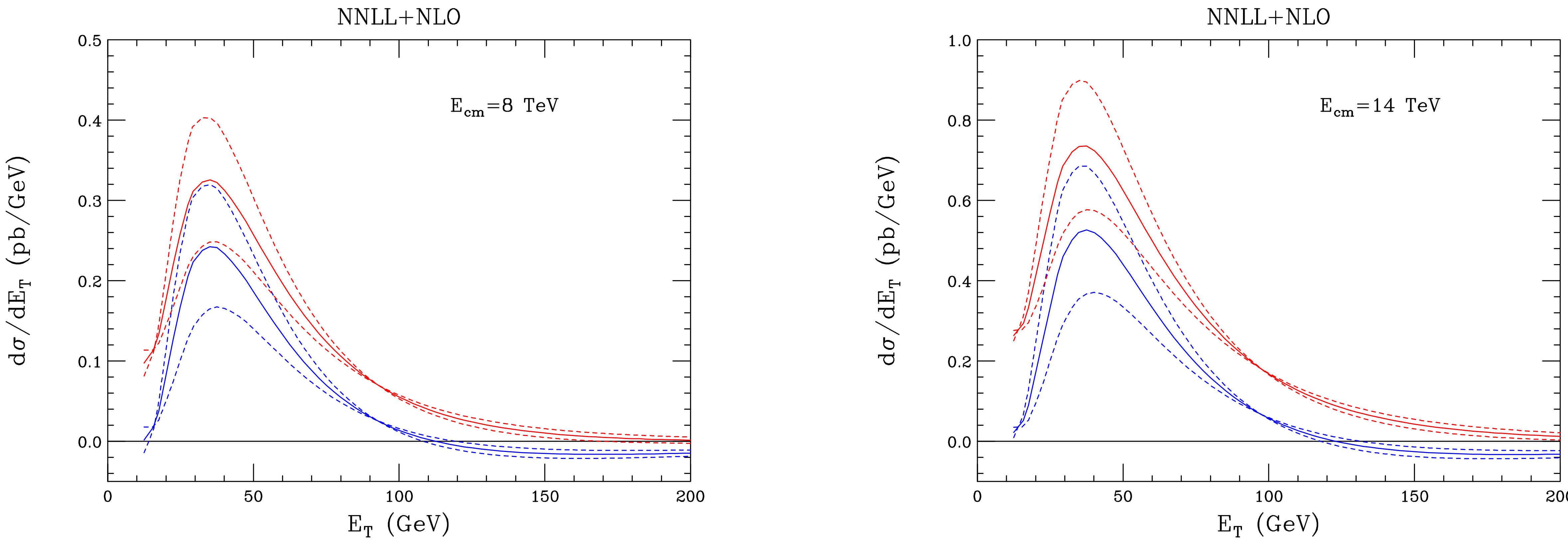


Figure 5: Transverse-energy distribution in Higgs boson production at the LHC at 8 and 14 TeV. Blue: resummed only. Red: resummed and matched to NLO. The solid curves correspond to $C_g^{(2)} = 0$, the dashed to $C_g^{(2)} = \pm 115.5$ (see text).

$$\frac{1}{\hat{\sigma}_{gg}}\frac{\mathrm{d}\hat{\sigma}_{gg}}{\mathrm{d}\,E_T} \sim \int_{-\infty}^{+\infty}\frac{\mathrm{d}\tau}{2\pi}\,\mathrm{e}^{i\tau E_T}\exp\left\{\alpha_{\mathrm{S}}\int \mathrm{d}^2\mathbf{p}_{\mathrm{T}}\left[\frac{A_g}{\mathbf{p}_{\mathrm{T}}^2}\ln\frac{m_H^2}{\mathbf{p}_{\mathrm{T}}^2}+\frac{B_g}{\mathbf{p}_{\mathrm{T}}^2}\right]\left(\mathrm{e}^{-i\tau|\mathbf{p}_{\mathrm{T}}|}-1\right)\right\}$$

Defined for $E_T \lessgtr 0$

For $E_T < 0$, can close t-contour in lower half-plane

No singularities in lower half-plane