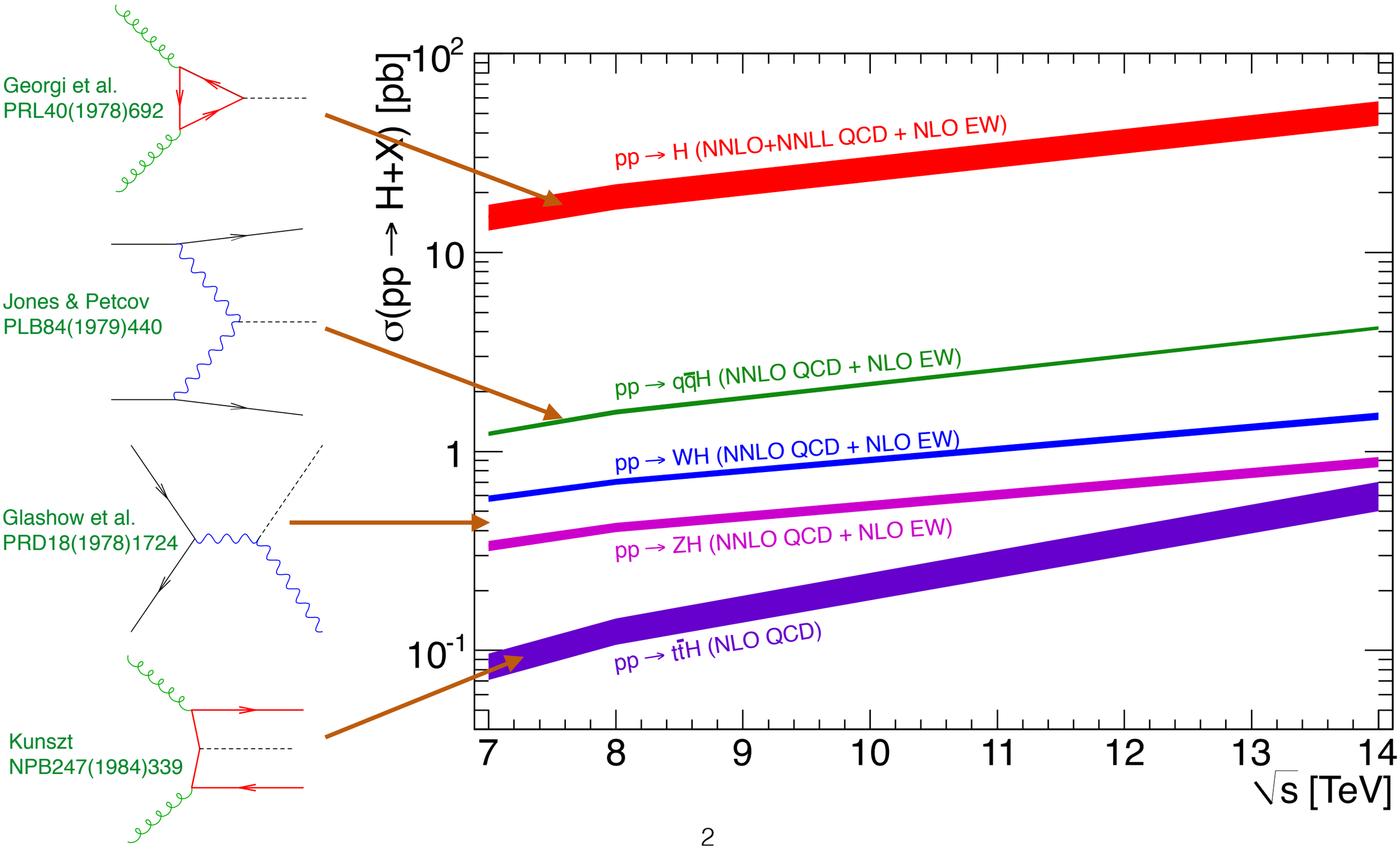
Higher-Order QCD Effects in Higgs Boson Production

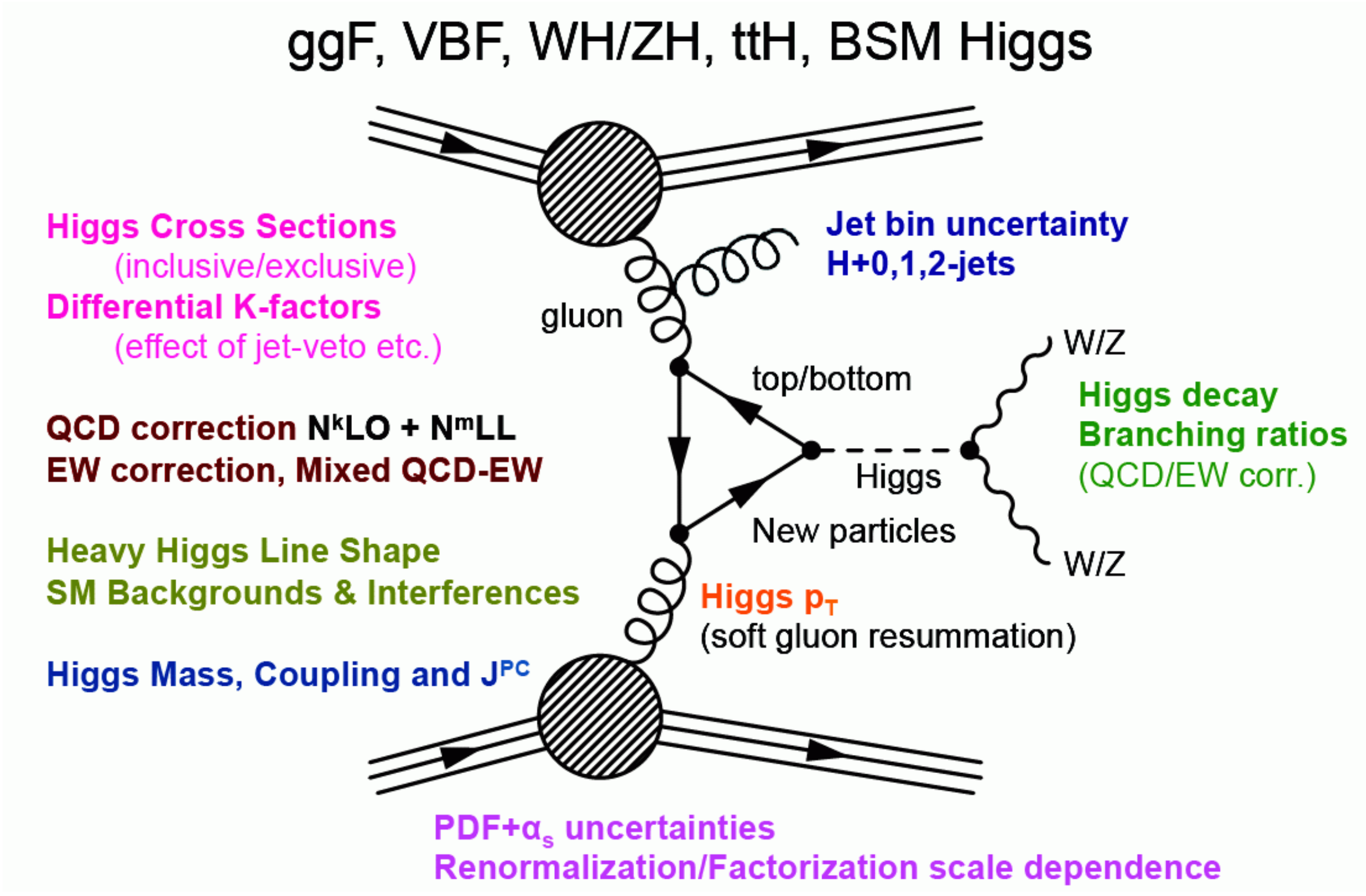
Bryan Webber

UNIVERSITY OF CAMBRIDGE

Higgs production cross sections



The challenges: (taken from [*R. Tanaka, talk at Aspen Higgs WS 03/13*])



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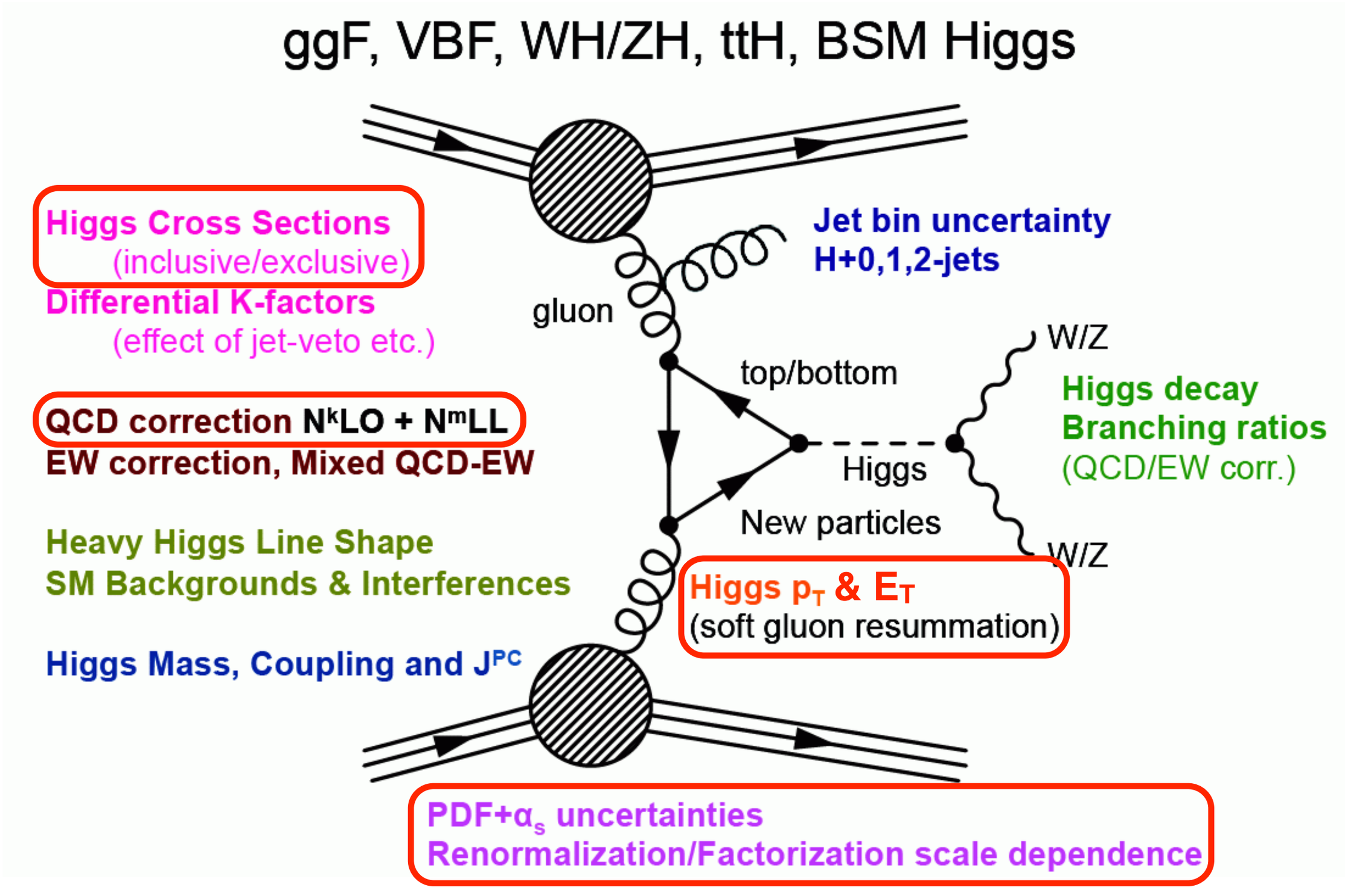
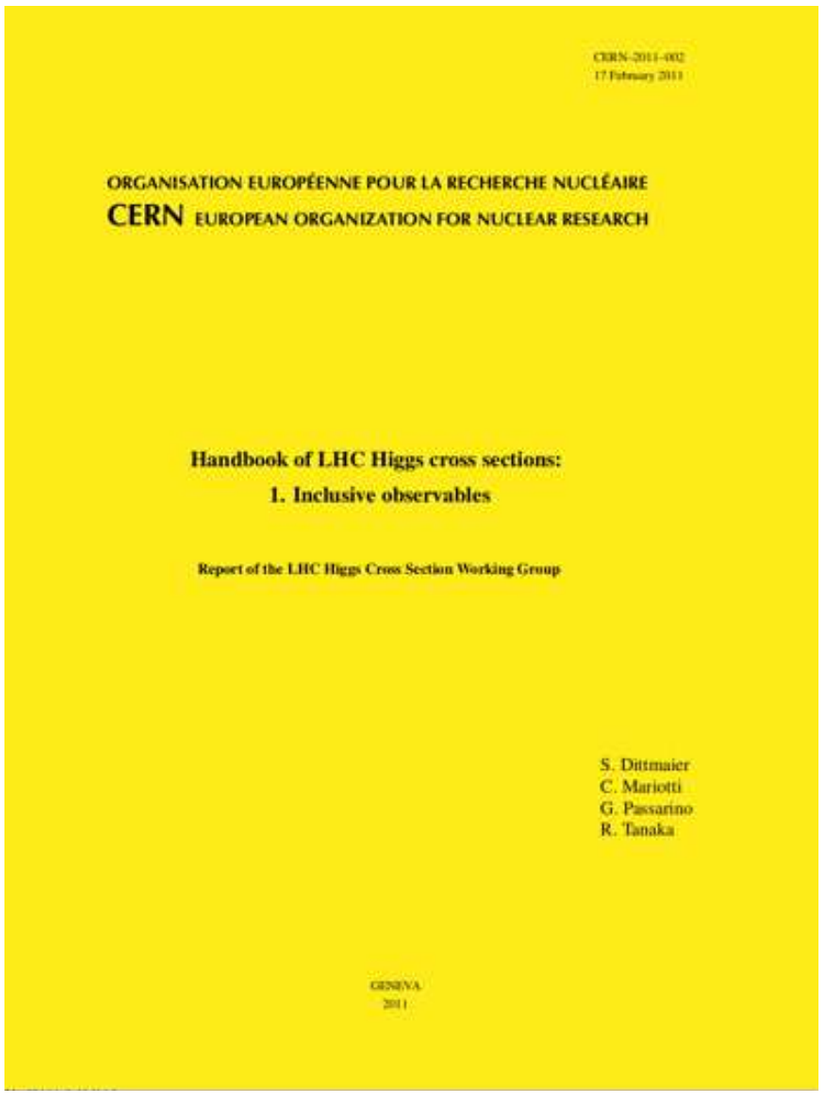
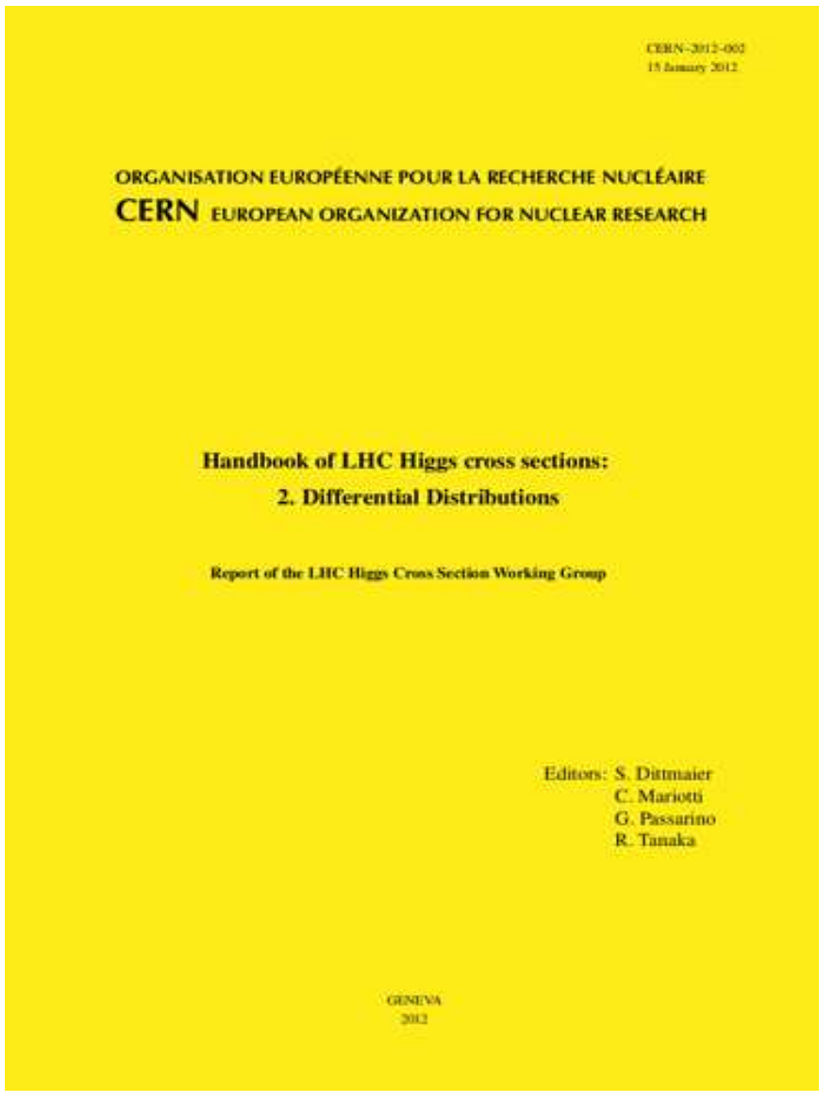
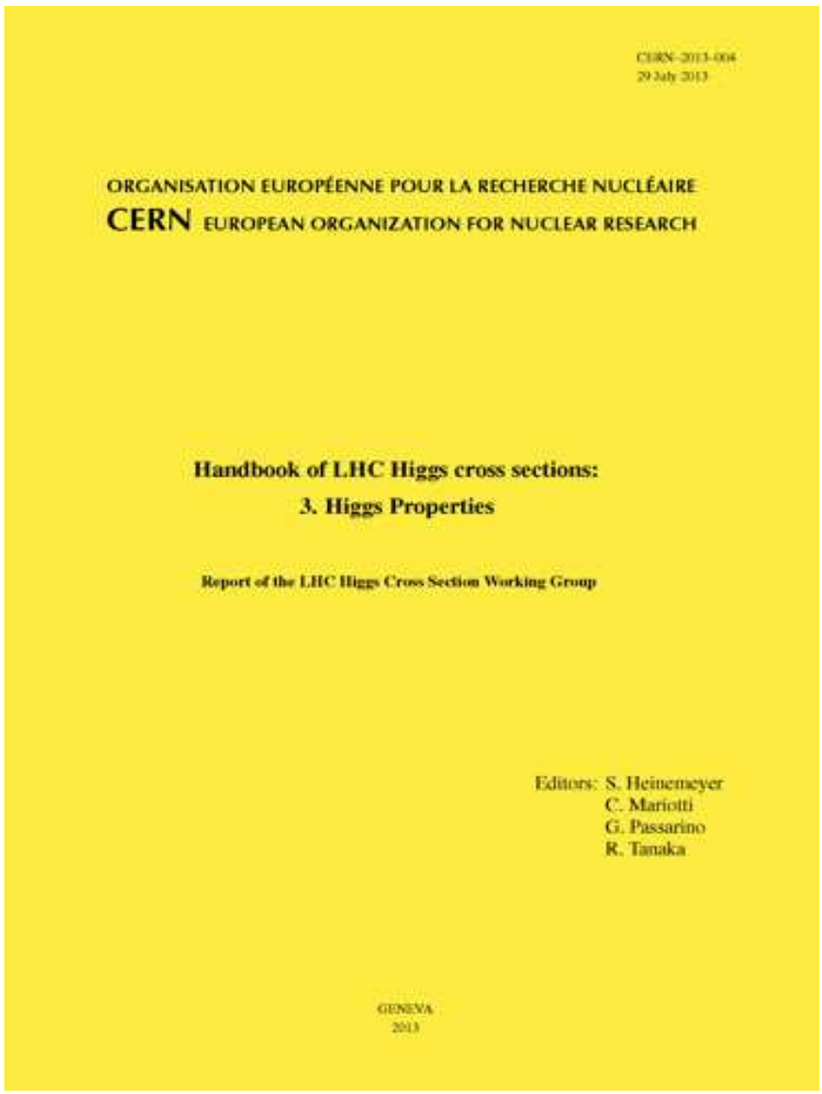


LHC Higgs Cross Section Working Group







arXiv:1101.0593, 1201.3084, 1307.1347

Higgs Production Cross Section

Inclusive (QCD) Cross Section

$$\sigma_{\mathrm{H}}(s) = \sum_{i,j} \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_i(x_1, \mu_F^2) \, f_j(x_2, \mu_F^2) \, \hat{\sigma}_{ij} \left(x_1 x_2 s, m_{\mathrm{H}}^2, \alpha_{\mathrm{S}}(\mu_R^2), \mu_F^2, \mu_R^2 \right)$$

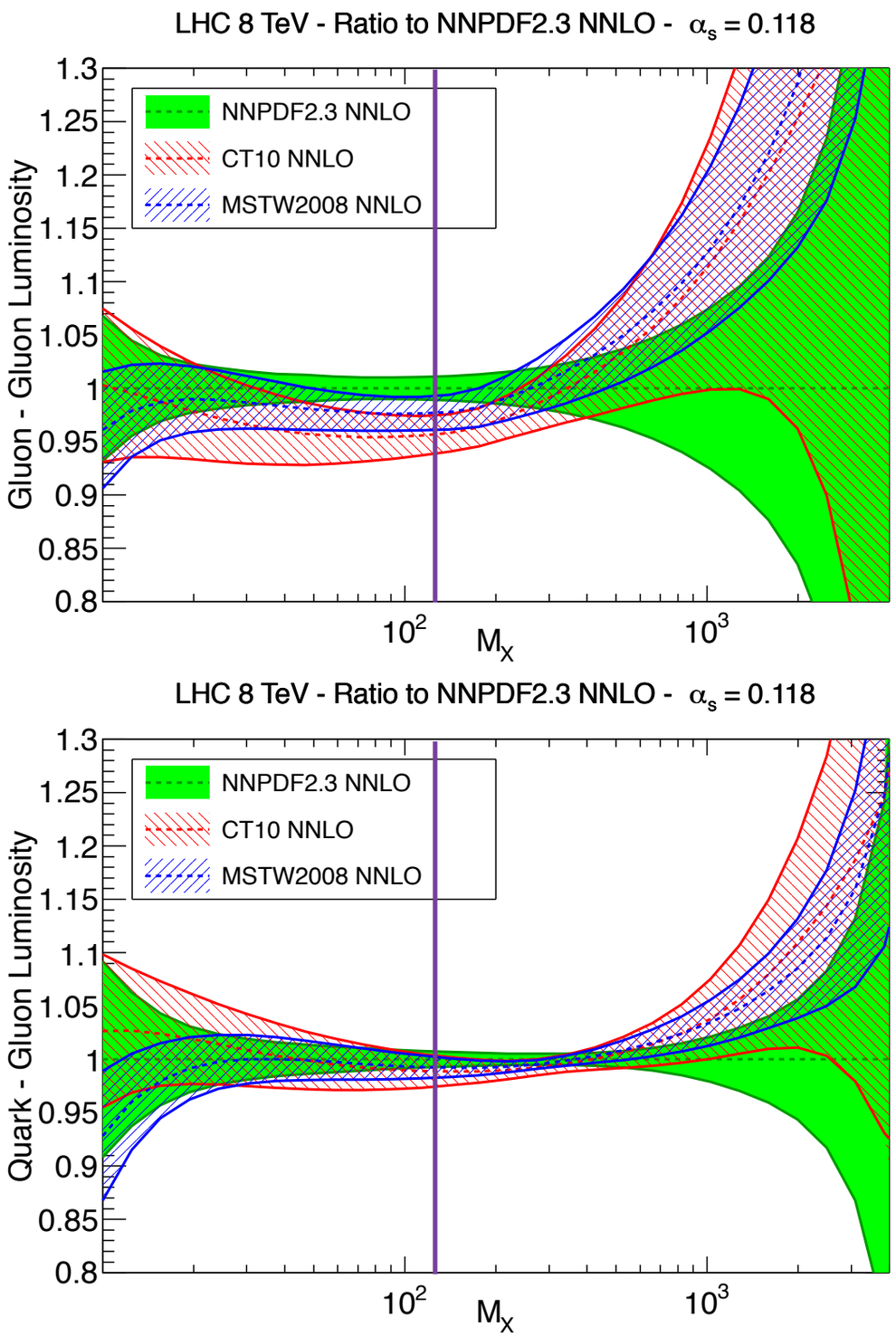
Table B.10: ggF cross sections at the LHC at 8 TeV and corresponding scale and PDF+α_{s} uncertainties computed according to the PDF4LHC recommendation.

HXSWG vol.3

M_{H}[GeV]	σ [pb]	QCD Scale [%]	PDF+α_{s} [%]
124.4	19.45	$+7.2$ -7.9	$+7.5$ -6.9
124.5	19.42	$+7.2$ -7.9	$+7.5$ -6.9
124.6	19.39	$+7.2$ -7.9	$+7.5$ -6.9
124.7	19.36	$+7.2$ -7.9	$+7.5$ -6.9
124.8	19.33	$+7.2$ -7.8	$+7.5$ -6.9
124.9	19.30	$+7.2$ -7.8	$+7.5$ -6.9
125.0	19.27	$+7.2$ -7.8	$+7.5$ -6.9
125.1	19.24	$+7.2$ -7.8	$+7.5$ -6.9
125.2	19.21	$+7.2$ -7.8	$+7.5$ -6.9
125.3	19.18	$+7.2$ -7.8	$+7.5$ -6.9
125.4	19.15	$+7.2$ -7.8	$+7.5$ -6.9
125.5	19.12	$+7.2$ -7.8	$+7.5$ -6.9
125.6	19.09	$+7.2$ -7.8	$+7.5$ -6.9
125.7	19.06	$+7.2$ -7.8	$+7.5$ -6.9
125.8	19.03	$+7.2$ -7.8	$+7.5$ -6.9
125.9	19.00	$+7.2$ -7.8	$+7.5$ -6.9
126.0	18.97	$+7.2$ -7.8	$+7.5$ -6.9
126.1	18.94	$+7.2$ -7.8	$+7.5$ -6.9
126.2	18.91	$+7.2$ -7.8	$+7.5$ -6.9
126.3	18.88	$+7.2$ -7.8	$+7.5$ -6.9
126.4	18.85	$+7.2$ -7.8	$+7.5$ -6.9
126.5	18.82	$+7.2$ -7.8	$+7.5$ -6.9

NNLO → $\sigma_{ggF}(8\,\mathrm{TeV}) = 19.1 \pm 2.0$ pb

PDF Uncertainties



Ball et al., 1211.5142

- Parton luminosity $\mathcal{L}_{ij}(M_X^2, s) =$

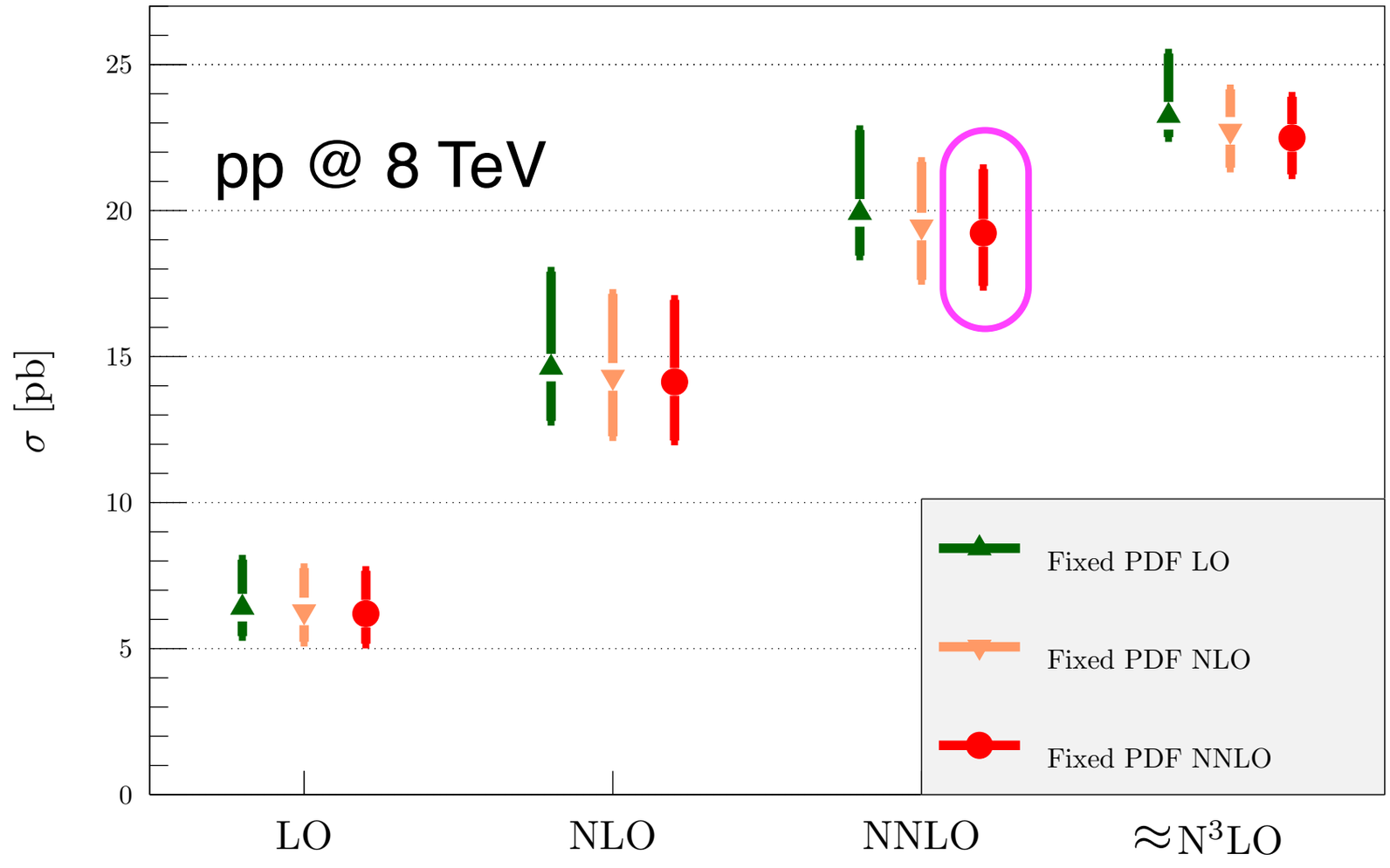
$$\int \mathrm{d}x_1 \mathrm{d}x_2 \, f_i(x_1, M_X^2) \, f_j(x_2, M_X^2) \, \delta\left(x_1 x_2 s - M_X^2\right)$$

- Relevant PDFs (relatively) well known at $x \sim M_H/\sqrt{s}$
- Some disagreement with CT10 $\mathcal{L}_{gg}$
- Remains true at 13 TeV
- Can be improved (in principle)

Inclusive (QCD) Cross Section

Ball et al., 1303.3590

Forte, Isigro, Vita, 1312.6688



- Higher-order effects are larger than x2 scale variation estimates
- $\sigma_{\rm ggF} \approx \sigma_{\rm LO}\left[1+\kappa\{\lambda\alpha_{\rm S}+(\lambda\alpha_{\rm S})^2+(\lambda\alpha_{\rm S})^3+\cdots\}\right]$

$\lambda \approx 5.6$

Inclusive (QCD) Cross Section

Ball et al., 1303.3590

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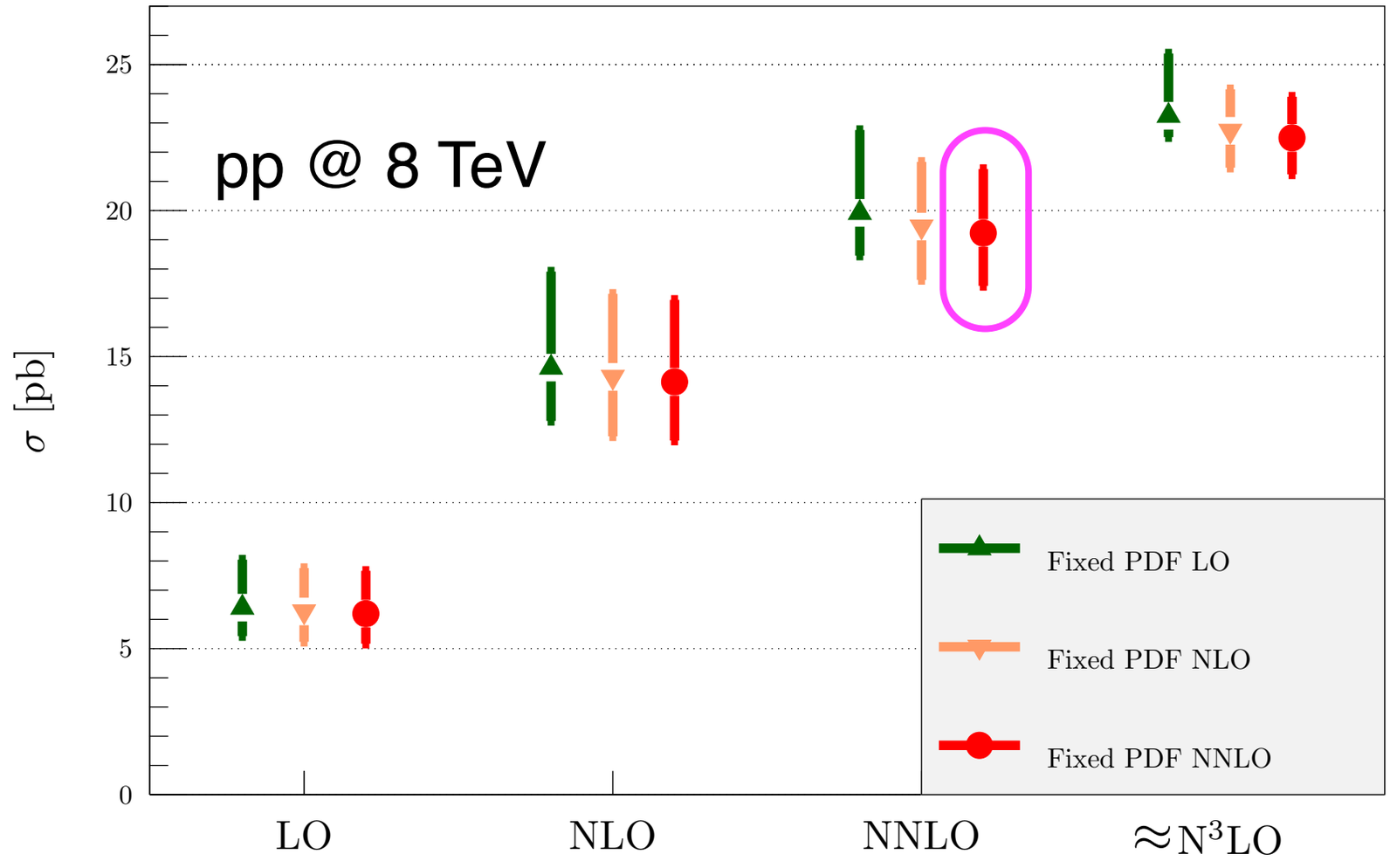

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- $\sigma_{\rm ggF} \approx \sigma_{\rm LO}\left[1+\kappa\{\lambda\alpha_{\rm S}+(\lambda\alpha_{\rm S})^2+(\lambda\alpha_{\rm S})^3+\cdots\}\right] \approx \sigma_{\rm LO}\left[1-\kappa+\frac{\kappa}{1-\lambda\alpha_{\rm S}}\right]$

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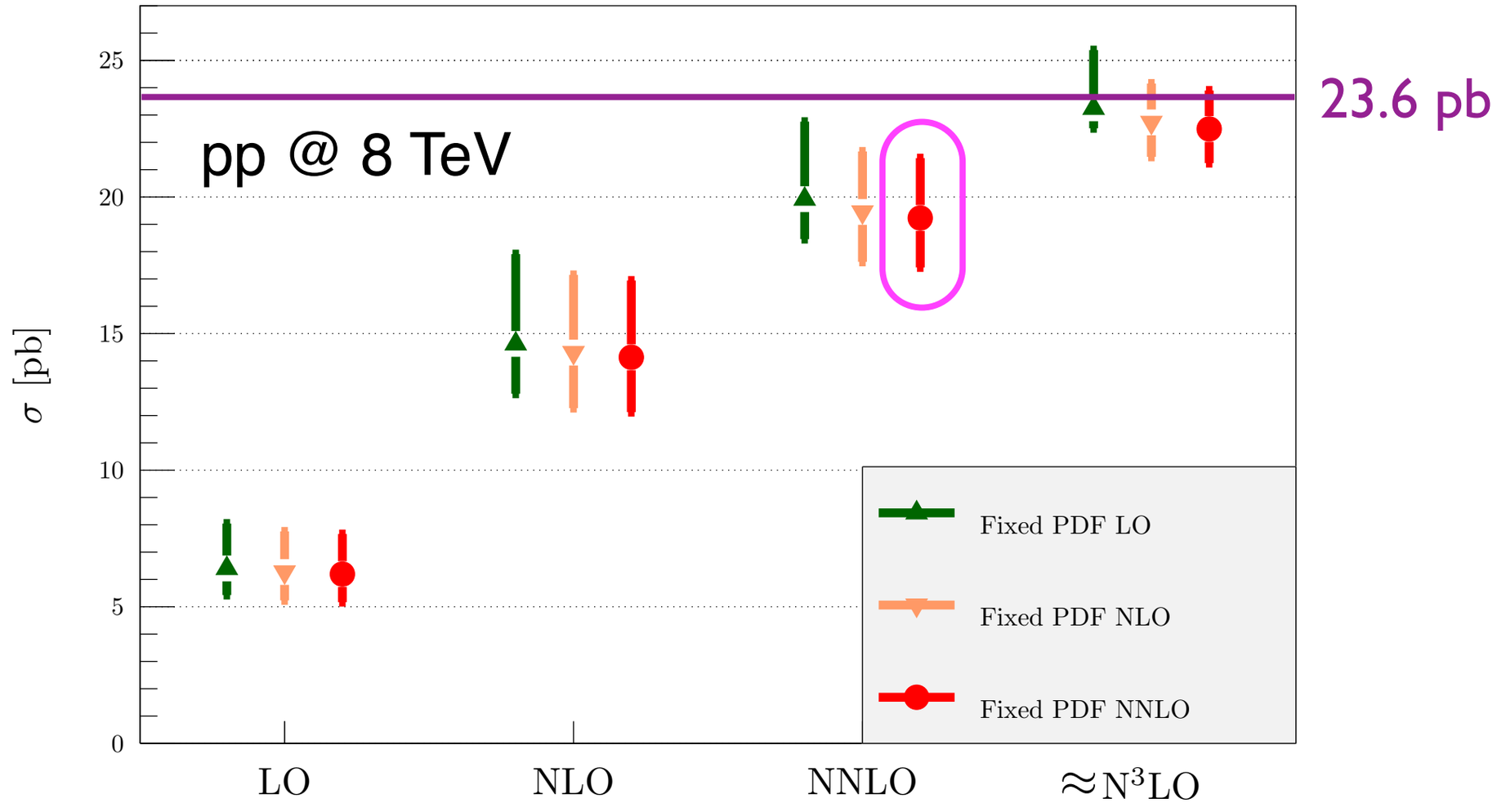

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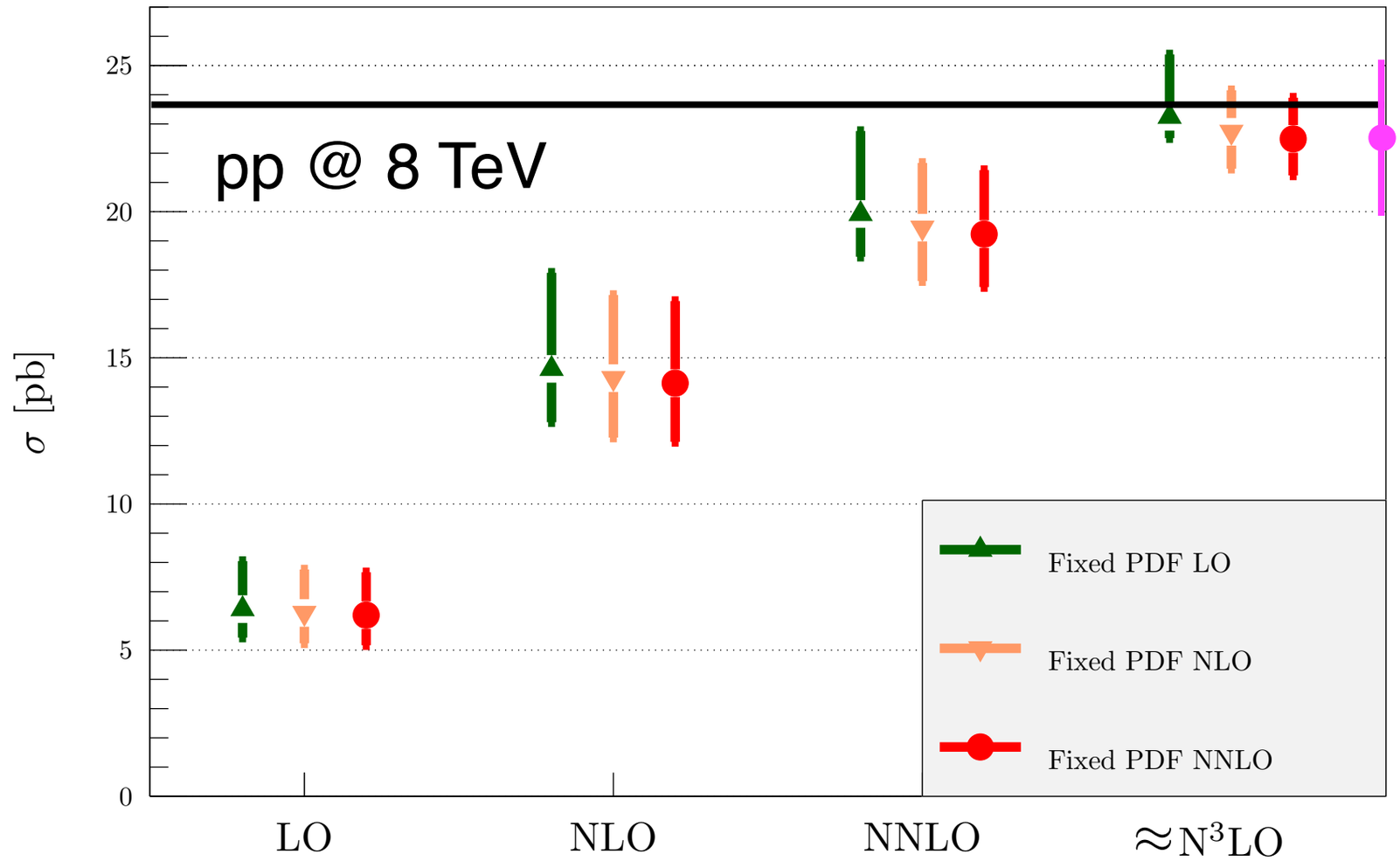
$\lambda \approx 5.6$

Inclusive (QCD) Cross Section



NNLO → σ_{ggF}(8 TeV) = 19.1± 2.0 pb

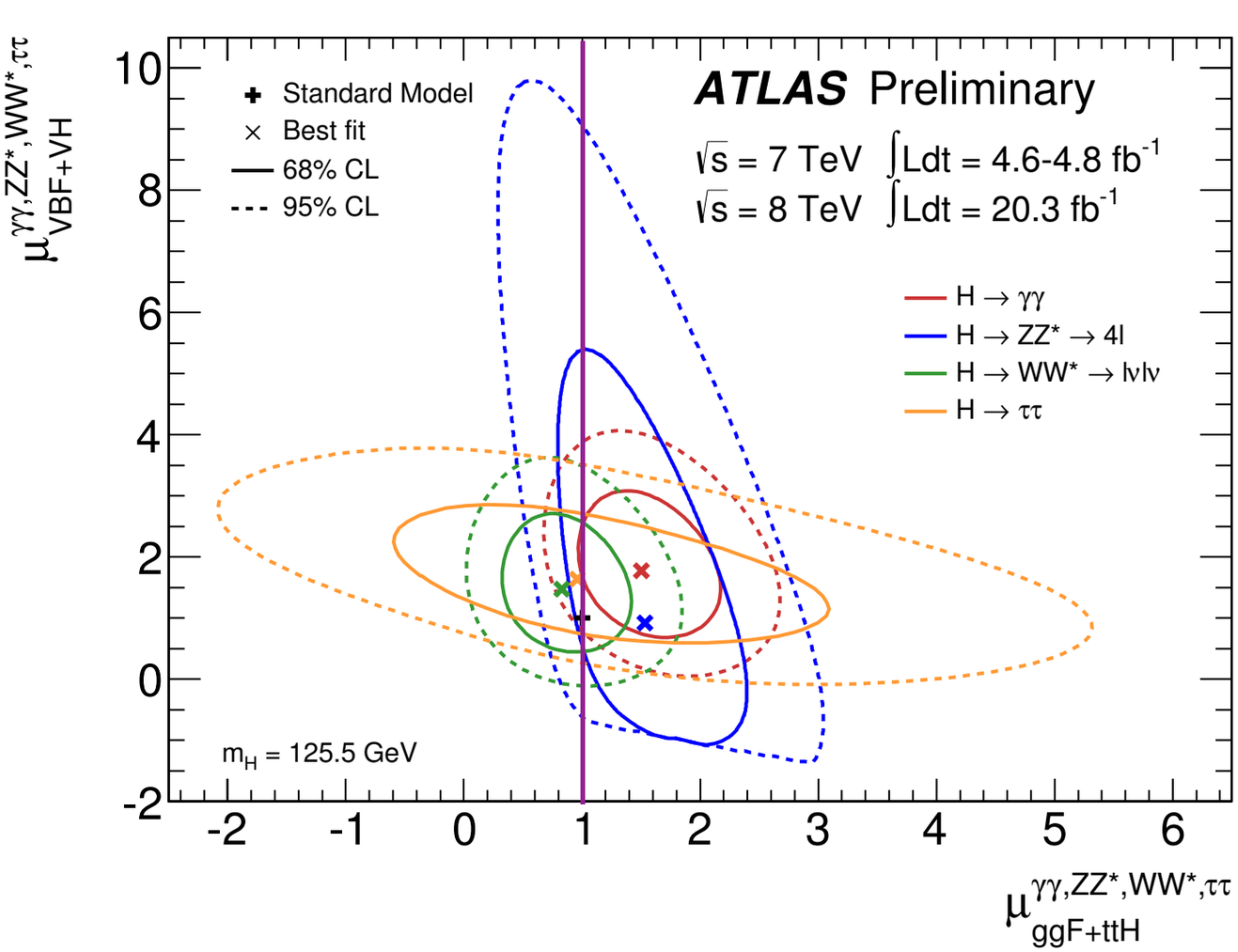
Series extrapolation: 23.6 ± ?? pb

David & Passarino, 1307.1843: 22.5 ± 2.6 pb

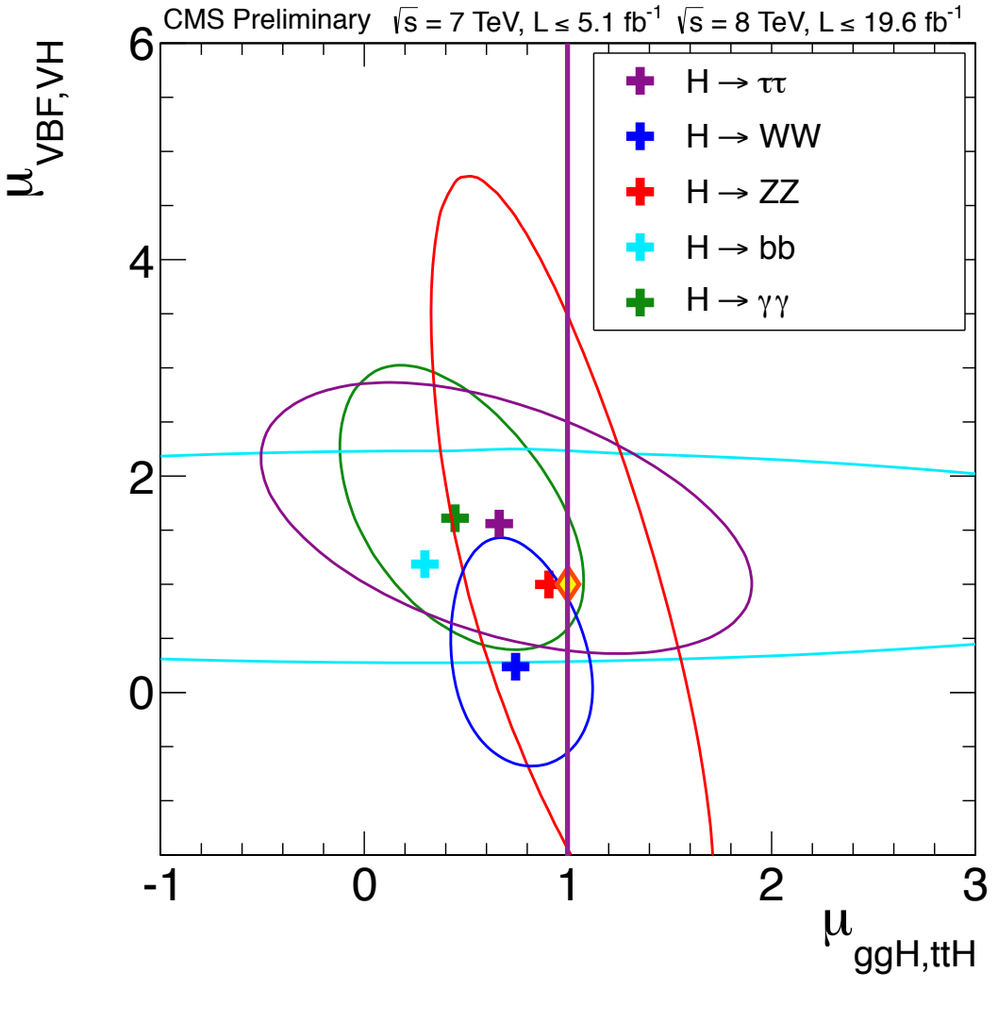
Full N³LO coming soon (Anastasiou et al.)

Inclusive (QCD) Cross Section

- ATLAS, but not CMS, find ggF excess in $\gamma\gamma$ and ZZ^* channels



ATLAS-CONF-2014-009 (Moriond EW)



CMS PAS HIG-13-005

Cross Sections at 13 TeV

HXSWG 05/04/2014

√s = 13.0 TeV

gluon-gluon Fusion Process

- All cross sections are in complex-pole-scheme from the dFG program. They are computed at NNLL QCD and NLO EW.

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	43.92	+7.4	-7.9	+7.1	-6.0
125.5	43.62	+7.4	-7.9	+7.1	-6.0
126.0	43.31	+7.4	-7.9	+7.1	-6.0

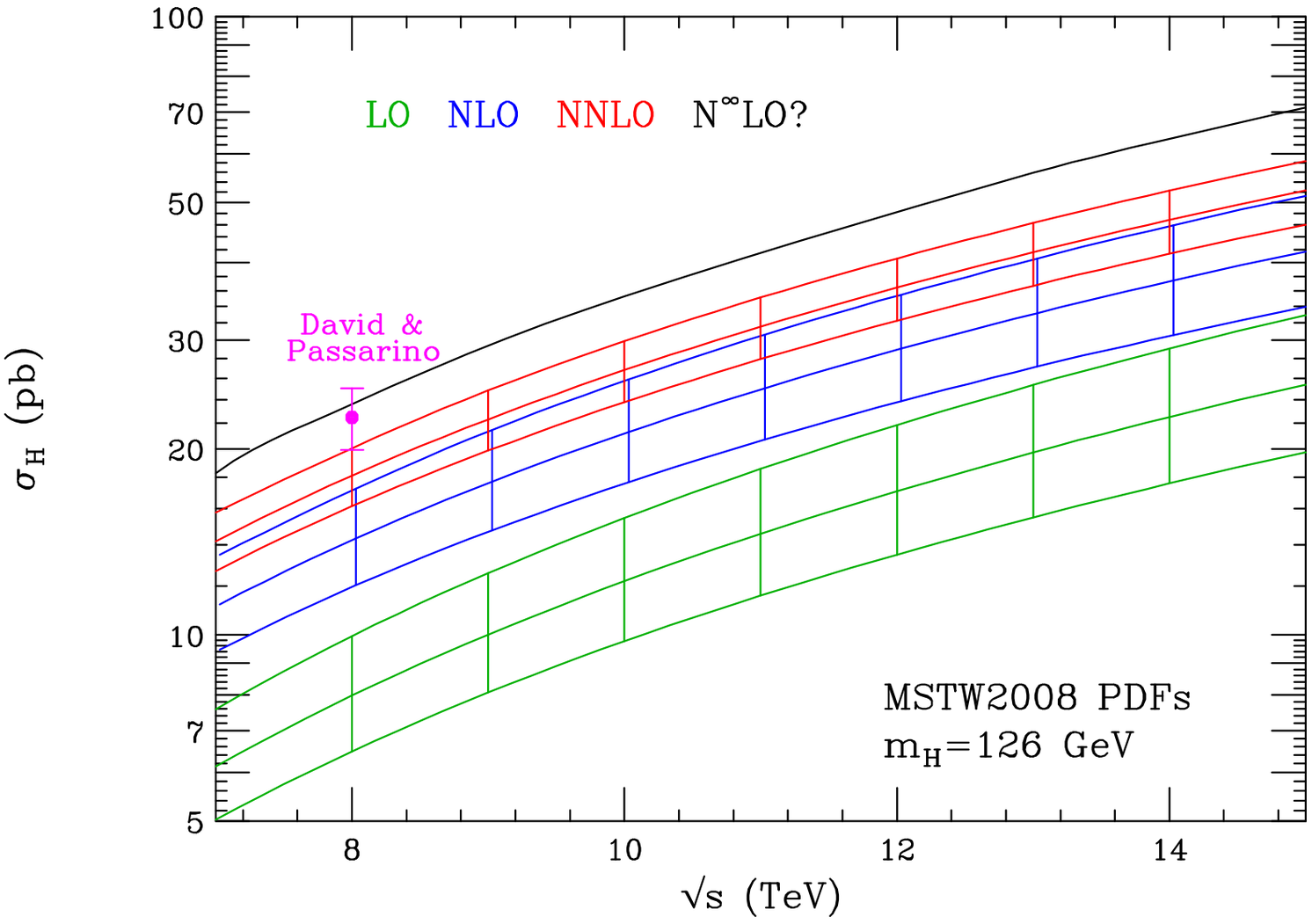
VBF Process

- At NNLO QCD and NLO EW. All cross sections are in complex-pole-scheme.

m_H (GeV)	Cross Section (pb)	+QCD Scale %	-QCD Scale %	+(PDF+α_s) %	-(PDF+α_s) %
125.0	3.748	+0.7	-0.7	+3.2	-3.2
125.5	3.727	+1.0	-0.7	+3.4	-3.4
126.0	3.703	+1.3	-0.6	+3.1	-3.1

Cross Section vs Energy

http://theory.fi.infn.it/grazzini/hcalculators.html



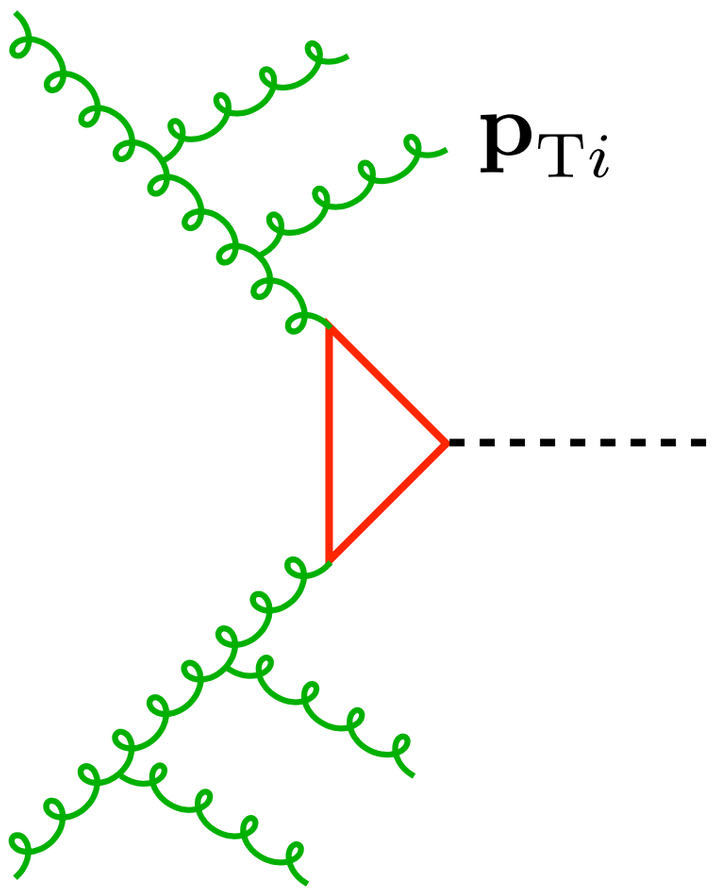
NNLO → $\sigma_{ggF}(13\,\text{TeV}) = 43.3 \pm 4.3$ pb

Series extrapolation: $\sigma_{ggF}(13\,\text{TeV}) = 55.9 \pm ??$ pb

My best guess: $\sigma_{ggF}(13\,\text{TeV}) = 53 \pm 8$ pb

Higgs Differential Cross Sections

Higgs q_T & E_T



- Higgs transverse momentum

$$\mathbf{q}_{\mathrm{T}} = -\sum \mathbf{p}_{\mathrm{T}i}$$

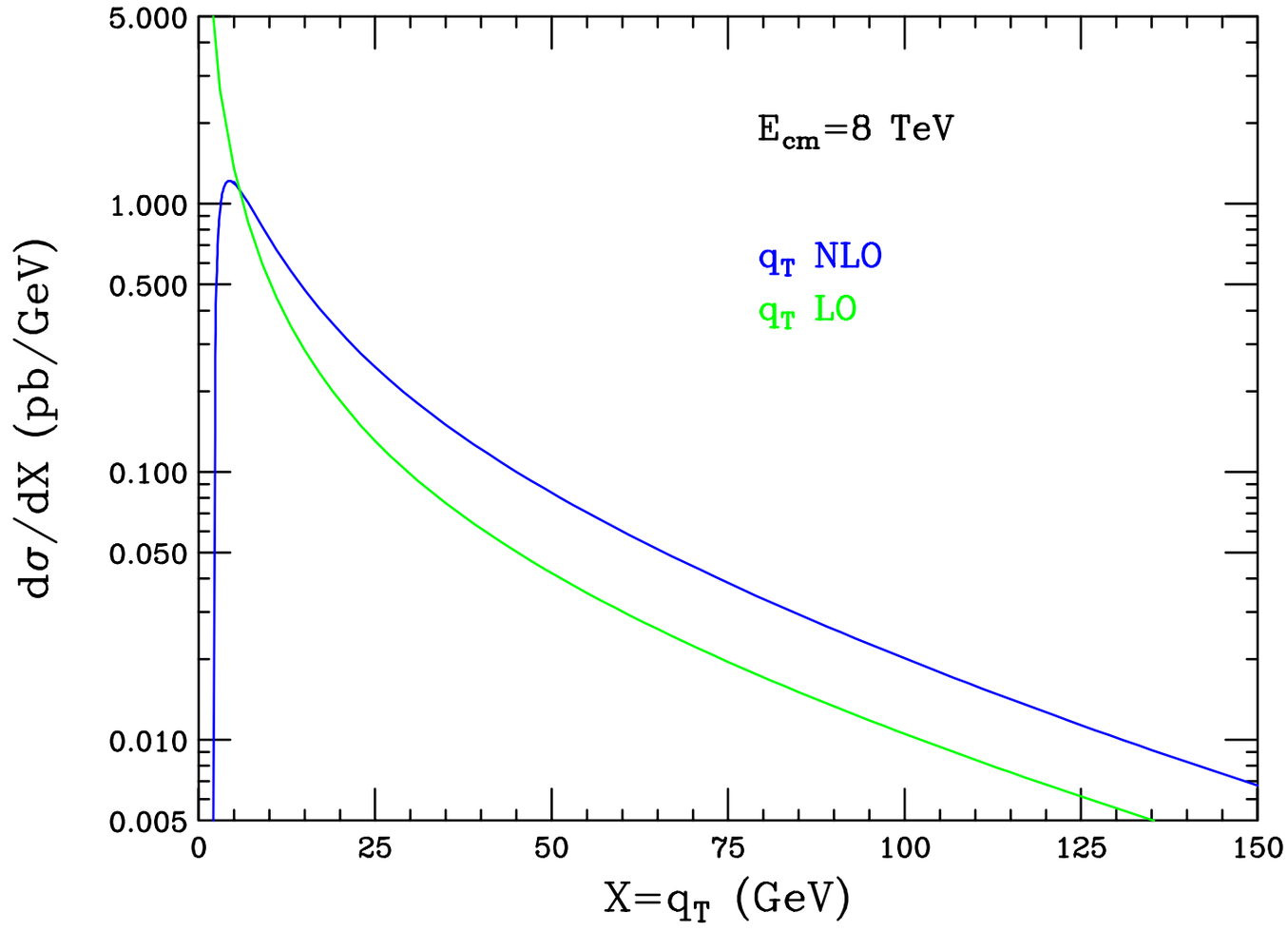
Bozzi et al. 0705.3887
Mantry & Petriello, 0911.4135
Catani & Grazzini, 1011.3918
de Florian et al. 1109.2109

- Radiated transverse energy

$$E_T = \sum |\mathbf{p}_{\mathrm{T}i}|$$

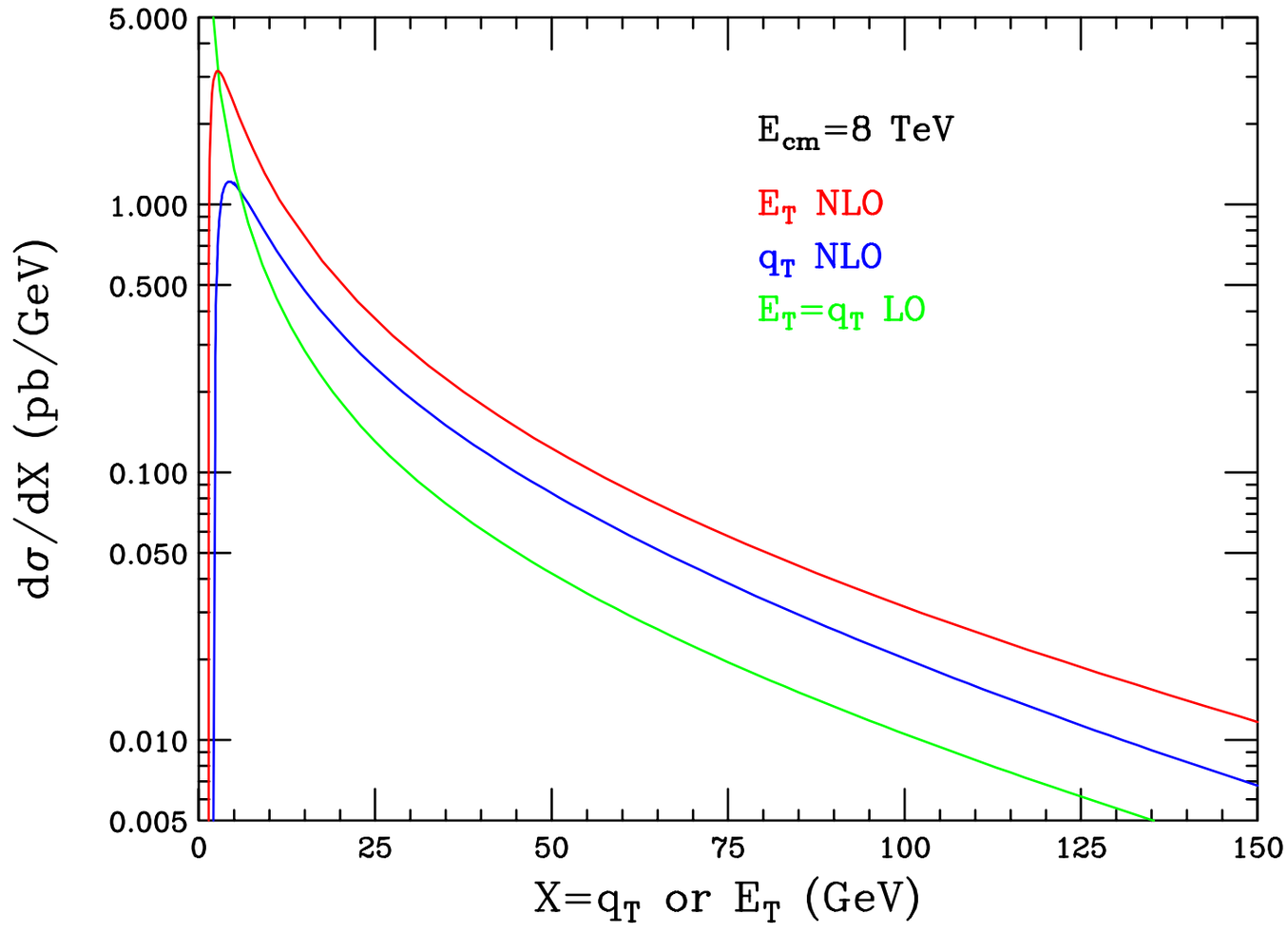
Papaefstathiou, Smillie, BW, 1002.4375
+Grazzini, 1403.3394

Higgs q_T (fixed order)



- $(\mathrm{N})\mathrm{LO} \underset{q_\mathrm{T}\to 0}{\longrightarrow} (-)\infty$
- Large logs of m_H^2/q_T^2 need resummation

Higgs q_T & E_T (fixed order)



- $(\mathrm{N})\mathrm{LO} \underset{E_\mathrm{T}\to 0}{\longrightarrow} (-)\infty$
- Large logs of m_H^2/E_T^2 need resummation

Resummation of Higgs q_T

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_a(x_1,\mu) f_b(x_2,\mu) \, \mathrm{d}\hat{\sigma}_{ab}(x_1 x_2 s, \mu, \ldots)$$

$$\frac{1}{\hat{\sigma}_{gg}} \frac{\mathrm{d}^2 \hat{\sigma}_{gg}}{\mathrm{d}\,\mathbf{q}_\mathrm{T}^2} \sim \delta^2(\mathbf{q}_\mathrm{T}) + \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right]_+ \delta^2(\mathbf{q}_\mathrm{T} + \mathbf{p}_\mathrm{T}) + \ldots$$

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$$\sim \int \frac{\mathrm{d}^2\mathbf{b}}{(2\pi)^2} \, \mathrm{e}^{i\mathbf{b}\cdot\mathbf{q}_\mathrm{T}} \left\{ 1 + \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right] \left(\mathrm{e}^{i\mathbf{b}\cdot\mathbf{p}_\mathrm{T}} - 1 \right) + \ldots \right\}$$

Resummation of Higgs q_T

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_a(x_1,\mu) f_b(x_2,\mu) \, \mathrm{d}\hat{\sigma}_{ab}(x_1 x_2 s, \mu, \ldots)$$

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$$\sim \int \frac{\mathrm{d}^2\mathbf{b}}{(2\pi)^2} \, \mathrm{e}^{i\mathbf{b}\cdot\mathbf{q}_\mathrm{T}} \left\{ 1 + \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right] \left(\mathrm{e}^{i\mathbf{b}\cdot\mathbf{p}_\mathrm{T}} - 1 \right) + \ldots \right\}$$

$$\sim \int \frac{\mathrm{d}^2\mathbf{b}}{(2\pi)^2} \, \mathrm{e}^{i\mathbf{b}\cdot\mathbf{q}_\mathrm{T}} \exp\left\{ \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right] \left(\mathrm{e}^{i\mathbf{b}\cdot\mathbf{p}_\mathrm{T}} - 1 \right) \right\}$$

Resummation & matching of Higgs q_T

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_a(x_1,\mu) f_b(x_2,\mu) \, \mathrm{d}\hat{\sigma}_{ab}(x_1 x_2 s, \mu, \ldots)$$

$$\frac{1}{\hat{\sigma}_{gg}} \frac{\mathrm{d}^2 \hat{\sigma}_{gg}}{\mathrm{d}\,\mathbf{q}_\mathrm{T}^2} \sim \delta^2(\mathbf{q}_\mathrm{T}) + \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right]_+ \delta^2(\mathbf{q}_\mathrm{T} + \mathbf{p}_\mathrm{T}) + \ldots$$

$$\sim \int \frac{\mathrm{d}^2\mathbf{b}}{(2\pi)^2} \, \mathrm{e}^{i\mathbf{b}\cdot\mathbf{q}_\mathrm{T}} \left\{ 1 + \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right] \left(\mathrm{e}^{i\mathbf{b}\cdot\mathbf{p}_\mathrm{T}} - 1 \right) + \ldots \right\}$$

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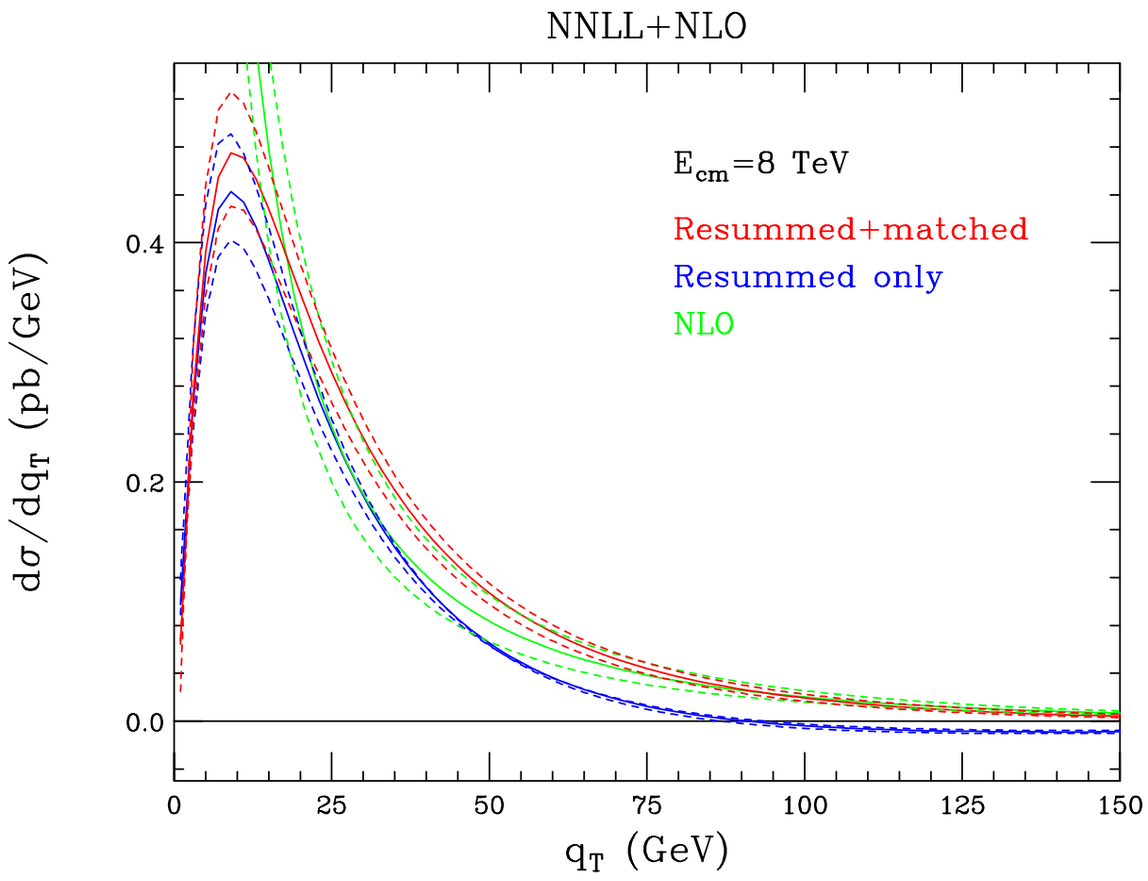
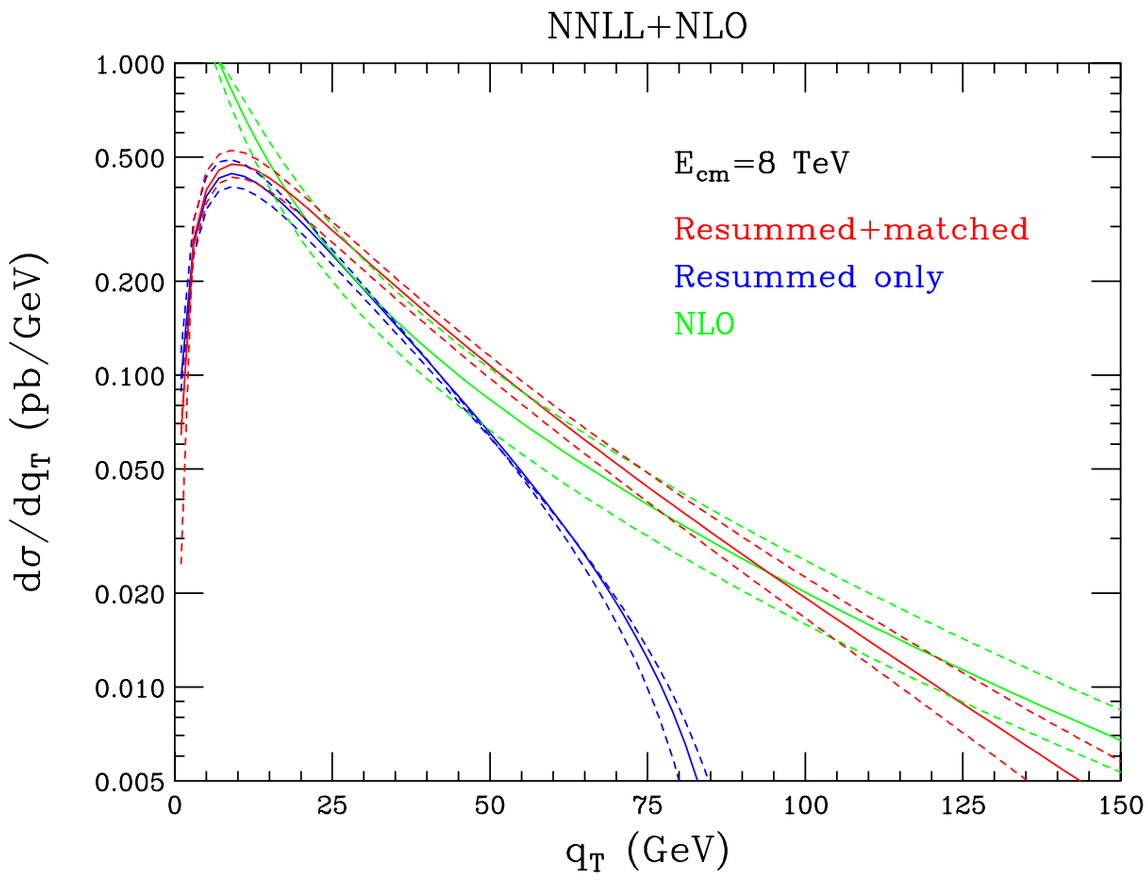
$$\frac{\mathrm{d}\sigma}{\mathrm{d}q_\mathrm{T}} = \left[\frac{\mathrm{d}\sigma}{\mathrm{d}q_\mathrm{T}} \right]_\mathrm{resum} - \left[\frac{\mathrm{d}\sigma}{\mathrm{d}q_\mathrm{T}} \right]_\mathrm{resum,NLO} + \left[\frac{\mathrm{d}\sigma}{\mathrm{d}q_\mathrm{T}} \right]_\mathrm{NLO}$$

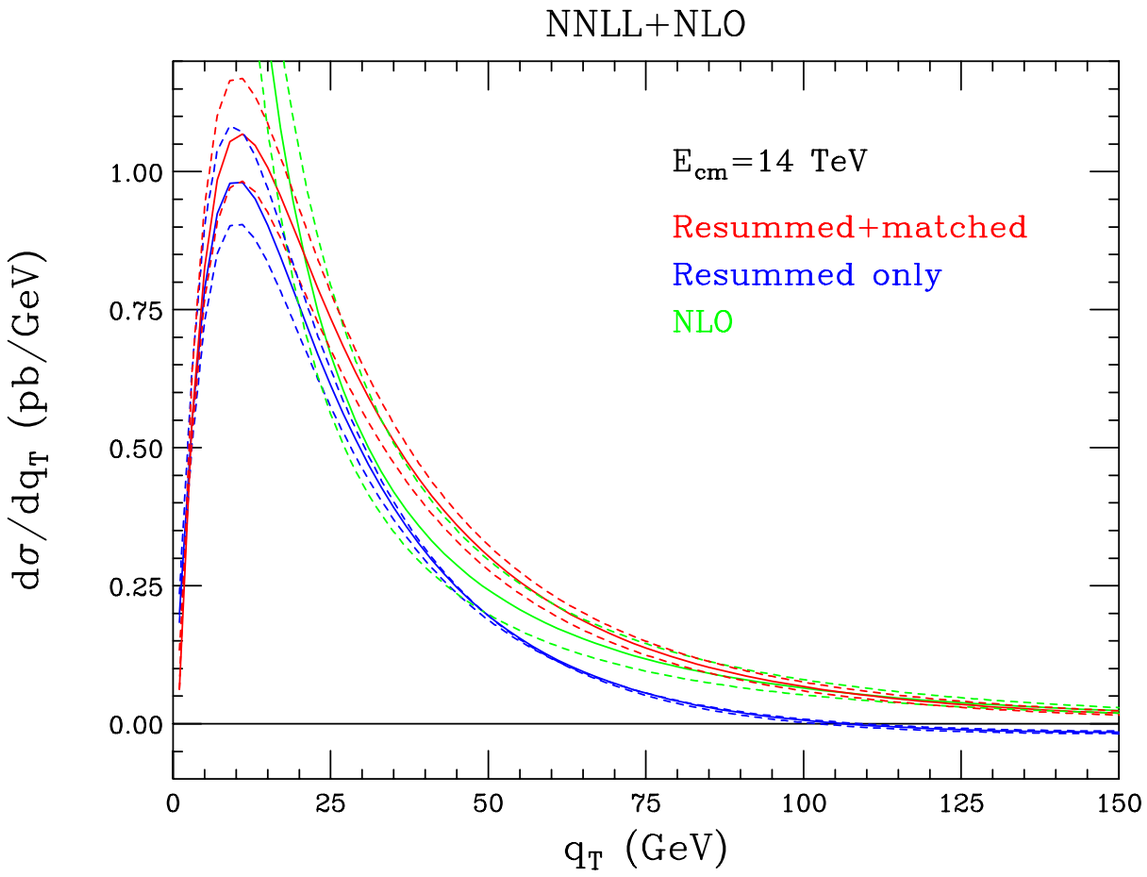
Higgs transverse momentum: 8 TeV

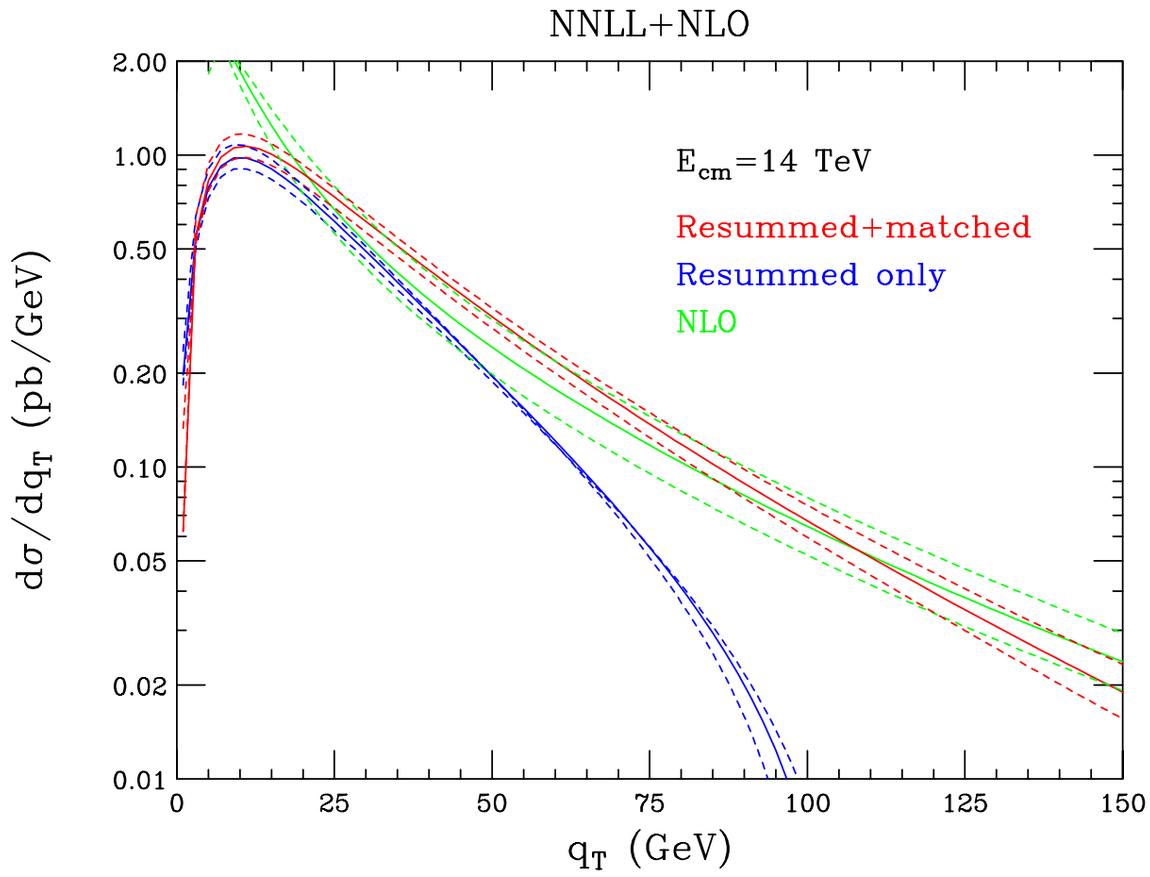




- Peak at ~10 GeV: $\log(m_H^2/q_T^2)$~5.1
- Resummation affects spectrum out to larger q_T

Higgs transverse momentum: 14 TeV





- Peak at ~10 GeV: $\log(m_H^2/q_T^2)\sim 5.1$
- Resummation affects spectrum out to larger q_T

Resummation of Higgs q_T

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_a(x_1,\mu) f_b(x_2,\mu) \, \mathrm{d}\hat{\sigma}_{ab}(x_1 x_2 s, \mu, \ldots)$$

$$\frac{1}{\hat{\sigma}_{gg}} \frac{\mathrm{d}^2\hat{\sigma}_{gg}}{\mathrm{d}\,\mathbf{q}_\mathrm{T}^2} \sim \delta^2(\mathbf{q}_\mathrm{T}) + \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right]_+ \delta^2(\mathbf{q}_\mathrm{T} + \mathbf{p}_\mathrm{T}) + \ldots$$

$$\sim \int \frac{\mathrm{d}^2\mathbf{b}}{(2\pi)^2} \, \mathrm{e}^{i\mathbf{b}\cdot\mathbf{q}_\mathrm{T}} \left\{ 1 + \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right] \left(\mathrm{e}^{i\mathbf{b}\cdot\mathbf{p}_\mathrm{T}} - 1 \right) + \ldots \right\}$$

$$\sim \int \frac{\mathrm{d}^2\mathbf{b}}{(2\pi)^2} \, \mathrm{e}^{i\mathbf{b}\cdot\mathbf{q}_\mathrm{T}} \exp\left\{ \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right] \left(\mathrm{e}^{i\mathbf{b}\cdot\mathbf{p}_\mathrm{T}} - 1 \right) \right\}$$

Resummation of Higgs E_T

$$\mathrm{d}\sigma = \int \mathrm{d}x_1 \mathrm{d}x_2 \, f_a(x_1,\mu) f_b(x_2,\mu) \, \mathrm{d}\hat{\sigma}_{ab}(x_1 x_2 s, \mu, \ldots)$$

$$\frac{1}{\hat{\sigma}_{gg}} \frac{\mathrm{d}^2\hat{\sigma}_{gg}}{\mathrm{d}\,\mathbf{q}_\mathrm{T}^2} \sim \delta^2(\mathbf{q}_\mathrm{T}) + \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right]_+ \delta^2(\mathbf{q}_\mathrm{T} + \mathbf{p}_\mathrm{T}) + \ldots$$

$$\sim \int \frac{\mathrm{d}^2\mathbf{b}}{(2\pi)^2} \, \mathrm{e}^{i\mathbf{b}\cdot\mathbf{q}_\mathrm{T}} \left\{ 1 + \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right] \left(\mathrm{e}^{i\mathbf{b}\cdot\mathbf{p}_\mathrm{T}} - 1 \right) + \ldots \right\}$$

$$\sim \int \frac{\mathrm{d}^2\mathbf{b}}{(2\pi)^2} \, \mathrm{e}^{i\mathbf{b}\cdot\mathbf{q}_\mathrm{T}} \exp\left\{ \alpha_\mathrm{S} \int \mathrm{d}^2\mathbf{p}_\mathrm{T} \left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2} \ln \frac{m_H^2}{\mathbf{p}_\mathrm{T}^2} + \frac{B_g}{\mathbf{p}_\mathrm{T}^2} \right] \left(\mathrm{e}^{i\mathbf{b}\cdot\mathbf{p}_\mathrm{T}} - 1 \right) \right\}$$

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

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

Resummation of Higgs E_T

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

- Defined for $E_T \leqslant 0$

Resummation of Higgs E_T

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

- Defined for $E_T \leqslant 0$
- For $E_T < 0$, can close τ-contour in lower half-plane

Resummation of Higgs E_T

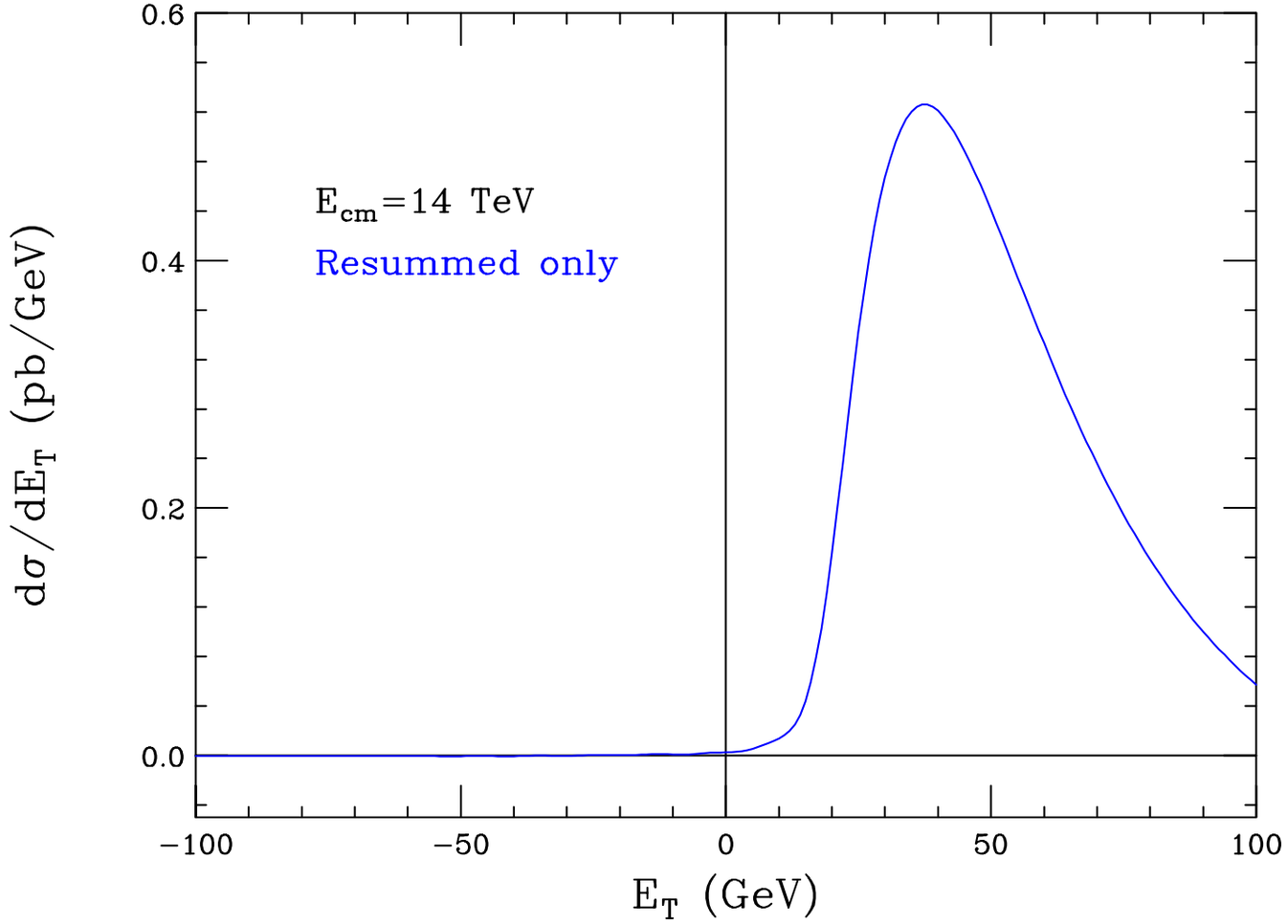
$$\frac{1}{\hat{\sigma}_{gg}}\frac{\mathrm{d}\hat{\sigma}_{gg}}{\mathrm{d}\,E_T} \sim \int_{-\infty}^{+\infty}\frac{\mathrm{d}\tau}{2\pi}\,\mathrm{e}^{i\tau E_T}\exp\left\{\alpha_\mathrm{S}\int \mathrm{d}^2\mathbf{p}_\mathrm{T}\left[\frac{A_g}{\mathbf{p}_\mathrm{T}^2}\ln\frac{m_H^2}{\mathbf{p}_\mathrm{T}^2}+\frac{B_g}{\mathbf{p}_\mathrm{T}^2}\right]\left(\mathrm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

- Defined for $E_T \leqslant 0$
- For $E_T < 0$, can close τ–contour in lower half-plane
- No singularities in lower half-plane

Resummation of Higgs E_T

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

- Defined for $E_T \leqslant 0$
- For $E_T < 0$, can close τ–contour in lower half-plane
- No singularities in lower half-plane



Resummation & matching of Higgs E_T

$$\left[\frac{d\sigma_H}{dQ^2\,dE_T}\right]_{\rm res.} = \frac{1}{2\pi}\sum_{a,b}\int_0^1 dx_1\int_0^1 dx_2\int_{-\infty}^{+\infty} d\tau\ {\rm e}^{-i\tau E_T}\ f_{a/h_1}(x_1,\mu)\ f_{b/h_2}(x_2,\mu)\ W_{ab}^H(x_1x_2s;Q,\tau,\mu)$$

$$W_{ab}^H(s;Q,\tau,\mu) = \int_0^1 dz_1\int_0^1 dz_2\ C_{ga}(\alpha_{\rm S}(\mu),z_1;\tau,\mu)\ C_{gb}(\alpha_{\rm S}(\mu),z_2;\tau,\mu)\ \delta(Q^2-z_1z_2s)\ \sigma_{gg}^H(Q,\alpha_{\rm S}(Q))\ S_g(Q,\tau)$$

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

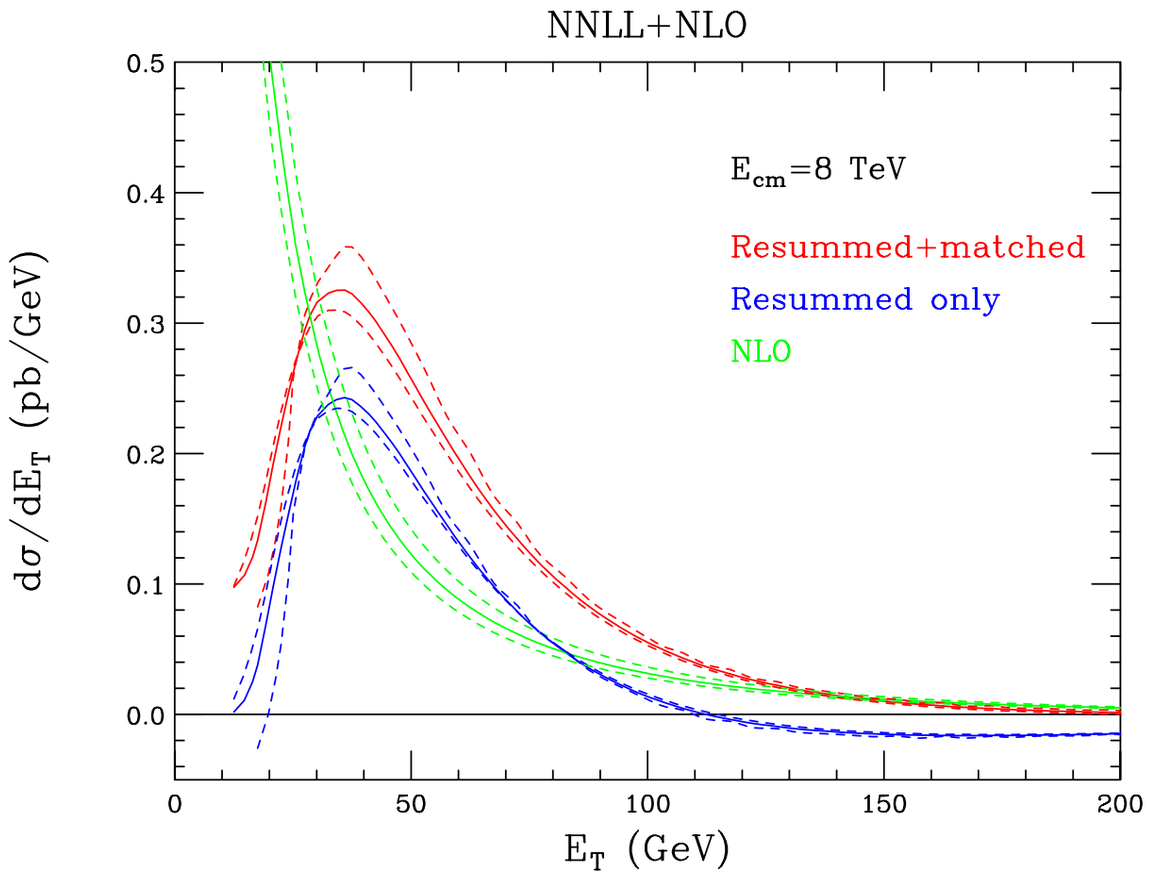
$$A_g(\alpha_{\rm S}) = \sum_{n=1}^{\infty}\left(\frac{\alpha_{\rm S}}{\pi}\right)^n A_g^{(n)}\ ,$$

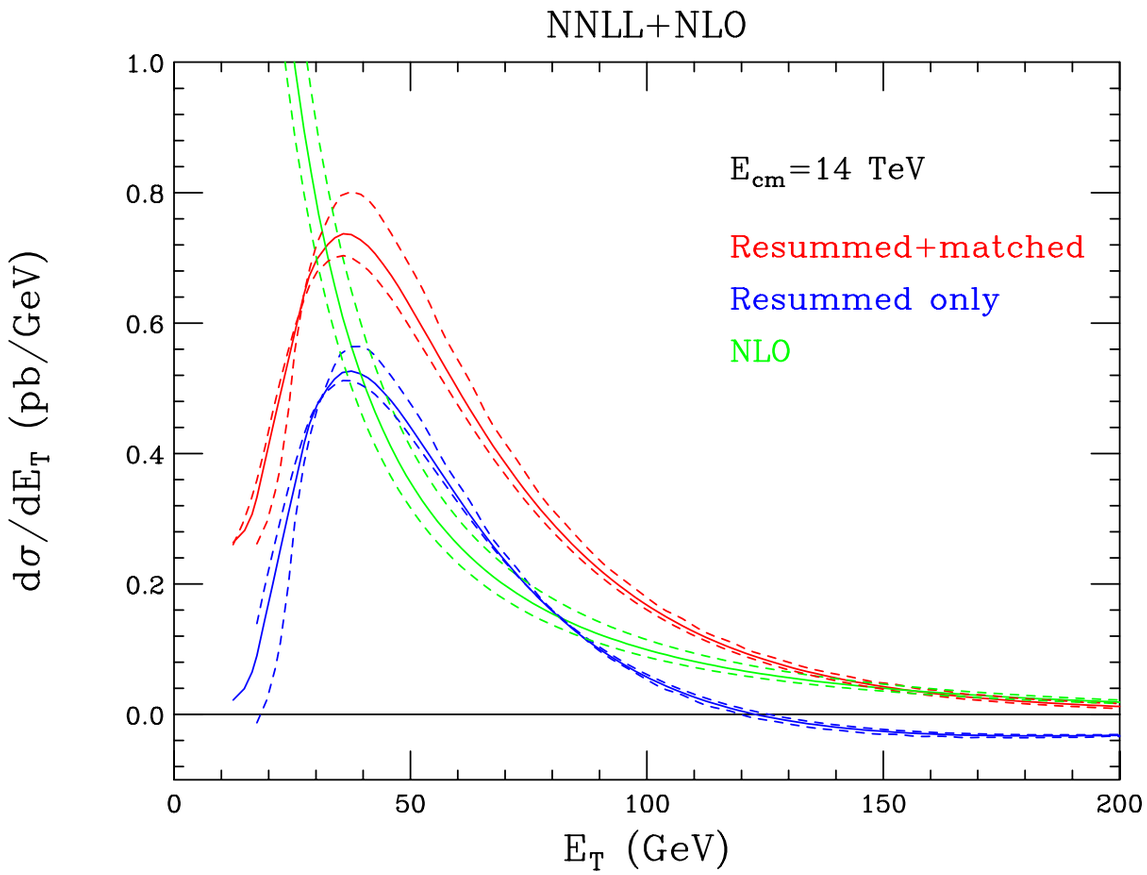
$$B_g(\alpha_{\rm S}) = \sum_{n=1}^{\infty}\left(\frac{\alpha_{\rm S}}{\pi}\right)^n B_g^{(n)}\ ,$$

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

$$\frac{d\sigma_H}{dE_T} = \left[\frac{d\sigma_H}{dE_T}\right]_{\rm resum} - \left[\frac{d\sigma_H}{dE_T}\right]_{\rm resum,NLO} + \left[\frac{d\sigma_H}{dE_T}\right]_{\rm NLO}$$

Transverse energy distribution

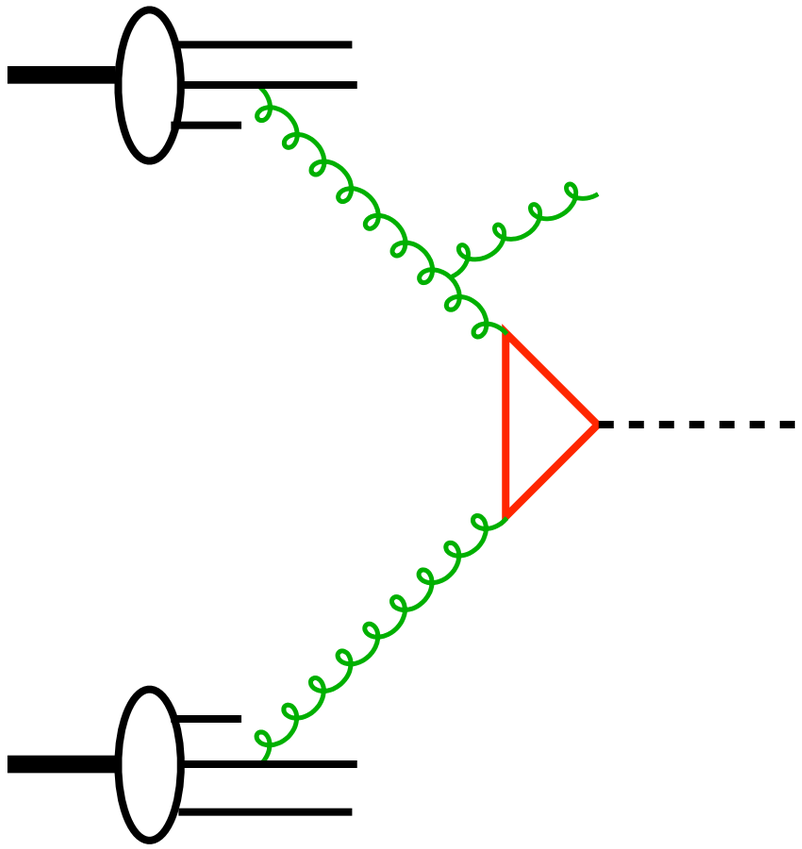




- Peak at ~35 GeV: $\log(m_H^2/E_T^2)$~2.6
- Resummation affects spectrum out to much larger E_T
- Unlike q_T, the Underlying Event also contributes…

Monte Carlo Simulation

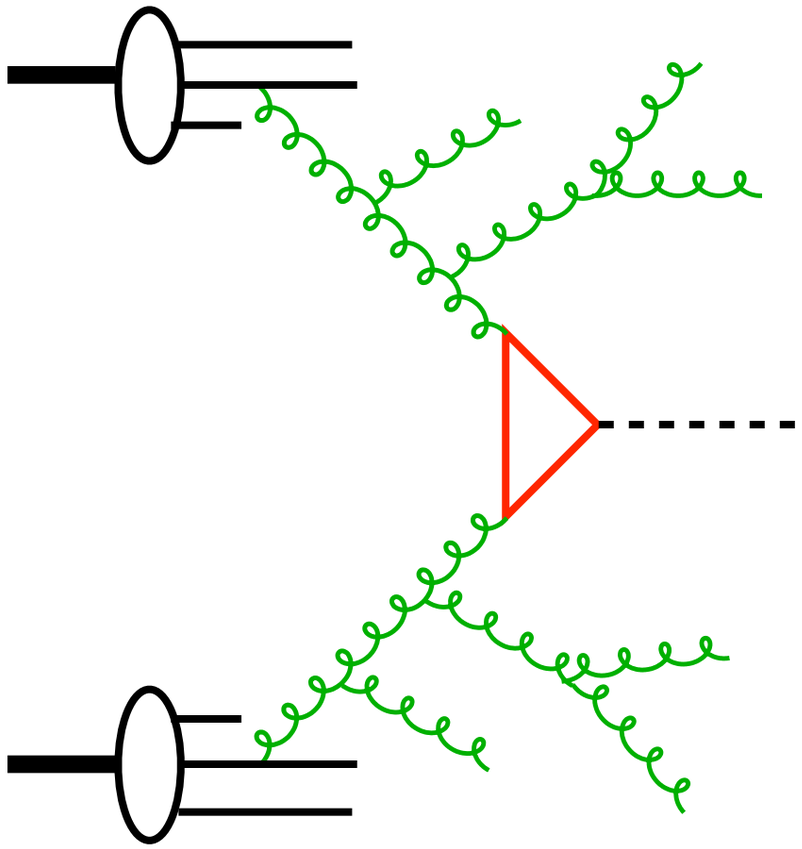
Monte Carlo simulation



- aMC@NLO: NLO with matching

Frixione, BW, hep-ph/0204244
Frederix et al., 1110.4738

Monte Carlo simulation



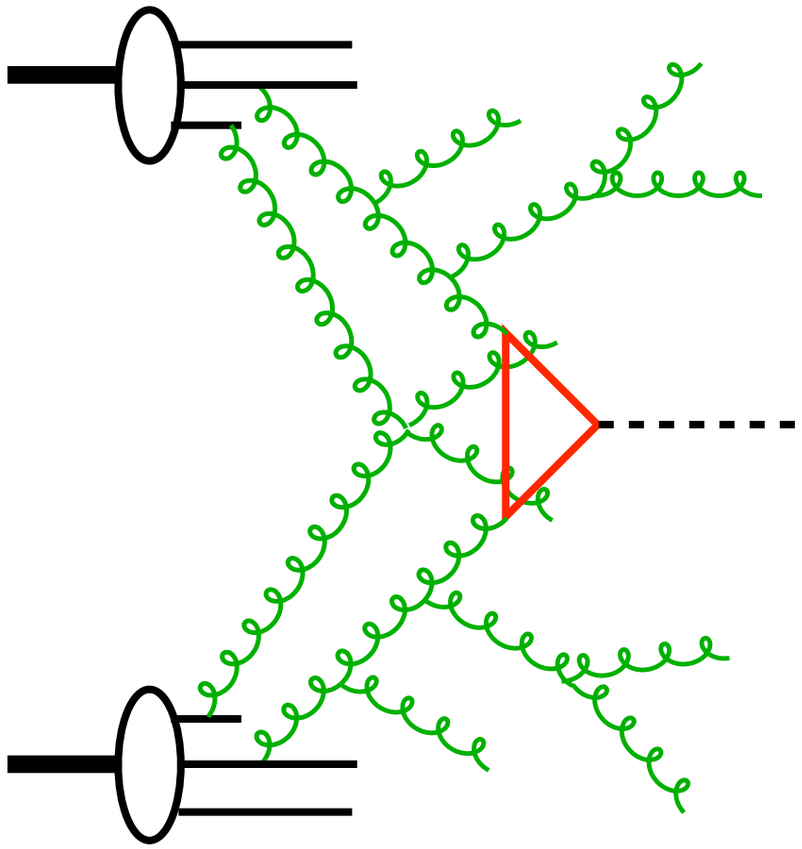
- aMC@NLO: NLO with matching to …
- Parton showers (≈ higher orders)

Frixione, BW, hep-ph/0204244

Frederix et al., 1110.4738

Bahr et al., 0812.0529,
http://projects.hepforge.org/herwig/

Monte Carlo simulation



- aMC@NLO: NLO with matching to …
- Parton showers (≈ higher orders)
- Underlying event model

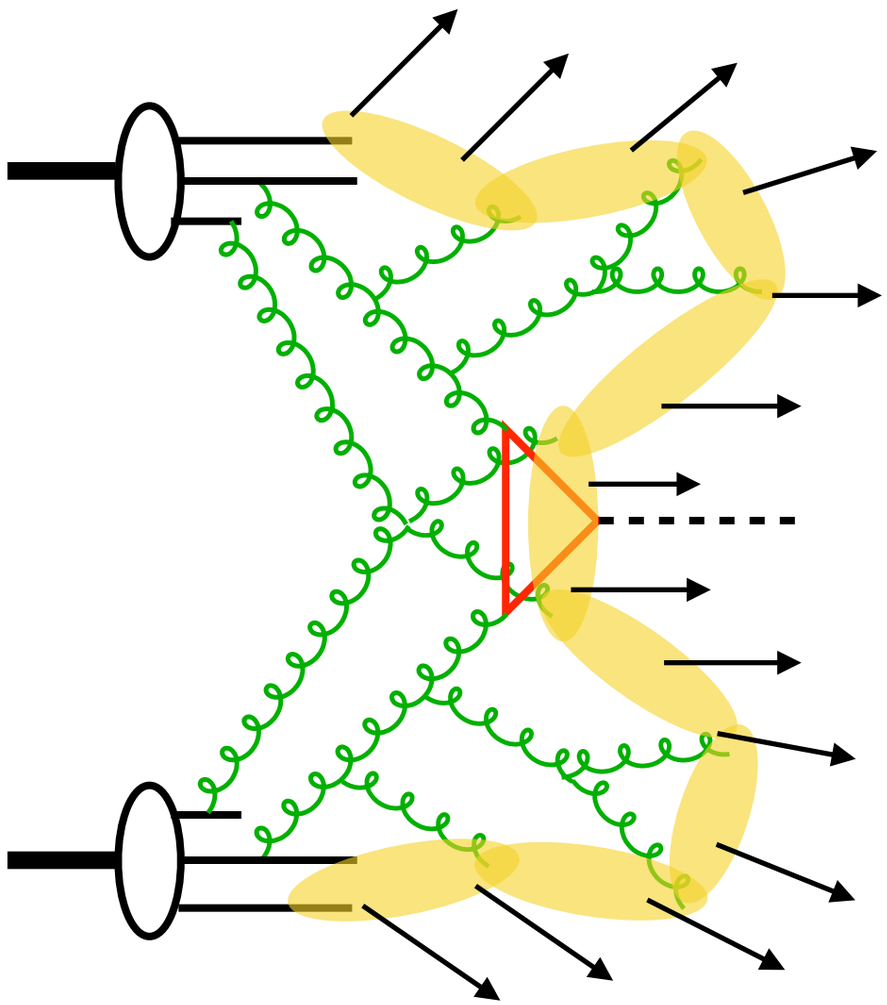
Frixione, BW, hep-ph/0204244

Frederix et al., 1110.4738

Bahr et al., 0812.0529,
http://projects.hepforge.org/herwig/

Borozan, Seymour, hep-ph/0207283

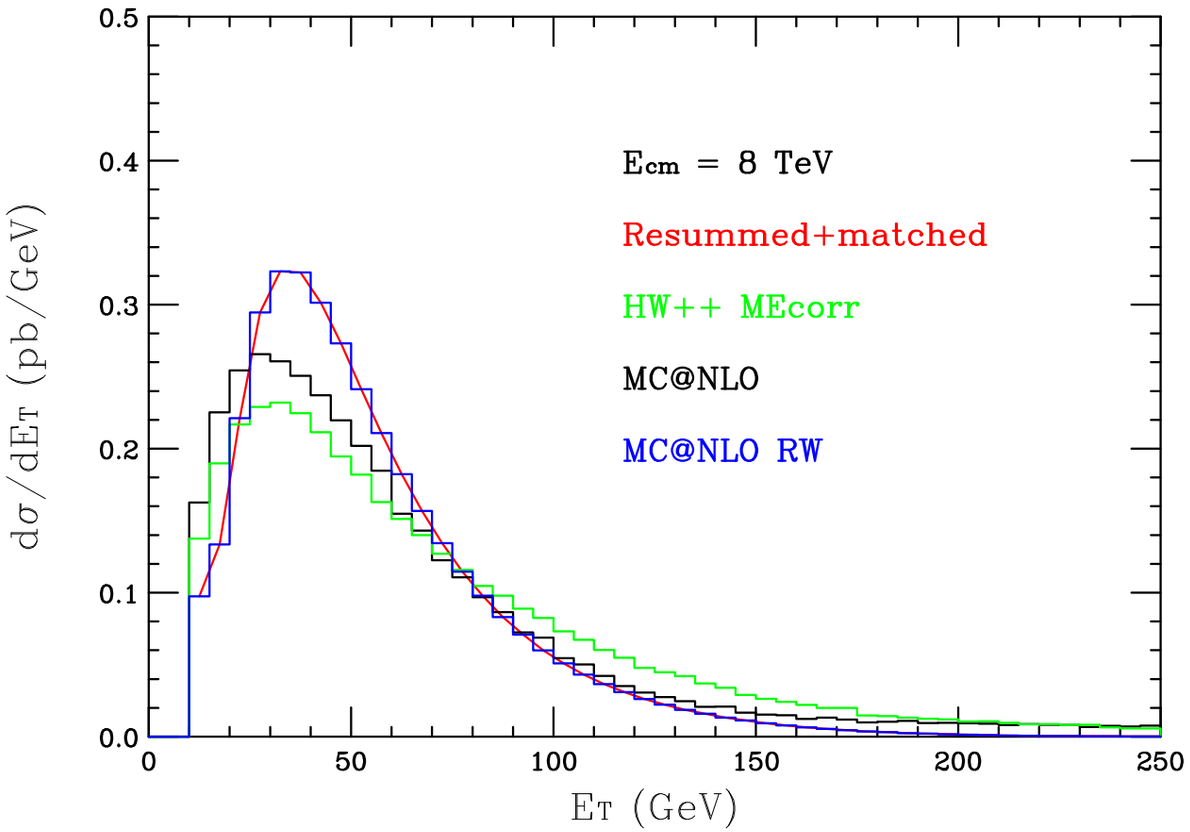
Monte Carlo simulation

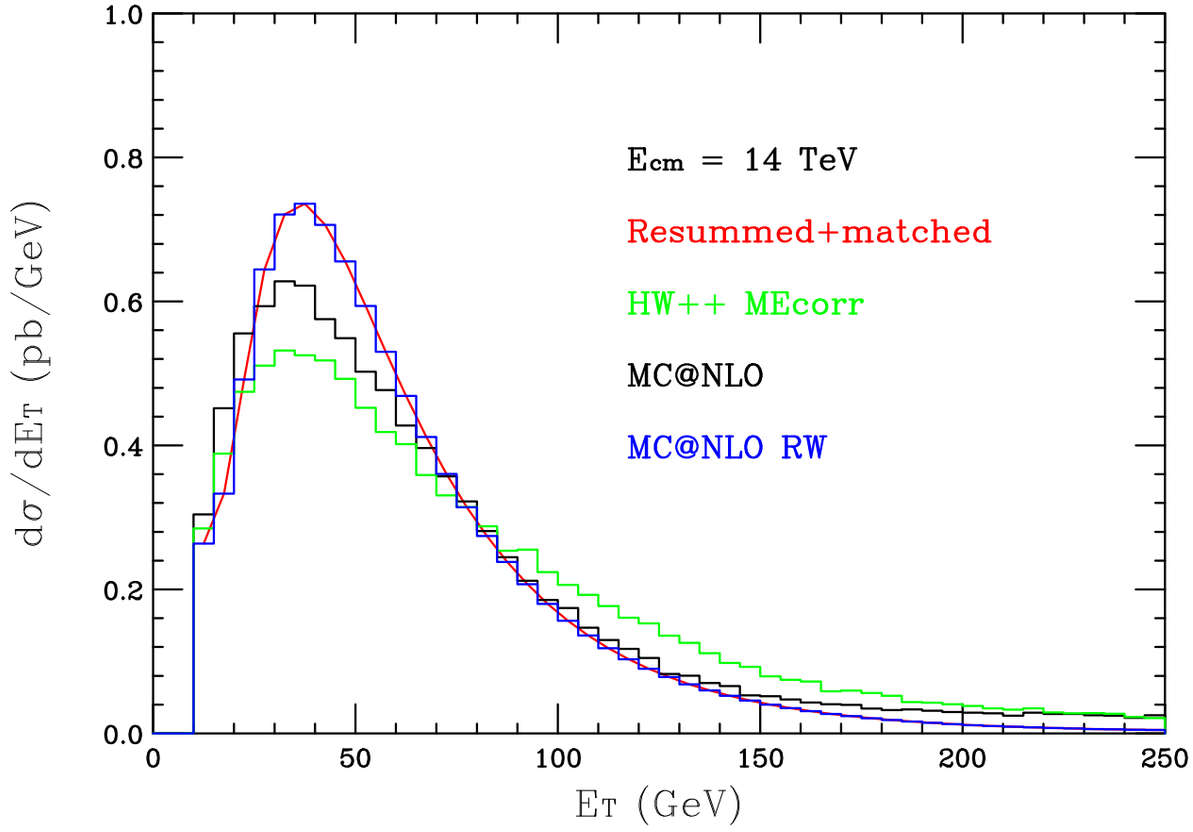


- aMC@NLO: NLO with matching to …
- Parton showers (≈ higher orders)
- Underlying event model
- Cluster hadronization model

Frixione, BW, hep-ph/0204244
Frederix et al., 1110.4738
Bahr et al., 0812.0529,
http://projects.hepforge.org/herwig/
Borozan, Seymour, hep-ph/0207283
BW, Nucl.Phys. B238(1984)492

Monte Carlo Higgs E_T

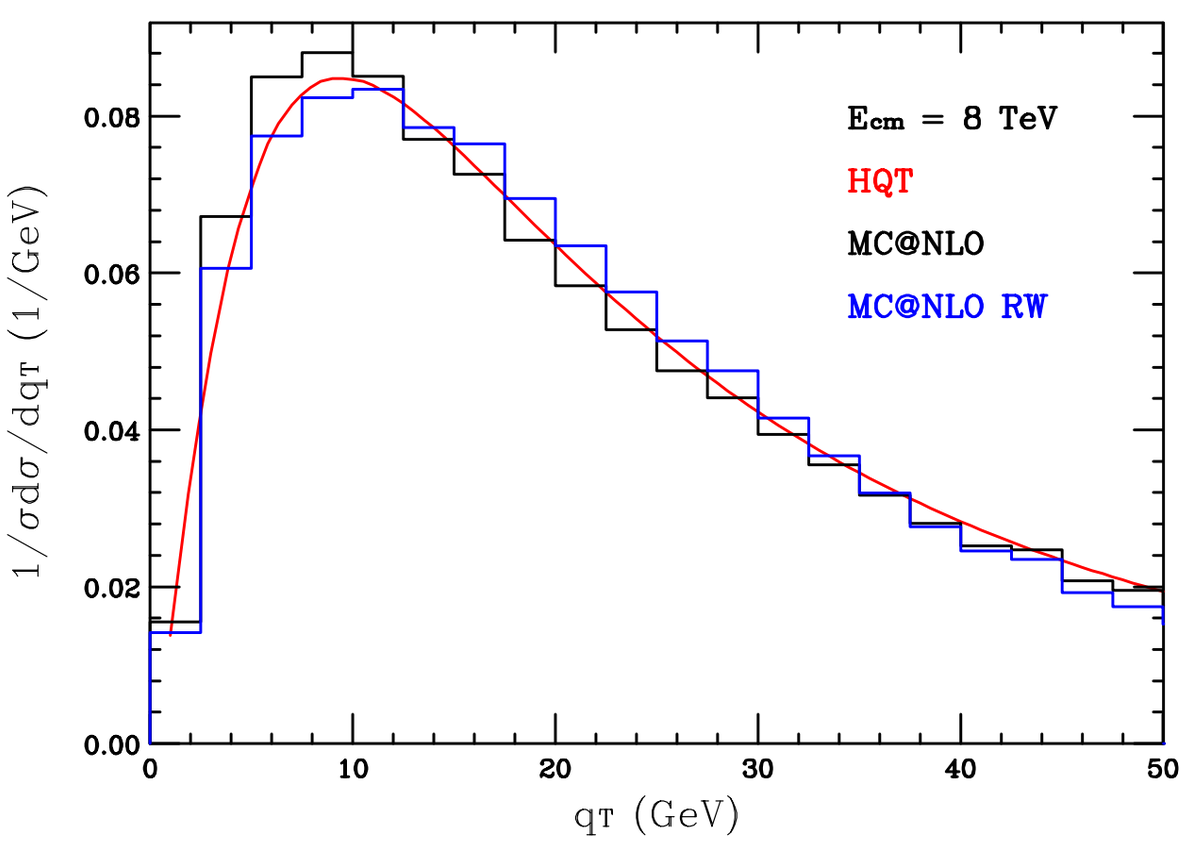


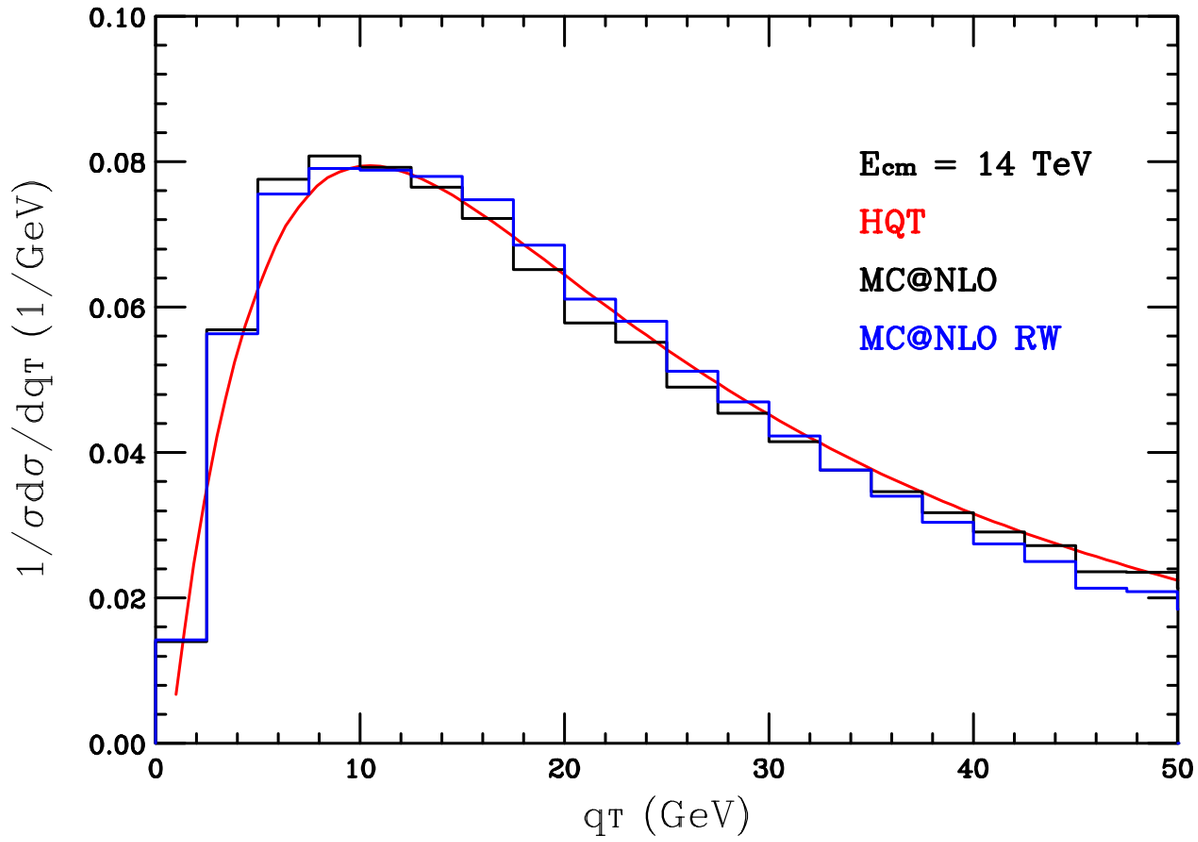


- RW = reweighted to agree with resummed+matched E_T
- Underlying event and hadronization NOT included

Grazzini, Papaefstathiou, Smillie, BW, 1403.3394

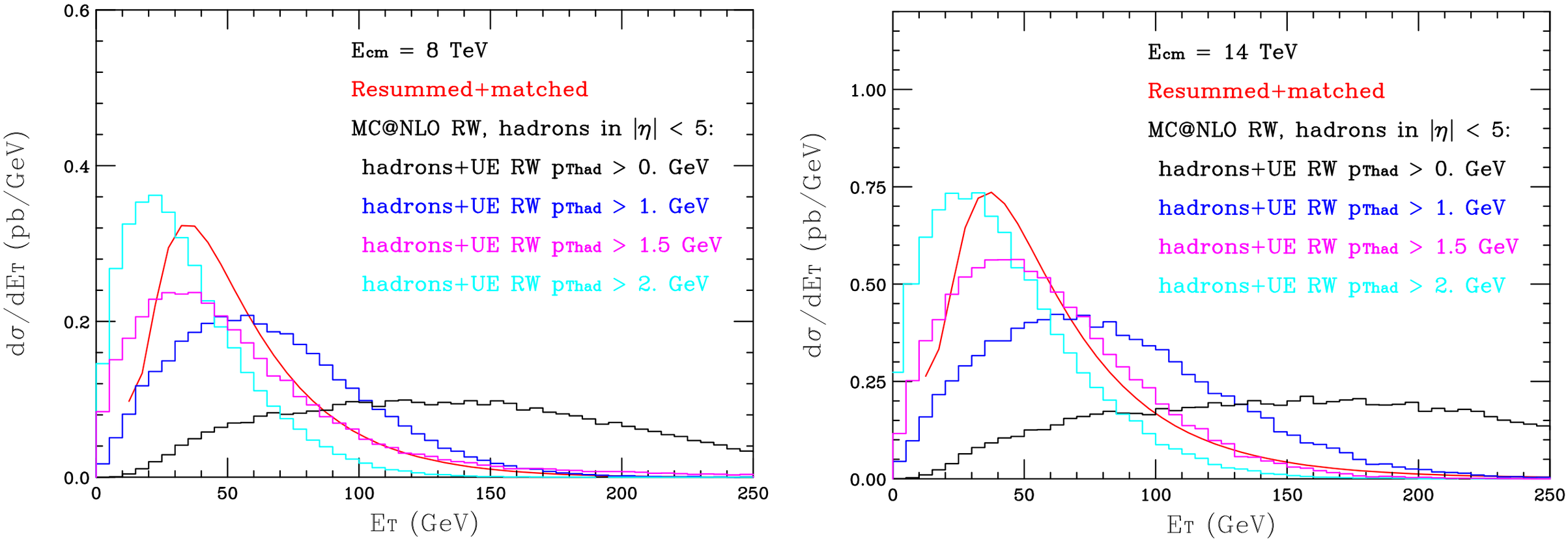
Monte Carlo Higgs q_T





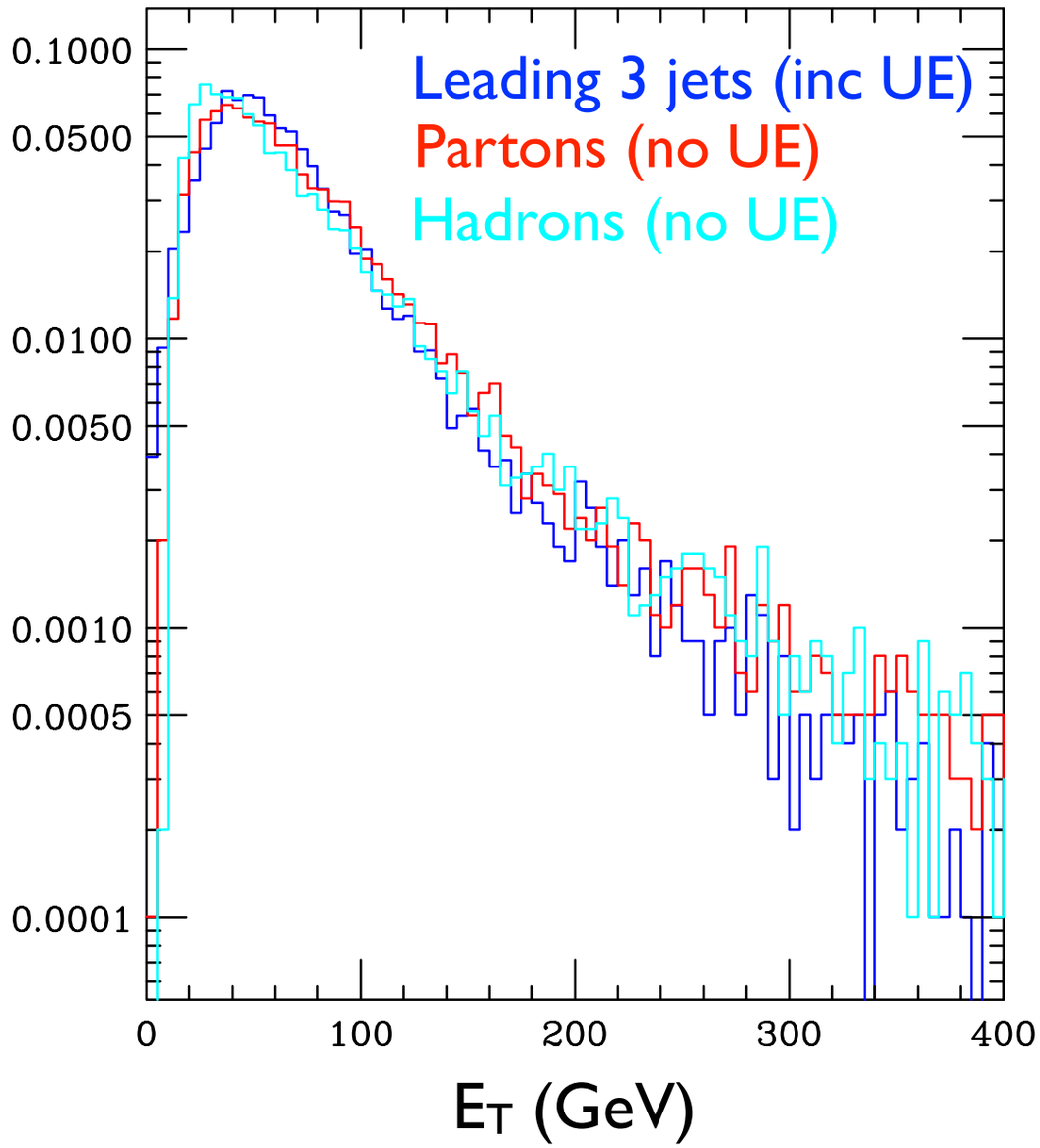
- RW = reweighted to agree with resummed+matched E_T
- Reweighting improves agreement with HQT (= resummed+matched q_T)

Monte Carlo Higgs E_T



- RW = reweighted to agree with resummed+matched E_T
- Underlying event and hadronization INCLUDED
- Strong dependence on minimum hadron p_T

Higgs E_T from jets?

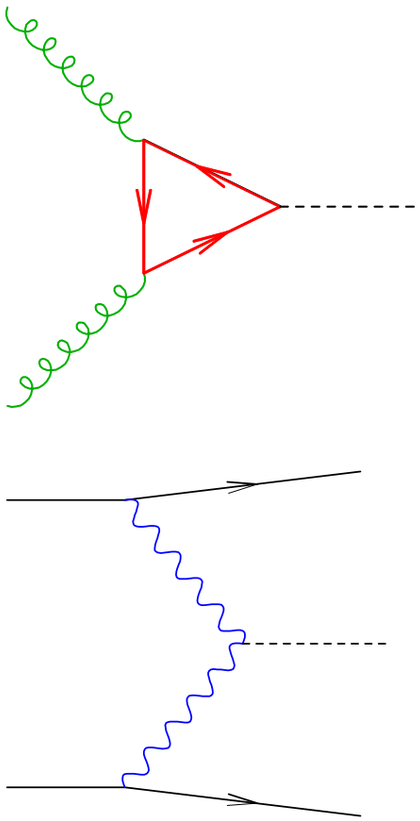


- Suggested by G Salam:
- Parton level ≈ E_T of leading n jets (anti-kt, R=0.7)
- Less sensitive to underlying event and hadronization

Papaefstathiou, BW, prelim.

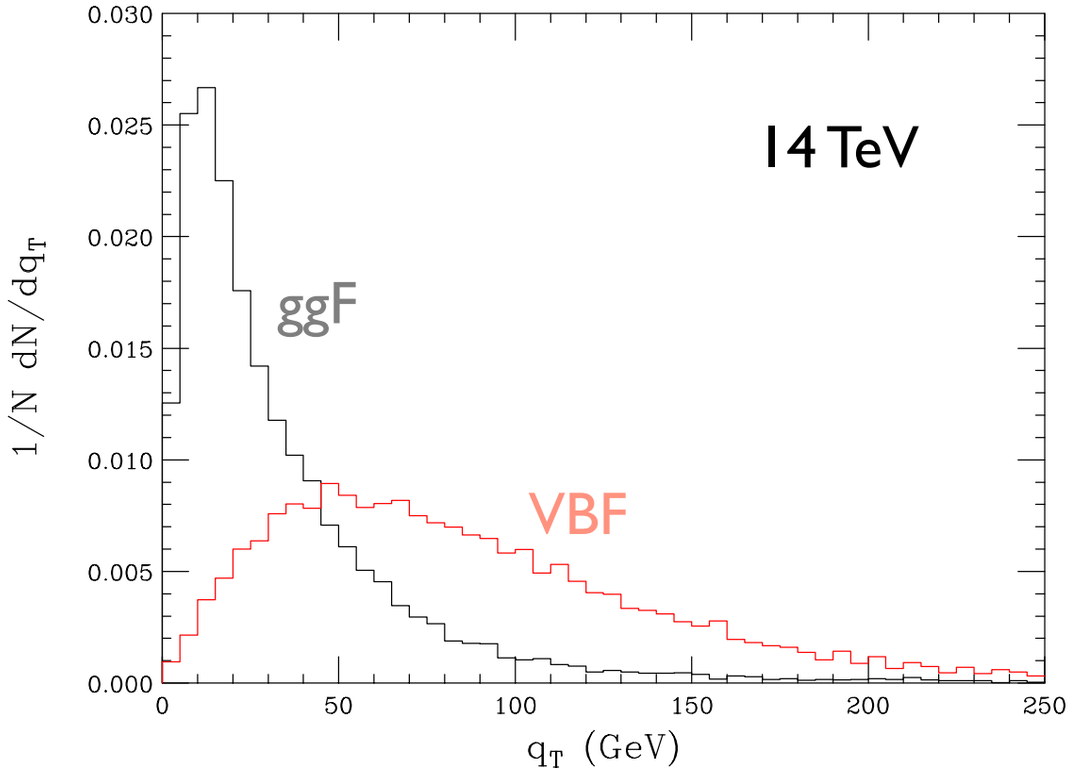
Selecting VBF

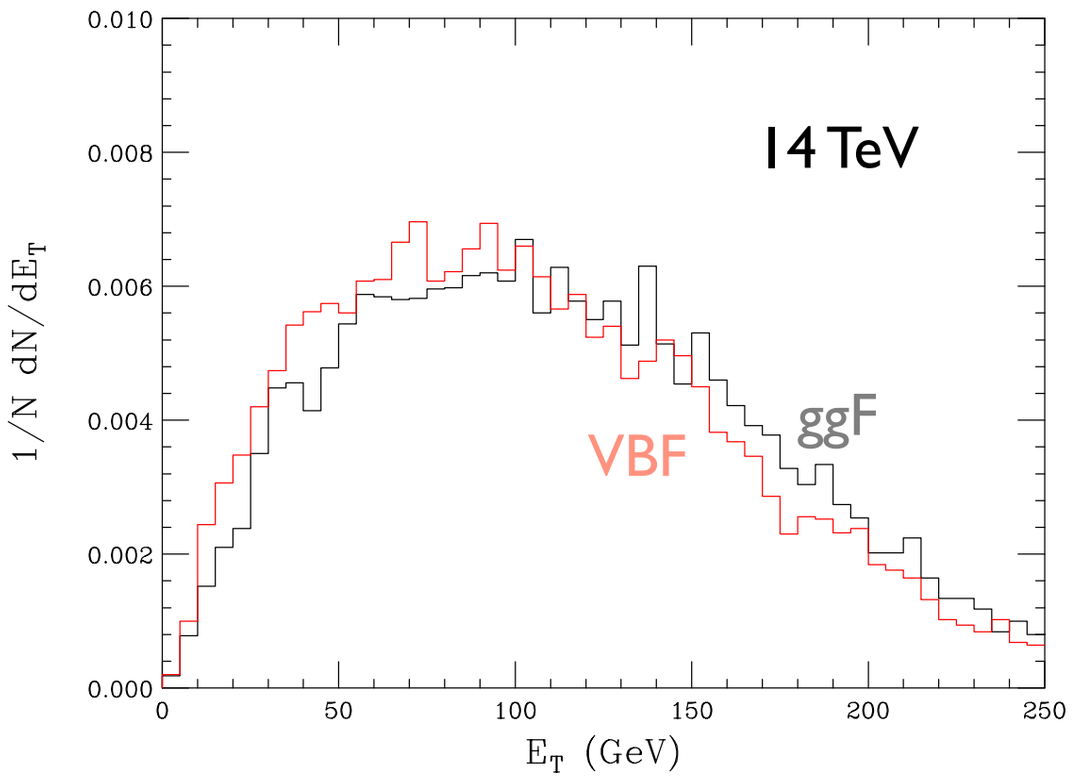
Monte Carlo Higgs q_T & E_T



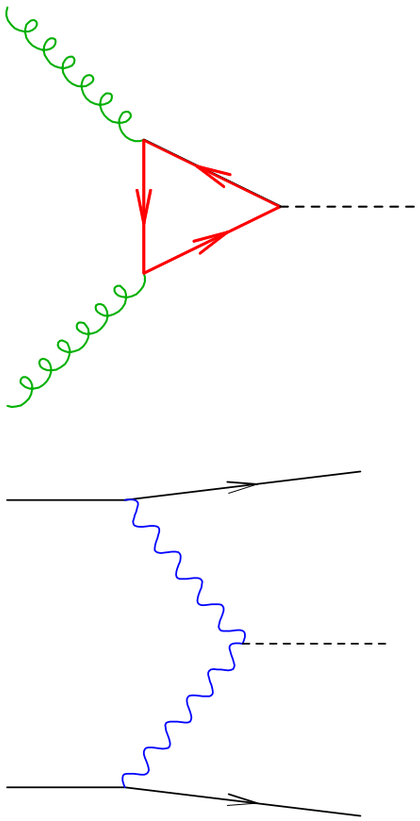
- Massless coloured vs massive colourless exchange
  - Big difference in q_T
  - Small difference in E_T

A Papaefstathiou, BW

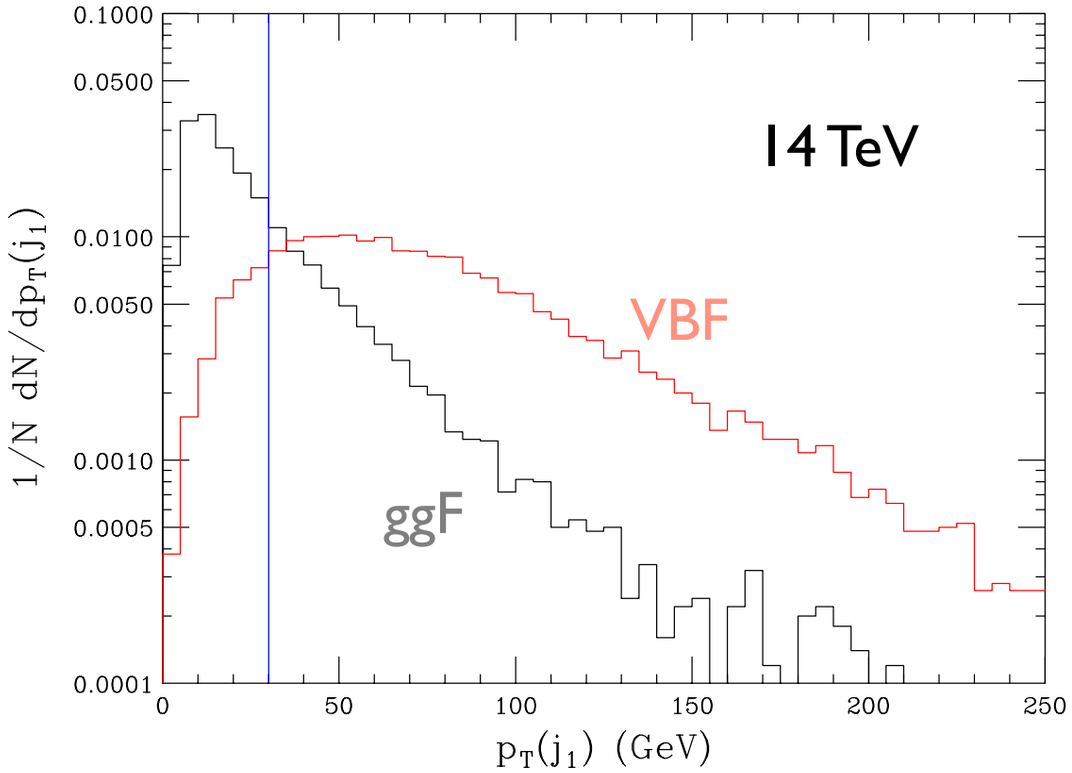


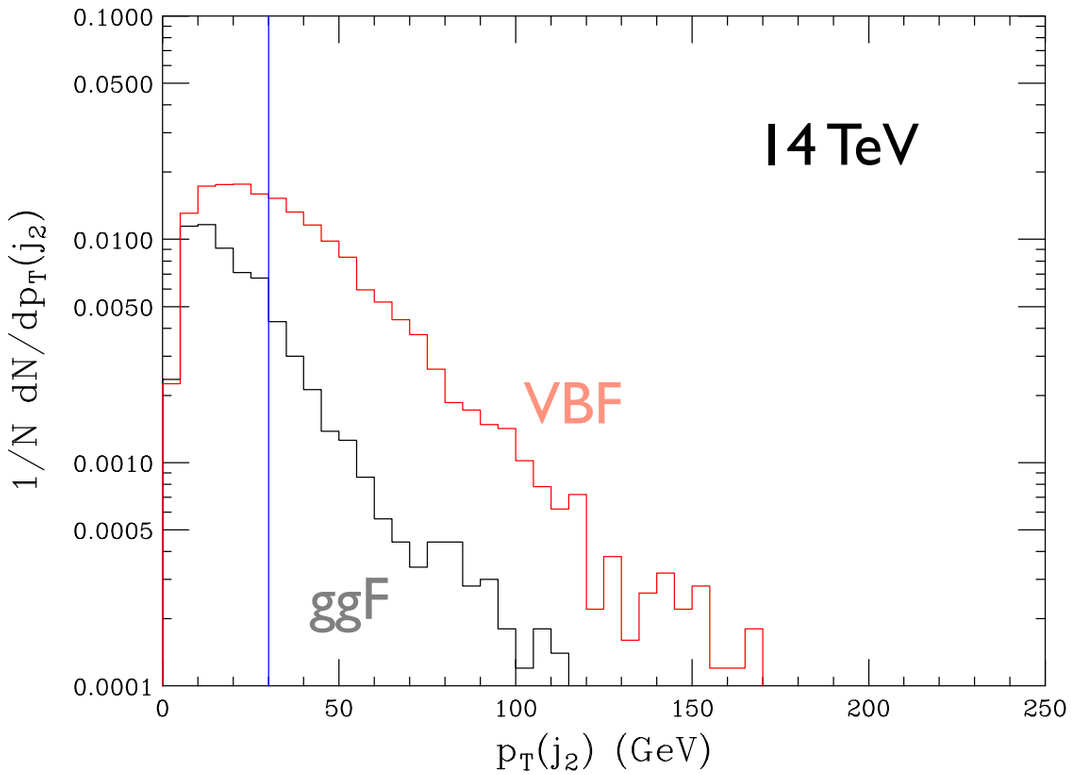


Leading jets p_T

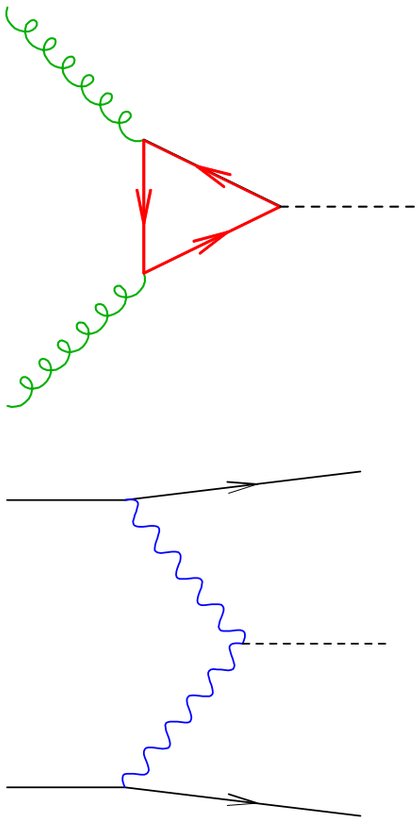


- Two hard leading jets in VBF

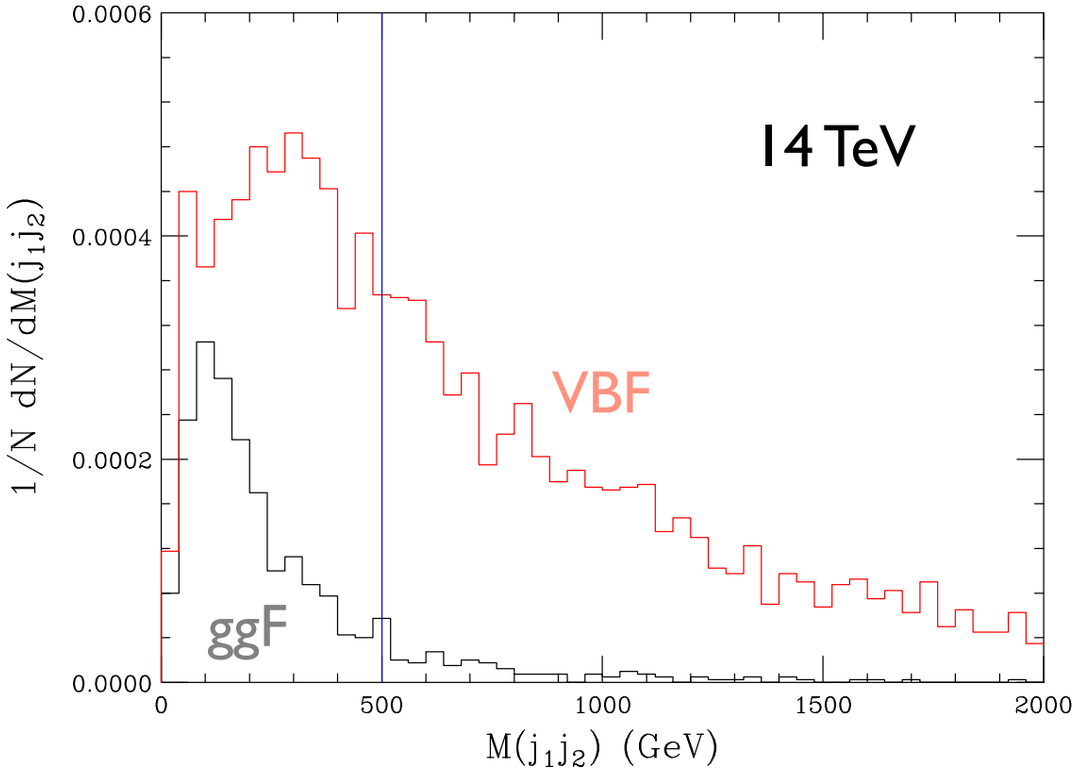


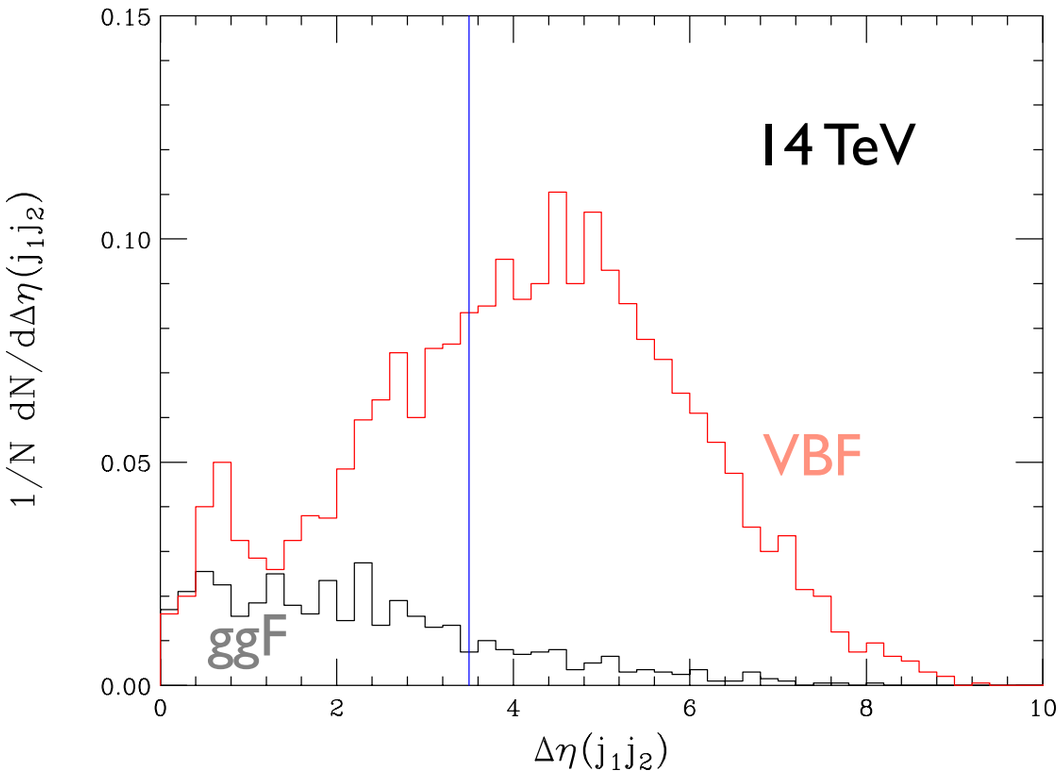


Leading jets M_{jj} and $\Delta\eta_{jj}$



- Cuts (~CMS):
  - $p_T(j_1)$, $p_T(j_2)$ > 30 GeV
  - $M(j_1j_2)$ > 500 GeV
  - $\Delta\eta(j_1j_2)$ > 3.5





Selecting VBF

- Cuts enhance VBF/ggF by ~25
- For 300 fb^{-1} at 14 TeV:

Mode	BR%	ggF(raw)	VBF(raw)	ggF(cut)	VBF(cut)
bb	56.10	10,000,000	720,000	96,000	170,000
WW	23.13	4,200,000	300,000	40,000	71,000
gg	8.49	1,500,000	110,000	15,000	26,000
tt	6.16	1,100,000	79,000	11,000	19,000
ZZ	2.90	520,000	37,000	5,000	8,900
cc	2.83	510,000	37,000	4,800	8,700
γγ	0.23	41,000	2,900	390	710
Zγ	0.16	29,000	2,100	270	490

Conclusions

Conclusions

- Higgs ggF cross section at 13 TeV is still very uncertain
  - My estimate: $\sigma_{ggF}(13\ \text{TeV}) = 53 \pm 11$ pb
- Higgs transverse momentum resummed to NNLL+NLO
  - Peak q_T ~10 GeV, independent of energy
- Radiated transverse energy resummed to NNLL+NLO
  - Peak E_T ~35 GeV in associated transverse energy
  - Contribution from Underlying Event reduced for jets
- VBF has broader q_T but similar E_T distribution
  - Jet cuts can enhance VBF/ggF by ~25

Thanks for listening!