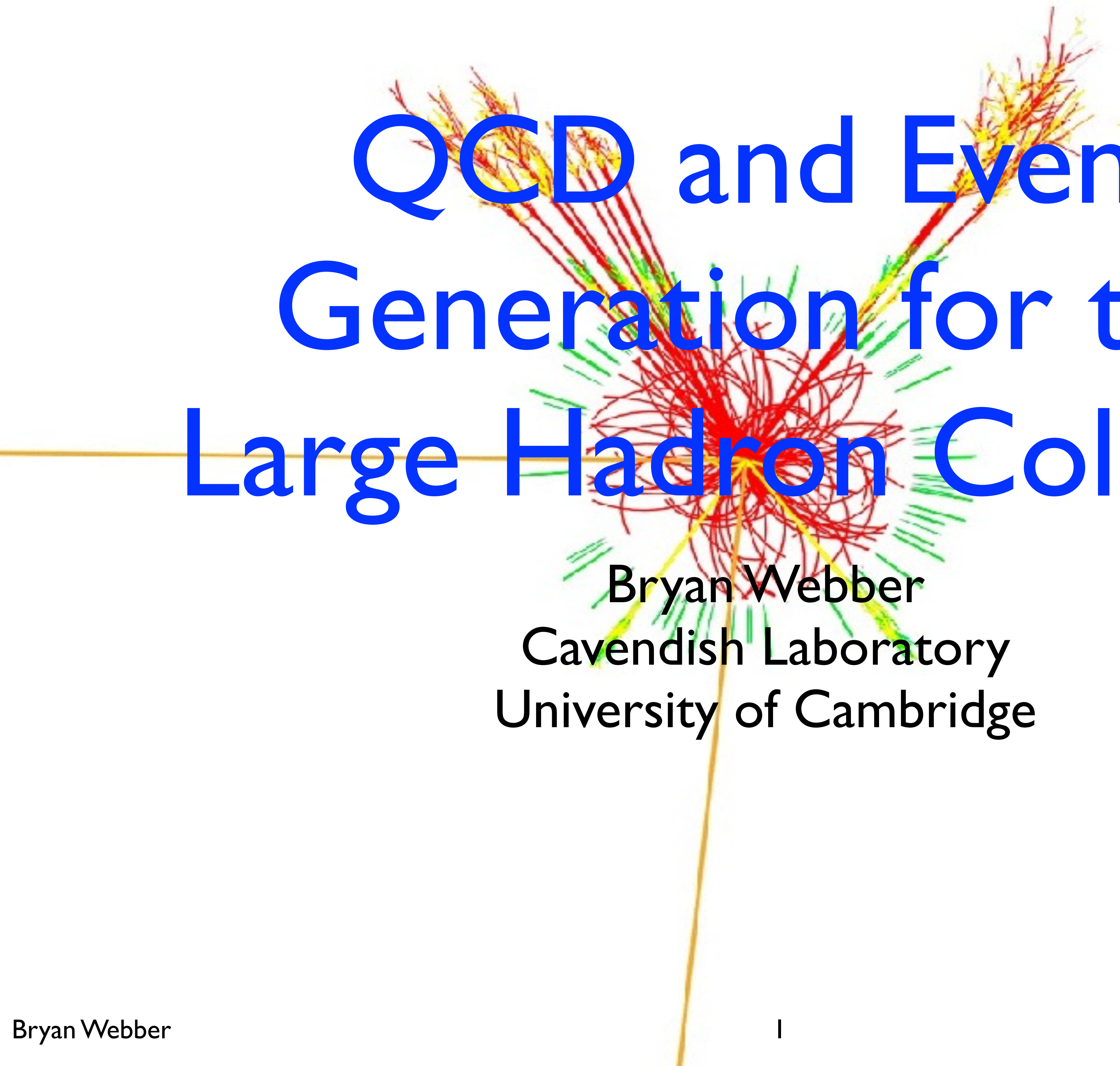


QCD and Event Generation for the Large Hadron Collider

Bryan Webber
Cavendish Laboratory
University of Cambridge

Outline

- QCD Basics
  - ★ Factorization, PDFs, running coupling
- QCD and Higgs boson production
  - ★ Inclusive production cross sections
  - ★ Differential cross sections, resummation
- QCD and Higgs boson decays
  - ★ Quark masses
  - ★ Uncertainties and prospects
- Monte Carlo event generation
  - ★ Perturbative and non-perturbative components
  - ★ Improvements: matching and merging
  - ★ Survey of results

References

- R.K. Ellis, W.J. Stirling & B.R. Webber, "QCD and Collider Physics" (C.U.P. 1996)
- A. Buckley et al., "General-purpose event generators for LHC physics", Phys.Rept. 504 (2011) 145 (MCNET-11-01, arXiv:1101.2599)
- M.H. Seymour & M. Marx, "Monte Carlo Event Generators", MCNET-13-05, arXiv:1304.6677
- A. Siódmok, "LHC event generation with general-purpose Monte Carlo tools", Acta Phys. Polon. B44 (2013)1587

QCD Basics

QCD Factorization

$$\sigma_{pp\to X}(s) = \sum_{i,j}\int_0^1 dx_1\, dx_2\, f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2)\hat{\sigma}_{ij\to X}\left(x_1x_2s, \alpha_S(\mu_R^2), \mu_F^2, \mu_R^2\right)$$

- $dx_1\, dx_2$: momentum fractions
- $f_i(x_1,\mu_F^2) f_j(x_2,\mu_F^2)$: parton distribution functions at scale μ_F
- $\hat{\sigma}_{ij\to X}$: hard process cross section, renormalised at scale μ_R

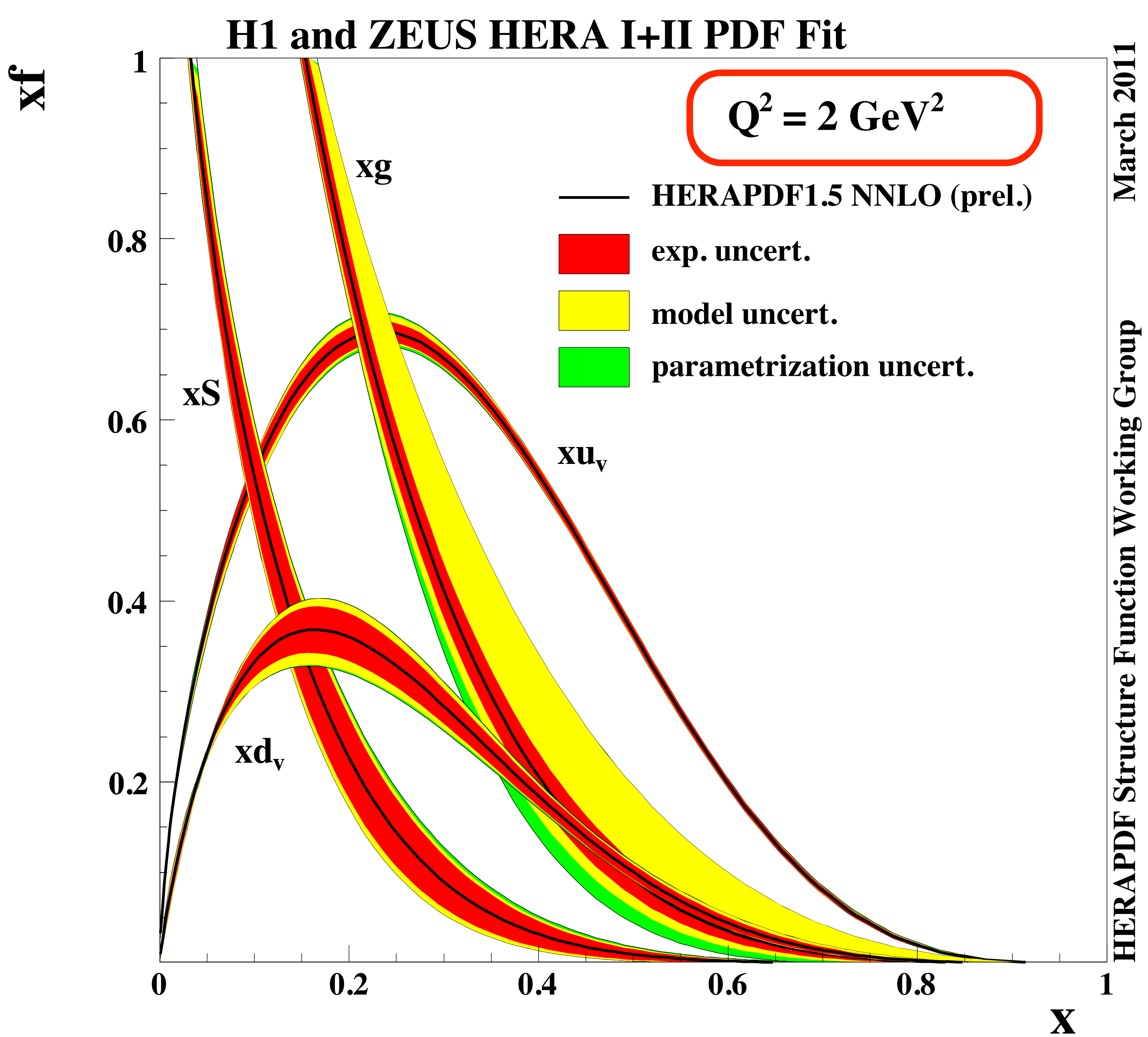
- Non-perturbative physics takes place over a much longer time scale, with unit probability
- Hence it cannot change the cross section
- Scale dependences of parton distribution functions and hard process cross section are perturbatively calculable, and cancel order by order

PDF Evolution

$$\mu^2 \frac{\partial}{\partial \mu^2} f_i(x,\mu^2) = \sum_j \int_x^1 \frac{d\xi}{\xi} P_{ij}\left(\frac{x}{\xi}, \alpha_S(\mu^2)\right) f_j(\xi,\mu^2)$$

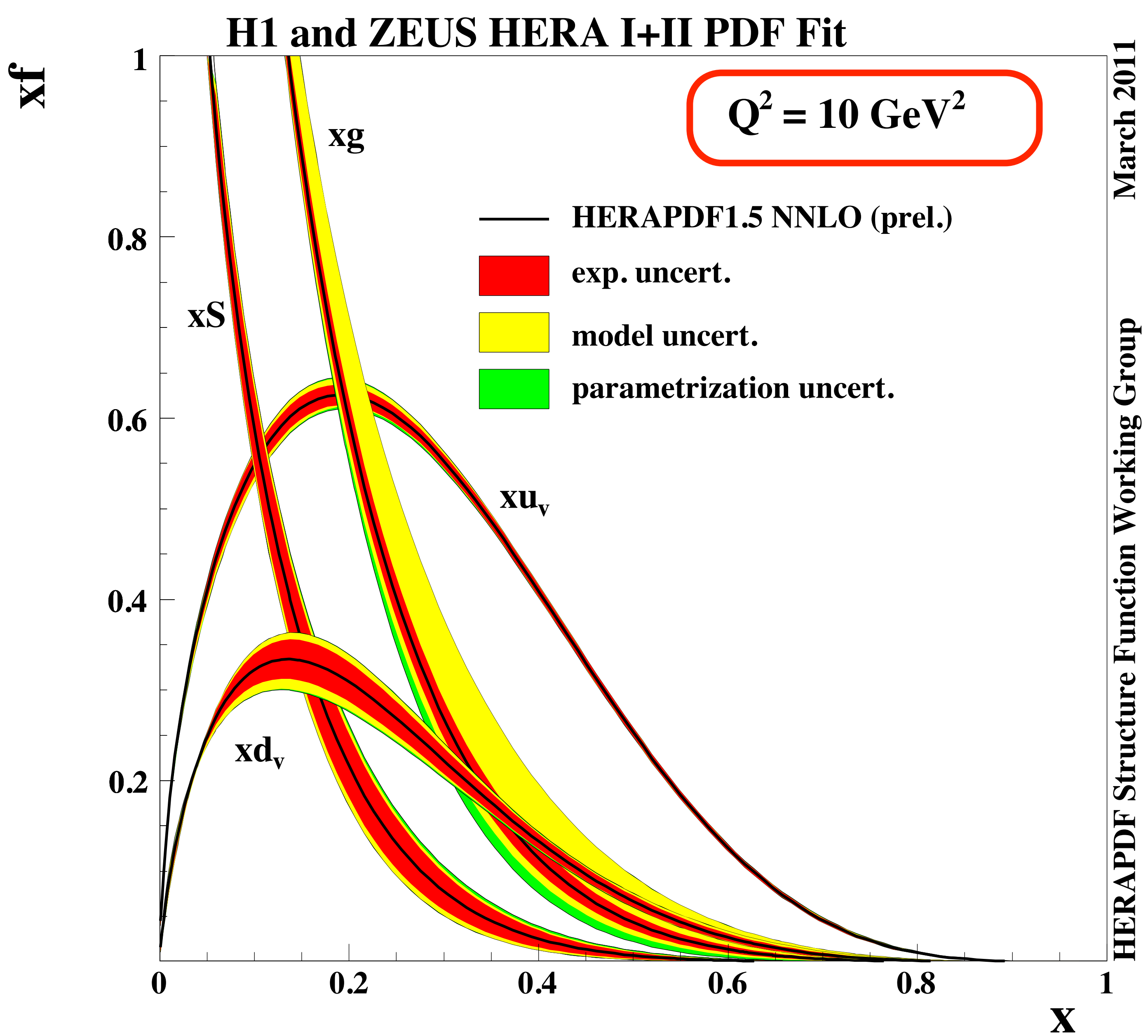
- PDFs measured in various processes at various scales
- Global fits satisfying evolution equations give PDF sets
- Generally done at NNLO nowadays

PDF Evolution



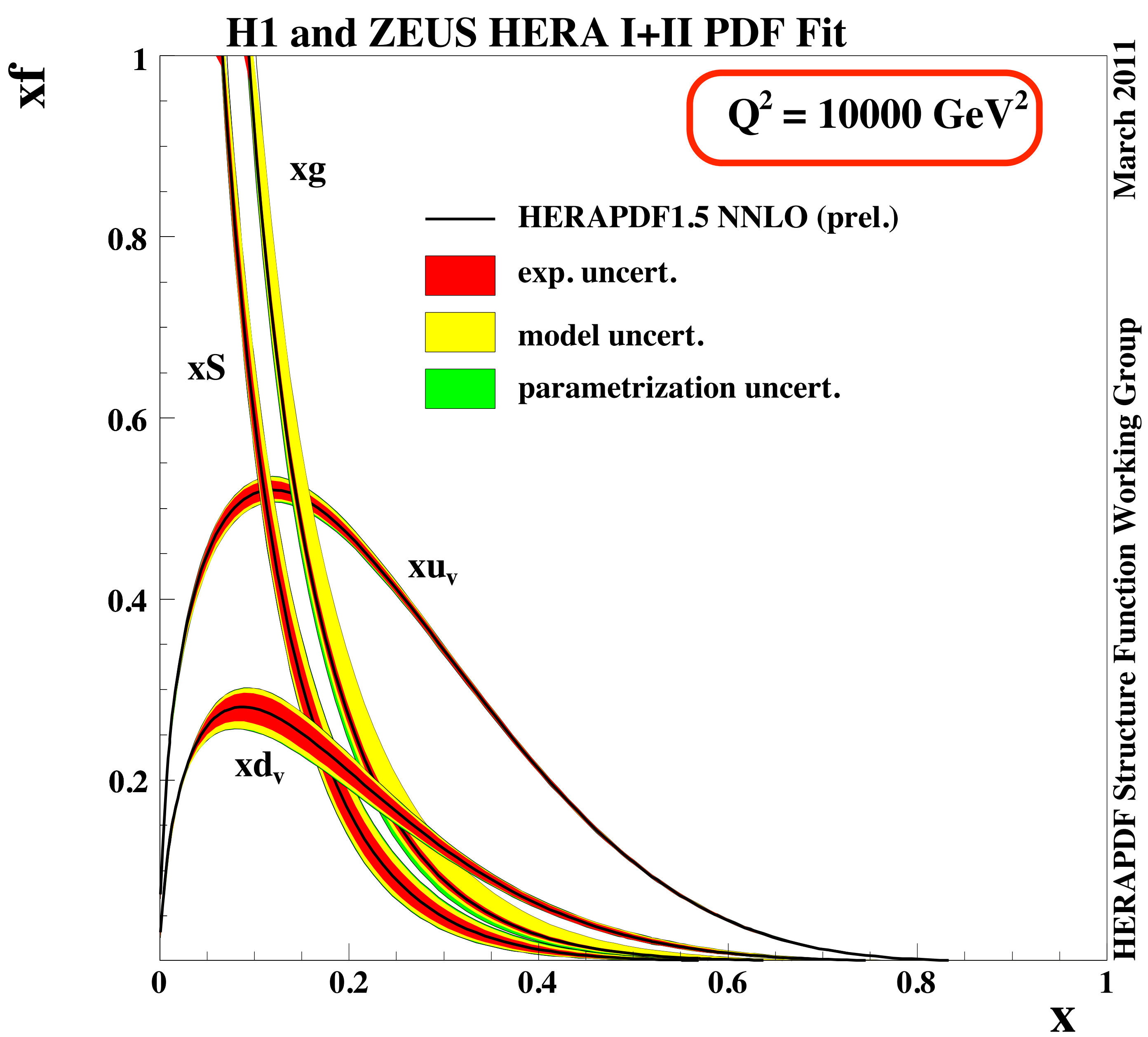
Fraction of proton momentum

PDF Evolution



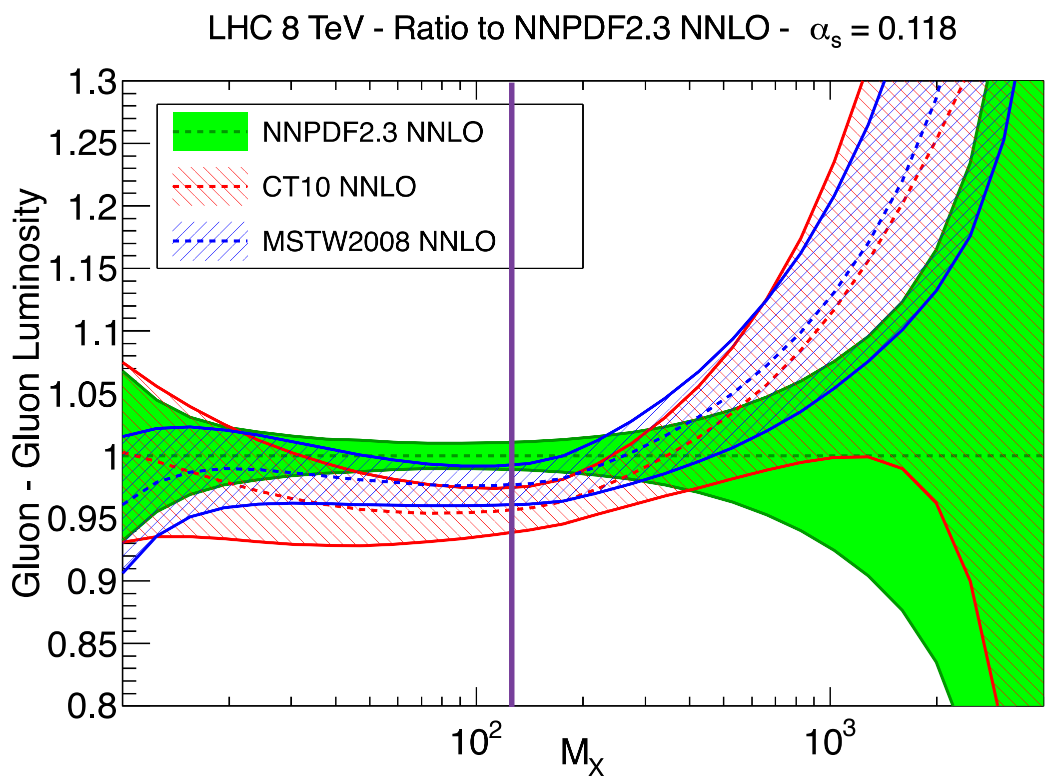
Fraction of proton momentum

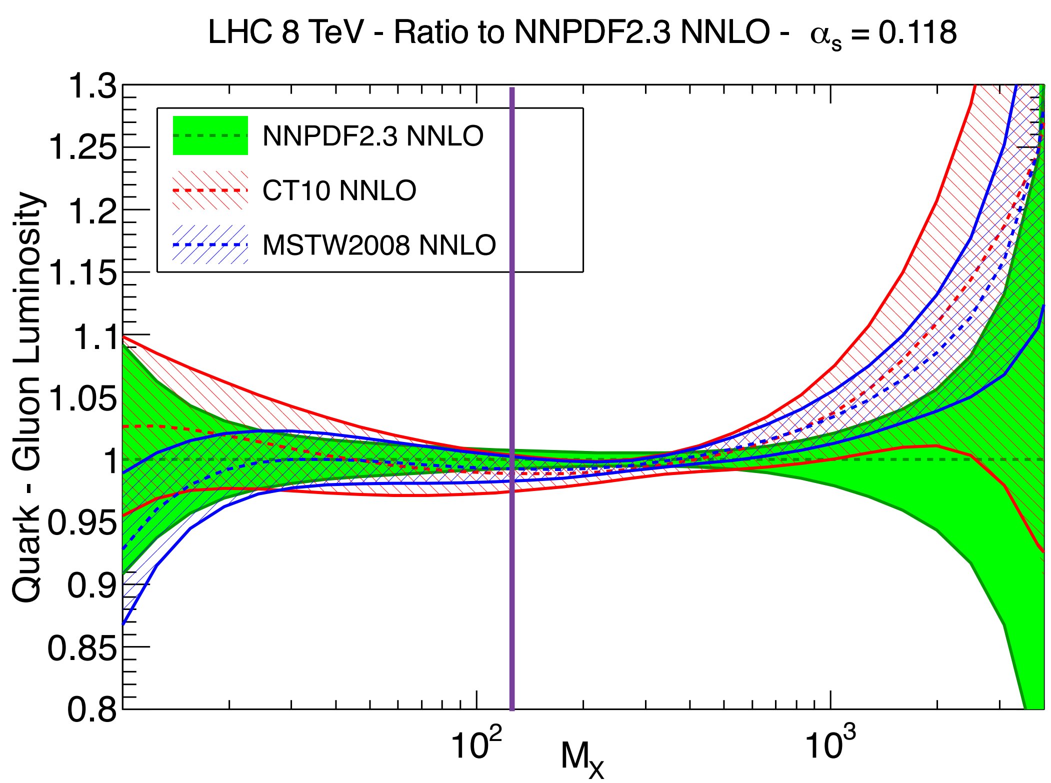
PDF Evolution



Fraction of proton momentum

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 ~ $M_H/\sqrt{s}$
- Some disagreement with CT10 $\mathcal{L}_{gg}$
- Remains true at 13 TeV
- Can be improved (in principle)

QCD Running Coupling

- Consider a dimensionless quantity R depending on a single hard scale Q
  - ★ Dependence on Q can only be via Q/μ
  - ★ But μ is arbitrary, so overall dependence on it must vanish

$$\Rightarrow \quad \mu^2 \frac{d}{d\mu^2} R(Q^2/\mu^2, \alpha_S) \equiv \left[\mu^2 \frac{\partial}{\partial \mu^2} + \mu^2 \frac{\partial \alpha_S}{\partial \mu^2} \frac{\partial}{\partial \alpha_S} \right] R = 0$$

- Define $t = \ln\left(\frac{Q^2}{\mu^2}\right), \quad \beta(\alpha_S) = \mu^2 \frac{\partial \alpha_S}{\partial \mu^2}$

$$\Rightarrow \quad \left[-\frac{\partial}{\partial t} + \beta(\alpha_S) \frac{\partial}{\partial \alpha_S} \right] R(e^t, \alpha_S) = 0$$

- Introduce $\alpha_S(Q^2)$ such that $t = \int_{\alpha_S}^{\alpha_S(Q^2)} \frac{dx}{\beta(x)}, \quad \alpha_S(\mu^2) \equiv \alpha_S$

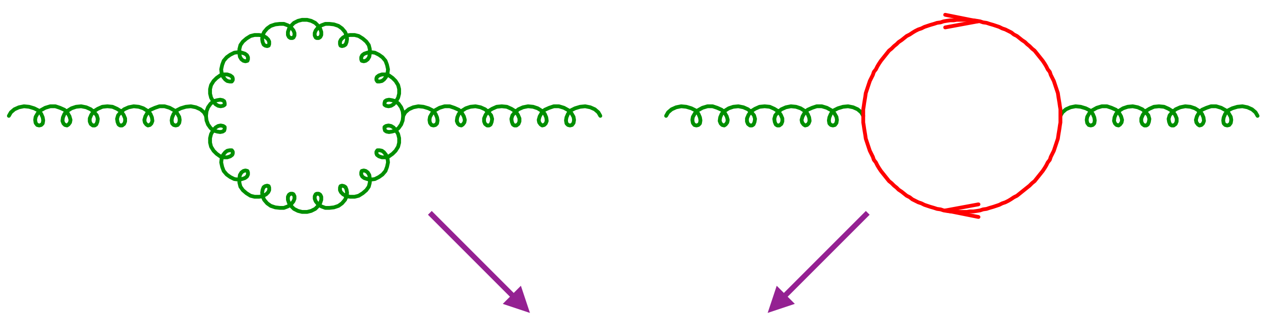
- Then solution is $R(1, \alpha_S(Q^2))$
  - ★ All scale dependence is absorbed in running coupling $\alpha_S(Q^2)$

QCD Running Coupling

$$\ln\left(\frac{Q^2}{\mu^2}\right) = \int_{\alpha_S(\mu^2)}^{\alpha_S(Q^2)} \frac{d\alpha_S}{\beta(\alpha_S)}, \quad \beta(\alpha_S) = -\alpha_S^2\,(\beta_0 + \beta_1\alpha_S + \ldots)$$

$$\Rightarrow \quad \ln\left(\frac{Q^2}{\mu^2}\right) = \frac{1}{\beta_0}\left[\frac{1}{\alpha_S(Q^2)} - \frac{1}{\alpha_S(\mu^2)}\right] + \ldots$$

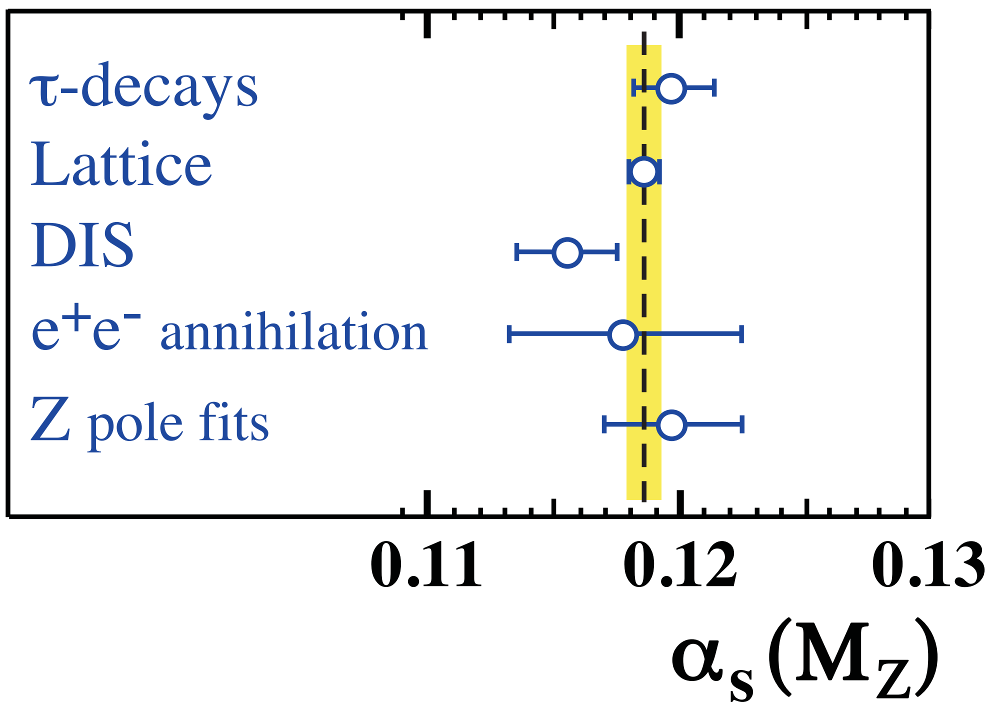
$$\Rightarrow \quad \alpha_S(Q^2) = \frac{\alpha_S(\mu^2)}{1 + \beta_0\,\alpha_S(\mu^2)\ln\left(Q^2/\mu^2\right)} + \ldots$$

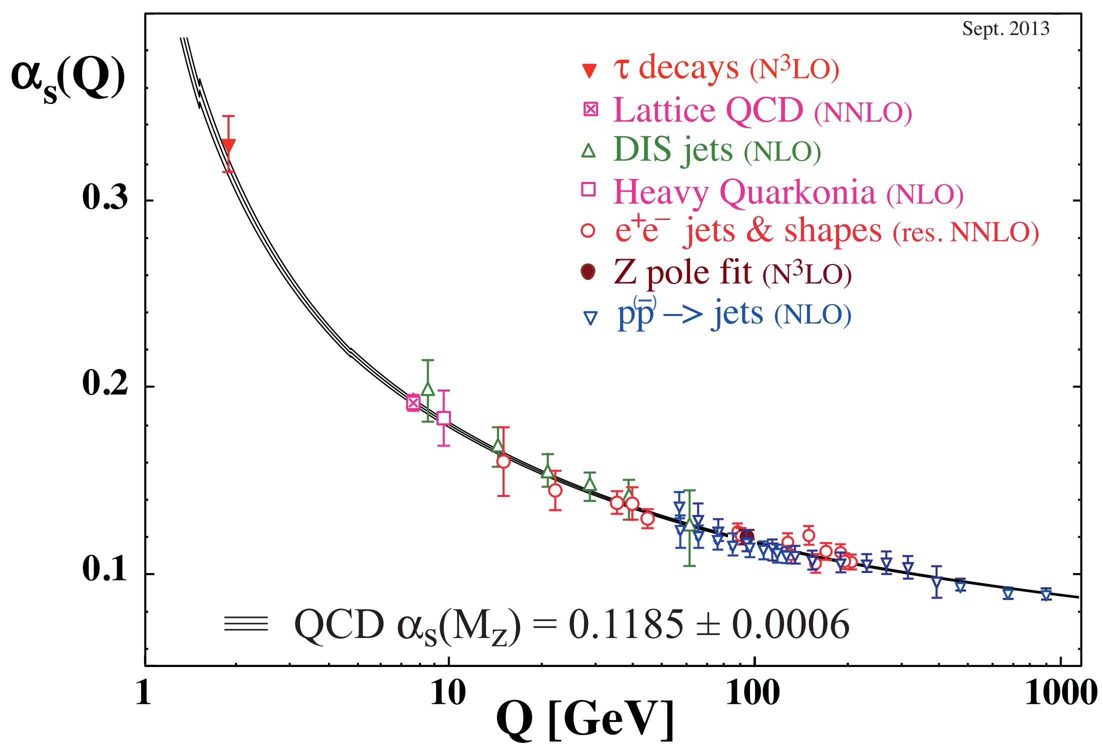


$$\beta_0 = (33 - 2n_f)/12\pi$$

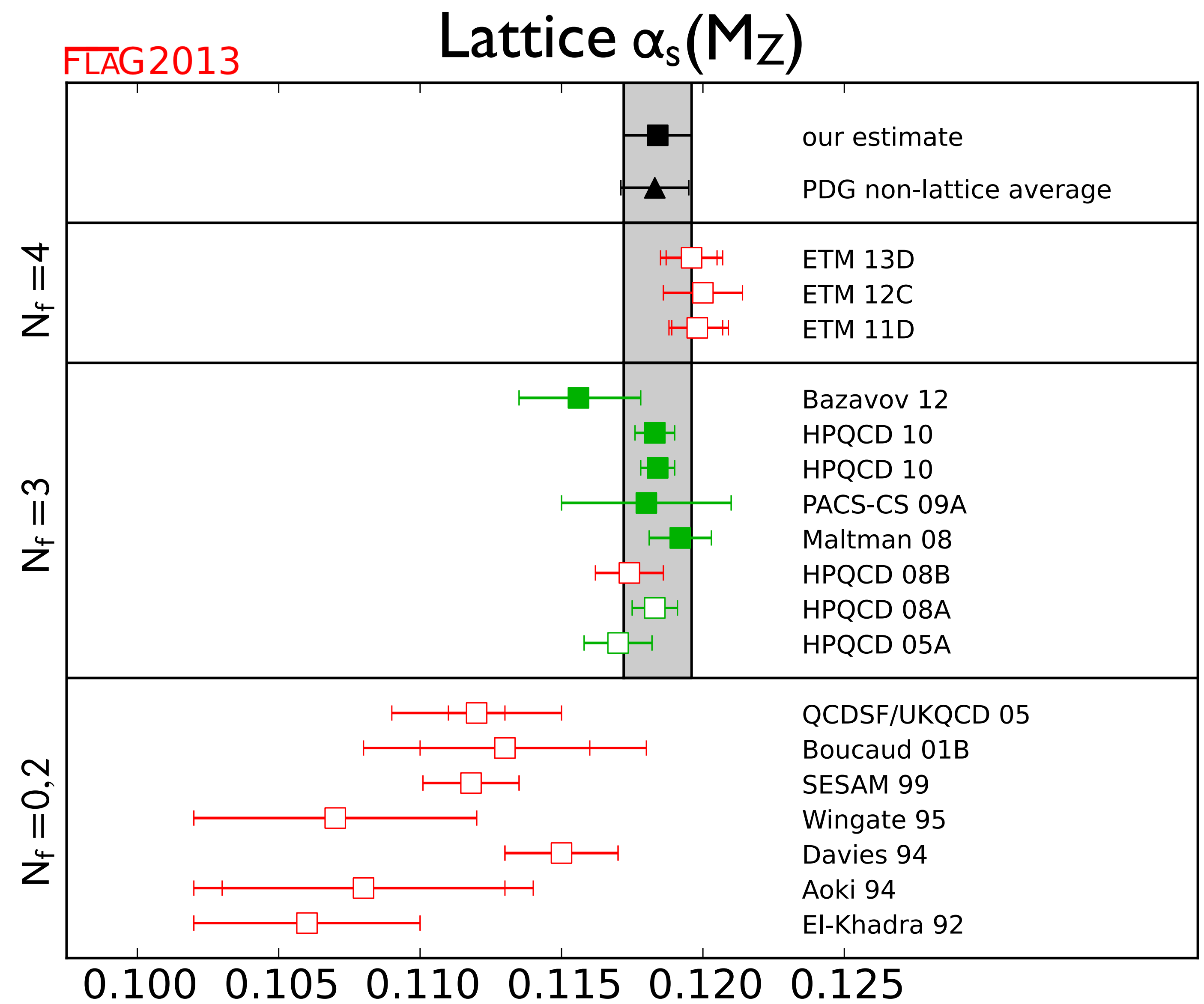
- $\beta_0>0$ means asymptotic freedom
- β-function known to 4 loops (β_3)

QCD Running Coupling





Bethke, Dissertori, Salam, RPP 2013



FLAG WG: Aoki et al., 1310.8555

$\alpha_S(M_Z)$=0.1185(5) [lattice]

$\alpha_S(M_Z)$=0.1183(12) [non-lattice]

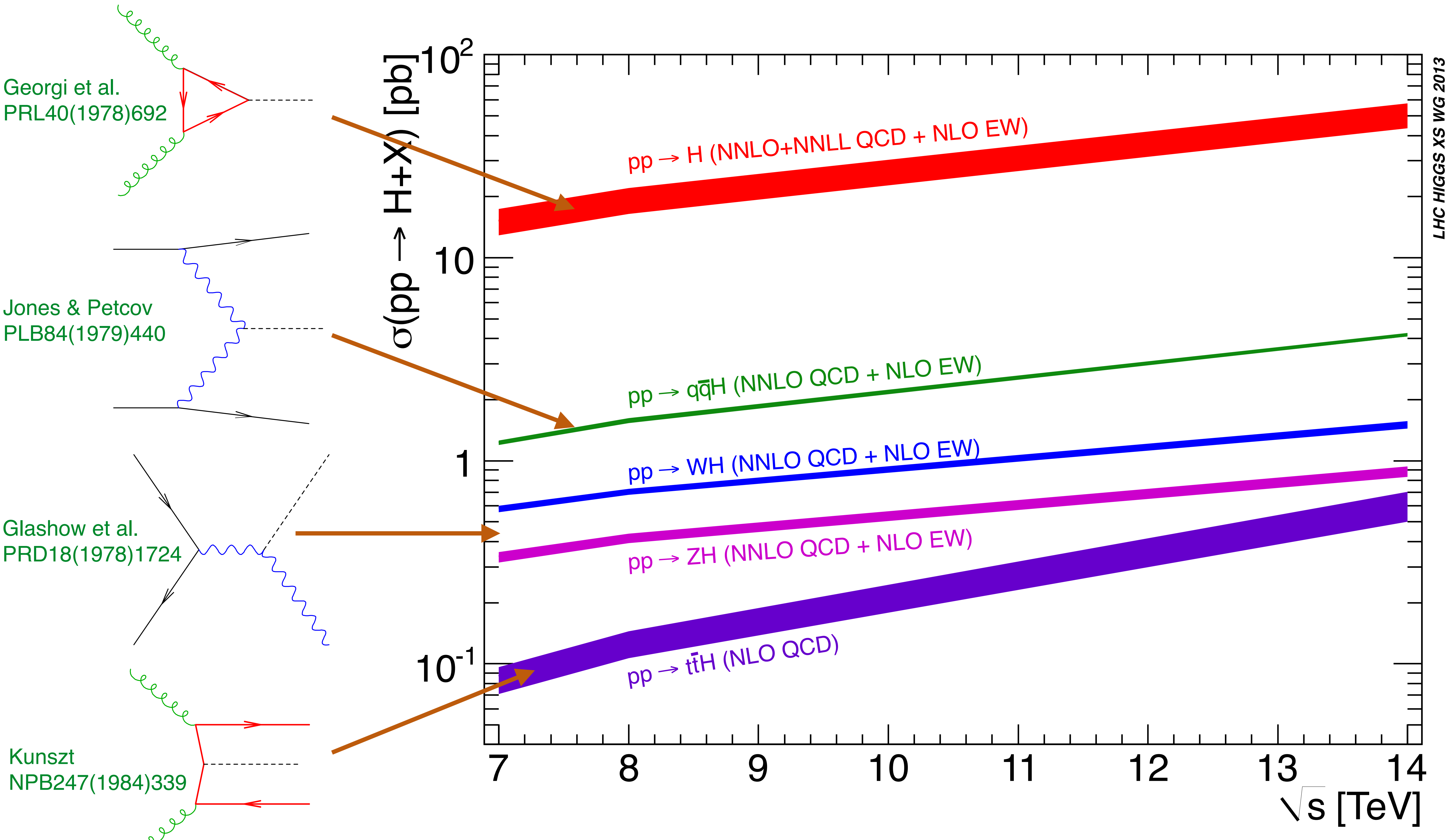
Lattice QCD Coupling

FLAG WG: Aoki et al., 1310.8555

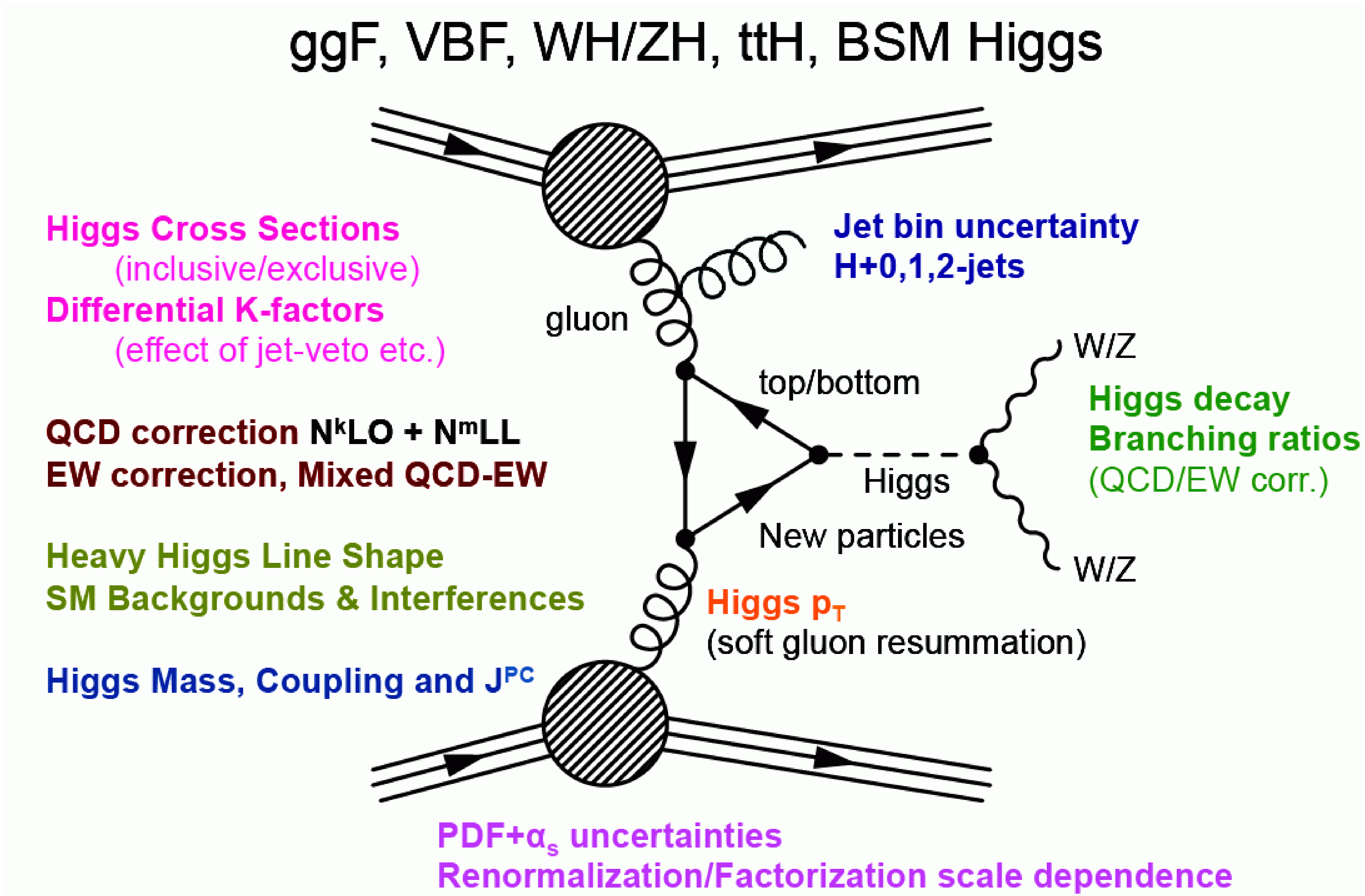
Collaboration	Ref.	N_f	publication status	renormalisation scale	perturbative behaviour	continuum extrapolation	$\alpha_{\overline{\rm MS}}(M_{\rm Z})$	Method	Table
ETM 13D	[544]	2+1+1	A	○	○	■	0.1196(4)(8)(16)	gluon-ghost vertex	37
ETM 12C	[545]	2+1+1	A	○	○	■	0.1200(14)	gluon-ghost vertex	37
ETM 11D	[546]	2+1+1	A	○	○	■	$0.1198(9)(5)(^{+0}_{-5})$	gluon-ghost vertex	37
Bazavov 12	[503]	2+1	A	○	○	○	$0.1156(^{+21}_{-22})$	Q-$\bar{Q}$ potential	33
HPQCD 10	[73]	2+1	A	○	○	○	0.1183(7)	current two points	36
HPQCD 10	[73]	2+1	A	○	★	★	0.1184(6)	Wilson loops	35
PACS-CS 09A	[486]	2+1	A	★	★	○	$0.118(3)^{\#}$	Schrödinger functional	32
Maltman 08	[517]	2+1	A	○	○	○	0.1192(11)	Wilson loops	35
HPQCD 08B	[85]	2+1	A	■	■	■	0.1174(12)	current two points	36
HPQCD 08A	[514]	2+1	A	○	★	★	0.1183(8)	Wilson loops	35
HPQCD 05A	[513]	2+1	A	○	○	○	0.1170(12)	Wilson loops	35
QCDSF/UKQCD 05	[518]	$0, 2 \to 3$	A	★	■	★	0.112(1)(2)	Wilson loops	35
Boucaud 01B	[539]	$2 \to 3$	A	○	○	■	0.113(3)(4)	gluon-ghost vertex	37
SESAM 99	[519]	$0, 2 \to 3$	A	★	■	■	0.1118(17)	Wilson loops	35
Wingate 95	[520]	$0, 2 \to 3$	A	★	■	■	0.107(5)	Wilson loops	35
Davies 94	[521]	$0, 2 \to 3$	A	★	■	■	0.115(2)	Wilson loops	35
Aoki 94	[522]	$2 \to 3$	A	★	■	■	0.108(5)(4)	Wilson loops	35
El-Khadra 92	[523]	$0 \to 3$	A	★	○	○	0.106(4)	Wilson loops	35

QCD and the Higgs Boson

Higgs production cross sections



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



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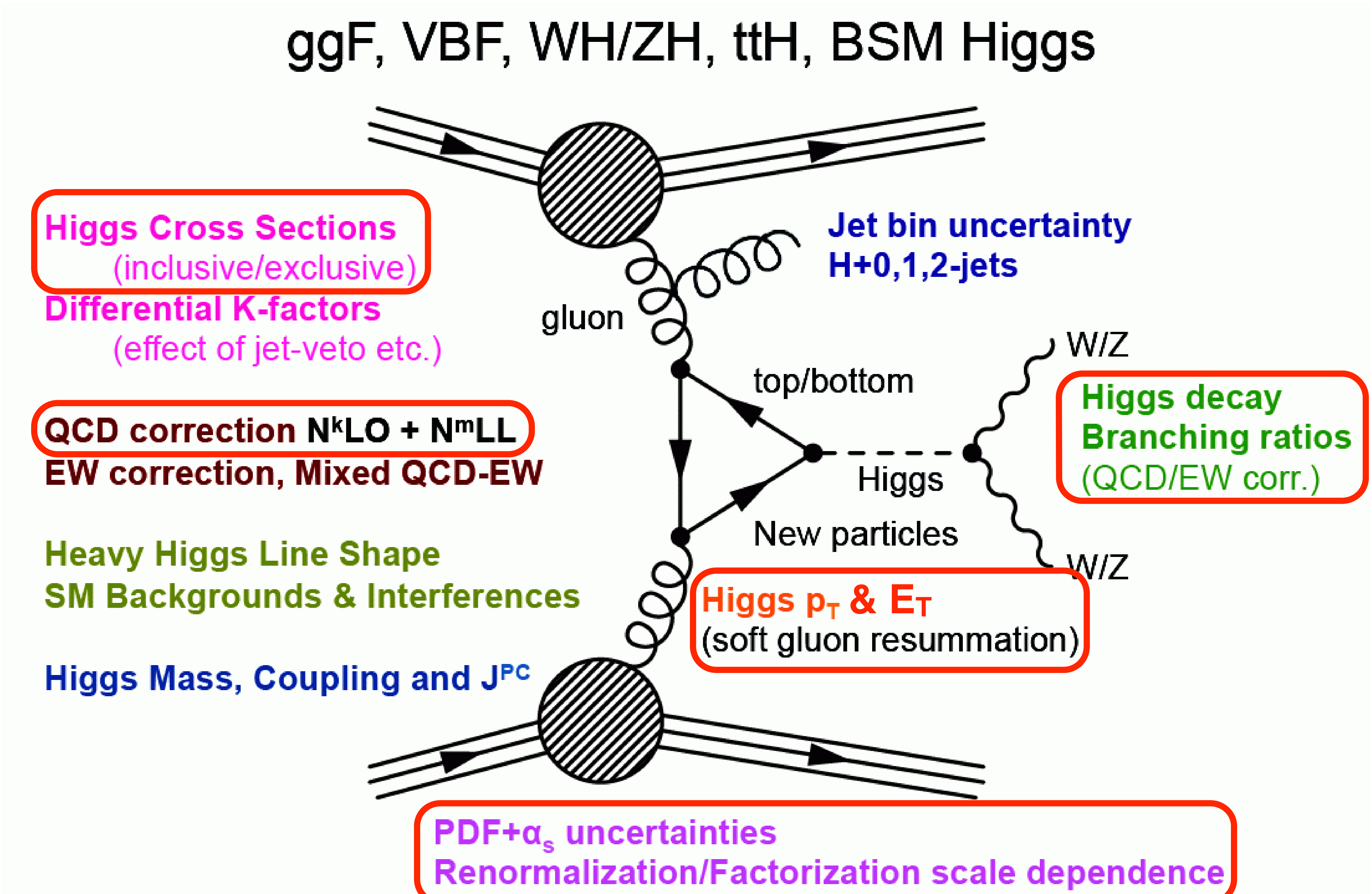

LHC Higgs Cross Section Working Group

CERN-2011-002
17 February 2011

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2011

CERN-2012-002
15 January 2012

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
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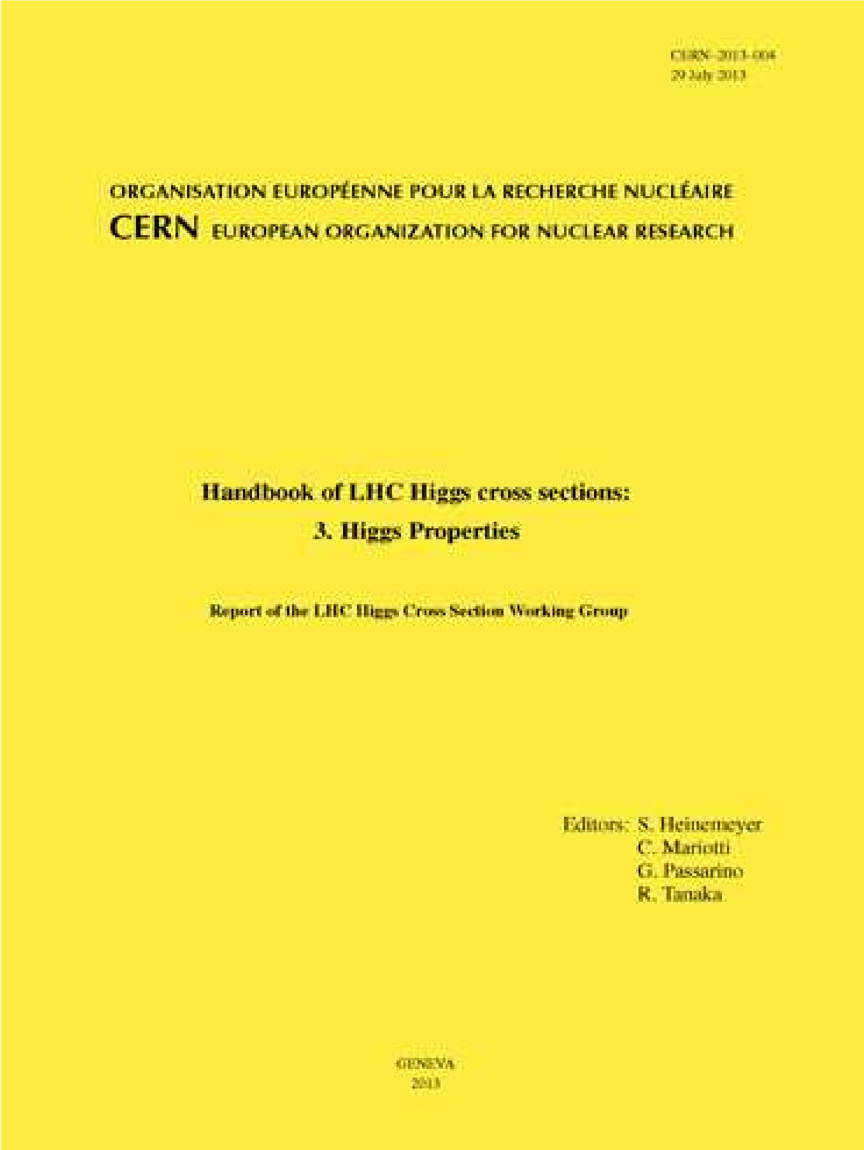
Handbook of LHC Higgs cross sections:
2. Differential Distributions

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2012



CERN-2013-004
29 July 2013

ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
3. Higgs Properties

Report of the LHC Higgs Cross Section Working Group

Editors: S. Heinemeyer
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2013

arXiv:1101.0593, 1201.3084, 1307.1347

Higgs Production Cross Section

Inclusive (QCD) Cross Section

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

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.

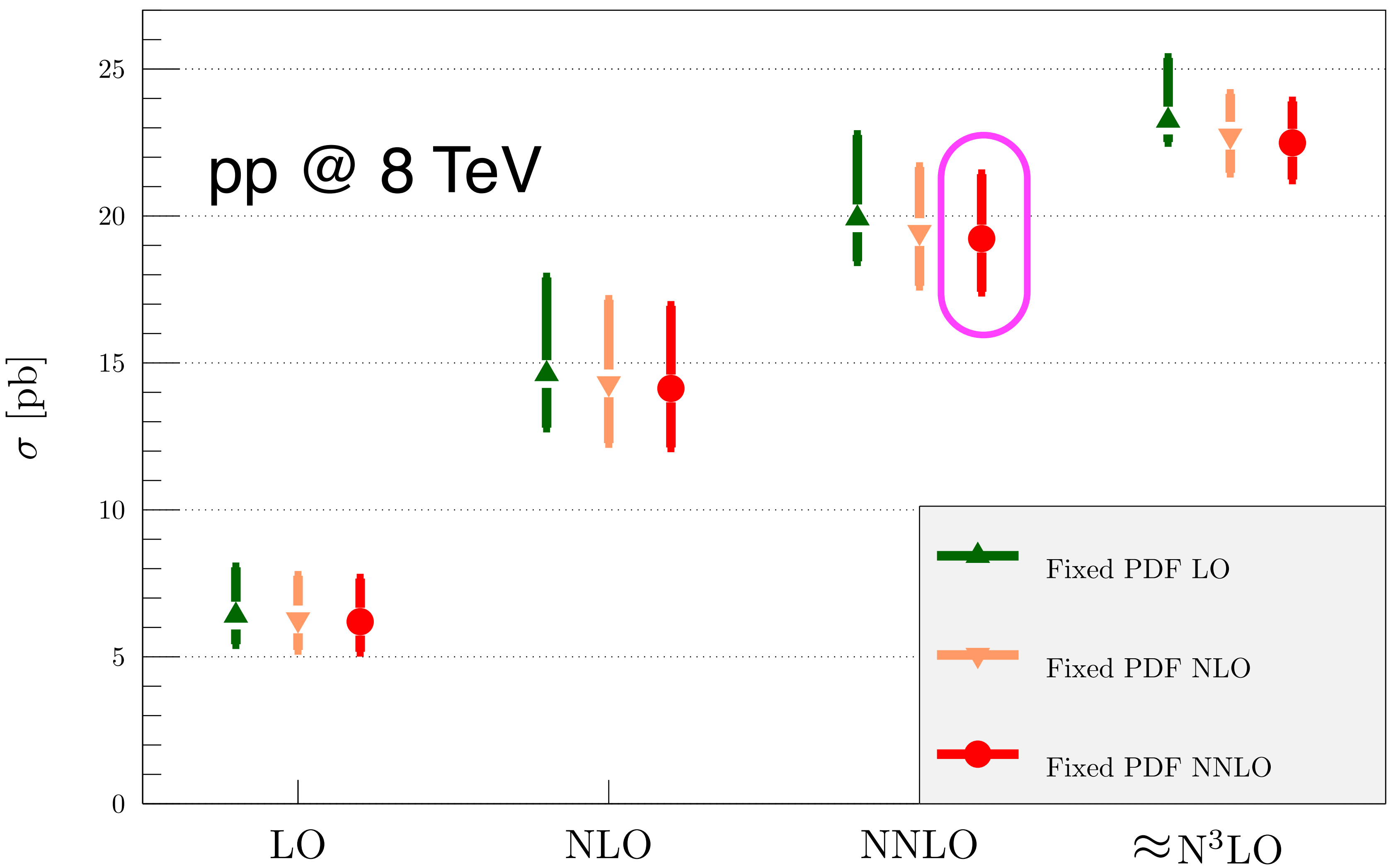
HXSWG vol.3

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

Inclusive (QCD) Cross Section

Ball et al., 1303.3590 Forte, Isgro, Vita, 1312.6688

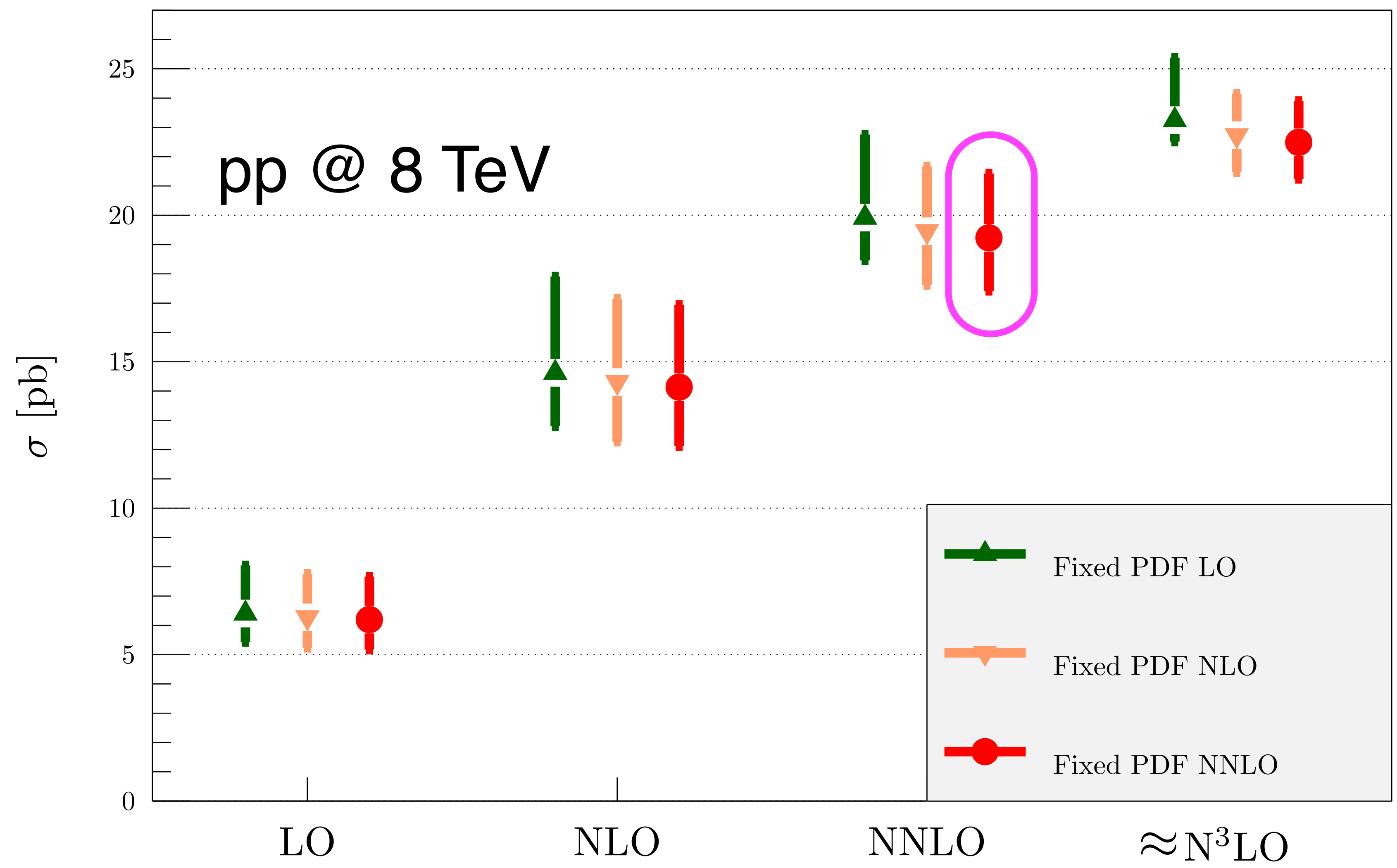


- Higher-order effects are larger than x2 scale variation estimates
- $\sigma_{\rm ggF} \approx \sigma_{\rm LO}\left[1+\kappa\{\lambda\alpha_{\rm S}+(\lambda\alpha_{\rm S})^2+(\lambda\alpha_{\rm S})^3+\cdots\}\right]$

$\lambda \approx 5.6$

Inclusive (QCD) Cross Section

Ball et al., 1303.3590 — Forte, Isgro, Vita, 1312.6688



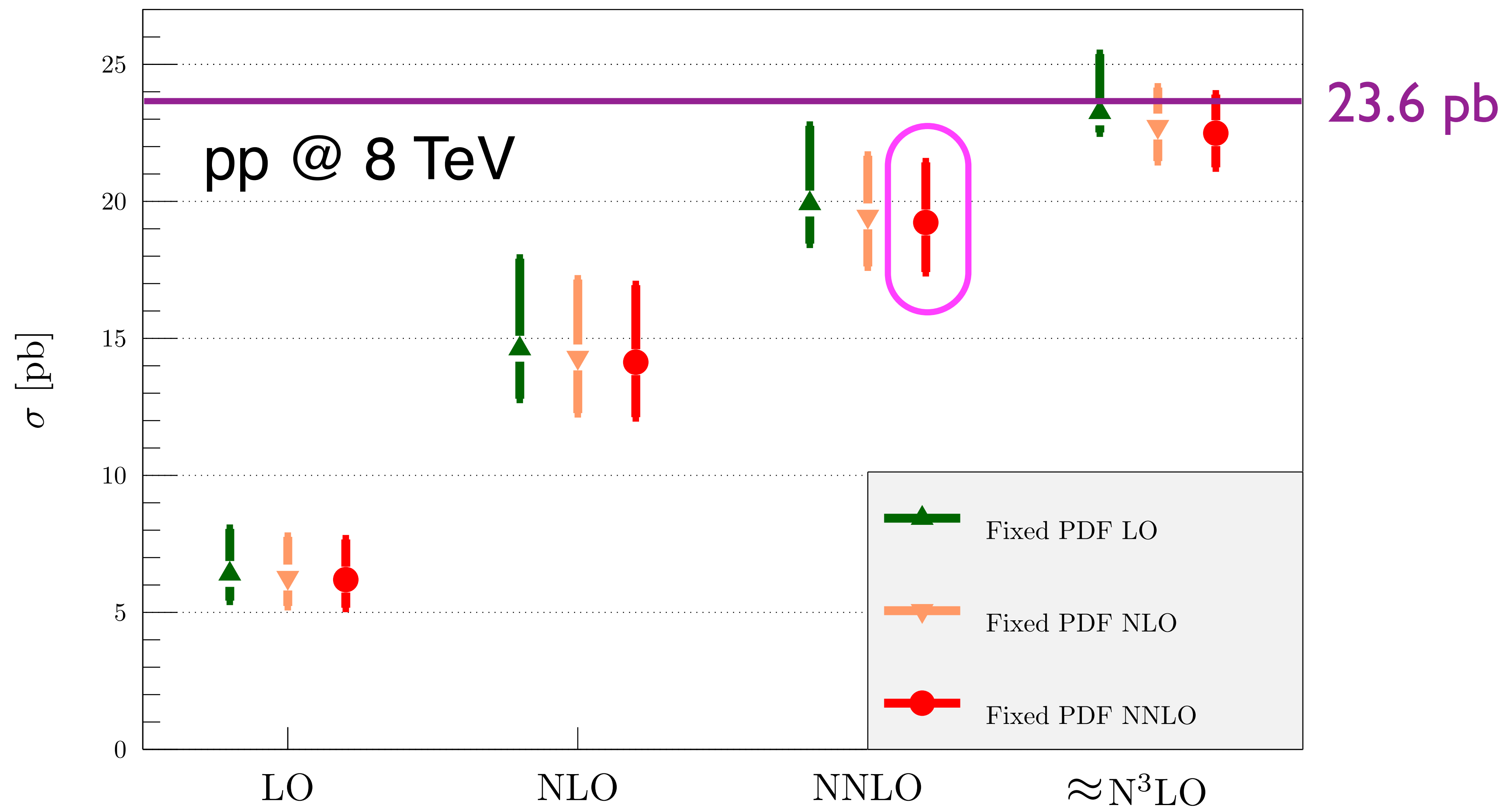
- Higher-order effects are larger than x2 scale variation estimates
- $\sigma_{\rm ggF} \approx \sigma_{\rm LO}\left[1+\kappa\{\lambda\alpha_{\rm S}+(\lambda\alpha_{\rm S})^2+(\lambda\alpha_{\rm S})^3+\cdots\}\right] \approx \sigma_{\rm LO}\left[1-\kappa+\frac{\kappa}{1-\lambda\alpha_{\rm S}}\right]$

$\lambda \approx 5.6$

Inclusive (QCD) Cross Section

Ball et al., 1303.3590

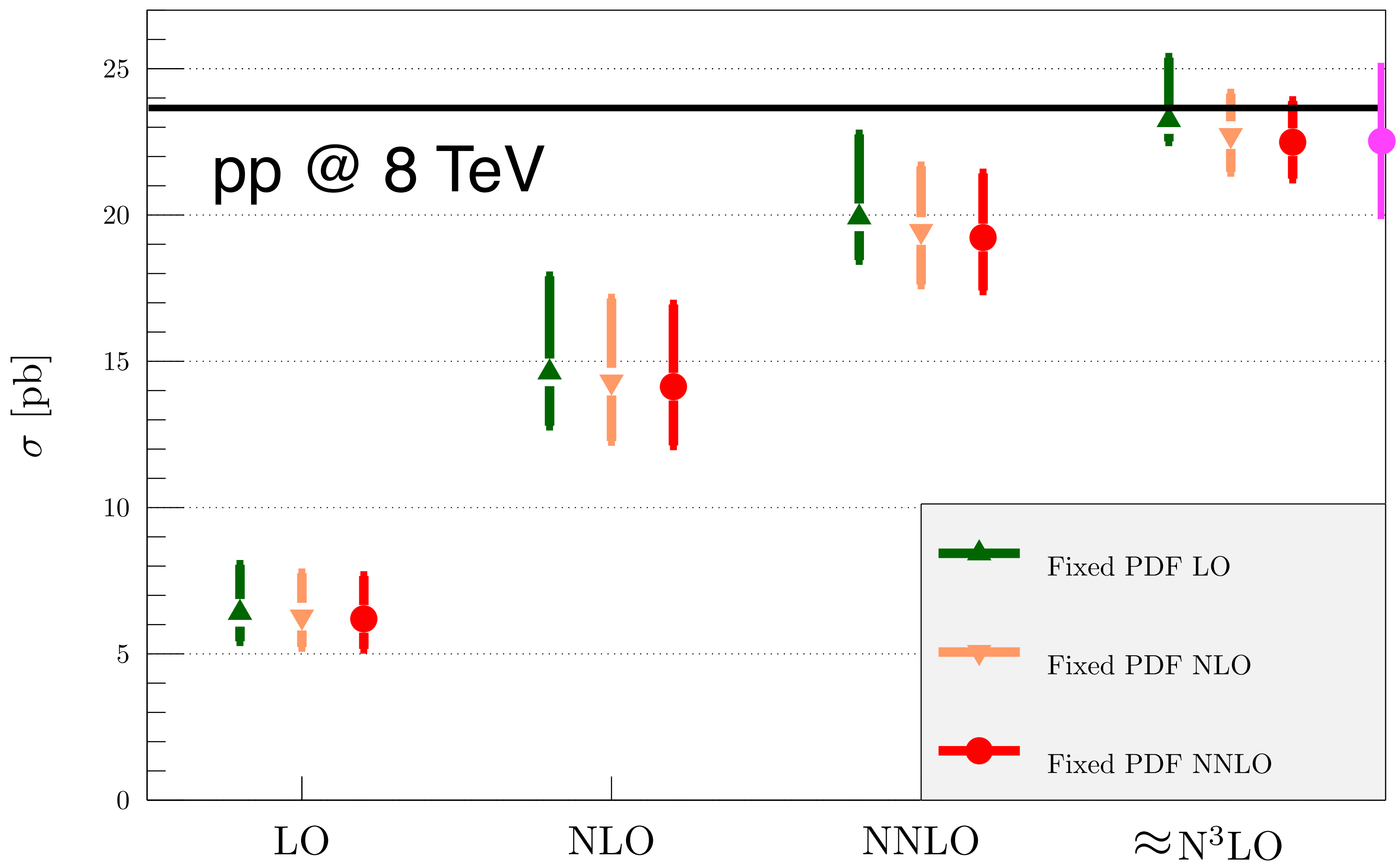
Forte, Isgro, Vita, 1312.6688



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

$\lambda \approx 5.6$

Inclusive (QCD) Cross Section



NNLO → σ_{ggF}(8 TeV) = 19.1± 2.0 pb

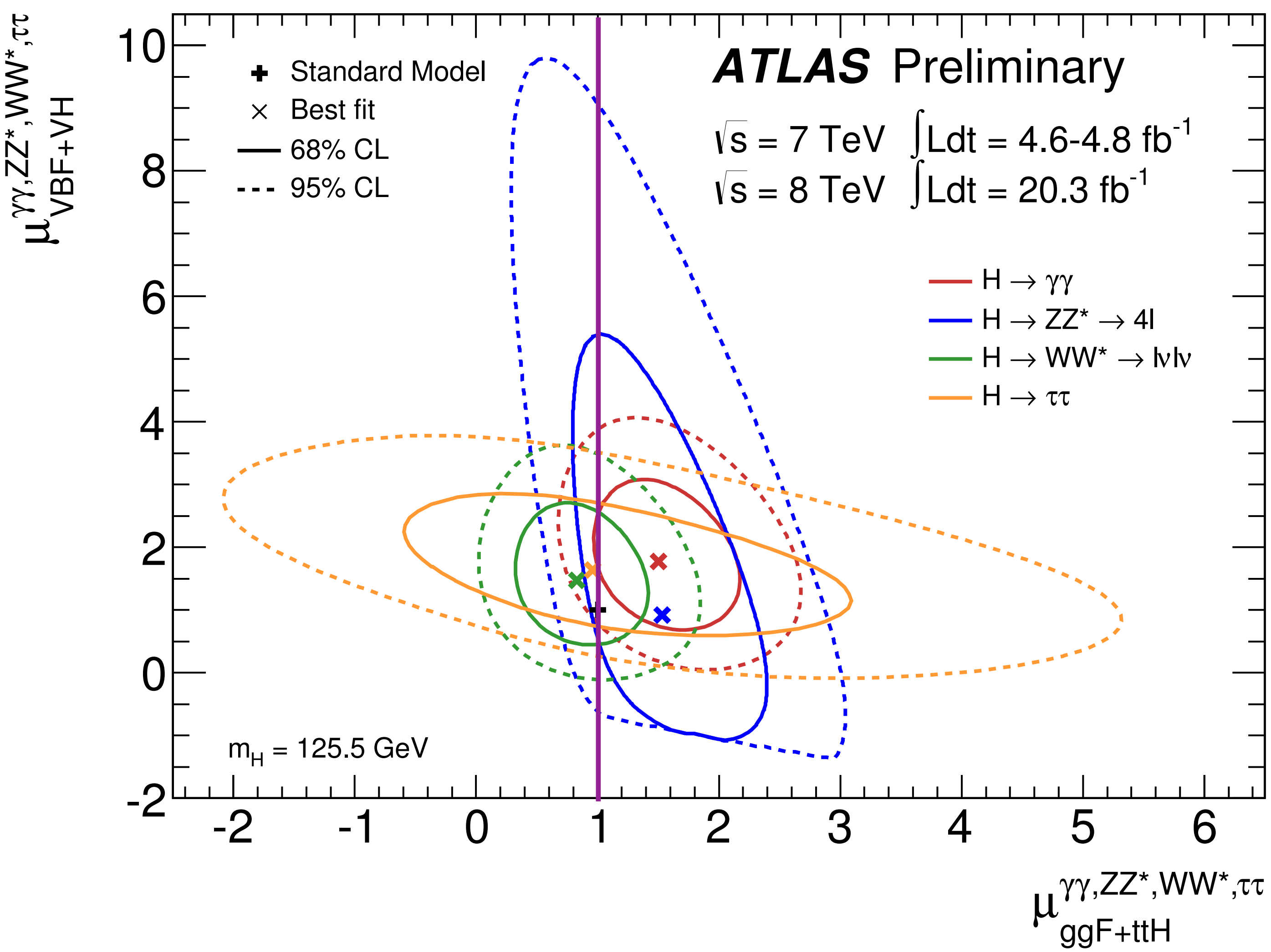
Series extrapolation: 23.6 ± ?? pb

David & Passarino, 1307.1843: 22.5 ± 2.6 pb

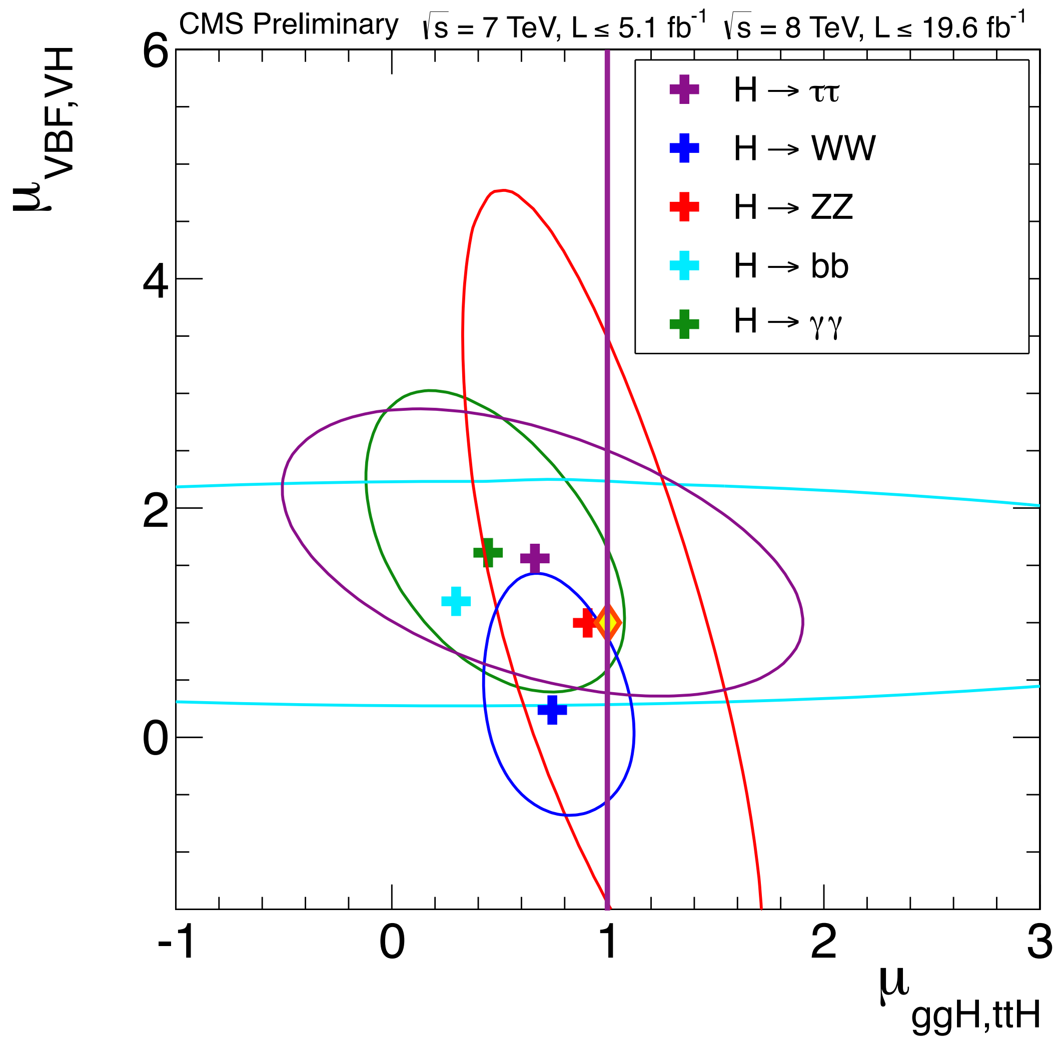
Full N^{3}LO coming soon (Anastasiou et al.)

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

$\sqrt{s}$ = 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

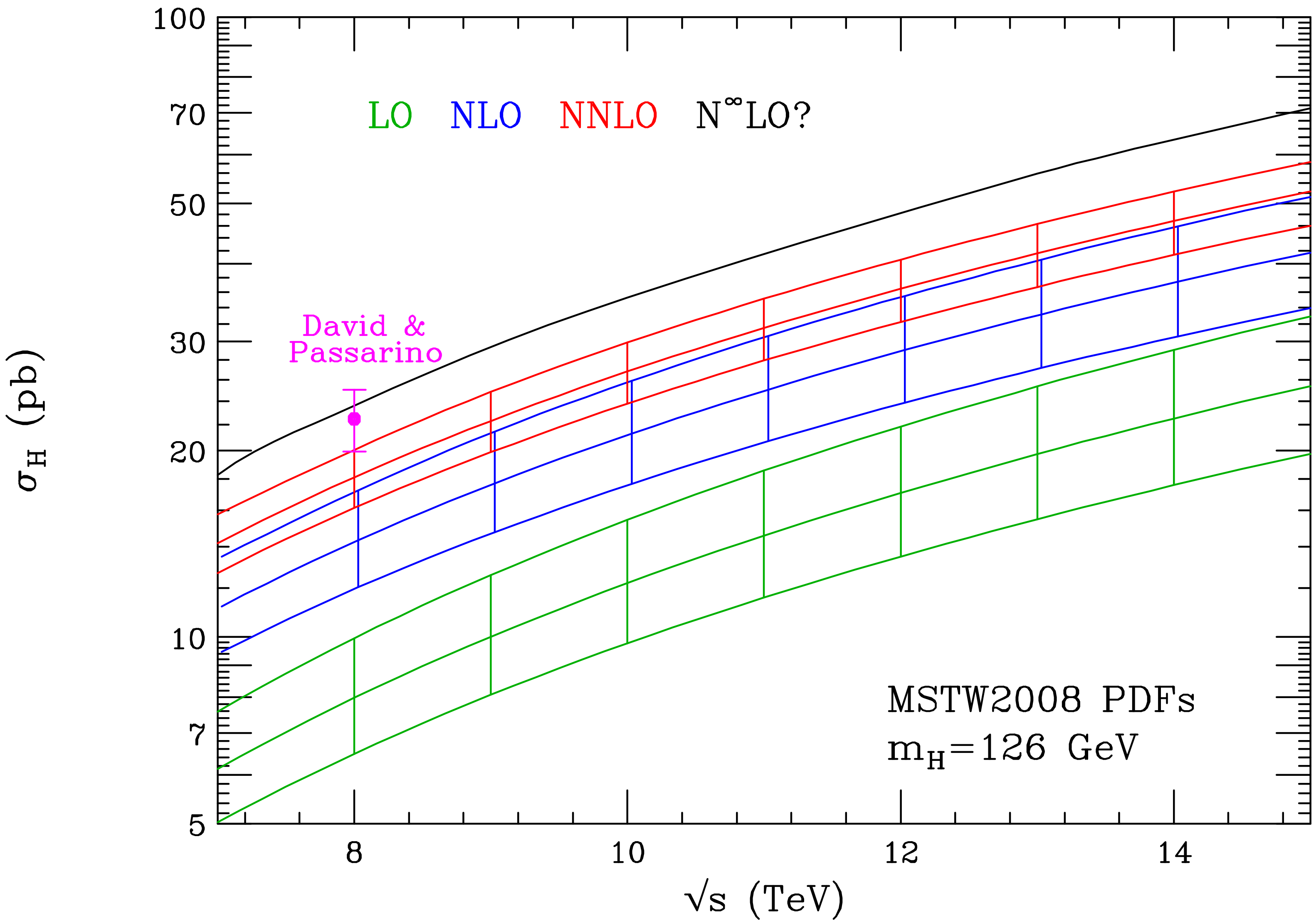
VBF Process

- 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



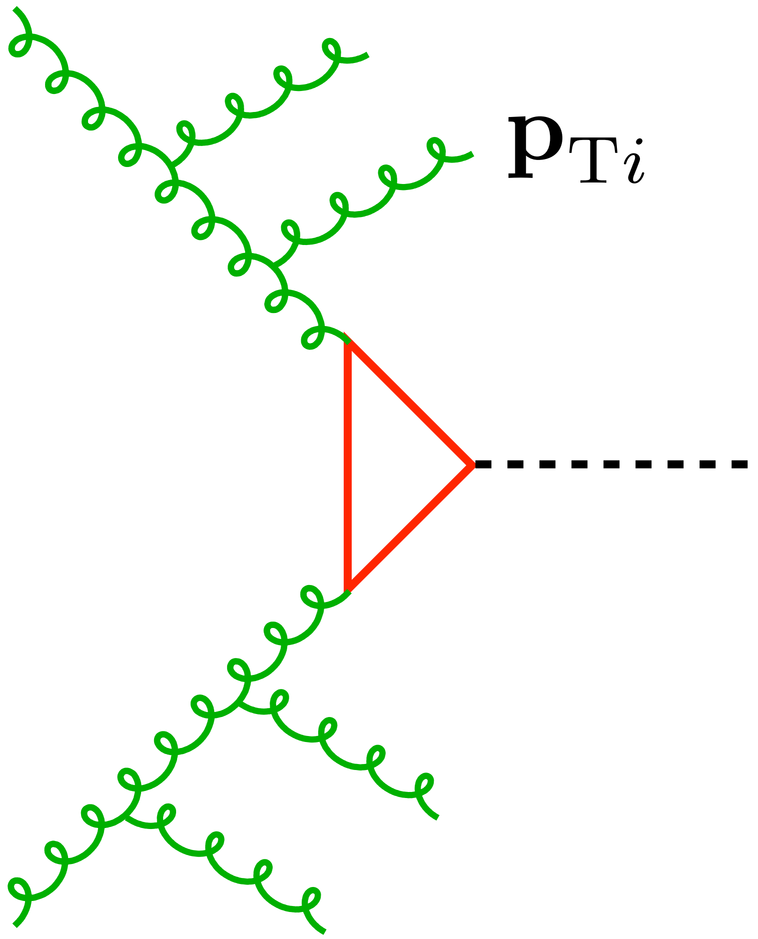
NNLO → σ_{ggF}(13 TeV) = 43.3 ± 4.3 pb

Series extrapolation: σ_{ggF}(13 TeV) = 55.9 ± ?? pb

My best guess: σ_{ggF}(13 TeV) = 53 ± 8 pb

Higgs Differential Cross Sections

Higgs q_T & E_T



- Higgs transverse momentum

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

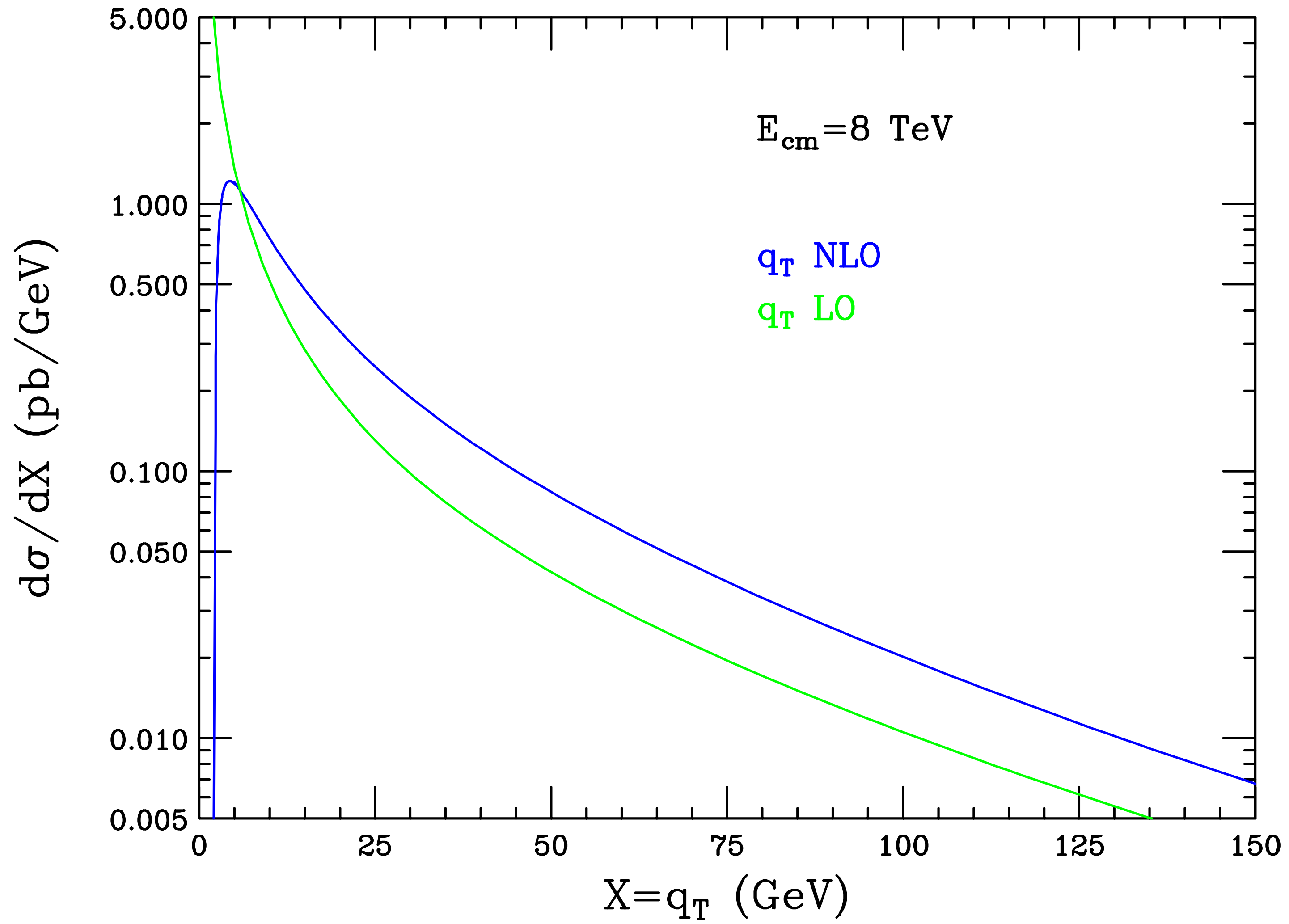
Bozzi et al. 0705.3887
Mantry & Petriello, 0911.4135
Catani & Grazzini, 1011.3918
de Florian et al. 1109.2109

- Radiated transverse energy

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

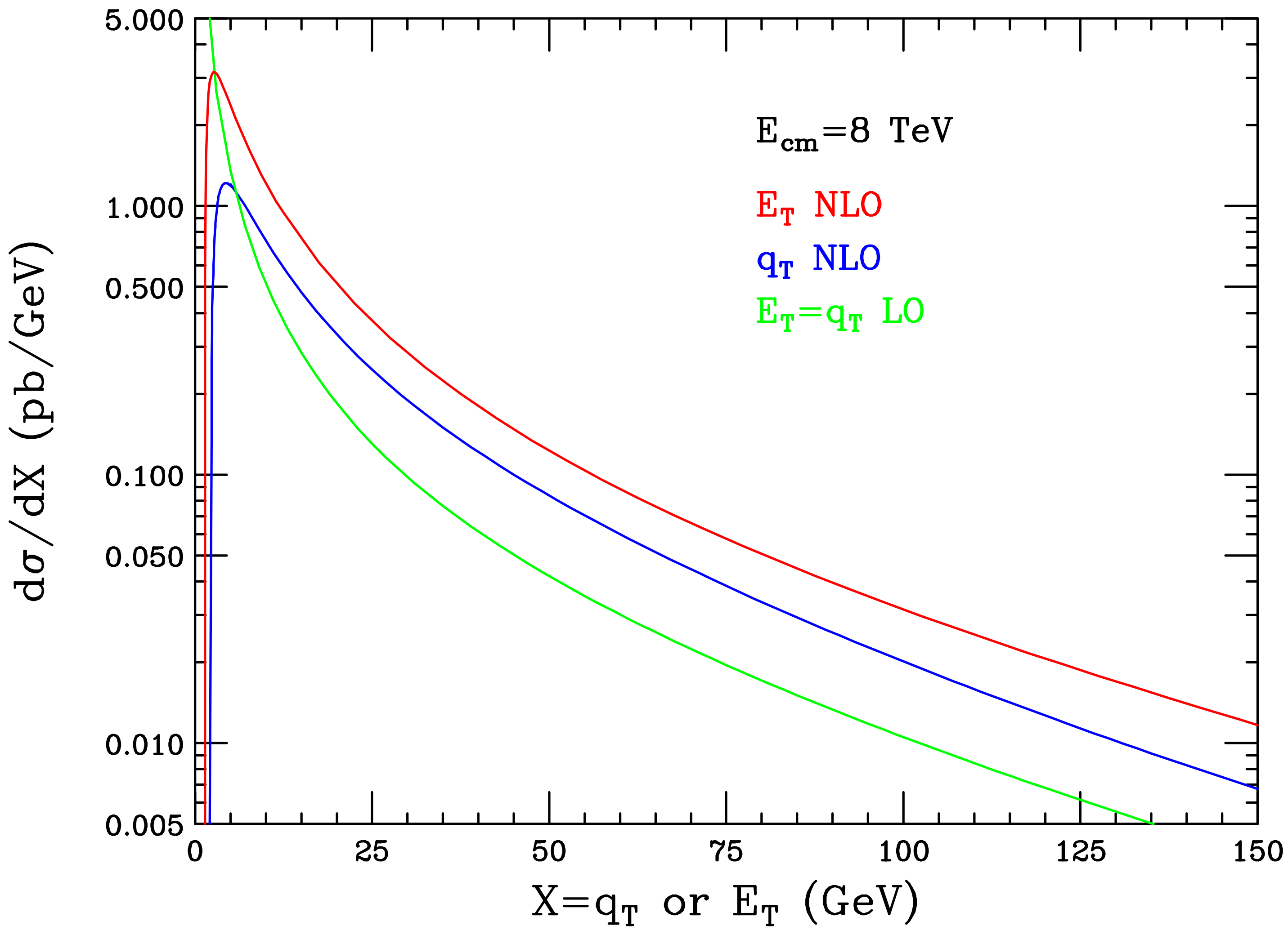
Papaefstathiou, Smillie, BW, 1002.4375
+Grazzini, 1403.3394

Higgs q_T (fixed order)



- $\text{(N)LO} \xrightarrow[q_T \to 0]{} (-)\infty$
- Large logs of m_H^2/q_T^2 need resummation

Higgs q_T & E_T (fixed order)



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

Resummation of Higgs q_T

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

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

Resummation of Higgs q_T

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

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

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

Resummation of Higgs q_T

$$d\sigma = \int dx_1 dx_2\, f_a(x_1,\mu) f_b(x_2,\mu)\, d\hat{\sigma}_{ab}(x_1 x_2 s, \mu, \ldots)$$

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

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

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

Resummation & matching of Higgs q_T

$$d\sigma = \int dx_1 dx_2\, f_a(x_1,\mu) f_b(x_2,\mu)\, d\hat{\sigma}_{ab}(x_1 x_2 s, \mu, \ldots)$$

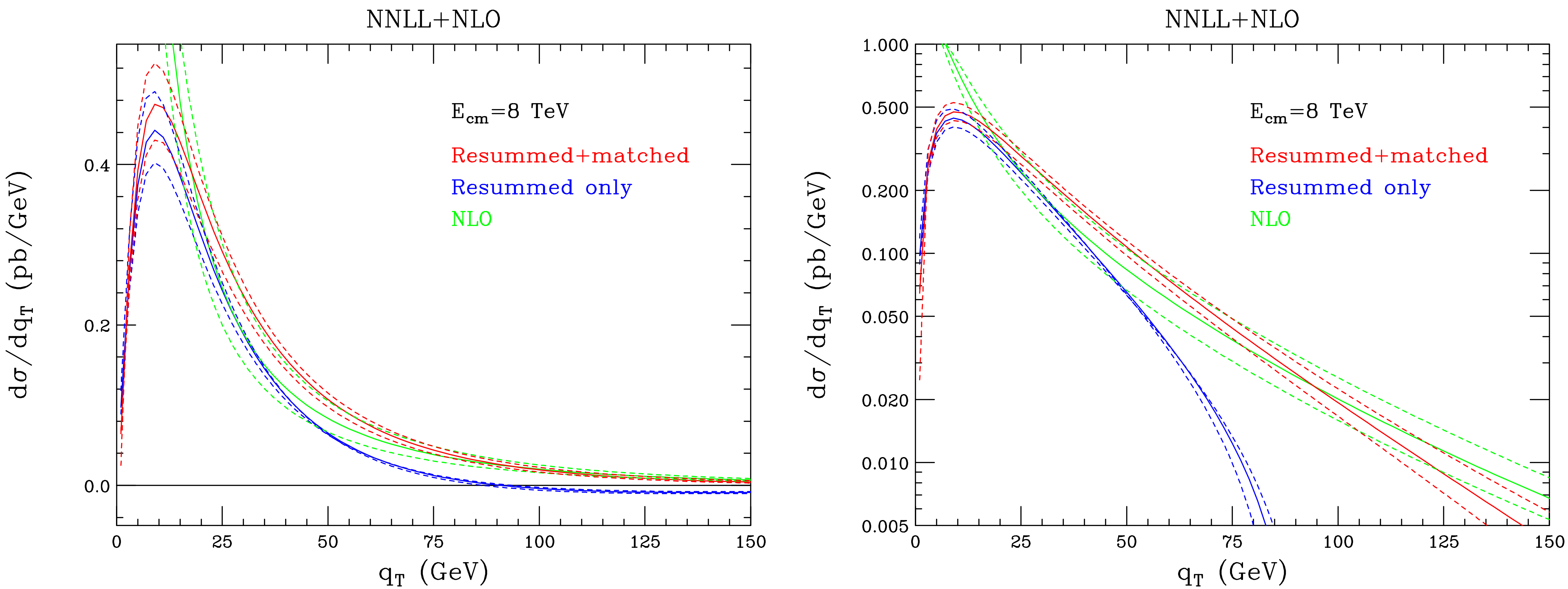
$$\frac{1}{\hat{\sigma}_{gg}} \frac{d^2\hat{\sigma}_{gg}}{d\,\mathbf{q}_T^2} \sim \delta^2(\mathbf{q}_T) + \alpha_S \int d^2\mathbf{p}_T \left[\frac{A_g}{\mathbf{p}_T^2} \ln\frac{m_H^2}{\mathbf{p}_T^2} + \frac{B_g}{\mathbf{p}_T^2}\right]_+ \delta^2(\mathbf{q}_T + \mathbf{p}_T) + \ldots$$

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

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

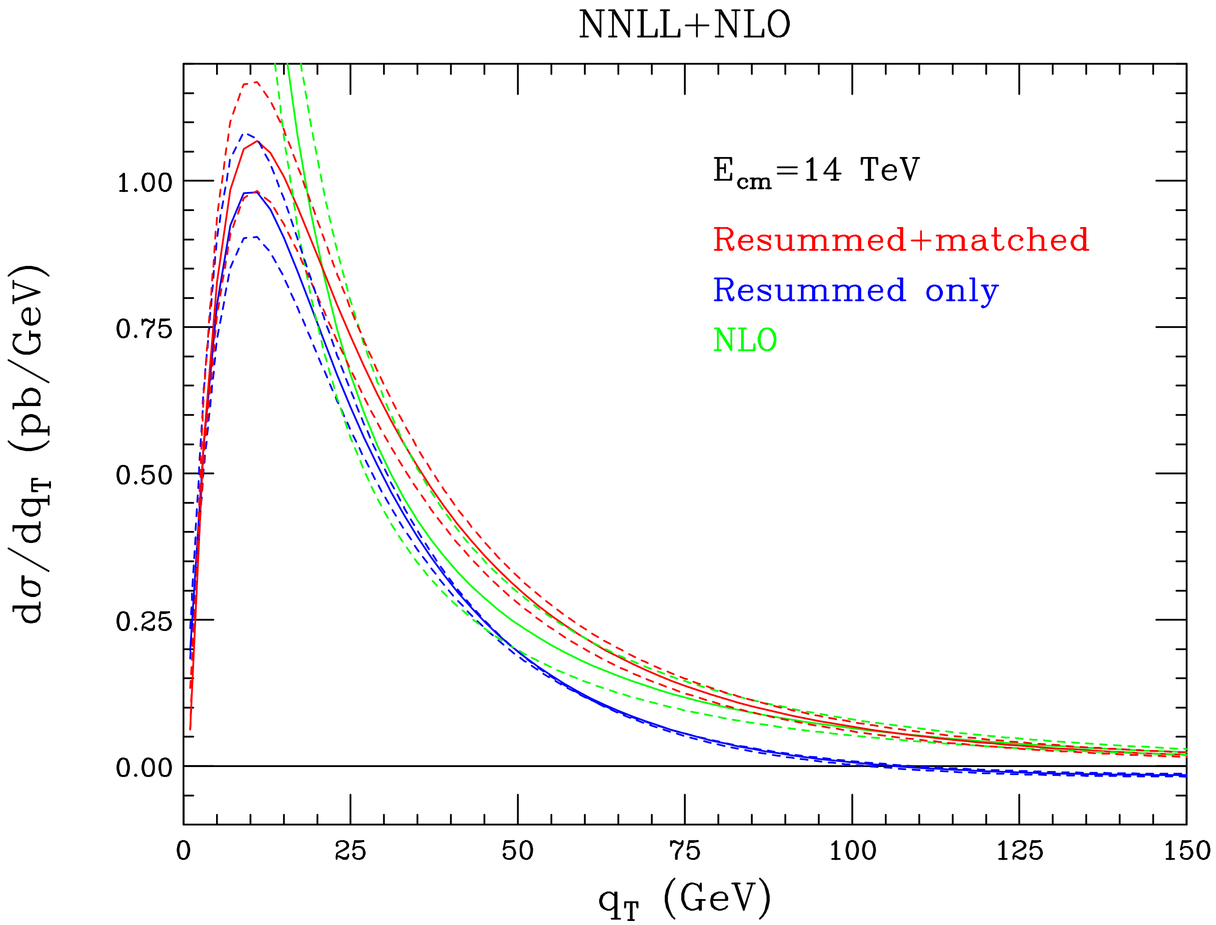
$$\frac{d\sigma}{dq_T} = \left[\frac{d\sigma}{dq_T}\right]_{\rm resum} - \left[\frac{d\sigma}{dq_T}\right]_{\rm resum,NLO} + \left[\frac{d\sigma}{dq_T}\right]_{\rm NLO}$$

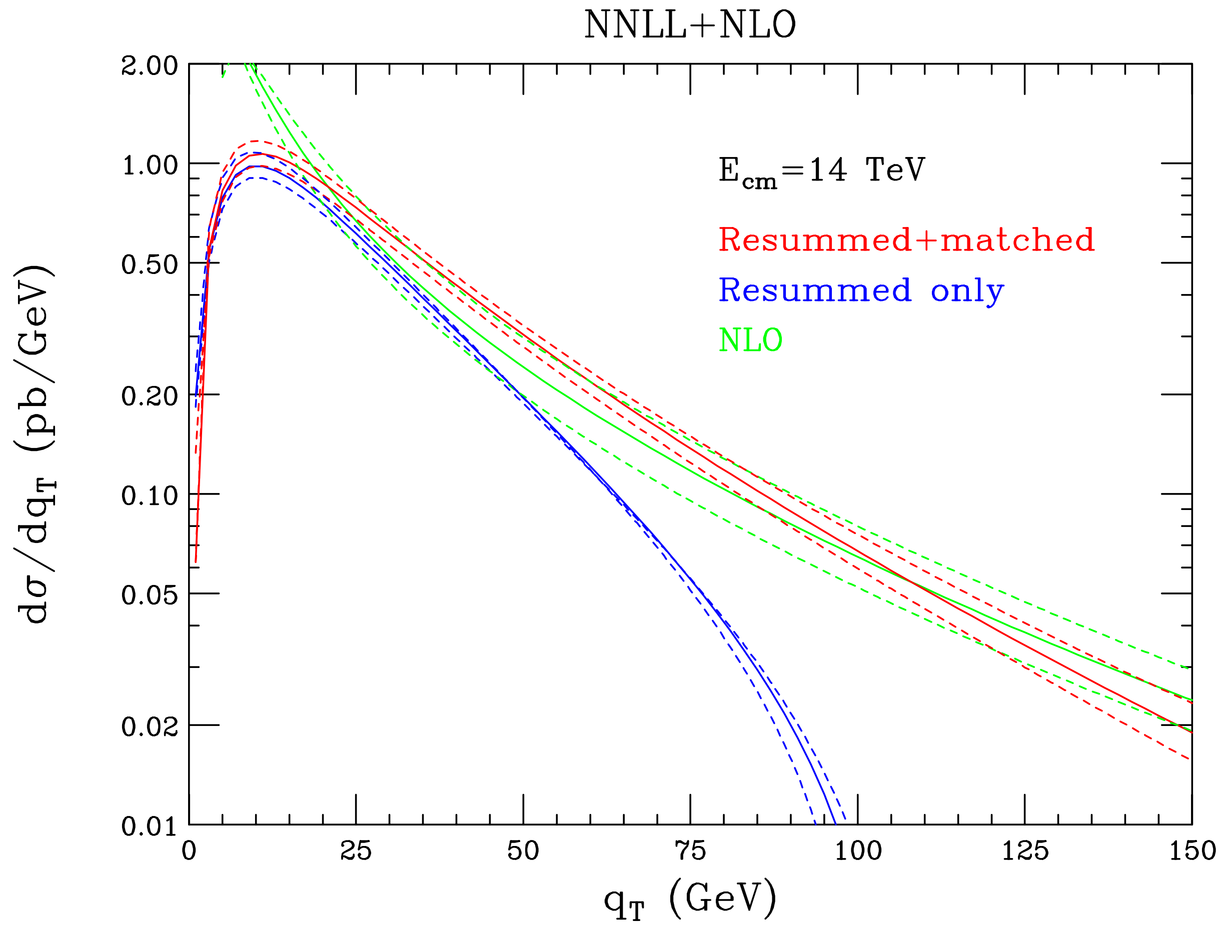
Higgs transverse momentum: 8 TeV



- 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: $\log(m_H^2/q_T^2)$~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

$$d\sigma = \int dx_1 dx_2\, f_a(x_1,\mu) f_b(x_2,\mu)\, d\hat{\sigma}_{ab}(x_1 x_2 s, \mu, \dots)$$

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

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

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

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

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

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 $E_T \lessgtr 0$

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 $E_T \lessgtr 0$
- For $E_T < 0$, can close τ−contour in lower half-plane

Resummation of Higgs E_T

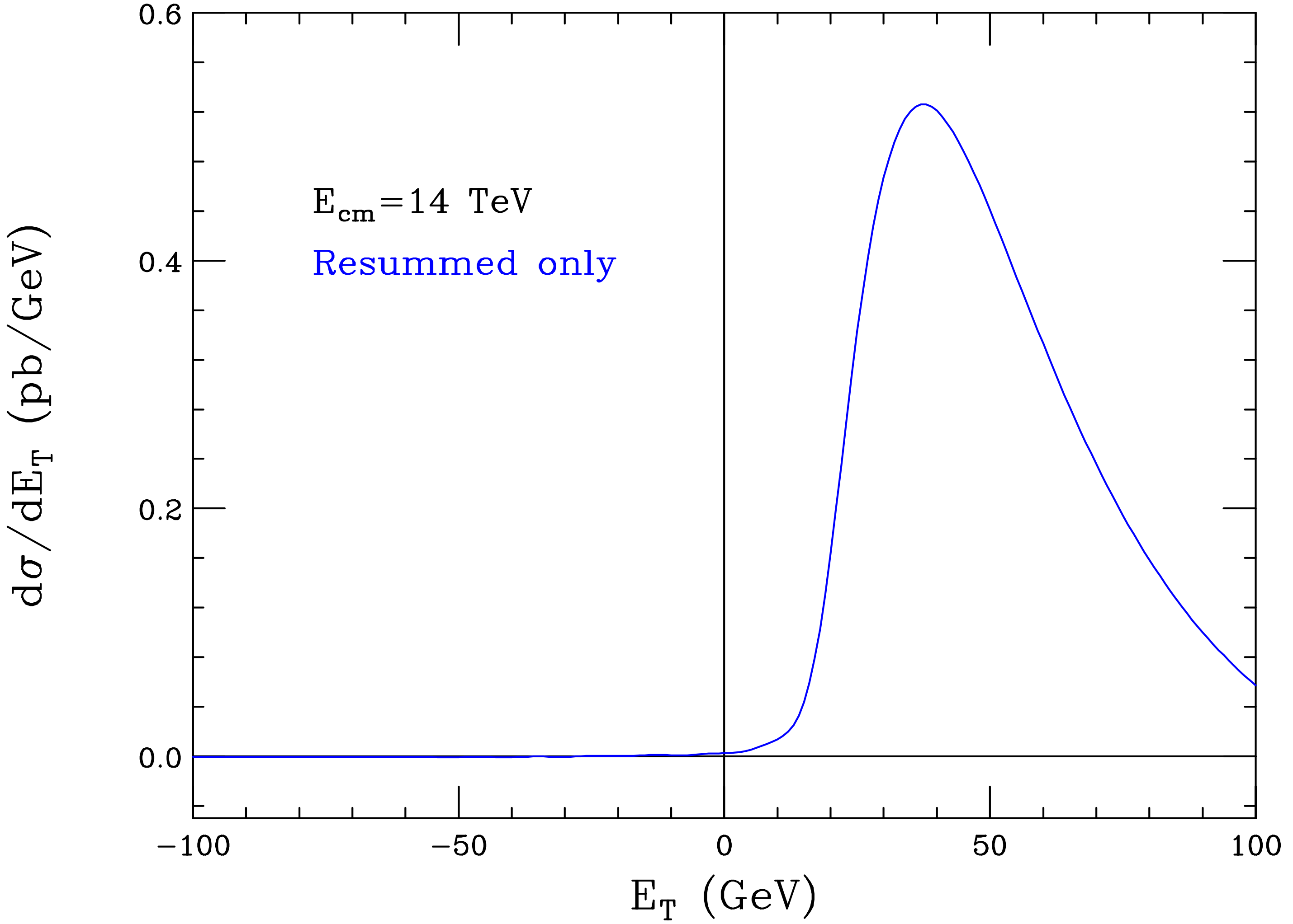
$$\frac{1}{\hat{\sigma}_{gg}}\frac{\mathrm{d}\hat{\sigma}_{gg}}{\mathrm{d}\,E_T} \sim \int_{-\infty}^{+\infty}\frac{\mathrm{d}\tau}{2\pi}\,\mathrm{e}^{i\tau E_T}\,\exp\left\{\alpha_{\mathrm{S}}\int \mathrm{d}^2\mathbf{p}_{\mathrm{T}}\left[\frac{A_g}{\mathbf{p}_{\mathrm{T}}^2}\ln\frac{m_H^2}{\mathbf{p}_{\mathrm{T}}^2}+\frac{B_g}{\mathbf{p}_{\mathrm{T}}^2}\right]\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

- Defined for $E_T \lessgtr 0$
- For $E_T < 0$, can close $\tau-$contour in lower half-plane
- No singularities in lower half-plane

Resummation of Higgs E_T

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

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



Resummation & matching of Higgs E_T

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

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

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

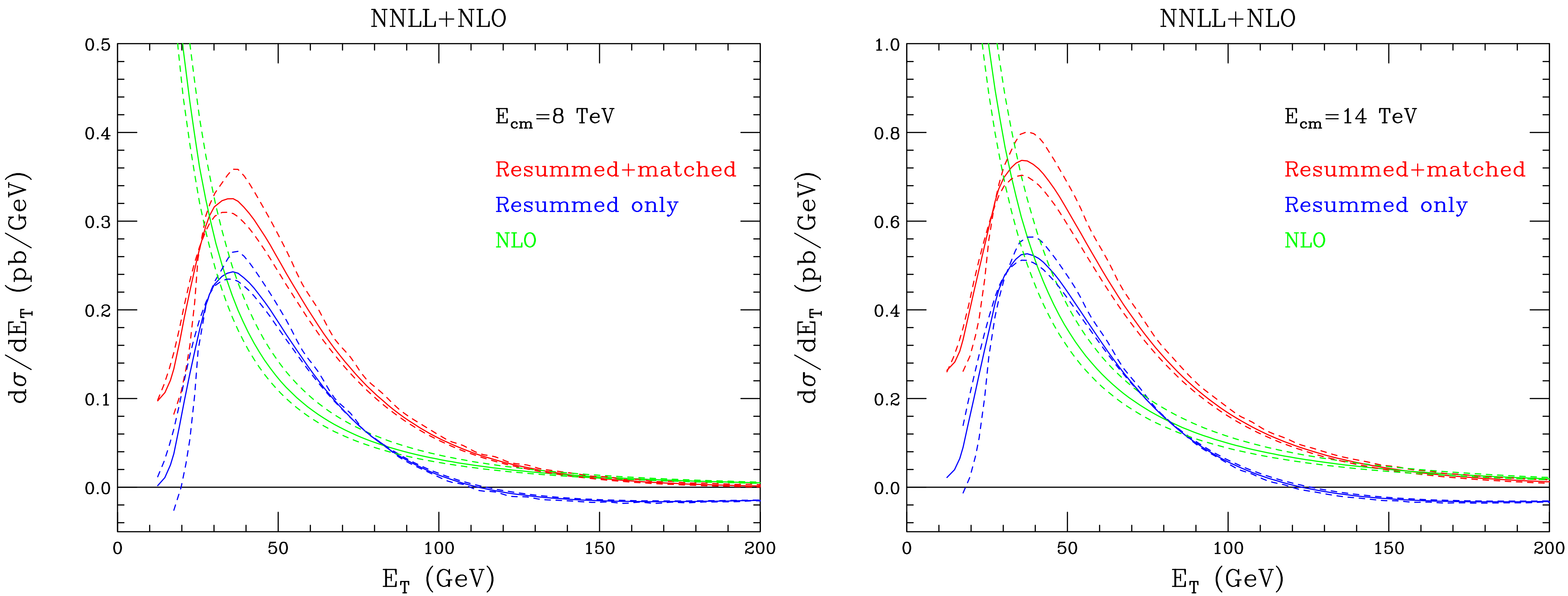
$$A_g(\alpha_{\rm S}) = \sum_{n=1}^{\infty}\left(\frac{\alpha_{\rm S}}{\pi}\right)^n A_g^{(n)}\;,$$

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

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

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

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…

Summary

- QCD factorization allows precise predictions for LHC
  - Scale dependence is a (rough) guide to precision
- Higgs ggF cross section at 13 TeV is still very uncertain
  - My estimate: σ_{ggF}(13 TeV) = 53 ± 11 pb
- Higgs transverse momentum resummed to NNLL+NLO
  - Peak q_T ~10 GeV, independent of energy
- Radiated transverse energy resummed to (N)NLL+NLO
  - Peak E_T ~35 GeV in associated transverse energy
  - Contribution from Underlying Event to be considered …