Università degli Studi di Milano

INFN Istituto Nazionale di Fisica Nucleare

Radiative corrections and Higgs boson studies

Alessandro Vicini

University of Milano, INFN Milano

St. Petersburg, August 31st 2015

The topics under discussion

total gluon fusion cross section

- fixed-order calculation → progress in the evaluation of multi-loop integrals
  critical issue: number of independent energy scales
- resummed results → progress in the reconstruction of analytical properties of the amplitudes
  interplay with (input from) fixed-order results
- PDFs → consistent sets that can be used with resummed partonic results
  avoid double counting in the prediction of the hadron-level xsec

given a residual scale uncertainty of 2-3% at N3LO,
which subdominant radiative effects are relevant at this level of accuracy ?

differential gluon fusion cross sections

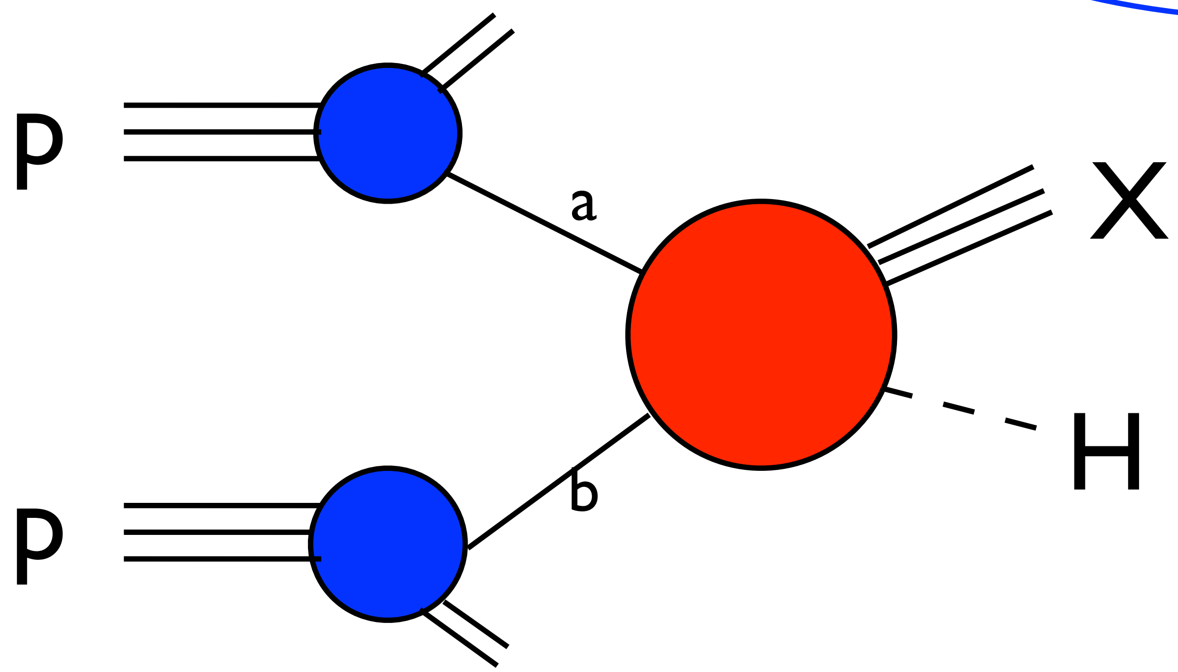
- matching → uncertainties associated to the combination in a single framework
  of all-orders and fixed-order results

  → higher accuracy in Shower Monte Carlo

  → relevance for precision Higgs physics and for BSM searches

The total ggF Higgs production cross section: fixed-order results

$$\sigma(P_1,P_2;m_H)=\sum_{a,b}\int_0^1 dx_1 dx_2\, f_{h_1,a}(x_1,M_F) f_{h_2,b}(x_2,M_F)\, \hat\sigma_{ab}(x_1P_1,x_2P_2,\alpha_s(\mu),M_F)$$



$$\hat\sigma_{ab}=\hat\sigma_0\left[\delta_{ag}\delta_{bg}\delta(1-z)+\sum_{l=1}^{\infty}\left(\frac{\alpha_s(\mu_R)}{\pi}\right)^l\hat\sigma_{ab}^{(l,QCD)}+\sum_{k=1}^{\infty}\left(\frac{\alpha(m_Z)}{2\pi}\right)^k\hat\sigma_{ab}^{(k,EW)}+mixed\ QCD\times EW\right]$$

LO exact Georgi Glashow Machacek Nanopoulos 1978

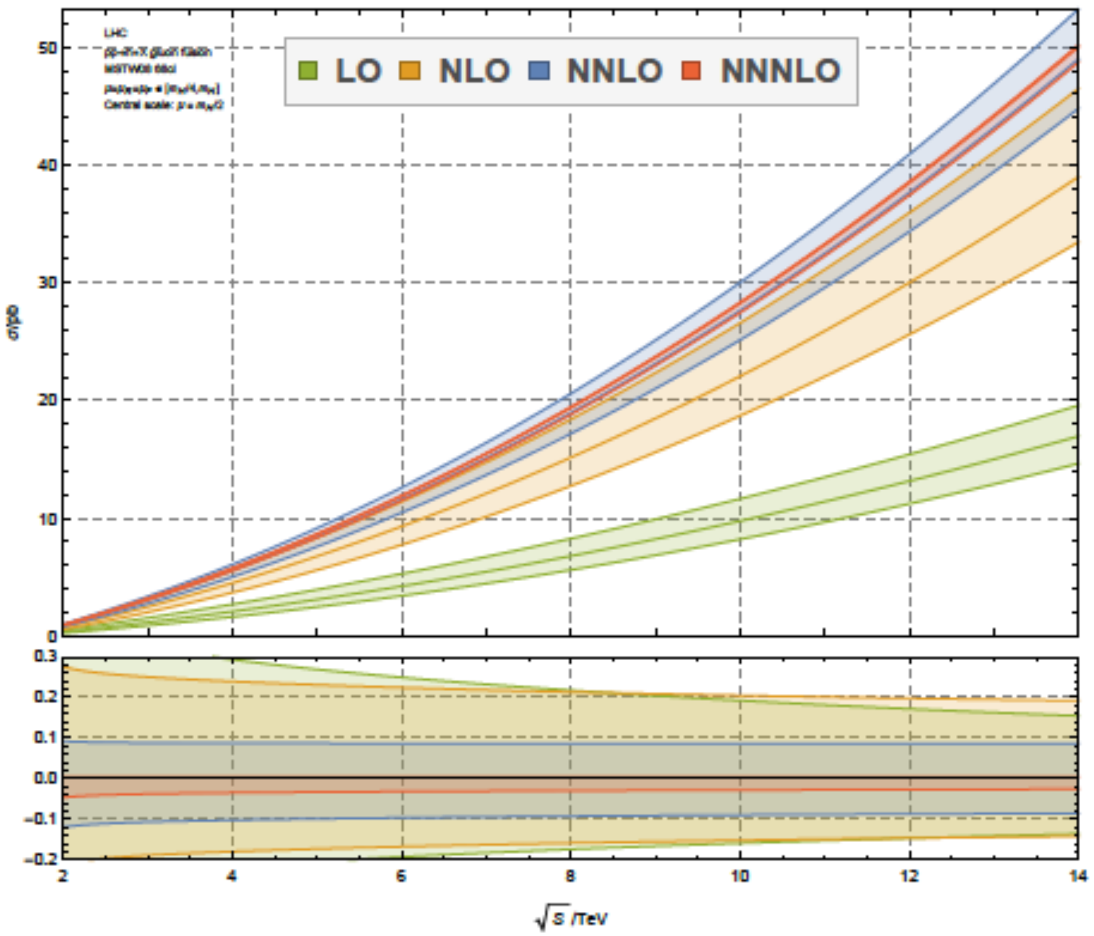
NLO-QCD HQET Dawson 1991, Djouadi Graudenz Spira Zerwas 1992
exact Spira Djouadi Graudenz Zerwas 1995 Aglietti Bonciani Degrassi AV 2006,2007 Anastasiou Beerli Bucherer Daleo Kunszt 2007

NNLO-QCD HQET Anastasiou Melnikov 2002 Harlander Kilgore 2002 Ravindran Smith van Neerven 2003

N3LO-QCD HQET Anastasiou, Duhr, Dulat, Herzog, Mistlberger 2015

NLO-EW exact l.q. Aglietti Bonciani Degrassi AV 2004 expansion tb Degrassi Maltoni 2004 exact full numerical Actis Passarino Sturm Uccirati 2008

The total ggF Higgs production cross section: fixed-order results



arxiv: 1503.06056: Anastasiou, Duhr, Dulat, Herzog, Mistlberger

reduction of the scale dependence to 2-3%

the N3LO band falls within the NNLO band

better convergence when using mh/2 as central scale

not completely cast in closed analytical form
but very good convergence of the adopted expansions

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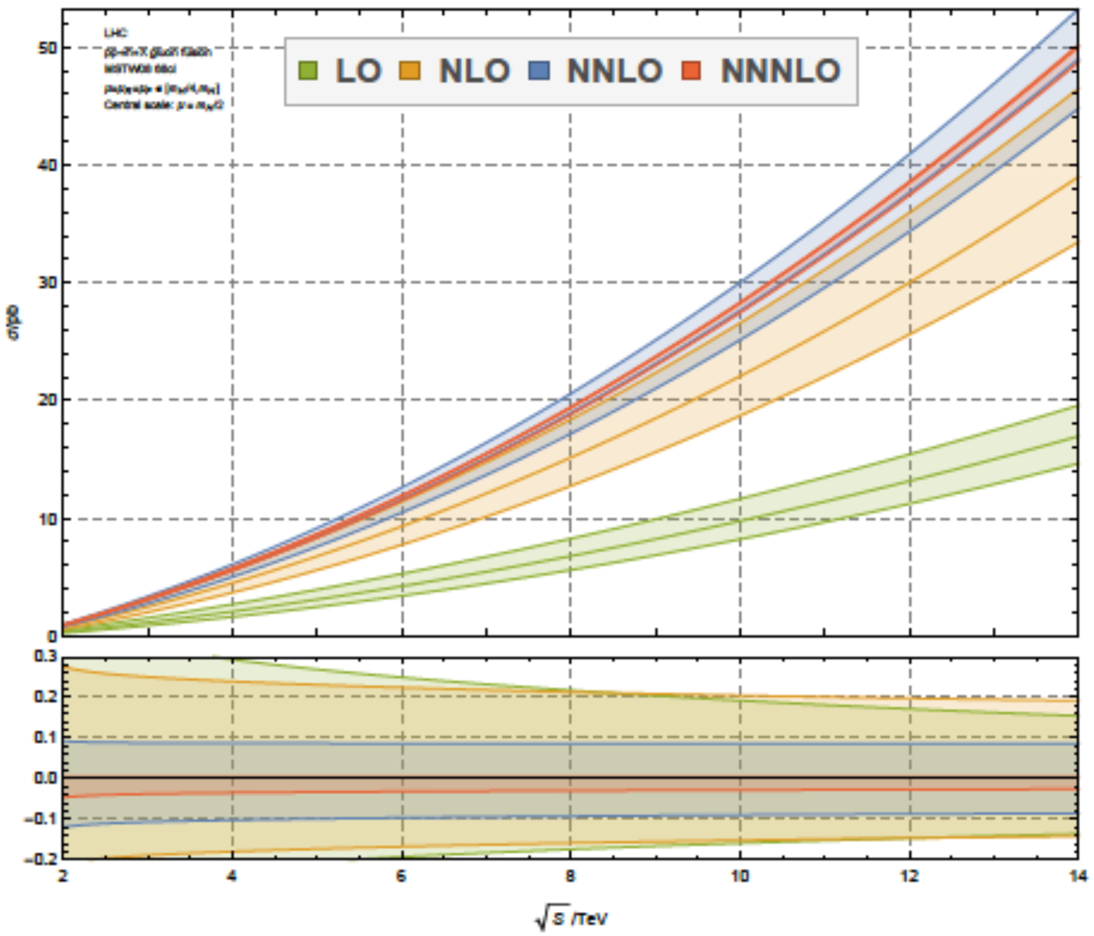

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- is scale variation sufficient to estimate the missing higher orders?
- are there other computational techniques to include subsets of higher-order corrections?
- is the EWxQCD interplay fully under control?
- how large are the missing NNLO quark-mass effects?
- are PDFs accurate and consistent?

Resummation

Inclusion to all perturbative orders in α_s of terms enhanced by large logarithmic factors

Given $z = \frac{m_H^2}{s}$ and $\sigma(N, m_H^2) \equiv \int_0^1 d\tau\, \tau^{N-2} \sigma(\tau, m_H^2)$ we have

$$\sigma_{res}(N, \alpha_s) = \sigma_0\, g_0(\alpha_s) \left[\frac{1}{\alpha_s} g_1(\alpha_s \log N) + g_2(\alpha_s \log N) + \alpha_s g_3(\alpha_s \log N) + \ldots \right]$$

soft expansion: inclusion of terms enhanced by $\log(1-z), \quad z \to 1$
$\log N, \quad N \to \infty$

Catani, de Florian, Grazzini (2001), Catani, de Florian, Nason, Grazzini (2005), Moch, Vogt (2005), Laenen, Magnea (2005), Anastasiou et al (2014, 2015), de Florian, Mazzitelli, Moch, Vogt (2014)

high-energy expansion: inclusion of terms enhanced by $\log(z), \quad z \to 0$

$\frac{1}{(N-\alpha)^k}, \quad \alpha = 1, 0, -1, \ldots$

Balitski, Fadin, Kuraev, Lipatov (1975-8), Hautmann (2002),
Altarelli, Ball. Forte (2002, 2006, 2008), Marzani, Ball, Del Duca, Forte, AV (2008),

The "true" exact result includes all the terms predicted in the two limits

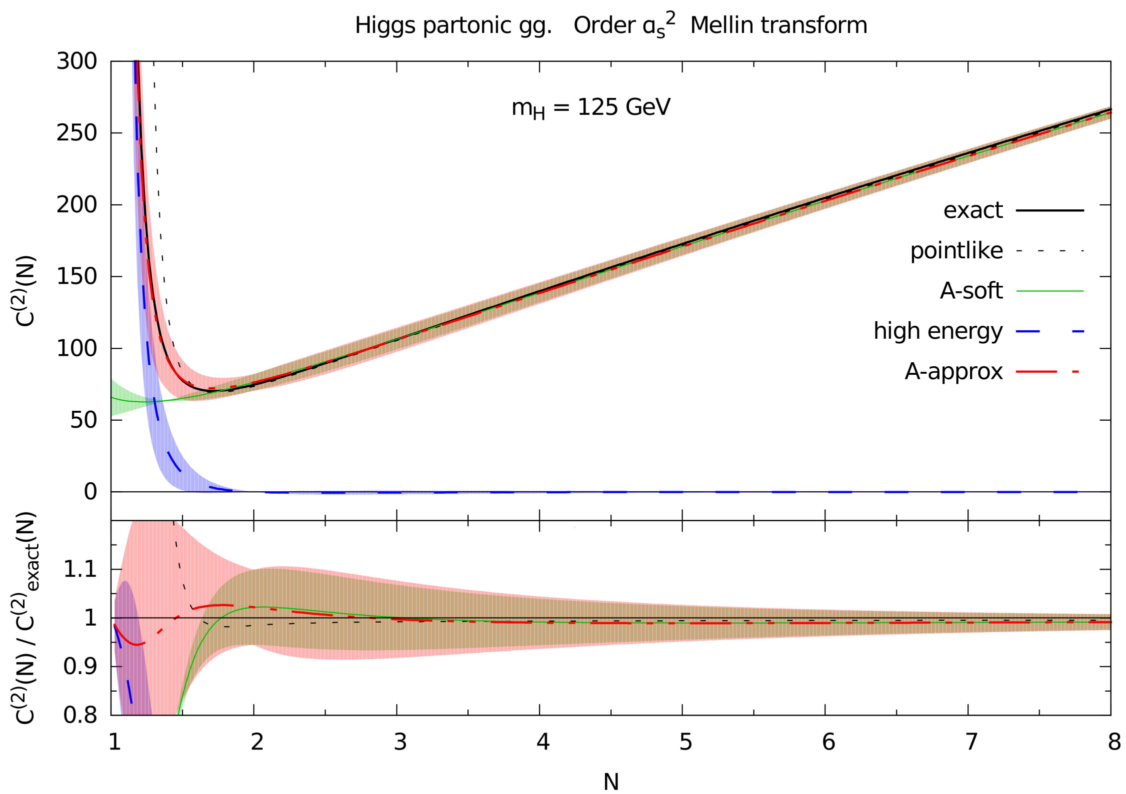
→ analytical constraints on the form of the resummed cross section
possibility to derive an approximation of the next fixed order expression
Ball, Bonvini, Forte, Marzani, Ridolfi (2013)

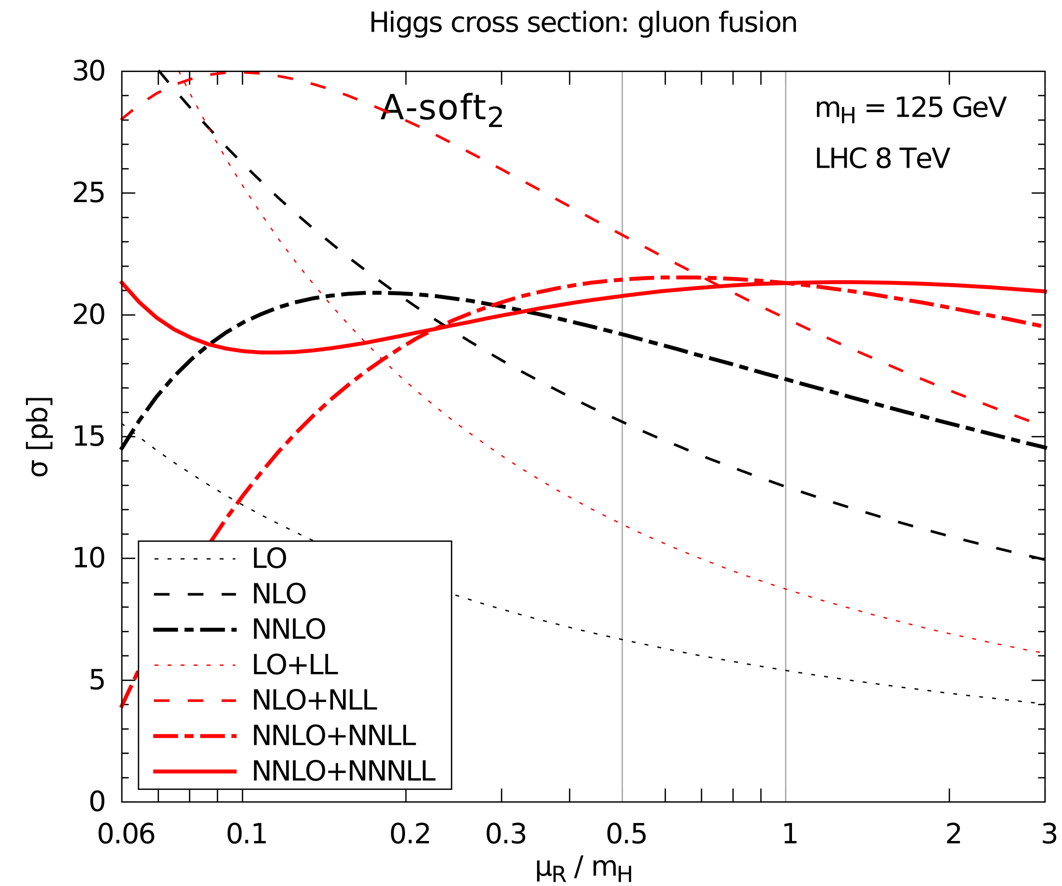
Resummation

Pro's: · the knowledge of the analytical properties of the scattering amplitude in two different regimes (soft and high-energy) constrains ("brackets") the structure of the xsec

· improved convergence order by order (in log accuracy) w.r.t. the fixed-order expansion

· improved stability under scale variations





Con's: · ambiguities in the inclusion of subleading terms

overall structure of the result

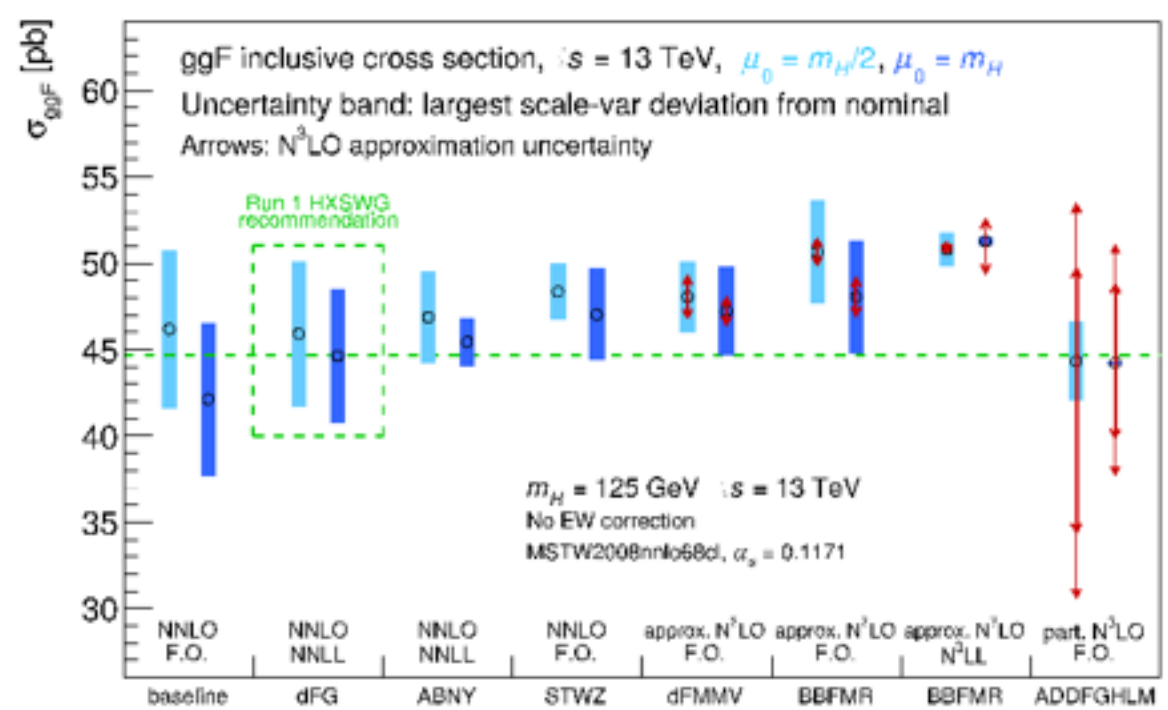
e.g. position of g0 in the resummed expression in Mellin space

choice of the logs

e.g. log(N) vs log(z), SCET vs QCD

exponentiation of constant terms

e.g. π^2 in SCET, use of DIS scheme



on-going discussion in the HXSWG

The total ggF Higgs production cross section: quark-mass effects

$\sqrt{S}$ =14 TeV	HQET	mt	mt,mb
LO	21.41	22.81 (+6.5%)	20.32 (-5.1%)
NLO	35.58	37.63 (+5.7%)	35.25 (-1.0%)

xsec in pb

percentages w.r.t. σ(HQET)

the exact treatment of only the top-quark yields a +6.5% increase at LO
a further small negative effect on the NLO K-factor

the inclusion of the bottom quark yields a sizeable negative effect at LO (-11.6% w.r.t. only-top)
partially compensated by a larger NLO K-factor

the negative effect of the bottom quark inclusion at LO
is due to an accidental destructive interference between the top and the bottom amplitudes

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defining K=σ(NLO)/σ(LO) we find K(HQET) = 1.66, K(mt) = 1.65, K(mt,mb) = 1.74
i.e. (mt,mb) mass effects increase the HQET K-factor by +8%

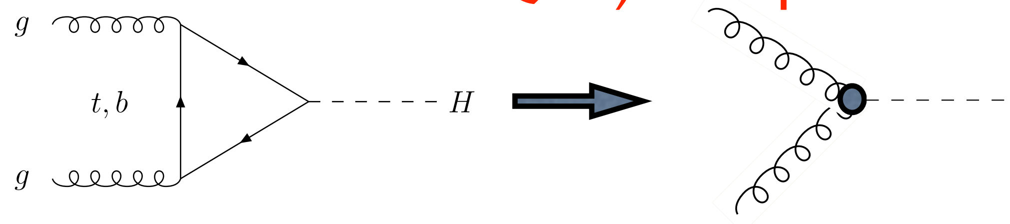
the top-quark mass effects have been studied at NNLO-QCD and are smaller than 1% of σ(NNLO)
Marzani, Ball, Del Duca, Forte, AV (2008), Harlander et al (2009,2010), Pak, Rogal, Steinhauser (2009)

simple recipe (M.Grazzini @ LesHouches): rescale NNLO+N3LO only by the top-quark LO effect;
caveat: this result might be significantly modified by non-trivial bottom effects

assuming the NLO pattern also at NNLO,
then one would expect a 2% (=0.08*0.25) increase of the xsec from the top-bottom interference at NNLO $\Rightarrow$ the evaluation of these effects is highly desirable

Counting the scales

Effective theory (HQET) mtop → infinity



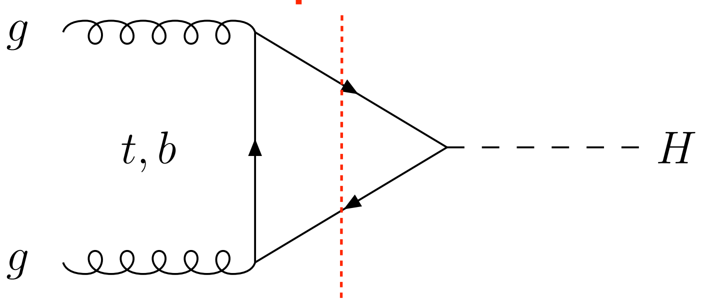
the partonic total cross sections depends only on $z = \frac{m_H^2}{s}$

the results are expressed in terms of

- constants
- polylogarithmic functions of one variable (z)

at LO, NLO-QCD, NNLO-QCD, N3LO-QCD
(some results not in closed form)

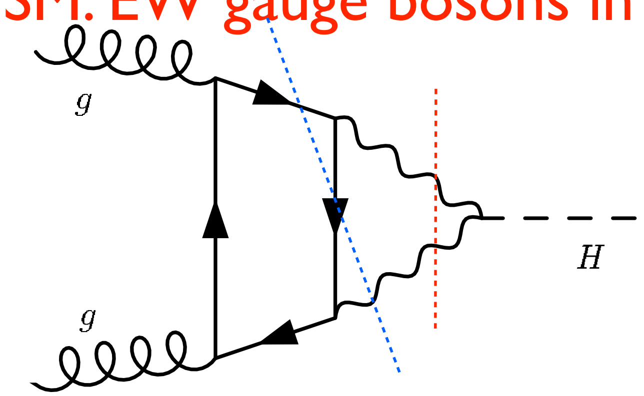
SM: exact dependence on the quark masses



real and virtual corrections depend on mq, mh, ŝ (via different ratios)

LO, NLO-QCD
one single threshold in the loop (gluons are massless)
→ the virtual results are expressed in terms of polylogarithmic functions of one variable $x = \frac{\sqrt{1-4\tau}-1}{\sqrt{1-4\tau}+1}$

SM: EW gauge bosons in the gluon fusion loop



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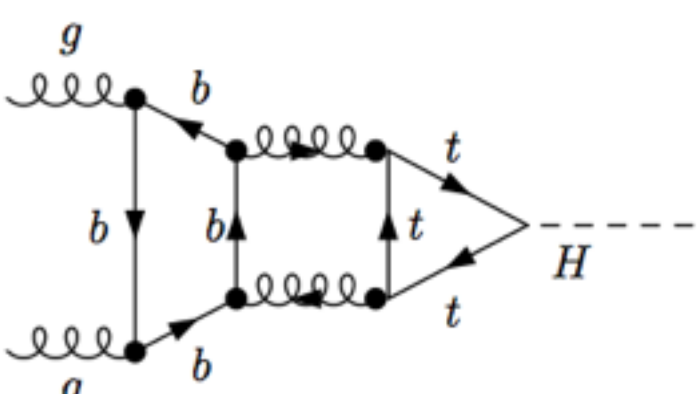

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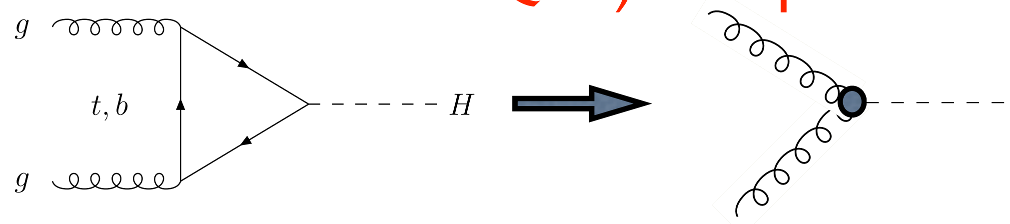

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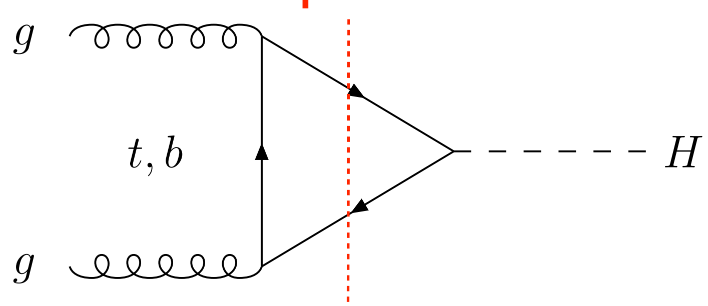

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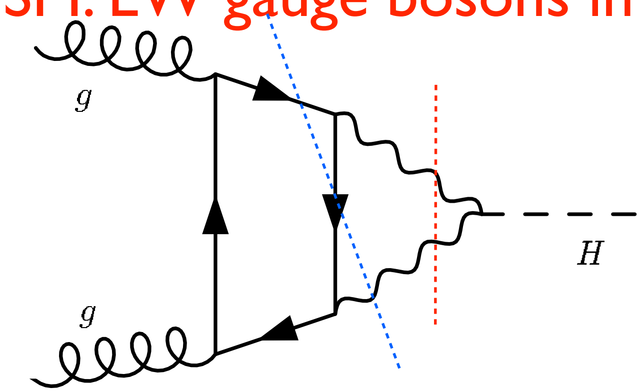
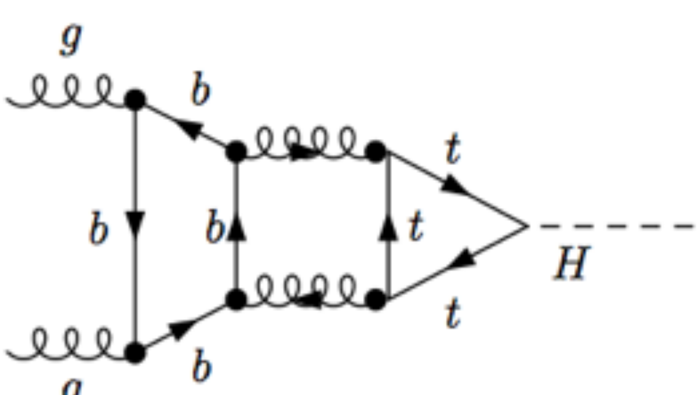


NLO-EW
2-loop integrals with 2 different thresholds
(light quarks, 1 or 2 internal massive lines)
→ enlargement of the basis of functions

in the case of top-bottom loop a closed analytical form is not available
→ expansions or numerical approaches

SM: exact dependence on the quark masses



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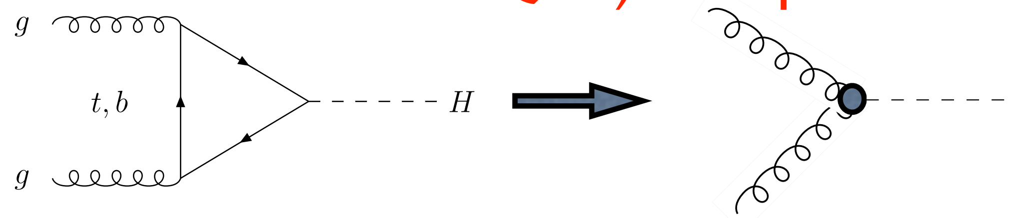

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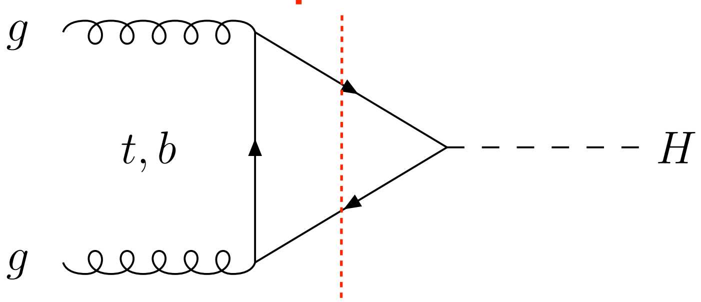

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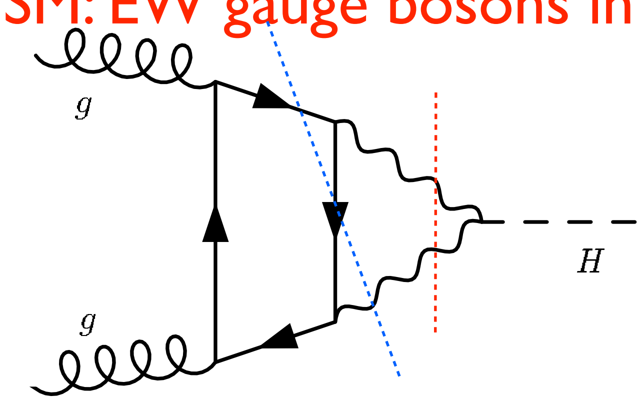

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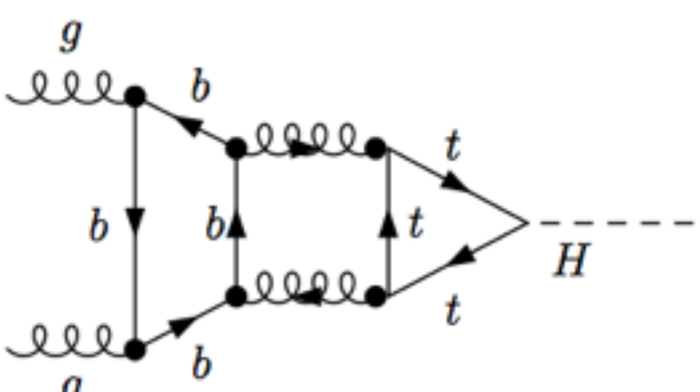


NNLO-QCD
3-loop integrals have higher level of complexity
presence in some diagrams of 2 massive closed loops
→ more thresholds in the analytical structure of the results
not known yet ☹

EW corrections

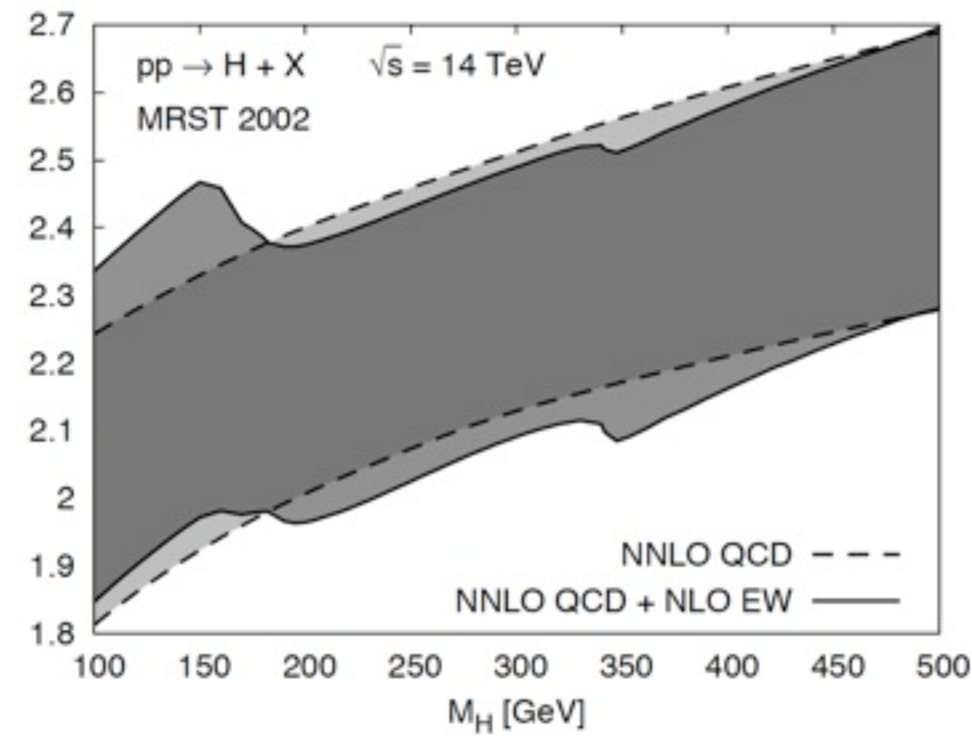
the NLO-EW corrections are completely available; for MH=125 GeV $\delta_{EW} \sim 0.05$
their inclusion in the hadron-level cross section can be done in a fully or partially factorized form

Actis, Passarino, Sturm, Uccirati, Phys.Lett.B670 (2008) 12

$$G_{ij} = G_{ij}^{(0)} + \alpha_s G_{ij}^{(1)} + \alpha_s^2 G_{ij}^{(2)} + \ldots$$ QCD coefficient function

$$\sigma^{(0)} G_{ij} \to \sigma^{(0)} (1 + \delta_{EW}) G_{ij}$$ Complete Factorization

$$\sigma^{(0)} G_{ij} \to \sigma^{(0)} \left[G_{ij} + \delta_{EW} G_{ij}^{(0)} \right]$$ Partial Factorization



- Complete Factorization automatically implements the factorization of the universal QCD initial state logarithms

- In the Partial Factorization approach the EW corrections modifies only the 2→1 kinematics
  ➔ the increase of the total cross-section is only of 1-2%, depending on MH

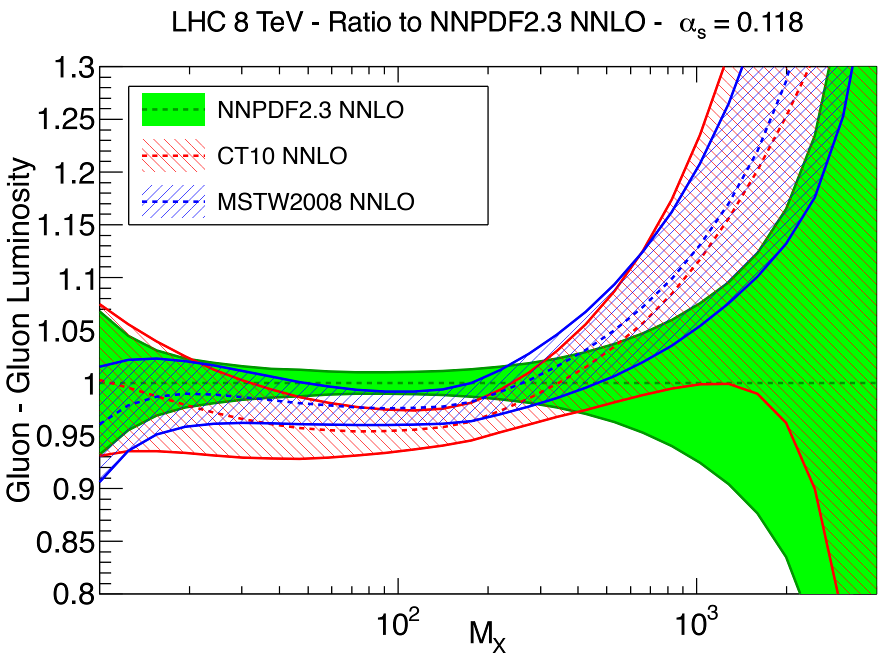
- How large are residual non-factorizable corrections?
  Estimate of the 3-loop $O(\alpha\alpha_s)$ Wilson coefficient of the Effective Lagrangian (mh=0)
  The non-factorizable terms are significantly different from zero,
  but their phenomenological impact is negligible (coupling constant suppression)
  Anastasiou, Boughezal, Petriello, JHEP 0904:003,2009

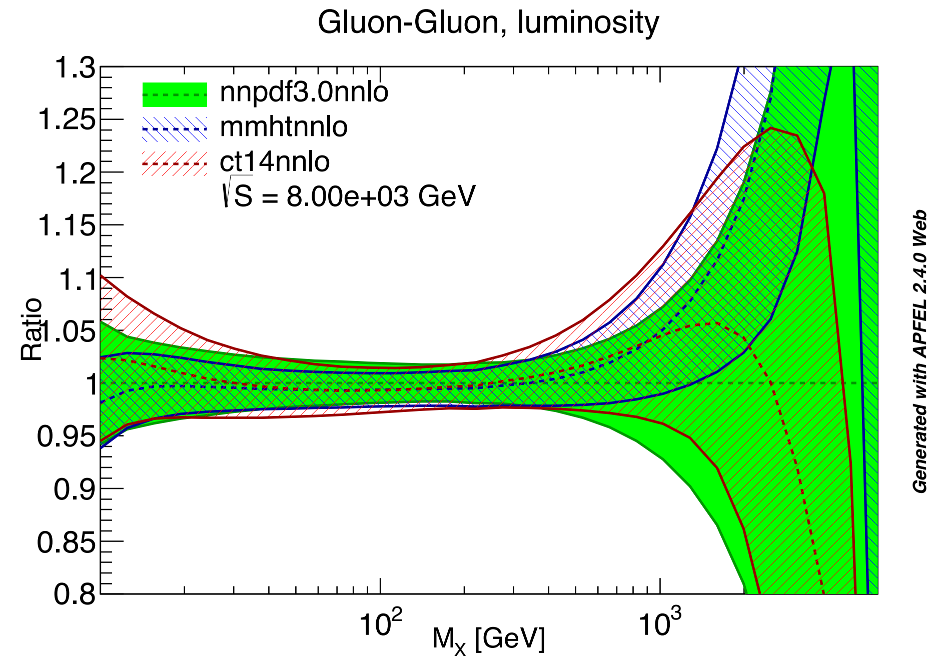
➔ Complete Factorization yields an accurate description of the $O(\alpha\alpha_s)$ terms

PDF progresses

- methodological progresses of global PDF collaborations → excellent agreement for gg luminosity

GLUON-GLUON





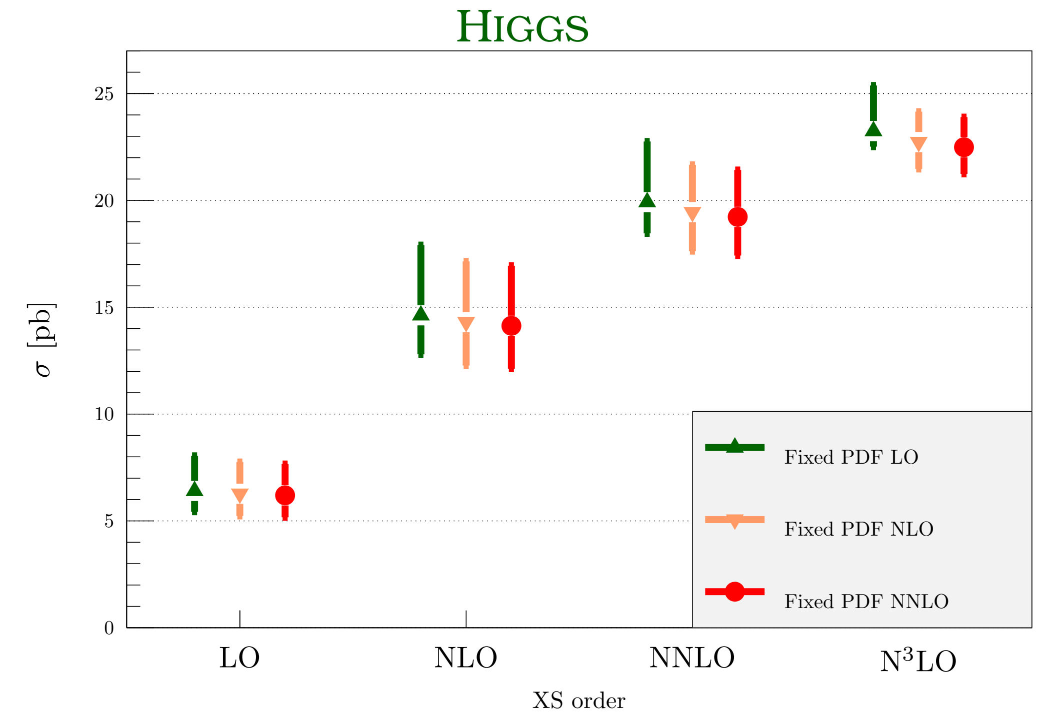
- comparison of NNLO predictions: central values agree within 0.6%
  similar estimates of the uncertainty bands

	CT14	MMHT2014	NNPDF3.0
8 TeV	18.66 pb -2.2% +2.0%	18.65 pb -1.9% +1.4%	18.77 pb -1.8% +1.8%
13 TeV	42.68 pb -2.4% +2.0%	42.70 pb -1.8% +1.3%	42.97 pb -1.9% +1.9%

J.Huston, PDF4LHC, April 2015

PDF

- do we need N3LO PDFs?
  formally yes but in practice no:
  the largest fraction of the uncertainty stems
  from the partonic xsec rather than from the PDFs
  Forte, Isgrò, Vita, arXiv:1312.6688, Phys.Lett.B731 (2014) 136

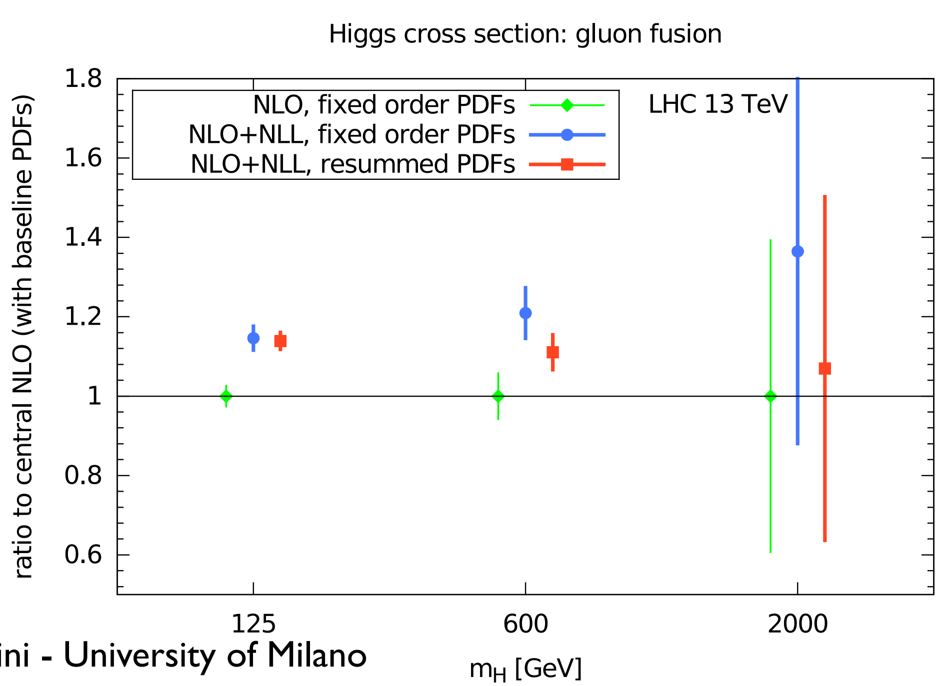


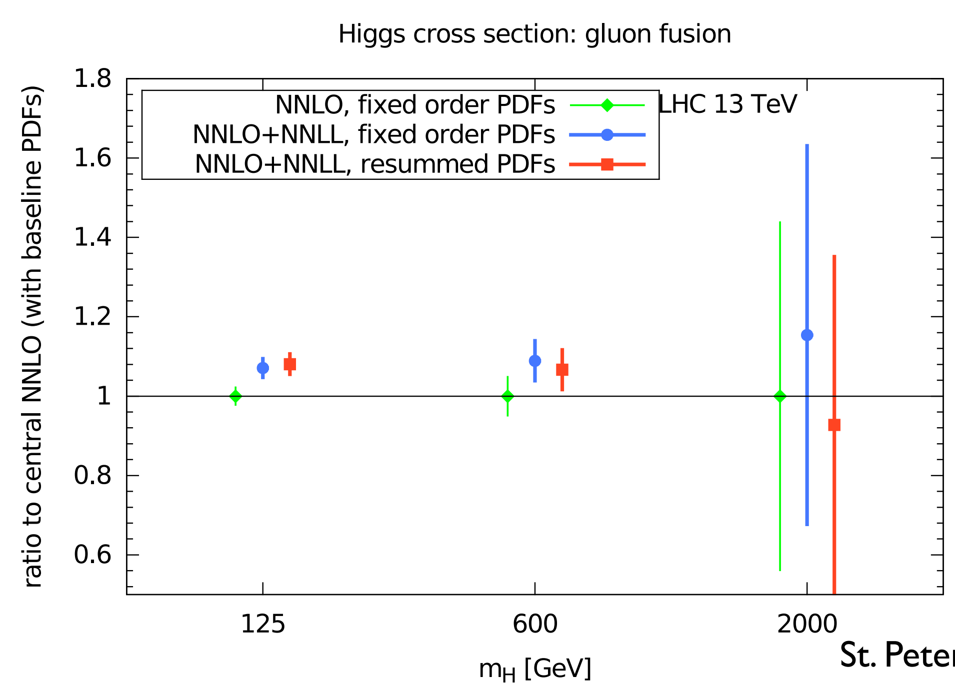
- are PDFs consistent with resummation?
  the hadron level xsec is the convolution of
  a partonic xsec with PDFs extracted from data both in the same perturbative approximation

  the convolution of a resummed partonic xsec with fixed-order PDFs would yield a double counting

  first set of global PDFs extracted using partonic results with (N)NLL threshold resummation
  Bonvini, Marzani, Rojo, Rottoli, Ubiali, Ball, Bertone, Carrazza, Hartland, arXiv:1507.01006

  in the case of a light Higgs (mh=125 GeV) negligible double counting effect

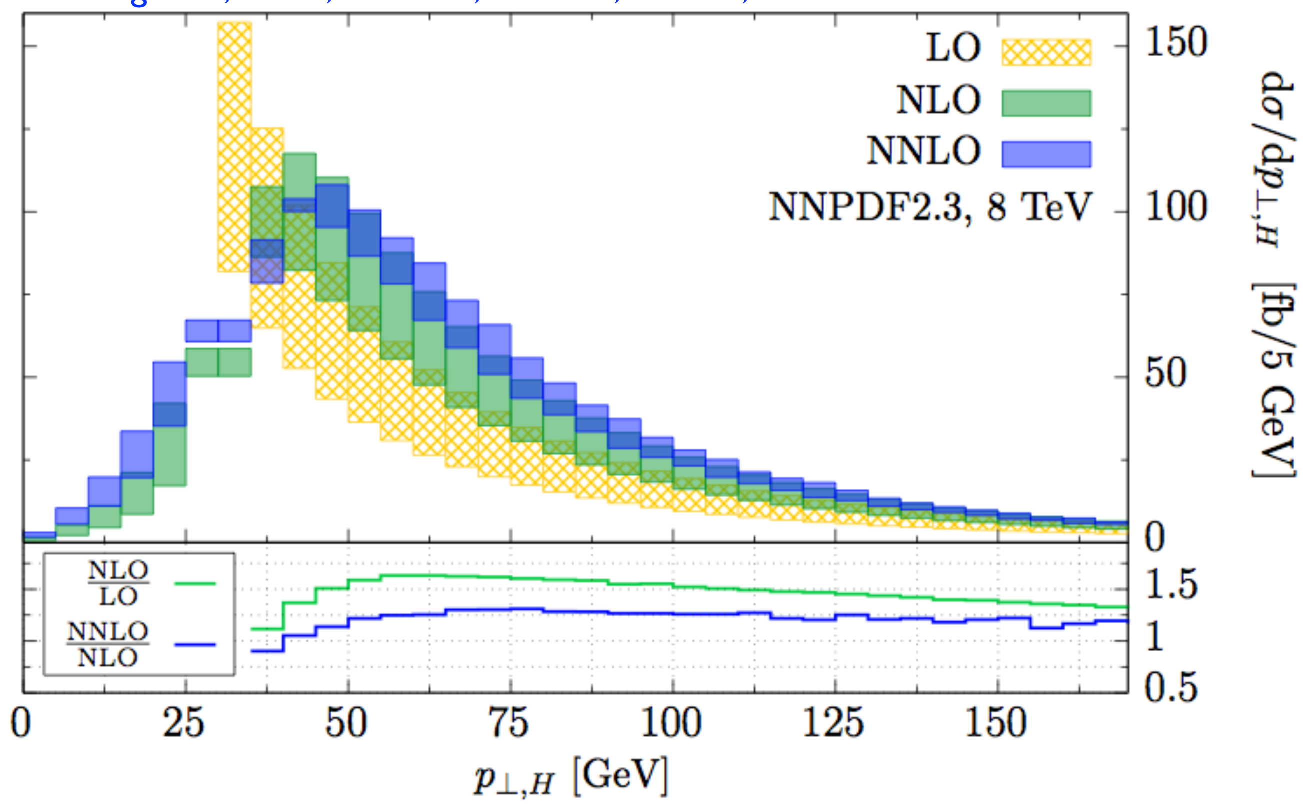




The Higgs+1 jet cross section in gluon fusion: NNLO-QCD results

Boughezal, Caola, Melnikov, Petriello, Schulze, arXiv:1302.6216, arXiv:1504.07922, Chen, Gehrmann, Glover, Jaquier, arXiv:1408.5325
Boughezal, Focke, Giele, Liu, Petriello arXiv:1505.03893

Boughezal, Caola, Melnikov, Petriello, Schulze, arXiv:1504.07922



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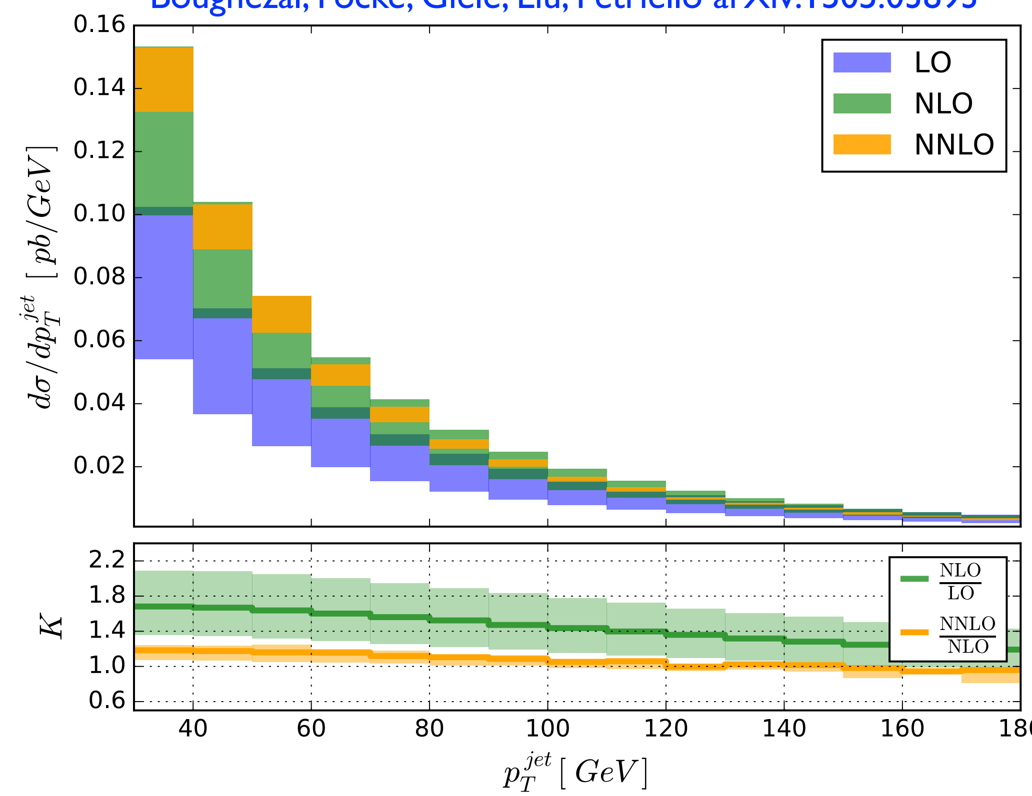
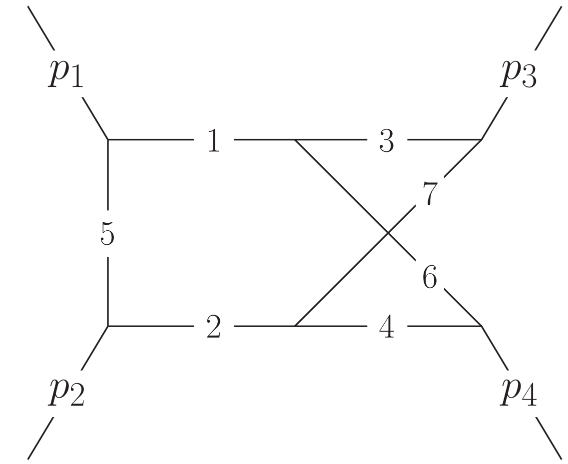


- same perturbative order $O(\alpha_s^5)$ as the N3LO calculation for the total xsec
- results obtained in the HQET, with three different computational techniques
- the 0-jet bin cross section at N3LO is available (by subtraction)
- results including Higgs decay (γγ, WW, ZZ) allow to compute fiducial cross sections
  Caola, Melnikov, Schulze, arXiv:1508.02684
- no evidence of perturbative breakdown of QCD for pt_cut(jet) = 30 GeV
- 2-loop 4-point integrals with one external massive line (and all internal partons massless)

Advances in 2-loop calculations: ZZ production

- impressive progress in the evaluation of the Master Integrals (MI) relevant for the calculation of 2-loop box diagrams with 2 external massive lines
  Gehrmann, Tancredi, Weihs, arXiv:1306.6344, Henn, Melnikov, Smirnov, arXiv:1402.0788, Caola, Henn, Melnikov, Smirnov: 1404.5590
  analytical results expressed in terms of Goncharov polylogarithms



- complexity of the problem related to the presence of several scales (S,T,M_3^2, M_4^2)

- the solution of the problem requires:
  1) identification of a set of Master Integrals which the amplitude depends upon
  2) formulation of a (system of) differential equations in the external invariant satisfied by the MI
  3) evaluation of boundary conditions

- important progress in the formulation of simple differential equations after the conjecture Henn, arXiv:1304.1806 about the possibility to systematically decouple the equations with the choice of a convenient MI basis

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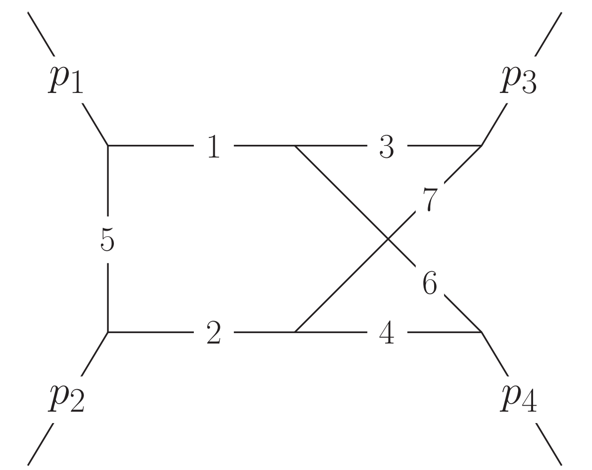

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- NLO calculation for gg →ZZ (background and Higgs signal-background interference) now possible (with massless quarks in the two-loop diagrams)

Caola, Hen, Melnikov, Smirnov, Smirnov arXiv:1408.6409, Caola, Hen, Melnikov, Smirnov, Smirnov arXiv:1503.08759

→ improvement in the determination of the Higgs width from the ratio of off-shell and on-shell xsecs

Caola, Melnikov, arXiv:1307.4985

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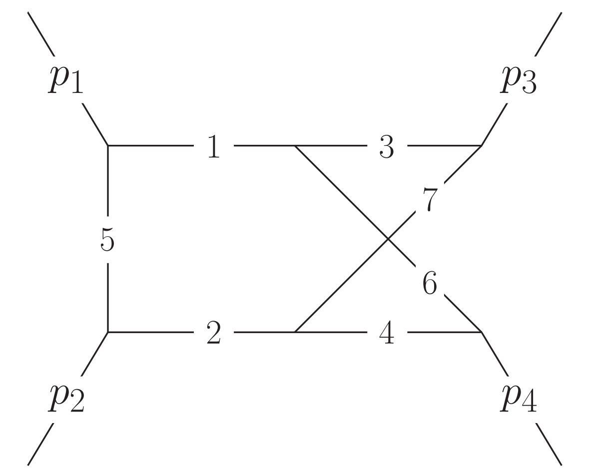

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  3) evaluation of boundary conditions

- important progress in the formulation of simple differential equations after the conjecture Henn, arXiv:1304.1806 about the possibility to systematically decouple the equations with the choice of a convenient MI basis

- NLO calculation for gg →ZZ (background and Higgs signal-background interference) now possible (with massless quarks in the two-loop diagrams)

Caola, Hen, Melnikov, Smirnov, Smirnov arXiv:1408.6409, Caola, Hen, Melnikov, Smirnov, Smirnov arXiv:1503.08759

→ improvement in the determination of the Higgs width from the ratio of off-shell and on-shell xsecs

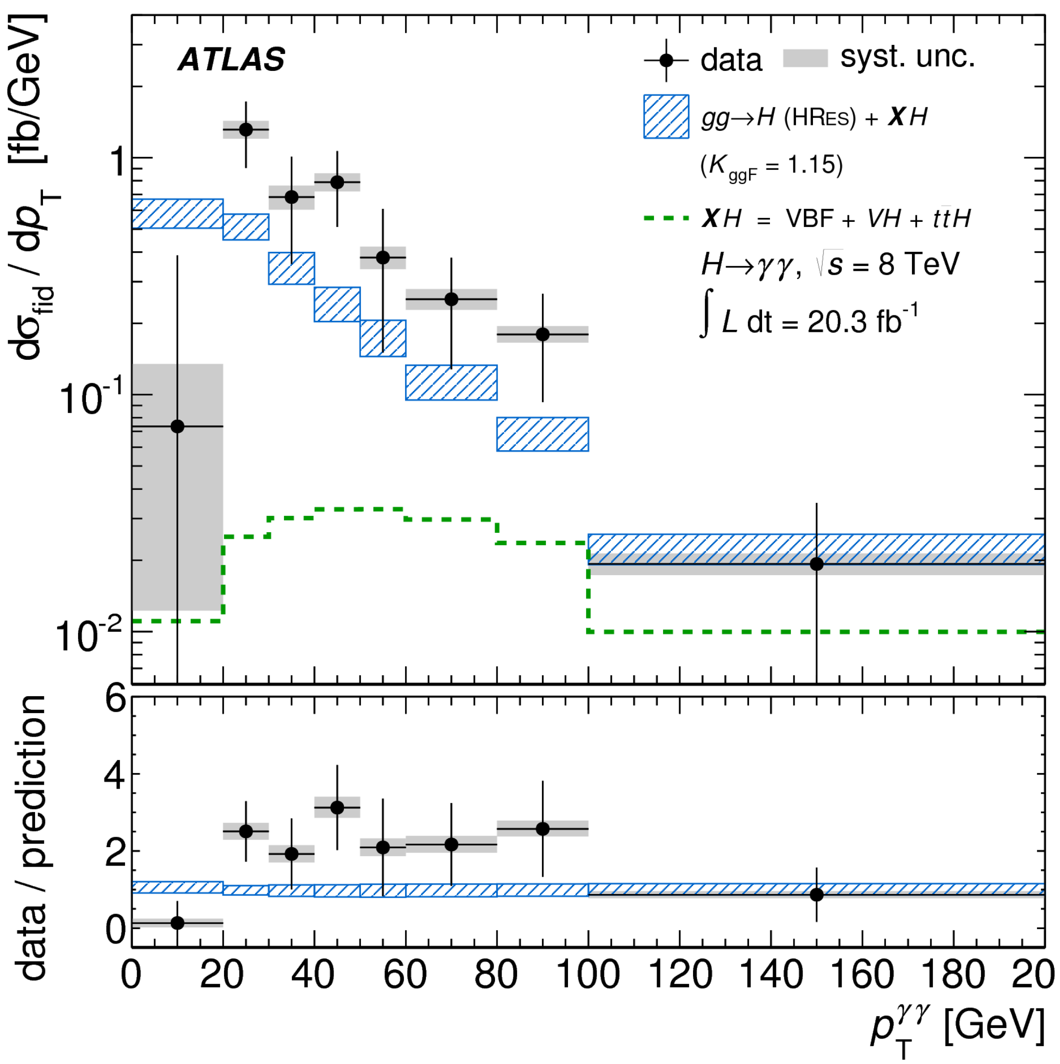
Caola, Melnikov, arXiv:1307.4985

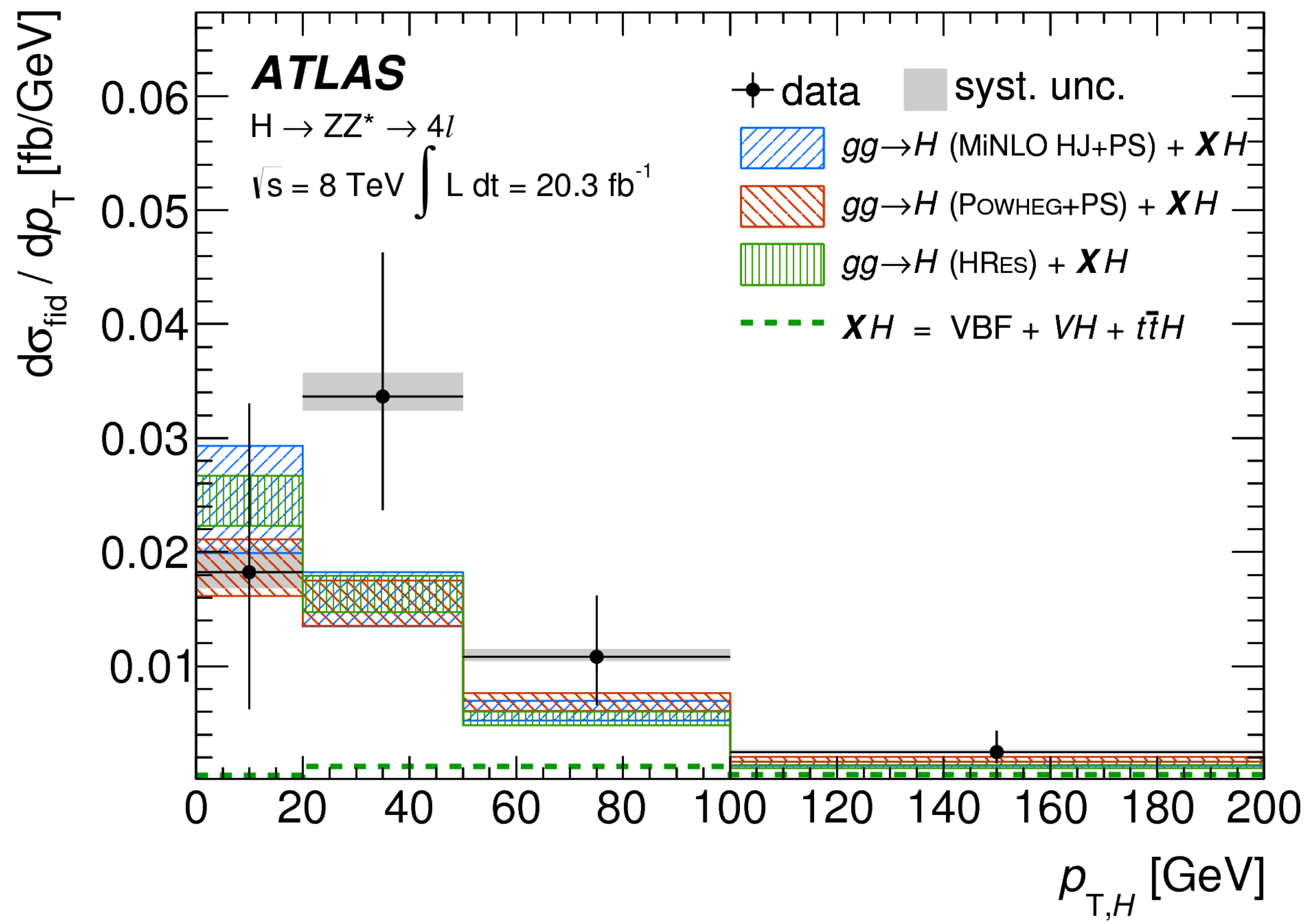
- Top-quark contributions expected to be important for the interference and to have a large K-factor

Dowling, Melnikov, arXiv:1503.01274

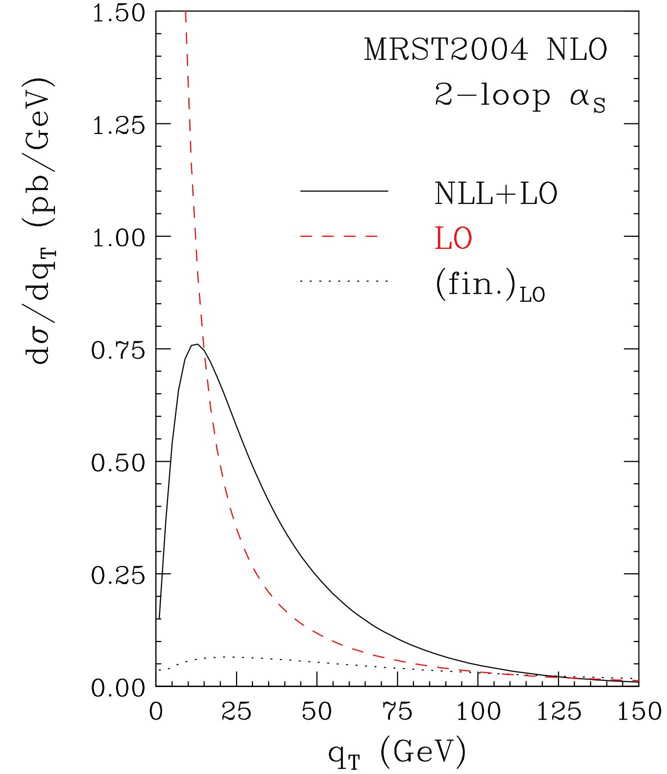
Higgs transverse momentum distribution

- first experimental results for the Higgs transverse momentum distribution





Higgs transverse momentum distribution



- the Higgs transverse momentum distribution diverges in fixed order perturbation theory
  → it requires the resummation to all orders of terms enhanced by log(ptH/mh) factors

- two different computational techniques:
  - analytical resummation (matched with fixed order)
  - matched Shower Monte Carlo

- accuracy
  for ptH→0 relies on the logarithmic accuracy of the calculation
  for large ptH relies on the perturbative accuracy

	inclusive observables	high ptH tail	resummation of ptH logs, ptH→0
MC@NLO / POWHEG	NLO	LO	(N)LL
analytic resum.: More-Sushi	NLO	LO	NLL
analytic resum.: HRes	NNLO	NLO	NNLL
NNLOPS / UN²LOPS	NNLO	NLO	(N)LL
GENEVA (Drell-Yan only, EFT)	NNLO	NLO	NNLL'

- matching N3LO + N3LL in the future?

- in these codes heavy quark mass effects are available,
  the Higgs ptH in gluon fusion is a multiscale problem/observable

Higgs transverse momentum distribution

- uncertainties
  - fixed-order uncertainties are estimated via renormalization/factorization scale variations

  - the matching between the resummed expression and the fixed-order matrix elements requires a dedicated formulation to avoid double counting → different prescriptions → ambiguities

  - the transition between resummed and fixed-order regime is parametrized by a matching scale
    the exact result does not depend on it, but in perturbation theory a dependence is left
    a convenient choice of its value can avoid the appearance of unmotivated spurious factors

  - the inclusion of multiple parton emissions is implemented with different algorithms that limit the phase space available to additional radiation

Dedicated study on the matching uncertainties, SM and BSM (preliminary)

Bagnaschi, Harlander, Mantler, AV, Wiesemann, *in progress*

- comparison of More-SusHi, analytic res. at NLO+NLL-QCD+SusHi, Mantler, Wiesemann, arXiv:1210.8263
  Harlander, Mantler, Wiesemann, arXiv:1409.0531

  aMCSusHi (Madgraph_aMC@NLO with SusHi), Mantler, Wiesemann, arXiv:1504.06625

  POWHEG gg_H_quark-mass-effects, gg_H_2HDM/MSSM Bagnaschi et al, arXiv:1111.2854

  the same PYTHIA8 tune (no hadronization effects) used in MC@NLO and POWHEG

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  the same PYTHIA8 tune (no hadronization effects) used in MC@NLO and POWHEG

- different codes (using different matching schemes and matching parameters) share a given fixed order accuracy NLO-QCD and differ by higher-orders (numerically not negligible)

  the total matching uncertainty has two distinct sources:

  1) use the same numerical value for the matching parameter in all the codes
     differences will be interpreted as due to the different matching schemes
     (comparison of central values)

  2) take one code and check the dependence (canonical variation) on its own matching parameter
     (resummation scale, Shower scale, hfact damping factor)
     repeat for each of the three codes compare the (width of) the resulting uncertainty bands

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- the top, bottom and interference contributions in gluon fusion have been evaluated separately
  with their dedicated matching scale choice;
  comparison of the Harlander, Mantler, Wiesemann and of the Bagnaschi, Vicini scale recommendations
  Harlander, Mantler, Wiesemann, arXiv:1409.0531, Bagnaschi, AV, arXiv:1505.00735

- analysis of different scenarios, to expose the impact of different choices for the matching parameter
  SM (top dominated), 2HDM bottom dominated, 2HDM large interference effects

Comparison of different matching scales

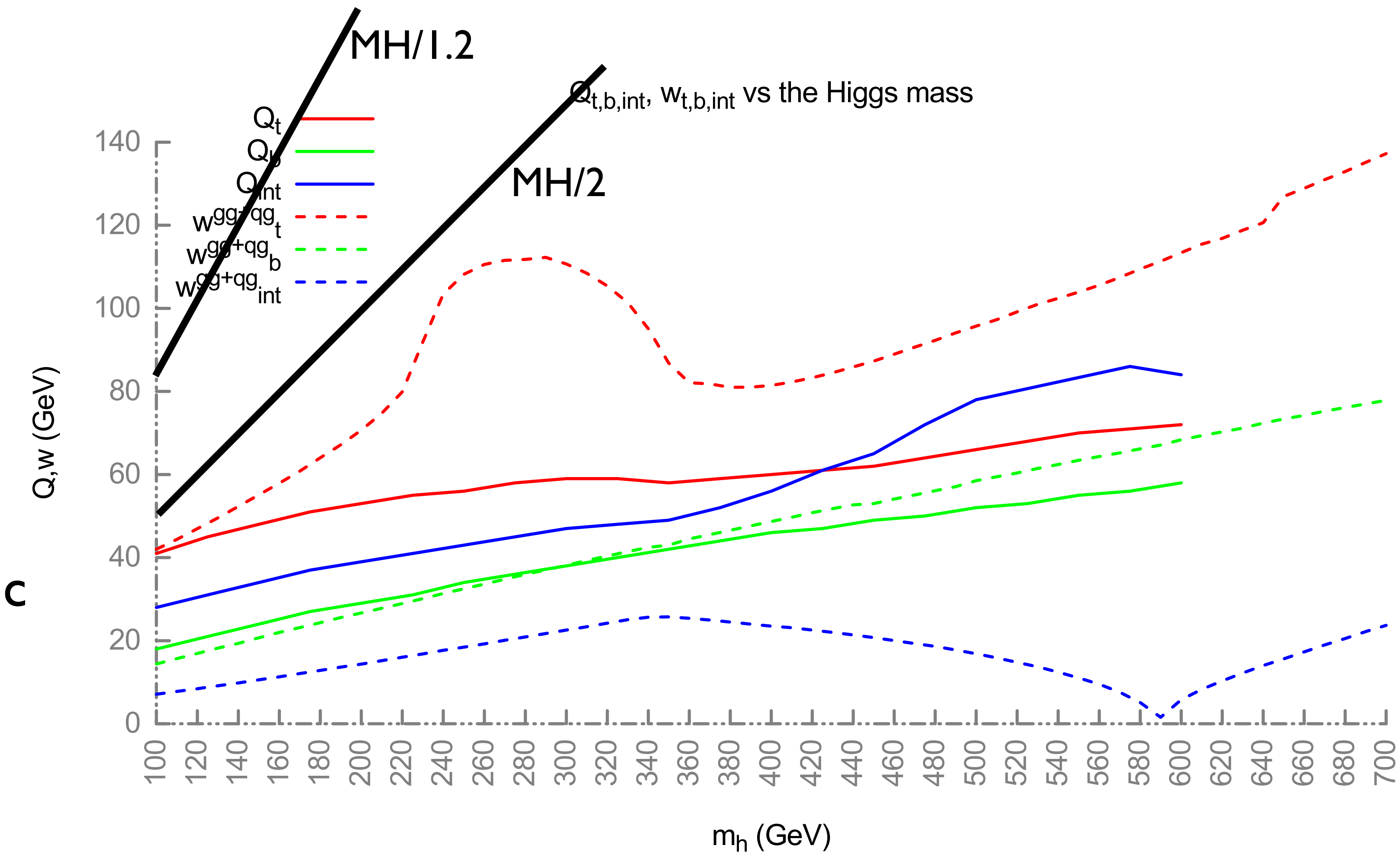
Harlander, Mantler, Wiesemann, arXiv:1409.0531, Bagnaschi, AV, arXiv:1505.00735

- comparison of HMW and BV results for the scale to be used in the matching parameter

HMW solid
BV dashed

HMW
constraints on the predictions of the AR code

BV
collinear behavior of the partonic squared matrix elements



- good agreement for the bottom scale prediction

top scales: for light Higgs, very good agreement
the partonic analysis probes the top-pair threshold,
otherwise the 2 prediction are within a factor 1.5

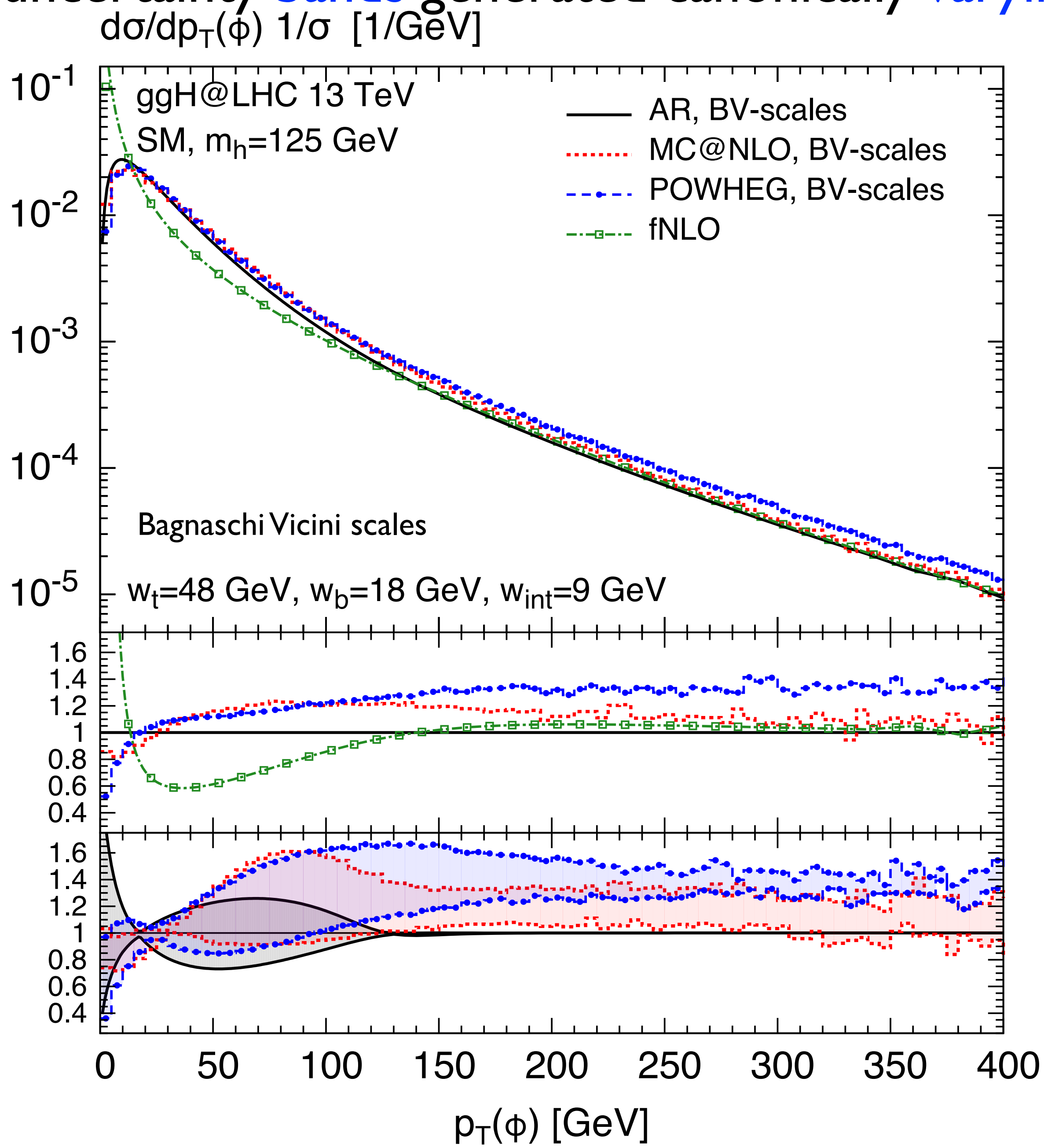
different approaches to the study of the interference terms behavior
(the results are a parameterizations of our ignorance)

- the naive choice MH/2 or MH/1.2 would lead to much larger scales

Comparison of different codes (preliminary) SM MH=125 GeV

Bagnaschi, Harlander, Mantler, AV, Wiesemann, *in progress*

uncertainty bands generated canonically varying ONLY the matching parameter, fixed muR and muF



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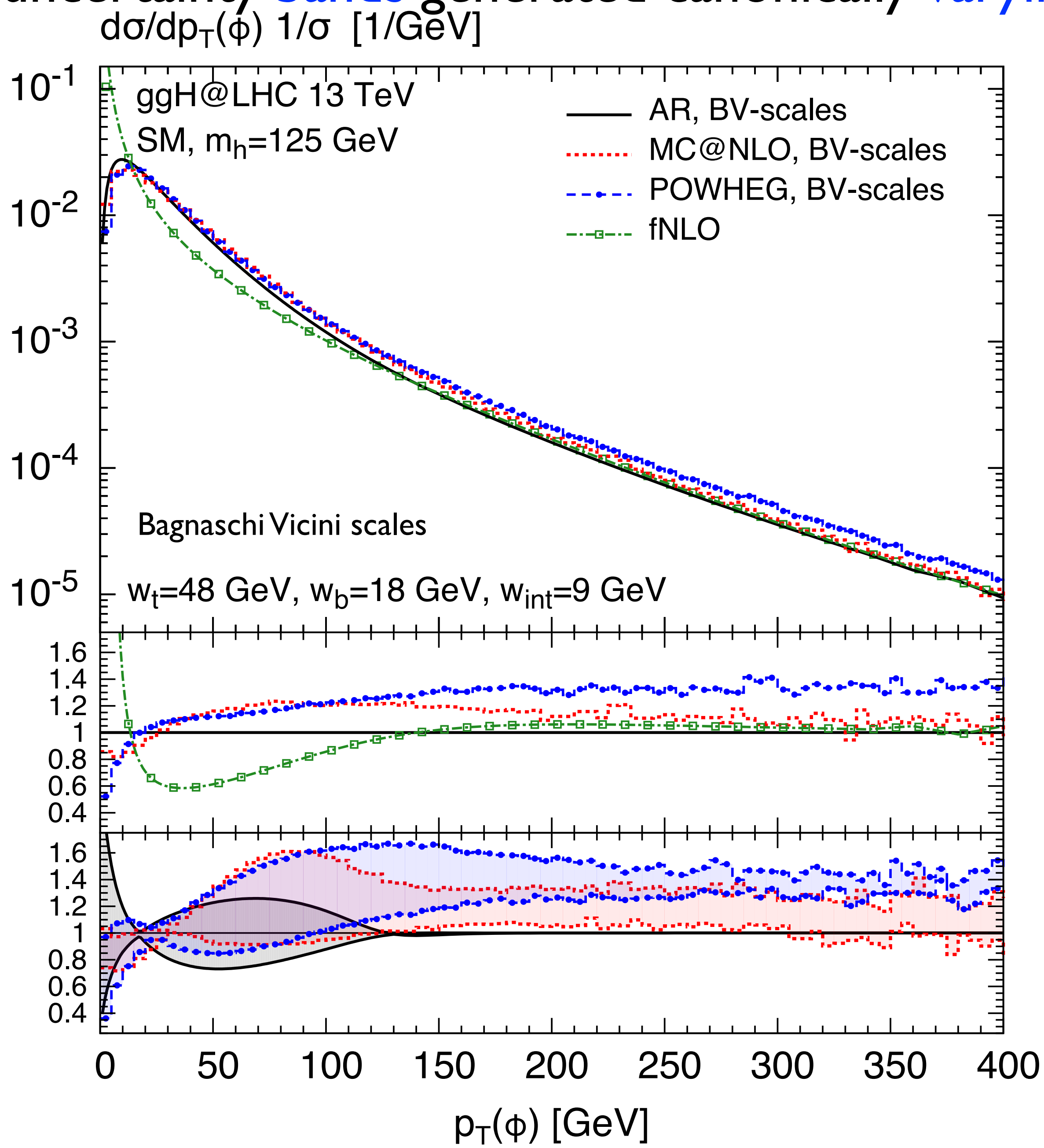

in the SM case More-SusHi fully equivalent to HqT @ NLO

the More-SusHi band is switched off for ptH>MH, the other bands overlap/are compatible

More-SusHi shows a distribution softer than the one of the Shower MC

unitarity constraint → "turning point" at ptH~20 GeV

the uncertainty is largest (±35%) for 50 < ptH < 100 GeV

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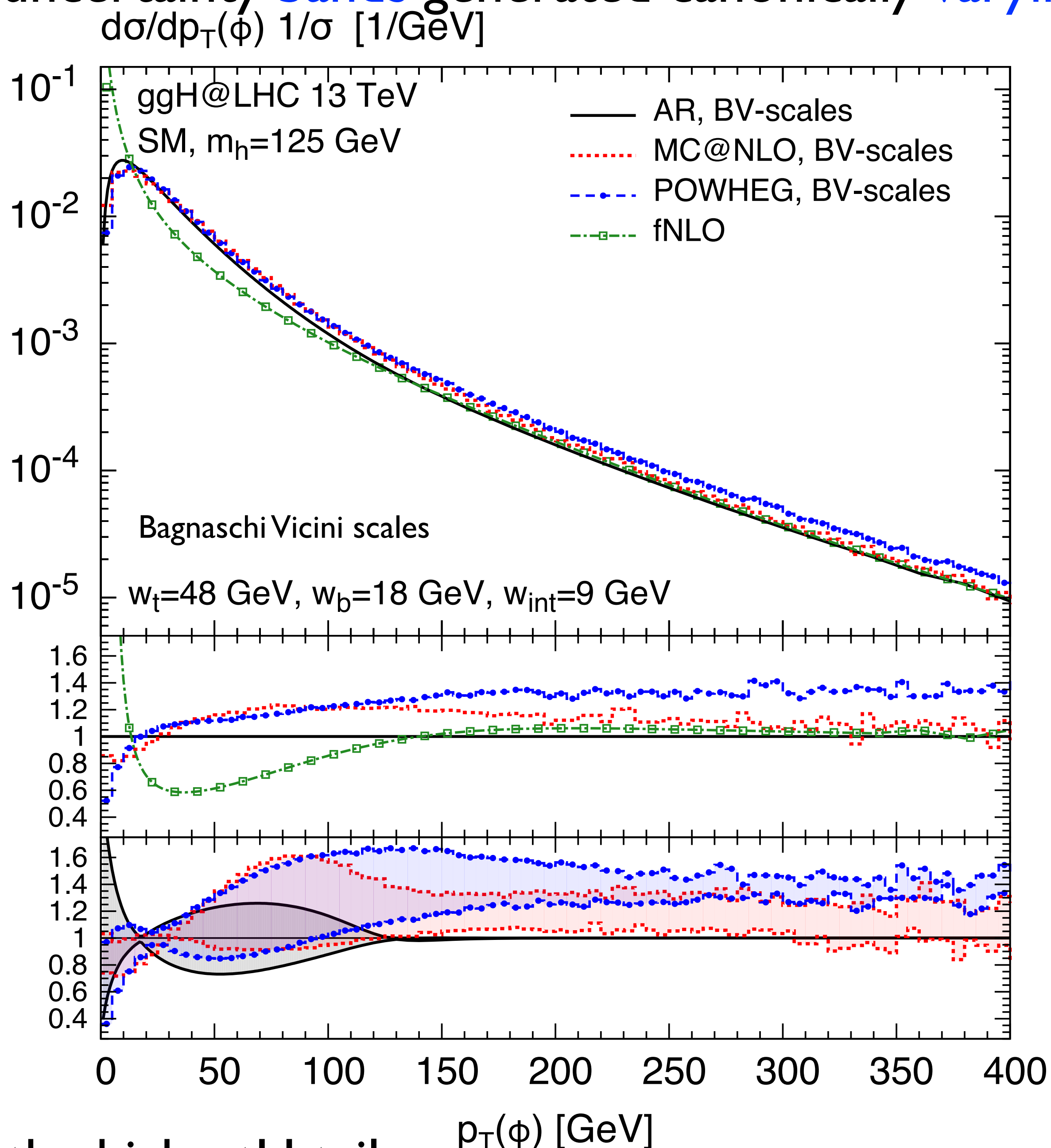

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the high-ptH tail

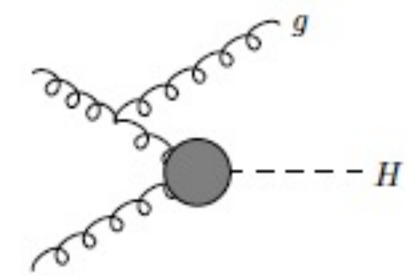
- only LO accurate in these 3 codes + the Parton Shower is not in its validity region (soft/collinear)
- the 3 codes fill the phase space with different upper bounds for the additional radiation
- the details of the results also depend on the PS parameters

⇒ codes with higher accuracy (e.g. HNNLOPS, UN²LOPS) are more reliable in the high-ptH tail

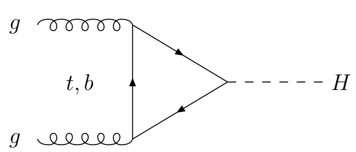
Higgs ptH distribution: a tool to discriminate models

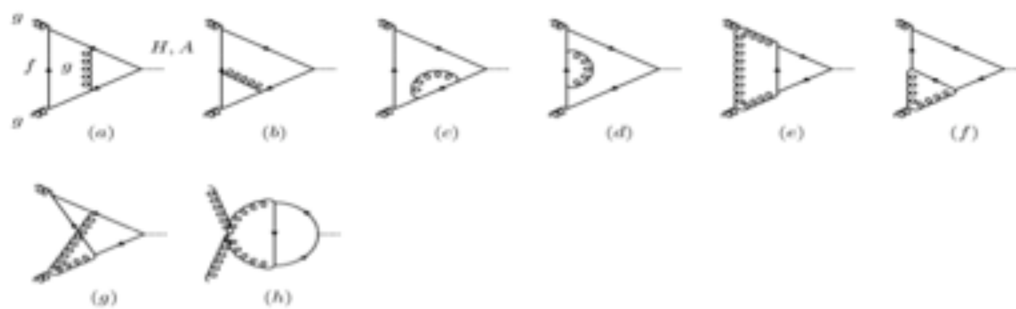
Langenegger Spira Starodumov Trueb 2006, Bagnaschi Degrassi Slavich AV 2011

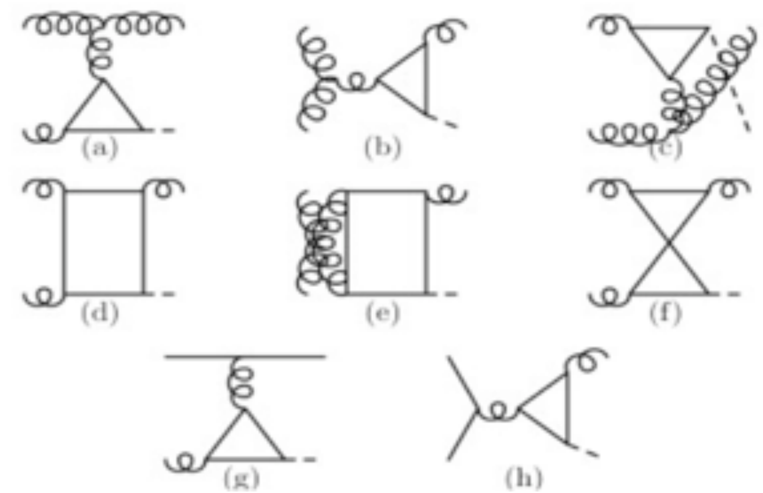
- the Higgs transverse momentum is due to its recoil against QCD radiation



- in the full theory (SM or BSM) gluon emissions occur also from internal lines of the loop







⇒ the distribution is sensitive to the BSM content running in the ggH loop

- in BSM searches we can not rely on the HQEFT (accurate only for a light Higgs)
  in the case of heavy Higgs searches, the full theory is important over the whole ptH range

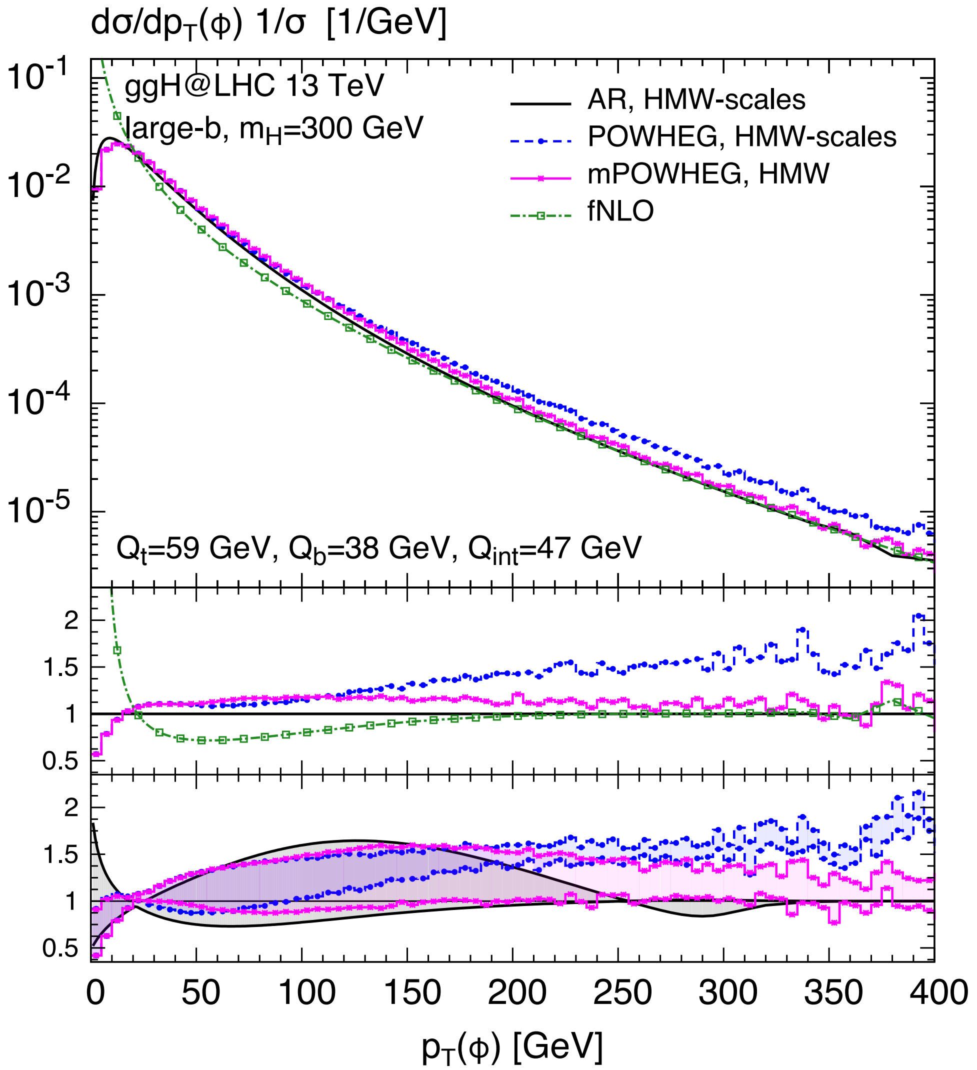
- the interplay between the bottom quark and other heavy particles might be non trivial,
  in particular when the strength of the coupling of the Higgs to the bottom quark is enhanced

- a proper choice of the matching scale value, in the case of bottom dominated scenarios, is crucial

Comparison of different codes (preliminary)   2HDM bottom dominated, heavy scalar

Bagnaschi, Harlander, Mantler, AV, Wiesemann, *in progress*

uncertainty bands generated canonically varying ONLY the matching parameter, fixed muR and muF



bottom dominance   the matching scale is 35 GeV, much larger than mb

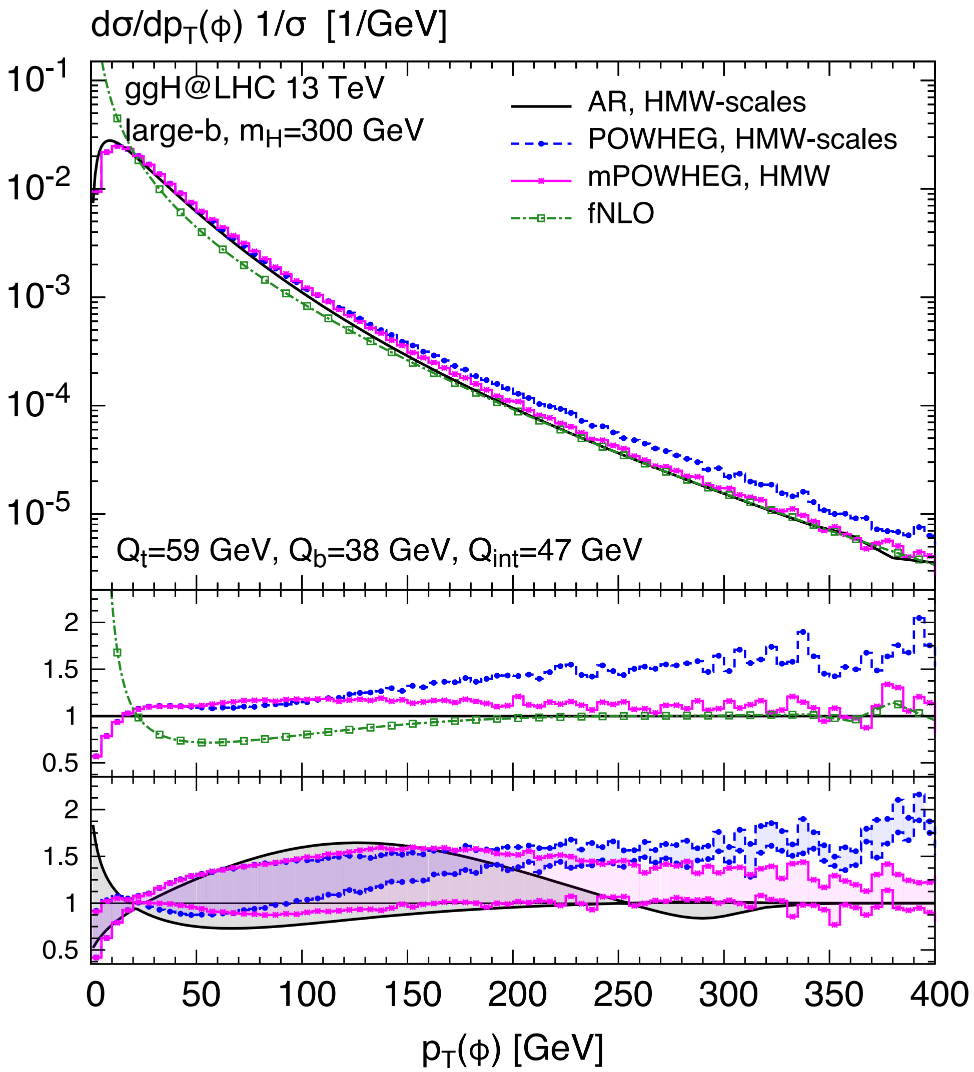
compatibility of the results for ptH < 150 GeV, significant differences for ptH > 250 GeV

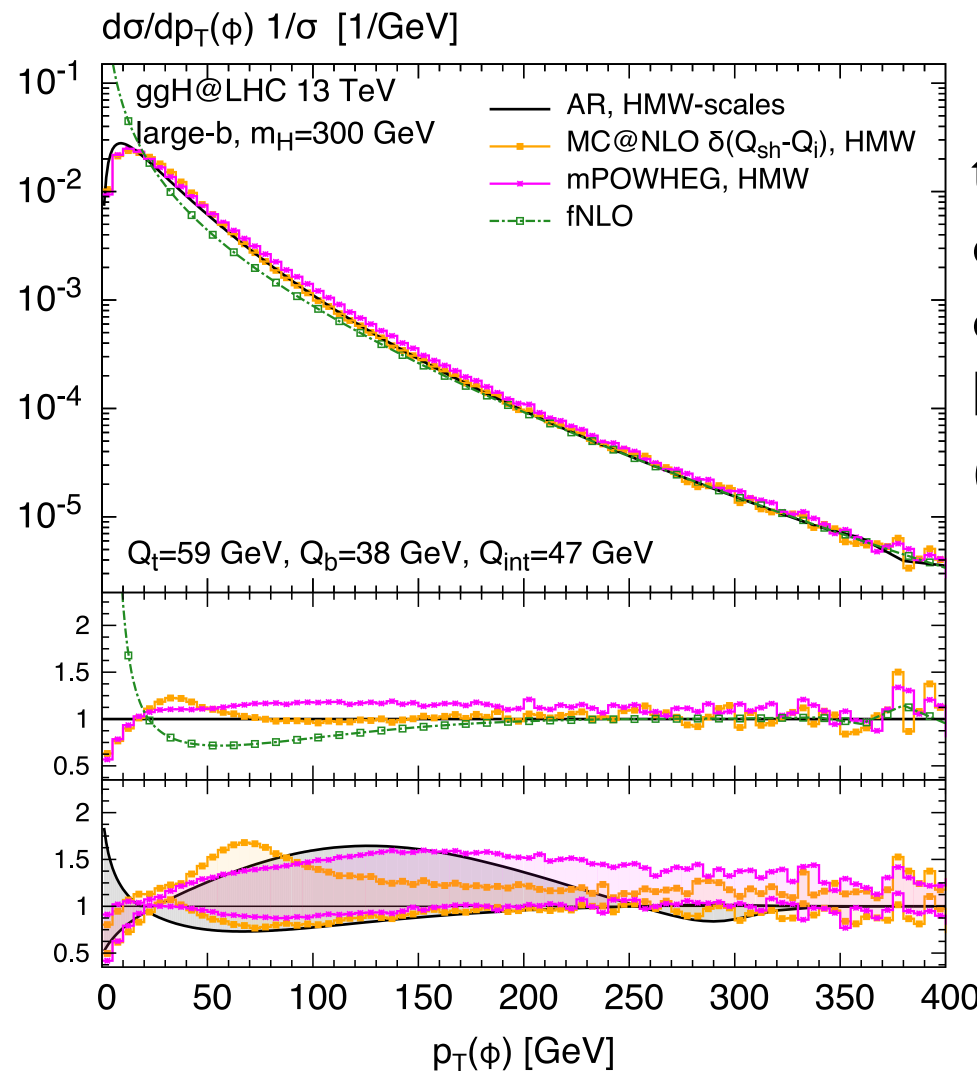
the disagreement is mostly due to the different default formulation of the 3 codes "out-of-the-box"
(the description of the high-ptH tail is LO only)

Comparison of different codes (preliminary)   2HDM bottom dominated, heavy scalar

Bagnaschi, Harlander, Mantler, AV, Wiesemann, *in progress*

uncertainty bands generated canonically varying ONLY the matching parameter, fixed muR and muF





two modified versions of MC@NLO and of POWHEG have been implemented (illustration purpose only)

MC@NLO different choice for the distribution used to extract the Shower scale
POWHEG reduction of the phase space available to the Parton Shower

better agreement in the high-ptH tail and in the overlap of the uncertainty bands

⇒ several algorithmic details are relevant in the prediction of the Higgs ptH distribution (and affect BSM searches)

Shower Monte Carlo matching with NNLO-QCD accuracy: NNLOPS

Hamilton, Nason, Oleari, Zanderighi, arXiv:1212.4504, Hamilton, Nason, Re, Zanderighi, arXiv:1309.0017, Hamilton, Nason, Zanderighi, arXiv:1501.04637

- steps to build a generator
  - POWHEG HJ is NLO accurate for all HJ observables, the limit ptjet → 0 is divergent
  - POWHEG HJ MiNLO is NLO accurate for all H and HJ observables
    the presence of an appropriate improved Sudakov form factor yields a regular ptjet → 0 limit and preserves the NLO accuracy
  - differential rescaling factor to multiply POWHEG HJ MiNLO to reach NNLO accuracy on the observables inclusive over radiation

$$\mathcal{W}(y) = \frac{\int d\sigma^{\rm NNLO}\ \delta\left(y - y\left(\Phi\right)\right)}{\int d\sigma^{\rm MINLO}\ \delta\left(y - y\left(\Phi\right)\right)} = \frac{c_2\alpha_{\rm S}^2 + c_3\alpha_{\rm S}^3 + c_4\alpha_{\rm S}^4}{c_2\alpha_{\rm S}^2 + c_3\alpha_{\rm S}^3 + c_4'\alpha_{\rm S}^4 + \ldots} = 1 + \frac{c_4 - c_4'}{c_2}\,\alpha_{\rm S}^2 + \ldots,$$

the weight $W(y)$ introduces $O(\alpha_s^5)$ spurious terms on the transverse momentum distributions → acceptable

  - variants of the rescaling factor

$$\mathcal{W}\left(y,\, p_{\rm T}\right) = h\left(p_{\rm T}\right)\frac{\int d\sigma_A^{\rm NNLO}\ \delta\left(y - y\left(\Phi\right)\right)}{\int d\sigma_A^{\rm MINLO}\ \delta\left(y - y\left(\Phi\right)\right)} + \left(1 - h\left(p_{\rm T}\right)\right).$$

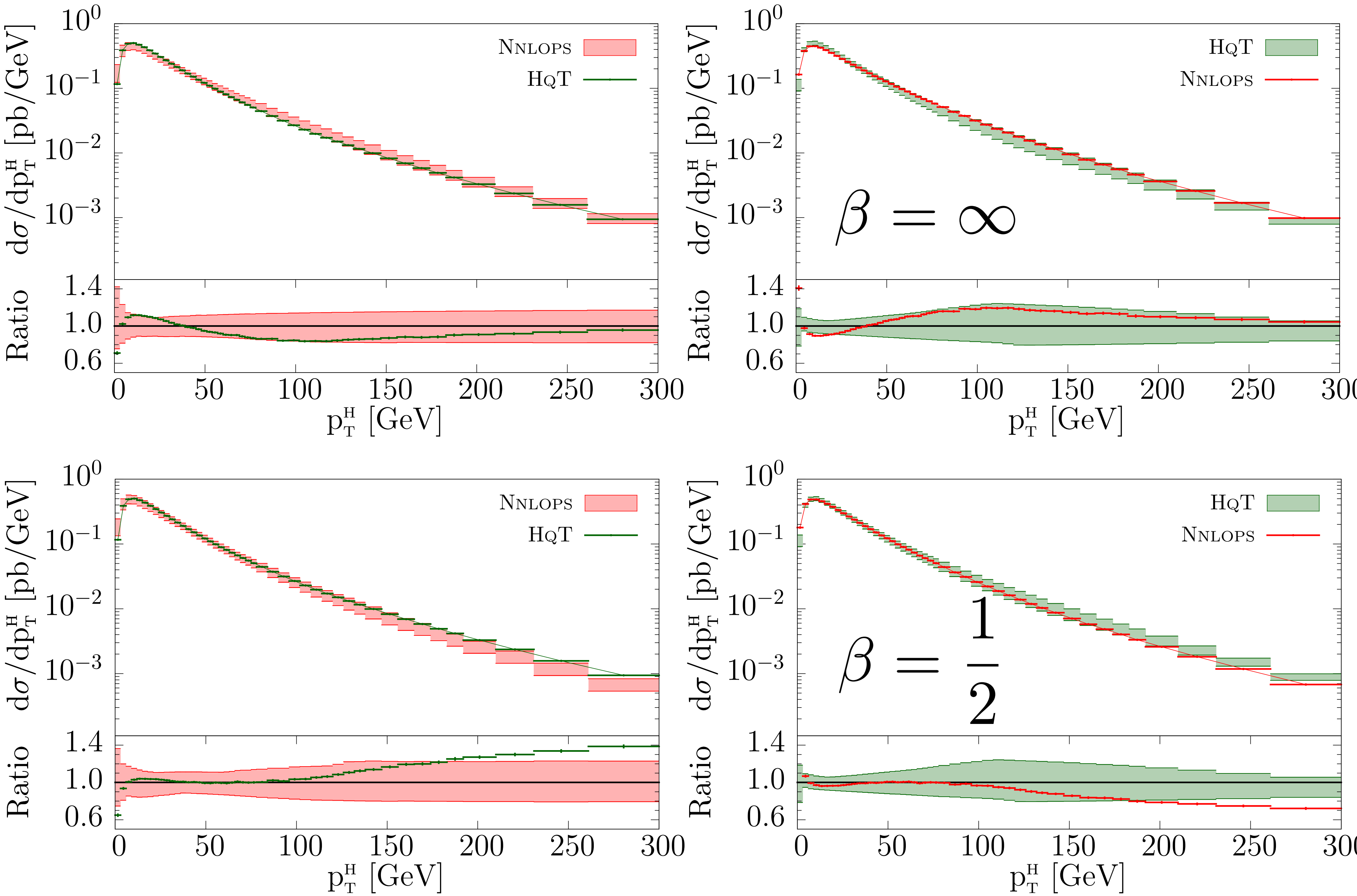
$$h(p_{\rm T}) = \frac{(\beta\, m_{\rm H})^\gamma}{(\beta\, m_{\rm H})^\gamma + p_{\rm T}^\gamma},$$

different possibilities to spread the rescaling factor over the entire ptH range ($\beta=\infty$) or in a smaller region (e.g. $\beta=1/2$)
any finite β modifies the shape of the ptH distribution

Shower Monte Carlo matching with NNLO-QCD accuracy: NNLOPS

Hamilton, Nason, Re, Zanderighi, arXiv:1309.0017

- comparison with HqT (muR=muF=Q=MH/2)
  The uncertainty bands have been obtained varying with a combination of ren./fact. scale variations of the HJ MiNLO generator and of the HNNLO simulation
- The high ptH tail has NLO accuracy



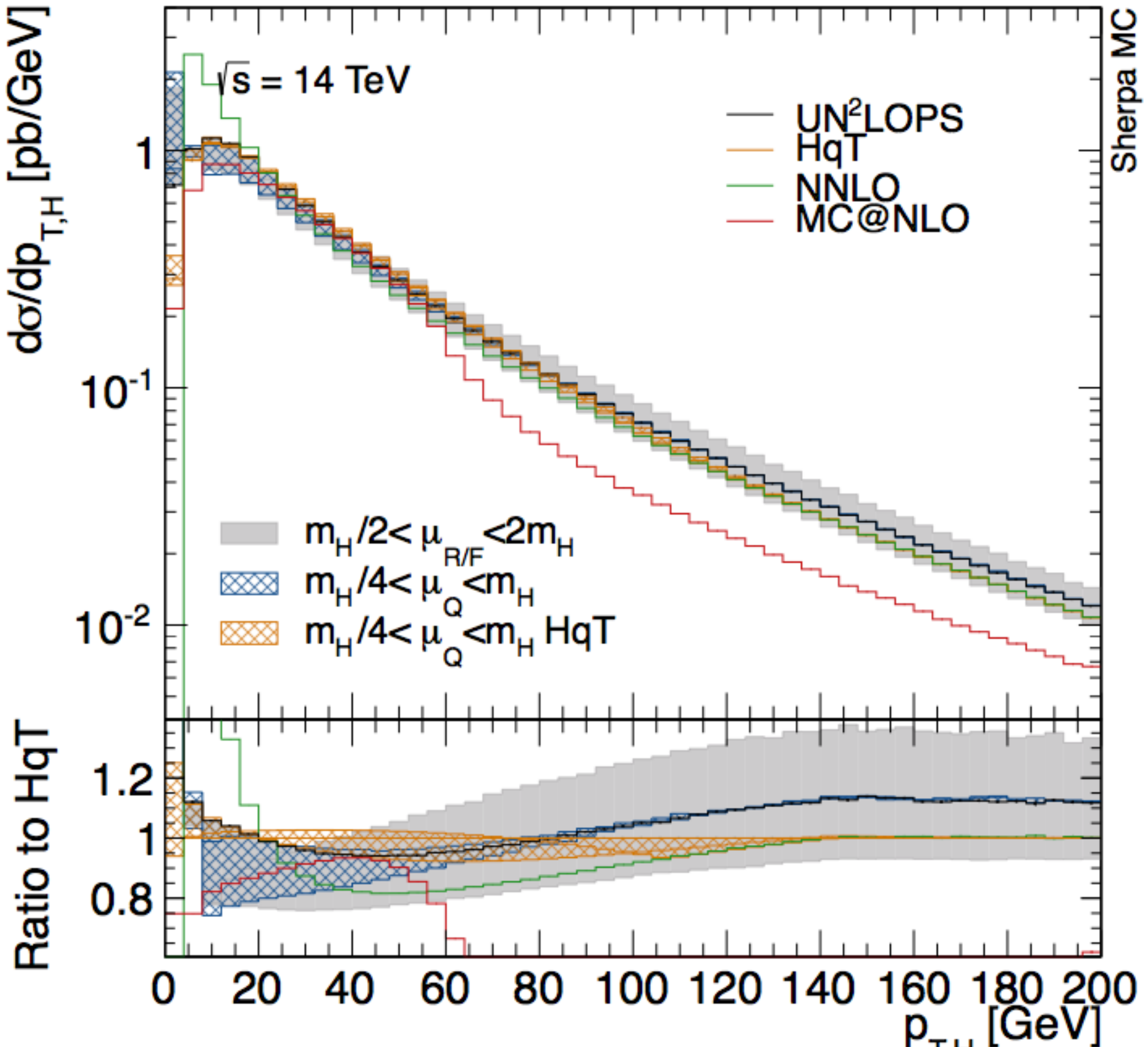
Different shapes compatible over the entire ptH range

Good agreement for ptH<100 GeV
Significant deviation ptH>200 GeV

The comparison with the results of HJ @ NNLO-QCD might help to understand the discrepancies

Shower Monte Carlo matching with NNLO-QCD accuracy: UN²LOPS

Lavesson, Lonnblad, arXiv:0811.2912, Hoeche, Li, Prestel, arXiv:1407.3773



- The UNLOPS scheme merges 0-jet and 1-jet samples (it requires a merging scale), it preserves the accuracy on the total xsec with the definition of a 0-jet bin which is not showered
- The UN²LOPS scheme extends the approach at $O(\alpha_s^2)$
- The virtual corrections are confined in the first bin and not spread over the whole spectrum

- The study of the uncertainty bands and the systematic comparison between NNLOPS and UN²LOPS is of great interest and will require a dedicated effort

Conclusions

- with the first N3LO results we are accessing the possibility of performing precision Higgs physics (total xsec, 0-jet bin xsec)

- given a 2-3% width of the scale uncertainty band, NNLO bottom-quark effects might still be relevant on-going discussion in the HXSWG about the inclusion of higher-order terms via resummation the size of the residual uncertainty

- impressive progress in the evaluation of multi-loop integrals the computational complexity of the problem depends on the number of independent scales (internal and/or external massive lines + kinematical invariants, number of thresholds)

  ⇒ NNLO results for Higgs+1 jet and NLO results for gg→ZZ are now possible and available

  ☞ still a lot to be done (e.g. to include bottom effects at NNLO)

- the prediction of the Higgs transverse momentum distribution is available with NNLO+NNLL (Hres) or with NNLO+PS (HNNLOPS, UN^{2}LOPS) accuracy

- the matching ambiguities can be numerically sizeable and should be considered together with ren./fac. scale variations detailed study at NLO level (SM and BSM) is available, desirable a similar study at NNLO

- a proper treatment of all the matching issues is relevant in BSM searches for heavy neutral scalars or for deviations from the SM coupling structure

Backup

Hadronic cross-section and mixed EW-QCD corrections

Anastasiou, Boughezal, Petriello, **JHEP 0904:003,2009**

Explicit evaluation of virtual 3-loop non-factorizable $\mathcal{O}(\alpha\alpha_s)$ corrections

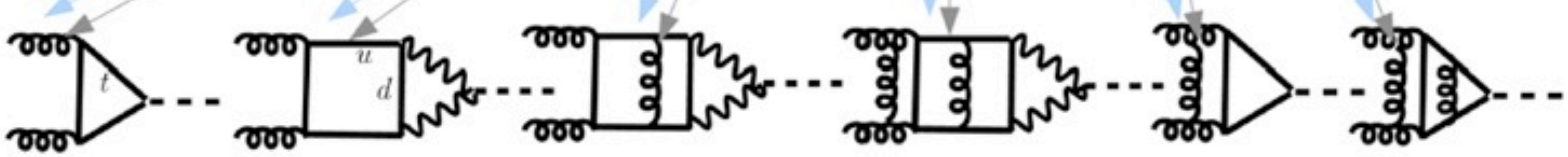
The QCD-LL factorization is assumed

(Taylor expansion of the diagrams to compute the Wilson coefficient of the effective lagrangian)

The validity of the effective theory above the first threshold (MW) is assumed

$$L_{eff} = -\alpha_s \frac{C_1}{4v} H\, G^a_{\mu\nu} G^{a\mu\nu}$$

$$C_1 = -\frac{1}{3\pi}\left\{1 + \lambda_{EW}\left[1 + a_s C_{1w} + a_s^2 C_{2w}\right] + a_s C_{1q} + a_s^2 C_{2q}\right\}$$



Radius of convergence $M_H \leq M_W$;however top-quark EFT valid up to 1 TeV > 2Mt, expect similarity here. Soft gluons dominate the cross section for $\tau = \frac{M_H^2}{s} \to 1$

$$C_{1q} = \frac{11}{4}, \quad C_{2q} = \frac{2777}{288} + \frac{19}{16}L_t + N_F\left(-\frac{67}{96} + \frac{1}{3}L_t\right)$$

$$\lambda_{EW} = \frac{3\alpha}{16\pi s_W^2}\left\{\frac{2}{c_W^2}\left[\frac{5}{4} - \frac{7}{3}s_W^2 + \frac{22}{9}s_W^4\right] + 4\right\}$$

Complete Factorization holds if $C_{1w} = C_{1q}$ & $C_{2w} = C_{2q}$

from Boughezal talk at APS-DPF 2009

$$C_1^{fac} = -\frac{1}{3\pi}(1 + \lambda_{EW})\left\{1 + a_s C_{1q} + a_s^2 C_{2q}\right\}$$

Hadronic cross-section and mixed EW-QCD corrections

Anastasiou, Boughezal, Petriello, **JHEP 0904:003,2009**

The subleading $\mathcal{O}(\alpha\alpha_s)$ terms, not enhanced by large soft/collinear logs,
do not factorize

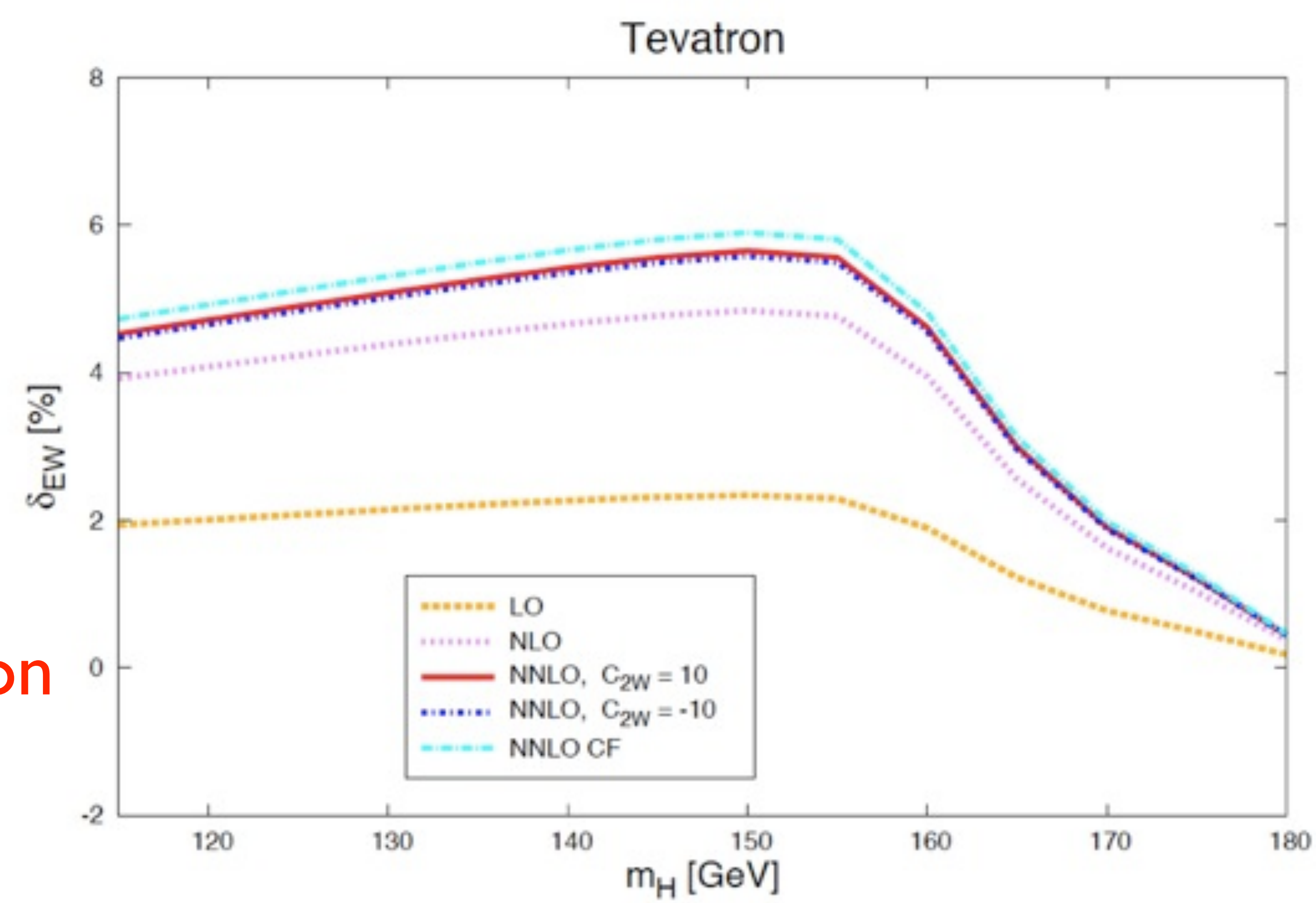
$$C_{1w} = \frac{7}{6}$$ to be compared with $$C_{1w}^{fac} = C_{1q} = 11/4$$

Very tiny numerical impact of the terms that violate the factorization hypothesis

$$\sigma_{EW}^{NNLO} = \sigma_{t,lf}^{(0)} \Big\{ G_{ij}^{(0)}(z) \left[1 + a_s(C_{1w} - C_{1q}) + a_s^2 \left(C_{2w} - C_{2q} + C_{1q}(C_{1q} - C_{1w}\right)\right]$$
$$+ a_s G_{ij}^{(1)}(z) \left[1 + a_s(C_{1w} - C_{1q})\right] + a_s^2 G_{ij}^{(2)} \Big\} \quad \text{(MRST2006 NNLO)},$$

$$a_s G_{ij}^{(1)}(z) \gg a_s \left(C_{1w} - C_{1q}\right)$$

The 3-loop virtual corrections indicate that Complete Factorization is phenomenologically a good approximation of the mixed EW-QCD corrections



Matching fixed-order matrix elements with Parton Shower: POWHEG

$$d\sigma^{\mathrm{NLO+PS}} = d\Phi_B \bar{B}^s(\Phi_B)\left[\Delta^s(p_\perp^{\mathrm{min}}) + d\Phi_{R|B}\frac{R^s(\Phi_R)}{B(\Phi_B)}\Delta^s(p_{\mathrm{T}}(\Phi))\right] + d\Phi_R R^f(\Phi_R) + d\Phi_R R_{reg}(\Phi_R)$$

$$\bar{B}^s = B(\Phi_B) + \left[V(\Phi_B) + \int d\Phi_{R|B} R^s(\Phi_{R|B})\right]$$

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$R = R_{reg} + R_{div}$ is the sum of all the real emission squared matrix elements, with a regular (divergent) behavior in the collinear limit

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$R_{div} = R^s + R^f$ R_div can be split in the sum of a singular part plus a finite remainder

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R^s enters in the Sudakov form factor $\Delta^s(p_T(\Phi))$

Matching fixed-order matrix elements with Parton Shower: POWHEG

$$d\sigma^{\mathrm{NLO+PS}} = d\Phi_B \bar{B}^s(\Phi_B) \left[\Delta^s(p_\perp^{\mathrm{min}}) + d\Phi_{R|B} \frac{R^s(\Phi_R)}{B(\Phi_B)} \Delta^s(p_{\mathrm{T}}(\Phi))\right] + d\Phi_R R^f(\Phi_R) + d\Phi_R R_{reg}(\Phi_R)$$

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$R_{div} = R^s + R^f$ R_div can be split in the sum of a singular part plus a finite remainder

R^s enters in the Sudakov form factor $\Delta^s(p_T(\Phi))$

$$R^s = \frac{h^2}{h^2 + p_T^2} R_{div} \qquad R^f = \frac{p_T^2}{h^2 + p_T^2} R_{div}$$

at low ptH, the damping factor → 1,
R_div tends to its collinear approximation,
at large ptH, the damping factor → 0 and
suppresses R_div in the Sudakov and in the [ ]

Matching fixed-order matrix elements with Parton Shower: POWHEG

$$d\sigma^{\rm NLO+PS} = d\Phi_B \bar{B}^s(\Phi_B)\left[\Delta^s(p_\perp^{\rm min}) + d\Phi_{R|B}\frac{R^s(\Phi_R)}{B(\Phi_B)}\Delta^s(p_{\rm T}(\Phi))\right] + d\Phi_R R^f(\Phi_R) + d\Phi_R R_{reg}(\Phi_R)$$

$$\bar{B}^s = B(\Phi_B) + \left[V(\Phi_B) + \int d\Phi_{R|B} R^s(\Phi_{R|B})\right]$$

$R = R_{reg} + R_{div}$ is the sum of all the real emission squared matrix elements, with a regular (divergent) behavior in the collinear limit

$R_{div} = R^s + R^f$ R_div can be split in the sum of a singular part plus a finite remainder

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$\bar{B}$ effectively rescales the events with ptH ≲ *h*

h is the effective upper limit for the inclusion of multiple parton emissions

the total cross section does NOT depend on the value of *h*

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B̲ effectively rescales the events with ptH ≲ *h*

h is the effective upper limit for the inclusion of multiple parton emissions

the total cross section does NOT depend on the value of *h*

the first (hardest) emission is generated according to the above formula
the following emissions are generated by the Shower (PYTHIA/HERWIG)
the PT of the second radiated parton is limited by the variable *scaleup*, by default the PT of the first
(it can still be quite hard, the limit changes event by event)

Matching fixed-order matrix elements with Parton Shower: MC@NLO

$$\left(\frac{d\sigma}{dO}\right)_{\mathrm{MC@NLO}} = \int d\Phi_n \left[B_n + V_n + \int d\Phi_1^{\mathrm{MC}}\, K_{n+1}^{\mathrm{MC}}\right] \mathcal{I}_n^{\mathrm{MC}}(O)$$
$$+ \int \left[d\Phi_{n+1} R_{n+1} - d\Phi_{n+1}^{\mathrm{MC}} K_{n+1}^{\mathrm{MC}}\right] \mathcal{I}_{n+1}^{\mathrm{MC}}(O)$$

Matching fixed-order matrix elements with Parton Shower: MC@NLO

$$\left(\frac{d\sigma}{dO}\right)_{\rm MC@NLO} = \int d\Phi_n \left[B_n + V_n + \int d\Phi_1^{\rm MC}\, K_{n+1}^{\rm MC}\right] \mathcal{I}_n^{\rm MC}(O)$$
$$+ \int \left[d\Phi_{n+1} R_{n+1} - d\Phi_{n+1}^{\rm MC} K_{n+1}^{\rm MC}\right] \mathcal{I}_{n+1}^{\rm MC}(O)$$

all the emissions of additional partons are generated in a first stage by the Shower (PYTHIA/HERWIG)

in MadGraph5_aMC@NLO
the initial phase-space available to the shower is fixed by a scale Q^s
Q^s is not a constant,
but it is extracted random in an interval around a central value Q_0, the shower scale,
related to the hard scale of the process

the hardest emission receives the exact real matrix element corrections,
with a MC counterterm to avoid a double counting

The Sudakov form factor, active in each emission of the Shower,
is based on the universal Altarelli-Parisi splitting function

The total cross section does not depend on the value of Q_0

Matching fixed-order and resummed results: analytical formulation

$$\frac{d\hat{\sigma}^{(\mathrm{res.})}_{V\,ab}}{dq_T^2}(q_T, M, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) = \frac{M^2}{\hat{s}} \int_0^\infty db\, \frac{b}{2}\, J_0(bq_T)\, \mathcal{W}^V_{ab}(b, M, \hat{s}; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2)\,,$$

$$\mathcal{W}^V_N(b, M; \alpha_S(\mu_R^2), \mu_R^2, \mu_F^2) = \underbrace{\mathcal{H}^V_N\left(M, \alpha_S(\mu_R^2); M^2/\mu_R^2, M^2/\mu_F^2, M^2/Q^2\right)}_{\text{process dependent}} \times \exp\{\underbrace{\mathcal{G}_N(\alpha_S(\mu_R^2), L; M^2/\mu_R^2, M^2/Q^2)}_{\text{universal}}\}\,,$$

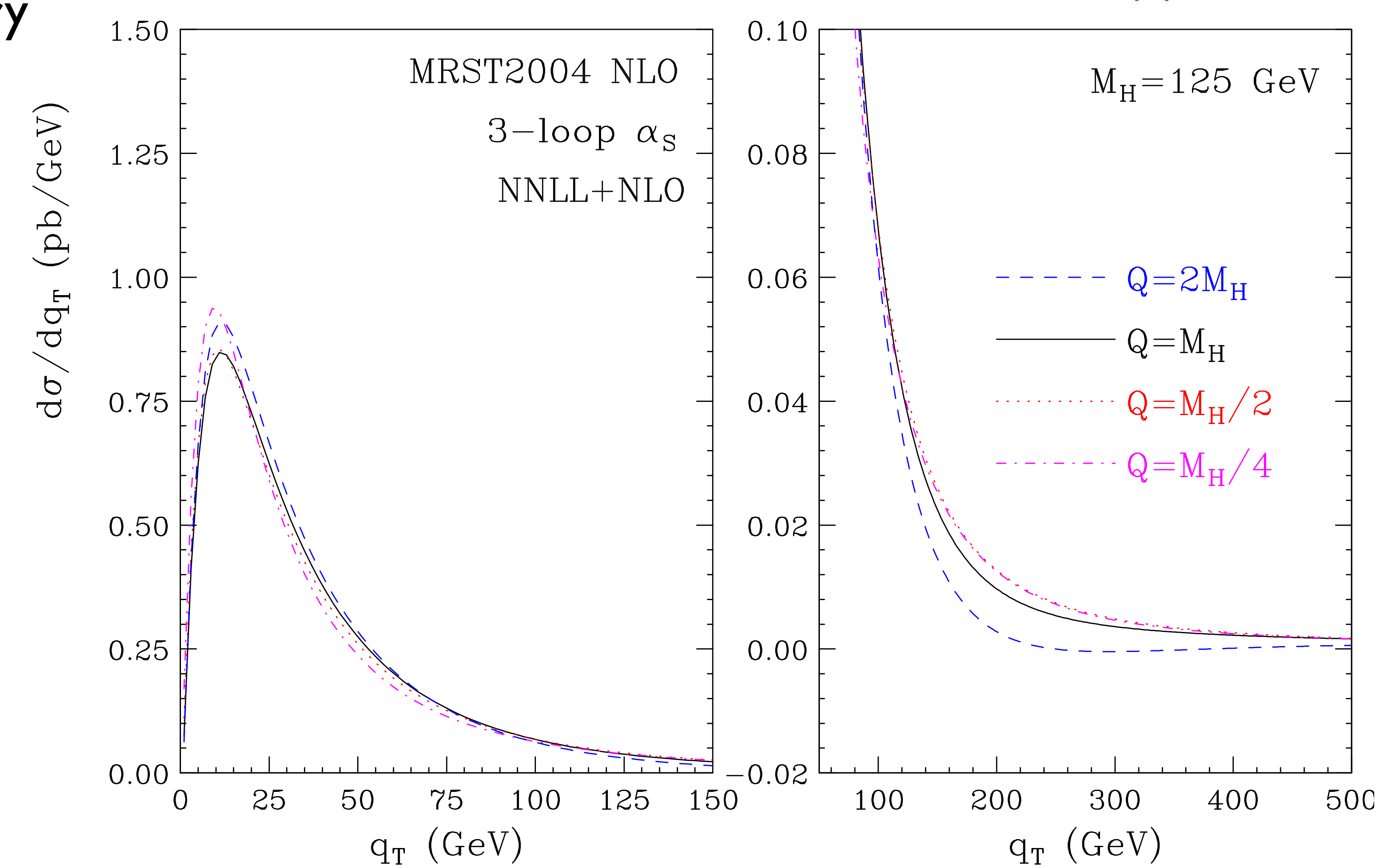
- the factorization (in conjugate space) of the cross section for multiple emissions can be defined at a given scale Q called resummation scale

- the physical result does not depend on Q, but at fixed order in perturbation theory a residual dependence on Q is left

- the choice of Q effectively determines the range of ptH where the resummation is effective

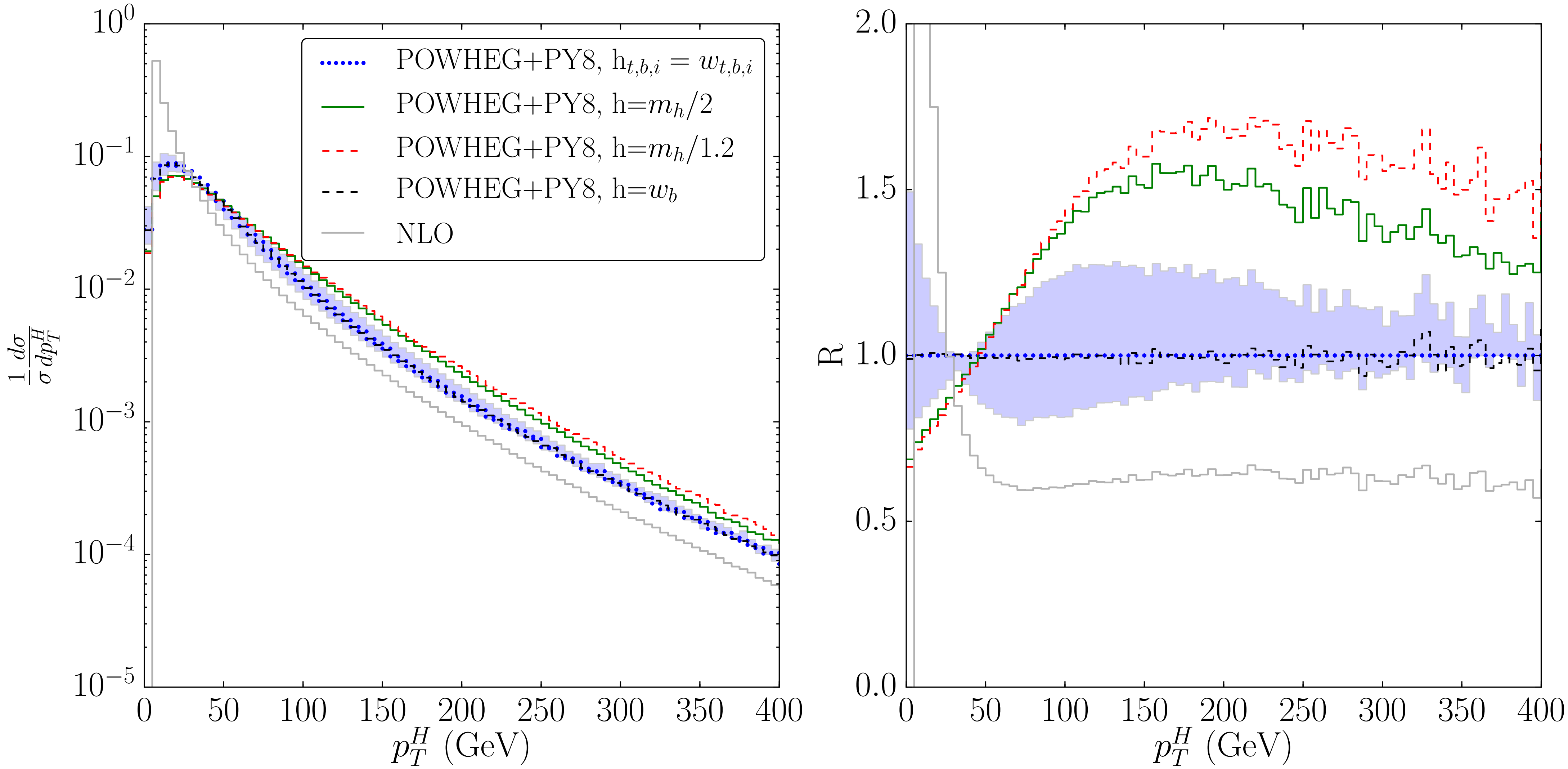
- the total xsec does not depend, also at fixed order, on Q

Bozzi Catani De Florian Grazzini, arXiv:hep-ph/0508068



Few results with POWHEG: 2HDM, Heavy scalar production

E.Bagnaschi,AV, arXiv:1505.00735



scenario bottom dominated

well described also by a
one scale run (bottom scale)

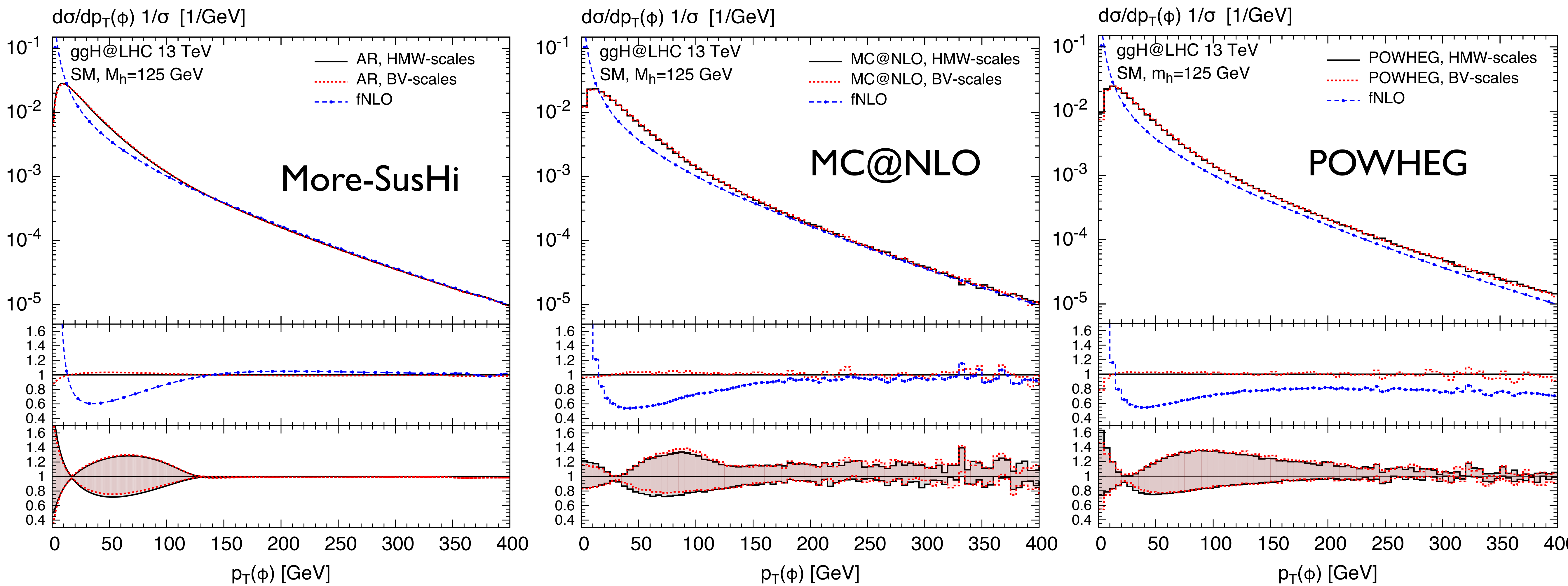
using MH/2 or even MH/1.2
would lead to a huge
discrepancy

Comparison of different codes (preliminary)   SM MH=125 GeV

Bagnaschi, Harlander, Mantler, AV, Wiesemann, *in progress*

2) same code → deviations due to the different numerical choices of the matching parameter

uncertainty bands generated canonically varying ONLY the matching parameter, fixed muR and muF



BV ~ HMW scales → in each plot the central values and the uncertainty bands overlap

the same plots are less trivial in BSM scenarios where the BV and HMW scales are

Choice of the resummation scale: analytical results in the HQEFT

G.Bozzi, S.Catani, D.De Florian, M.Grazzini, arXiv:hep-ph/0508068

- in the HQEFT (pointlike ggH vertex) the only hard scattering scale is MH;
  the resummation of log(ptH/MH) is valid for ptH→0; these logs vanish for ptH=MH
  ⇒ the resummation scale is typically chosen Q=MH/2

  for a light Higgs, subleading terms that could spoil the factorization of the cross section are numerically small up to large ptH values ~ MH/2
  ⇒ the use/extrapolation of the resummed expression up to ptH~Q=MH/2 is justified

- in the full theory (SM or BSM) the radiation resolves the hard scattering vertex for ptH ~ mq :
  in the ptH→0 limit the resummation is in any case possible
  but
  the extrapolation of this result for ptH > mq is not automatically guaranteed (multiscale process)

- the problem appears with the bottom quark for ptH ~ O(mb)
  in the SM the bulk of the bottom mass effects and of the associated ambiguities is of O(10%)
  in BSM models where the bottom role is enhanced, the treatment of these effects is delicate