Università degli Studi di Milano

INFN Istituto Nazionale di Fisica Nucleare

Matching uncertainties in the prediction of the Higgs transverse momentum distribution in the SM and in the 2HDM

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The general framework

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  → any model that describes the EWSB sector must include such a state in its spectrum

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  → to test the SM-only hypothesis and to measure, in this framework, the Higgs parameters
  → to appreciate possible tensions with the SM and to focus on the most promising kinematical regions that might provide hints of new physics
  → under the assumption of an extended model (e.g. a 2HDM), we want to correctly restrict the parameter space of the model:
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- Higgs production in gluon fusion and its decay into a photon pair has a special status
  because it involves loops in both steps,
  offering a handle to test the presence of new virtual particles,
  whose direct real production is not (yet) possible with the available energy/luminosity

Plan of the talk

- few quick remarks on the recent progresses
  for the total xsec and for the H+1jet production in gluon fusion

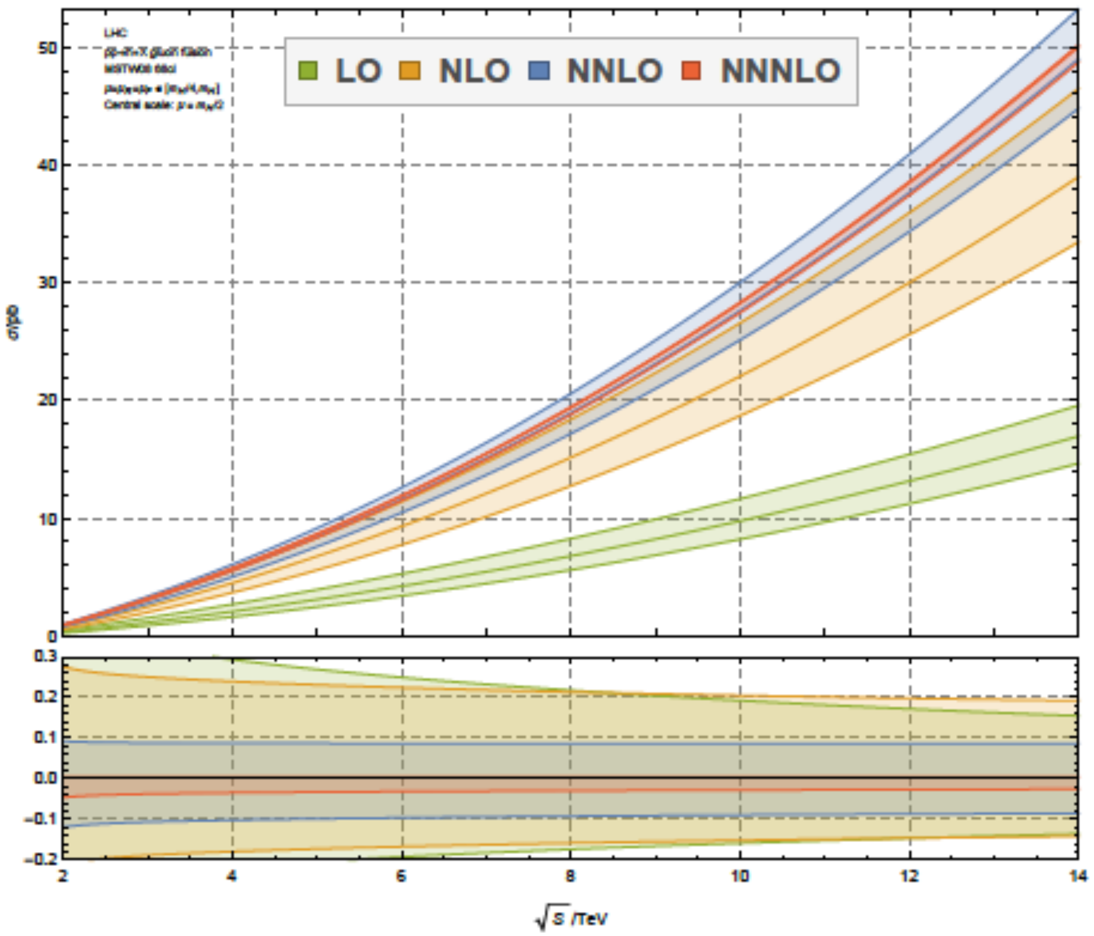
- the Higgs transverse momentum distributions
  - general comments
  - mass effects in gluon fusion
  - matching ambiguities and uncertainties

- comparison of different approaches to choose a sensible central value for the matching parameters

- comparison of different matching schemes in the SM and in the 2HDM with NLO-QCD accuracy

- few comments about NNLO-QCD accurate results

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

Mueller, Oeztuerk, arXiv:1512.08570

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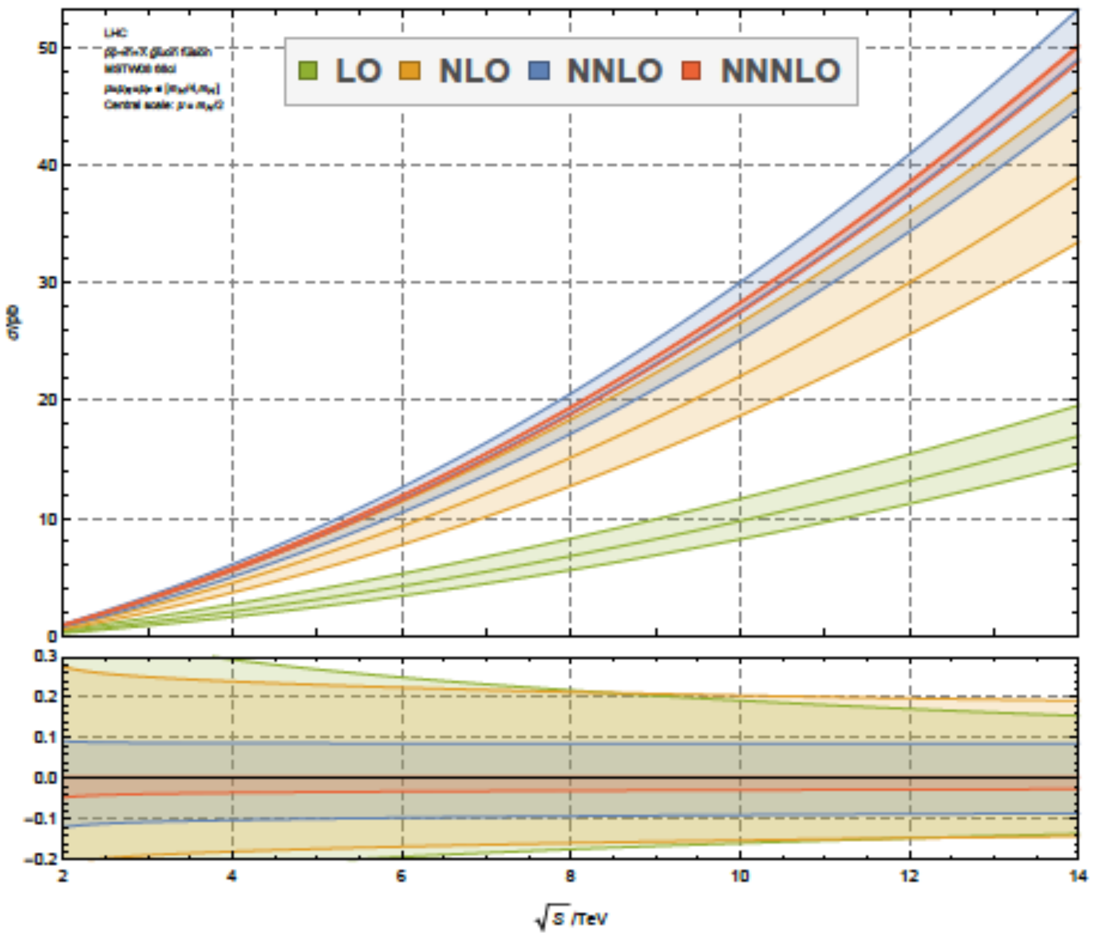

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- is scale variation sufficient to estimate the missing higher orders?
- are there other computational techniques to include subsets of higher-order corrections?
- is the EWxQCD interplay fully under control?
- how large are the missing NNLO quark-mass effects? Mueller, Oeztuerk, arXiv:1512.08570
- are PDFs accurate and consistent?

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 (it depends on mb) 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%

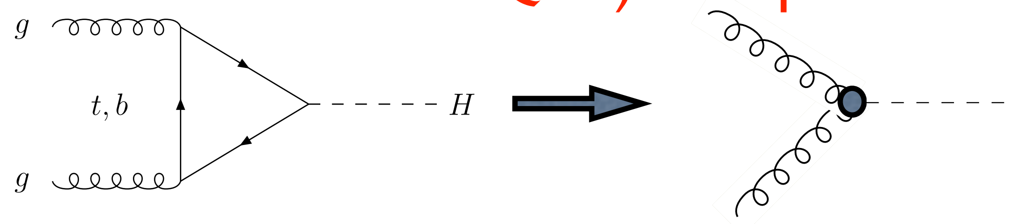
the top-quark mass effects have been studied at NNLO-QCD and are smaller than 1% of σ(NNLO)
Marzani, Ball, Del Duca, Forte, AV (2008), Harlander et al (2009,2010), Pak, Rogal, Steinhauser (2009)

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



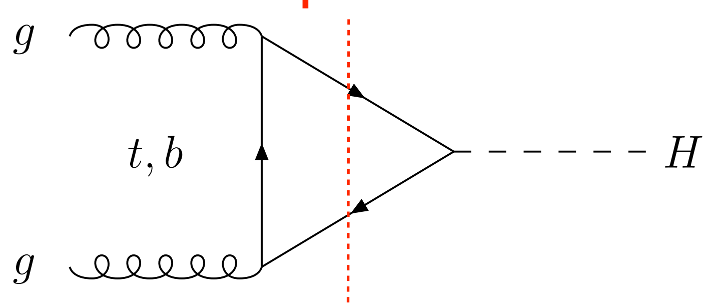
the partonic total cross sections depends only on $z = \frac{m_H^2}{s}$

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)

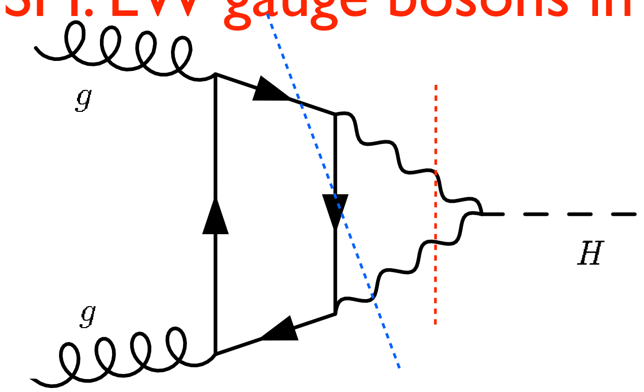
SM: exact dependence on the quark masses



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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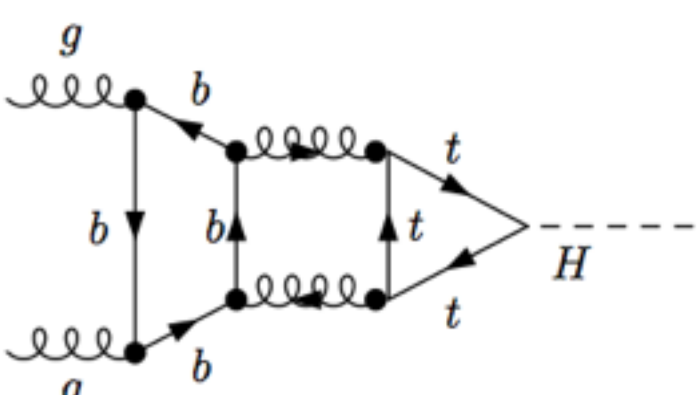

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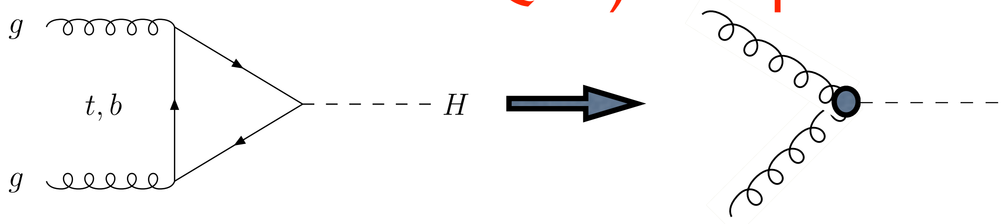

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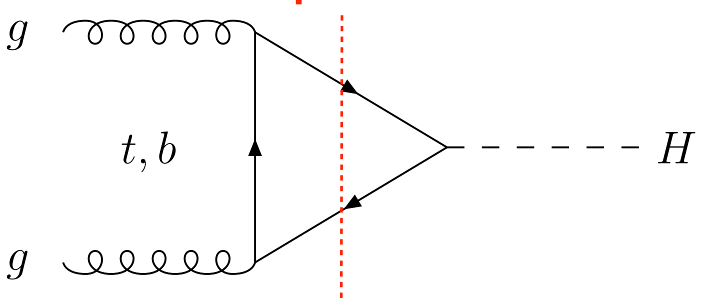

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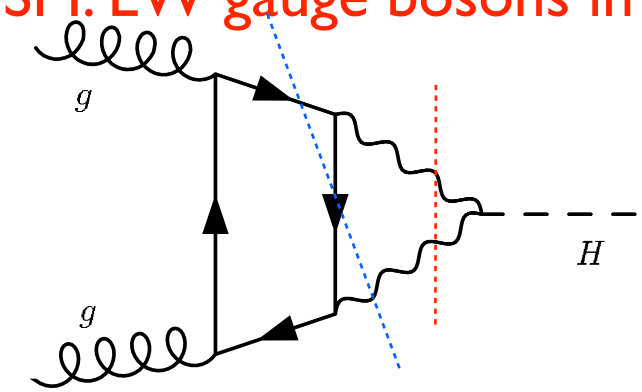

NLO-EW

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

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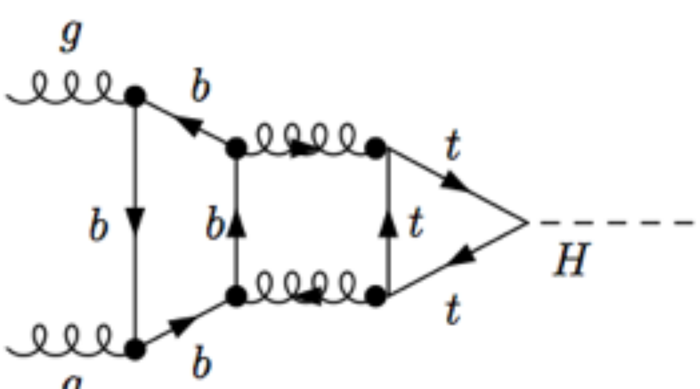

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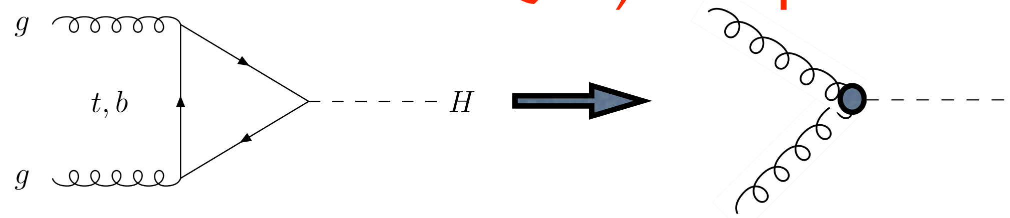

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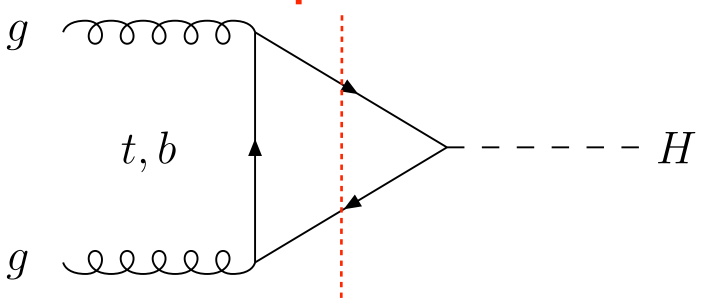

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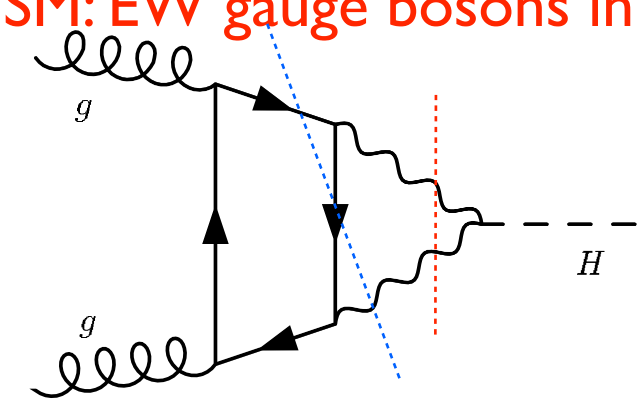

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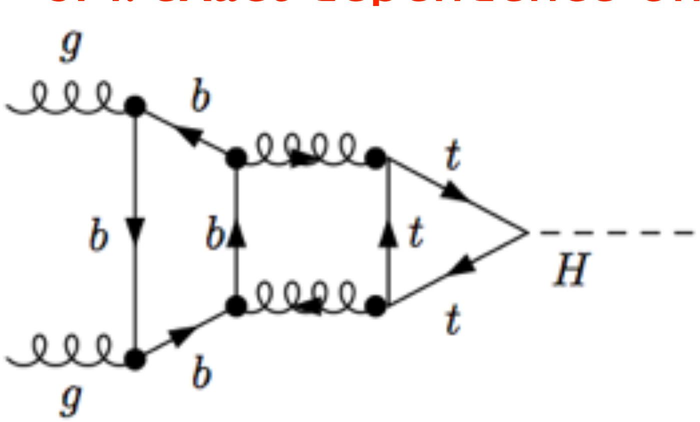

NNLO-QCD

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 ☹

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

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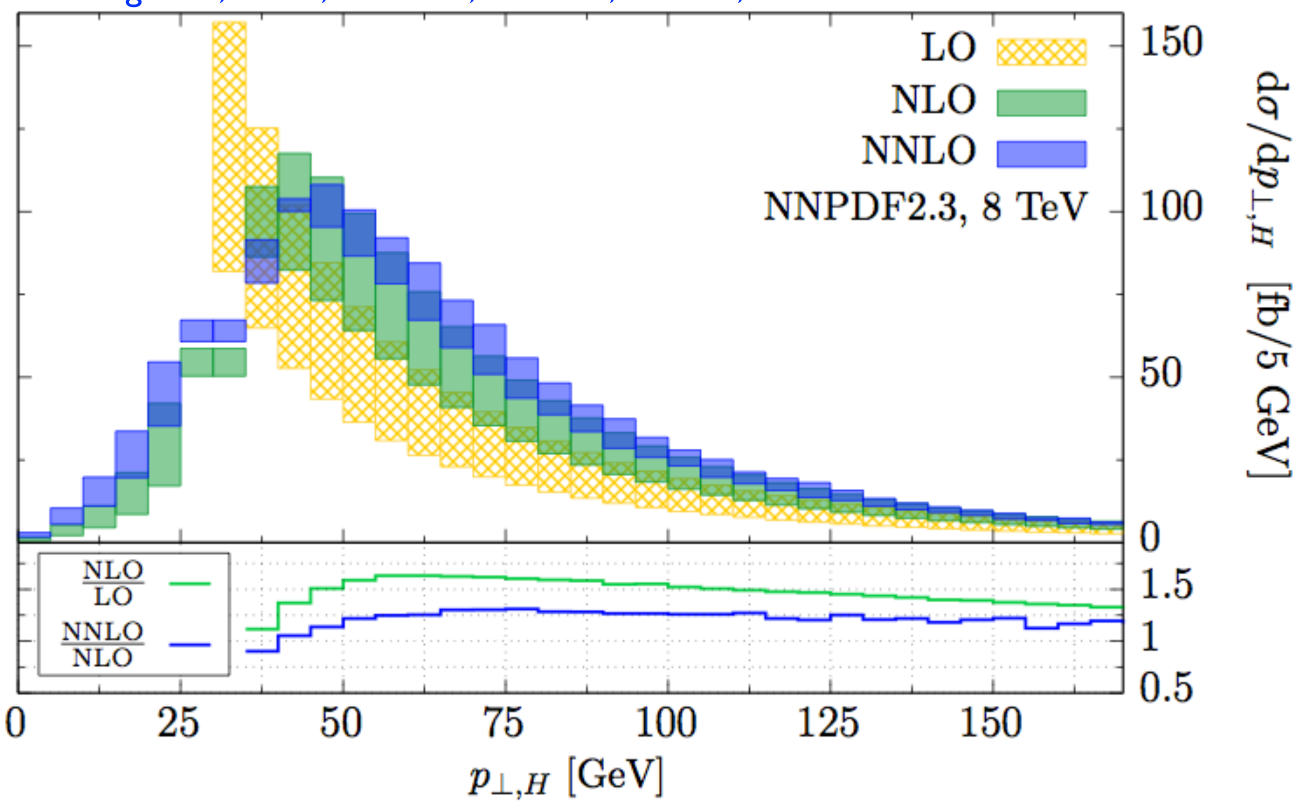

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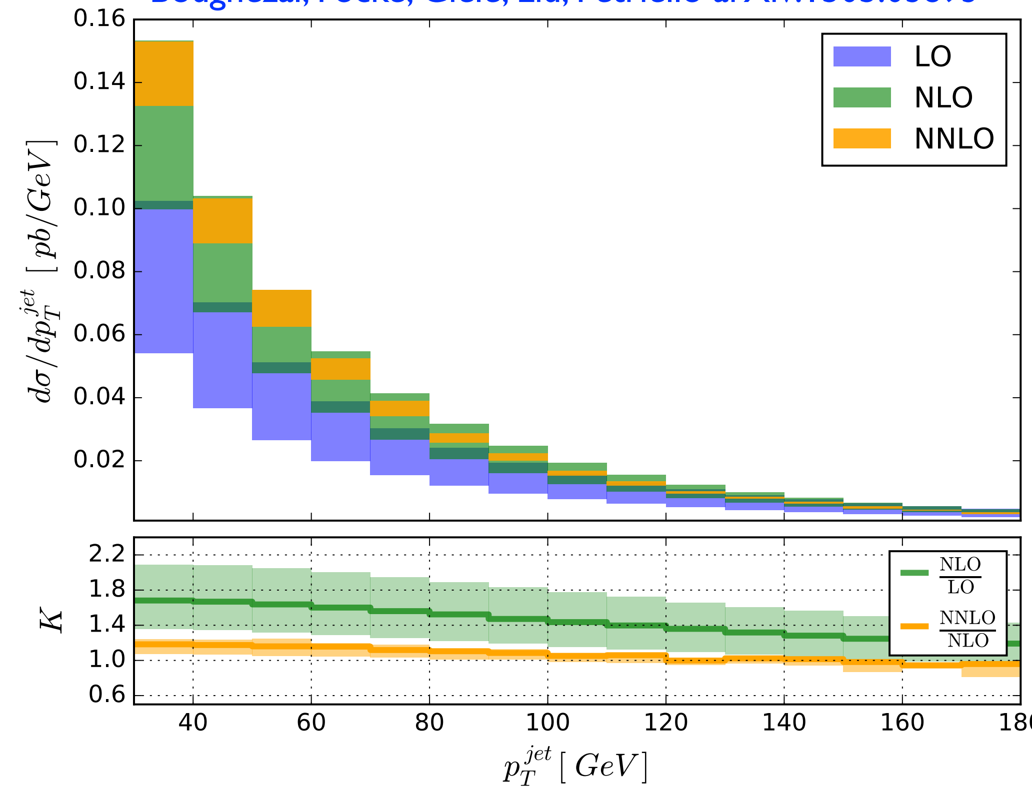
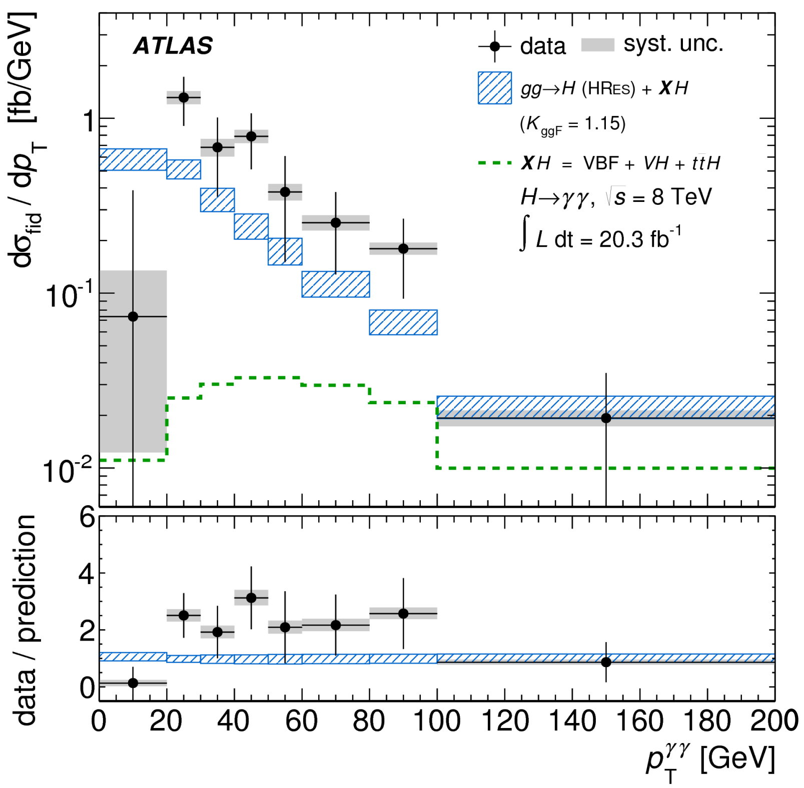
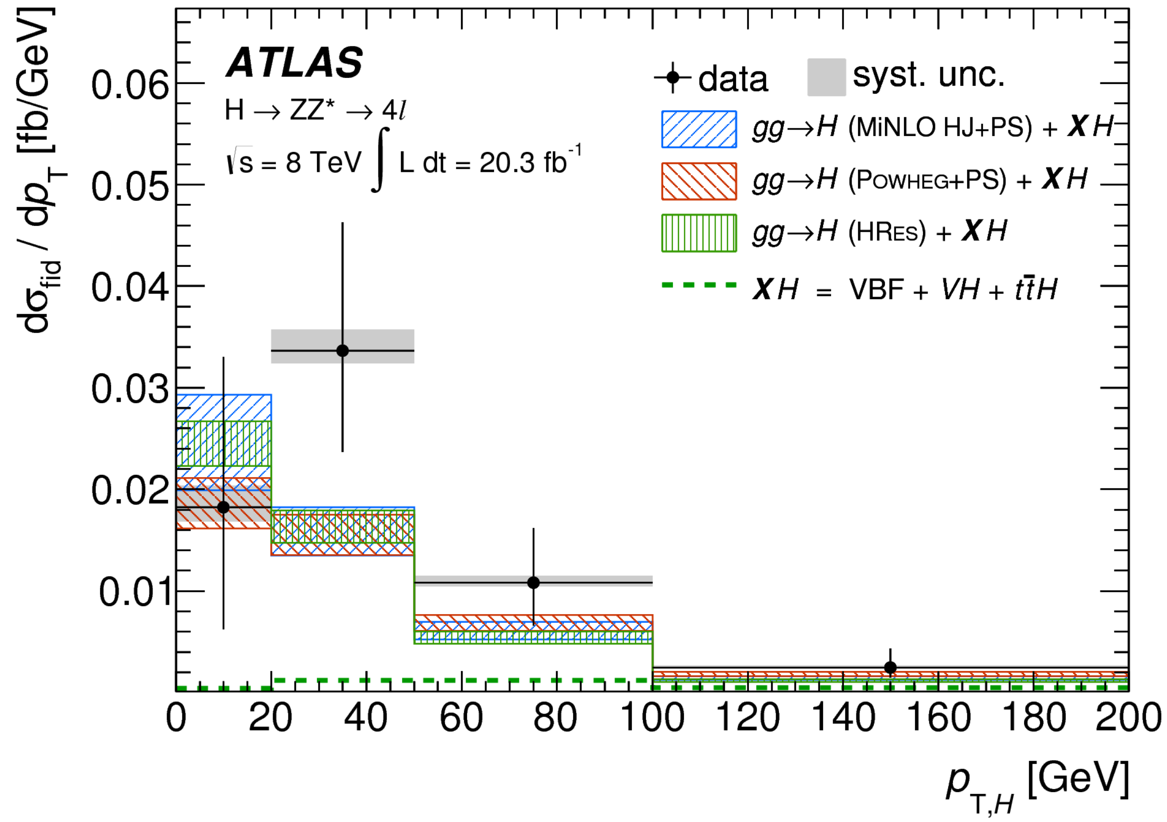
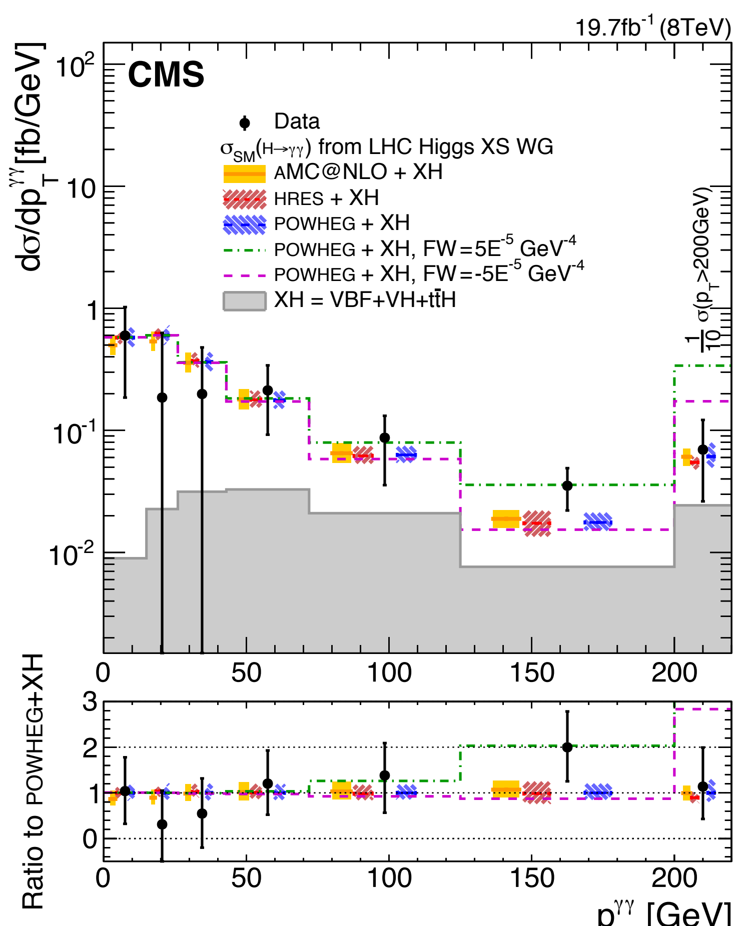


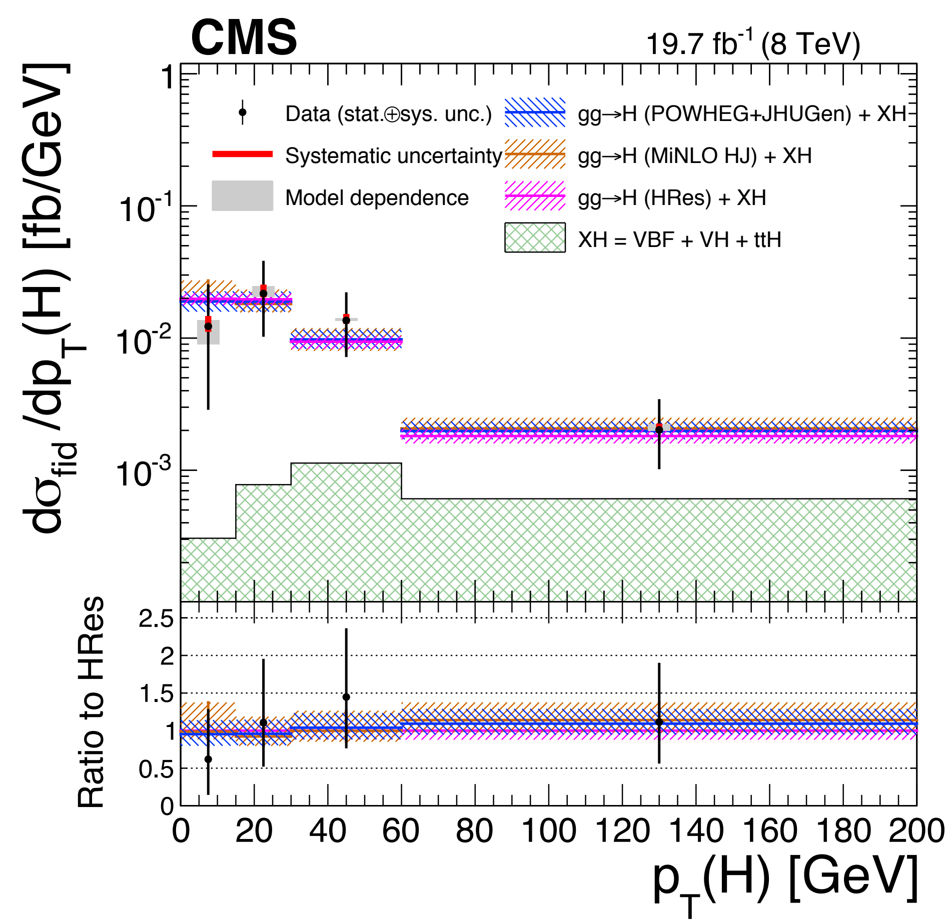
- same perturbative order $O(\alpha_s^5)$ as the N3LO calculation for the total xsec
- results obtained in the HQET, with three different computational techniques
- the 0-jet bin cross section at N3LO is available (by subtraction)
- results including Higgs decay (γγ, WW, ZZ) allow to compute fiducial 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)
- Higgs+1 jet at NLO-QCD including mass effects is not available yet (cfr. previous slide)
  Frederix, Frixione, Vryonidou, Wiesemann, arXiv:1604.03017

Higgs transverse momentum distribution: first experimental results





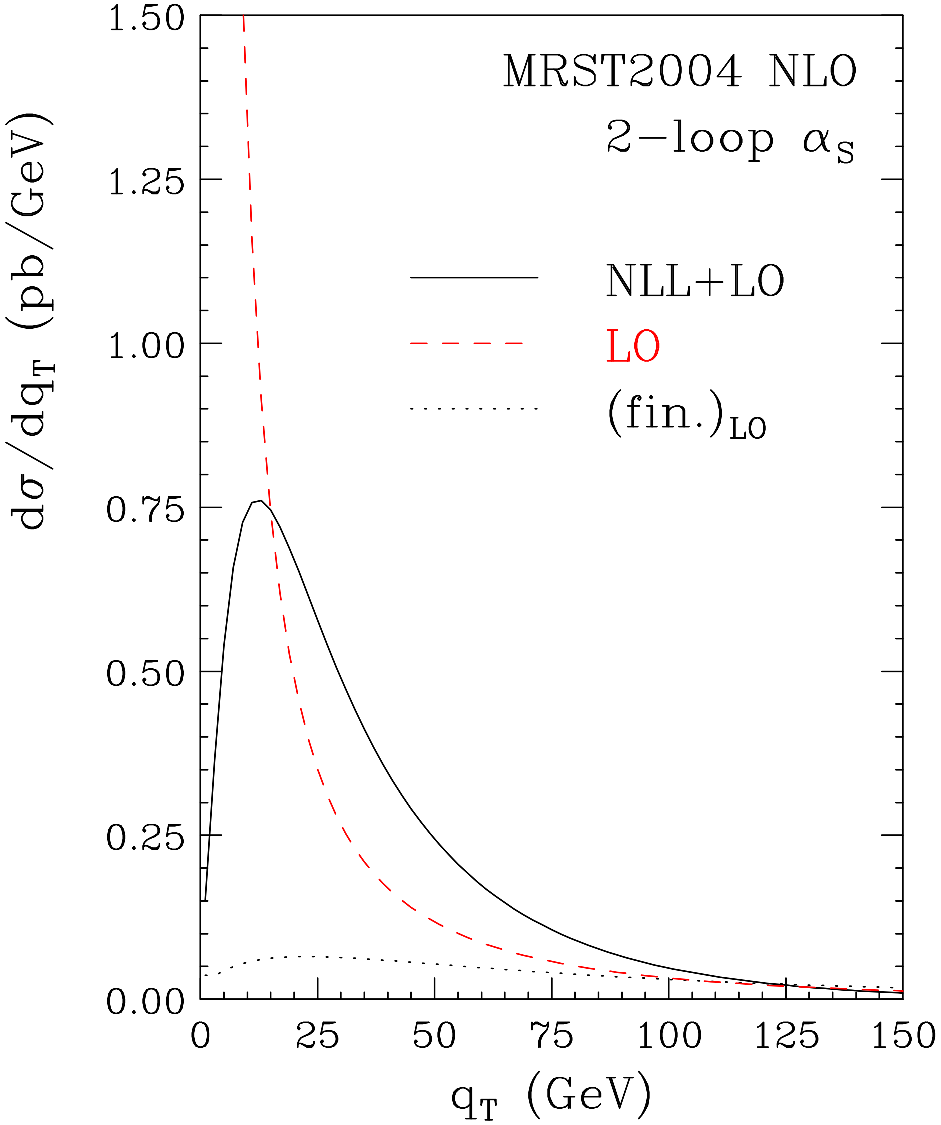




Higgs transverse momentum distribution

- 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



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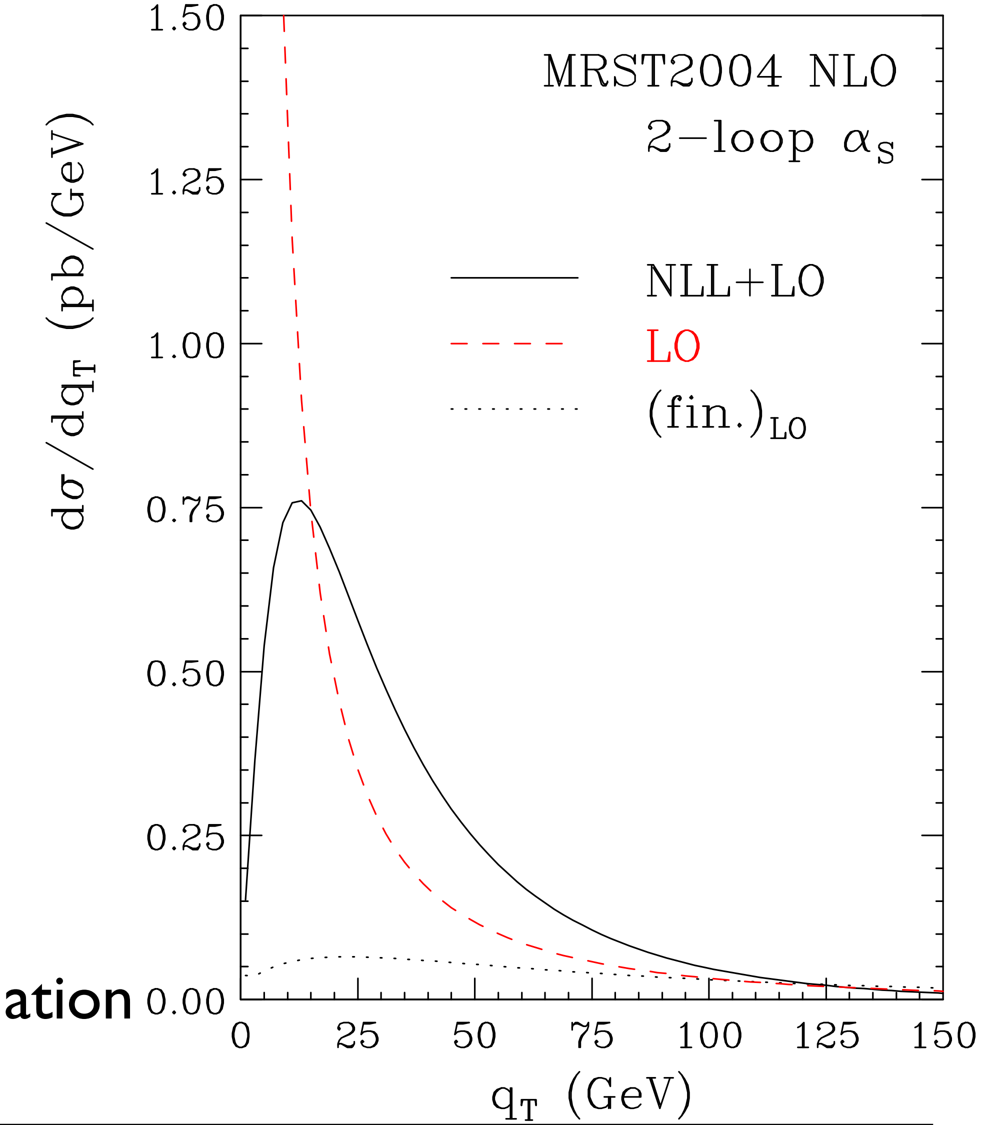


- accuracy
  for ptH→0 relies on the logarithmic accuracy of the calculation
  for large ptH relies on the perturbative accuracy

	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'

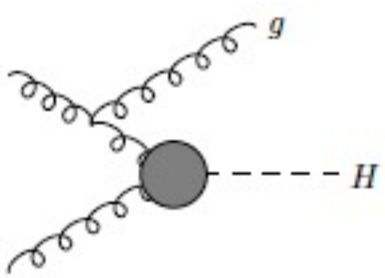
- new approaches (cfr. Monni, Re, Torrielli, arXiv:1604.02191) ; matching N3LO + N3LL in the future?
  (relevant also fro DY ptZ (and in turn for MW))

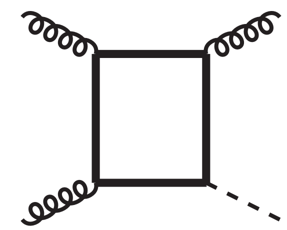
- in these codes (except UN²LOPS) heavy quark mass effects are available at NLO, making the Higgs ptH in gluon fusion a multiscale problem/observable

The Higgs transverse momentum distribution in the HQEFT and in the full SM

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

- at small ptH the leading contribution comes from radiation from the incoming partons
  at larger ptH, the emitted partons can resolve the structure of the quark loops





- triangle diagrams → one threshold at $s=4\,m_q^2$
  box diagrams → enhanced contribution at ptH ~ mq

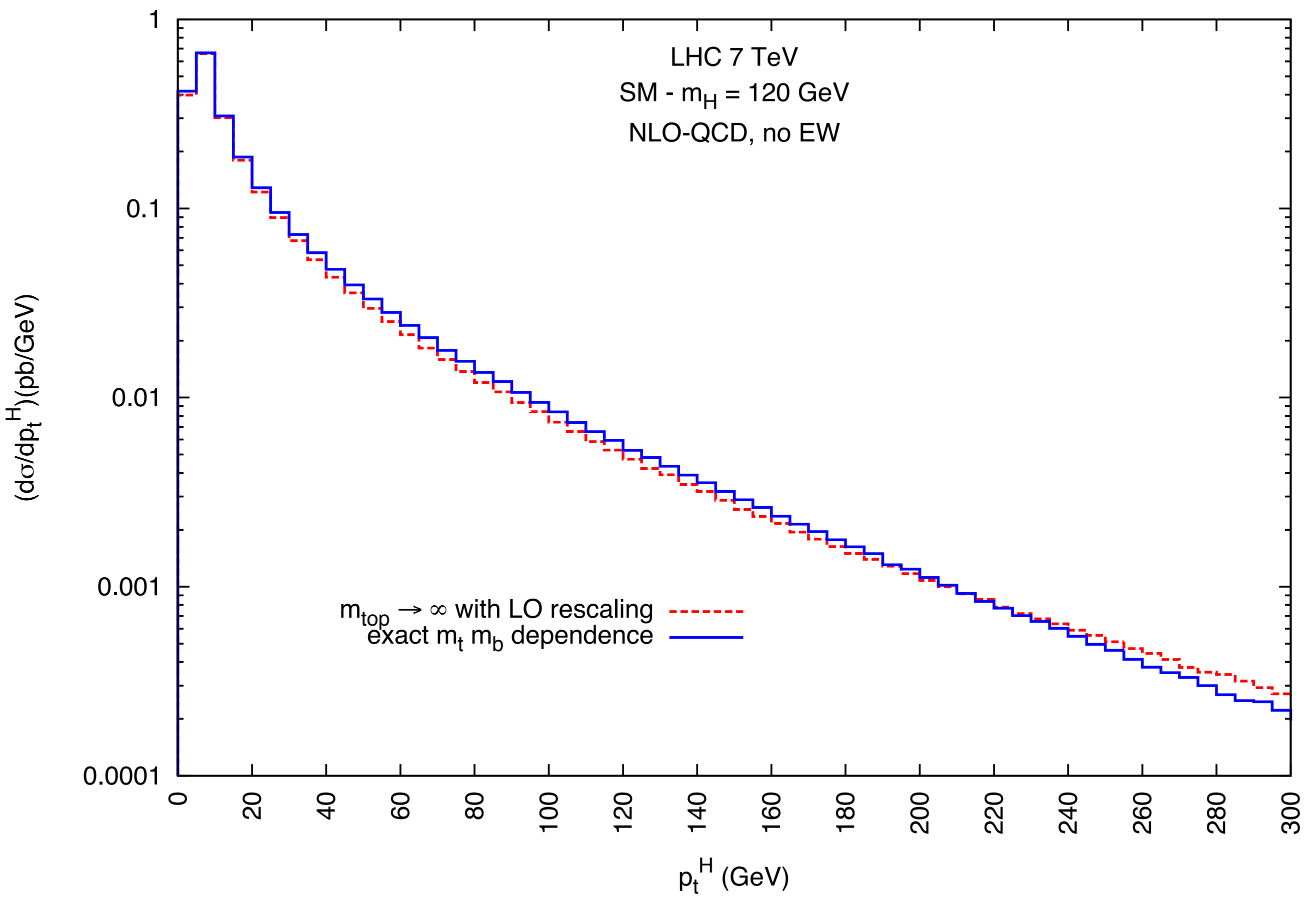
  in the case of the top, mass effects are evident for ptH > 150 GeV
  with the bottom, the effects start at ptH ~ 10 GeV

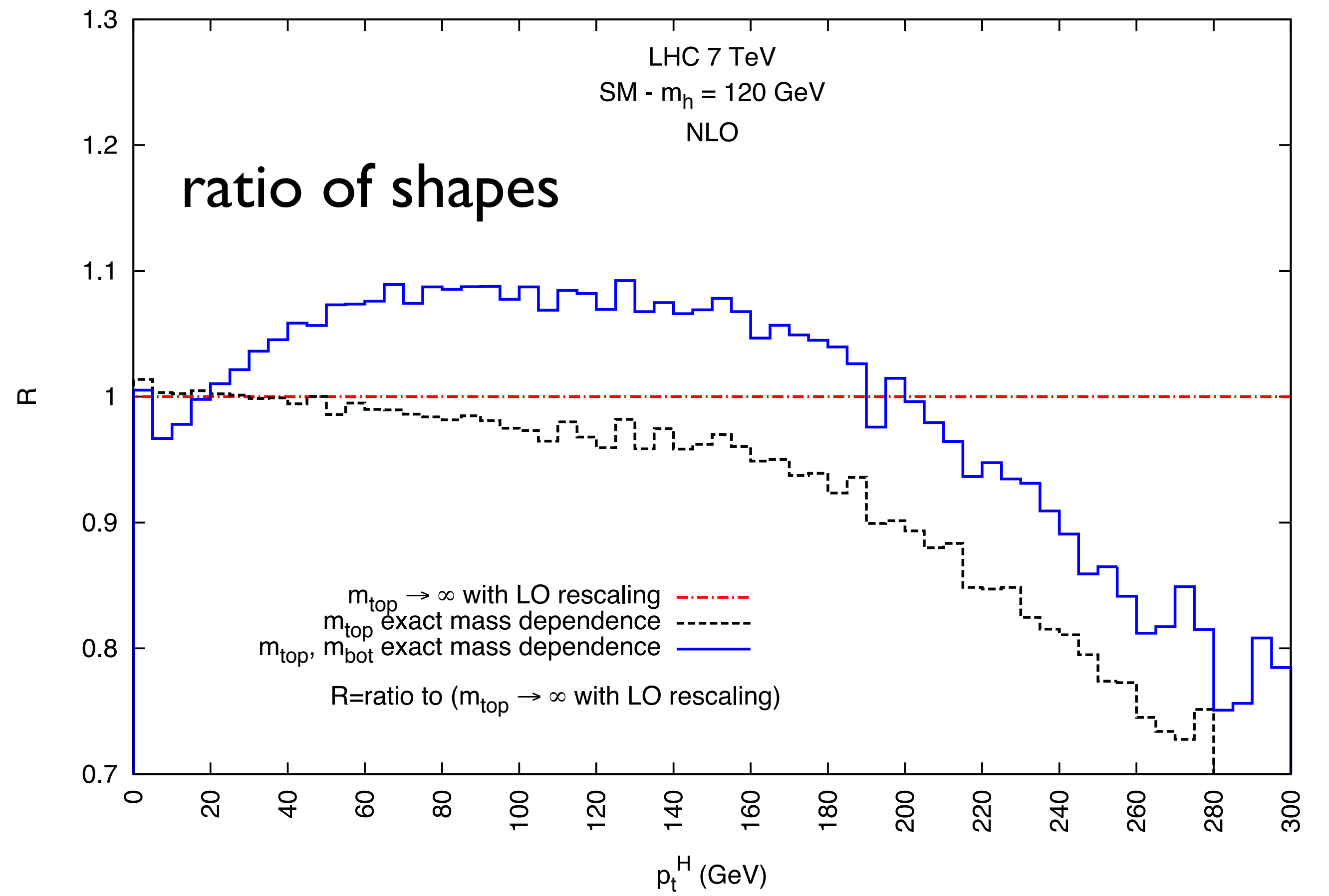
- every diagram is proportional to the corresponding Higgs-fermion Yukawa coupling
  → the bottom diagrams have a suppression factor mb/mt ~1/36 w.r.t. the corresponding top diagrams
  → the squared bottom diagrams are negligible (in the SM)
  the bottom effects are due to the top-bottom interference terms (genuine quantum effects)

$$|\mathcal{M}(gg\to gH)|^2 = |\mathcal{M}_t+\mathcal{M}_b|^2 = |\mathcal{M}_t|^2 + 2\mathrm{Re}(\mathcal{M}_t\mathcal{M}_b^\dagger) + |\mathcal{M}_b|^2$$

Quark mass effects at NLO

Spira, Djouadi, Graudenz, Zerwas, hep-ph/9504378





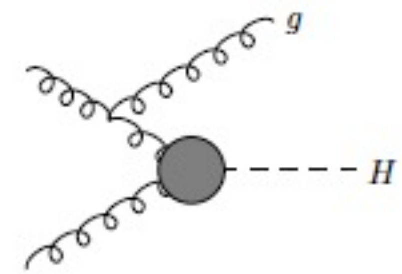
- very good agreement of independent codes

- at fixed order the distribution is divergent in the limit ptH → 0
- the top mass effects are small up to ptH ~ mtop
- the bottom diagrams distort the shape by O(10%)

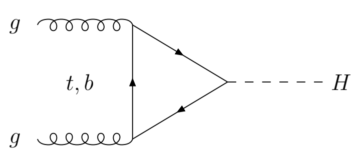
Higgs ptH distribution: a tool to discriminate models

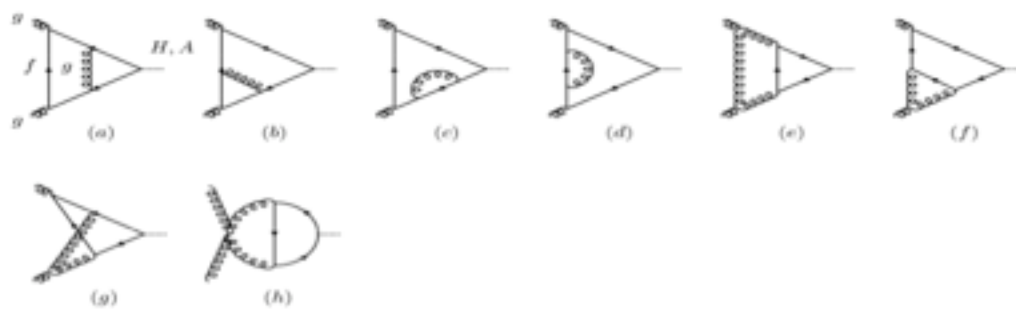
Langenegger Spira Starodumov Trueb 2006, Bagnaschi Degrassi Slavich AV 2011

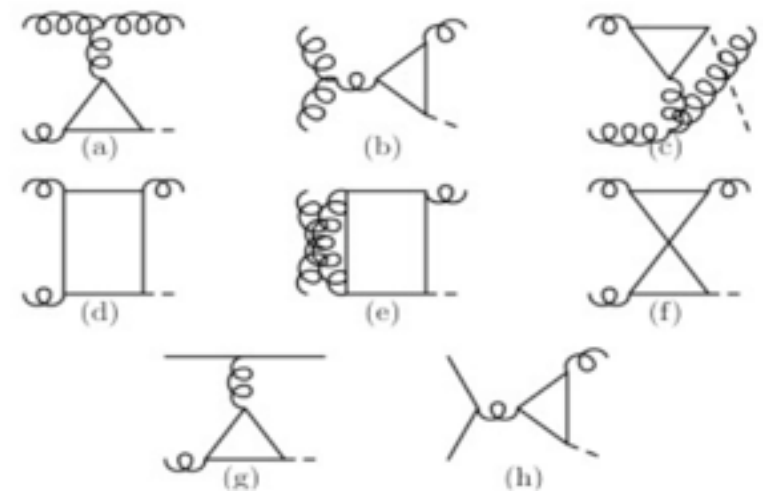
- the Higgs transverse momentum is due to its recoil against QCD radiation



- 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

The 2 topics under discussion

Matching uncertainties

- the fixed-order Higgs transverse momentum distribution diverges for ptH→0
  ⇒ need to resum to all orders log(ptH/MH) terms
- a sensible distribution with a given perturbative accuracy
  is obtained after the matching of fixed-order and resummed results:
- the matching parameter has a different meaning (i.e. it controls different perturbative terms)
  in the various approaches (analytic resummation, shower MC)
- parameterization of the matching ambiguities
  →choice of a "reasonable" value of the matching parameter
  →evaluation of uncertainty bands (variation of the matching parameter in a given range)

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Gluon fusion as a multiscale problem

- BSM predictions for the gluon fusion differential cross sections
- enhanced role of the bottom quark loop → gluon fusion as a multiscale problem
- non-trivial evaluation of the theoretical uncertainty on this distribution

Matching fixed-order matrix elements with Parton Shower: POWHEG

P. Nason, hep-ph/0409146, S. Alioli, P. Nason, C. Oleari, E. Re, arXiv:0812.0578, arXiv:1002.2581

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

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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 [ ]

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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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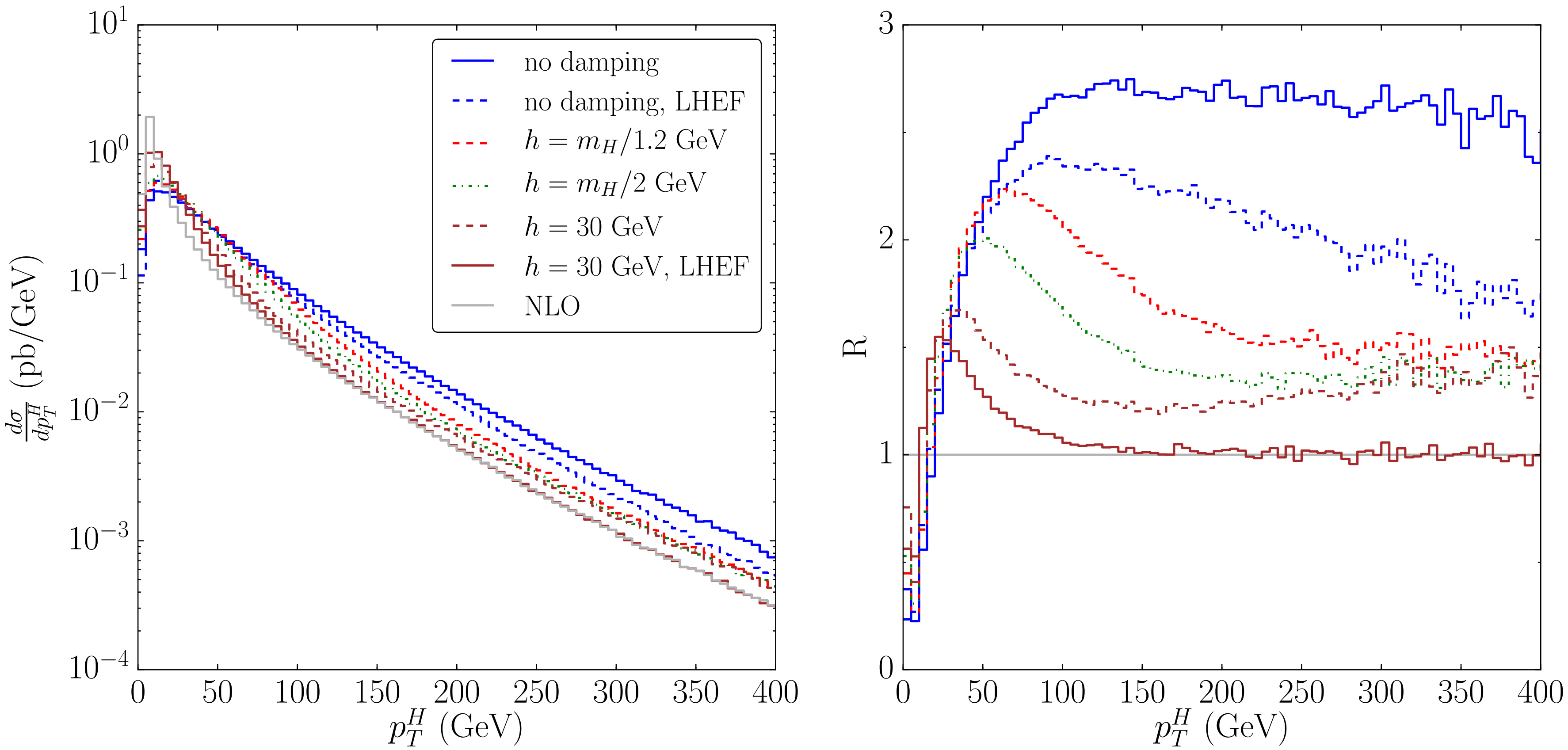
the first (hardest) emission is generated according to the above formula

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)

POWHEG results: LHEF and after-shower events for different h values



- at LHEF level
  without a damping factor, the effect of Bbar is spread over the whole ptH spectrum,
  with a damping, the fixed-order prediction is recovered

$$d\sigma = \bar{B}(\Phi_B) d\Phi_B \left\{ \Delta_{t_0} + \Delta_t \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi_r \right\} + R^f d\Phi + R_{\rm reg} d\Phi$$
$$\approx \bar{B}(\Phi_B) \frac{R^s(\Phi)}{B(\Phi_B)} d\Phi + R^f d\Phi + R_{\rm reg} d\Phi$$
$$\equiv K(\Phi_B) R^s(\Phi) d\Phi + R^f d\Phi + R_{\rm reg} d\Phi,$$
$$K(\Phi_B) \equiv \frac{\bar{B}(\Phi_B)}{B(\Phi_B)} = 1 + \mathcal{O}(\alpha_s)\,.$$

- after showering the event
  the effects of the additional radiation provided by the shower remain at all ptH values

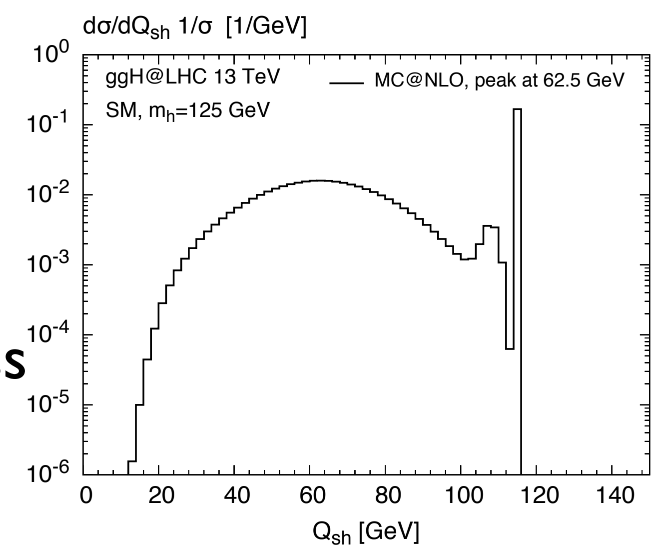
Matching fixed-order matrix elements with Parton Shower: MC@NLO

S. Frixione, B. Webber, hep-ph/0204244, hep-ph/0207182

$$\left(\frac{d\sigma}{dO}\right)_{MC@NLO} = \sum_{n\geq 0}\int \left[B + \hat{V}_{fin} + \int R^s_{MC@NLO}\, d\Phi_r^{MC}\right] \frac{d\Phi_B\, d\Phi_n^{MC}}{dO} \mathcal{I}_n(t_1 = Q_{sh})$$
$$+ \sum_{n\geq 1}\int \left[R\, \frac{d\Phi\, d\Phi_{n-1}}{dO} - R^s_{MC@NLO} \frac{d\Phi^{MC} d\Phi^{MC}_{n-1}}{dO}\right] \mathcal{I}_{n-1}(t_1 = Q_{sh})$$

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 randomly in an interval around
a central value Q_0, the shower scale, related to the hard scale of the process
the PT of the hardest parton generated by the Shower is limited by Q^s



the hardest emission receives the exact real matrix element corrections in the full phase-space,
with a MC counterterm to avoid a double counting

The Sudakov form factor, used 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

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

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

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

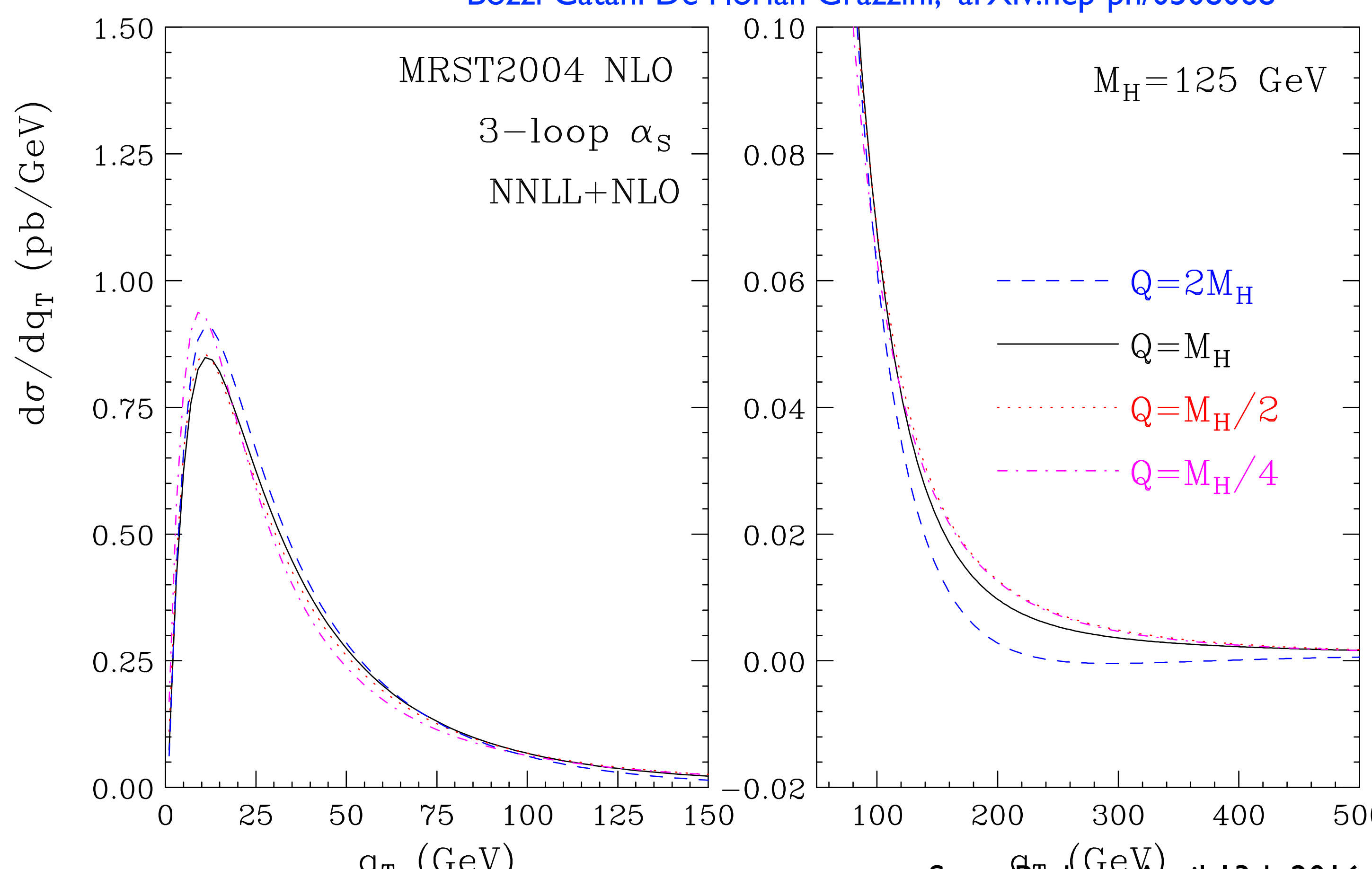
process dependent

universal

$$\left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\mathrm{f.o.+l.a.}} = \left[\frac{\mathrm{d}\sigma^{(\mathrm{res})}}{\mathrm{d}p_T^2}\right]_{\mathrm{l.a.}} + \left[\frac{\mathrm{d}\sigma}{\mathrm{d}p_T^2}\right]_{\mathrm{f.o.}} - \left[\frac{\mathrm{d}\sigma^{(\mathrm{res})}}{\mathrm{d}p_T^2}\right]_{\mathrm{f.o.}}$$

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

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



- 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

Matching fixed-order and resummed results for the Higgs ptH distribution

- do the matching parameters have the same meaning ?
  - the resummation scale Q stems from the factorization of the cross section in conjugate space
  - the Parton Shower starting scale Q_0 sets the (order of magnitude of the) largest scale for the shower first emission
  - the *h* value in the POWHEG damping factor sets the range of ptH over which the normalization factor $\underline{B}$ is spread (where the Sudakov form factor is active)

  they control different subsets of higher-order corrections

→ the different approaches (analytical resummation, Shower MC) can be compared in terms of the respective uncertainty bands, obtained by varying in a given range the matching parameter
  - the choice of the central value of the parameter requires a discussion

- both analytical and Montecarlo matching formulations fulfill a unitarity constraint, i.e. the integral of the ptH distribution, in the absence of acceptance cuts, coincides with the corresponding fixed-order calculation
  - the unitarity constraint induces a specific correlation between the low- and the high-ptH tails
  - this correlation spreads also effects due the Parton Shower over the whole distribution
  - the constraint is partially removed in HRes, because the high-ptH tail is described with the pure fixed order results
  - the constraint is used by HMW to derive a criterium for the resummation-scale choice
    R.Harlander, H.Mantler, M.Wiesemann, arXiv:1409.0531

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$$\int dp_\perp^2 \frac{d\sigma}{dp_\perp^2} = \sigma_{tot}^{NLO}$$

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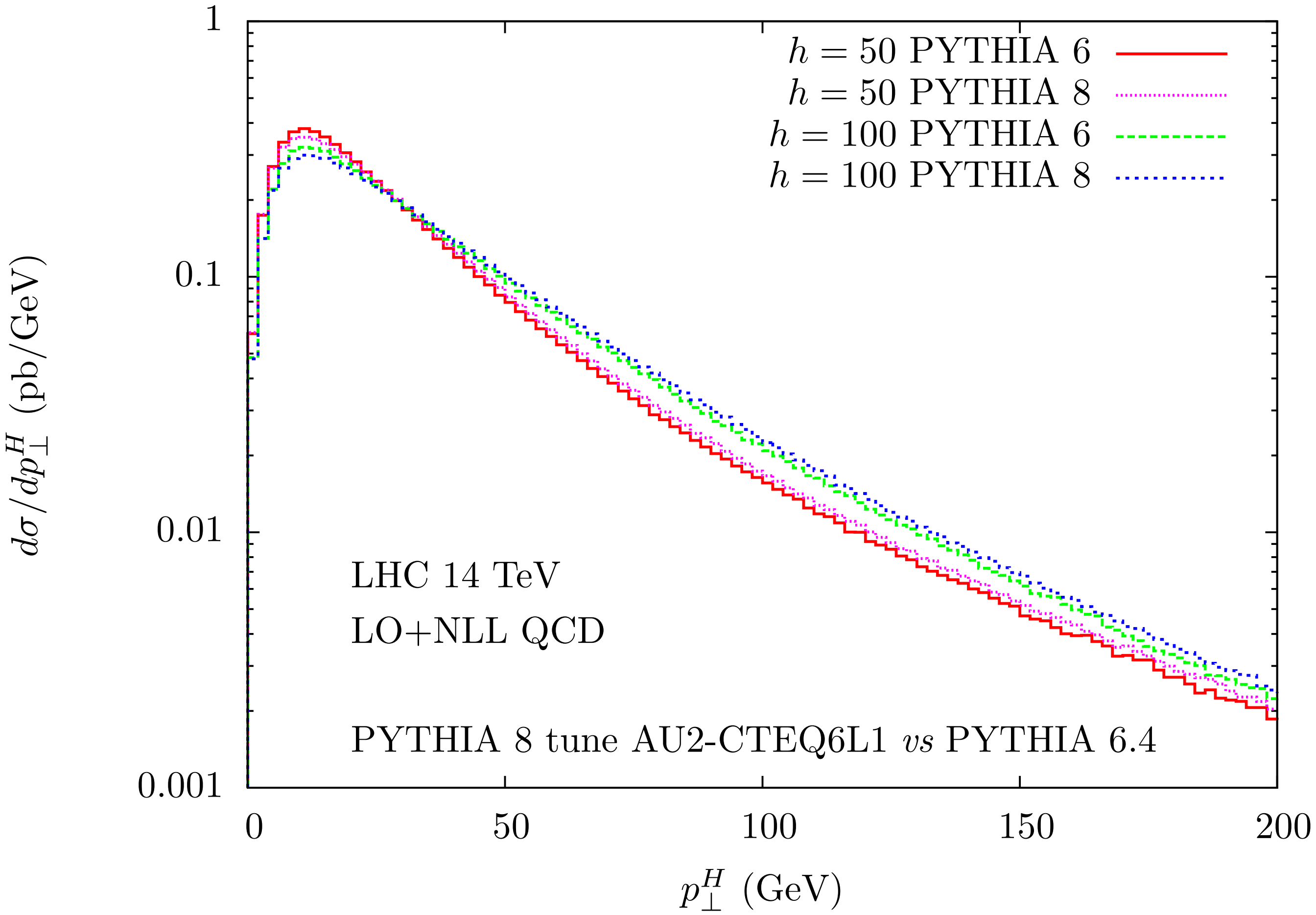
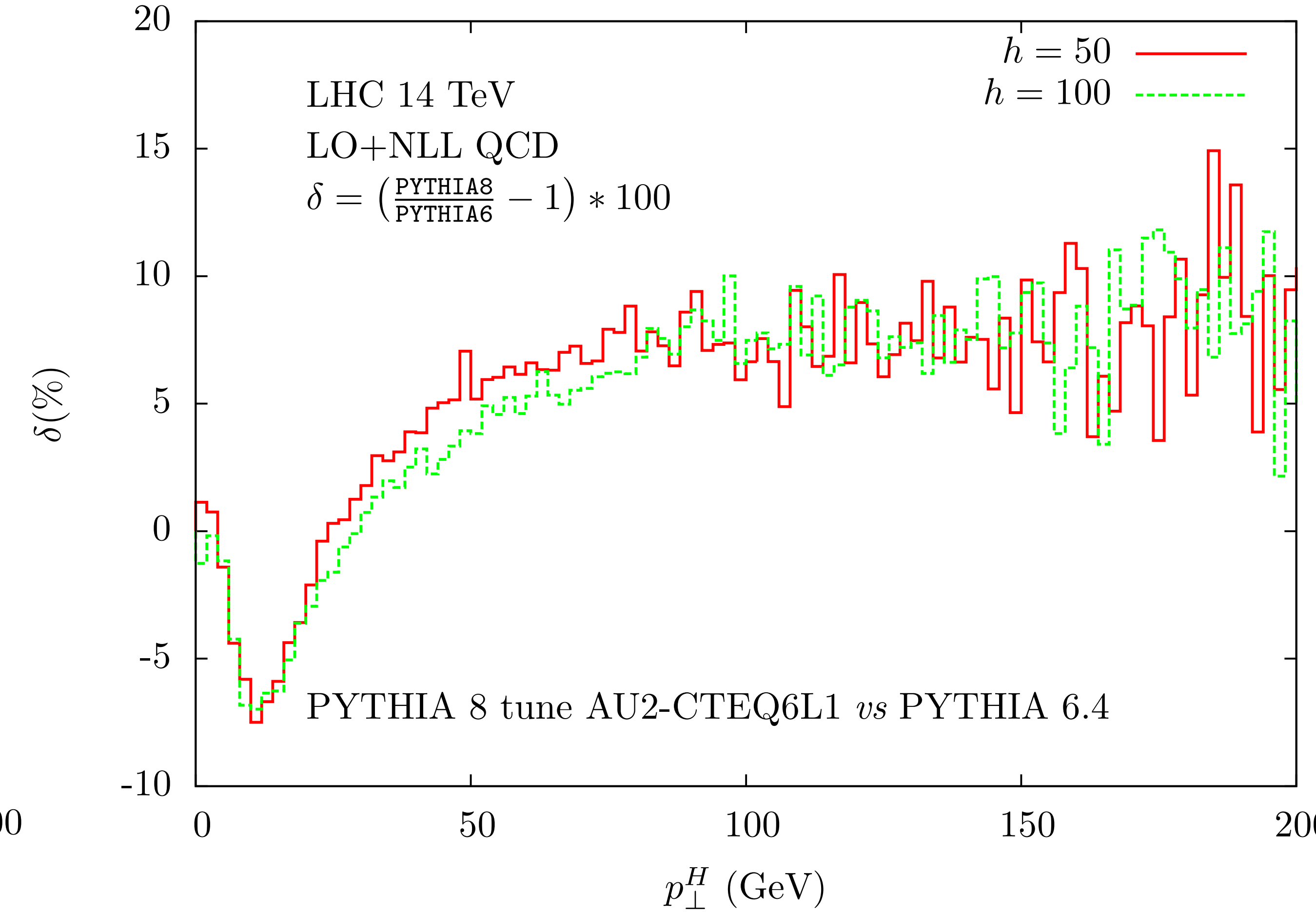
Correlation of low-ptH and high-ptH tails: PYTHIA6 *vs* PYTHIA8





- starting from the same LHEF events, shower with PYTHIA8 AU2 CTEQ6L
  PYTHIA6.4
- important change (-7%) of the height of the peak of the distribution (from PY6 to PY8)
- unitarity forces the high-ptH tail of the distribution to increase, by +7%, for ptH>70 GeV
- the effect is almost independent of the chosen value of *h*

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 HQET (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 (cfr. Bagnaschi AV, arXiv:1505.00735)
  ⇒ the use/extrapolation of the resummed expression up to ptH~Q=MH/2 is justified

- which scale(s) should be used for the matching parameter?
  does it matter in precision SM Higgs measurements? and in BSM searches?

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- 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%) or less
  in BSM models where the bottom role is enhanced, the treatment of these effects is delicate

- which scale(s) should be used for the matching parameter?
  does it matter in precision SM Higgs measurements? and in BSM searches?

Choice of the resummation scale: SM, two scales approach

M. Grazzini, H.Sargsyan, arXiv:1306.4581

- the Higgs ptH spectrum, with quark masses, is a 3 scales problem (mb, MH, mt), the first "threshold" of the hard scattering process is at ptH ~ mb

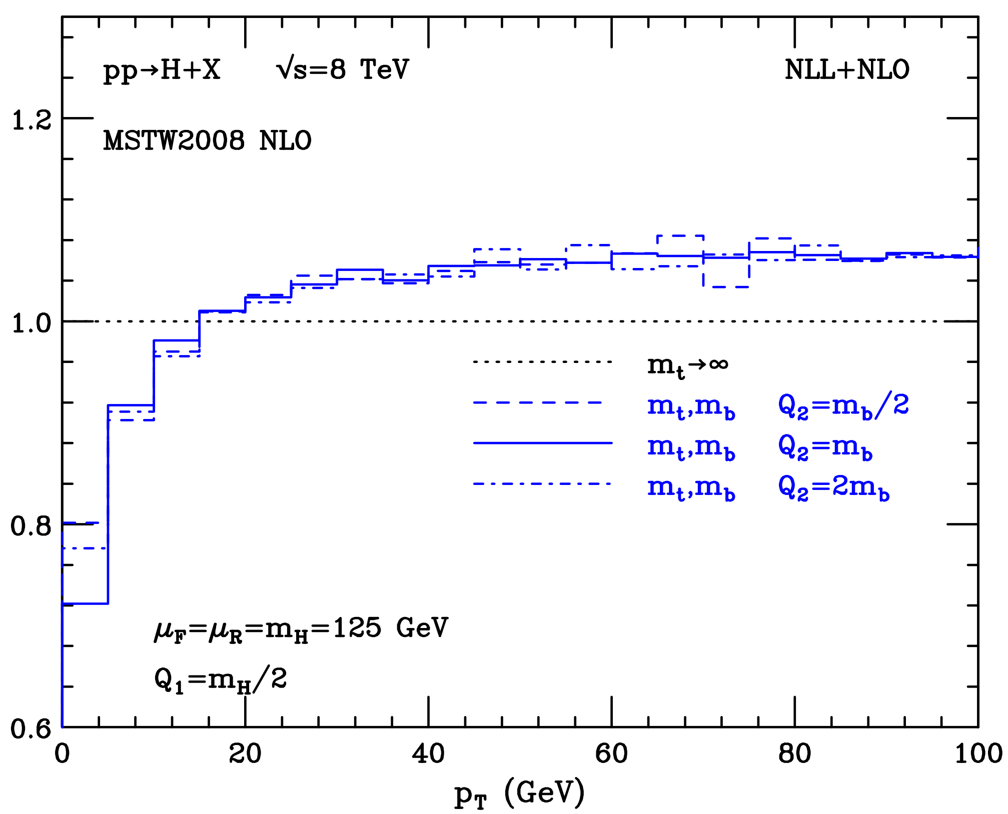
$$|\mathcal{M}(t+b)|^2 = |\mathcal{M}(t)|^2 + \left[2Re\mathcal{M}(t)\mathcal{M}^\dagger(b) + |\mathcal{M}(b)|^2\right]$$

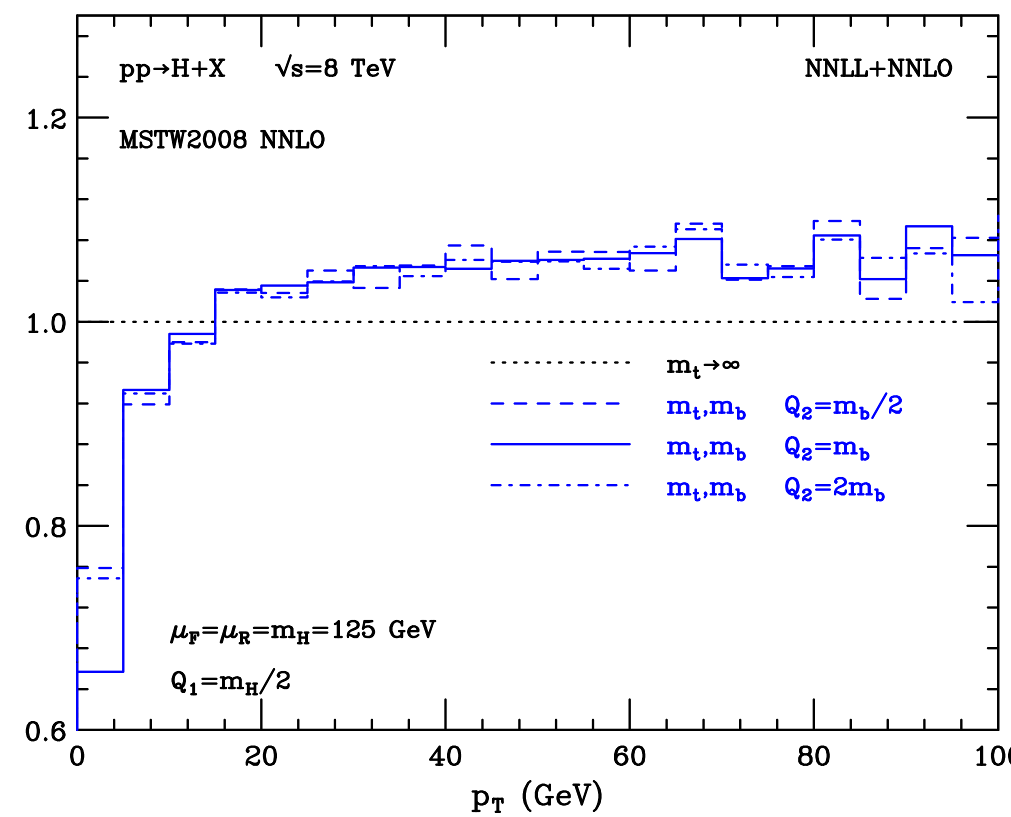
high scale — low scale

- the two-scales treatment is introduced by observing that, for the total cross section (no cuts)

$$\sigma(t+b) = \sigma(t, h_t) + [\sigma(t+b, h_b) - \sigma(t, h_b)]$$

- HRes: two different resummation scales
  - Q1 = MH/2 (top contribution)
  - Q2 = mb (bottom and interference terms); chosen from the analysis of the *qg* channel





Choice of the resummation scale: positivity requirement (HMW)

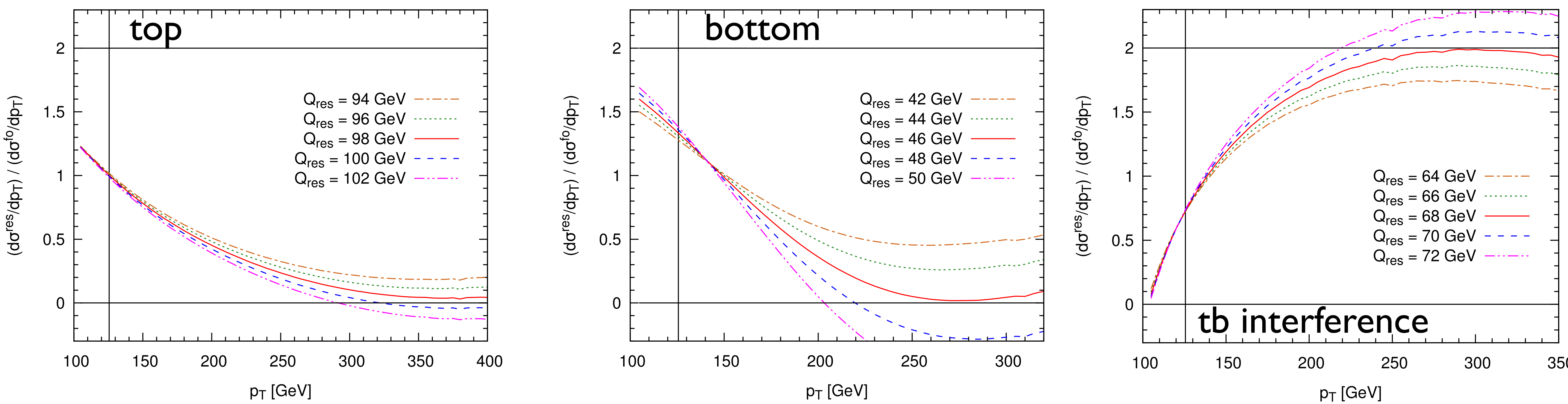
R.Harlander, H.Mantler, M.Wiesemann, arXiv:1409.0531

- analysis done separately for top squared, bottom squared and top-bottom interference

$$\sigma(\mathrm{top}+\mathrm{bot}) = \sigma(\mathrm{top},\mu_t) + \sigma(\mathrm{bot},\mu_b) + \\ + [\sigma(\mathrm{top}+\mathrm{bot},\mu_i) - \sigma(\mathrm{top},\mu_i) - \sigma(\mathrm{bot},\mu_i)] ,$$

- constraint derived from the hadron level cross section (AR code)
- separately, fixed order (for ptH>0) and resummed expression (for ptH≥0) are positive definite
  after the matching, the expression might become negative, as a consequence of the unitarity constraint

$$\left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.+l.a.}} = \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{l.a.}} + \left[\frac{d\sigma}{dp_T^2}\right]_{\text{f.o.}} - \left[\frac{d\sigma^{(\text{res})}}{dp_T^2}\right]_{\text{f.o.}}$$



(a) (b) (c)

- a maximal value for the resummation scale is thus allowed,
  in order to preserve the positivity of the distribution in the whole ptH range
  in order to remain close to the fixed order prediction

Choice of the matching scale: analysis of the partonic matrix elements (BV)

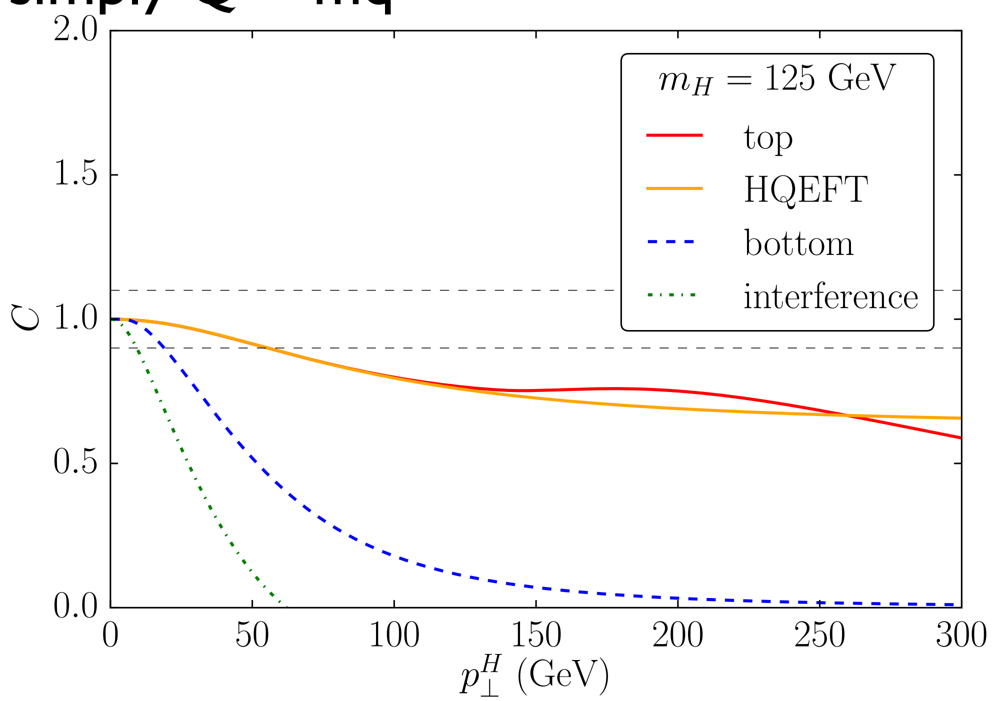
E.Bagnaschi,AV, arXiv:1505.00735

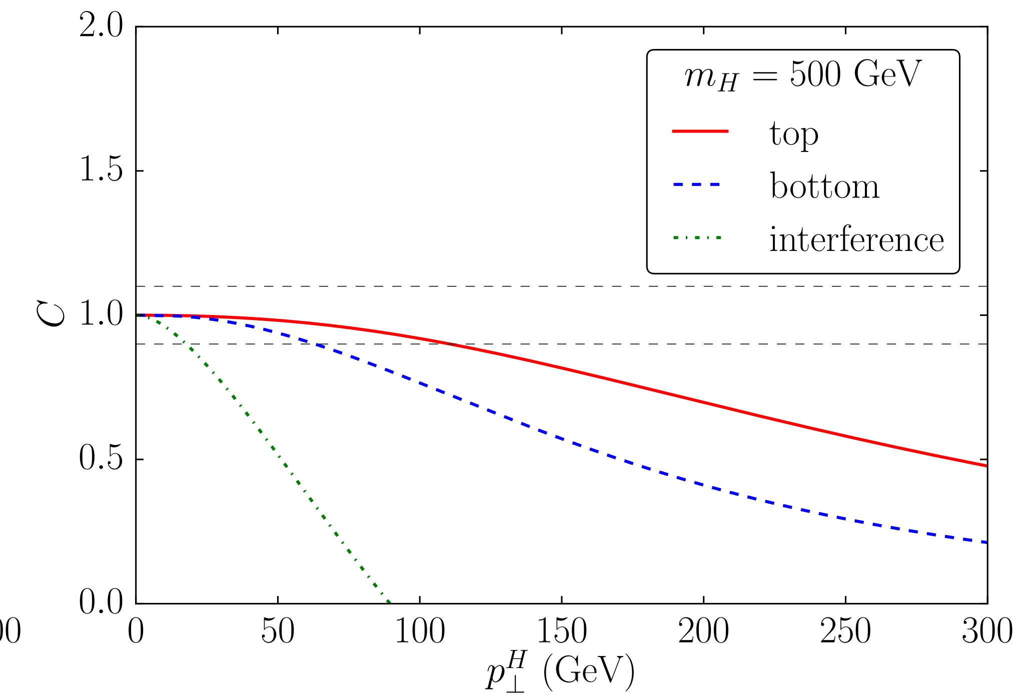
- discussion of the validity of the collinear approximation of the squared matrix elements
  to find the value of ptH where the collinear non-factorizable terms become important;
  a 10% deviation is considered relevant (i.e. O(α_s))
  as the size of a subleading term

$$C(p_\perp^H) = \frac{|\mathcal{M}_{exact}(p_\perp^H)|^2}{|\mathcal{M}_{div}(p_\perp^H)/p_\perp^H|^2}$$

- the "breaking" of the collinear approximation signals that
  the log(ptH) resummation formalism, which is based on the collinear factorization hypothesis
  can not be applied/extrapolated in a fully justified way above a certain ptH value

- the "breaking" of the collinear approximation may occur at a value of ptH that depends
  non trivially on the scale of the process and on the mass of the quark in the loop
  it is not simply Q = mq





- also in the HQEFT we observe "breaking" of the collinear approximation
  the scale associated to the bottom is of O(20 GeV) for light Higgs and is increasing with MH
  the top-bottom interference terms are typically associated with lower values

Choice of the matching scale: analysis of the partonic matrix elements (BV)

E.Bagnaschi,AV, arXiv:1505.00735

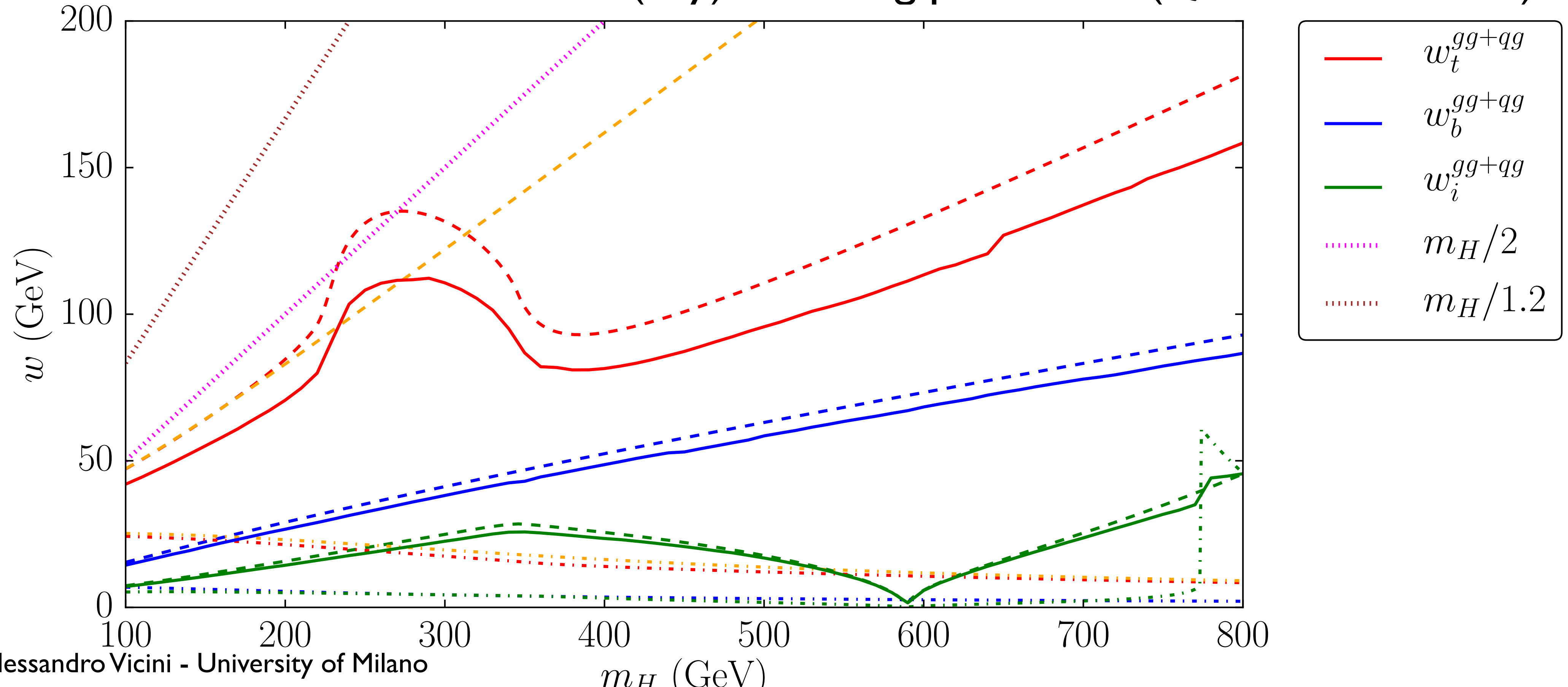
- determination of the scale where the collinear approximation breaks down
  separately for gg→gH   qg→qH channels
  separately for only-top, only-bottom, top-bottom interference terms

- analysis at parton level,
  independent of the details of the hadron-level matching approach/generator

- the separate analysis for top, bottom and interference contribution
  makes the results independent of the strength of the the Higgs-quark coupling
  → model independent   (as long as no additional particles beside quarks are considered)

$$C(p_\perp^H) = \frac{|\mathcal{M}_{exact}(p_\perp^H)|^2}{|\mathcal{M}_{div}(p_\perp^H)/p_\perp^H|^2}$$

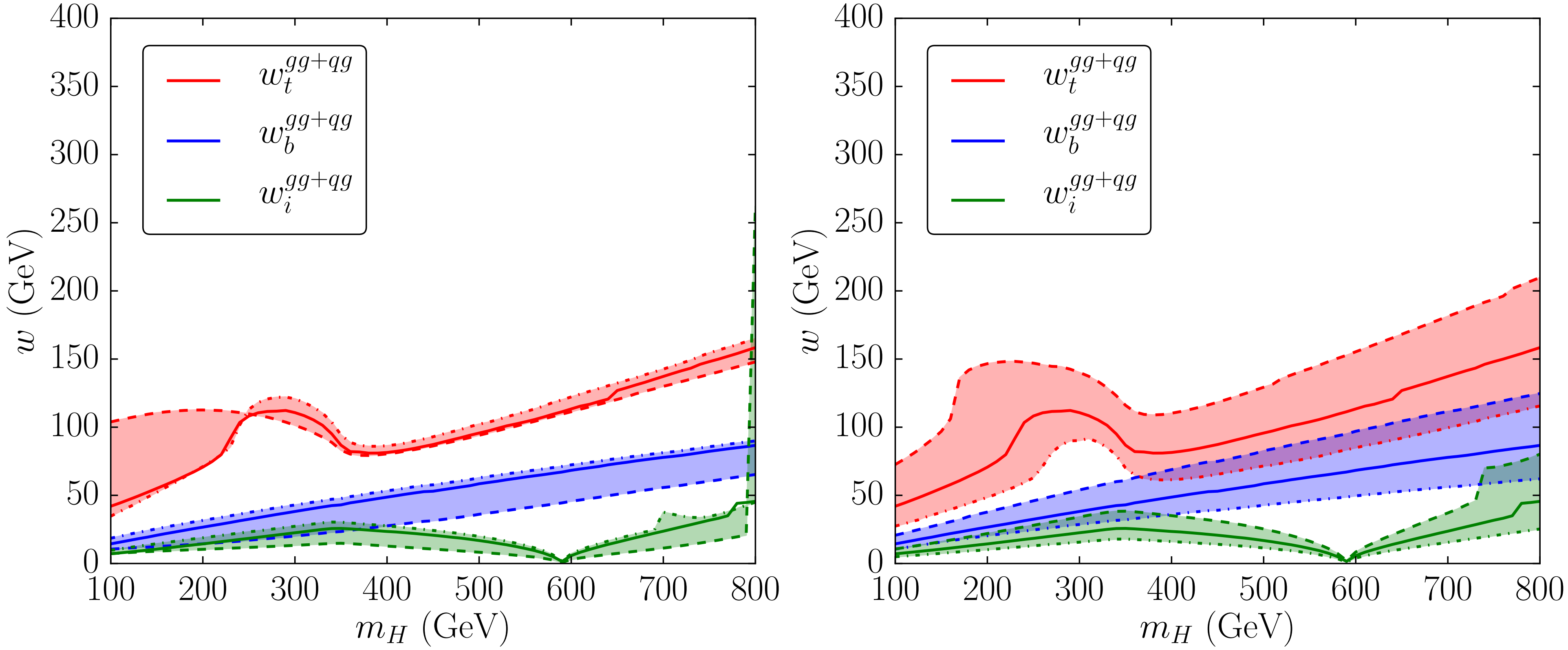
- proposal: use the scale at which the collinear approximation breaks down
  as the central value for (any) matching parameter (Q, shower scale, *h*)



Choice of the resummation scale: analysis of the partonic matrix elements

E.A.Bagnaschi,AV, arXiv:1505.00735

- dependence of the "breaking" scale on the auxiliary parameters s_soft and Cbar



- final scale determined as the weighted average of gg and qg channels using as weights the fixed-order results for ptH>0

$$w^{gg+qg}(m_H) \equiv \int_{w^{qg}}^{w^{gg}} dp_\perp^H \left(w^{gg} \frac{\frac{d\sigma^{gg}}{dp_\perp^H}}{\frac{d\sigma^{gg+qg}}{dp_\perp^H}} + w^{qg} \frac{\frac{d\sigma^{qg}}{dp_\perp^H}}{\frac{d\sigma^{gg+qg}}{dp_\perp^H}} \right) \times \frac{\frac{d\sigma^{gg+qg}}{dp_\perp^H}}{\sigma^{interval}}$$

- the top-bottom interference terms are not positive definite
  when, for a given MH, the LO (gg→H) interference vanishes, there is no need for LL resummation

Comparison of different matching scales

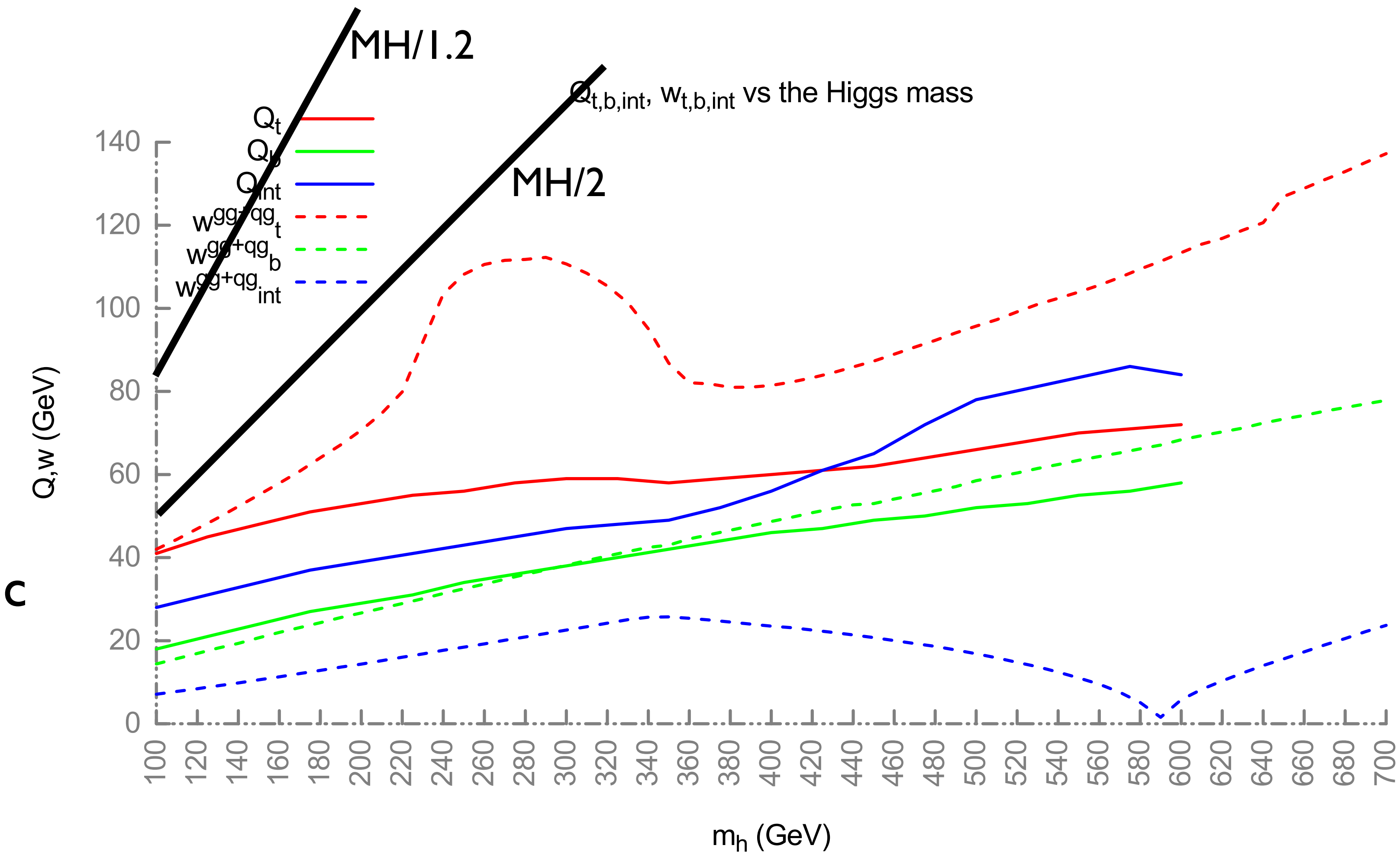
Harlander, Mantler, Wiesemann, arXiv:1409.0531, Bagnaschi, AV, arXiv:1505.00735

- 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

The 2HDM in a nutshell

- 2 complex scalar doublets Φ_1 and Φ_2 with VEVs v_1 and v_2
  3 d.o.f. are the longitudinal polarization of Ws and Z
  5 d.o.f. are in the physical spectrum: 2 charged scalars, 2 neutrals CP-even, 1 neutral CP-odd

- input parameters are: α, $\tan\beta = v_2/v_1$, Mh, MH, MA, M±, M_{12}

- the presence of additional discrete symmetries forbids the appearance of tree-level FCNC leading to different types of models;
  the couplings of the Higgs scalars to fermions are:

	Type I	Type II	Lepton-specific	Flipped
ξ_h^u	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
ξ_h^d	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
ξ_h^ℓ	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
ξ_H^u	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
ξ_H^d	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
ξ_H^ℓ	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ξ_A^ℓ	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

2HDM scenarios considered in Bagnaschi, Harlander, Mantler, AV, Wiesemann, arXiv:1510.08850

scenario	$\tan\beta$	$\sin(\beta-\alpha)$	ϕ	σ_t/pb		σ_b/pb		$-\sigma_{\text{int}}$/pb	
				LO	NLO	LO	NLO	LO	NLO
SM	—	—	H	20.027	33.400	0.220	0.268	2.410	2.433
			A	46.355	78.125	0.244	0.291	4.202	4.506
large-b	50	0.999	H	0.002	0.005	5.085	7.089	0.163	0.199
			A	0.005	0.010	9.984	13.408	0.334	0.412
large-t	1.0	0.999	H	3.715	6.788	0.002	0.003	−0.132	−0.168
			A	12.844	23.832	0.004	0.005	0.334	0.428
large-int	3.2	−0.6	h	2.453	4.091	2.192	2.674	2.665	2.677
	7.1	−0.26	A	0.255	0.473	0.201	0.270	0.334	0.430
low-m_A	36.9	0.998	A	0.399	0.552	$2.480 \cdot 10^5$	$2.292 \cdot 10^5$	89.70	−693.6

- compatibility with additional phenomenological constraints checked against the parameter space bounds computed with the code 2HDMC
- no special interest in these points, but that they illustrate the different possible behavior of the Higgs ptH distribution

Comparison of different codes

Bagnaschi, Harlander, Mantler, AV, Wiesemann, arXiv:1510.08850

- 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)
  share a given fixed order accuracy NLO-QCD and differ by higher-orders (numerically not negligible)
  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 on its own matching parameter (canonical variation)
     repeat for each of the three codes
     compare the (width of) the resulting uncertainty bands

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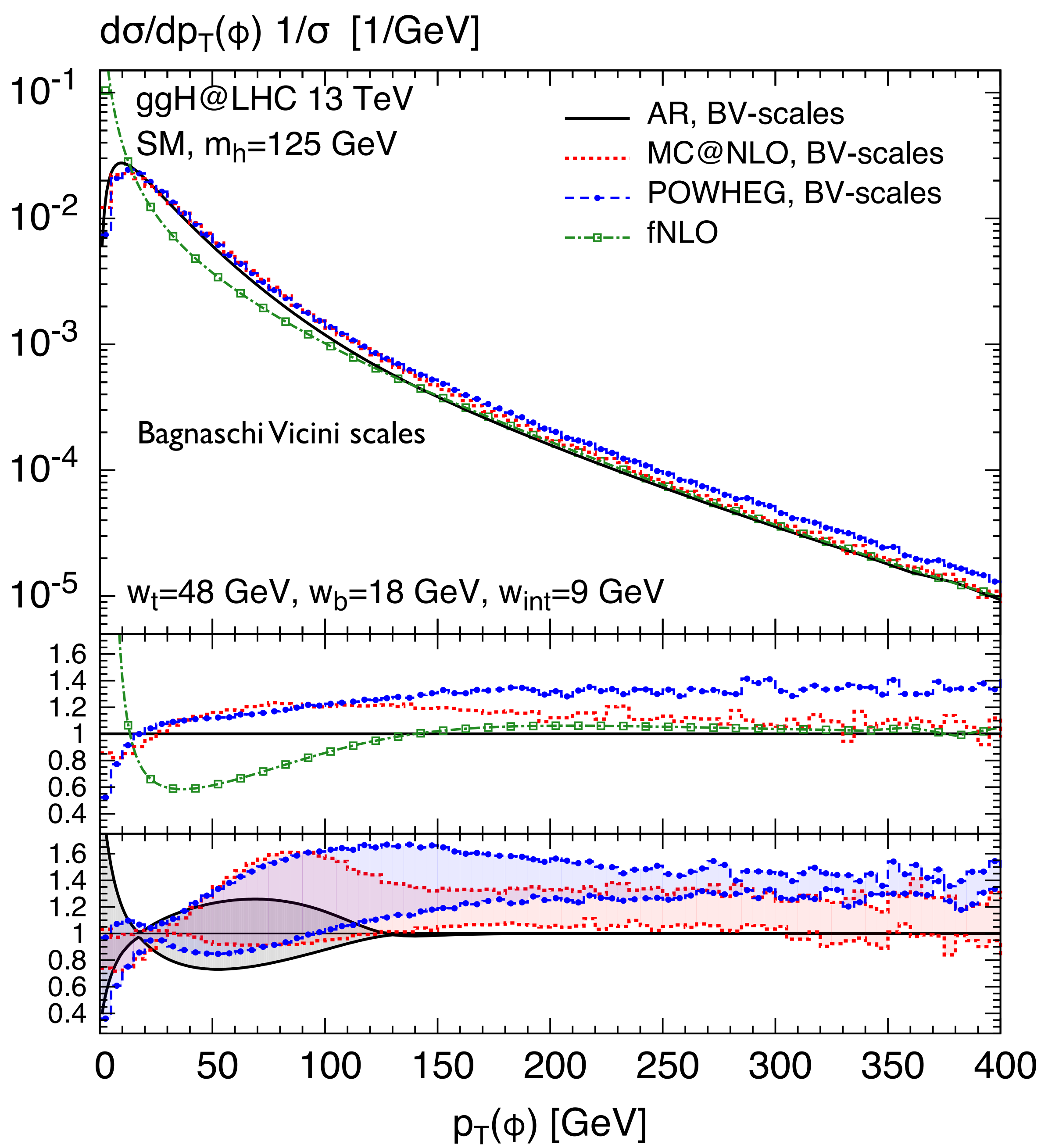
- analysis of different scenarios to expose the impact of different choices for the matching parameter
  - SM (top dominated)
  - 2HDM bottom dominated
  - 2HDM top dominated
- in all the runs top, bottom and interference contributions have been evaluated
  with their dedicated scale choice (3 scales)

Comparison of different codes   SM MH=125 GeV

Bagnaschi, Harlander, Mantler, AV, Wiesemann, arXiv:1510.08850

- same value of the matching parameter → deviations due to the different matching schemes
- uncertainty bands generated canonically varying ONLY the matching parameter, fixed muR and muF



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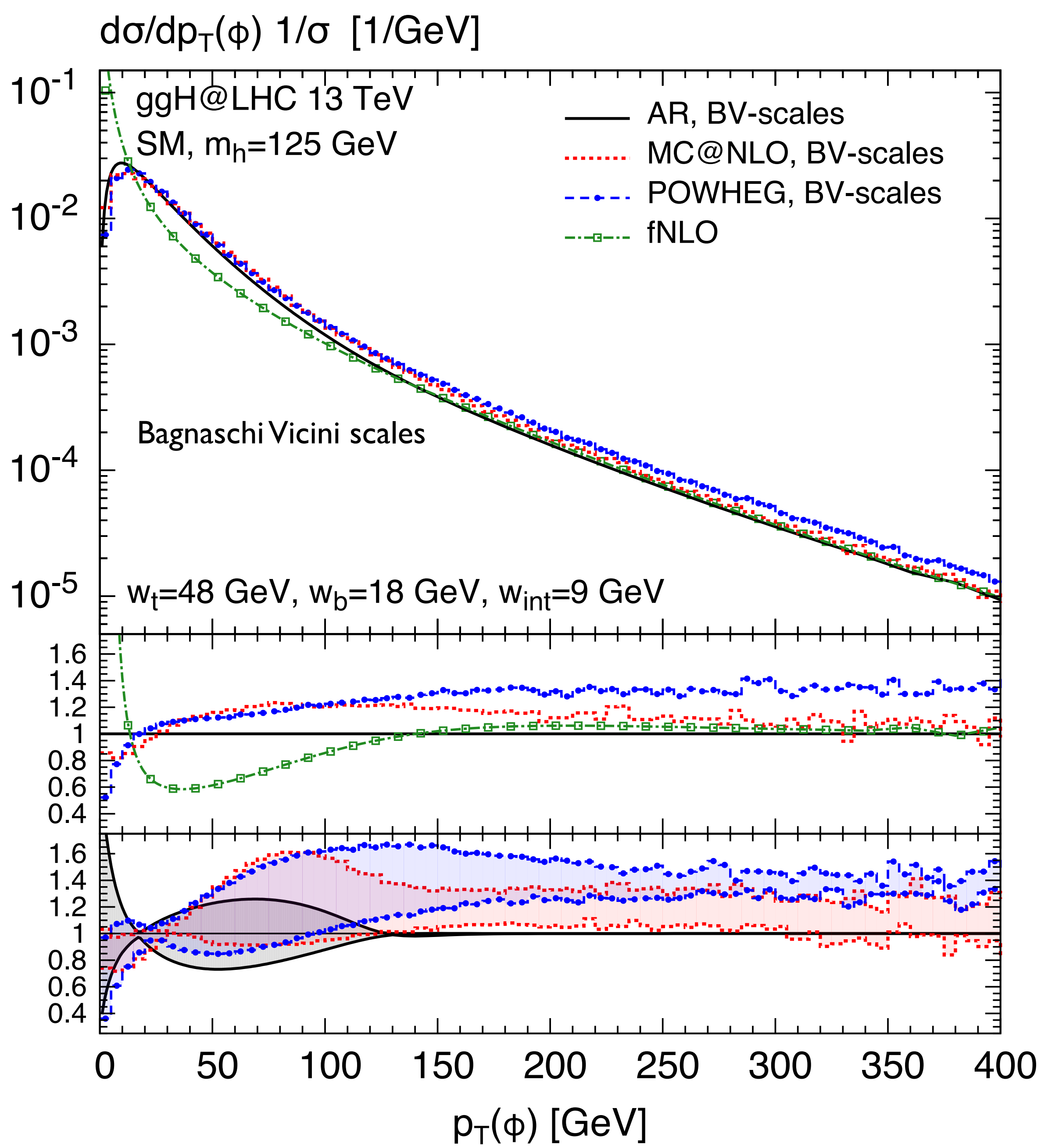

in the SM case More-SusHi fully equivalent to HqT @ NLO

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 MCs

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

the uncertainty is largest (±35%) for 50 < ptH < 100 GeV but also for ptH→0 in More-Sushi

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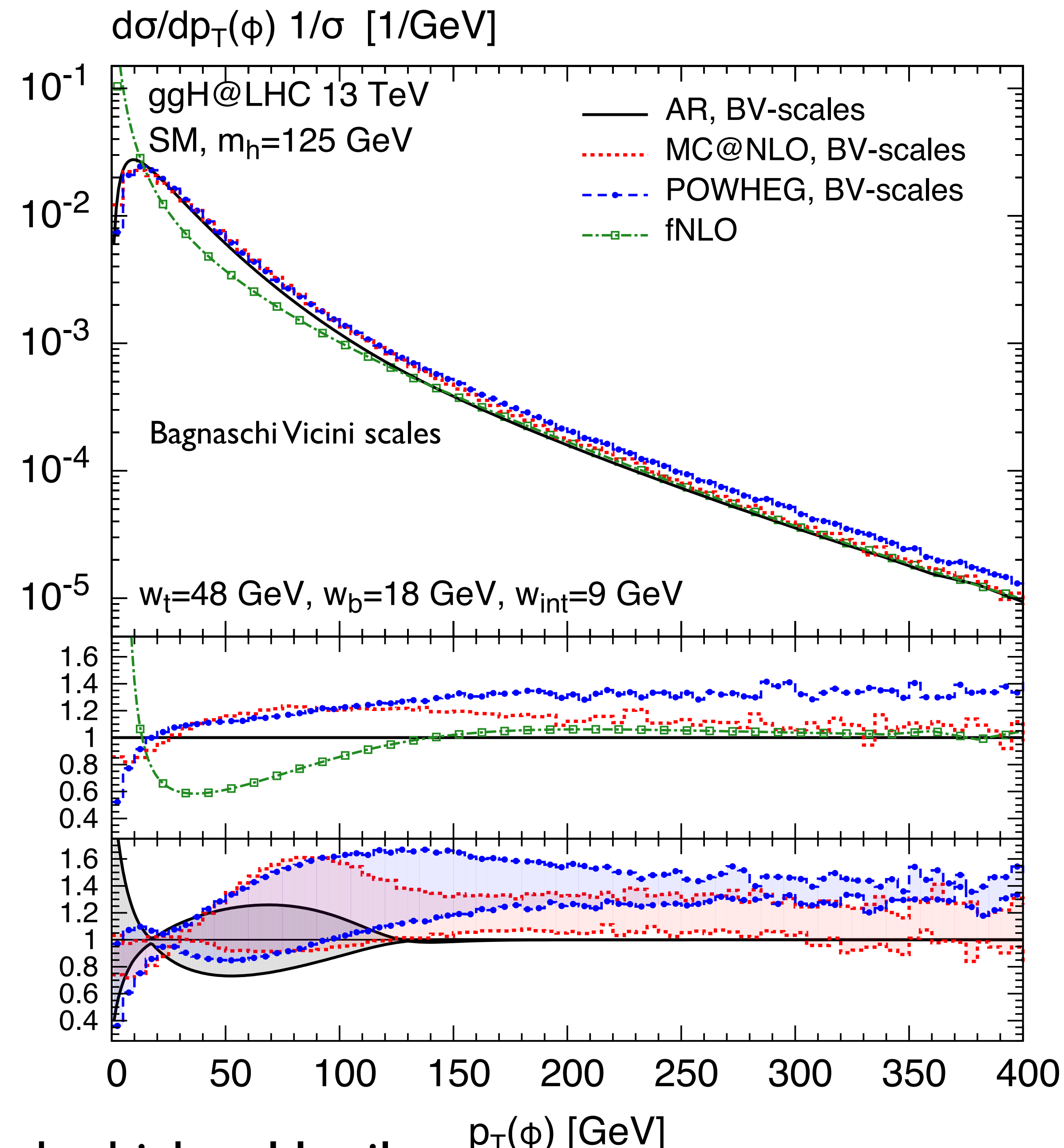

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the high-ptH tail

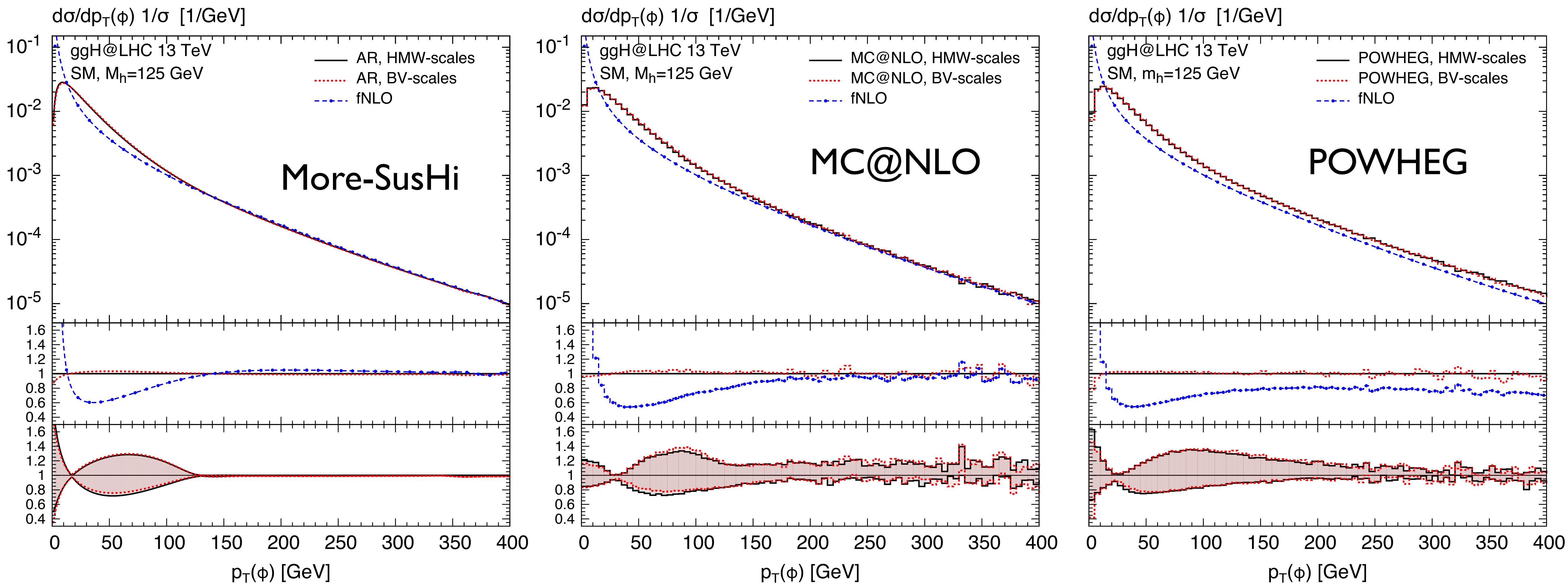
- only LO accurate in these 3 codes + the Parton Shower is not in its validity region (soft/collinear)
- the 3 codes fill the phase space with different upper bounds for the additional radiation
- the details of the results also depend on the PS parameters

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

Comparison of different codes SM MH=125 GeV

Bagnaschi, Harlander, Mantler, AV, Wiesemann, arXiv:1510.08850

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

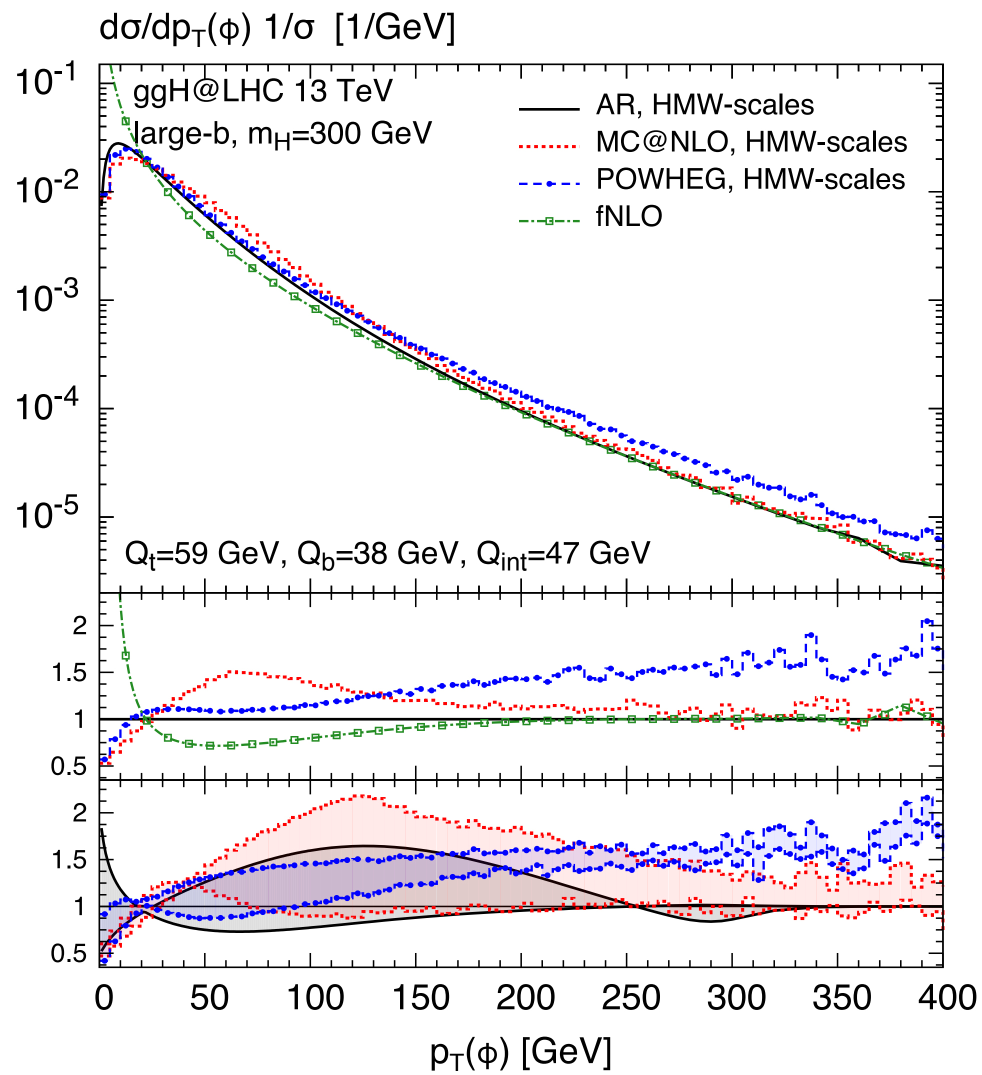


BV ~ HMW for a light Higgs → in each plot the central values and the uncertainty bands overlap

Comparison of different codes — 2HDM bottom dominated, heavy scalar

Bagnaschi, Harlander, Mantler, AV, Wiesemann, arXiv:1510.08850

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



bottom dominance   the matching scale is 38 GeV, much larger than mb

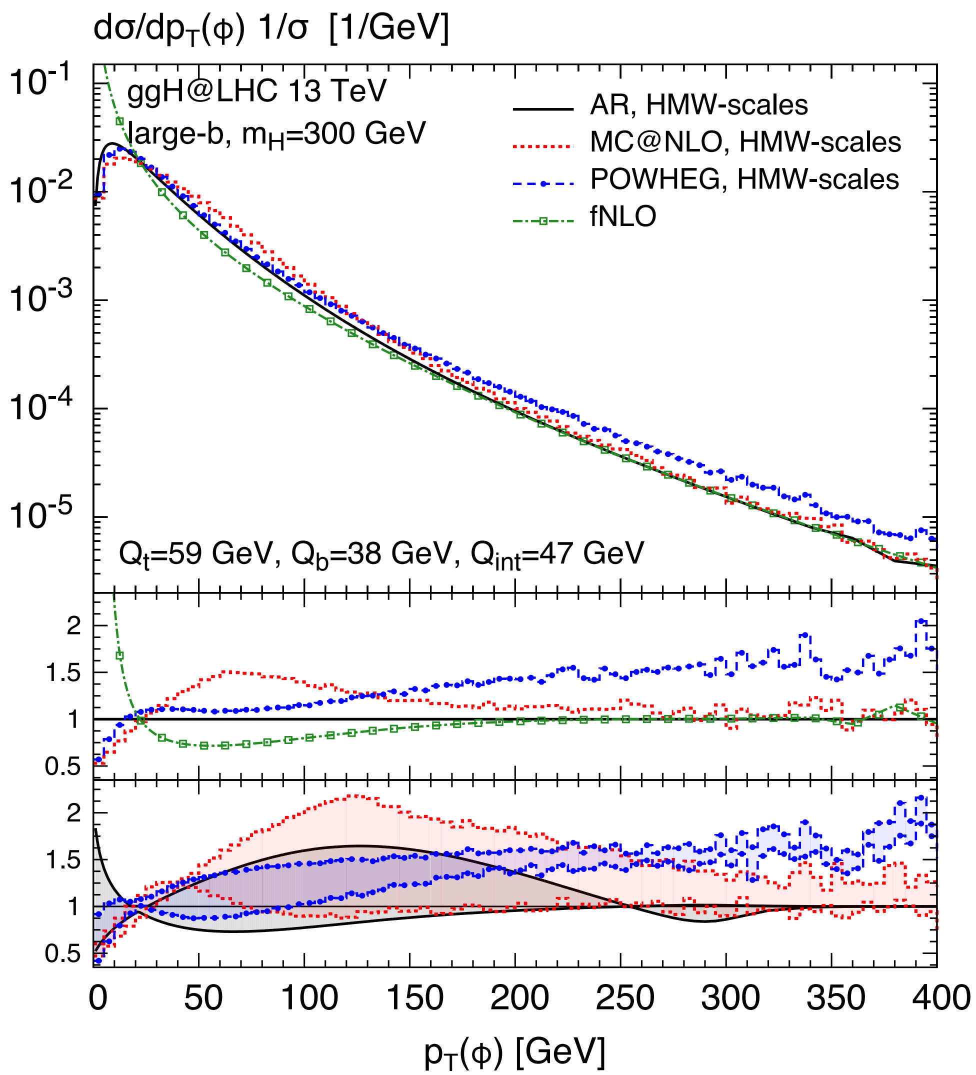
compatibility of the results for ptH < 150 GeV, significant differences for ptH > 250 GeV

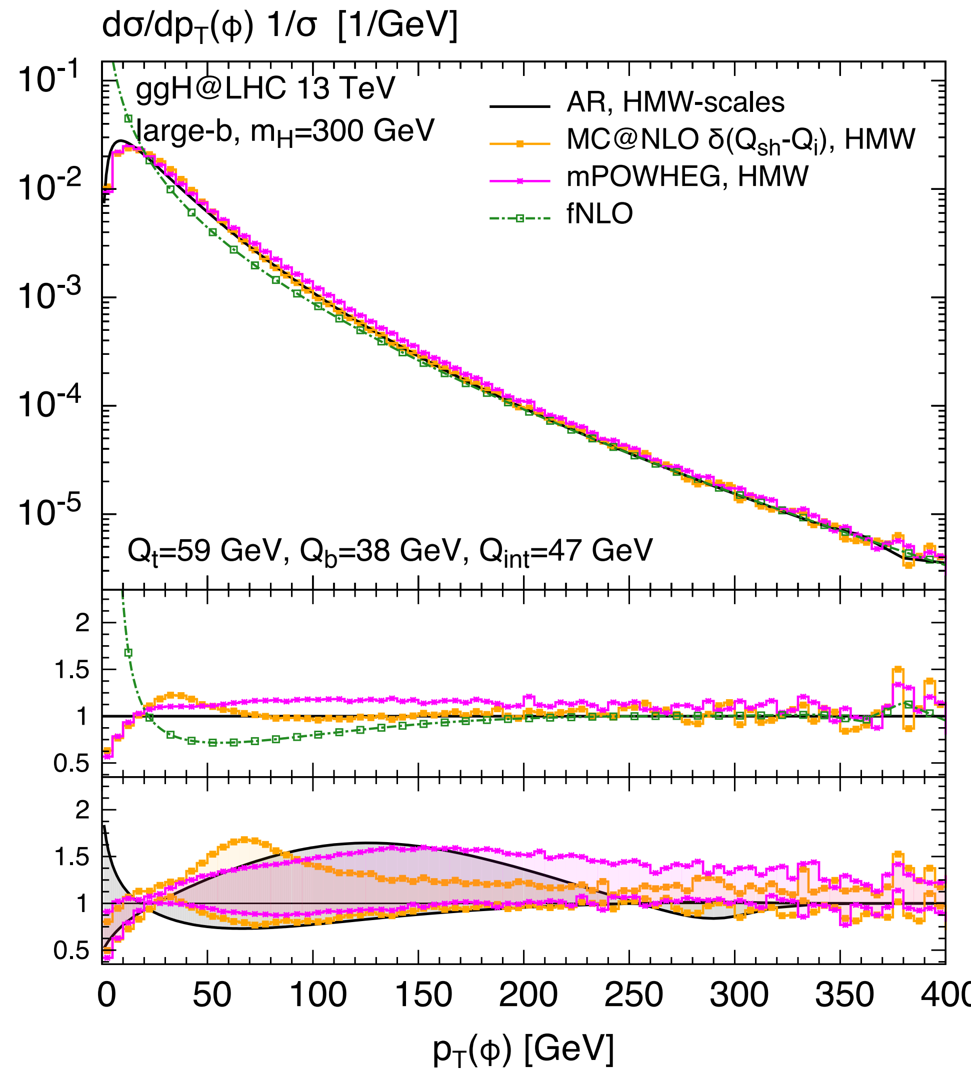
the disagreement is mostly due to the different default formulation of the 3 codes "out-of-the-box"
(the description of the high-ptH tail is LO only)

Comparison of different codes   2HDM bottom dominated, heavy scalar

Bagnaschi, Harlander, Mantler, AV, Wiesemann, arXiv:1510.08850

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

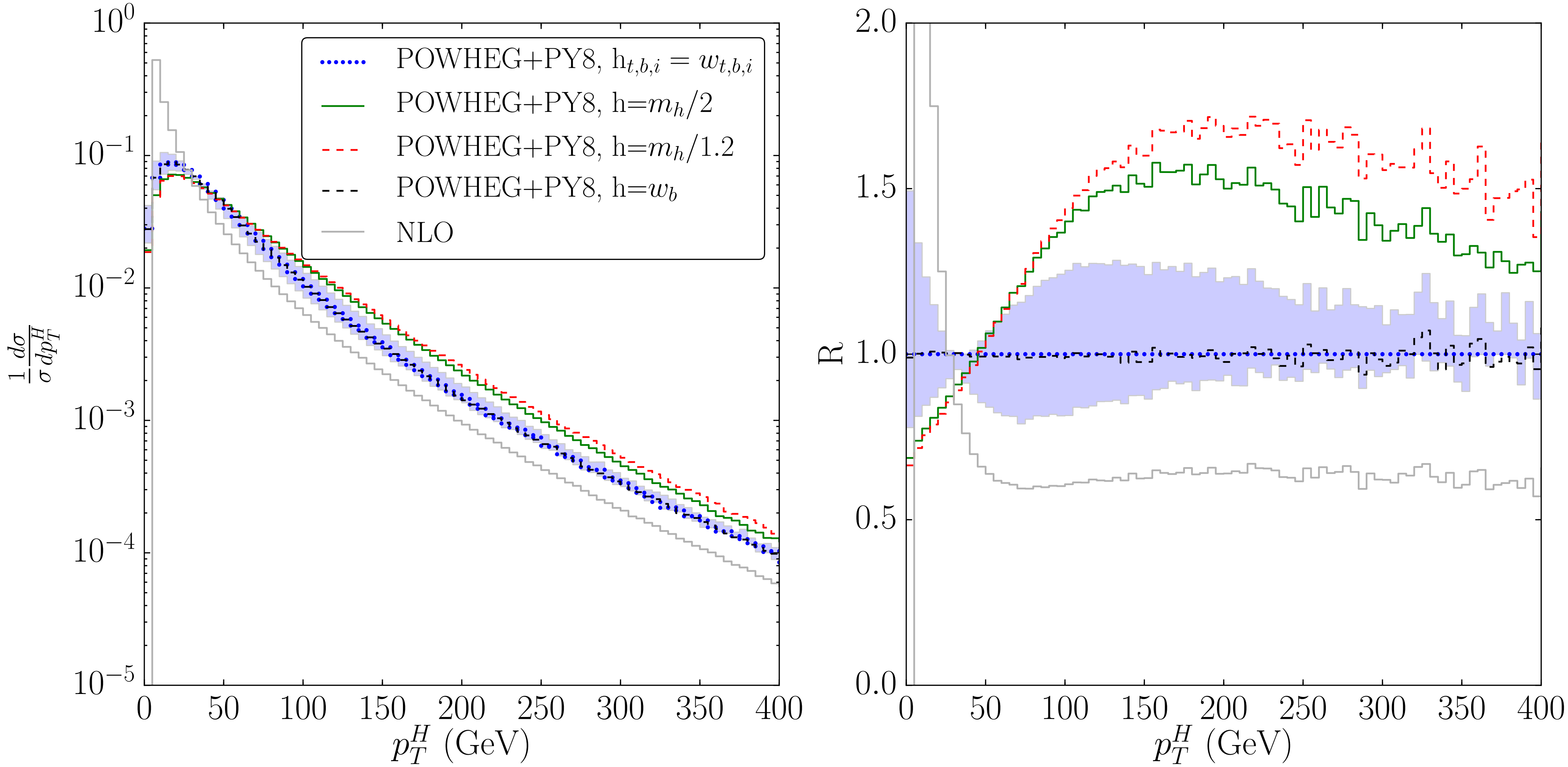
POWHEG reduction of the phase space available to the Parton Shower (limited now by Q_i)

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 (may affect BSM searches)

Few results with POWHEG: 2HDM, bottom dominated scenario, Heavy scalar

E.Bagnaschi,AV, arXiv:1505.00735

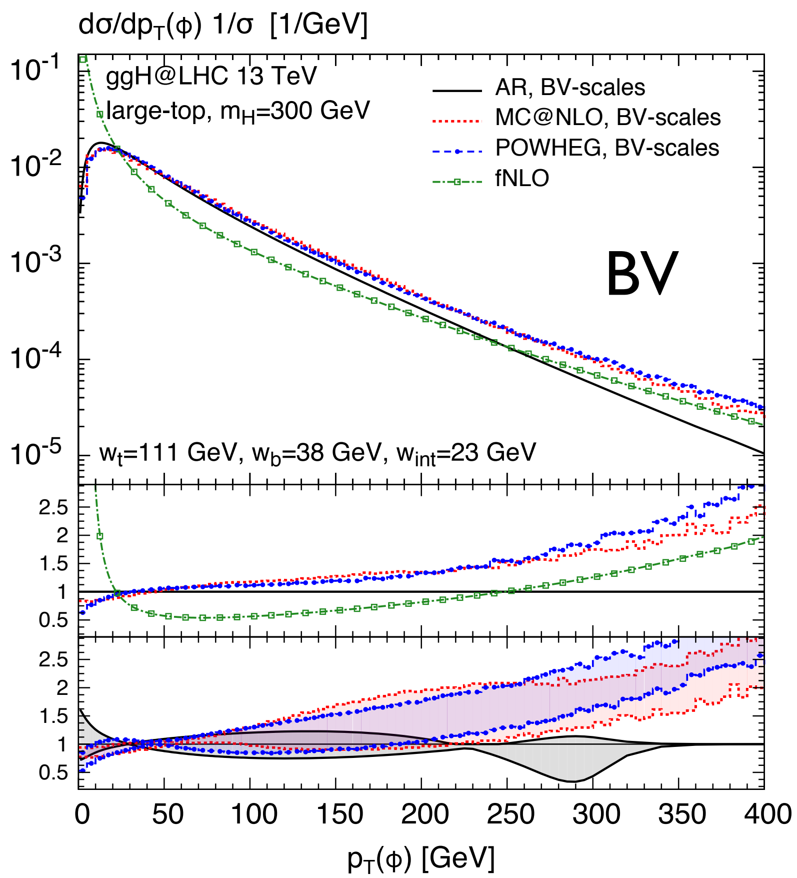


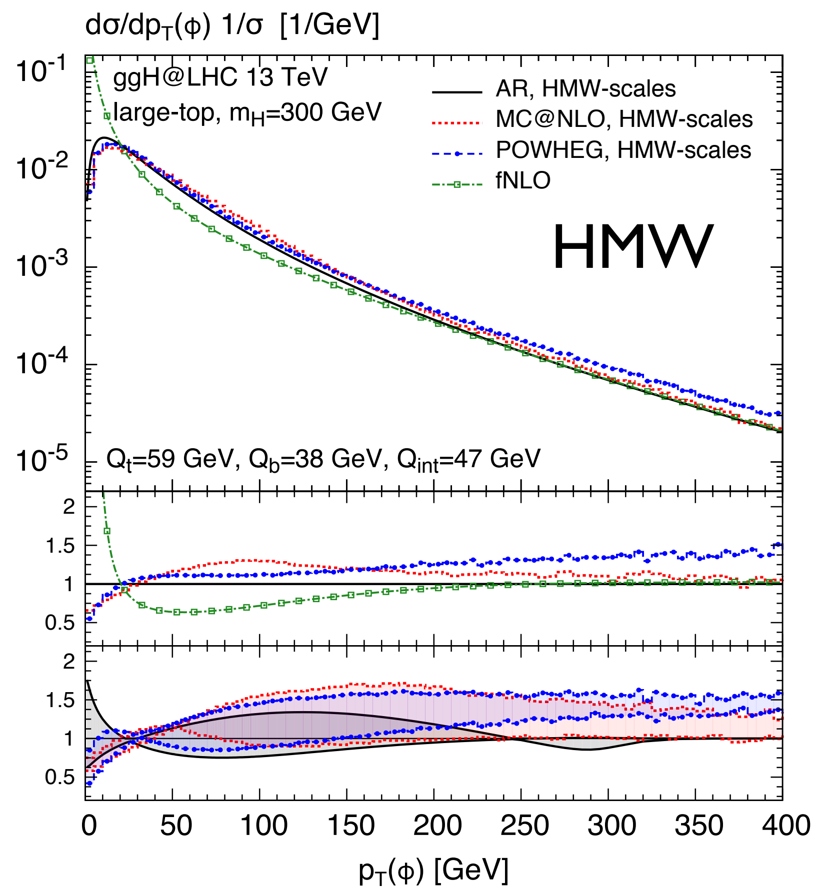
scenario bottom dominated

a posteriori we observe that it is well described also by a one scale run (bottom scale)

using MH/2 or even MH/1.2 would lead to a huge discrepancy w.r.t. our best prediction

Comparison of different codes 2HDM top dominated, heavy scalar



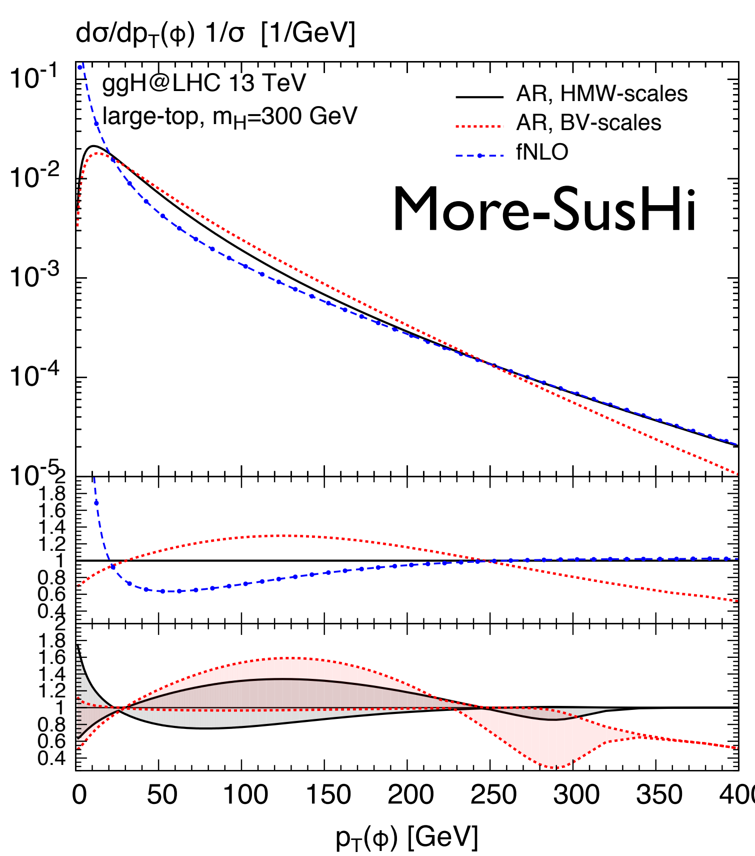


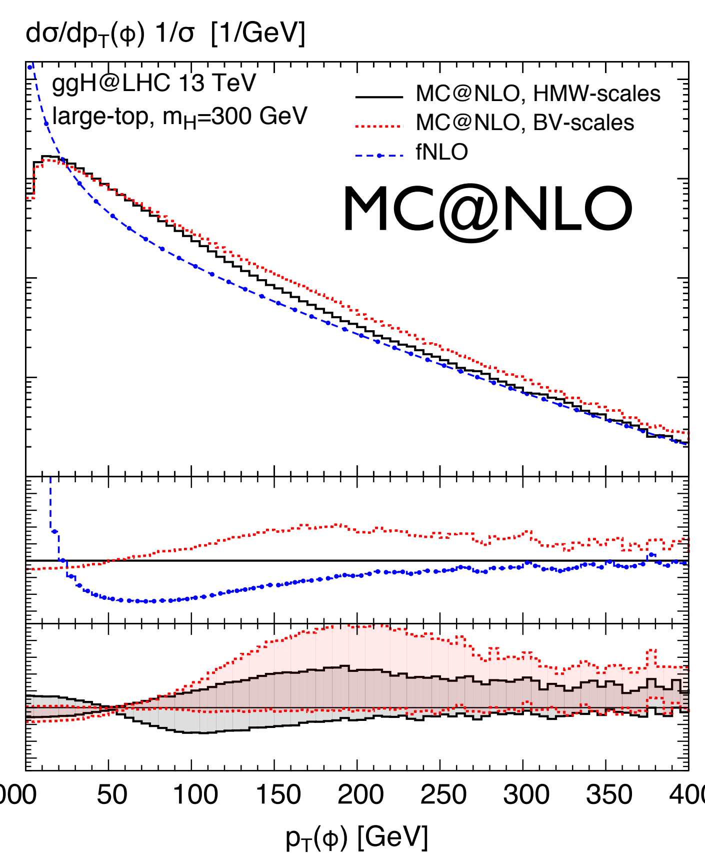
scenario top dominated

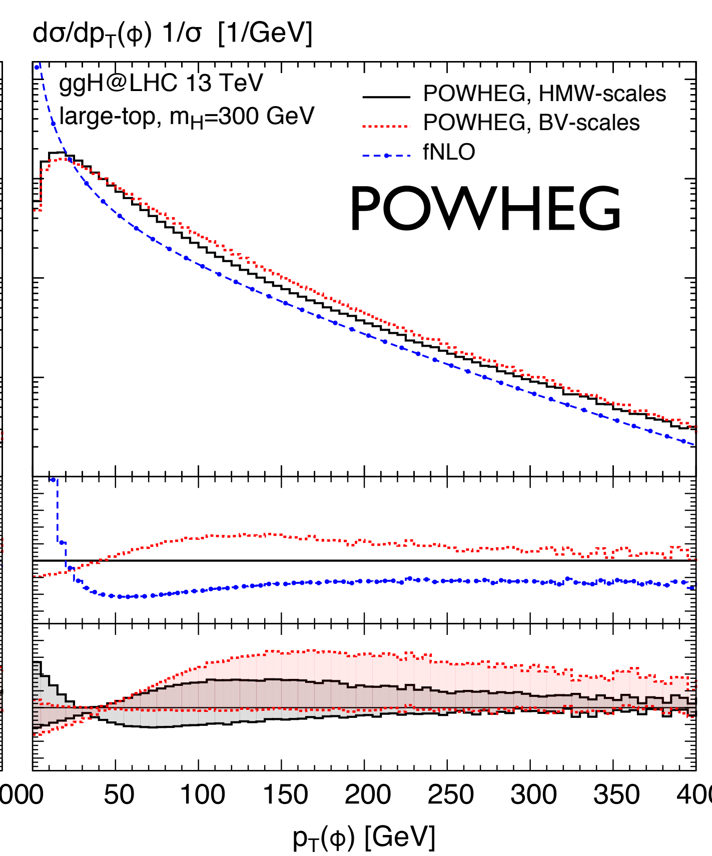
BV and HMW scales differ

Monte Carlo and analytic resummation differ at large ptH, with BV scales

the two Monte Carlo are compatible within the uncertainty bands







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

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

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

  - variants of the rescaling factor

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

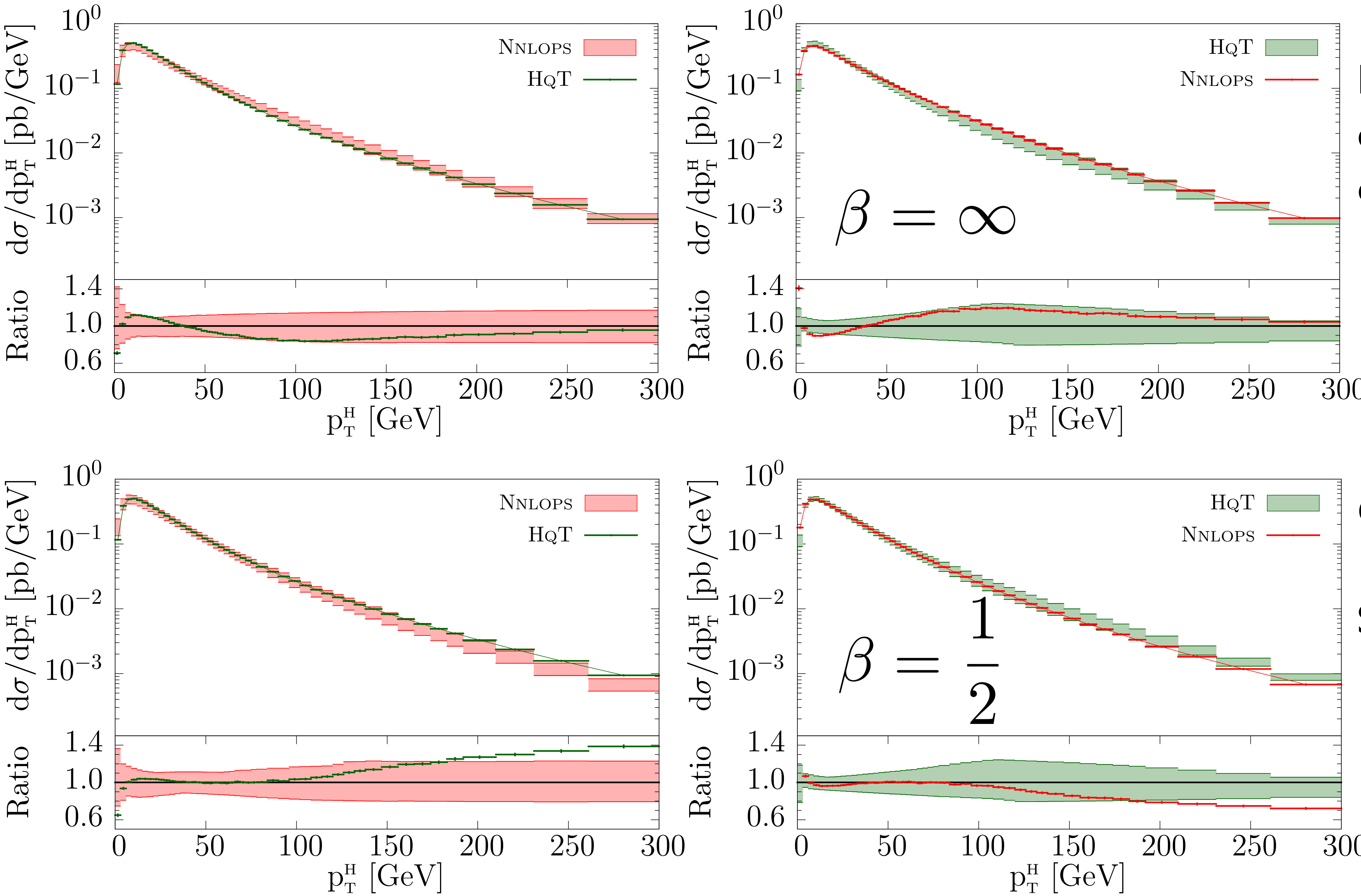
$$h(p_{\rm T}) = \frac{(\beta\, m_{\rm H})^\gamma}{(\beta\, m_{\rm H})^\gamma + p_{\rm T}^\gamma},$$

    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



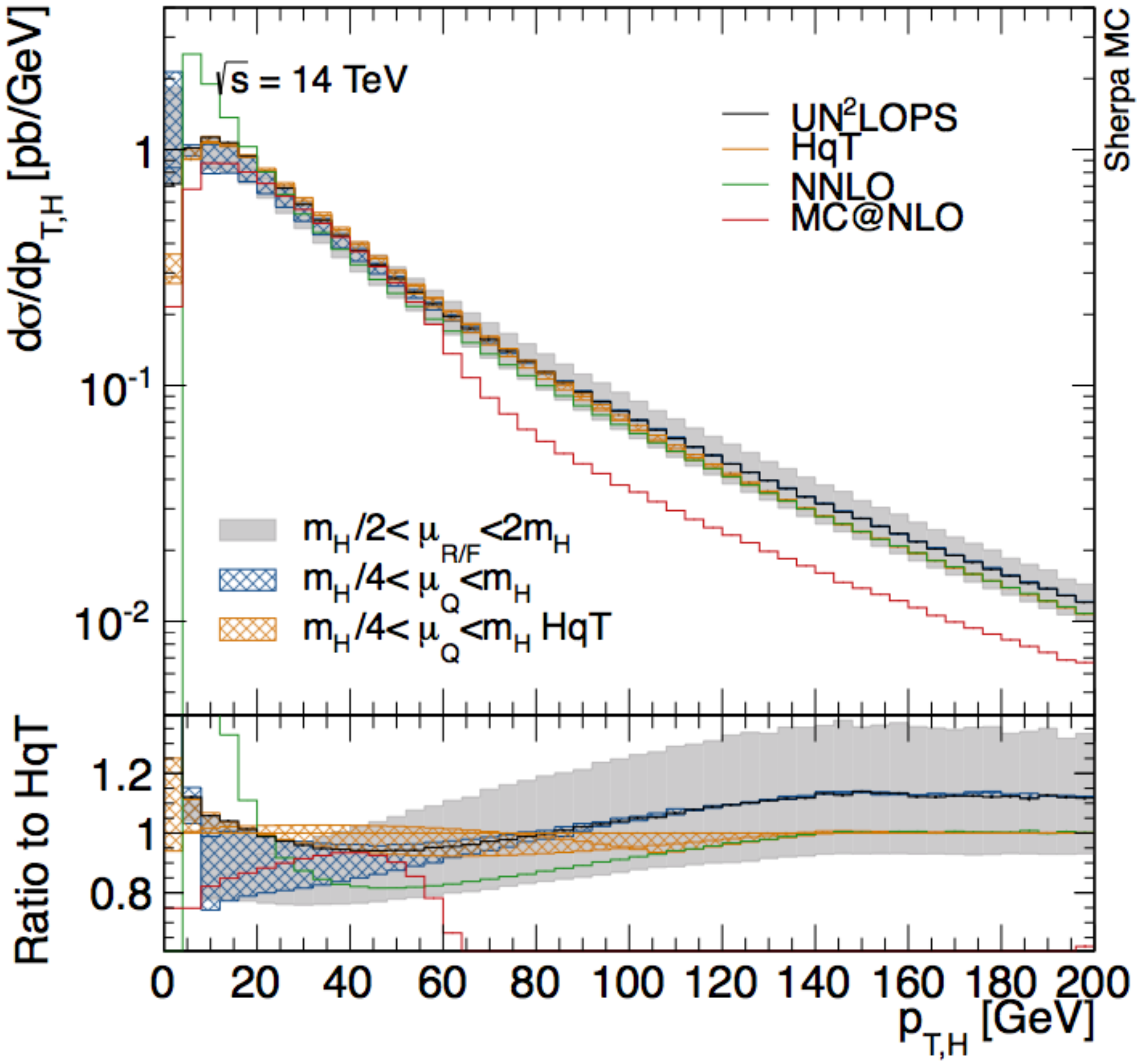
Different shapes compatible over the entire ptH range

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

Resummation of bottom-quark effects in gluon fusion

Banfi, Monni, Zanderighi, arXiv:1308.4634
Hamilton, Nason, Zanderighi, arXiv:1501.04637
Melnikov, Penin, arXiv:1602.09020

- when ptH ≪ mb, in the limit ptH→0, the usual resummation technique can be applied to resum to all orders terms enhanced by log(ptH/mb) factors (instead of the canonical log(ptH/mh))

- in the intermediate region mb < ptH < mh there are left, in principle, corrections proportional to log(mb/mh), which could be numerically large

- these terms are non factorizable and turn out to be of moderate size so that their resummation to all orders is not urgently needed

- the comparison in NNLOPS of two options that fully (don't) exponentiate these finite corrections shows that the impact of bottom corrections is at the 5% level on Higgs ptH, but decreases to the 2-3% level in the case of the jet-veto distribution, when additional cuts are imposed

Summary 1

- 1 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

- 2 the prediction of the Higgs transverse momentum distribution in gluon fusion
  - requires the matching of fixed- and all-orders results
  - because of the presence of top- and bottom-quark loops, is a multiscale problem

- 3a comparison of 3 codes that
  share NLO accuracy on the total xsec and NLL accuracy in the resummation of log(ptH/Q)
  differ by higher-order terms (w.r.t. alphas) and by subleading logarithmic terms
  which are differently included via the various matching prescriptions
  have only LO accuracy in the prediction of the large ptH tail of the distribution

- 3b comparison of two different methods for the choice of the central values of the
  matching parameters

- 4a the matching ambiguities can be numerically sizeable (max at intermediate ptH) and
  should be considered together with ren./fac. scale variations
- 4b the most conservative view is to consider the envelope of the 3 matching uncertainty bands
  as the estimate of this kind of uncertainty
  a less dramatic proposal, based on the mutual compatibility of the 3 codes, could be
  that at least one uncertainty band is computed, with the preferred generator

Summary II

- 5 for the prediction of the ptH spectrum, at large ptH values, codes like HRes or NNLOPS are more adequate, for they have NLO accuracy in that region

- 6a the predictions depend also on algorithmic details (e.g. handling of Parton Shower effects)

- 6b a detailed study at NLO level (SM and BSM) of the matching uncertainties is available, it is desirable a similar study at NNLO

- 7 the bottom-quark loop with enhanced coupling to the Higgs boson may have a non trivial role in the BSM prediction of the Higgs ptH distribution
  a SM-like analysis fails to predict the correct shape

- 8 heavy scalars resolve the loop structure (both top and bottom) also at very small ptH values
  the HQEFT is not reliable in these cases
  an exact calculation is needed

- 9 this study suffers (now) of the low experimental precision of ptH data
  but
  a discussion on the matching uncertainties should be started also for ptZ,
  where the experimental precision is now below 1%

Backup

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

Choice of the matching scale: analysis of the partonic matrix elements (BV)

E.A.Bagnaschi,AV, arXiv:1505.00735

Scalar, collinear deviation scale w (GeV)									
m_H (GeV)	w_t^{gg}	w_b^{gg}	w_i^{gg}	w_t^{qg}	w_b^{qg}	w_i^{qg}	w_t^{gg+qg}	w_b^{gg+qg}	w_i^{gg+qg}
125	55	19	9	24	7	5	48	18	9
200	85	29	16	21	5	5	71	27	14
300	132	41	25	17	4	4	111	38	23
350	102	47	28	15	4	4	87	43	26
400	94	52	26	14	4	3	81	49	23
500	111	63	18	13	3	2	96	58	17
600	133	73	6	13	3	0	113	68	6
700	157	83	25	9	2	2	137	78	24
800	181	93	46	8	2	36	158	87	46

Pseudoscalar, collinear deviation scale w (GeV)									
m_H (GeV)	w_t^{gg}	w_b^{gg}	w_i^{gg}	w_t^{qg}	w_b^{qg}	w_i^{qg}	w_t^{gg+qg}	w_b^{gg+qg}	w_i^{gg+qg}
125	60	19	11	24	7	6	52	18	10
200	126	29	18	22	5	5	102	27	16
300	122	41	28	18	4	4	103	38	25
350	82	47	25	15	4	4	70	43	23
400	99	52	15	14	4	2	86	49	14
500	127	63	15	12	3	2	109	58	14
600	155	73	36	11	3	51	132	68	39
700	184	83	69	10	2	18	160	77	60
800	212	92	277	9	2	10	184	86	239

a 2HDM run in POWHEG

- model input parameters

the user chooses -the values of the input parameters α, $\tan\beta$ and the Higgs mass (Mh, MH, MA)
-the type of 2HDM model (I and II implemented, same conventions as in SusHi)
and writes them in `powheg.input`

the same values should be written in the HDECAY input file `hdecay.in` together with a choice for $M\pm$, M_{12}

HDECAY must be started first to compute the Higgs decay widths in that parameter space point;
the total widths are written in `br.l3_2HDM`, `br.h3_2HDM`, `br.a3_2HDM`
→ these files must be present in the POWHEG run directory

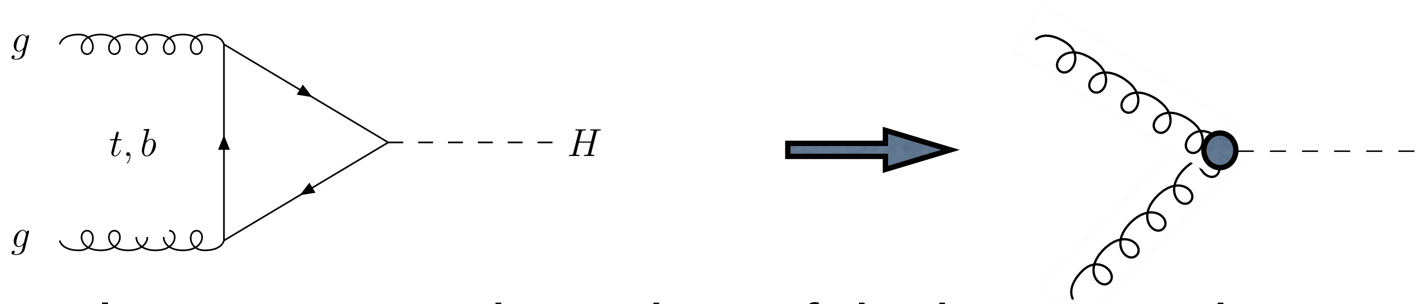
- QCD and generation parameters are defined as usual in `powheg.input`
the complex pole scheme, relevant for the heavy Higgs studies, is not yet available

Effective lagrangian in the HQET (large mtop limit)

- in the limit of large mt, the full QCD lagrangian is well approximated by the (gauge invariant) effective lagrangian

$$\mathcal{L}_{eff} = -\frac{1}{4}\left[1 - \frac{\alpha_s}{3\pi}\frac{H}{v}(1+\Delta)\right] \, \mathrm{Tr} G_{\mu\nu}G^{\mu\nu}$$

- the top triangle loop shrinks to a pointlike interaction vertex



- the effective lagrangian is independent of the heavy quark mass
  $\Rightarrow$ this process is a heavy quark counter

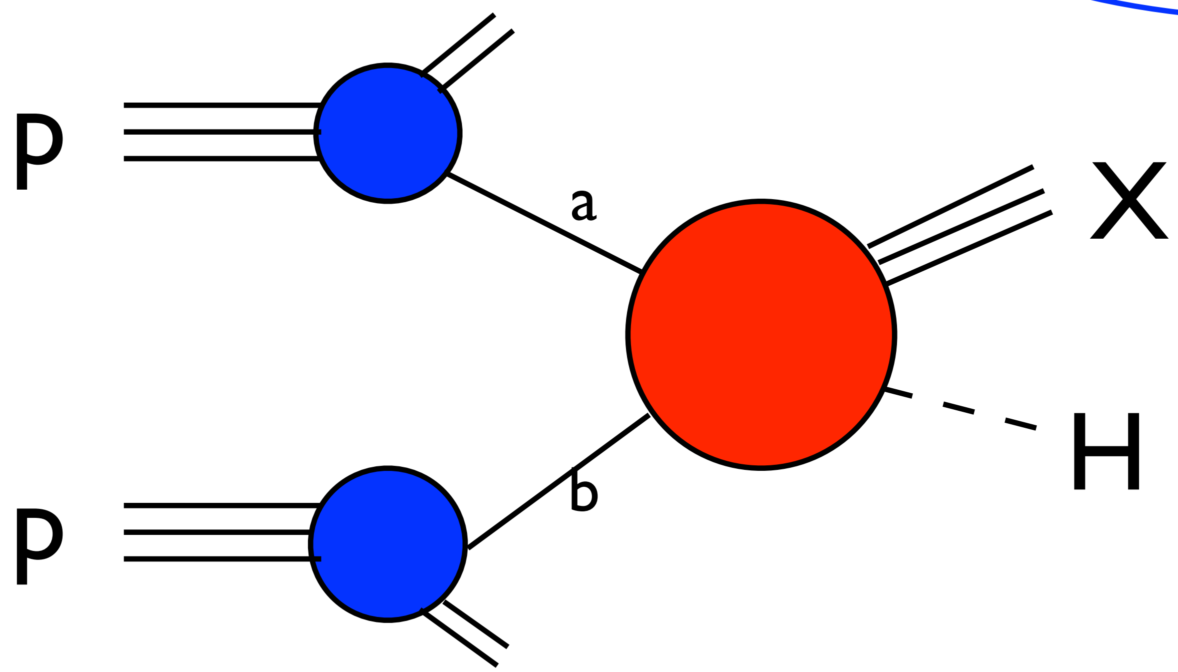
- in the effective lagrangian approach, one loop less to be computed

- delicate is the effective lagrangian approach:
  in presence of light particles in the loop, in the high-energy limit

- Cross section dominated by the lowest order threshold kinematics
  Large contribution due to soft gluon emission at the threshold

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

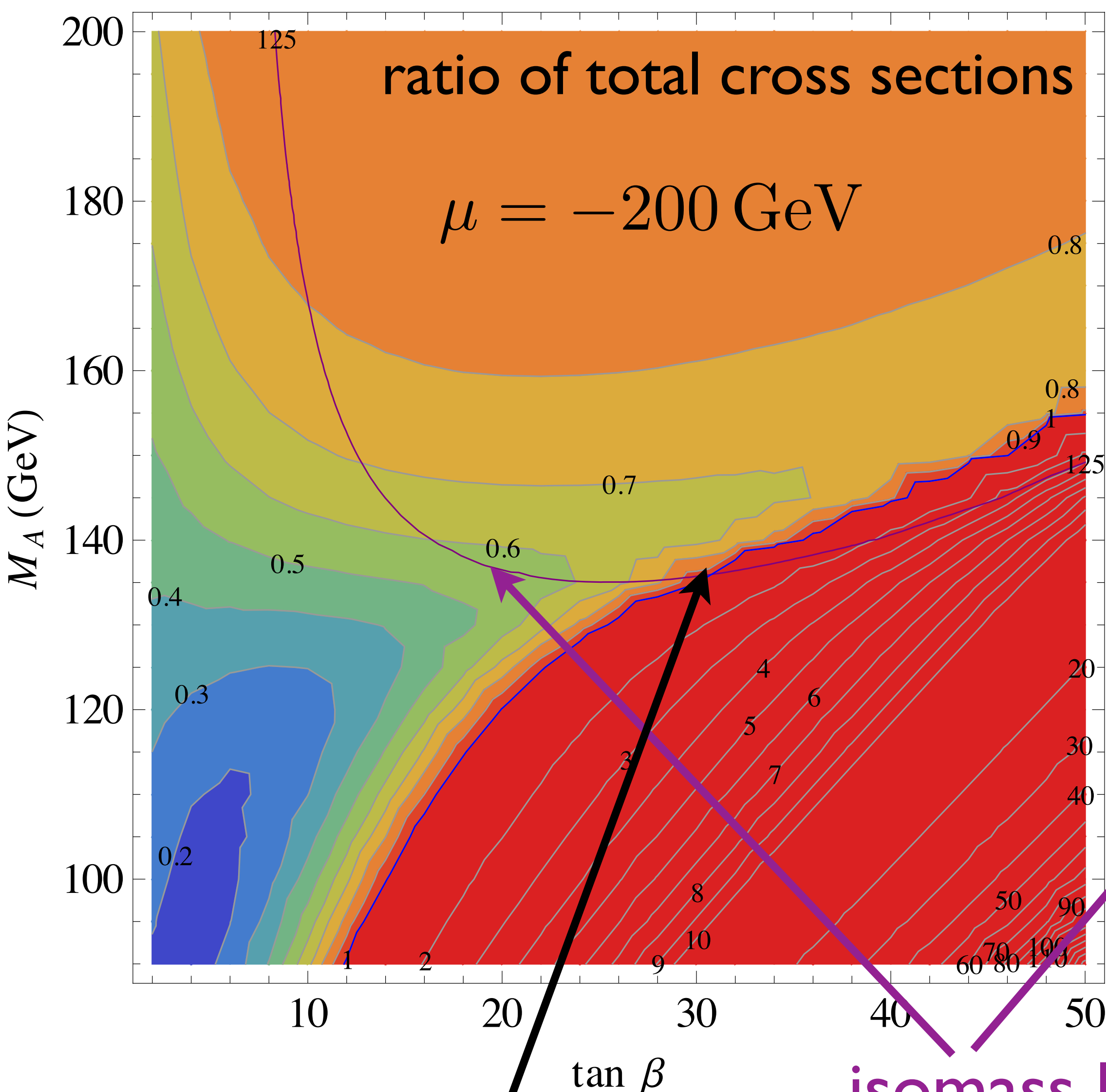
NNLO-QCD HQET Anastasiou Melnikov 2002 Harlander Kilgore 2002 Ravindran Smith van Neerven 2003

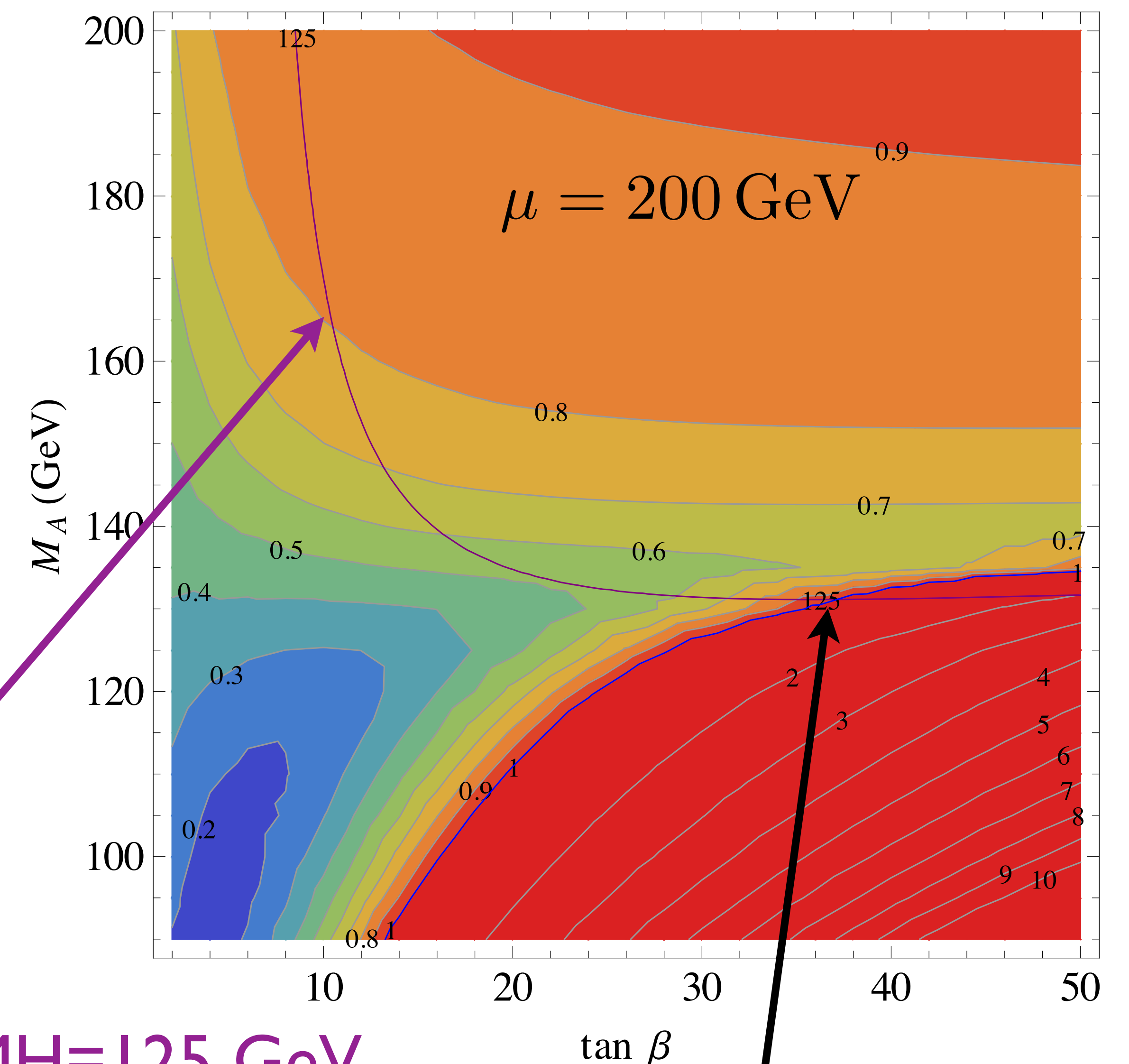
N3LO-QCD HQET Anastasiou, Duhr, Dulat, Herzog, Mistlberger 2015

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

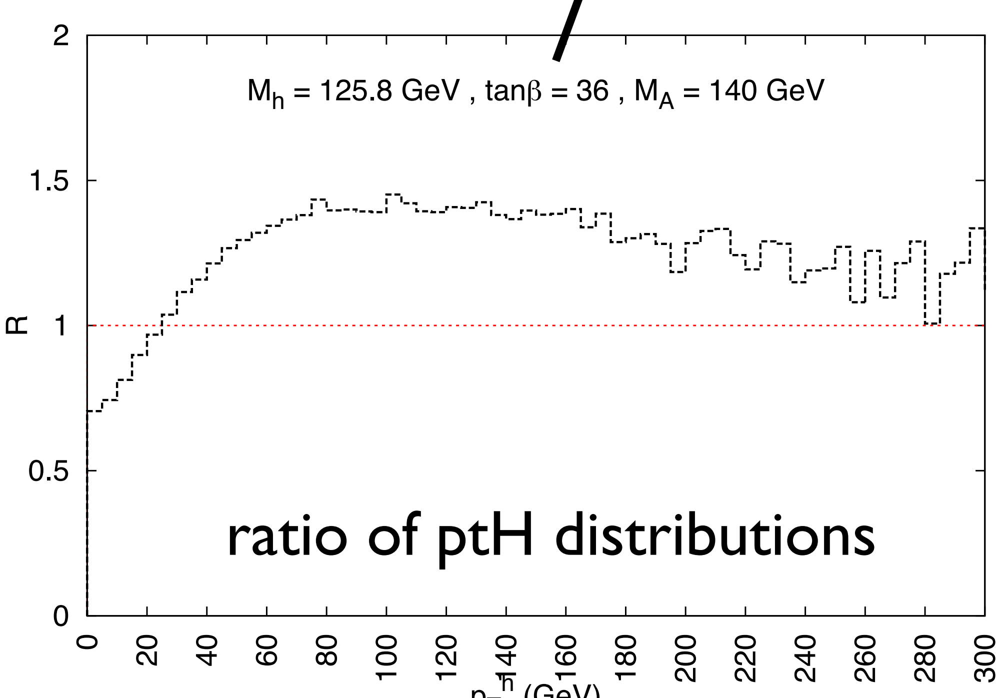
Ratios full MSSM/SM, h_0 production

mQ=mU=mD=1000 GeV, X^t=2500 GeV, M_3=800 GeV, M_2=2 M_1=200 GeV

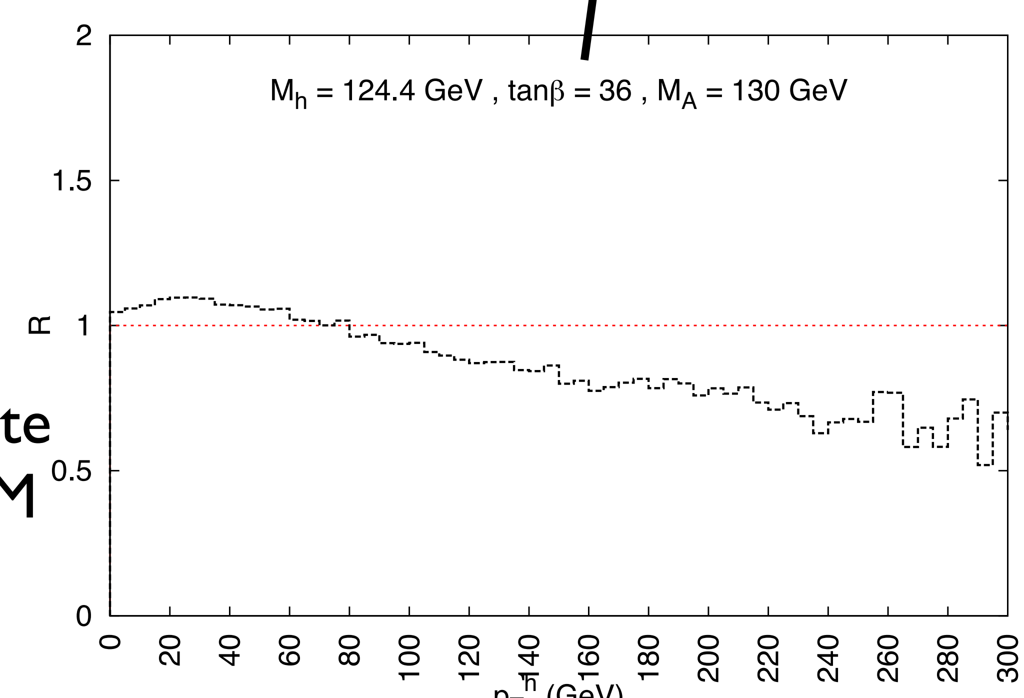




isomass line MH=125 GeV



not only the BR
but also the ptH distr
can help to discriminate
between SM and MSSM



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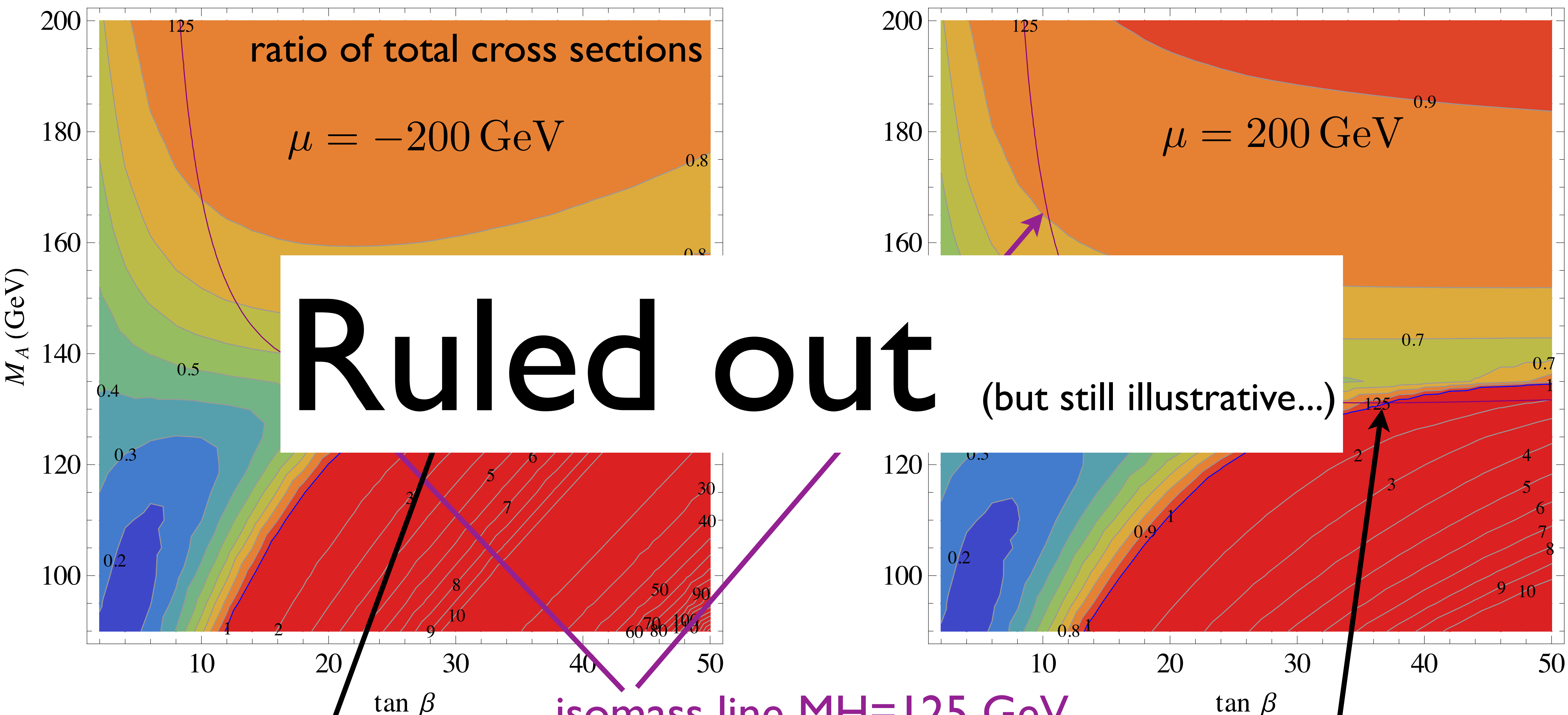

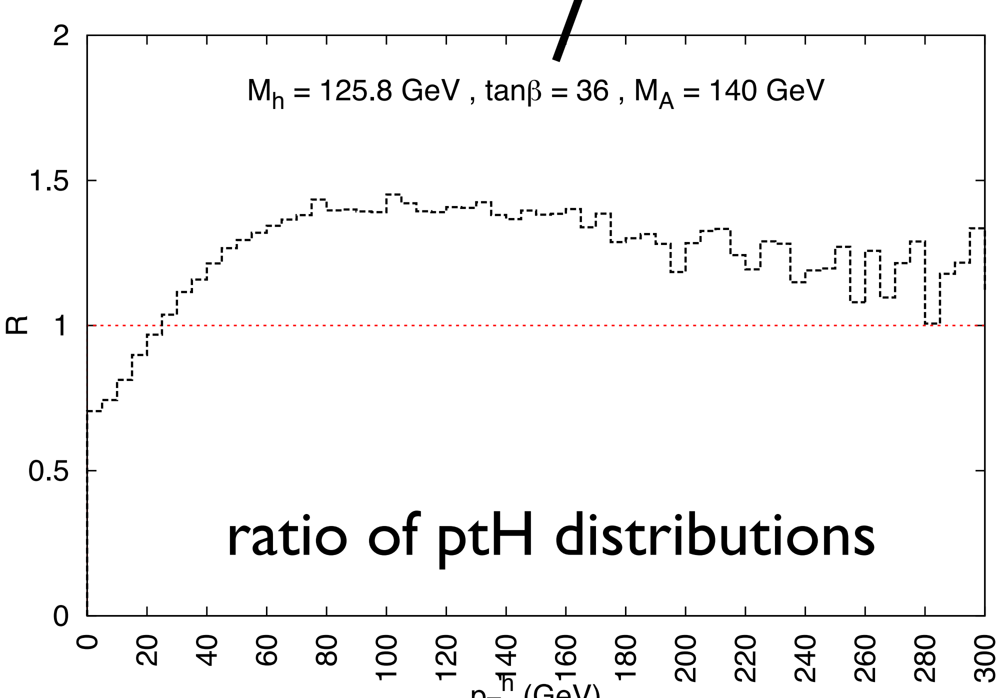

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