Università degli Studi di Milano

INFN Istituto Nazionale di Fisica Nucleare

The gluon fusion process in POWHEG in the SM, MSSM and 2HDM: the Higgs transverse momentum distribution

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University of Milano, INFN Milano

TIFR, January 7th 2014

in collaboration with: E. Bagnaschi, G. Degrassi, P. Slavich

Outline

- Introduction to gluon fusion
- Higgs ptH distribution in the HQET limit
- gluon fusion with quark mass effects in the SM
- uncertainties affecting the ptH distribution
- two-scales description of the Higgs ptH distribution
- gluon fusion BSM: MSSM and 2HDM

Basic references

The POWHEG code to simulate the gluon fusion in the SM, MSSM and 2HDM

- can be found at http://powhegbox.mib.infn.it/
  in the directories gg_H_quark-mass-effects/
  gg_H_MSSM/
  gg_H_2HDM/

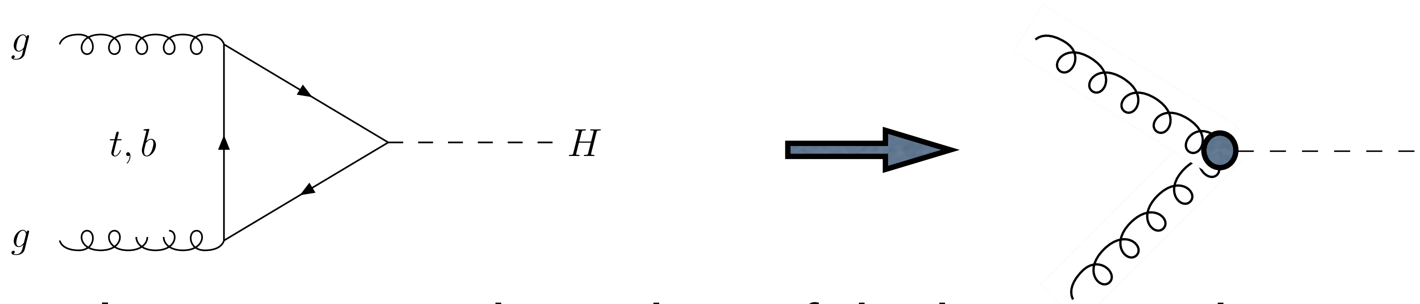
- is described in Bagnaschi, Degrassi, Slavich, Vicini, JHEP 1202 (2012) 088, arXiv:1111.2854
  extends the original code by Alioli, Nason, Oleari, Re, JHEP 0904 (2009) 002, arXiv:0812.0578

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



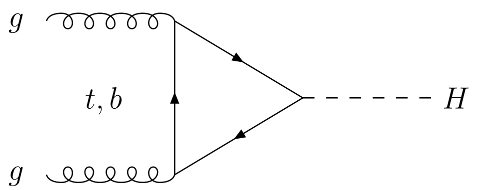
- the effective lagrangian is independent of the heavy quark mass
  $\Rightarrow$ this process is a heavy quark counter

- 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 gluon fusion process: existing literature for the total cross section



LO-QCD

Georgi Glashow Machacek Nanopoulos 1978

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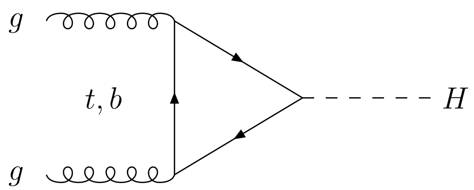

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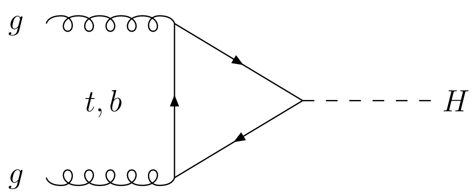
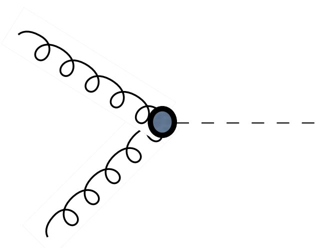


Effective theory (HQET) mtop → infinity



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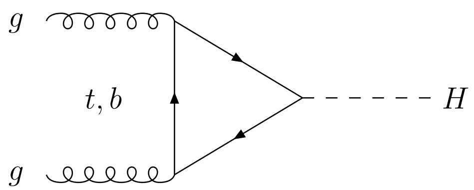

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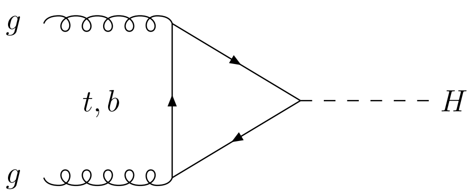

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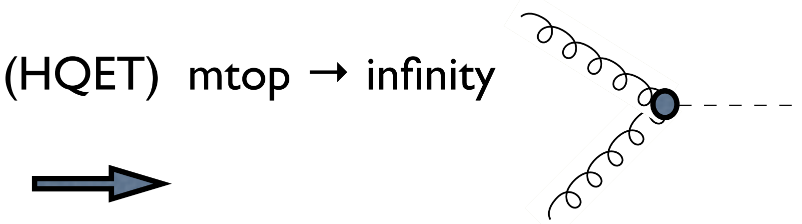


NLO-QCD

HQET Dawson 1991, Djouadi Graudenz Spira Zerwas 1992

exact Spira Djouadi Graudenz Zerwas 1995

Aglietti Bonciani Degrassi AV 2007

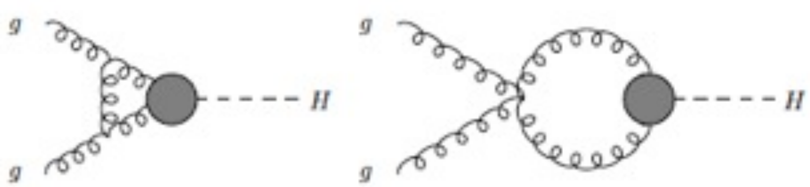
Anastasiou Beerli Bucherer Daleo Kunszt 2007

HIGLU

POWHEG

FeHipro

HQET



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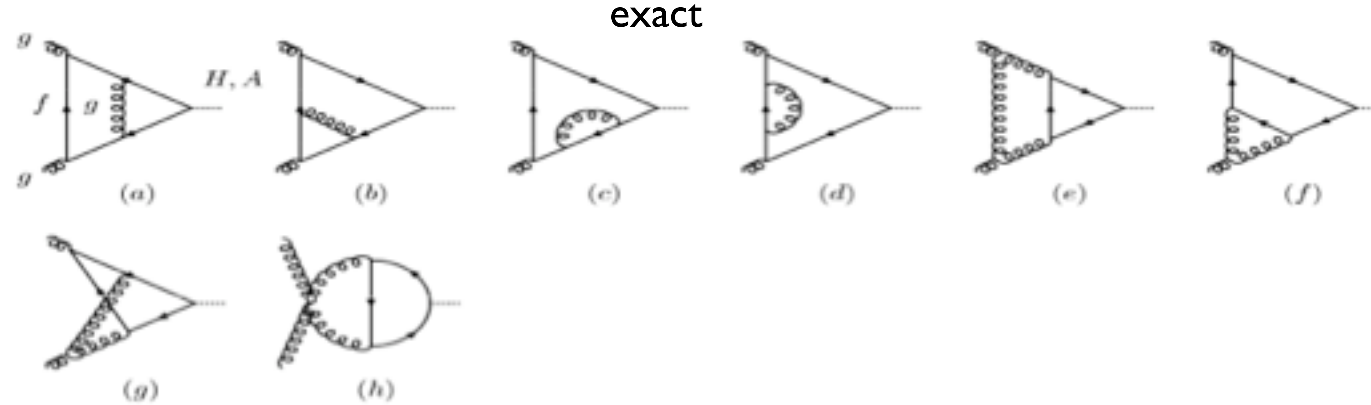

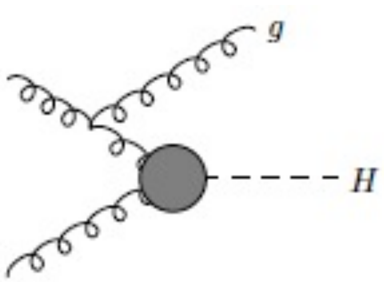

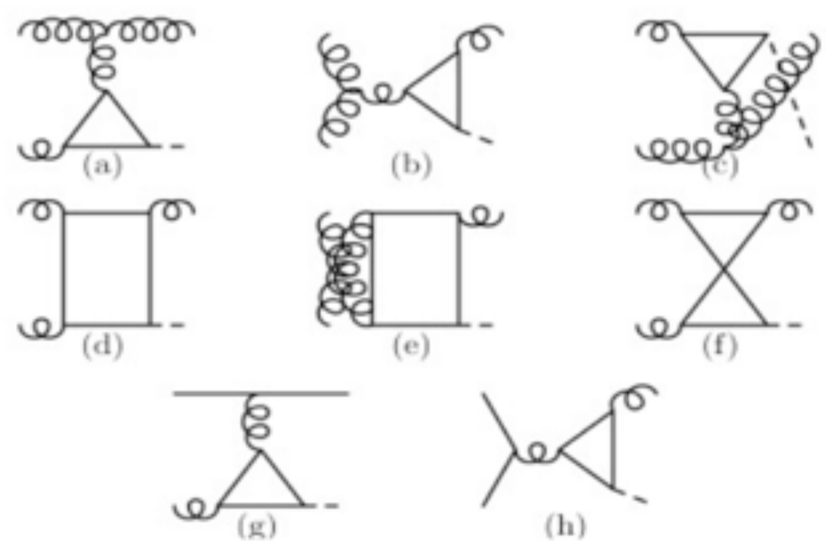

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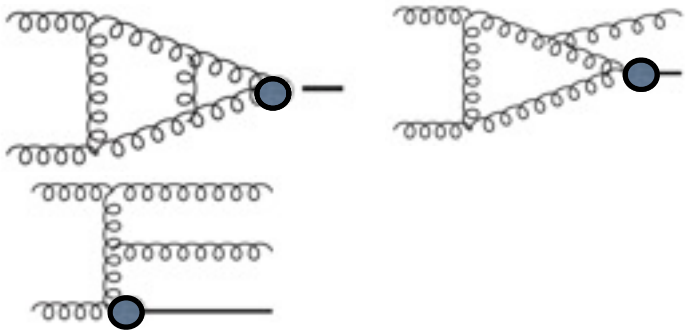

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iHixs, ggh@nnlo, HNNLO

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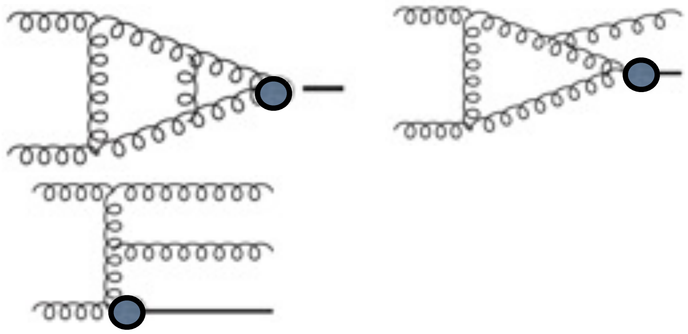

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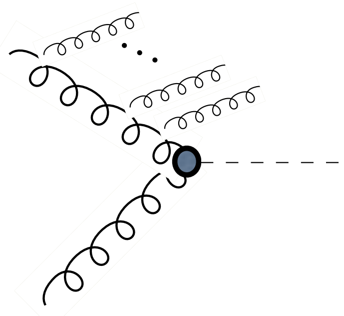

NNLO-QCD + soft gluon resummation NNLL-QCD
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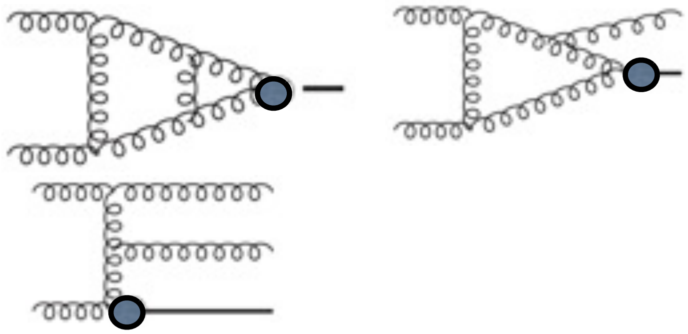

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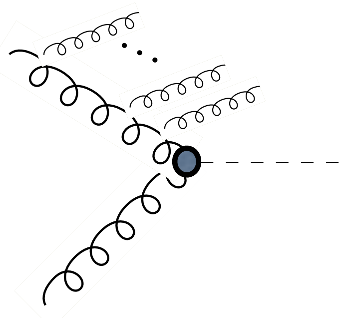

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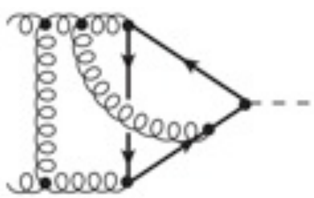

NNLO-QCD + finite top mass effects

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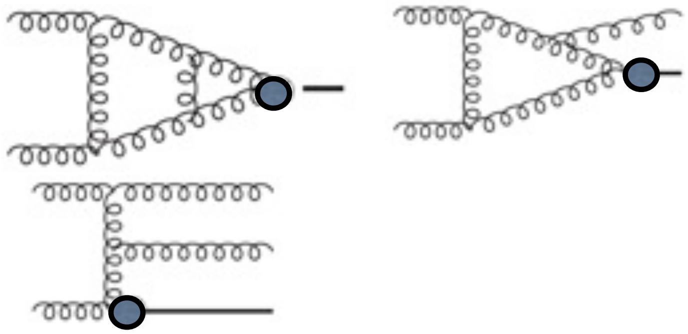

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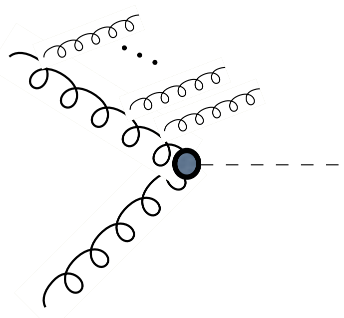

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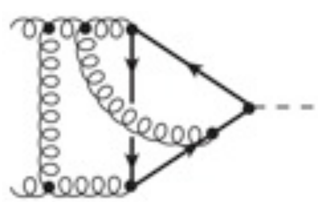

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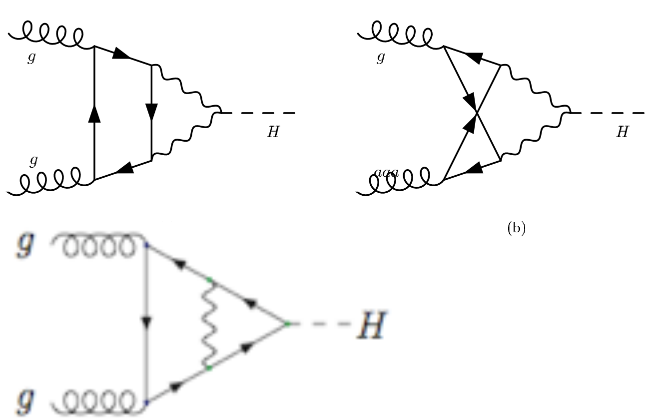

NLO-EW

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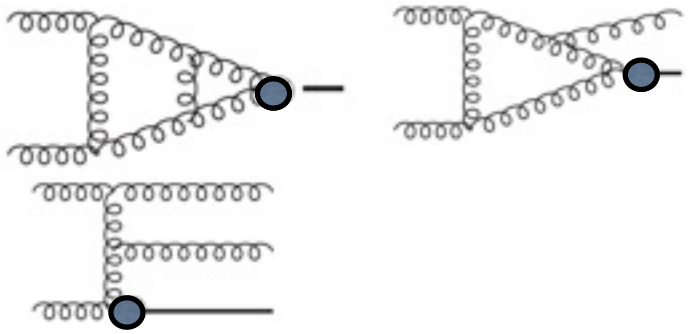

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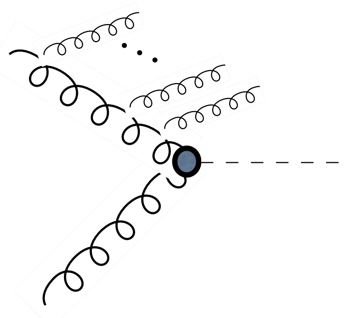

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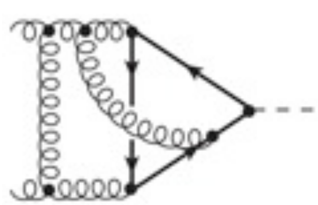

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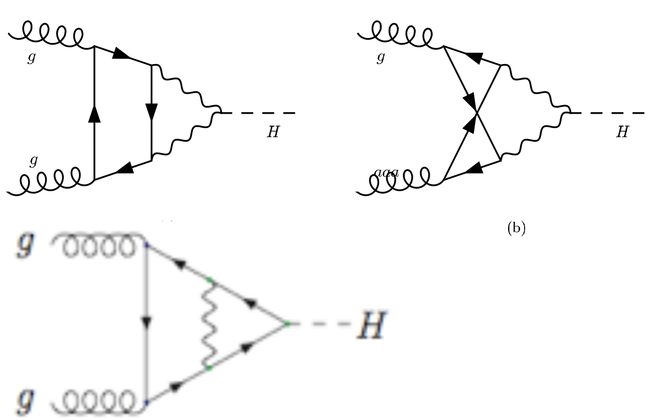

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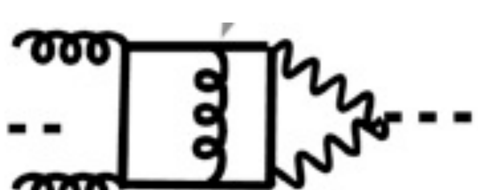
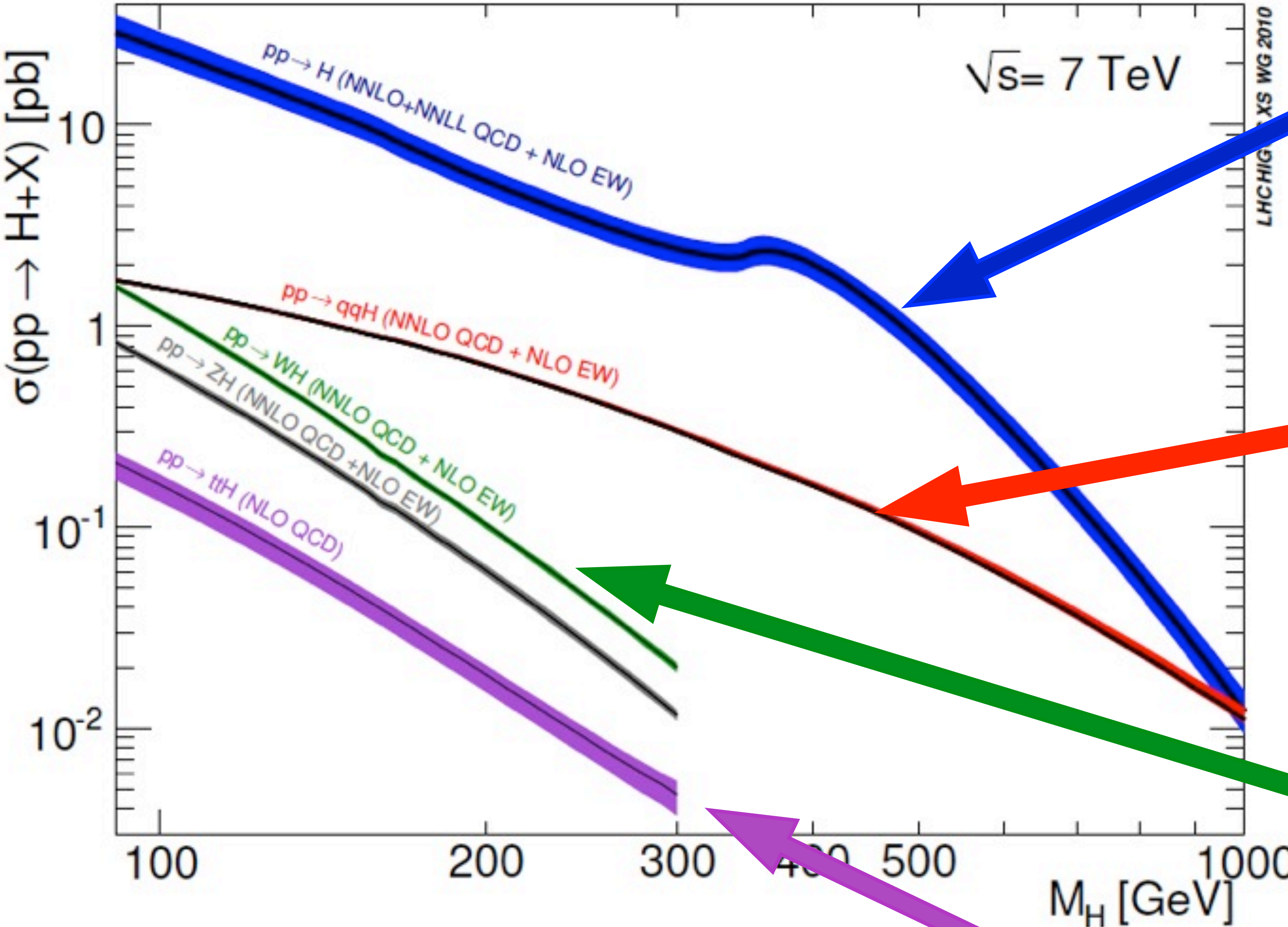


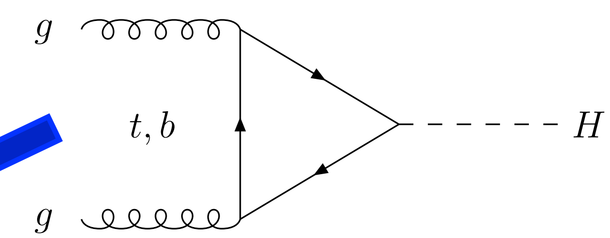
mixed NLO EWxQCD
Anastasiou Boughezal Petriello 2009

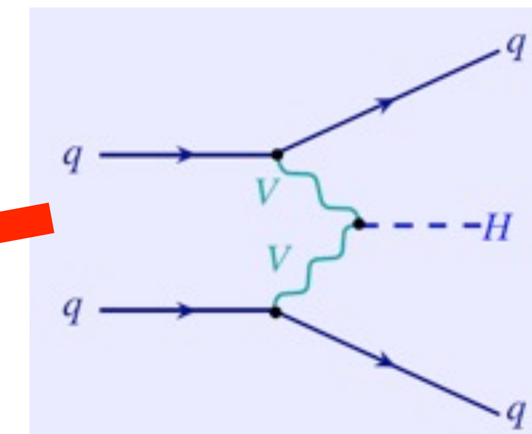
iHixs

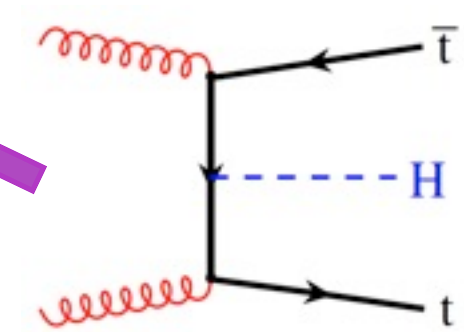
The total production cross section

- Yellow Report 1 of the Higgs Cross Section Working Group, arXiv:1101.0593









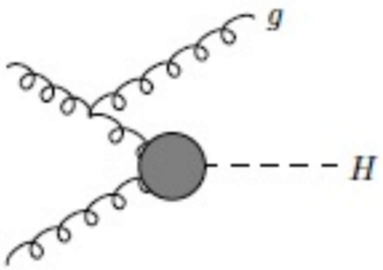
- the gluon fusion process dominates
  but weak-boson fusion has a very good signal/background ratio

- the uncertainty bands include: PDF+alphas uncertainty, scale uncertainty

Heavy Quark Effective Theory (HQET)

Higgs transverse momentum distribution in the HQET (heavy top limit)

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



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

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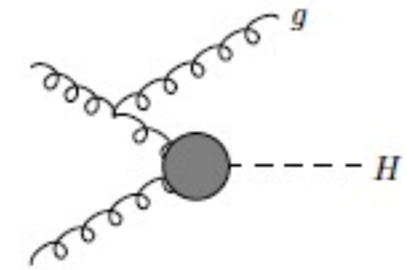

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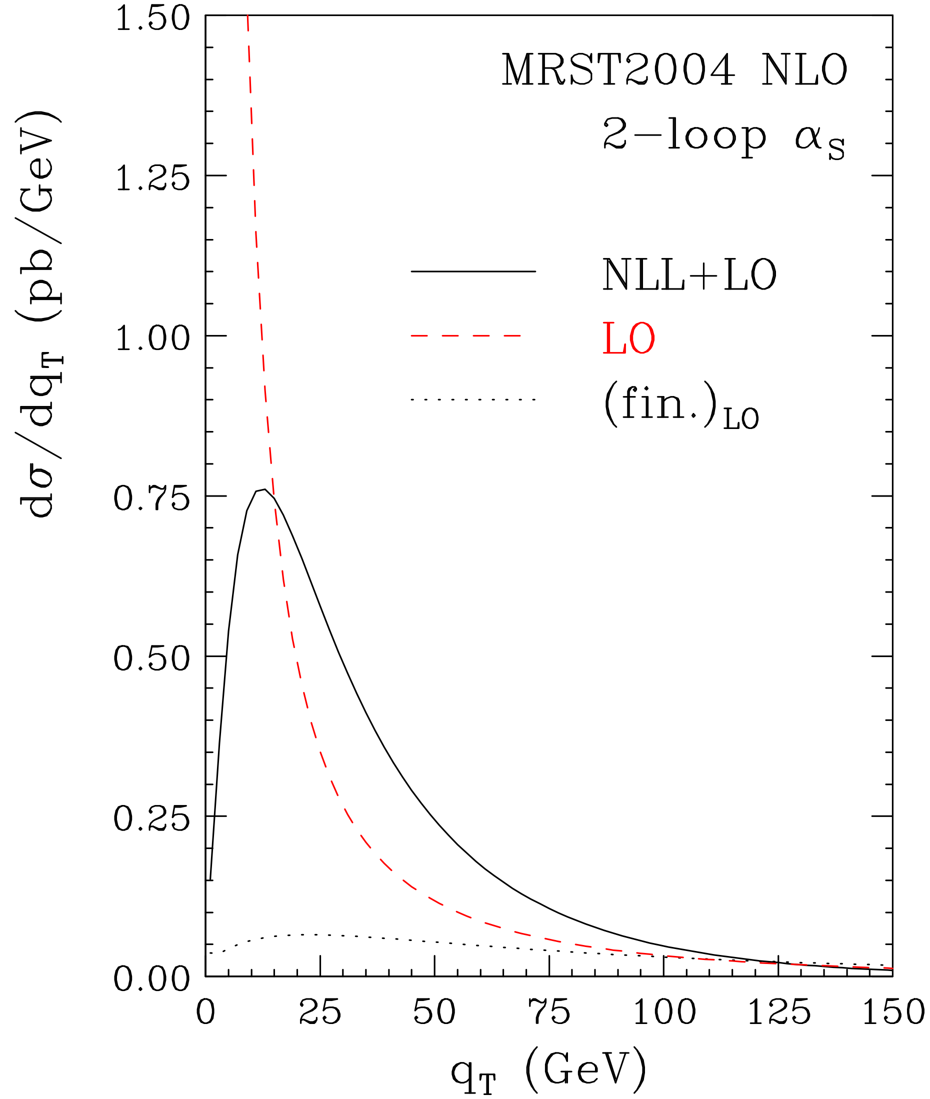
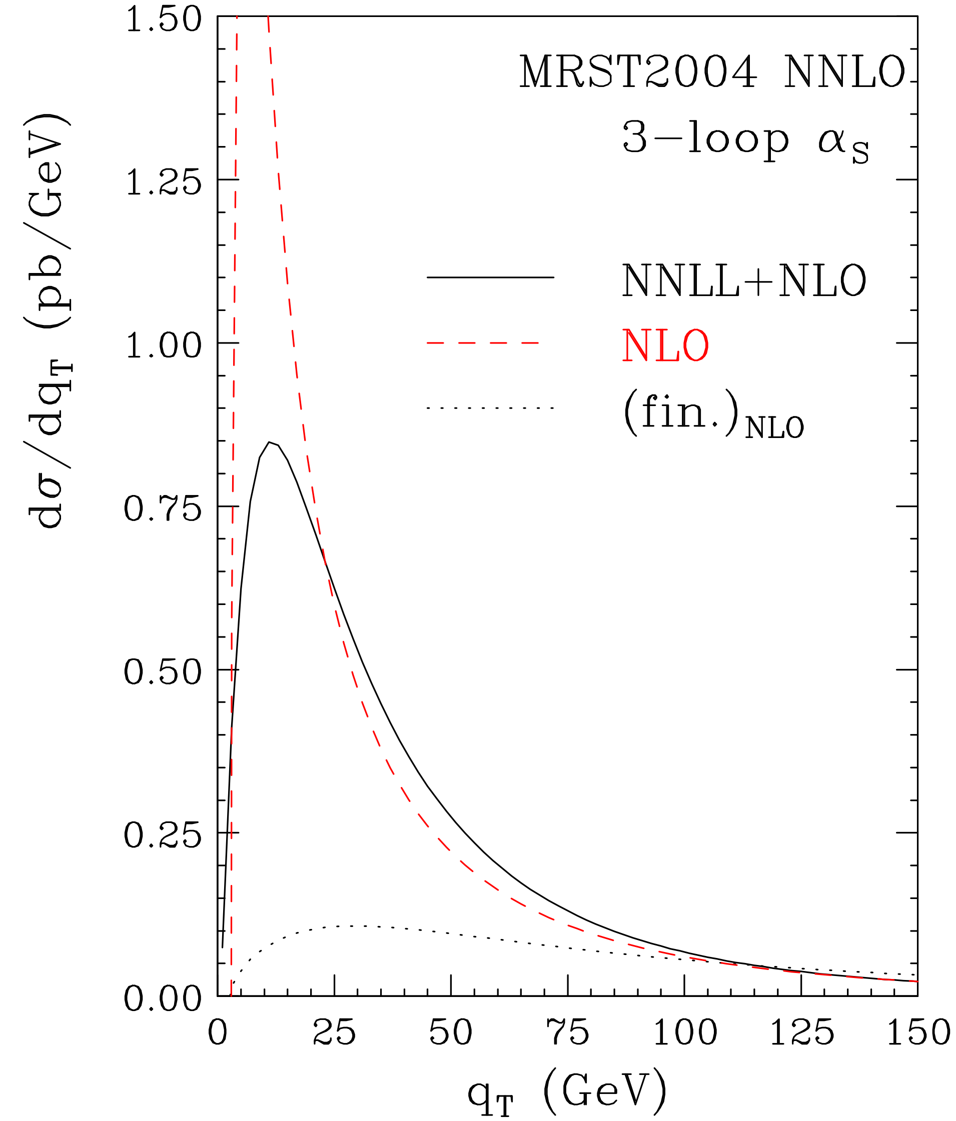




- at low ptH, the fixed order ptH distribution diverges for ptH → 0 (both at LO and at NLO)
- the resummation to all orders of the divergent log(ptH) terms is regular in the limit ptH → 0

Resummation of log(ptH) terms and resummation scale Q

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

process dependent

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

universal

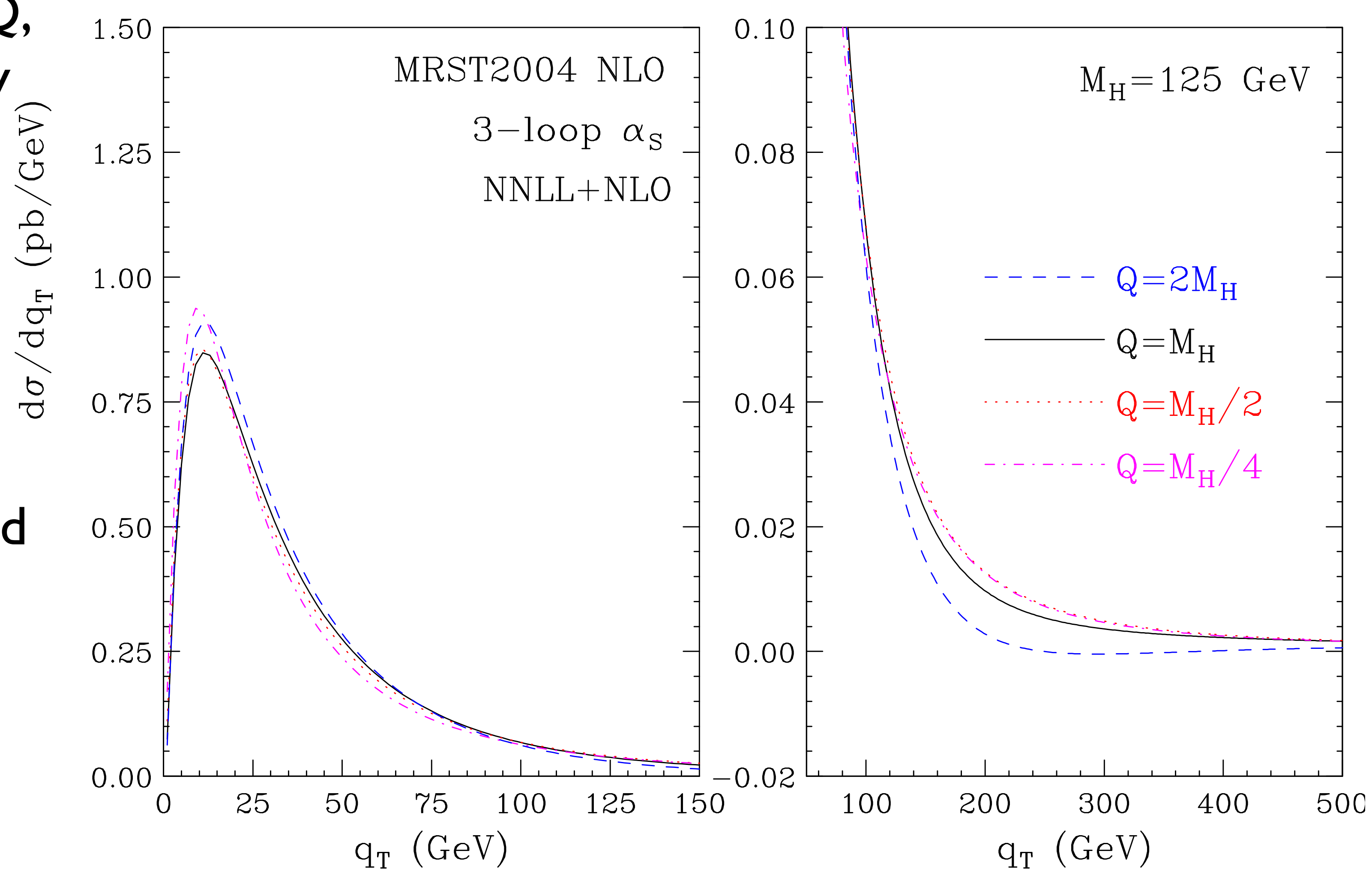
- the factorization (in conjugate space) of the cross section for multiple emissions can be defined at a given scale Q called resummation scale

- 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 cross section does NOT depend on the value of Q

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



Matching NLO matrix elements and Parton Shower

Matching NLO matrix elements and Parton Shower

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

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

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

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

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

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

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POWHEG

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

MC@NLO

$$R^s \propto \frac{\alpha_s}{t}P_{ij}(z)B(\Phi_B)$$

$$R^f = R - R^s$$

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 square bracket

the scale *h* fixes the upper limit for the Sudakov form factor to play a role,
effectively is the upper limit for the inclusion of multiple parton emissions

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

YR2 comparisons arXiv:1201.3084

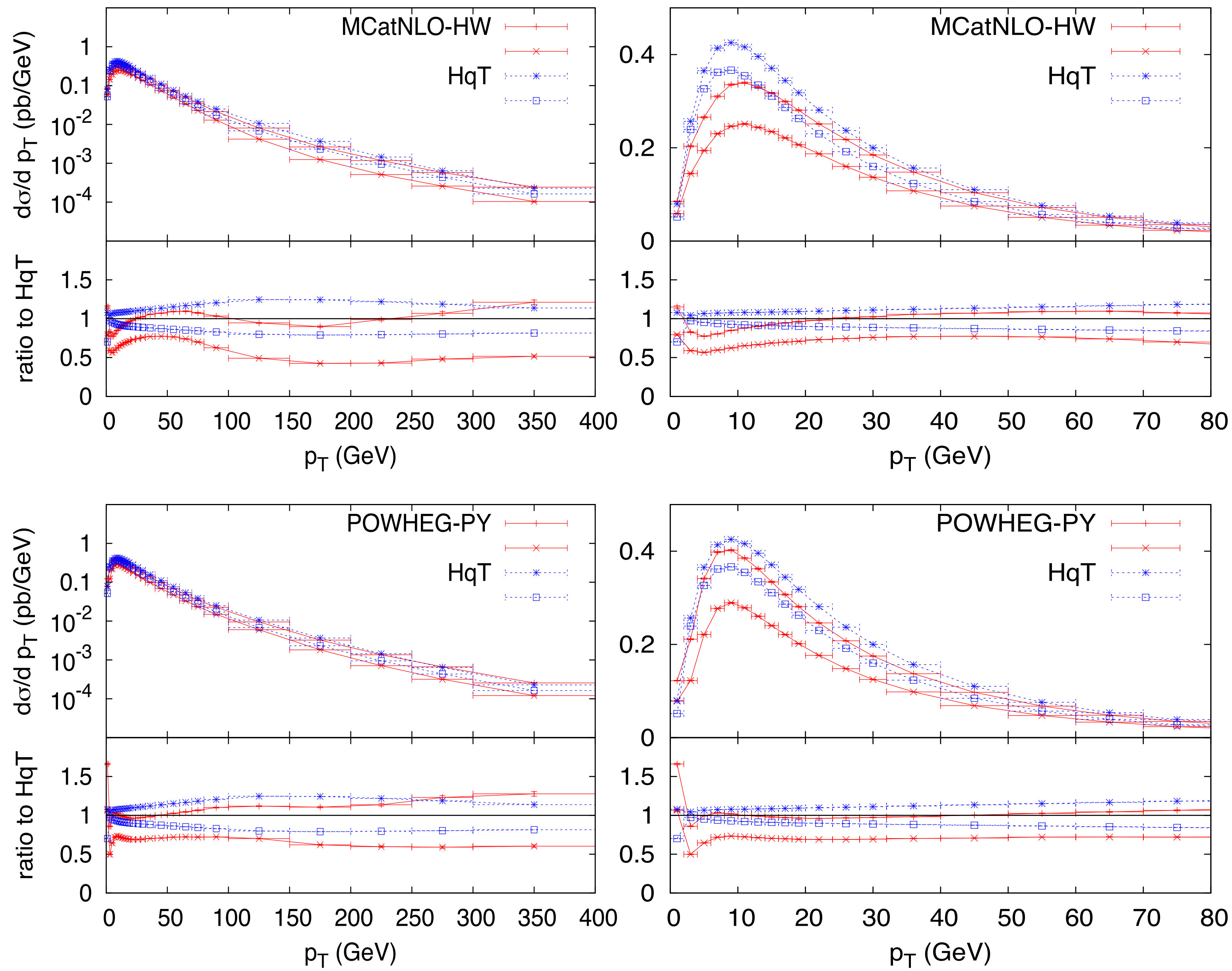


Fig. 22: Uncertainty bands for the transverse-momentum spectrum of the Higgs boson at LHC, 7 TeV, for a Higgs mass $M_{\rm H} = 120$ GeV. On the upper plots, the MC@NLO+HERWIG result obtained using the non-default value of the reference scale equal to $M_{\rm H}$. On the lower plots, the POWHEG+PYTHIA output, using the non-default $R^s + R^f$ separation. The uncertainty bands are obtained by changing $\mu_{\rm R}$ and $\mu_{\rm F}$ by a factor of two above and below the central value, taken equal to $M_{\rm H}$, with the restriction $0.5 < \mu_{\rm R}/\mu_{\rm F} < 2$.

- MC@NLO should be run with the factorisation and renormalisation scale equal to $M_{\rm H}$.
- POWHEG should be run with the h parameter equal to $M_{\rm H}/1.2$. For $M_{\rm H} = 120$ GeV, this setting is achieved introducing the line `hfact 100` in the `powheg.input` file.

Quark mass effects (2011-2012)

Gluon fusion in POWHEG with quark mass effects

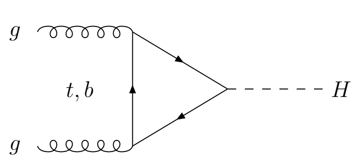
(Bagnaschi Degrassi Slavich Vicini, arXiv:1111.2854)

- the code is an event generator which describes the process
  $pp \to H+X$
  with NLO-QCD accuracy matched with a QCD parton shower

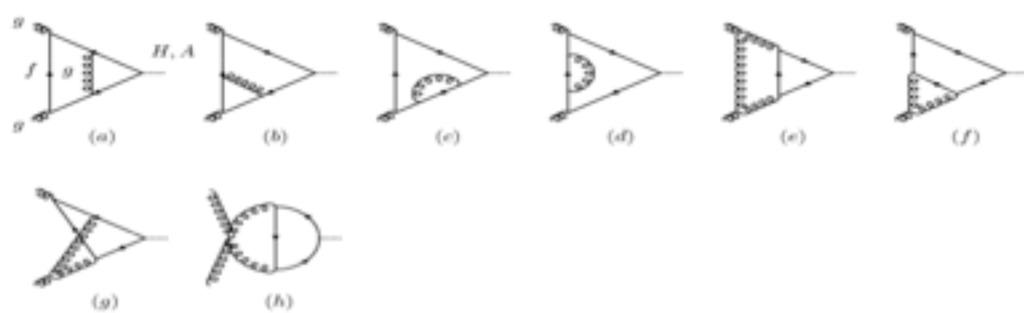
- full NLO-EW corrections (Actis et al. 2009) are applied in a factorized form to the QCD cross section

- the matrix elements retain the exact dependence on the quark masses in the loops (top, bottom, charm, ...)

LO



NLO virtual



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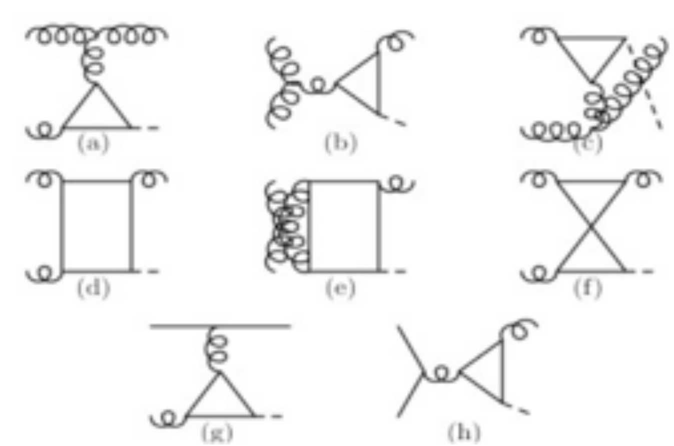
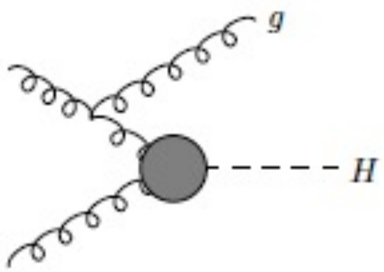


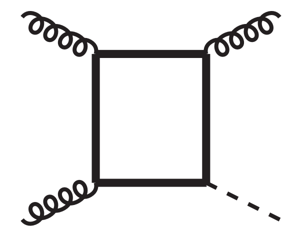
- the Complex Mass Scheme is implemented, relevant for heavy higgs searches

Quark mass effects at NLO

- 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





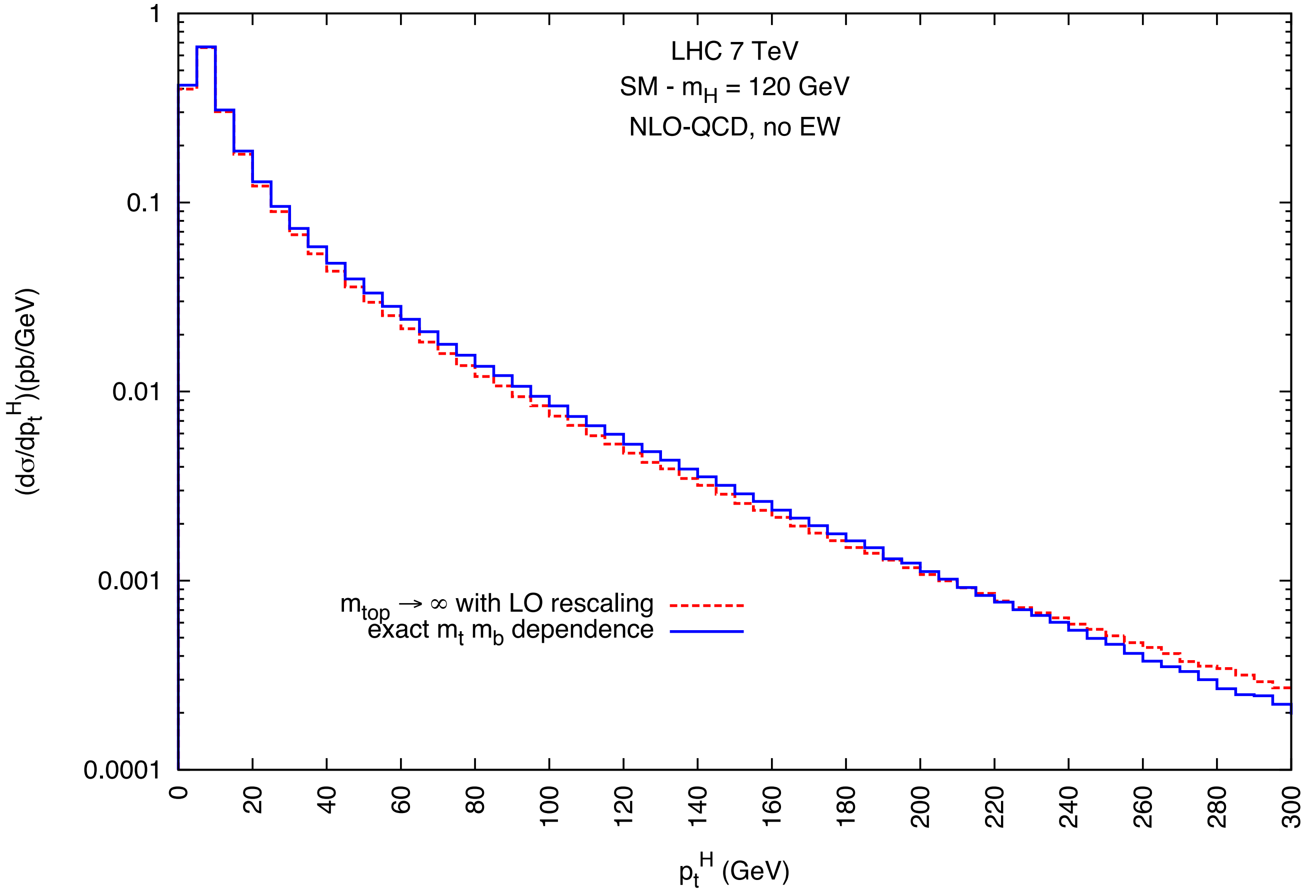
- triangle diagrams → one threshold at $s=4\ mq^2$
  box diagrams → enhanced contribution at ptH ~ mq

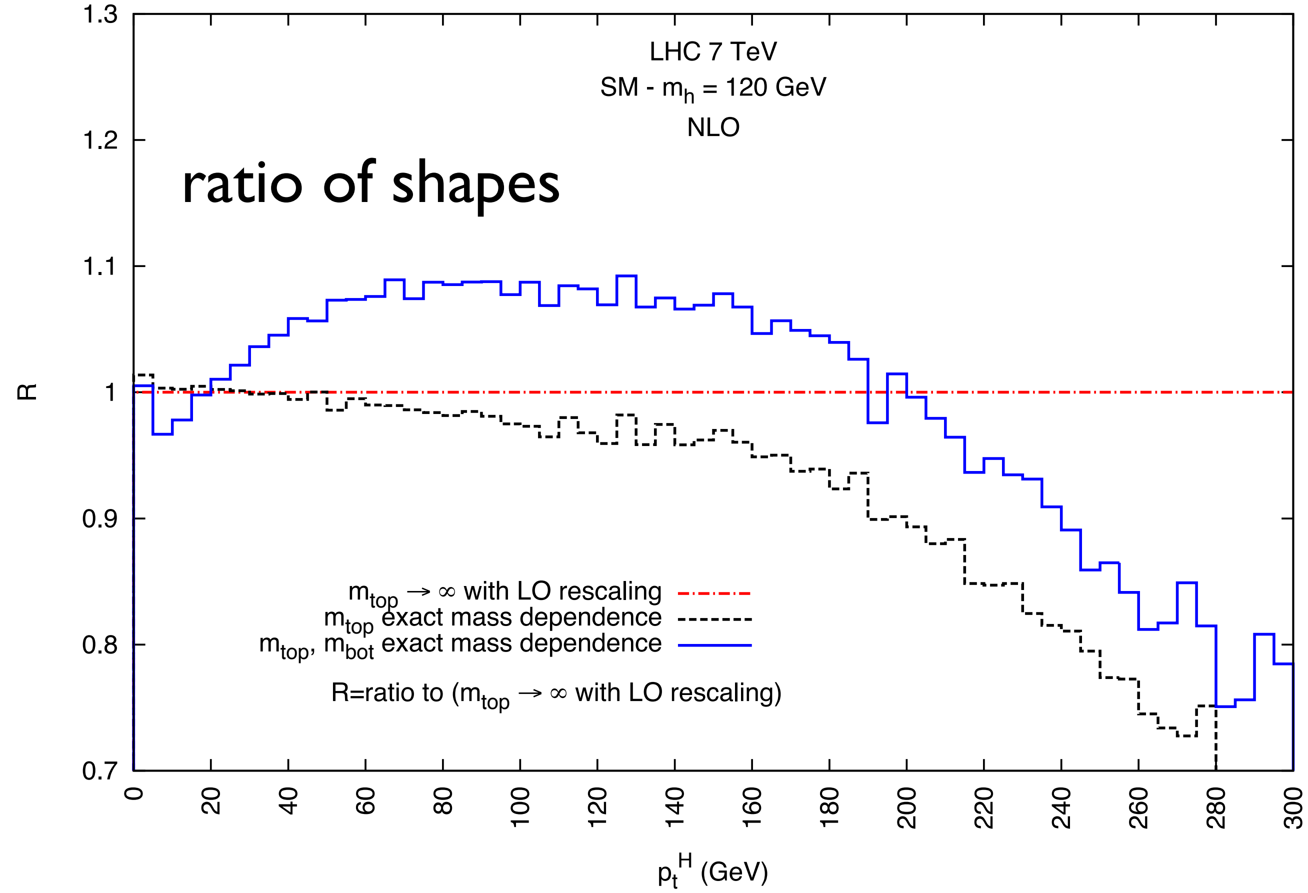
  in the case of the top, mass effects are evident for ptH > 150 GeV
  with the bottom, the effects start at ptH ~ 10 GeV

- 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





- very good agreement with 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%)

Quark mass effects in POWHEG

events are generated according to

$$d\sigma = \bar{B}(\bar{\mathbf{\Phi}}_1)\, d\bar{\mathbf{\Phi}}_1 \left\{ \Delta\left(\bar{\mathbf{\Phi}}_1, p_T^{min}\right) + \Delta\left(\bar{\mathbf{\Phi}}_1, p_T\right) \frac{R\left(\bar{\mathbf{\Phi}}_1, \Phi_{\rm rad}\right)}{B\left(\bar{\mathbf{\Phi}}_1\right)}\, d\Phi_{\rm rad} \right\}$$

$$+ \sum_q R_{q\bar{q}}\left(\bar{\mathbf{\Phi}}_1, \Phi_{\rm rad}\right) d\bar{\mathbf{\Phi}}_1 d\Phi_{\rm rad}\,,$$

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quark mass effects affect

- the overall normalization (LO, NLO virtual and real corrections)

$$\bar{B}(\bar{\mathbf{\Phi}}_1) = B_{gg}(\bar{\mathbf{\Phi}}_1) + V_{gg}(\bar{\mathbf{\Phi}}_1) + \int d\Phi_{\rm rad} \left\{ \hat{R}_{gg}\left(\bar{\Phi}_1, \Phi_{\rm rad}\right) + \sum_q \hat{R}_{gq}\left(\bar{\Phi}_1, \Phi_{\rm rad}\right) + \hat{R}_{qg}\left(\bar{\Phi}_1, \Phi_{\rm rad}\right) \right\} + c.\, r.$$

Quark mass effects in POWHEG

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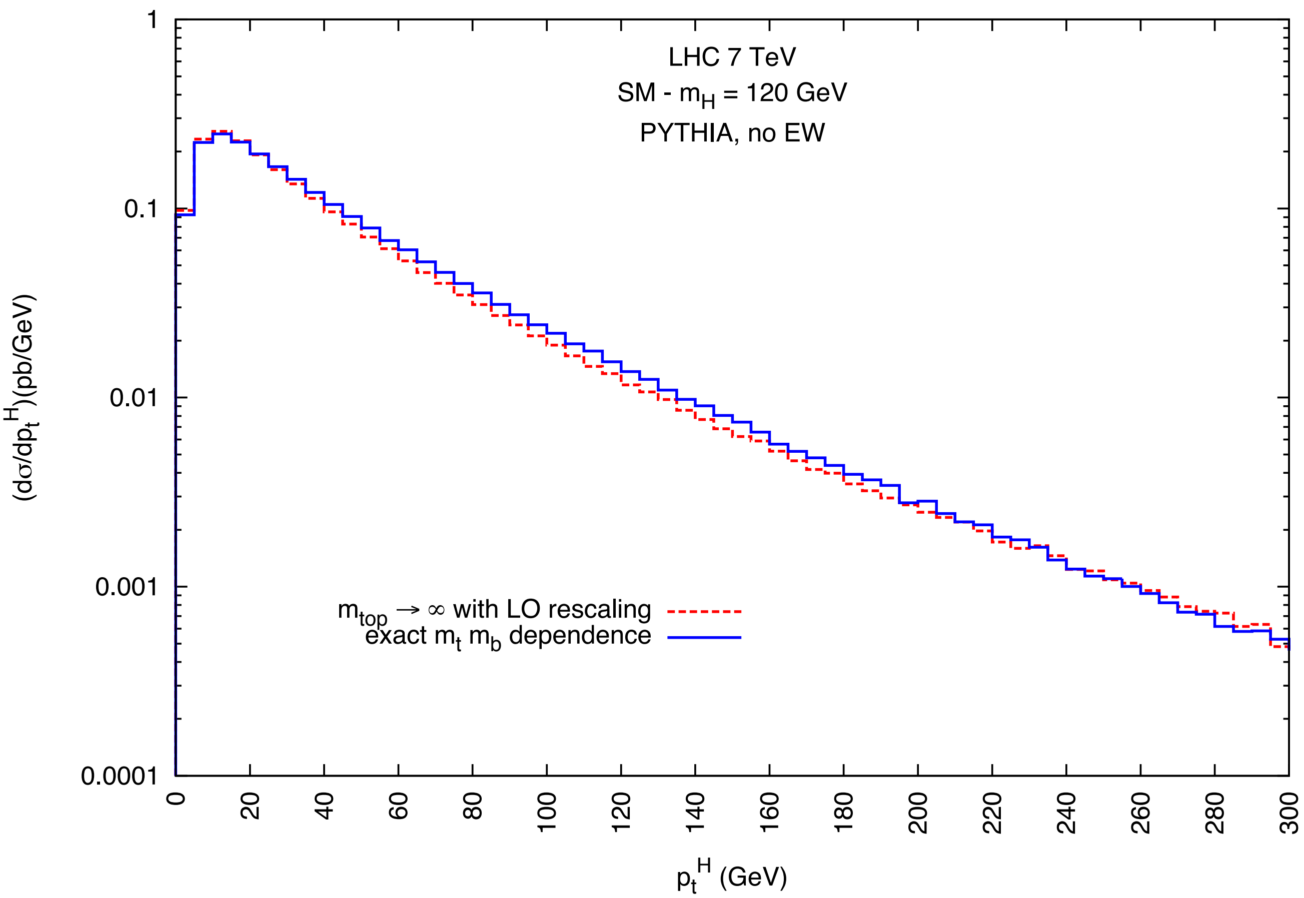
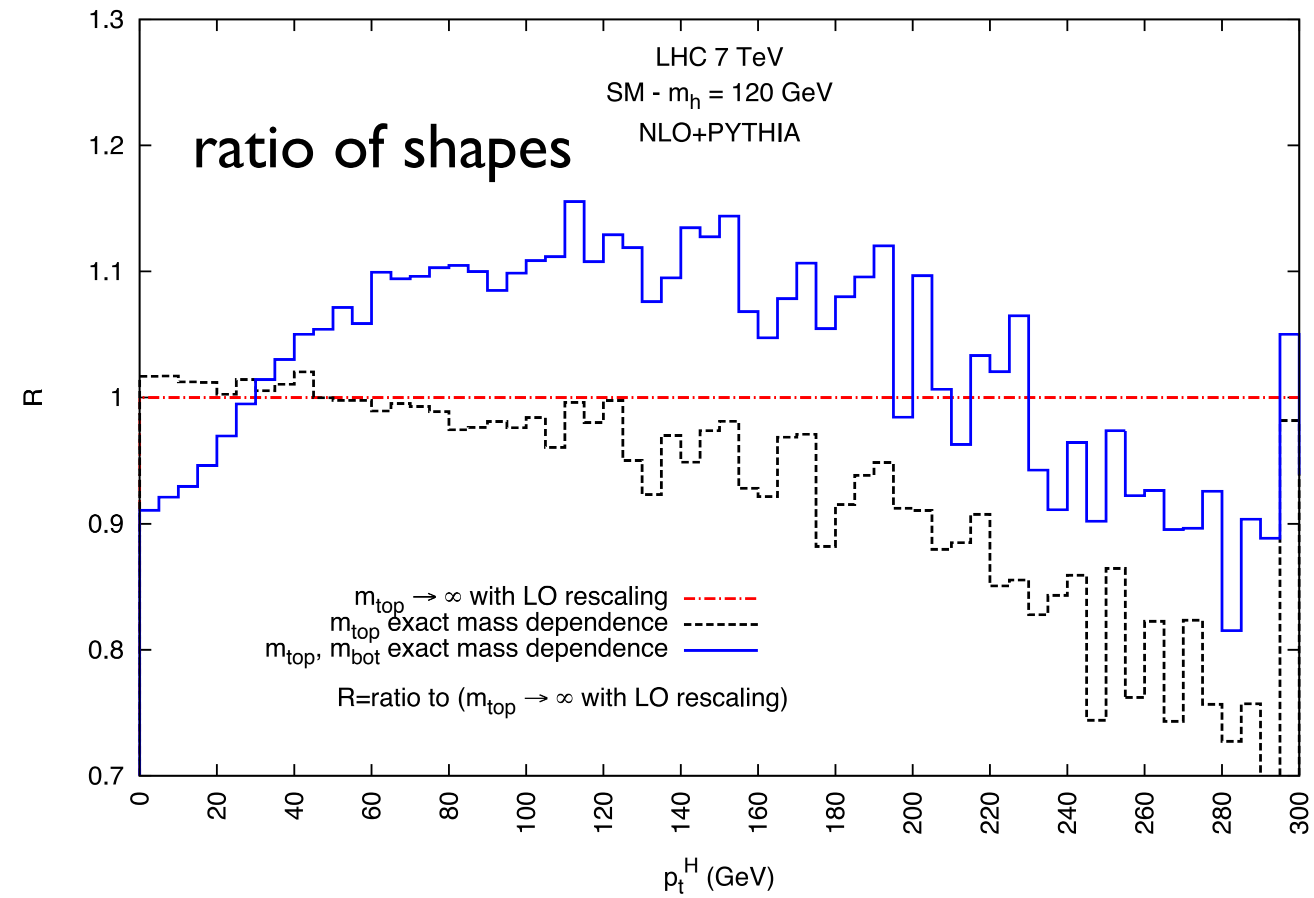
- the shape of the distributions (real emission amplitude, Sudakov form factor)

$$\Delta(\bar{\Phi}_1, p_T) = \exp\left\{ -\int d\Phi_{\rm rad} \frac{R(\bar{\Phi}_1, \Phi_{\rm rad})}{B(\bar{\Phi}_1)} \theta(k_T - p_T) \right\}$$

Quark mass effects in POWHEG



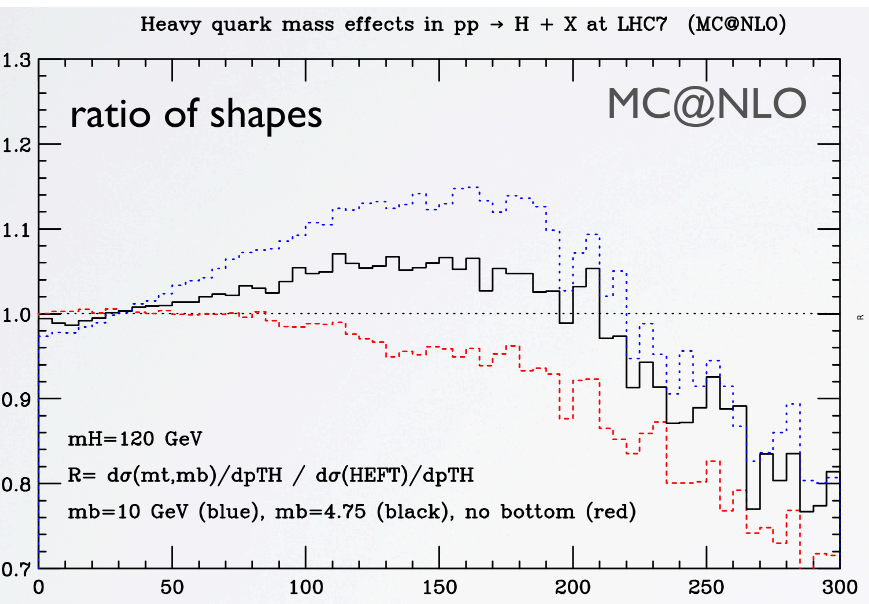


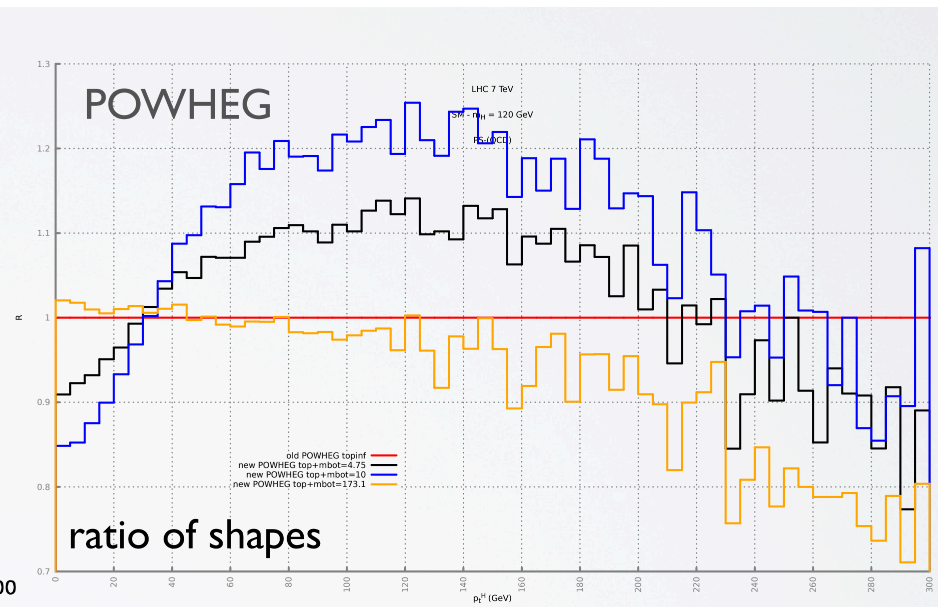
- only top: at small ptH the Sudakov form factor is weakly affected by the exact top mass effects from ptH~150 GeV we find the NLO behavior

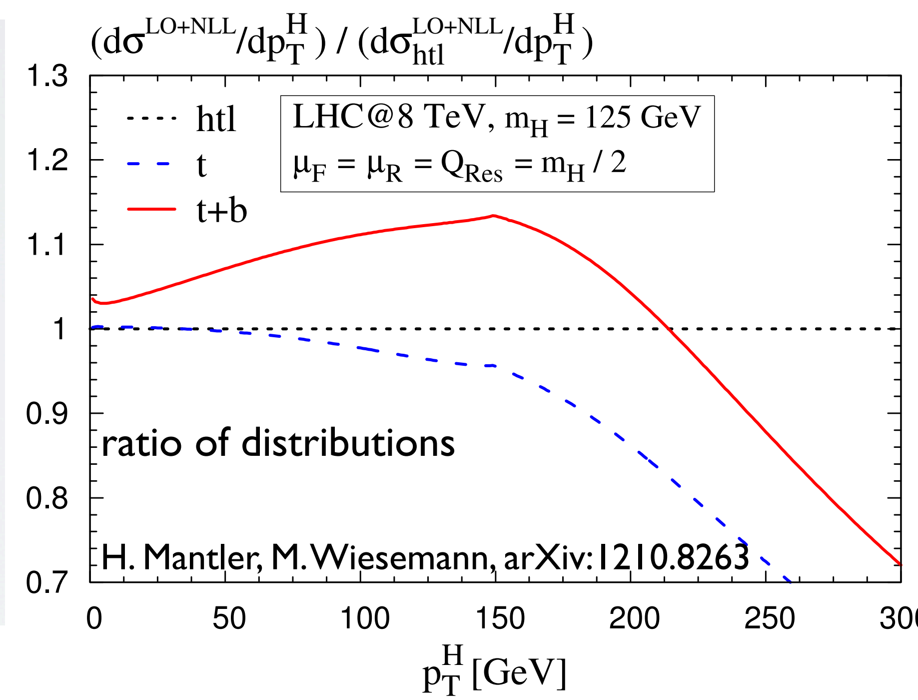
- top+bottom: the bottom diagrams modify the Sudakov form factor → suppression at small ptH the unitarity constraint enhances the distortion at intermediate ptH

$$\Delta(\bar{\Phi}_1, p_T) = \exp\left\{ - \int d\Phi_{\rm rad} \frac{R(\bar{\Phi}_1, \Phi_{\rm rad})}{B(\bar{\Phi}_1)} \theta(k_T - p_T) \right\}$$

Quark mass effects after the resummation of multiple gluon emissions (beginning 2013)



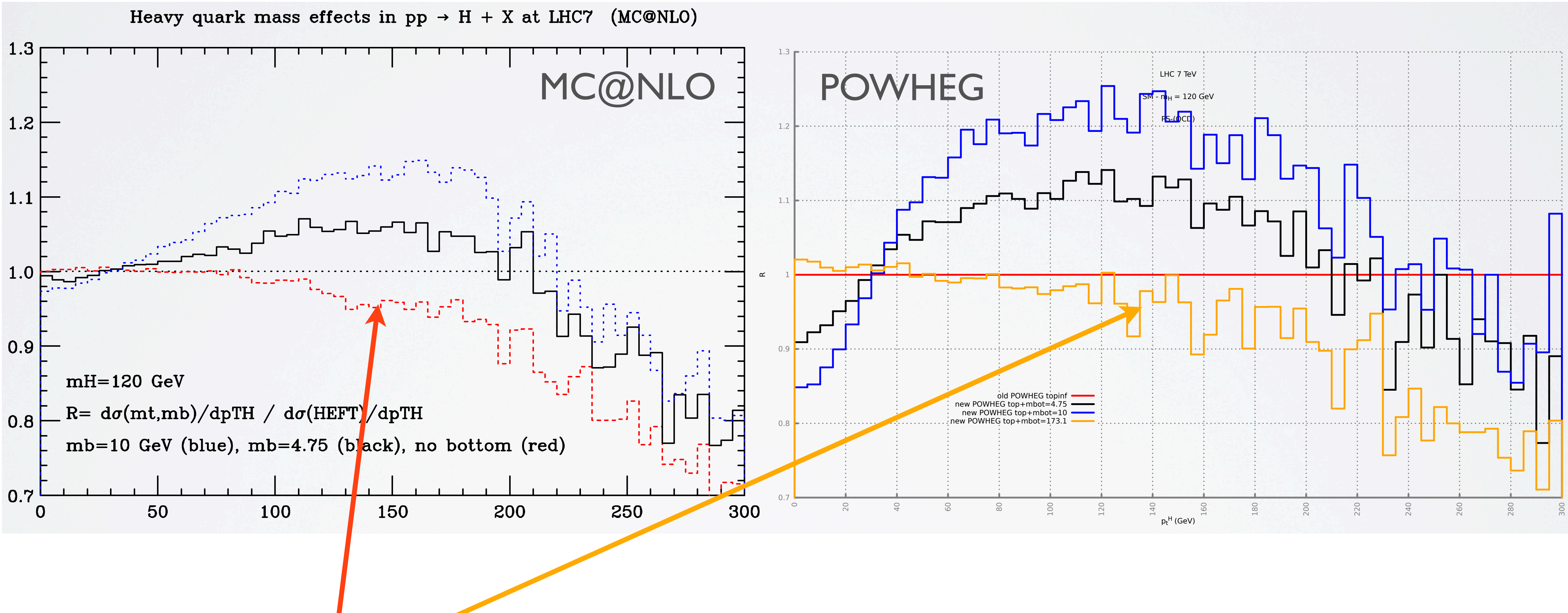




- different impact of the quark-mass effects after the matching with Parton Shower or after the analytical resummation

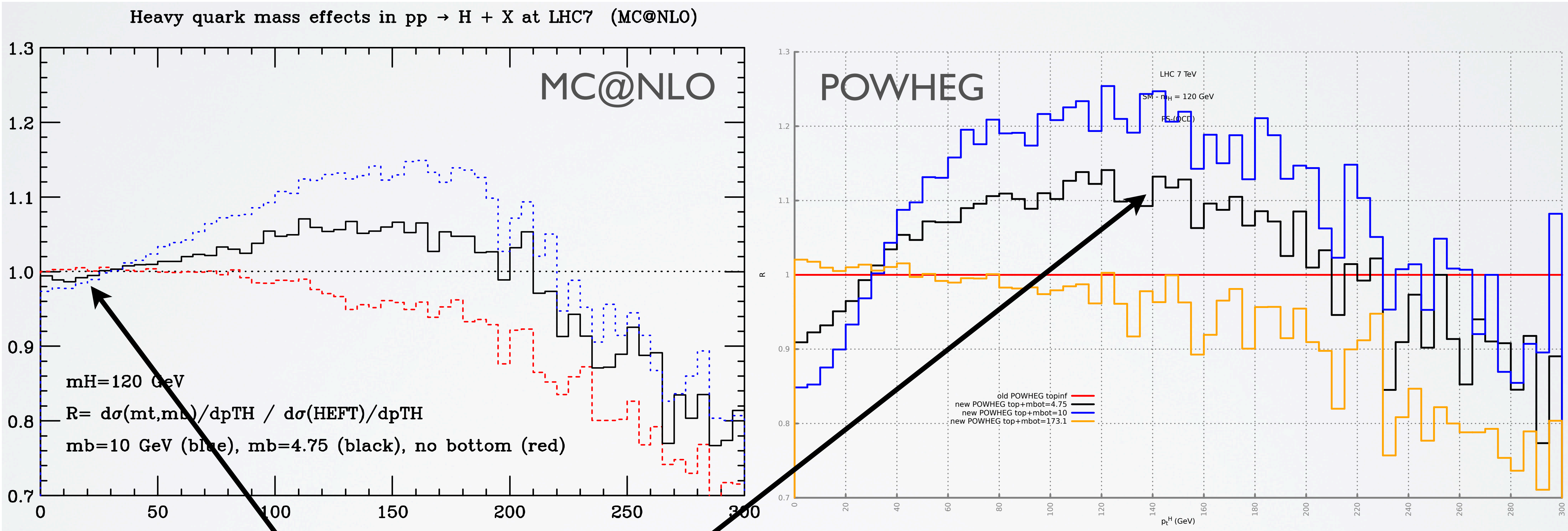
- MC@NLO and Mantler-Wiesemann share an additive matching approach
  POWHEG has a different Sudakov form factor

Comparison with MC@NLO



only top predictions (red vs yellow) in good agreement

Comparison with MC@NLO



only top predictions (red vs yellow) in good agreement

top+bottom predictions (black): visible difference

Comparison with MC@NLO

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

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

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

MC@NLO

$$R^s \propto \frac{\alpha_s}{t} P_{ij}(z) B(\Phi_B)$$

$$R^f = R - R^s$$

the universal collinear splitting function is used
in the Sudakov

the full matrix element R is used only in the regular part

POWHEG

$$R^s = \frac{h^2}{h^2 + p_{\rm T}^2} R\,, \qquad R^f = \frac{p_{\rm T}^2}{h^2 + p_{\rm T}^2} R$$

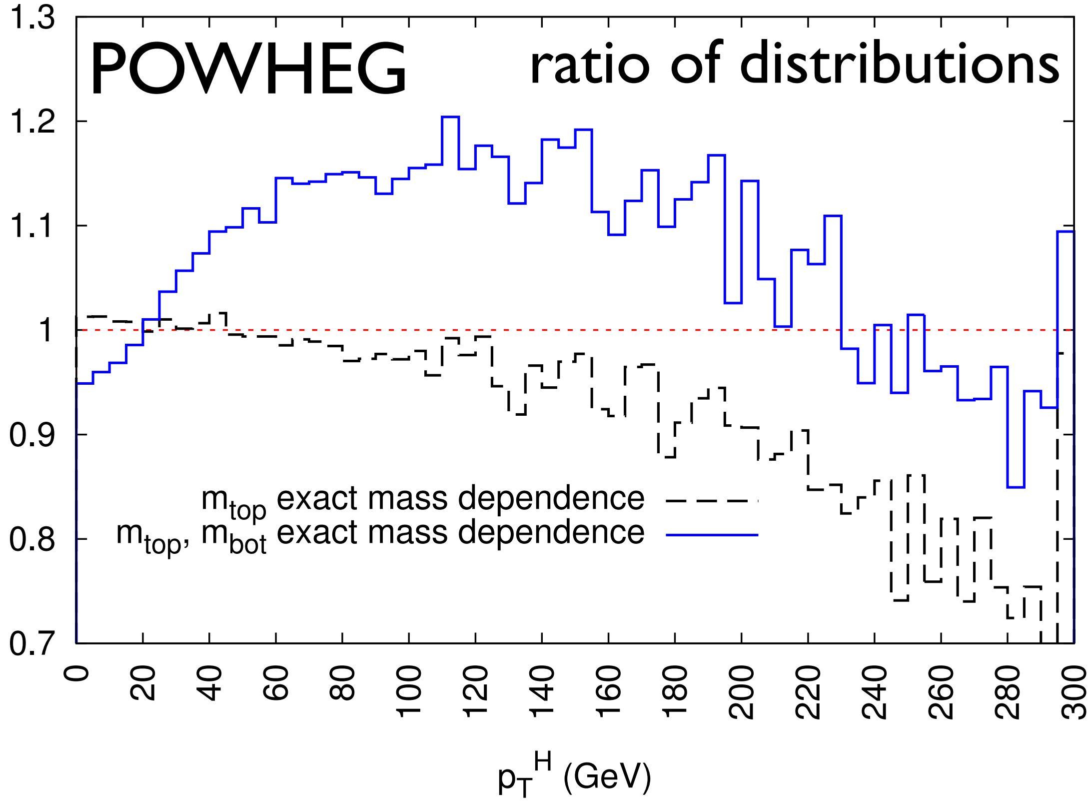
the scale *h* divides low from large ptH values

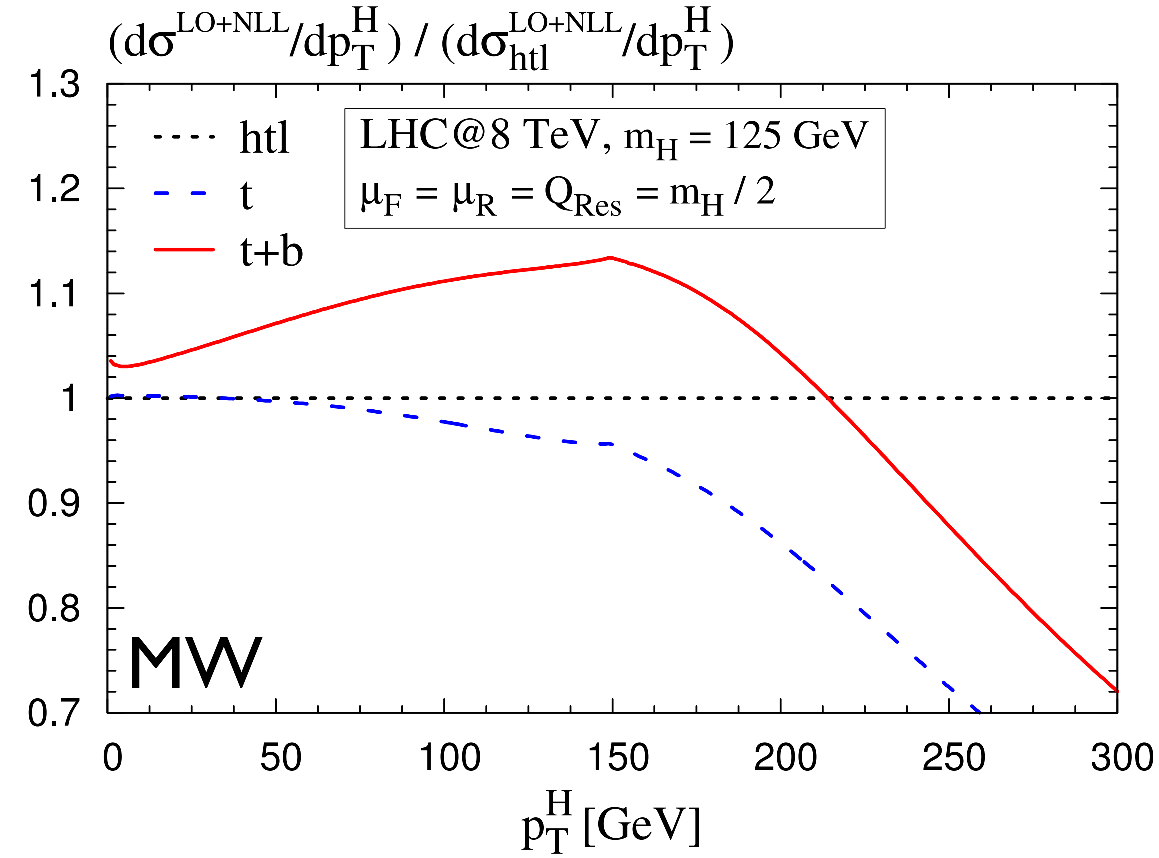
at low ptH, R tends to its collinear approximation
at large ptH the damping factor suppresses R in the Sudakov

- the two approaches exactly agree at NLO-QCD, they differ by higher order corrections

Comparison with analytical resummation

H. Mantler, M. Wiesemann, arXiv:1210.8263





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

resummation of logs(ptH)
applied to the LO process gg→H (only triangles)

exact fixed order NLO calculation
subtracted of its logs(ptH)

analogous to the shower term in MC@NLO

analogous to Rf in MC@NLO

Comments (beginning 2013)

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- the Higgs transverse momentum distribution is a multiscale observable in LO (mb, mt, MH) and raises the question of the matching with multiple gluon radiation

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- the range of validity of the resummation is different for top and bottom

- MC@NLO and MW use a similar reorganization of the perturbative expansion and obtain a similar description of the small ptH region

  both approaches assume the validity of the resummation up to a large scale
  where the bottom contribution is already resolved
  top and bottom in this region behave differently

- POWHEG includes higher orders differently;
  the differences appear in higher orders and are beyond the accuracy of the calculation;
  the size of the differences provides an estimate of missing higher orders

- the quark mass effects in POWHEG are, with good approximation, independent of *hfact*

Quark mass effects (2013)

Recent developments in the treatment of the quark mass effects

- H. Mantler, M. Wiesemann, arXiv:1210.8263
  S. Frixione, talk at Higgs Cross Section Working Group meeting, December 7th 2012
  M. Grazzini, H. Sargsyan, arXiv:1306.4581
  A. Vicini, talk at the HXSWG meeting, July 23rd 2013

Quark-mass effects in HRes (Grazzini Sargsyan, arXiv:1306.4581)

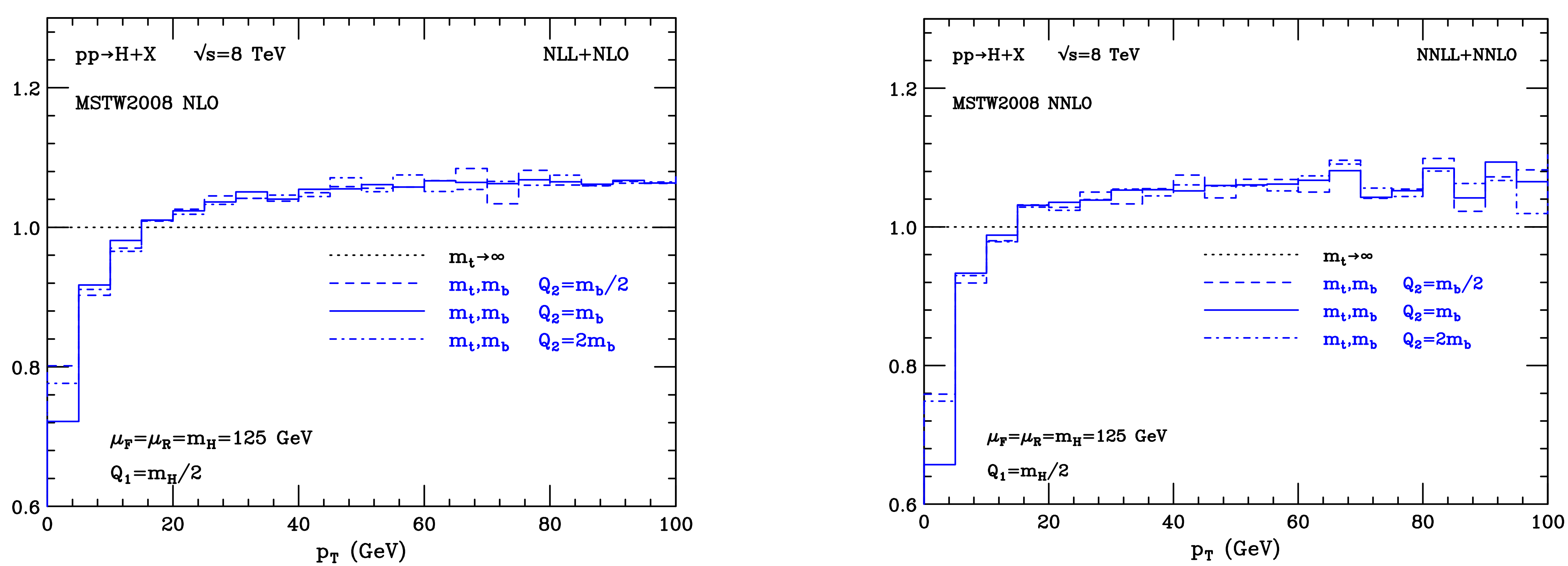
- In the resummation formalism,
  separate the pure top-quark contributions, from the bottom-quark ones

$$\mathcal{W}^{(N_1,N_2)} \longrightarrow \mathcal{W}^{(N_1,N_2)}_{\rm top} + \mathcal{W}^{(N_1,N_2)}_{\rm bot}$$

where

$$\mathcal{W}^{(N_1,N_2)}_{\rm top}(b) = \sigma_{LO}(m_t)\mathcal{H}^{(N_1,N_2)}(m_H^2/Q_1^2;m_t)\ \exp\{\mathcal{G}^{(N_1,N_2)}(\widetilde{L}_{Q_1};m_H^2/Q_1^2)\}$$

$$\mathcal{W}^{(N_1,N_2)}_{\rm bot}(b) = \left[\sigma_{LO}(m_t,m_b)\mathcal{H}^{(N_1,N_2)}(m_H^2/Q_2^2;m_t,m_b) - \sigma_{LO}(m_t)\mathcal{H}^{(N_1,N_2)}(m_H^2/Q_2^2;m_t)\right] \times \exp\{\mathcal{G}^{(N_1,N_2)}(\widetilde{L}_{Q_2};m_H^2/Q_2^2)\}\ ,$$



A proposal to treat quark-mass effects with POWHEG

- In the following identity the square bracket is a correction to the first, only-top, term because of the yukawa suppression of the bottom coupling

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

- The first term contains the full top-quark squared amplitude; the square bracket contains the top-bottom interference and the bottom squared amplitude

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- The total cross section is independent of the choice of *h*
  → the total cross section, including quark-mass effects, can be written as

$$\sigma(t+b) = \sigma(t, h = m_H/1.2) + [\sigma(t+b, h = m_b) - \sigma(t, h = m_b)]$$

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- Since the first term depends only on the top quark, a sensible choice is *h*=MH/1.2

- Since the square bracket contains the top-bottom interference and the bottom squared amplitude, but no pure top-quark contribution, a sensible choice is *h*=mb

- We propose to use the above formula also for the differential distributions

Quark mass effects after the resummation of multiple gluon emissions (end 2013)

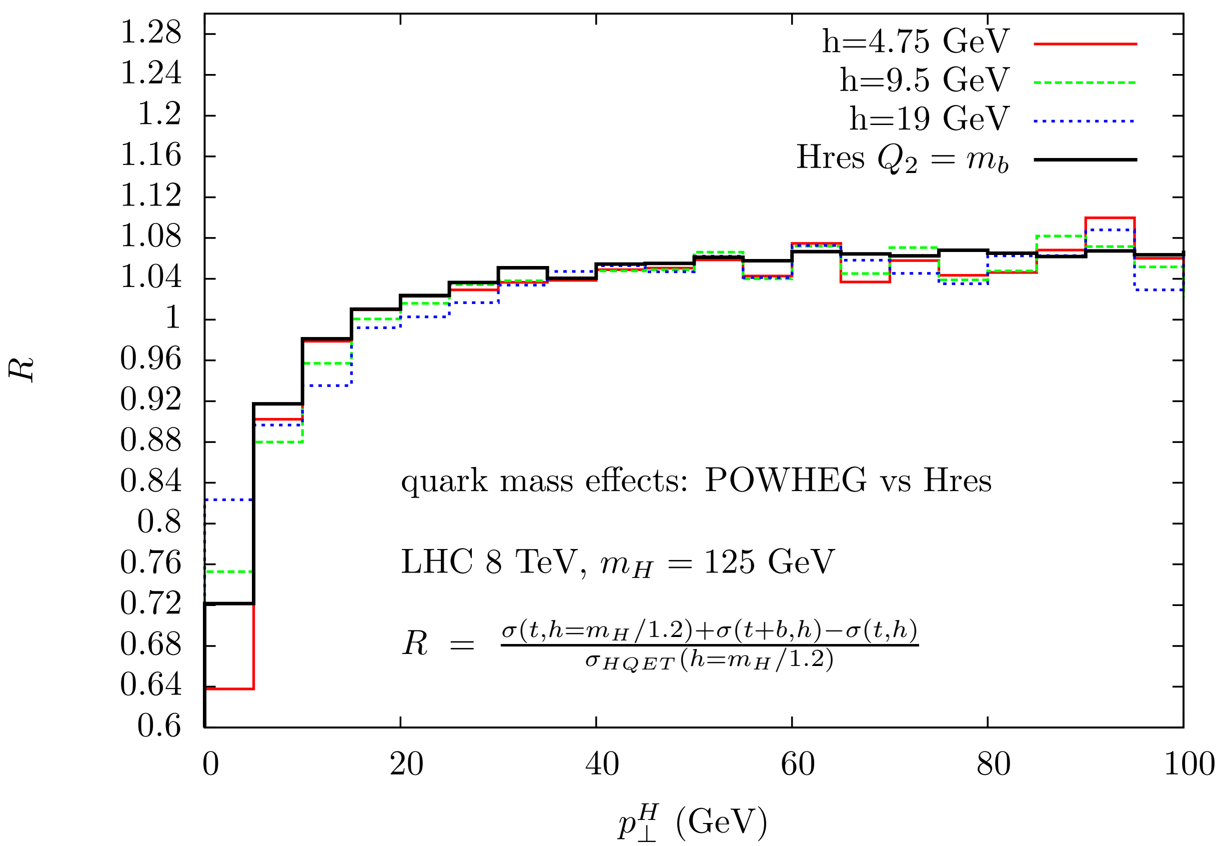
- the Higgs ptH spectrum, with quark masses, is a 3 scales problem (mb, MH, mt), the first "threshold" of the hard scattering process is at ptH ~ mb

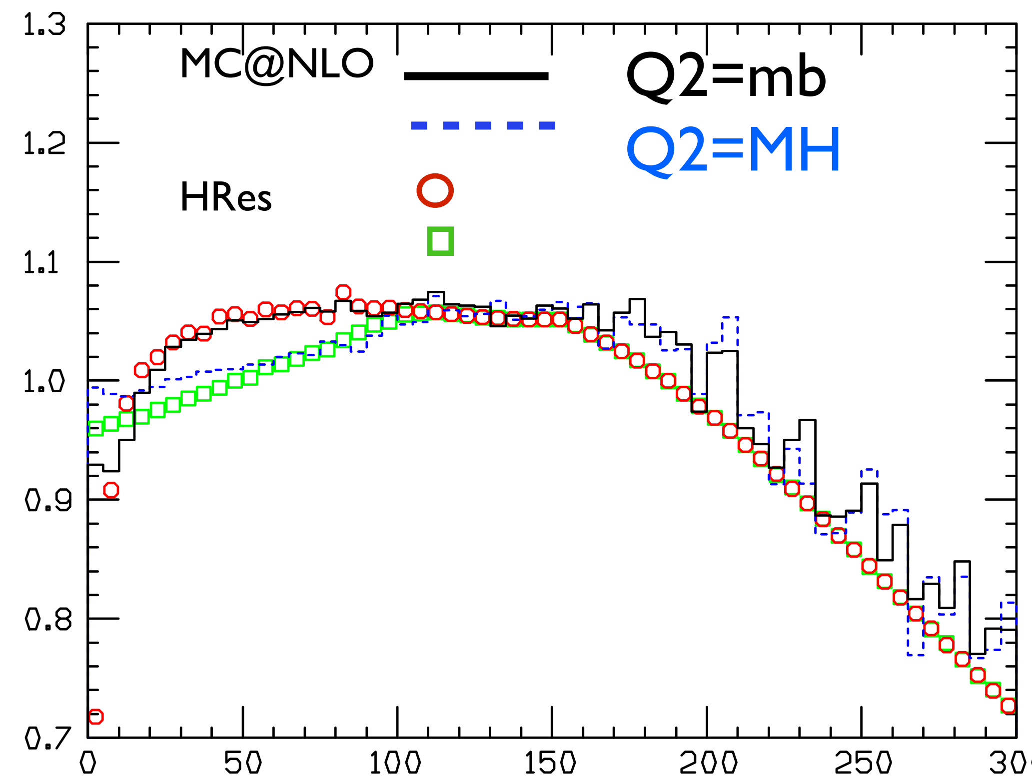
$$|\mathcal{M}(t+b)|^2 = |\mathcal{M}(t)|^2 + \left[2Re\mathcal{M}(t)\mathcal{M}^\dagger(b) + |\mathcal{M}(b)|^2\right]$$

M. Grazzini, H. Sargsyan, arXiv:1306.4581

high scale　　　　low scale

- HRes: two different resummation scales (Q1 and Q2)
  POWHEG: two different values of the parameter *h* (*ht* and *hb*)
  MC@NLO: two different scales at which the shower is switched off

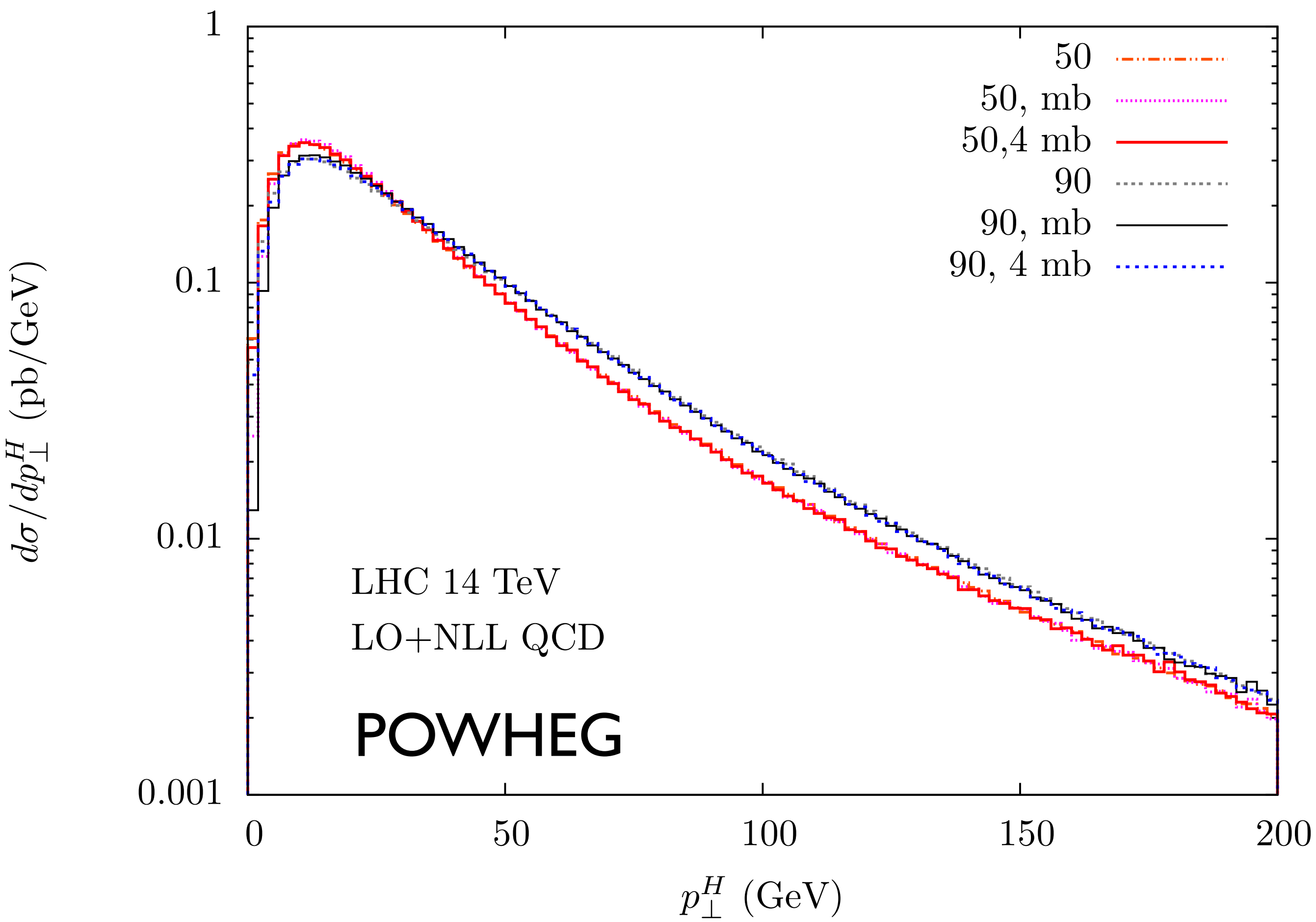


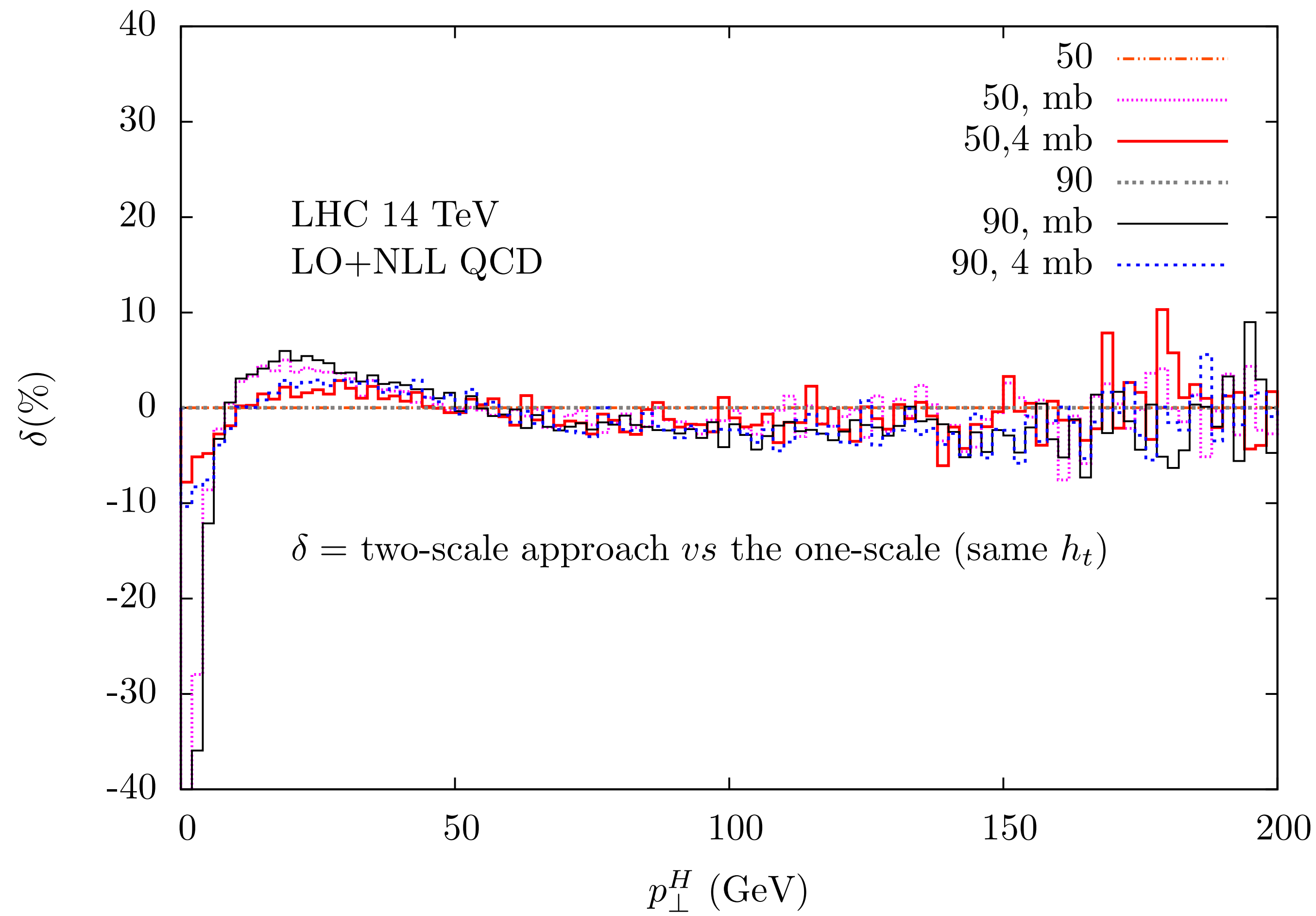


- good agreement in the comparison of (MC@NLO, POWHEG) *vs* HRes

- the "old" differences between MC@NLO and POWHEG apparently stem from the region of intermediate ptH, together with the unitarity constraint

POWHEG comparison of two-scales *vs* one-scale approaches





- *ht*: 50 GeV (from helicity analysis) and 90 (from tuning with HRes)
  hb: 4 mb (from helicity analysis) and mb (as in HRes)

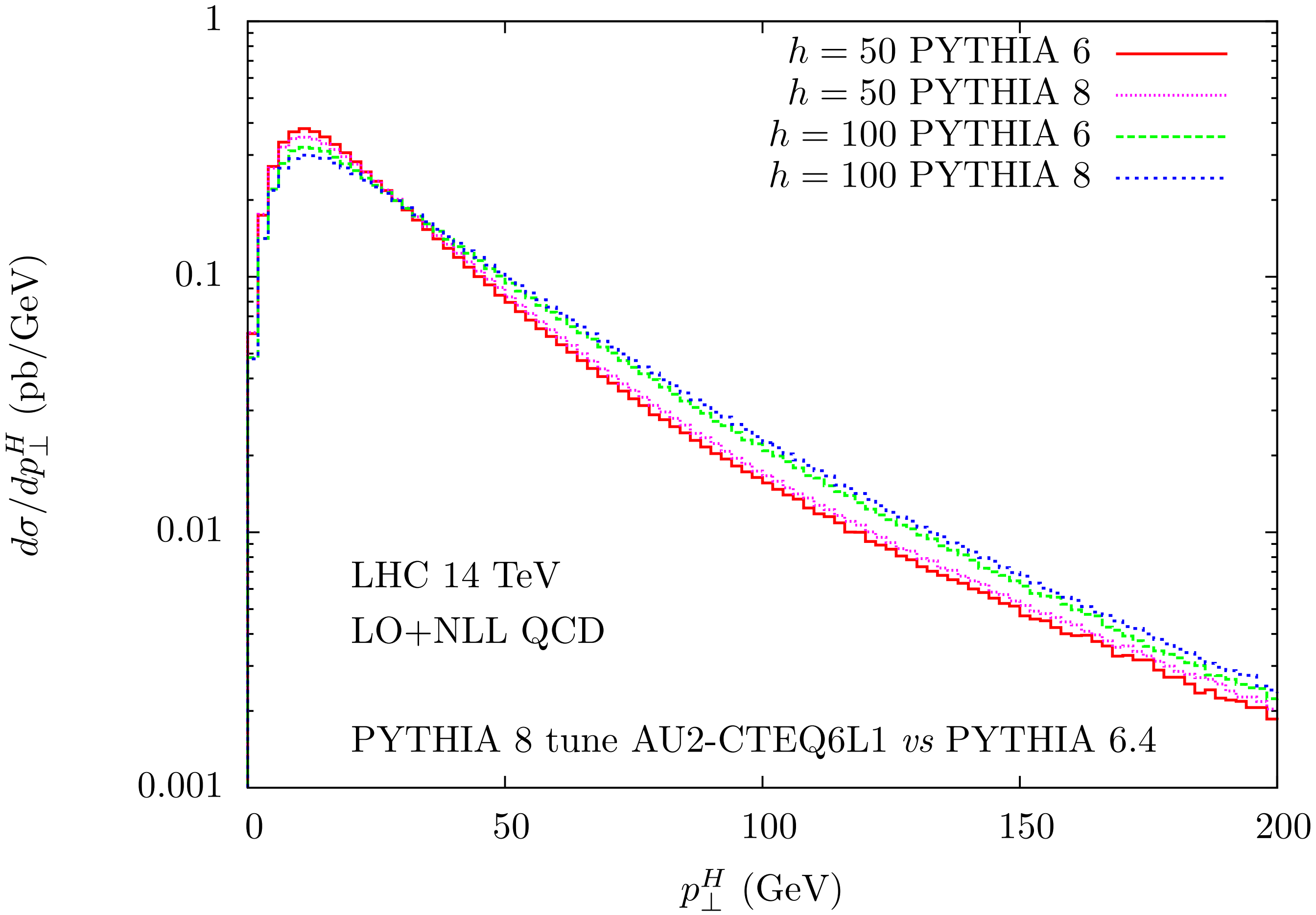
- in the SM the top-quark amplitude is dominant and thus the choice of *ht* is crucial for the shape

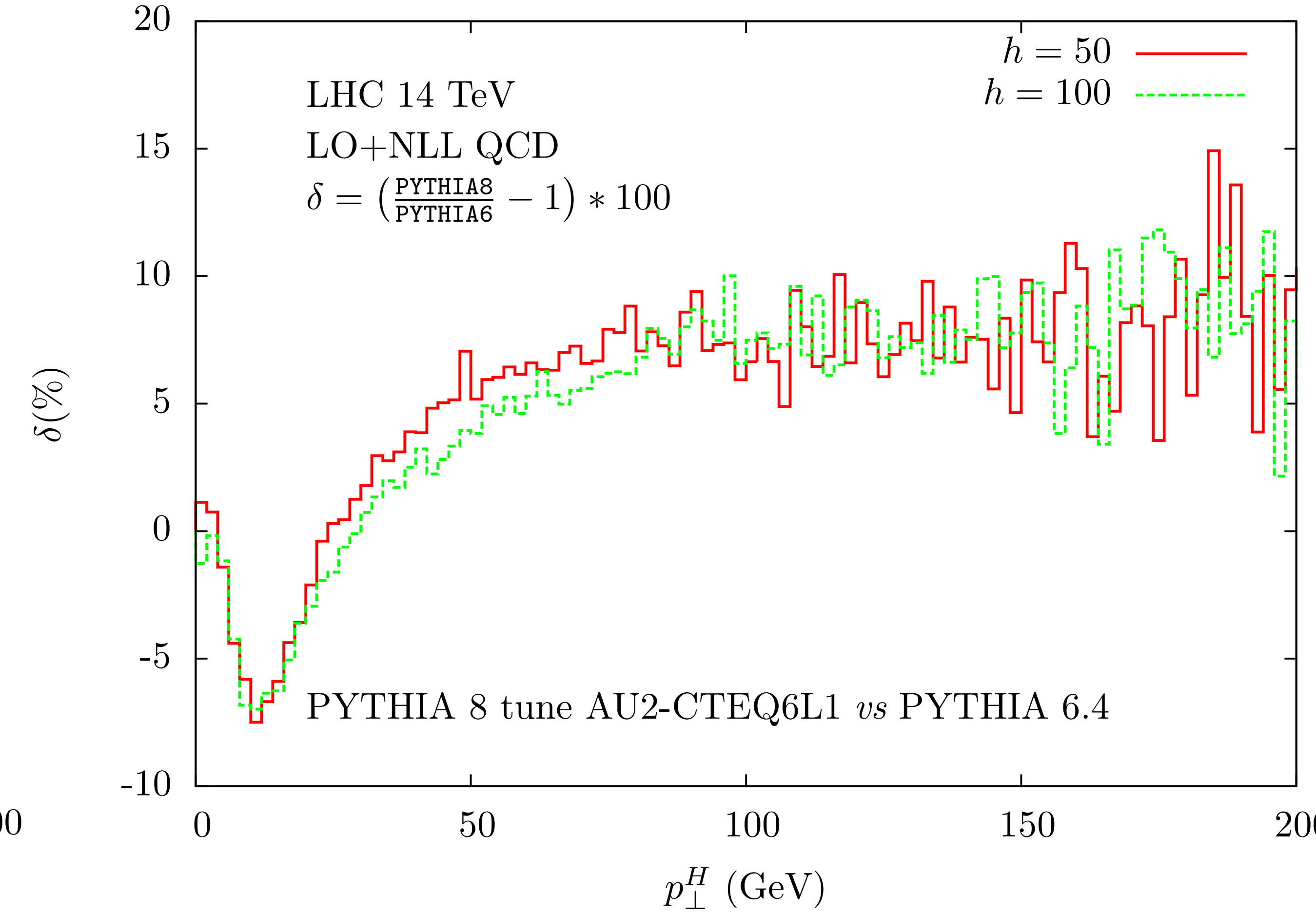
- differences appear in the low (ptH<10 GeV) and in the intermediate (20<ptH<50 GeV) regions

- setting *hb*=4 mb obviously reduces the difference between the two approaches

- in the intermediate ptH region, the differences do not exceed the 5% level

POWHEG comparison of PYTHIA 6 *vs* PYTHIA 8 effects





- 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*
- the tuning of *h* is affected by the change of the shower (PYTHIA6 *h* = MH/1.2 ~105 GeV,
  PYTHIA8 *h* = ~90 GeV)

Tuning POWHEG to mimic the HRes shape

$$\chi^2 = \sum_{i \in bins} w(i) \left[\frac{1}{\sigma_{tot}^{HRes}} \frac{d\sigma_i^{HRes}}{dp_\perp^H} - \frac{1}{\sigma_{tot}^{POWHEG}} \frac{d\sigma_i^{POWHEG}}{dp_\perp^H} \right]^2$$

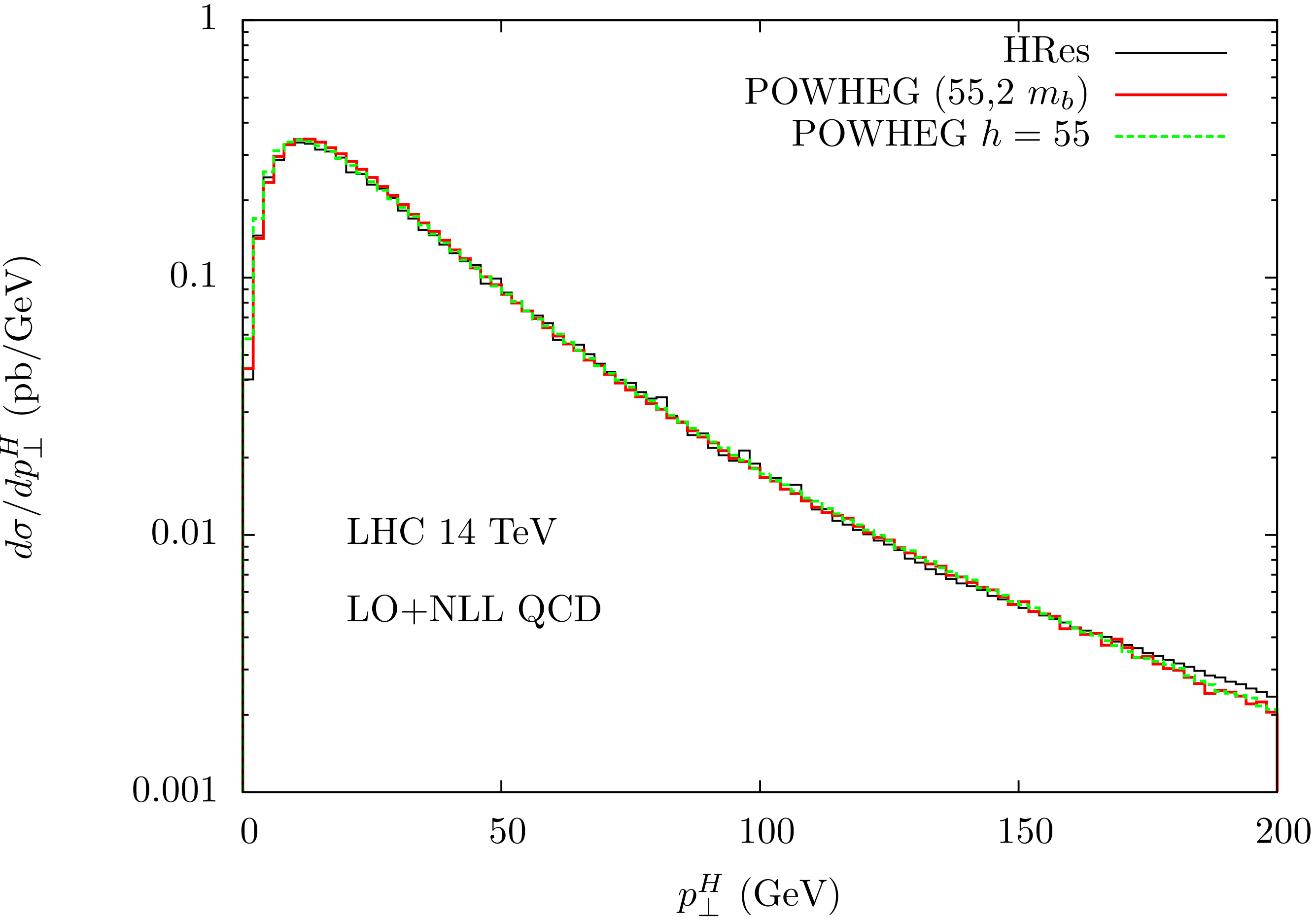
- HRes scales fixed at: Q1=MH/2, Q2=mb
  POWHEG scales scanned over: 50 < ht < 150 GeV (5 GeV steps), mb/2 < hb < 2 mb (1 GeV steps)

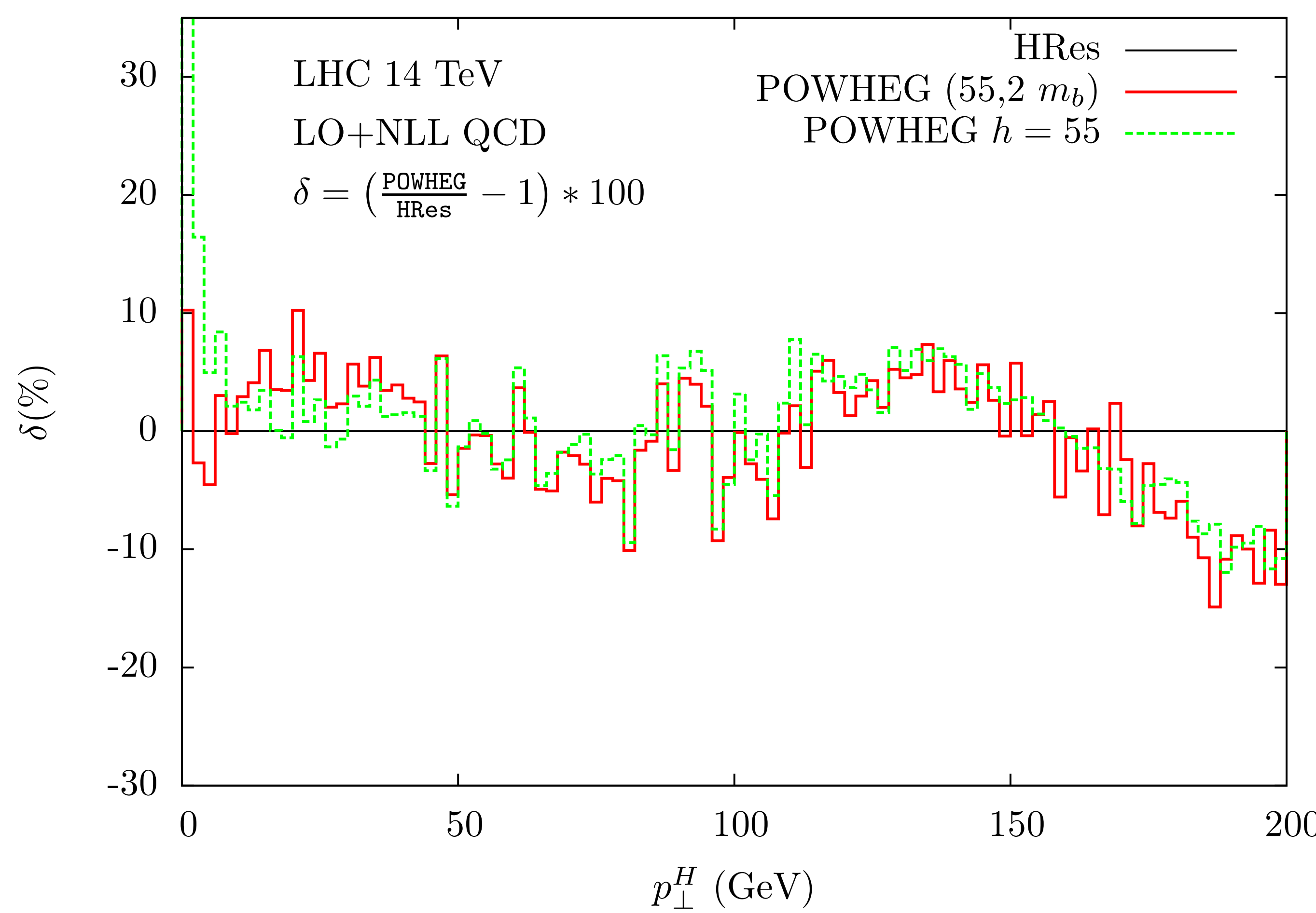
- for each scale choice in POWHEG, compute χ^2; look for the global minimum

- two χ^2 definitions: w(i) constant, w(i) proportional to the xsec
  (prop. to xsec → more importance to the peak,
  constant → more importance to the tail)

- the comparison of the shapes allows to apply a global rescaling factor
  K_NNLO = σ_NNLO / σ_NLO = 1.254

Tuning POWHEG to mimic the HRes shape at LO+NLL

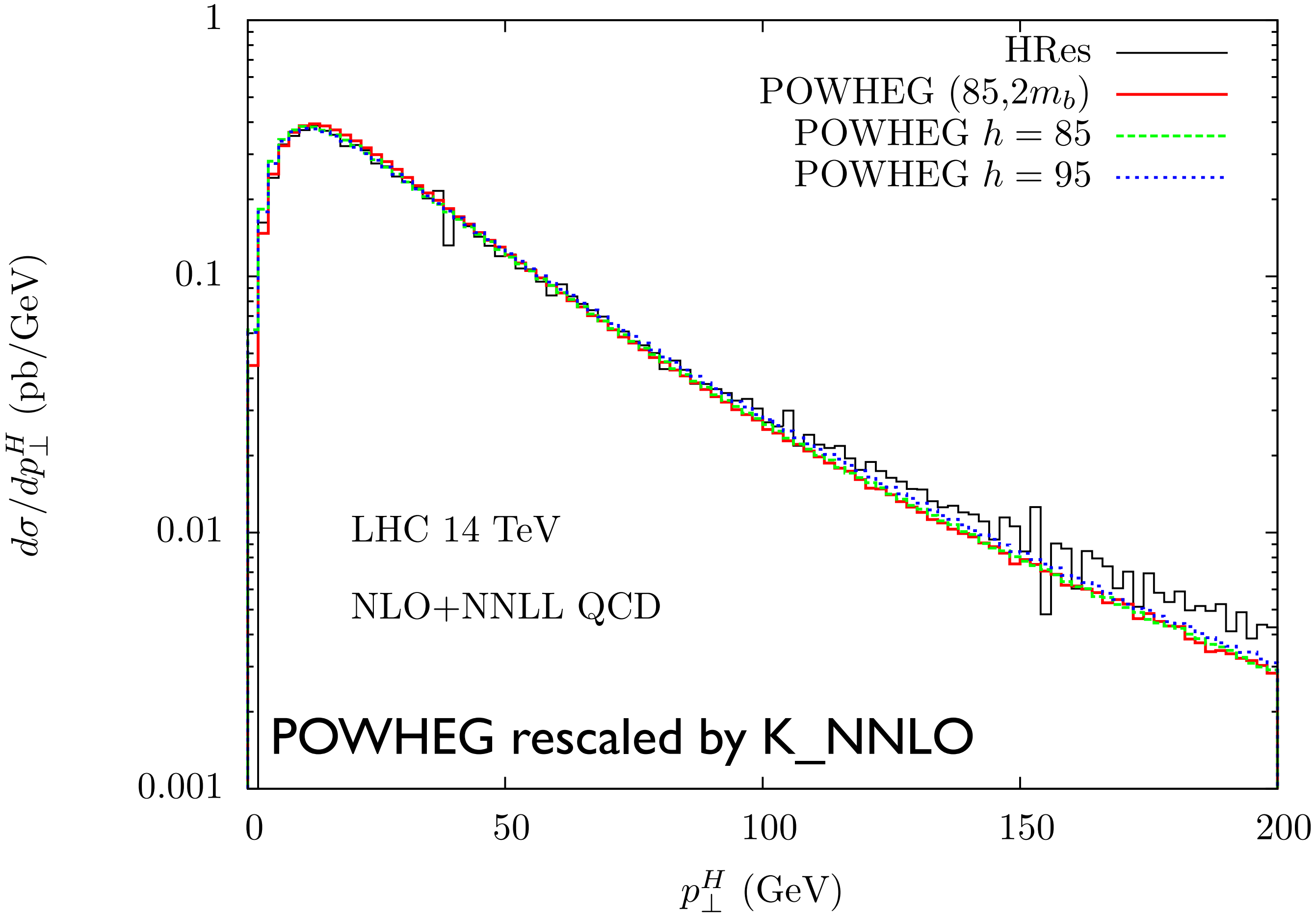


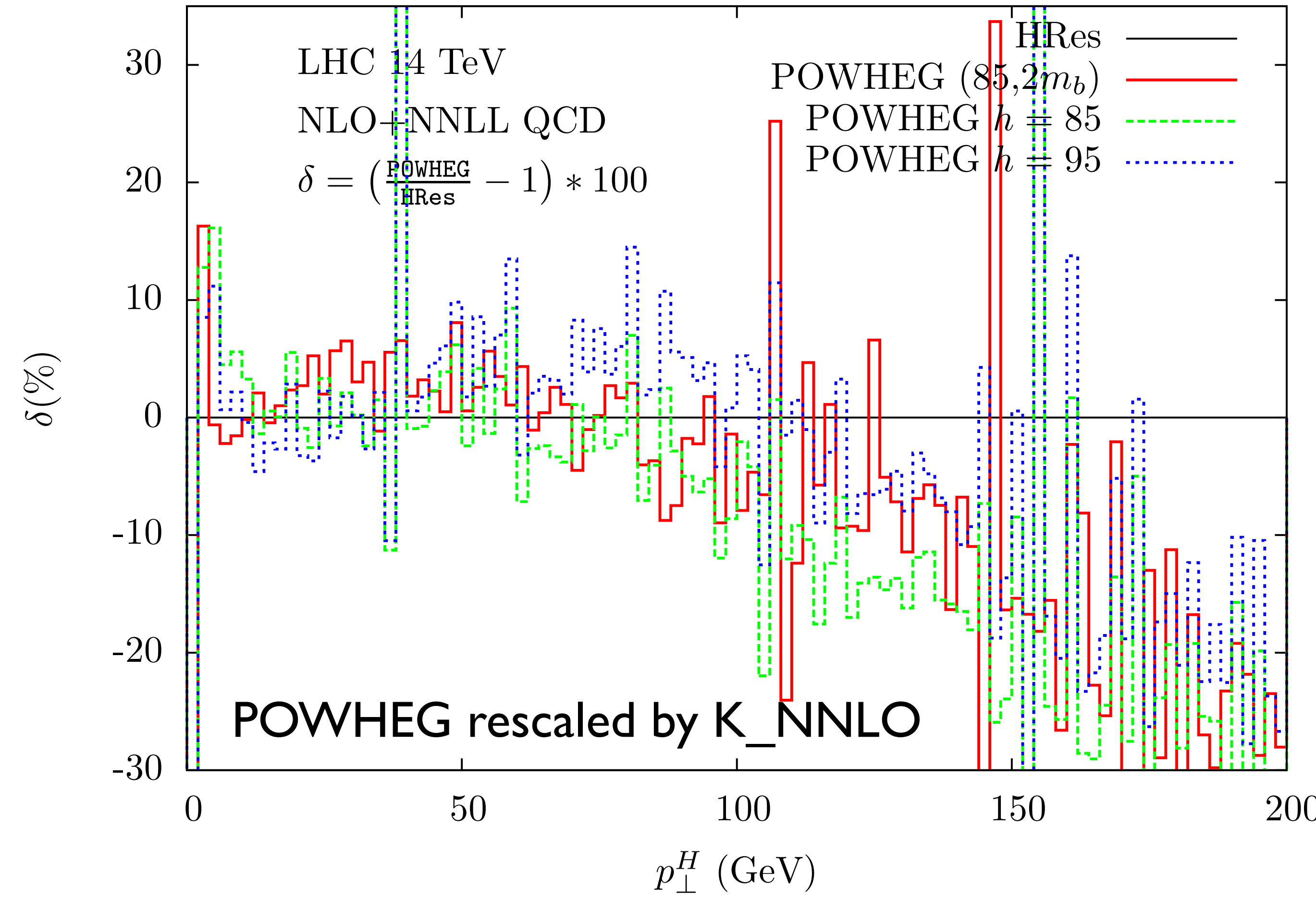


- at LO+NLL the result does not depend on w(i)
  the preferred *ht* ~ Q1, a variation of *hb* modifies χ^2 at the percent level
- the preferred *h* is close the Q1=MH/2

one scale fit   *h*=55 GeV
two scales fit   *ht*=55 GeV, *hb*=2 mb

Tuning POWHEG to mimic the HRes shape at NLO+NNLL

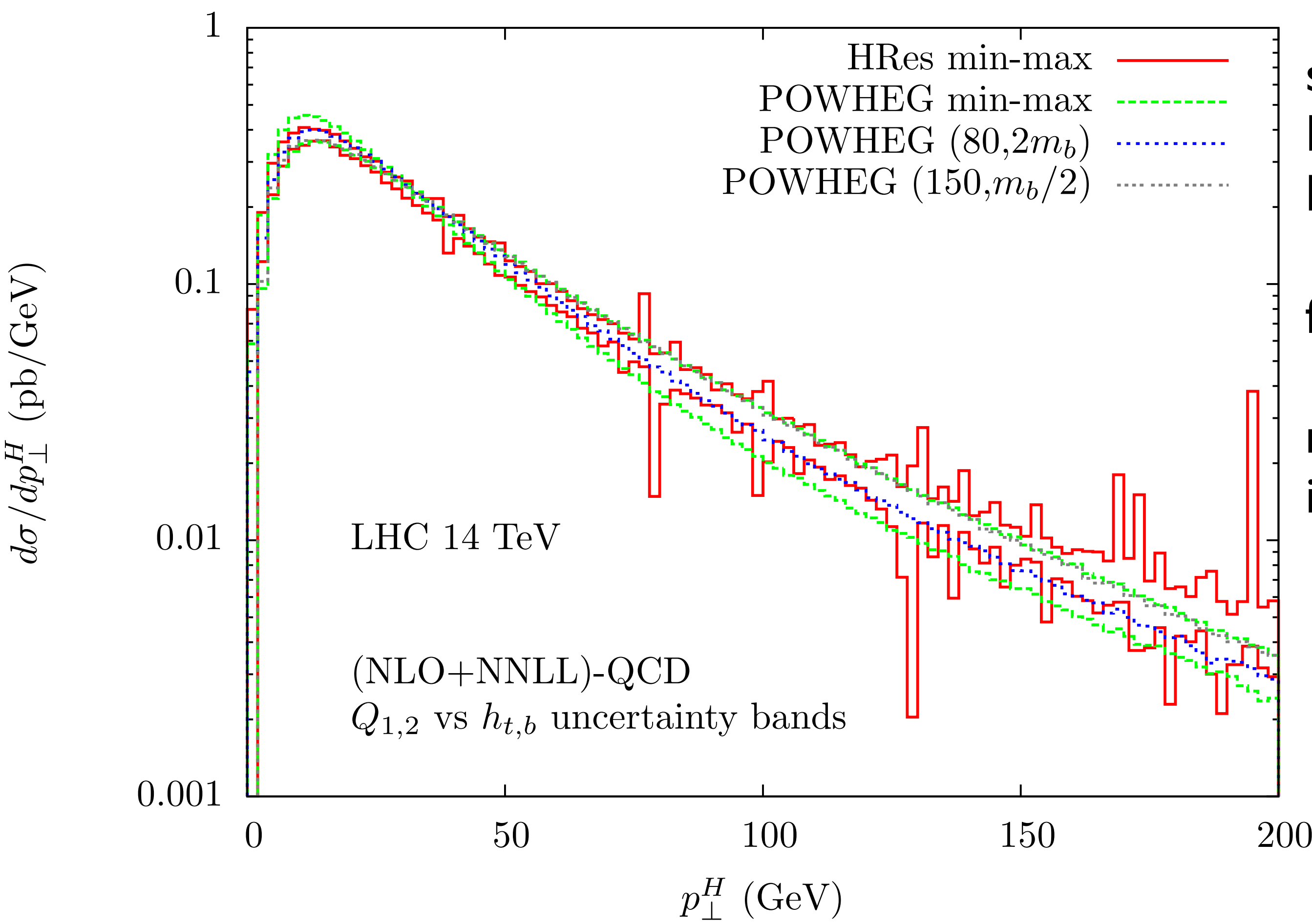




- HRes predictions computed with Q1=MH/2 and Q2=mb
- a large value of *h* forces POWHEG to mimic the large ptH tail of the HRes NLO+NNLL
- the best fit mimics the shape at the ±5% level for ptH<100 GeV
- the fit results depends on the importance (w(i)) that we give to the tail of the distribution
- the use of PYTHIA8 forces the tuning towards smaller values of *ht* (w.r.t. PYTHIA6)

one scale fit	*h*=85 GeV	w(i) prop.to xsec
	h=95 GeV	w(i) constant
two scales fit	*ht*=85 GeV, *hb*=2 mb	

POWHEG resummation uncertainty band compared to HRes



scale variation

HRes at NLO+NNLL: MH/4 < Q1<MH, mb/2 < Q2 < 2 mb

POWHEG: 50 < *ht* < 150 GeV, mb/2 < *hb* < 2 mb

for fixed renormalization and factorization scales μR=μF=MH

min-max envelope:
in each bin consider the minimum and the maximum values

- the lower (upper) edge of the (rescaled) POWHEG envelope has an integrated xsec compatible with the corresponding HRes lower (upper) edge integrated xsec at the 6% (-2%) level

- the POWHEG predictions, rescaled by a global factor K_NNLO, are compatible with the HRes results

  the POWHEG uncertainty band, varying *ht* and *hb*, is comparable in width with the one by HRes

SM Conclusions

- The use of *hfact* to control the range where multiple parton emissions plays a role allows to treat in a different way top and bottom parts of the amplitude

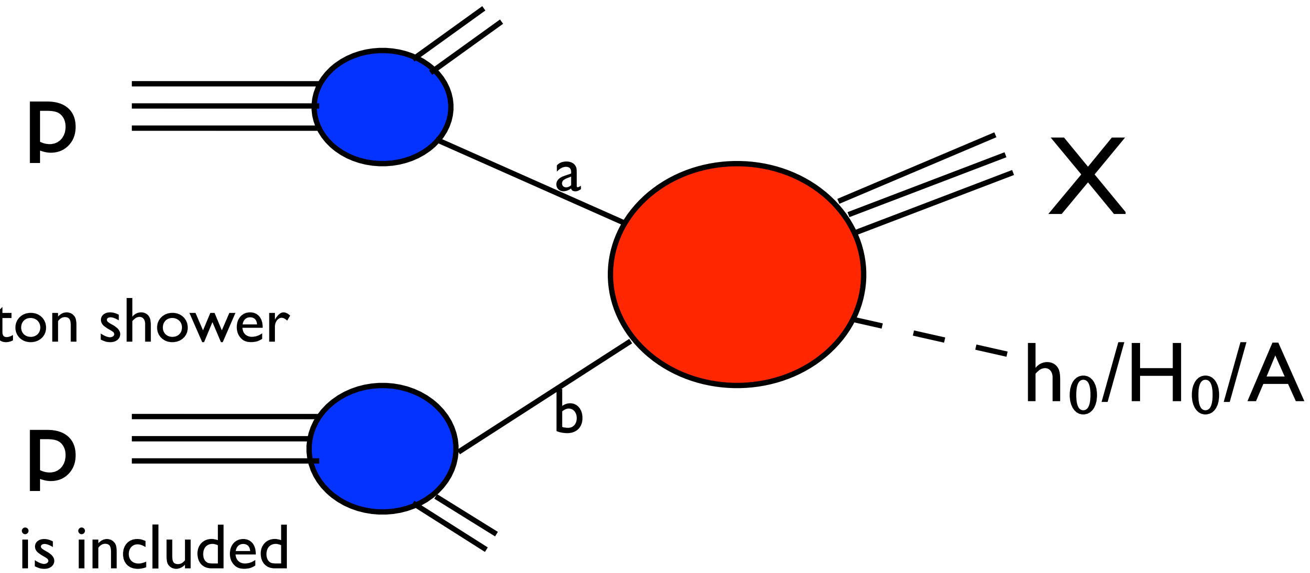
- A simple combination of 3 POWHEG runs reproduces quite accurately the LO+NLL Hres calculation
  the reweighting factors to match the new HRes should be mostly due to NNLO-QCD corrections
  rather than to quark-mass effects

- The 2-scales recipe is conservative (resummation is applied only where we know it is valid)

  The agreement between POWHEG, HRes and MC@NLO suggests that
  previous discrepancies were due to the bottom contribution enhanced by resummation effects
  i.e. different Sudakov factors + unitarity constraint
  (it is not yet clarified if those effects were properly treated, it deserves further investigation)

- The effects of the bottom treatment in the SM are small but not negligible
  they can be further enhanced in the MSSM by $\tan\beta$

The gluon fusion process in the MSSM in POWHEG



- the code is an event generator
  which describes the MSSM processes
  $pp \to h_0+X$, $pp \to H_0+X$, $pp \to A+X$
  with NLO-QCD accuracy matched with QCD parton shower

- at LO, the exact contribution of quarks and squarks is included
  at NLO, the quark contribution is included exactly
  NLO-QCD corrections to the squark diagrams and SUSY-QCD corrections
  are included via expansions

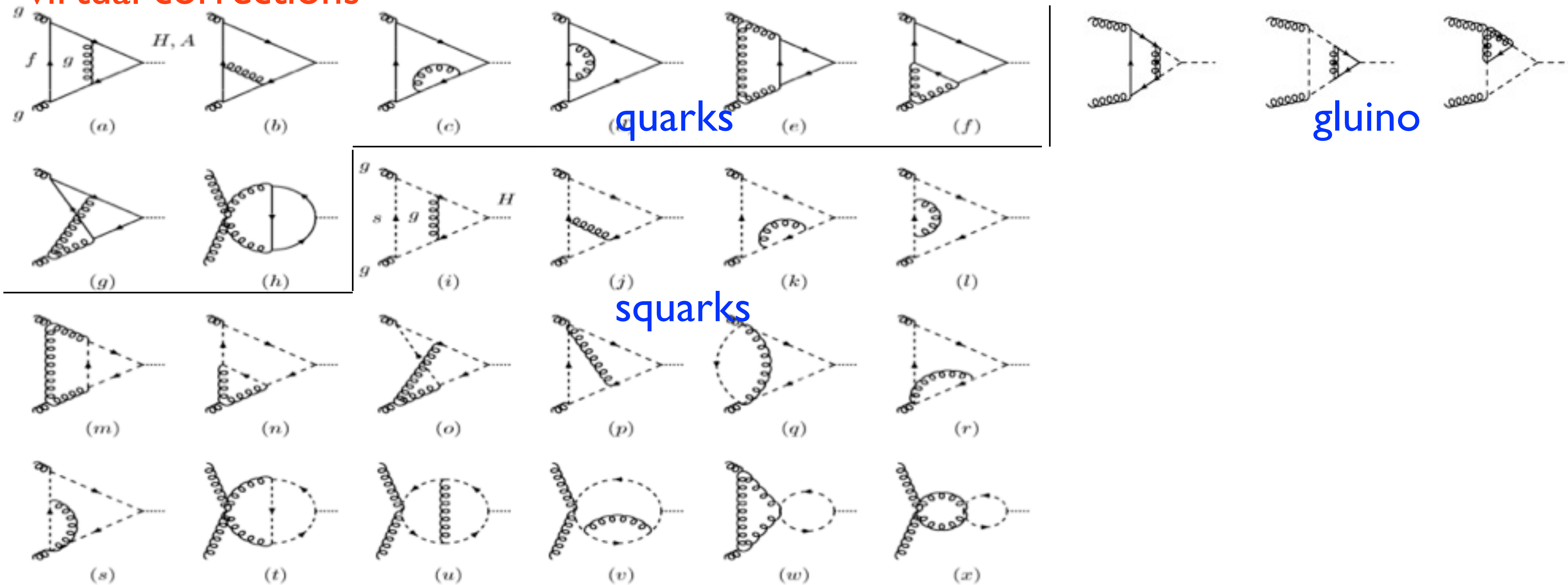
- NLO-EW corrections due to light-quark loops (Aglietti et al, 2004), with MSSM couplings,
  are factorized w.r.t. the MSSM NLO-QCD cross section

Checks

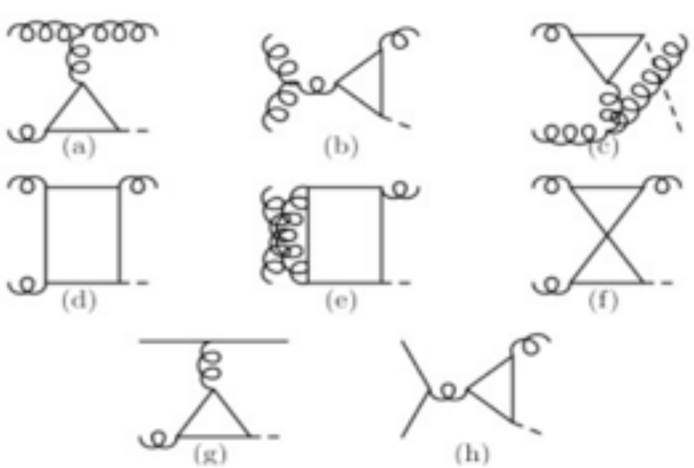
- the total and differential cross section has been carefully checked in close collaboration
  with the authors of SusHi (Harlander, Liebler, Mantler)

MSSM: Feynman diagrams

virtual corrections



real corrections



only
quarks and squarks

The MSSM code: input file

- the MSSM parameters can be computed in two renormalization schemes: DRbar (e.g. with SoftSusy) or On-Shell (e.g. with FeynHiggs)

- depending on the scheme chosen, the parameters (Higgs mass, squark masses, mixing angles) necessary to POWHEG to compute the cross section, must be determined as follows:

  DRbar: a SLHA-compliant file must be computed e.g. by SoftSusy

  OS: POWHEG uses the FeynHiggs library (it must be installed, version $\geq$ 2.9) to compute masses and couplings

- once the MSSM parameters are computed, the simulation proceeds exactly as in the SM case: a scan in the MSSM parameter space is as simple as the generation of the input files

- the POWHEG run (before showering) yields in output a SLHA-compliant file with the values of all the parameters used in the computation;
  this file can be read by PYTHIA, if necessary, for a consistent evaluation of the decay processes

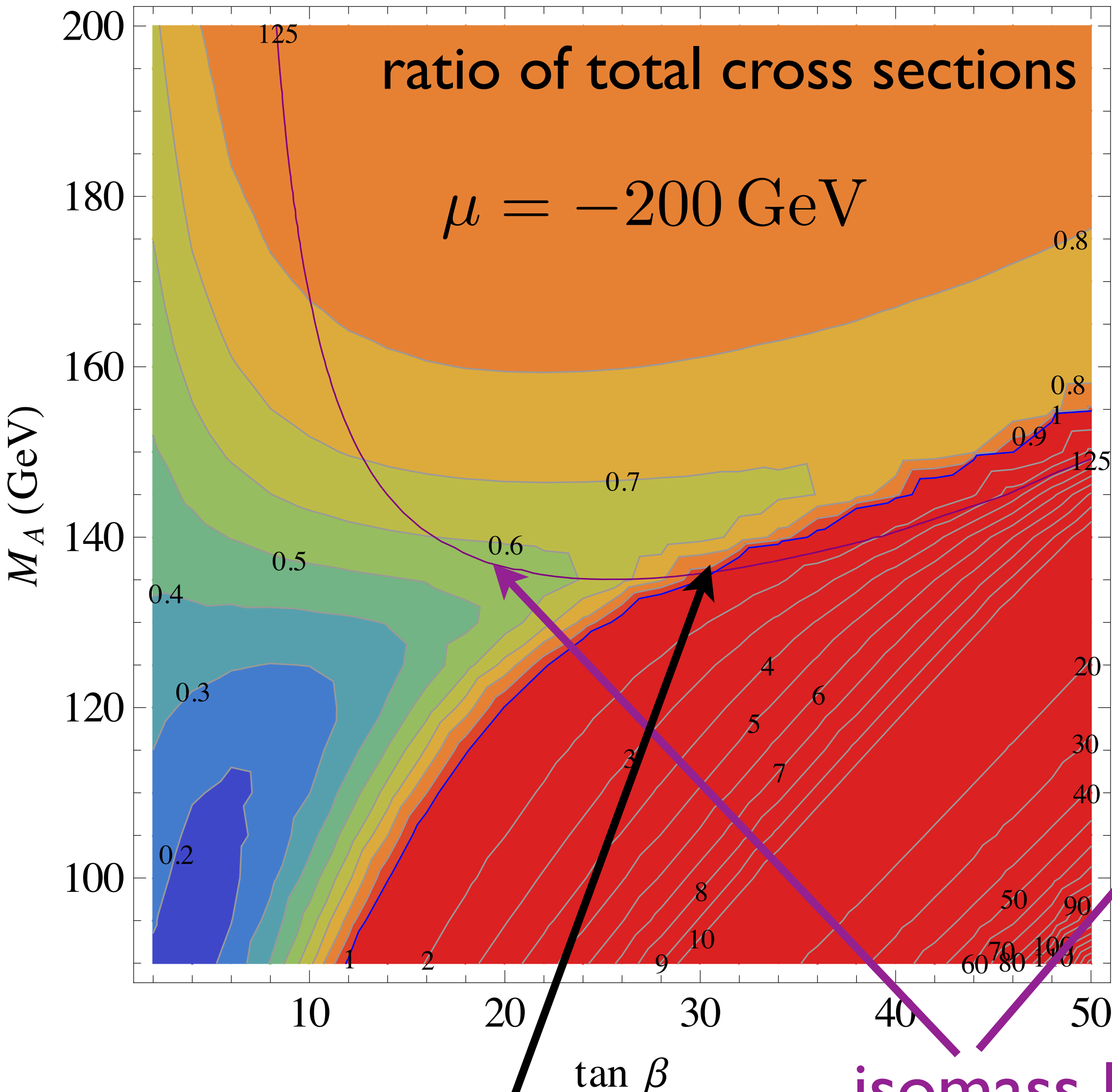
The MSSM code: basic analytical structure

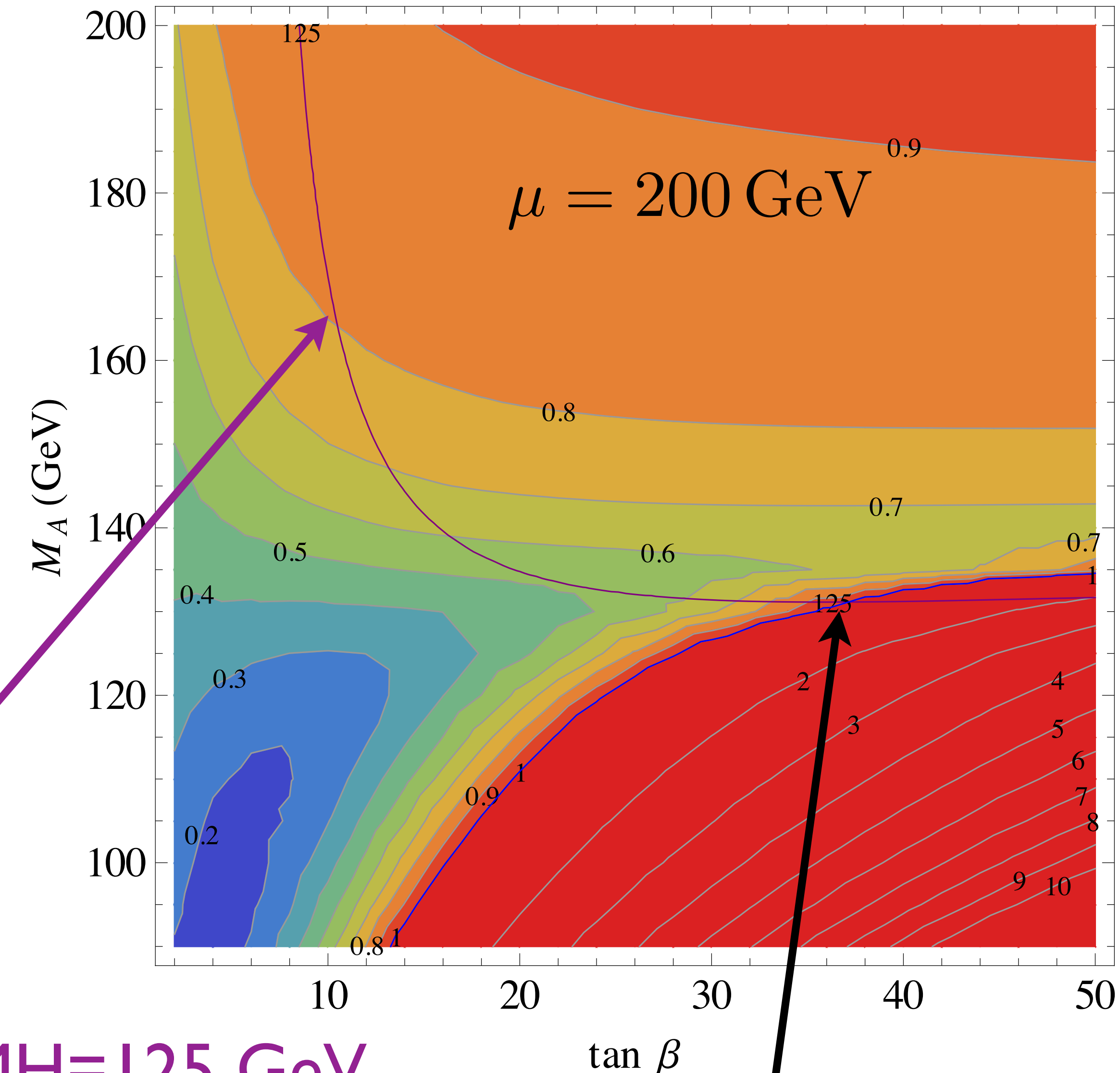
$$|\mathcal{M}(gg \to gH)|^2 = |\mathcal{M}_t + \mathcal{M}_{\tilde{q}} + \mathcal{M}_b|^2$$
$$= |\mathcal{M}_t|^2 + 2\mathrm{Re}(\mathcal{M}_t \mathcal{M}_b^\dagger) + |\mathcal{M}_b|^2 + 2\mathrm{Re}(\mathcal{M}_{\tilde{q}} \mathcal{M}_b^\dagger) + 2\mathrm{Re}(\mathcal{M}_{\tilde{q}} \mathcal{M}_t^\dagger)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

- the bottom contribution can receive an important tanβ enhancement
- the interference of the bottom and squarks diagrams may yield non negligible effects
- the ptH distribution can be significantly distorted by MSSM corrections
  → relevance of an exact treatment of the mass effects (absent in the HQET SM analysis)
    - it has an impact on the estimate of the acceptance
    - it is an observable *per se*

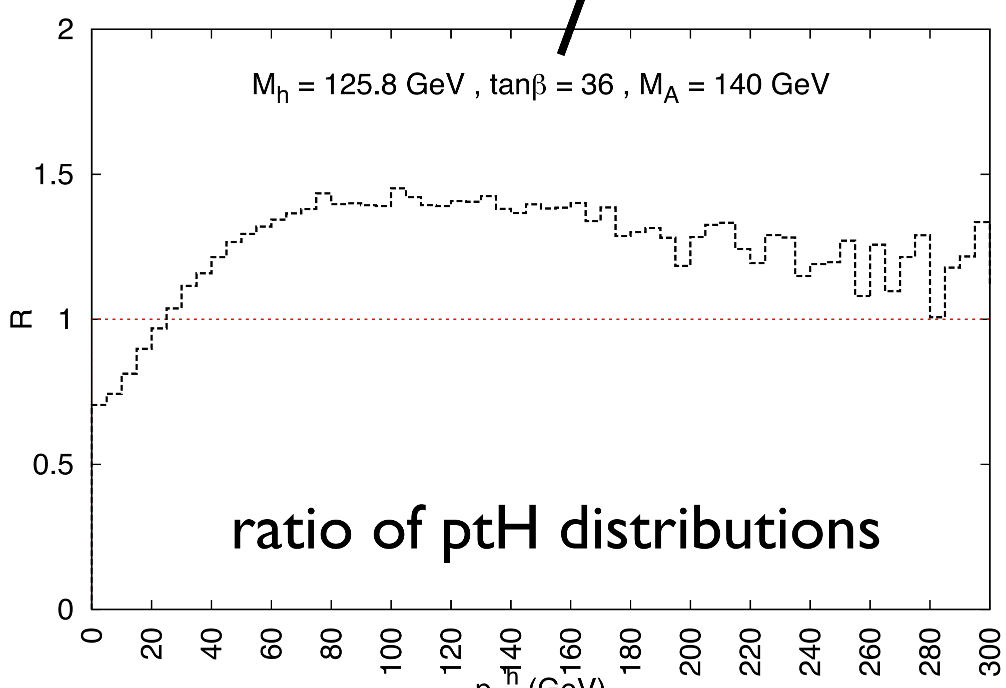
Ratios full MSSM/SM, h_0 production

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

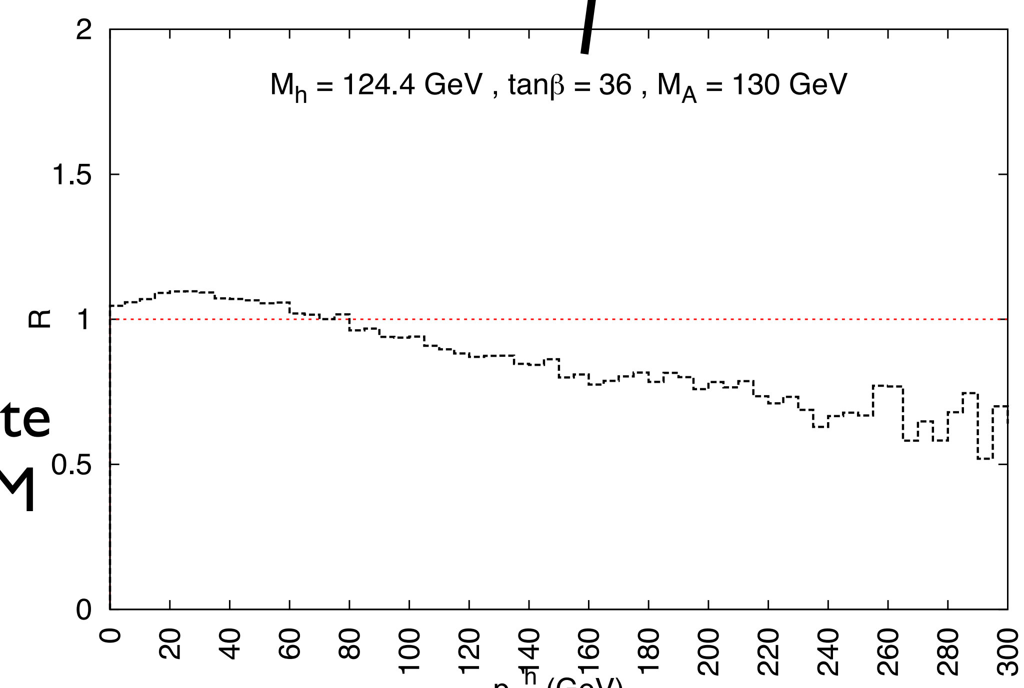




isomass line MH=125 GeV



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



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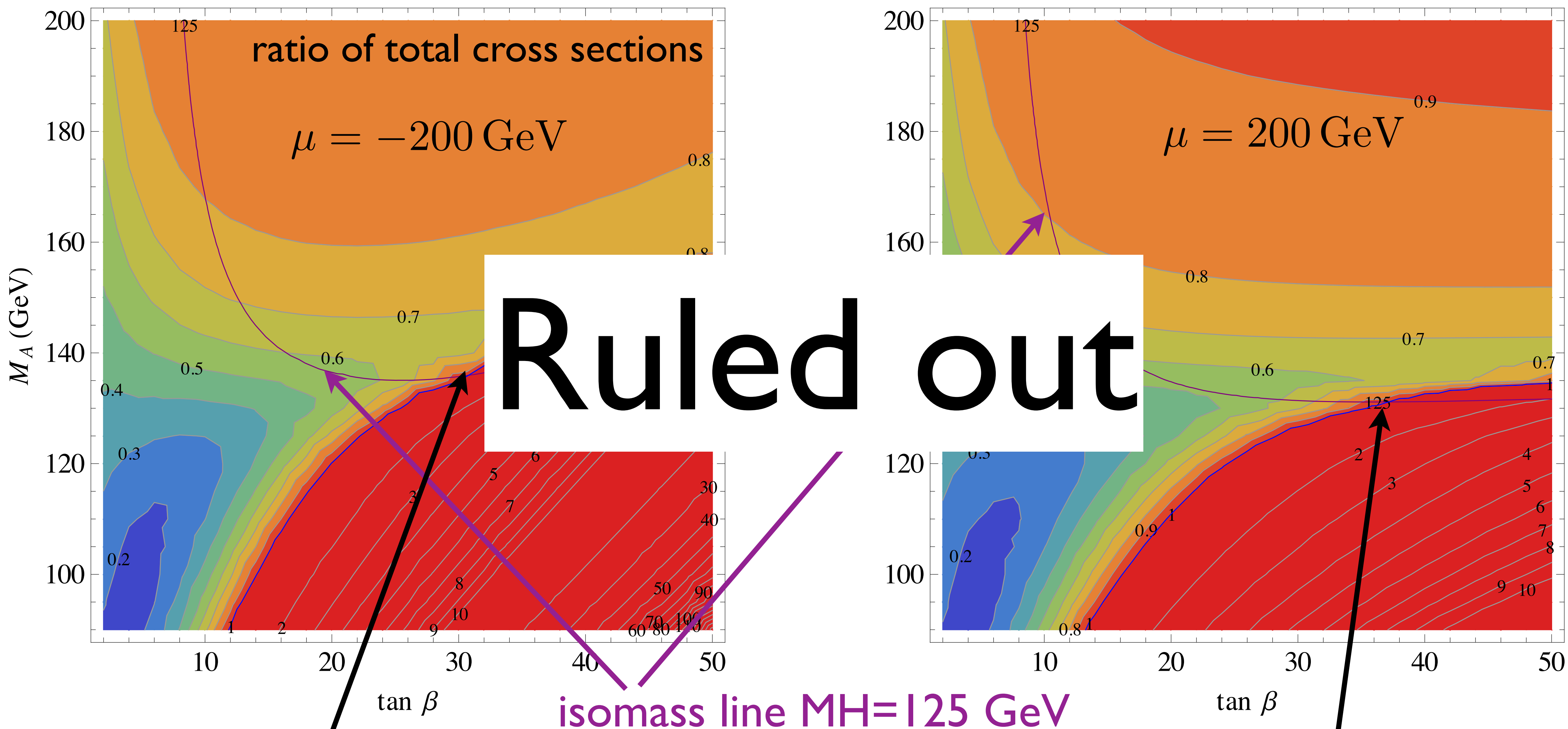

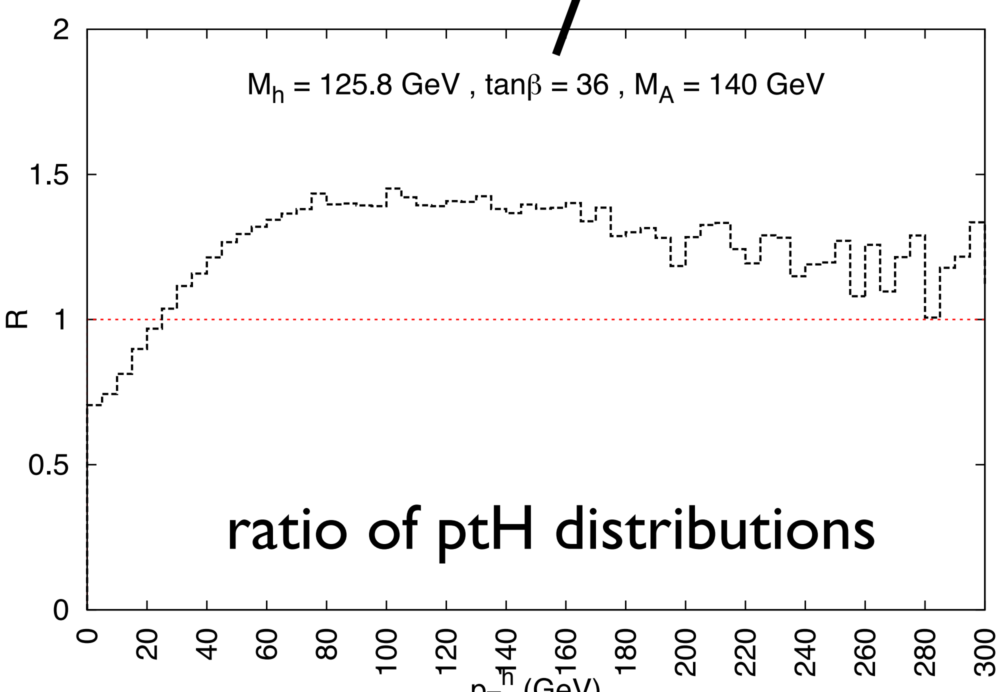

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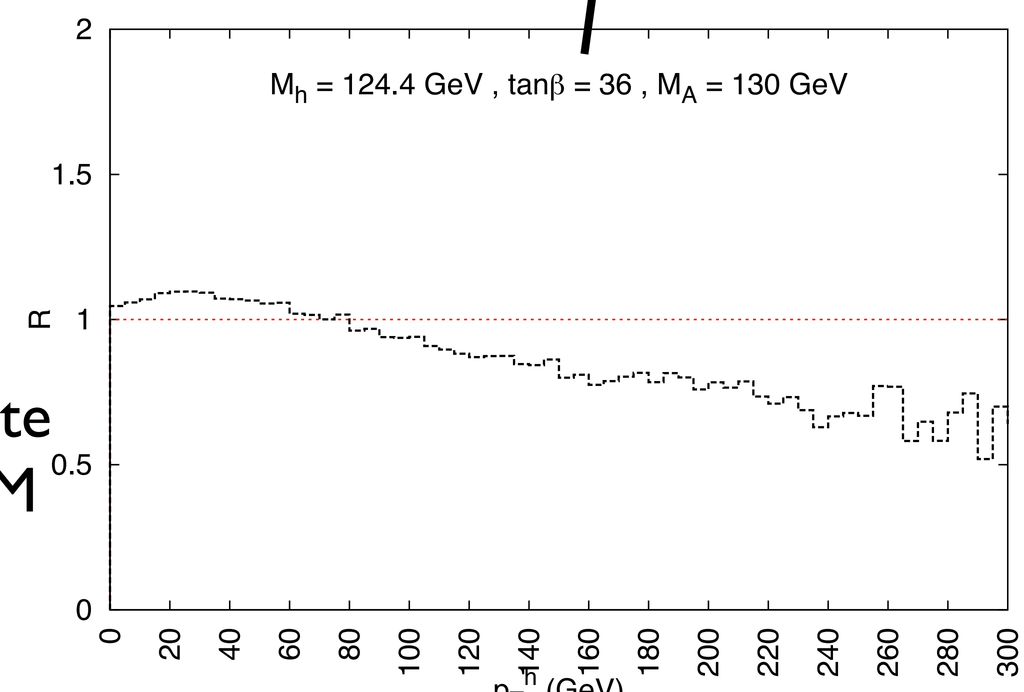
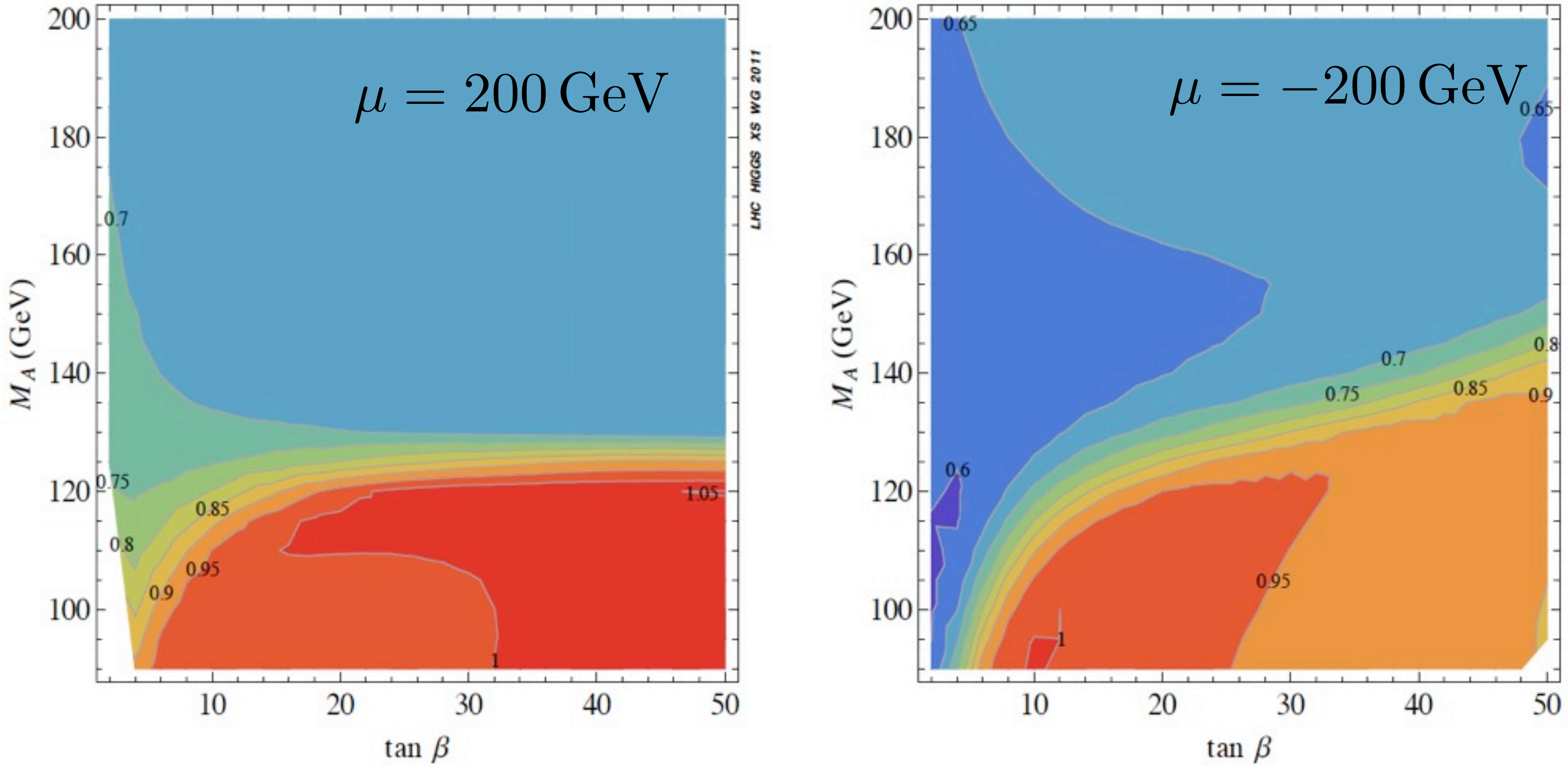


MSSM: role of the squarks, light higgs, ratio full MSSM *vs* MSSM only quarks

- the squarks induce always a negative correction: moderate when σ(MSSM) ≫ σ(SM)
  more sizeable when σ(MSSM) < σ(SM)

mQ=mU=mD=500 GeV, X^t=1250 GeV, M_3=400 GeV, M_2=2 M_1=200 GeV



- In the Yellow Report arXiv:1101.0593 the cross section for neutral Higgs production have been computed including only the quark contributions.

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	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

a 2HDM run in POWHEG

- model input parameters

the user chooses -the values of the input parameters α, tanβ 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

Differences with respect to the SM analysis

- in the type II, the coupling to down-type fermions is enhanced by $\tan\beta$
  the role of the bottom-quark amplitude, in the interference with the top, but also squared,
  can be radically different than in the SM

- some trivial cases are excluded by the experimental available constraints on a light scalar;
  other scenarios (e.g. heavy Higgs searches in the decoupling limit) can be delicate

- the inclusion of resummation effects is more problematic than in the SM:
  it is a 3 scales problem (O(mb), O(m_phi), O(mt)), like in the SM, but
  the bottom amplitude is NOT a small correction, it can be the leading contribution

- following a two-scales approach,
  up to which scale can we safely apply the resummation formalism to the top (bottom) contributions ?
  are these scales dependent on MH ?

- is a one-scale approach viable?
  if yes, up to which scale can we safely apply the resummation formalism ?

Exact matrix elements and collinear limit

$$|\mathcal{M}(m)|^2 = \sum_{\lambda_1,\lambda_2,\lambda_3=\pm1} |\mathcal{M}^{\lambda_1,\lambda_2,\lambda_3}(m)|^2 = \sum_{\lambda_1,\lambda_2,\lambda_3=\pm1} |\mathcal{M}_{div}^{\lambda_1,\lambda_2,\lambda_3}(m)/p_\perp^H + \mathcal{M}_{reg}^{\lambda_1,\lambda_2,\lambda_3}(m)|^2$$

- we discuss the validity of the collinear approximation of the amplitude,
  to find the value of ptH where the non-factorizable terms become important;
  a 10% deviation is considered relevant

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

- 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 in a fully justified way

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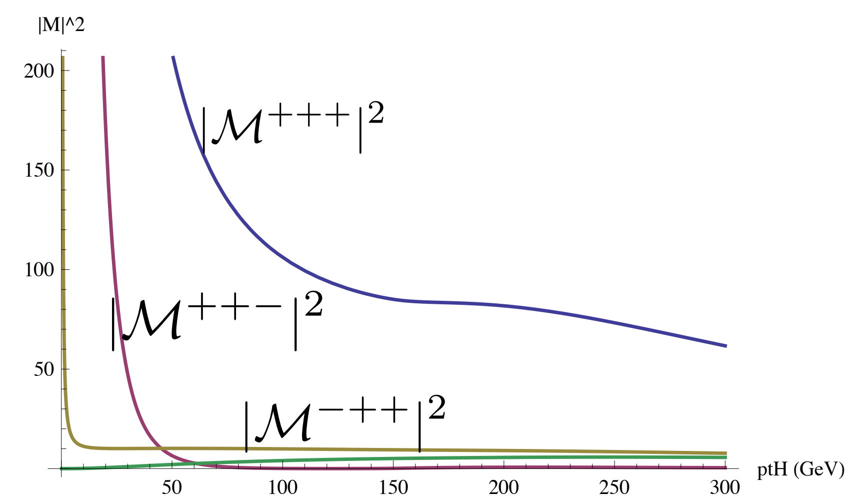
- 8 helicity amplitudes: related by parity (4+4) and by the symmetry of the process

- we discuss, at fixed partonic *s* , the 3 amplitudes with a soft+collinear or only collinear divergence for $u \to 0$

- dominance of the amplitudes with soft+collinear divergence

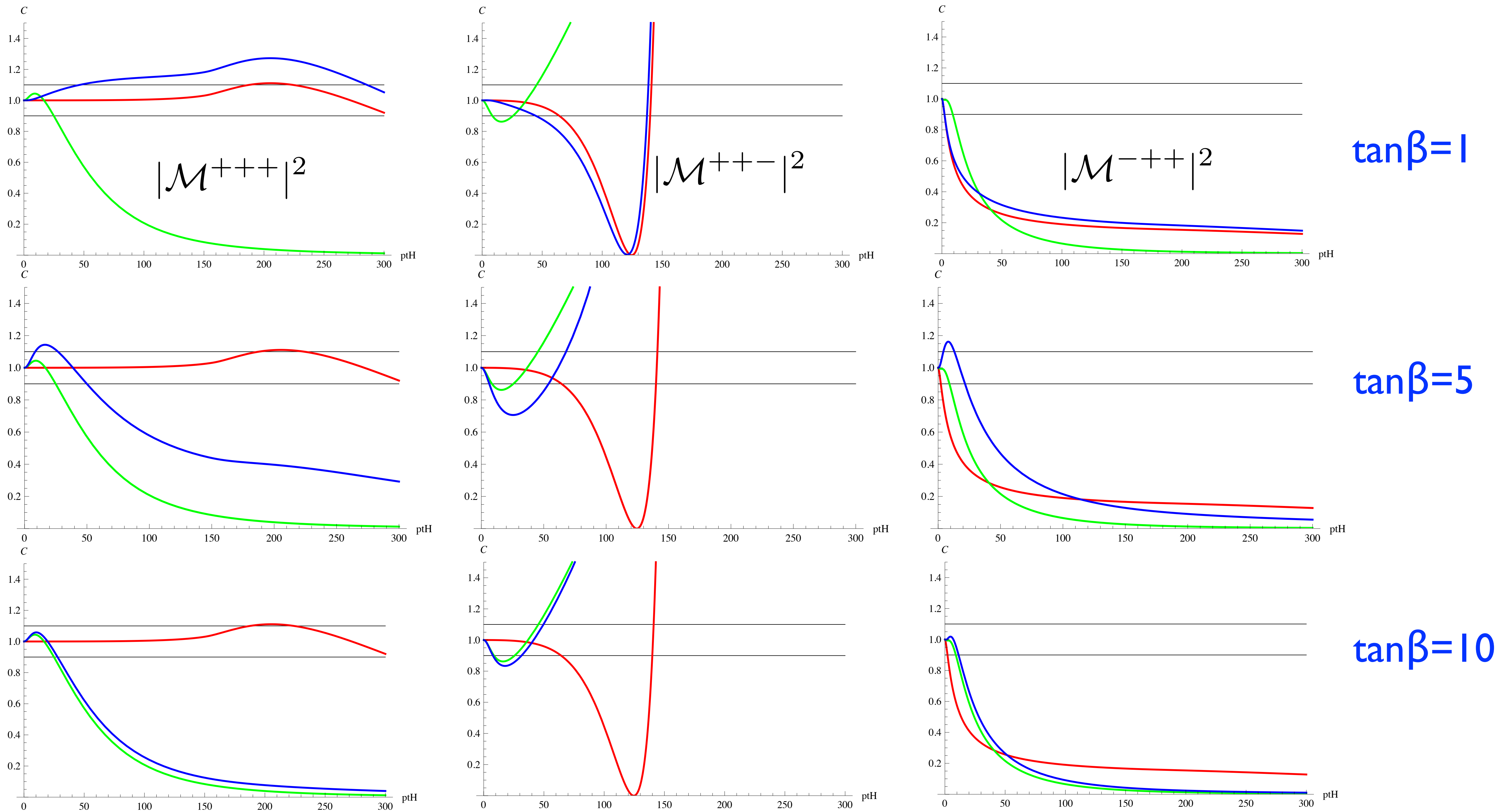


- the results depend on partonic *s*; the choice of the smallest possible *s* allowed value guarantees that the contribution under study has the largest PDF weight at hadron level (small changes when using other choices of *s*)

Toy example to illustrate the role of tanβ: light Higgs with mh=125 GeV

$$\mathcal{M} = \frac{1}{\tan\beta}\,\mathcal{M}^t + \tan\beta\,\mathcal{M}^b$$

amplitudes evaluated with: only top, only bottom, top+bottom

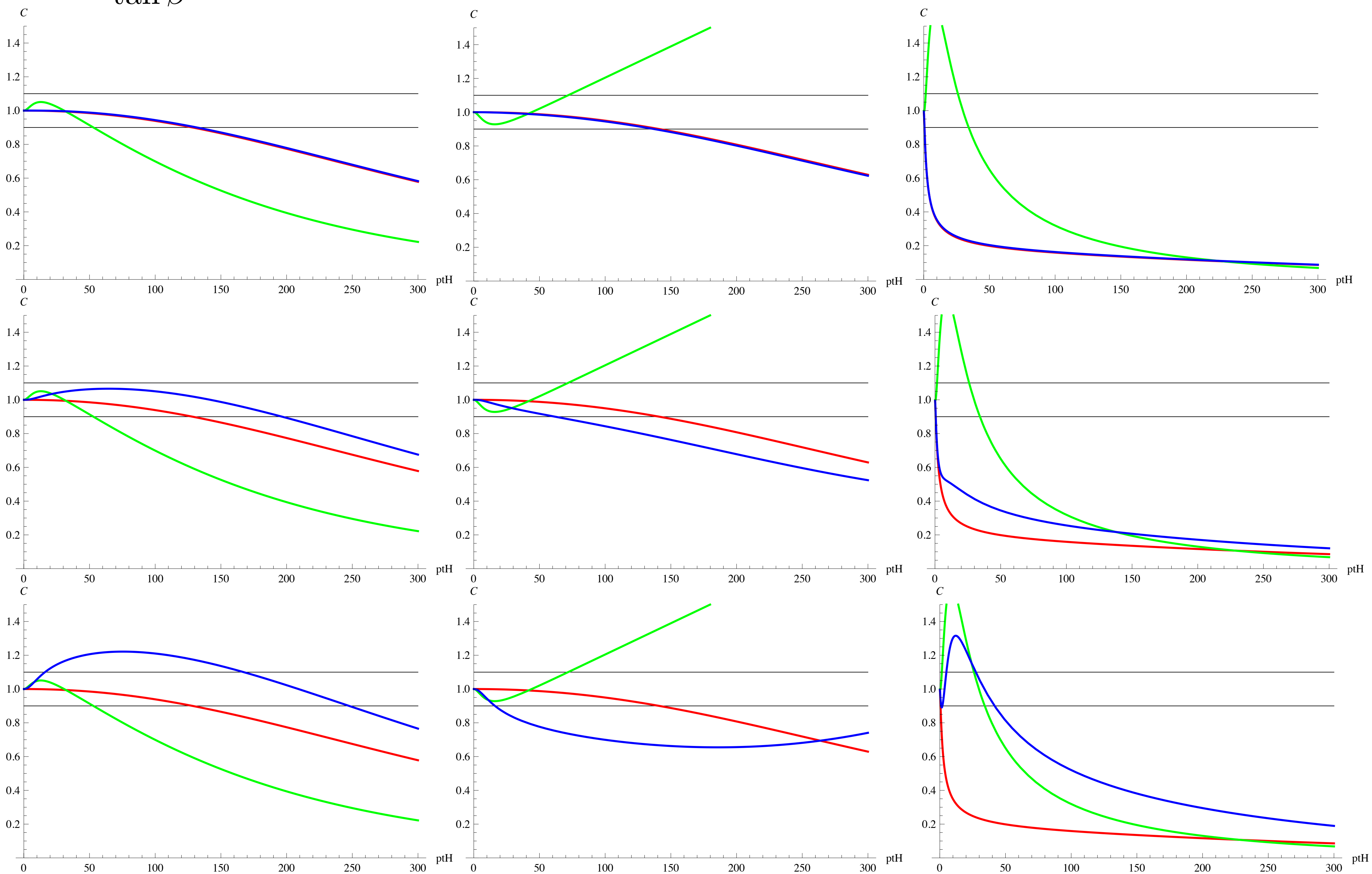


- the single-quark ratios are independent of tanβ
- for the full amplitude, the scale choice at which the collinear approximation fails is dominated by the bottom at large tanβ

Toy example to illustrate the role of tanβ: heavy Higgs with MH=500 GeV

$$\mathcal{M} = \frac{1}{\tan\beta}\,\mathcal{M}^t + \tan\beta\,\mathcal{M}^b$$

amplitudes evaluated with: only top, only bottom, top+bottom



tanβ=1

tanβ=5

tanβ=10

- the large MH value pushes the scale at which the collinear approximation fails for the only-bottom case, towards *hb* ~ 50 GeV

Comments

- in the two-scales approach,
  the scale at which the factorization breaks, for the only-top and for the only-bottom amplitudes,
  is independent of tanβ, but depends on MH:

  for the top, *ht* ~ O(60 GeV) with MH=125 GeV and *ht* ~ O(125 GeV) for MH=500 GeV
  for the bottom, *hb* ~ O(20 GeV) with MH=125 GeV and *hb* ~ O(60 GeV) for MH=500 GeV

  it is possible to prepare a table of *ht* and *hb* as a function of MH

- in the two-scales approach,
  we use *ht* for the only-top squared amplitude
  hb for the interference terms and bottom squared amplitude
  we potentially miss the resummation of terms proportional to the top-bottom interference
  (only keep the first term from the fixed-order calculation)

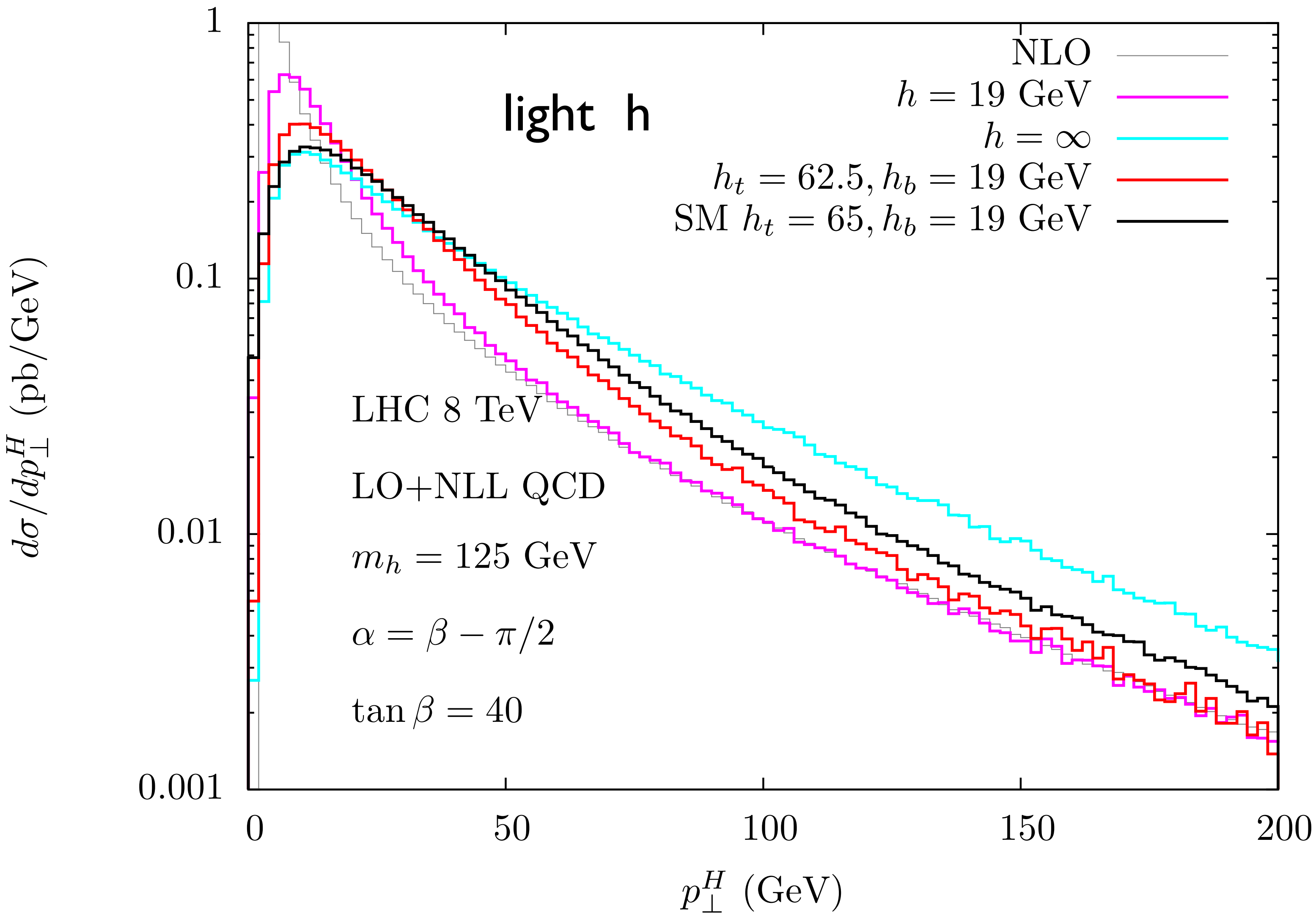
- a one-scale approach is possible,
  but the value of the scale *h* from the amplitude analysis strongly depends on tanβ
  there are regimes where a one-scale approach offers a good approximation of the two-scales results
  but it requires an *ad hoc* tuning

- the usage of *h*=MH/1.2 for a heavy Higgs is not justified! (e.g. for MH=500 GeV we get *h*=416 GeV)

Light and Heavy CP-even Higgs and in a decoupling limit

- in a type II 2HDM, the choice α=β-π/2 is called a decoupling limit because it makes the light CP-even scalar *h* SM-like, i.e. the couplings to the fermions are like in the SM

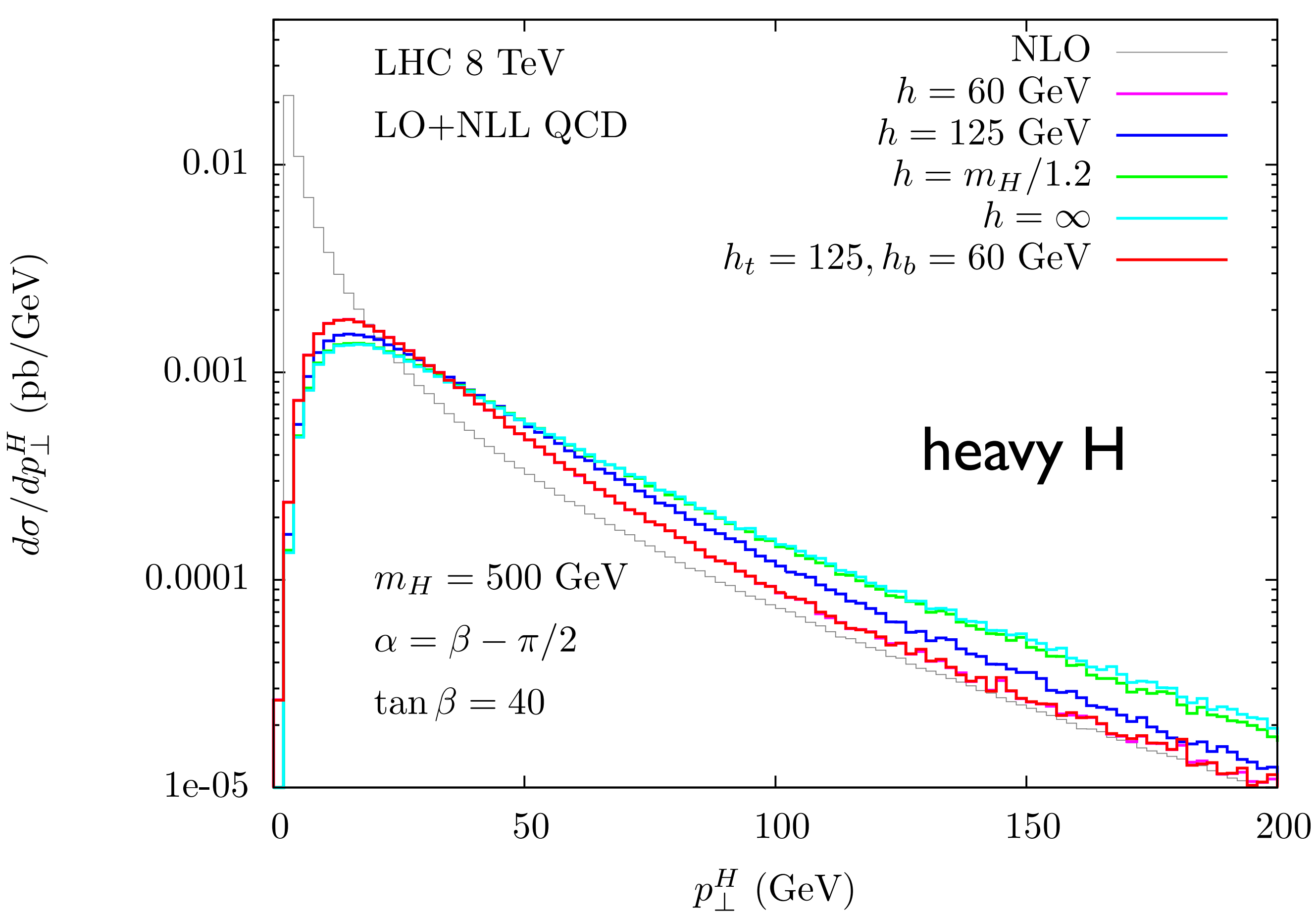
- the couplings of the heavy CP-even scalar H to the fermions instead are tanβ enhanced (down type) or suppressed (up type) w.r.t. the SM ones

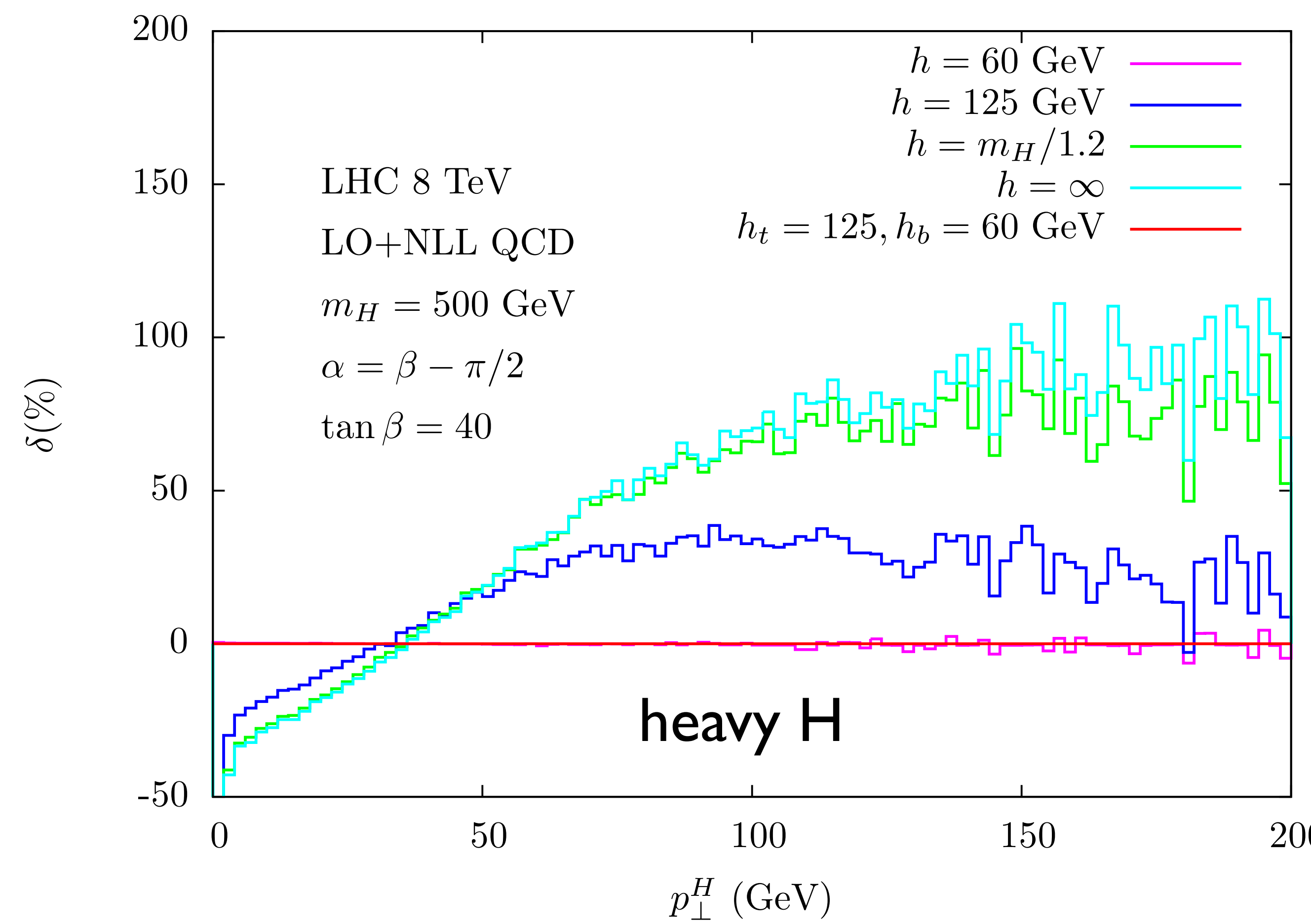


- in this decoupling limit the light CP-even scalar is SM-like (cfr red *vs* black)

Light and Heavy CP-even Higgs and in a decoupling limit

- the prediction for the heavy CP-even scalar is dominated by the bottom-quark amplitude
- the use of *ht*=MH/1.2 as single scale (light green line) is not justified
- the use of *ht* as single scale (blue line) differs from the two-scales treatment at the ±30% level
- given the bottom dominance, the two-scales result is perfectly approximated by *h*=*hb*=60 GeV





Conclusions

- Higgs production via gluon fusion in the 2HDM available in the POWHEG-BOX directory gg_H_2HDM
- it requires HDECAY to consistently compute the total decay width in the 2HDM
- the enhanced role of the bottom-quark amplitude requires a two-scale approach to set the resummation scales
- a one-scale approach may provide a good approximation of the two-scales results, but the precise single scale strongly depends on tanβ
- the precise measurement of the Higgs ptH distribution can help to recognize a BSM signal, even with a total rate for the light scalar compatible with the present data

Back-up

Basic references for the Higgs ptH spectrum, including multiple parton emissions

- Analytical resummation of the Higgs ptH spectrum in HQET

  Balazs, Yuan, arXiv:hep-ph/0001103
  Bozzi, Catani, De Florian, Grazzini, arXiv:hep-ph/0508068
  De Florian, Ferrera, Grazzini, Tommasini, arXiv:1109.2109

- Shower Montecarlo description of the Higgs ptH spectrum in HQET

  Frixione, Webber, arXiv:hep-ph/0309186
  Alioli, Nason, Oleari, Re, arXiv:0812.0578
  Hamilton, Nason, Re, Zanderighi, arXiv:1309.0017

- quark mass effects

  Bagnaschi, Degrassi, Slavich, Vicini, arXiv:1111.2854
  Mantler, Wiesemann, arXiv:1210.8263
  S. Frixione, talk at Higgs Cross Section Working Group meeting, December 7th 2012
  Grazzini, Sargsyan, arXiv:1306.4581
  S. Frixione, talk at the HXSWG meeting, July 23rd 2013
  A. Vicini, talk at the HXSWG meeting, July 23rd 2013
  Banfi, Monni, Zanderighi, arXiv:1308.4634

Multiple parton emissions via Parton Shower

- the Parton Shower "dresses" the hard event with QCD radiation

- QCD emissions are enhanced in the collinear limit

- The cross section factorizes in the collinear limit,
  so that multiple emissions can be described iterating a basic factorization formula

$$|\mathcal{M}_{n+1}|^2 d\Phi_{n+1} \to |\mathcal{M}_n|^2 d\Phi_n \frac{\alpha_s}{2\pi} \frac{dt}{t} P_{q,qg}(z) dz \frac{d\Phi}{2\pi}$$

- The showering process stops when the virtuality of the last emission is below the Λ_{QCD} scale
  where QCD becomes non perturbative (hadronization regime i.e. hadrons formation)

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- The Parton Shower has LL-QCD accuracy
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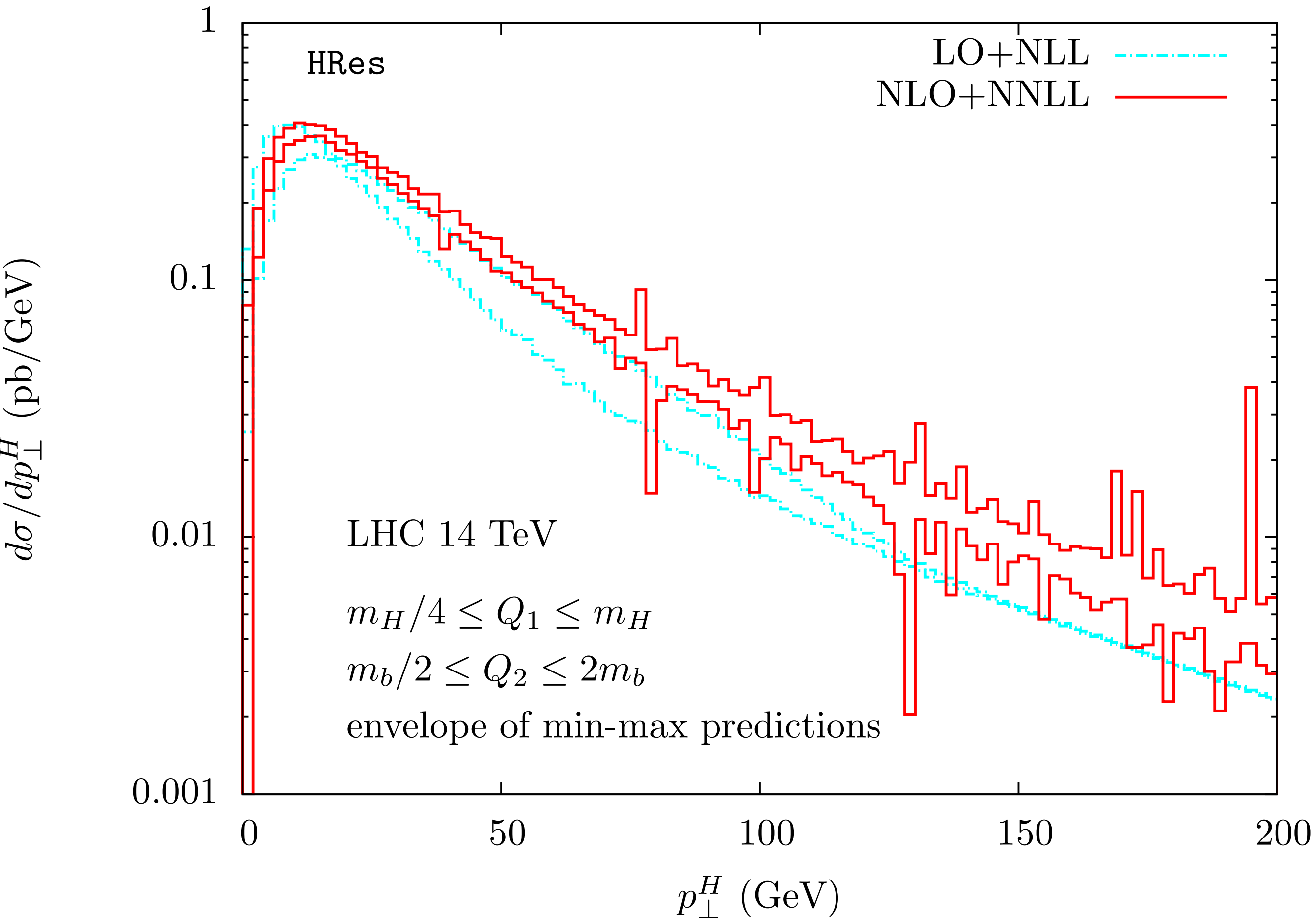
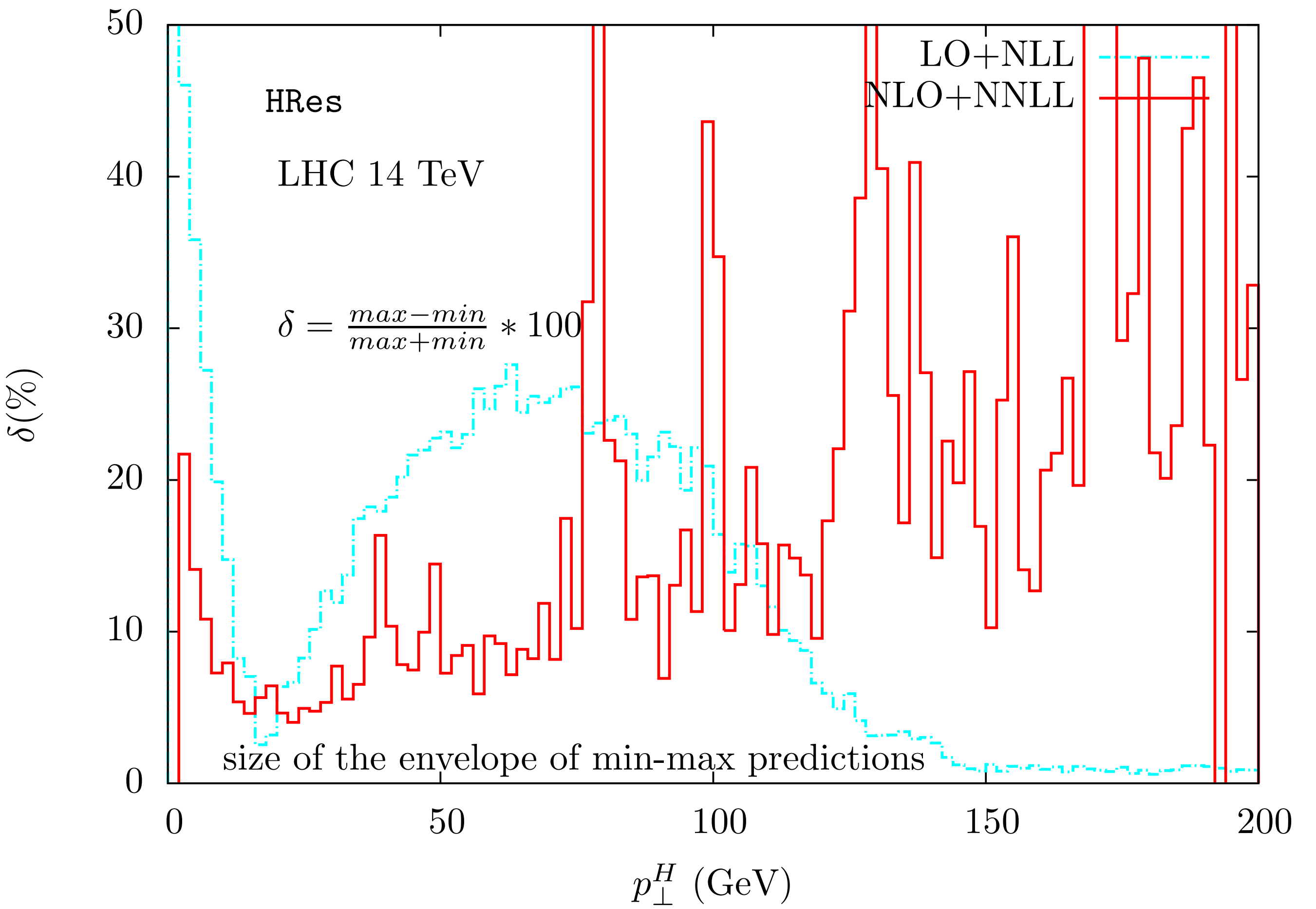
- We wish to merge the properties of the Parton Shower
  with the NLO-QCD accuracy for the total cross section from fixed order results
  without making double countings

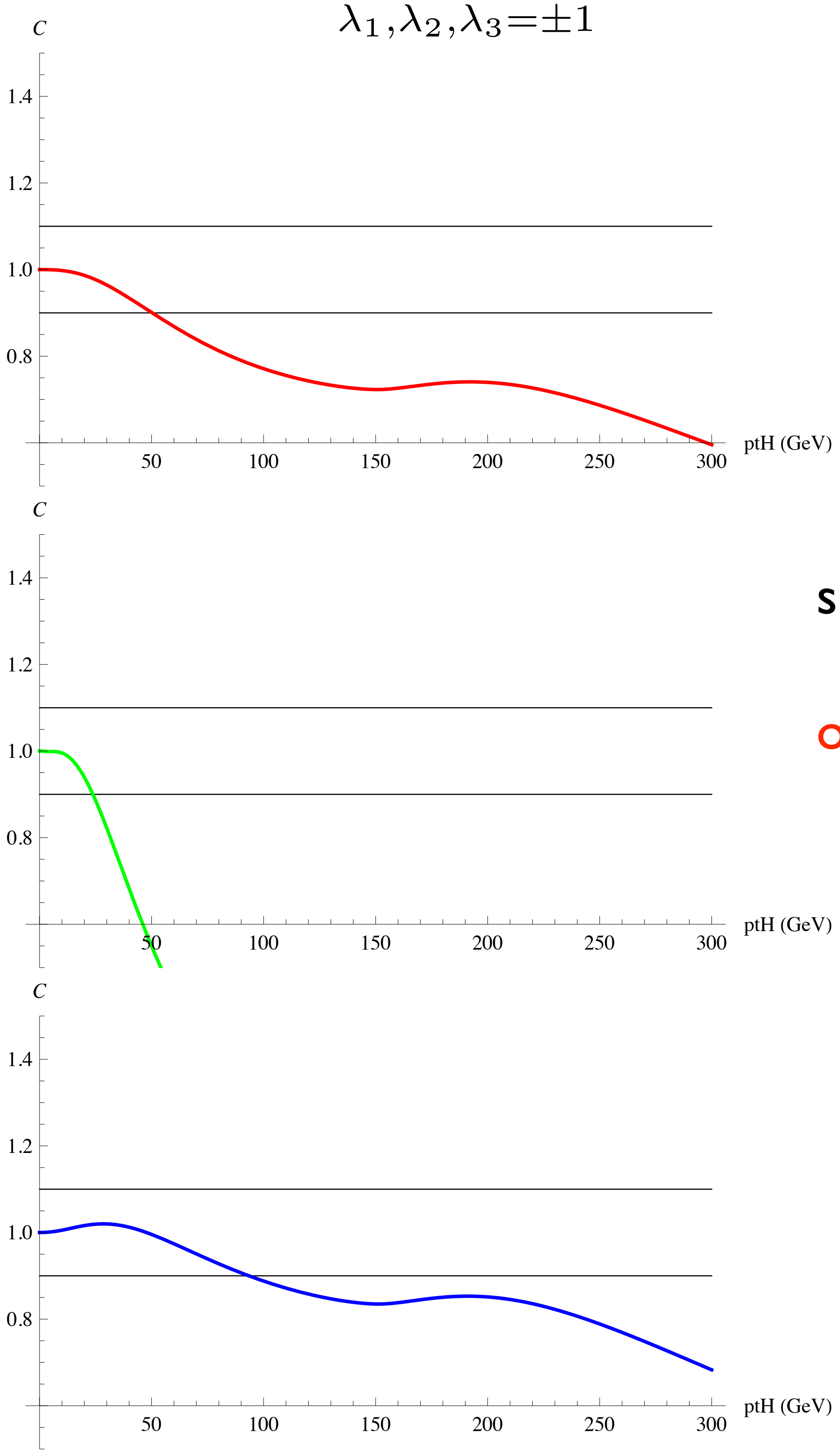
HRes uncertainty bands at LO+NLL and at NLO+NNLL





Collinear approximation of the full amplitude summed over helicities

$$|\mathcal{M}(m)|^2 = \sum_{\lambda_1,\lambda_2,\lambda_3=\pm1} |\mathcal{M}^{\lambda_1,\lambda_2,\lambda_3}(m)|^2 = \sum_{\lambda_1,\lambda_2,\lambda_3=\pm1} |\mathcal{M}_{div}^{\lambda_1,\lambda_2,\lambda_3}(m)/p_\perp^H + \mathcal{M}_{reg}^{\lambda_1,\lambda_2,\lambda_3}(m)|^2$$

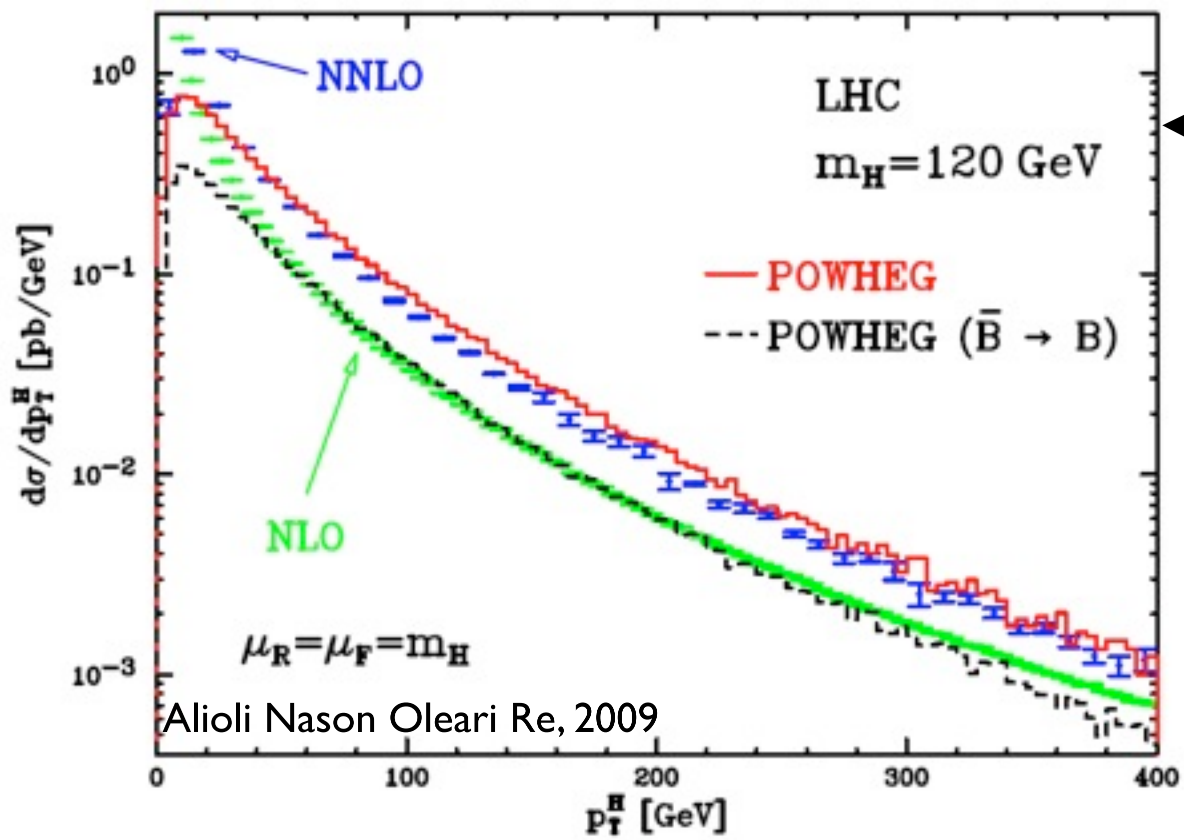


$$C(p_\perp^H) = \frac{|\mathcal{M}_{exact}(p_\perp^H)|^2}{|\mathcal{M}_{div}(p_\perp^H)/p_\perp^H|^2}$$

sum over helicities of the amplitudes evaluated with:

only top, only bottom, top+bottom

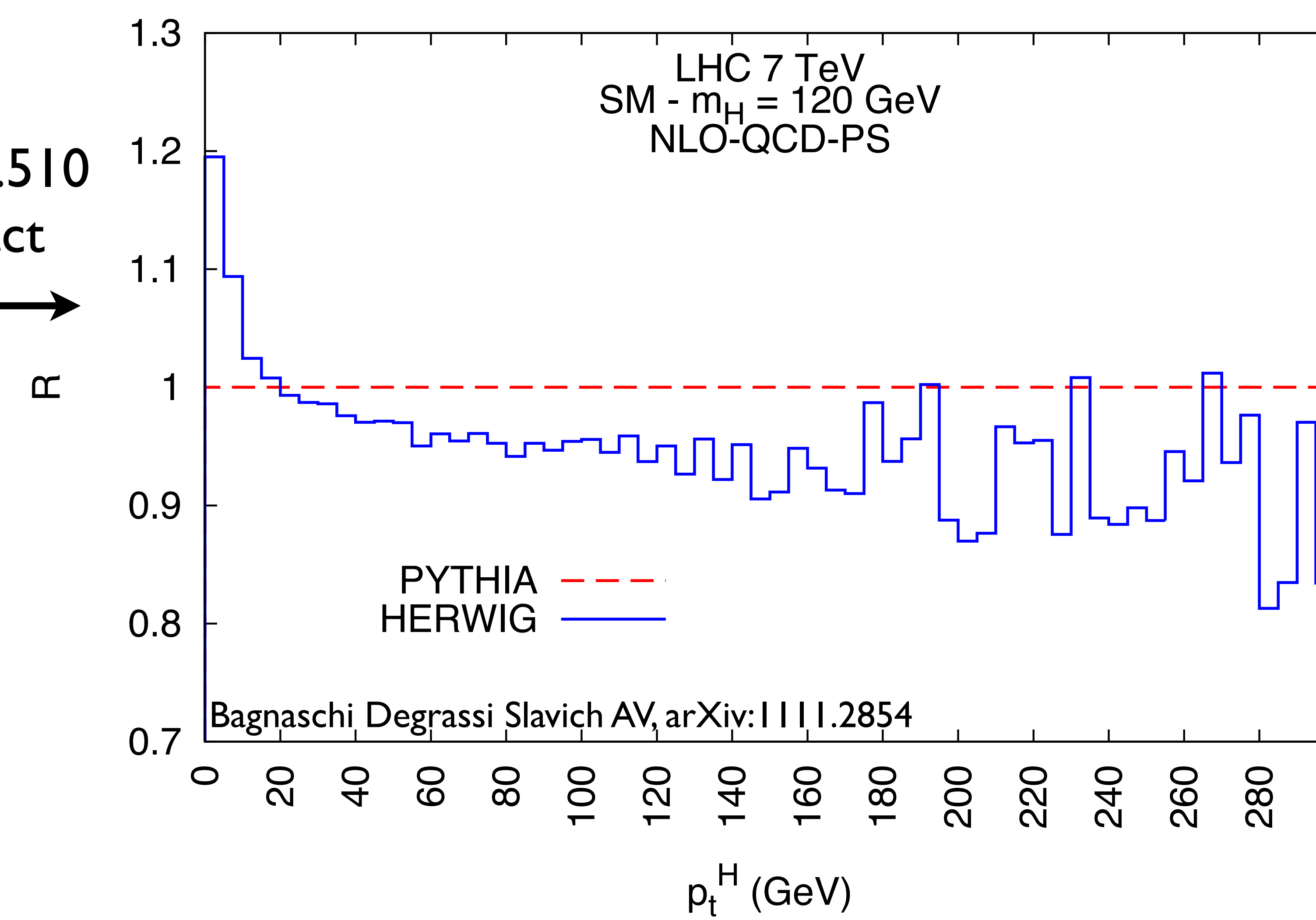
SM: open questions about the Higgs transverse momentum distribution



POWHEG has a strong enhancement of the shape at large pt (due to the large K-factor) which brings it accidentally very close to HNNLO

comparison PYTHIA 6.4.21 vs HERWIG 6.510
non perturbative parameter have a strong impact on the low ptH tail of the distribution →

need to perform a tuning of the non-perturbative parameters using the NLO-SMC to compare with the data



MSSM: perturbative content

$$\sigma(h_1+h_2\to H+X) = \sum_{a,b}\int_0^1 dx_1 dx_2\; f_{a,h_1}(x_1,\mu_F^2)\, f_{b,h_2}(x_2,\mu_F^2)\times$$
$$\times\int_0^1 dz\,\delta\left(z-\frac{\tau_H}{x_1x_2}\right)\hat\sigma_{ab}(z)\,,$$

$$\hat\sigma_{ab}(z)=\sigma^{(0)}\,z\,G_{ab}(z)$$

$$\sigma^{(0)}=\frac{G_\mu\alpha_s^2(\mu_R^2)}{128\sqrt{2}\,\pi}\left|\sum_{i=0,1/2}\lambda_i\left(\frac{A^2}{m_0^2}\right)^{1-2i}T(R_i)\,\mathcal{G}_i^{(1l)}\right|^2$$

$$G_{ab}(z)=G_{ab}^{(0)}(z)+\frac{\alpha_s(\mu_R^2)}{\pi}G_{a,b}^{(1)}(z)$$

$$G_{ab}^{(0)}(z) = \delta(1-z)\,\delta_{ag}\,\delta_{bg}\,,$$
$$G_{gg}^{(1)}(z) = \delta(1-z)\left[C_A\frac{\pi^2}{3}+\beta_0\ln\left(\frac{\mu_R^2}{\mu_F^2}\right)+\sum_{i=0,1/2}\mathcal{G}_i^{(2l)}\right]+\ldots$$

$$\mathcal{G}_i^{(2l)} = \lambda_i\left(\frac{A^2}{m_0^2}\right)^{1-2i}T(R_i)\left(C(R_i)\,\mathcal{G}_i^{(2l,C_R)}(x_i)+C_A\,\mathcal{G}_i^{(2l,C_A)}(x_i)\right)$$
$$\times\left(\sum_{j=0,1/2}\lambda_j\left(\frac{A^2}{m_0^2}\right)^{1-2j}T(R_j)\,\mathcal{G}_j^{(1l)}\right)^{-1}+h.c.$$

$$\mathcal{F}_{1/2}^{(1l)} = -4y_{1/2}\left[2-\left(1-4y_{1/2}\right)\,H(0,0,x_{1/2})\right]$$
$$\mathcal{F}_0^{(1l)} = 4y_0\left[1+2\,y_0\,H(0,0,x_0)\right]\,.$$

MSSM: perturbative content

$$\lambda_t = \frac{\cos\alpha}{\sin\beta}\,, \qquad \lambda_b = -\frac{\sin\alpha}{\cos\beta}$$

$$\begin{aligned}\lambda_{\tilde{t}_1} \;=\; & -\frac{\sin\alpha}{\sin\beta}\left\{-\frac{1}{2}\sin 2\theta_t\,\mu\,m_t + \frac{1}{8}m_Z^2\sin 2\beta\left[1+\cos 2\theta_t\left(1-\frac{8}{3}\sin^2\theta_W\right)\right]\right\} \\ & +\frac{\cos\alpha}{\sin\beta}\left\{m_t^2+\frac{1}{2}\sin 2\theta_t\,A_t\,m_t - \frac{1}{4}m_Z^2\sin^2\beta\left[1+\cos 2\theta_t\left(1-\frac{8}{3}\sin^2\theta_W\right)\right]\right\}\end{aligned}$$

$$\begin{aligned}\lambda_{\tilde{b}_1} \;=\; & -\frac{\sin\alpha}{\cos\beta}\left\{m_b^2+\frac{1}{2}\sin 2\theta_b\,A_b\,m_b - \frac{1}{4}m_Z^2\cos^2\beta\left[1+\cos 2\theta_b\left(1-\frac{4}{3}\sin^2\theta_W\right)\right]\right\} \\ & +\frac{\cos\alpha}{\cos\beta}\left\{-\frac{1}{2}\sin 2\theta_b\,\mu\,m_b + \frac{1}{8}m_Z^2\sin 2\beta\left[1+\cos 2\theta_b\left(1-\frac{4}{3}\sin^2\theta_W\right)\right]\right\}\,.\end{aligned}$$

Parametrization of the inclusion of higher order contributions

very preliminary!!

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

$$R^s = \bar{R} + b(R - \bar{R})$$
$$R^f = (1-b)(R - \bar{R}) + R_{q\bar{q}}$$

$$\bar{R} = R_{HQET}\frac{\sigma_{LO}(t+b)}{\sigma_{LO}^{HQET}}$$

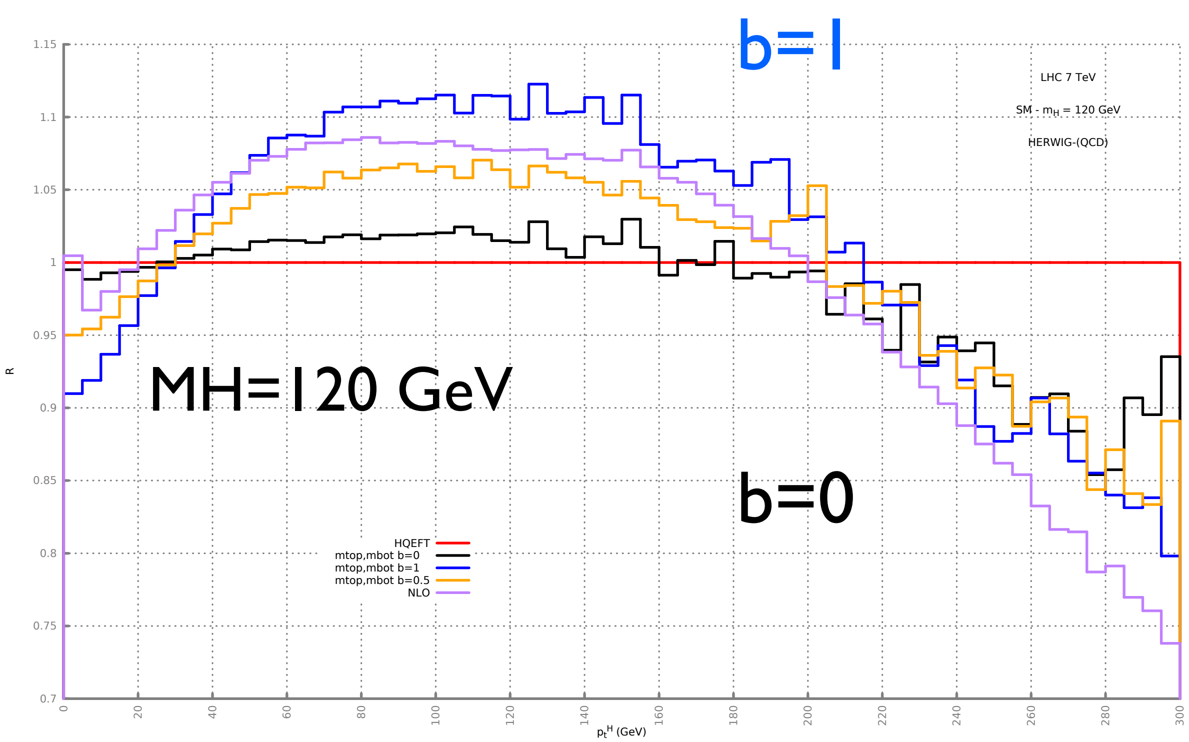
we can set the *b* parameter ($0 \le b \le 1$) from the input file

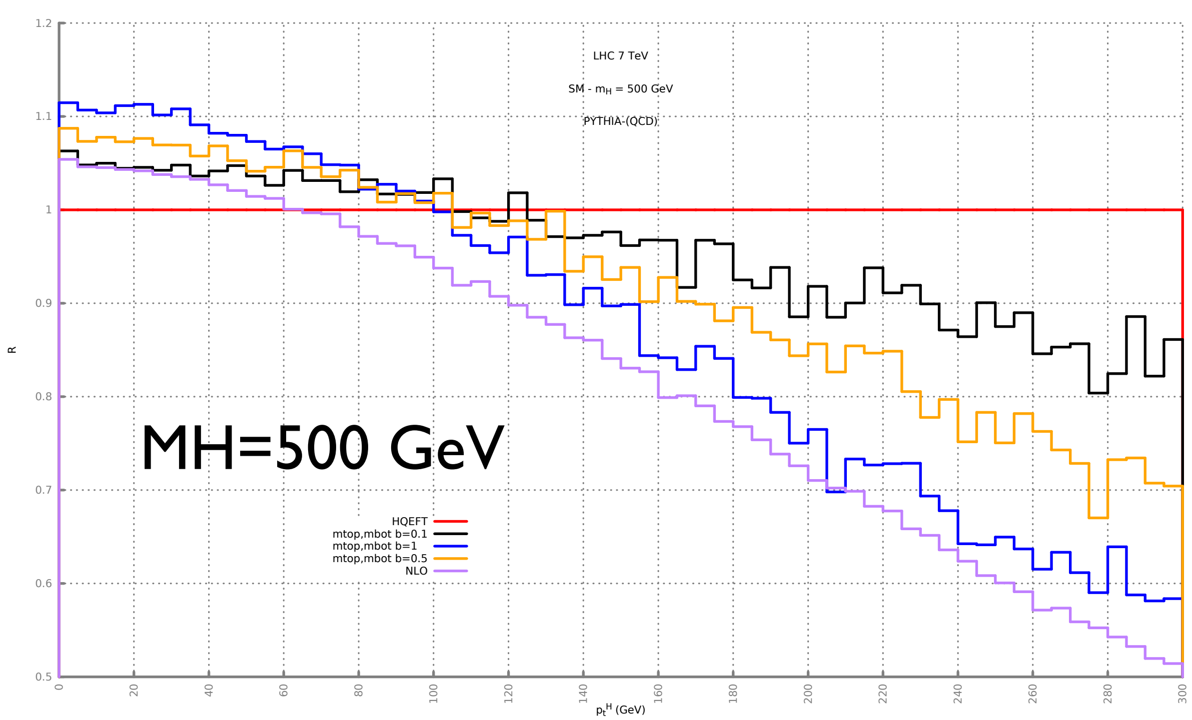
$b = 0$ the Sudakov does not contain quark mass effects, present only in the regular terms (similar to the MC@NLO approach, but the Sudakov is still non universal)

$b = 1$ the Sudakov contains the exact real matrix element; there are no extra regular terms, beyond the qqbar initiated process (identical by construction to the POWHEG approach)

the *b* parameter can help to parametrize the uncertainty band associated to the quark mass effects

The Higgs ptH distribution: estimate of the quark mass uncertainty

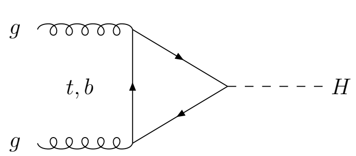


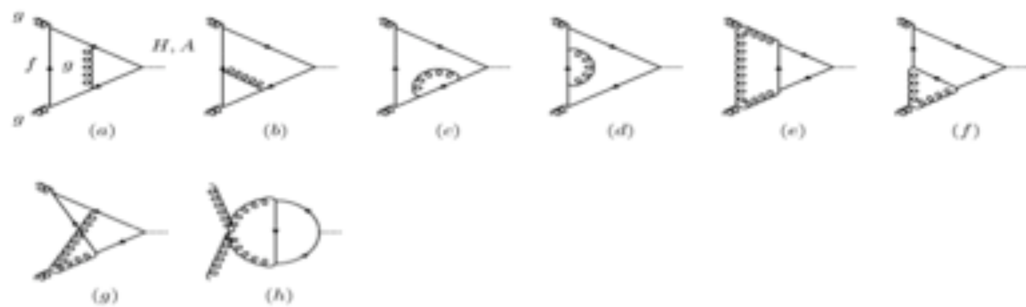


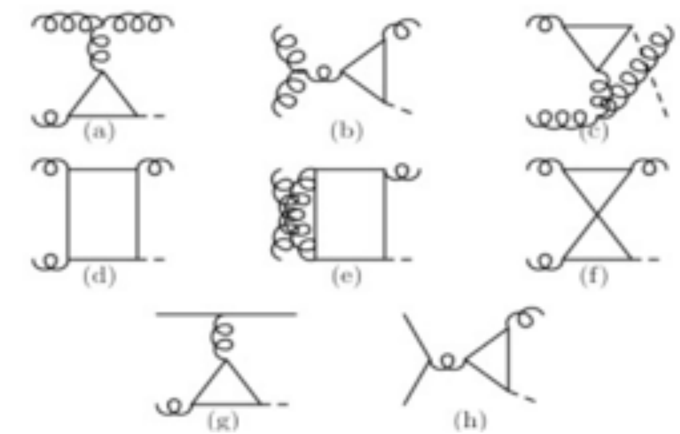
very preliminary!!

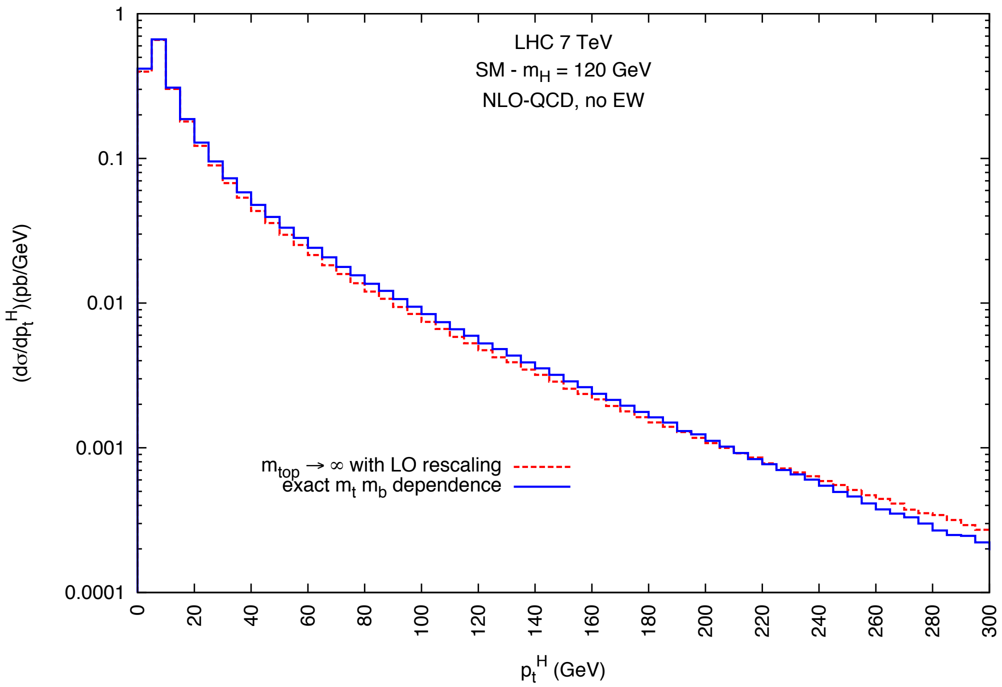
- the use of the *b* parameter allows to span a whole range of intermediate cases between the prescriptions *à la* MC@NLO and the POWHEG one
- in all the cases the total cross-section is exactly preserved
- the band of the blu/black curves provides an estimate of the size of the uncertainty in the evaluation of quark mass effects
- in purple: NLO results
- for MH=500 GeV, top mass effects are important already at low ptH

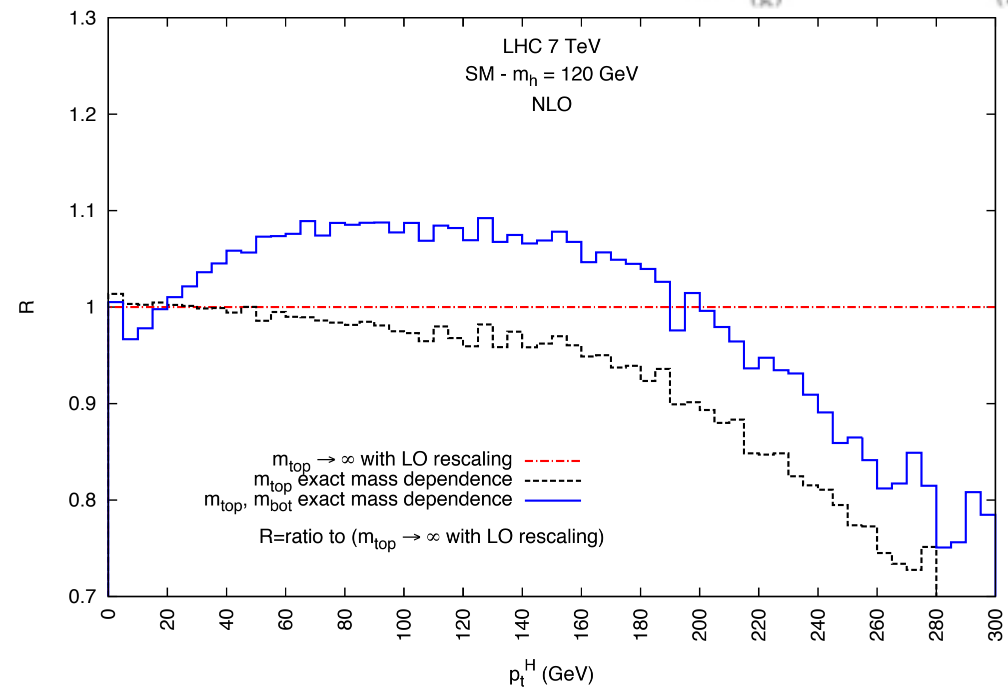
Quark mass effects at fixed order (no resummation, no Parton Shower)











- very good agreement between independent codes

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

- 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)

Exact matrix elements and collinear limit

$$|\mathcal{M}(m)|^2 = \sum_{\lambda_1,\lambda_2,\lambda_3=\pm 1} |\mathcal{M}^{\lambda_1,\lambda_2,\lambda_3}(m)|^2 = \sum_{\lambda_1,\lambda_2,\lambda_3=\pm 1} |\mathcal{M}_{div}^{\lambda_1,\lambda_2,\lambda_3}(m)/p_\perp^H + \mathcal{M}_{reg}^{\lambda_1,\lambda_2,\lambda_3}(m)|^2$$

- we discuss the validity of the collinear approximation of the amplitude, to find the value of ptH where the non-factorizable terms become important; a 10% deviation is considered relevant

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

- 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 in a fully justified way

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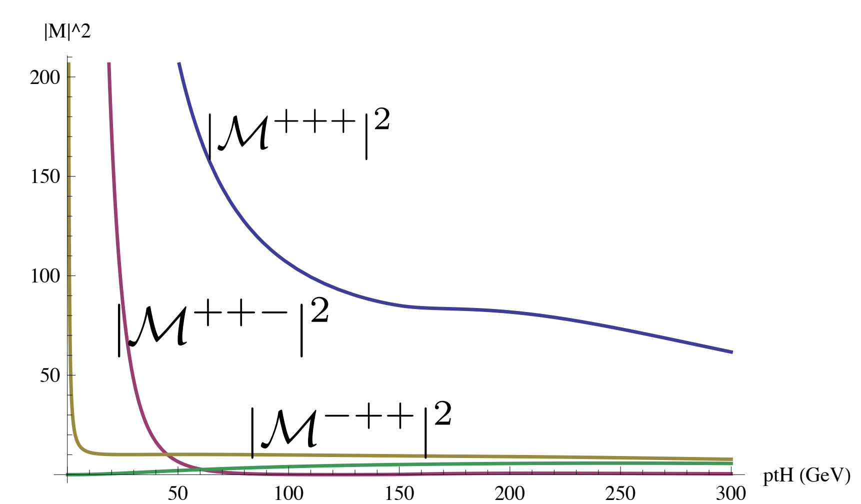
- 8 helicity amplitudes:
  related by parity (4+4) and by the symmetry of the process

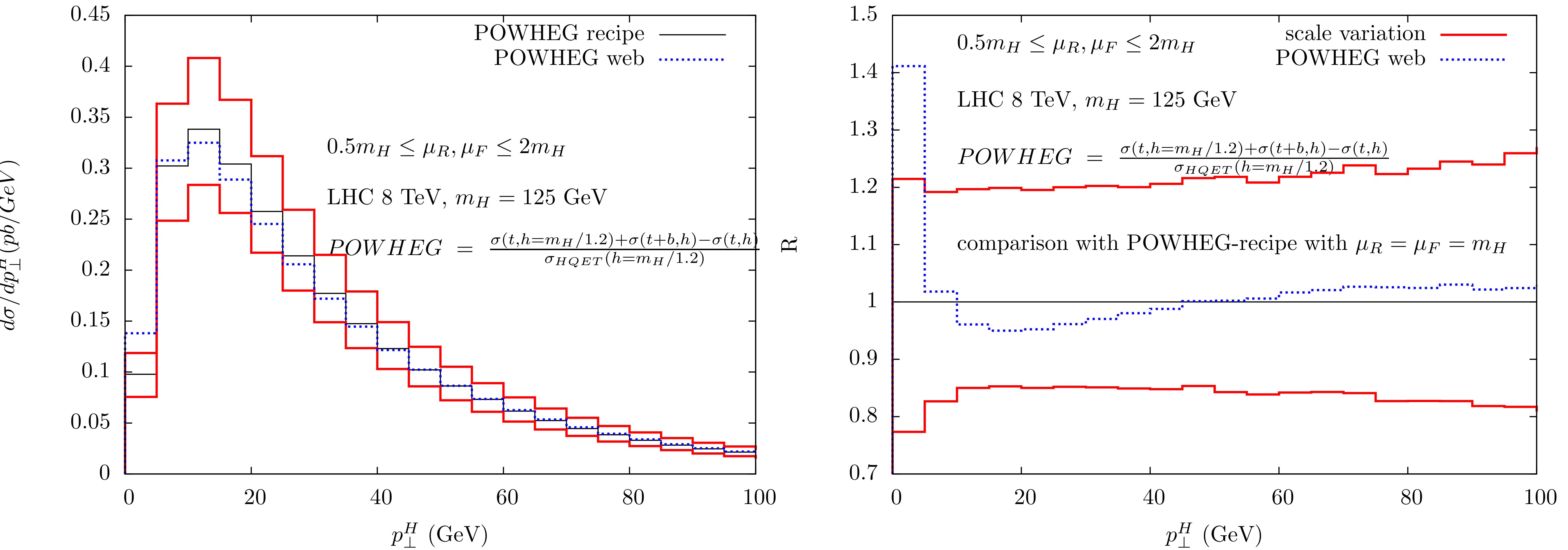
- we discuss, at fixed partonic *s* , the 3 amplitudes
  with a soft+collinear or only collinear divergence for *u*→0

- dominance of the amplitudes with soft+collinear divergence



- the results depend on partonic *s*; the choice of the smallest possible *s* allowed value guarantees
  that the contribution under study has the largest PDF weight at hadron level
  (small changes when using other choices of *s*)

Scale variation (preliminary)



- Canonical renormalization and factorization scale variation (red) computed with the new recipe
- Comparison with the present quark-mass-effect POWHEG version in the POWHEG-box (blue)