The Higgs transverse momentum distribution in Shower Montecarlo codes for pp→H+X: mass effects in the SM and in the 2HDM/MSSM

Alessandro Vicini
University of Milano, INFN Milano

June 17th 2014

in collaboration with: E. Bagnaschi, G. Degrassi

important discussions with: S. Frixione, M. Grazzini, F. Maltoni, P. Nason, C. Oleari

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

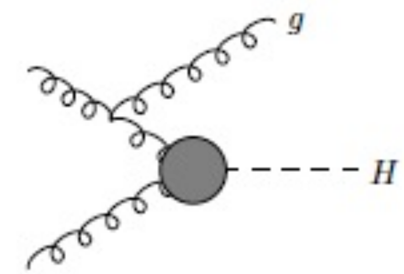
  Bagnaschi, Degrassi, Slavich, Vicini, arXiv:1111.2854
  Mantler, Wiesemann, arXiv:1210.8263
  S. Frixione, talk at Higgs Cross Section Working Group meeting, December 7th 2012
  Grazzini, Sargsyan, arXiv:1306.4581
  S. Frixione, talk at the HXSWG meeting, July 23rd 2013
  A. Vicini, talk at the HXSWG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

Outline

- matching NLO matrix elements for inclusive Higgs production and Parton Shower
- quark mass effects in the SM
- two-scales vs one-scale description of the Higgs ptH distribution
  in presence of quark mass effects

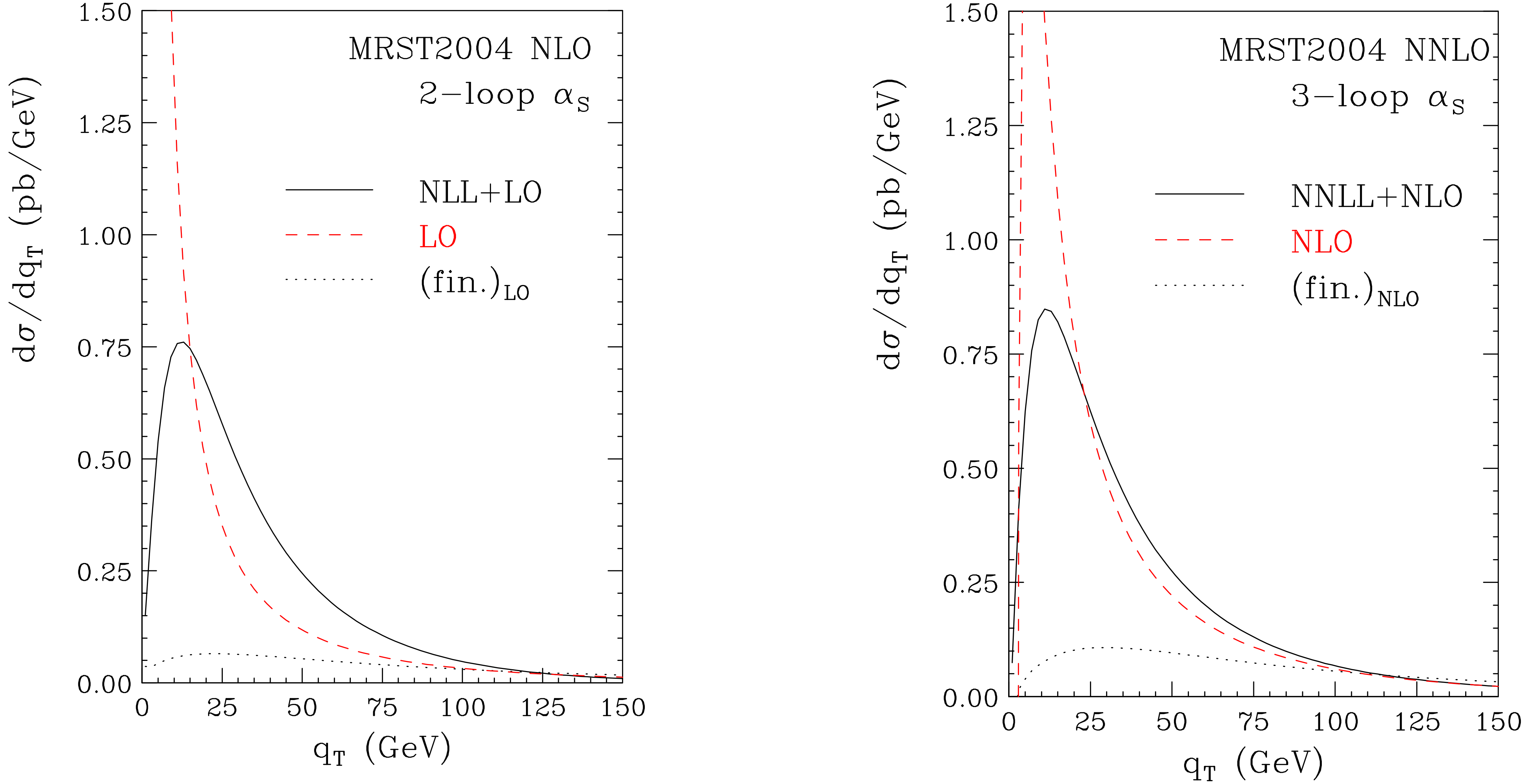
- one (old) MSSM example to emphasize the role of the ptH distribution to recognize BSM signals
- Higgs production via gluon fusion in the 2HDM in the POWHEG-BOX
- one 2HDM example in the decoupling limit: possible issues in the searches for a heavy Higgs

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



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

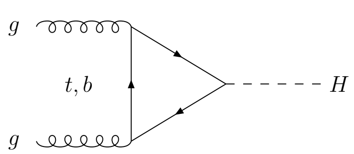
Bozzi Catani De Florian Grazzini, arXiv:hep-ph/0508068

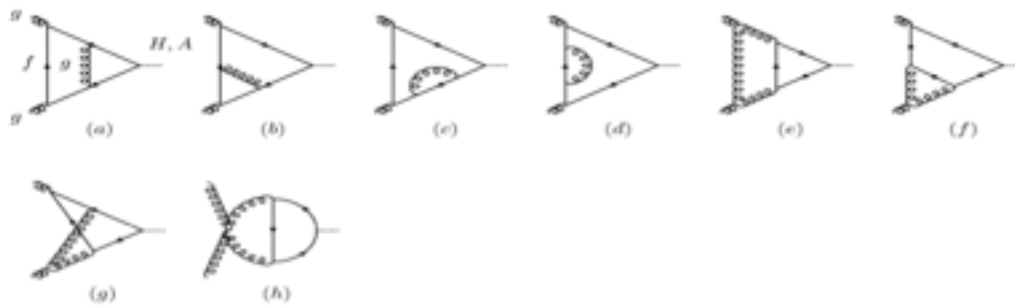


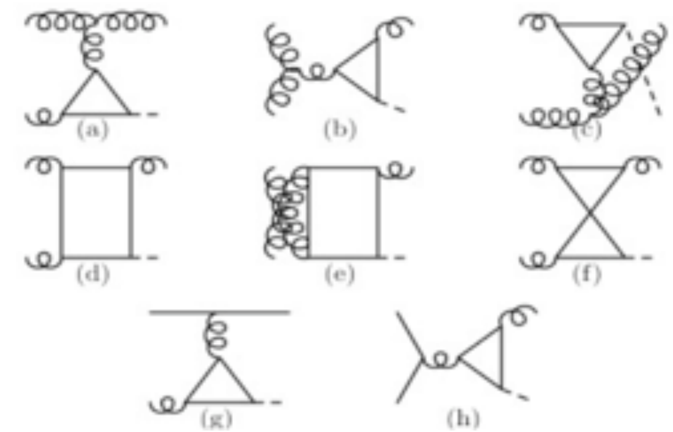
- at low ptH, the fixed order ptH distribution diverges for ptH → 0 (both at LO and at NLO)

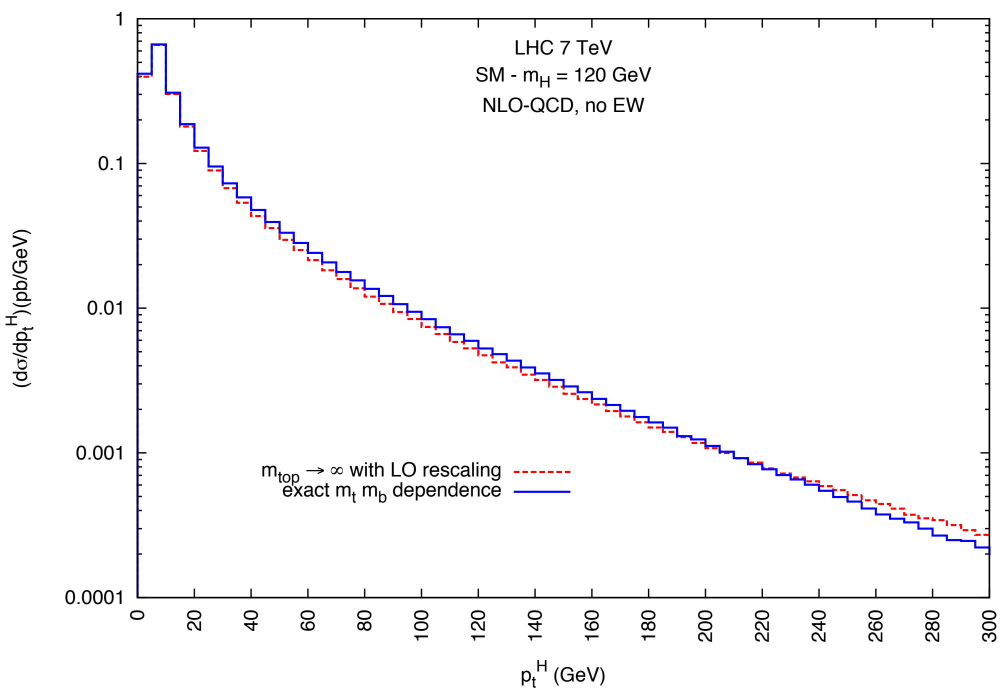
- the resummation to all orders of the divergent log(ptH) terms yields a regular distribution in the limit ptH → 0
  different approaches: analytical (up to NLO+NNLL), via Parton Shower (up to LO+NLL)

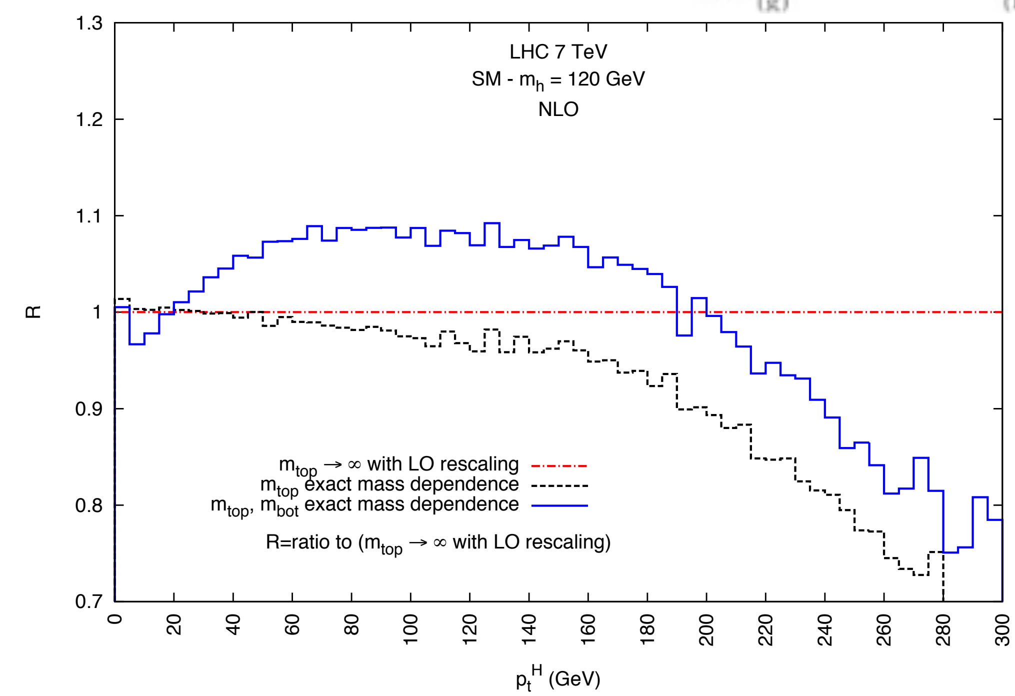
Quark mass effects at fixed order (no resummation, no Parton Shower)











- 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)

Matching NLO matrix elements and Parton Shower

Matching NLO matrix elements and Parton Shower

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

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

Matching NLO matrix elements and Parton Shower

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

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

$R = R_{reg} + R_{div}$ 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 $\Delta^s(p_T(\Phi))$

Matching NLO matrix elements and Parton Shower

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

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

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

$R_{div} = R^s + R^f$ 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 $\Delta^s(p_T(\Phi))$

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*

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

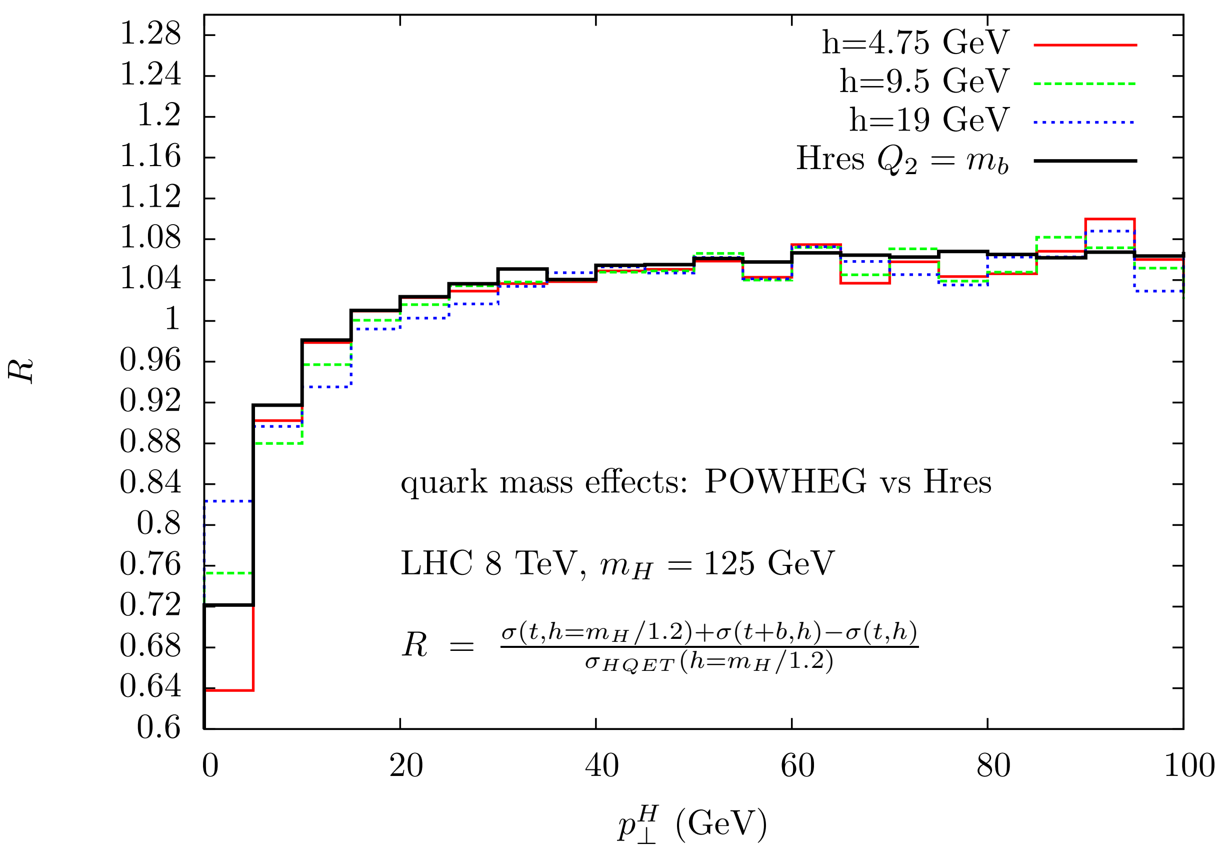
- the Higgs ptH spectrum, with quark masses, is a 3 scales problem (mb, MH, mt), the first "threshold" of the hard scattering process is at ptH ~ mb

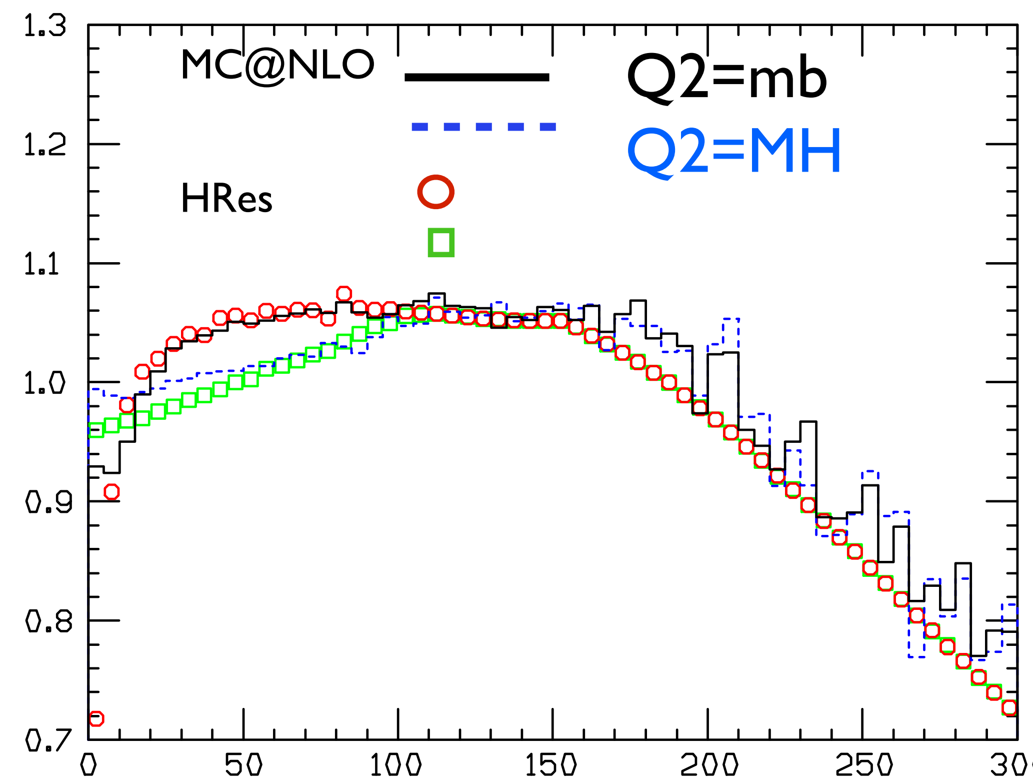
$$|\mathcal{M}(t+b)|^2 = |\mathcal{M}(t)|^2 + \left[2Re\mathcal{M}(t)\mathcal{M}^\dagger(b) + |\mathcal{M}(b)|^2\right]$$

high scale — low scale

M. Grazzini, H. Sargsyan, arXiv:1306.4581

- 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

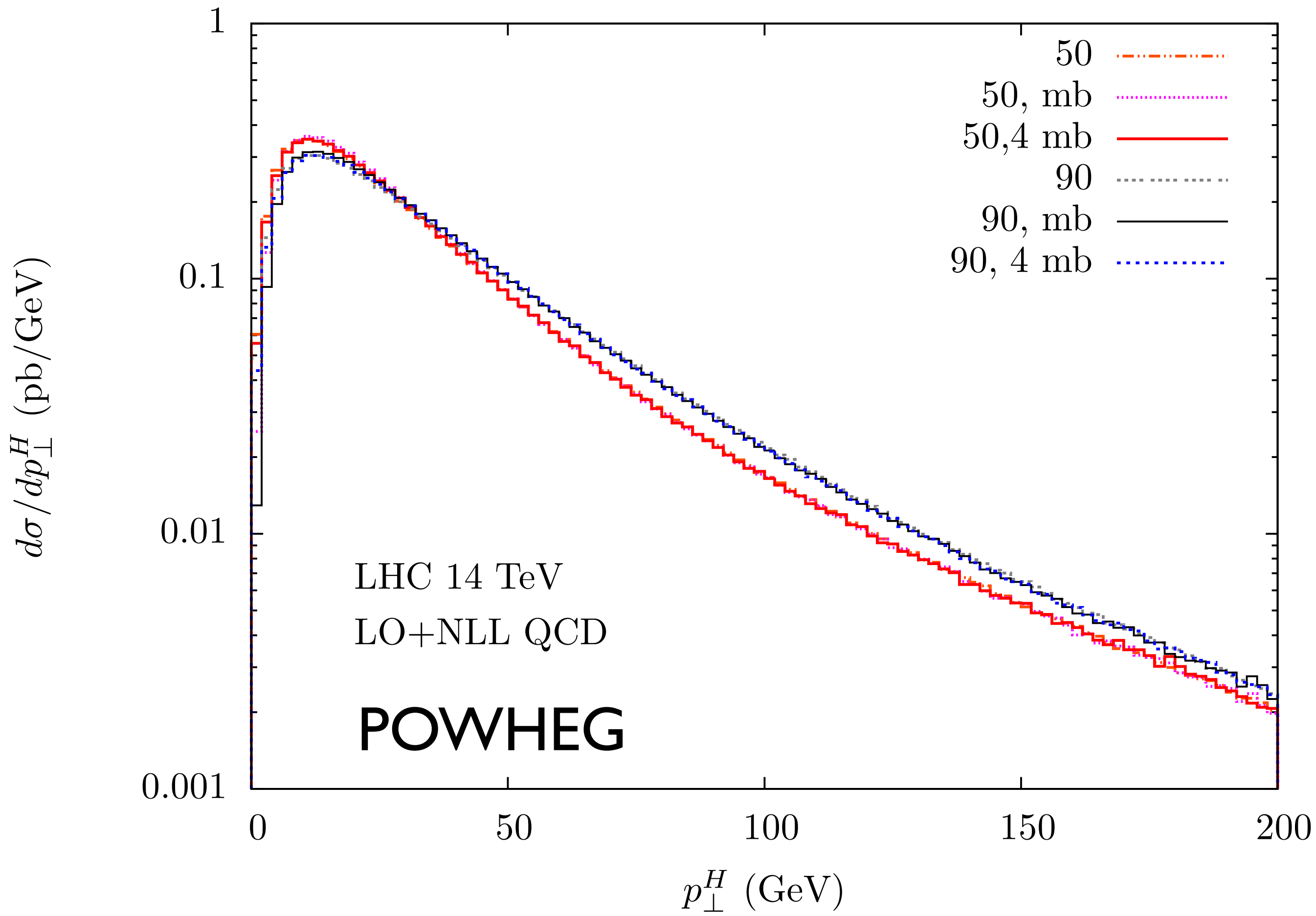


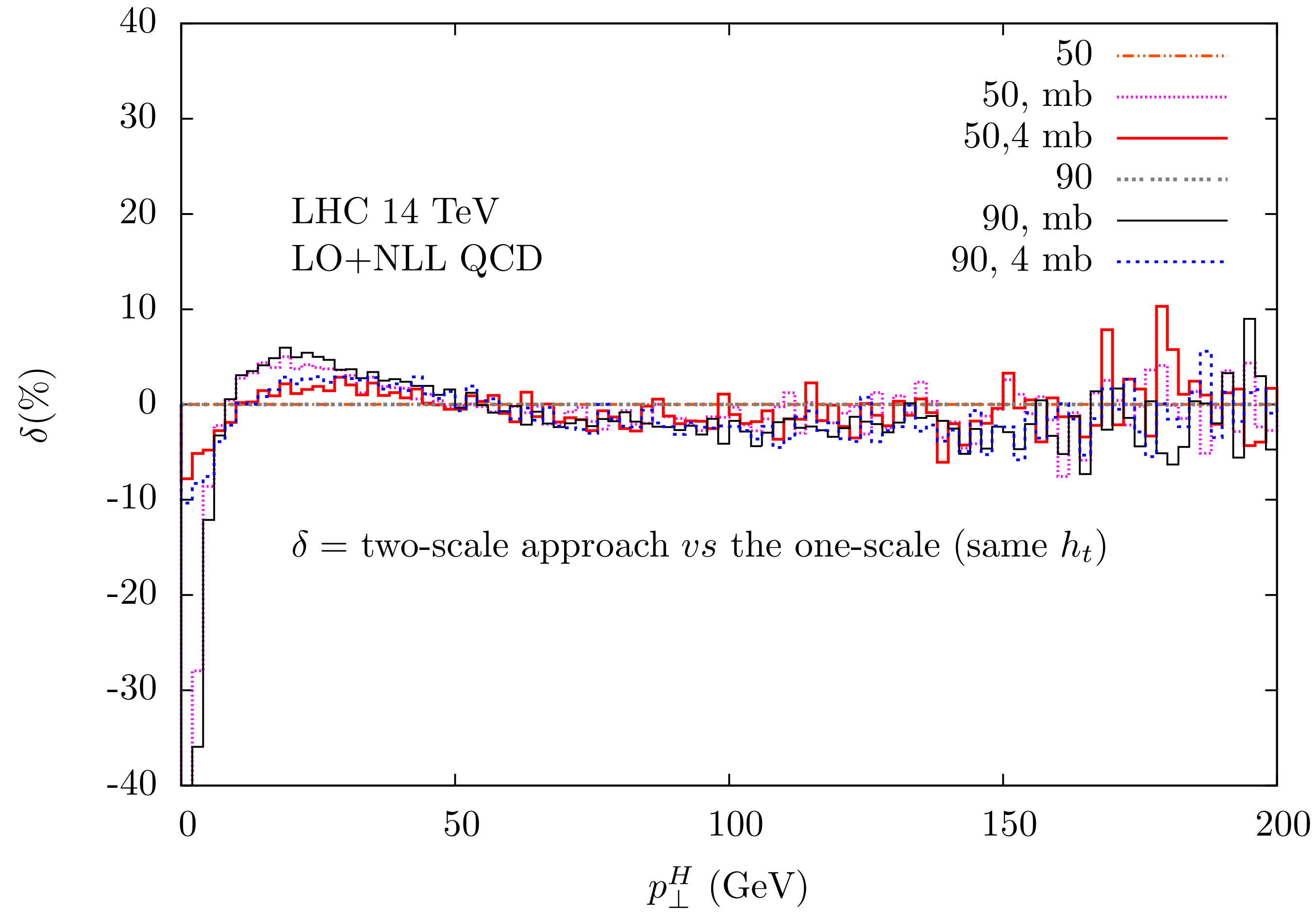


- good agreement in the comparison of (MC@NLO, POWHEG) *vs* HRes

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

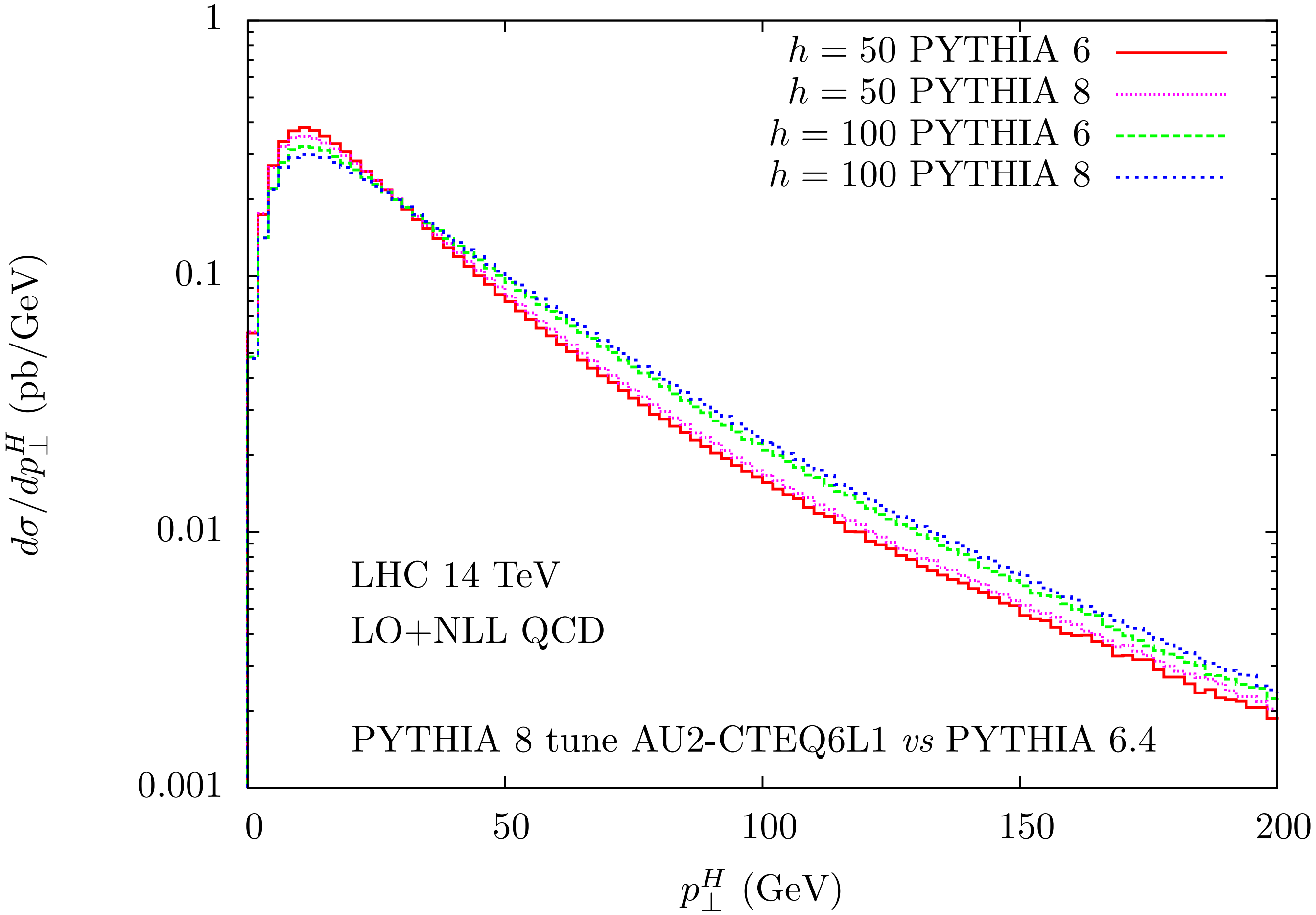
POWHEG comparison of two-scales *vs* one-scale approaches

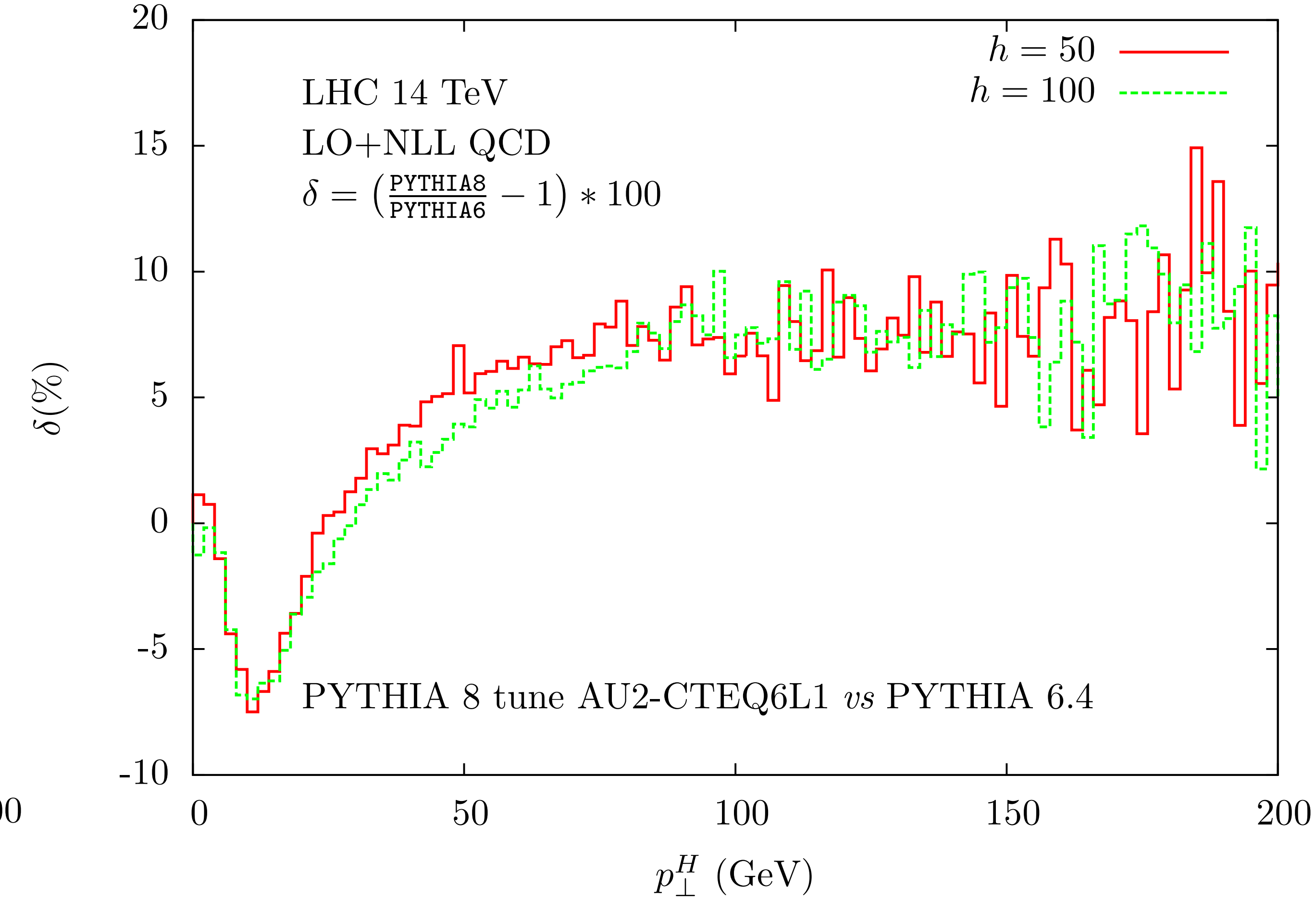




- *ht*: 50 GeV (from helicity analysis) and 90 (from tuning with HRes)
  hb: 4 mb (from helicity analysis) and mb (as in HRes)
- in the SM the top-quark amplitude is dominant and thus the choice of *ht* is crucial for the shape
- differences appear in the low (ptH<10 GeV) and in the intermediate (20<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)

Higgs production via gluon fusion in POWHEG in the MSSM and in the 2HDM

- Higgs production via gluon fusion in the MSSM available in the POWHEG-BOX directory gg_H_MSSM

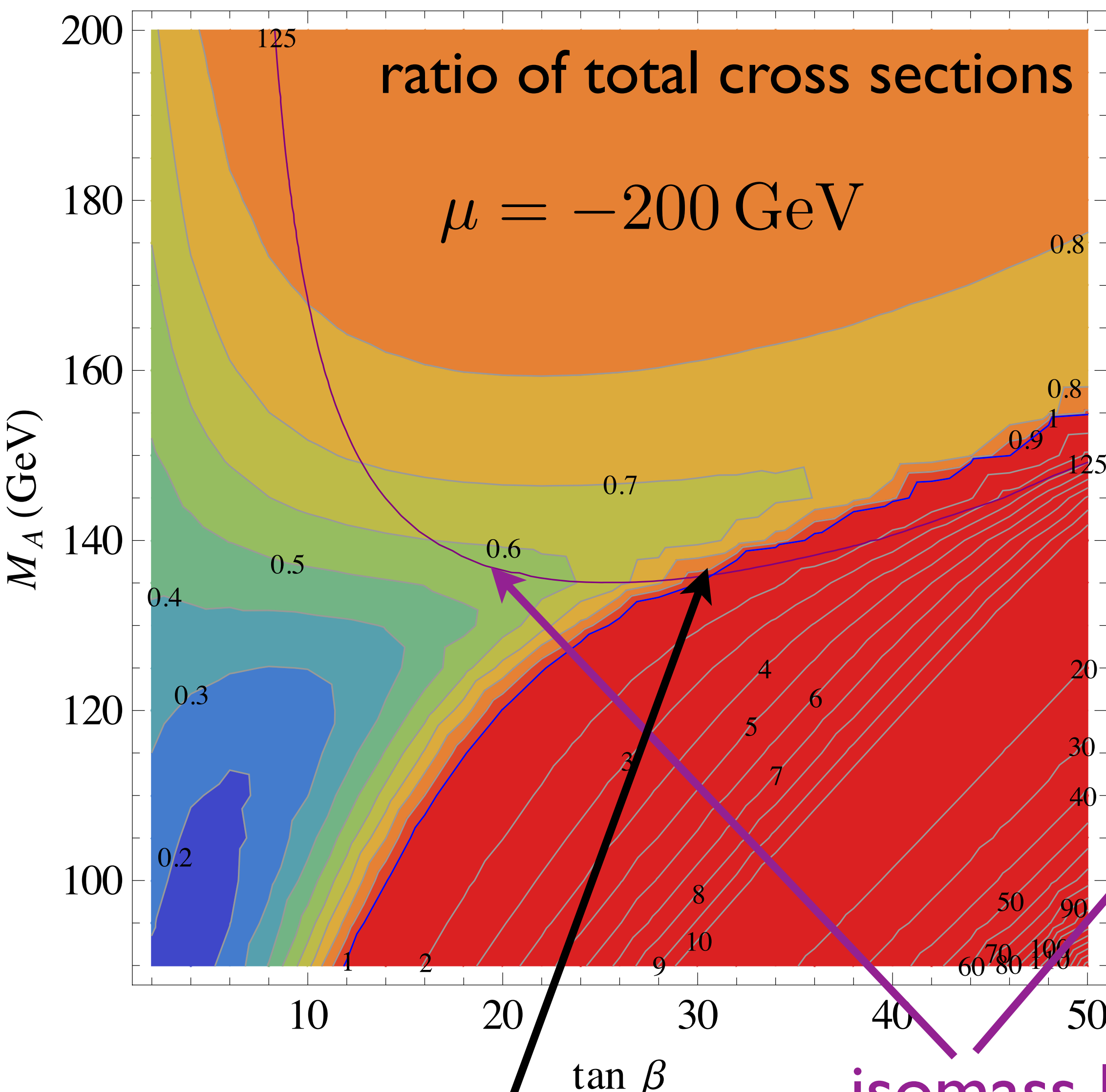
- it requires FeynHiggs to consistently compute the relevant MSSM parameters; a consistent treatment of the Higgs decay, based on PYTHIA, can be obtained using the SLHA format to communicate all the MSSM parameters

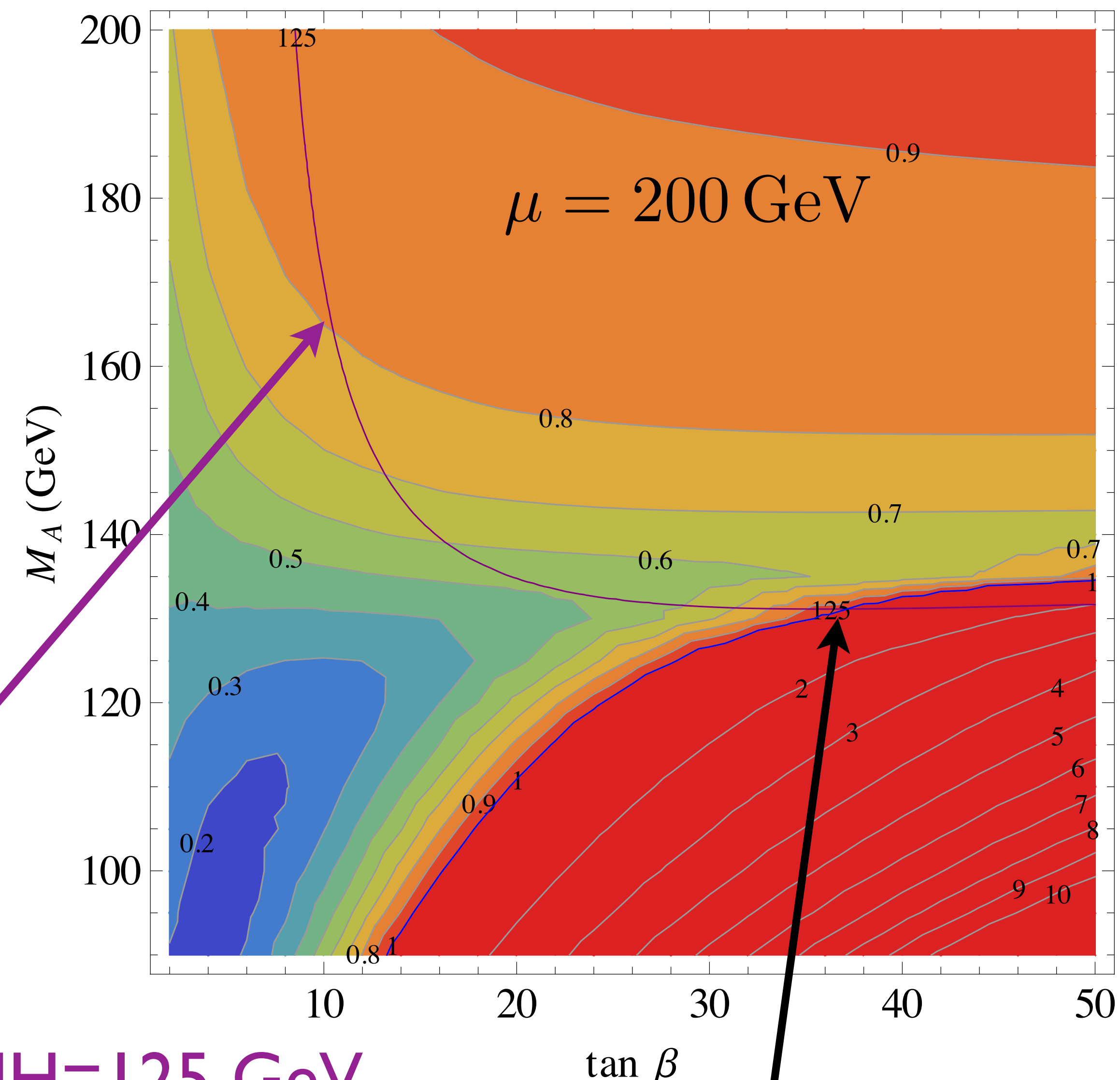
- Higgs production via gluon fusion in the 2HDM available in the POWHEG-BOX directory gg_H_2HDM

- it requires HDECAY to consistently compute the total decay width in the 2HDM

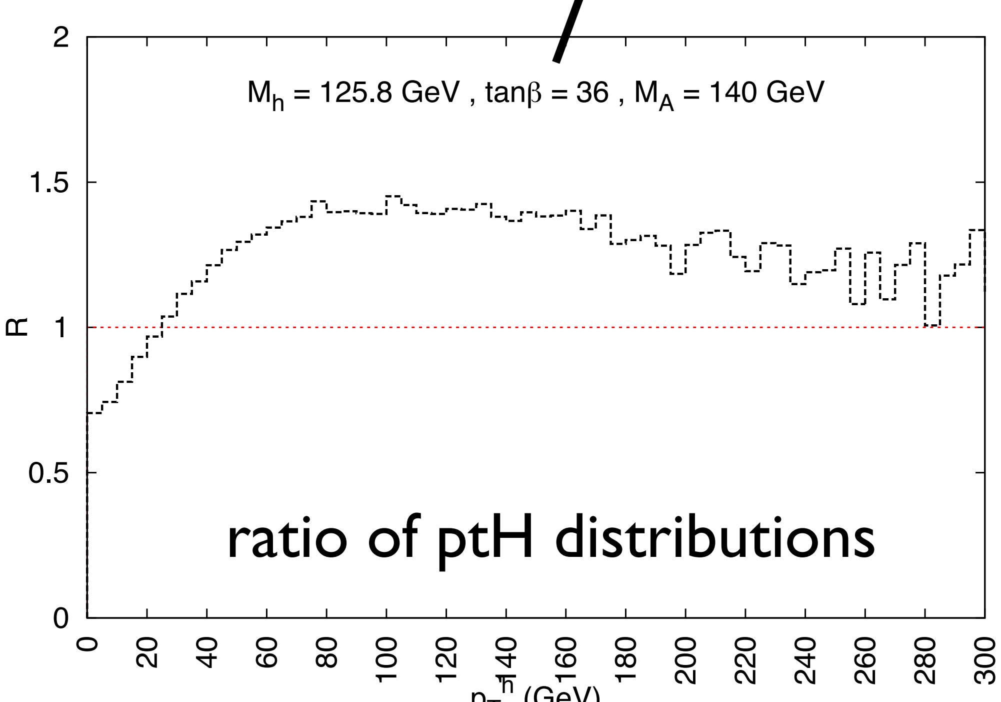
Ratios full MSSM/SM, h_0 production

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

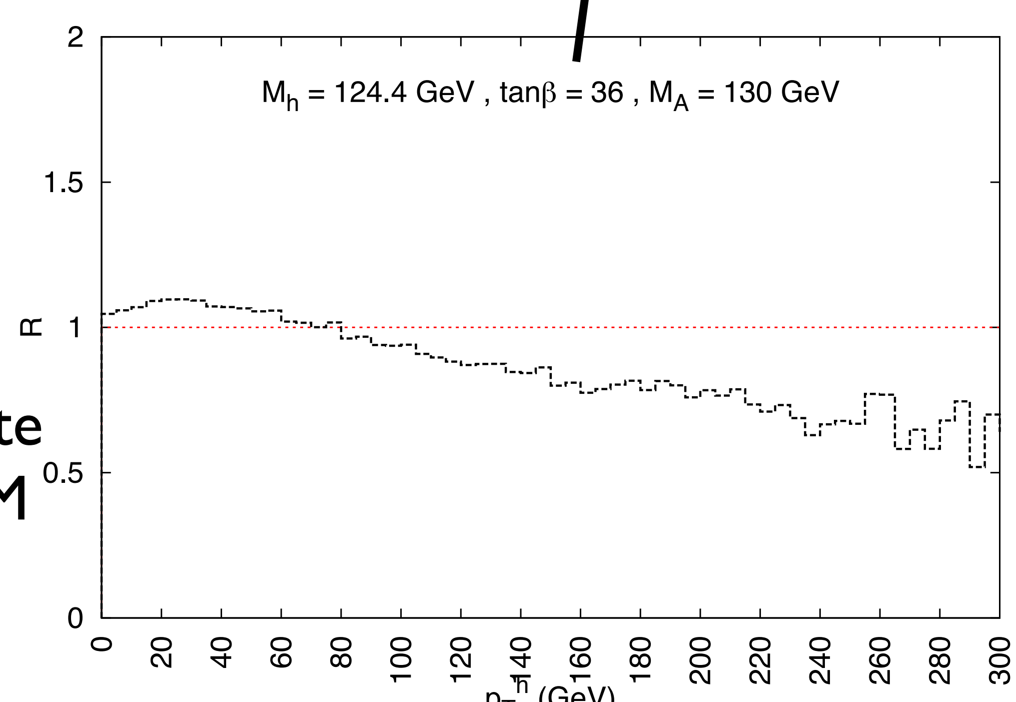




isomass line MH=125 GeV

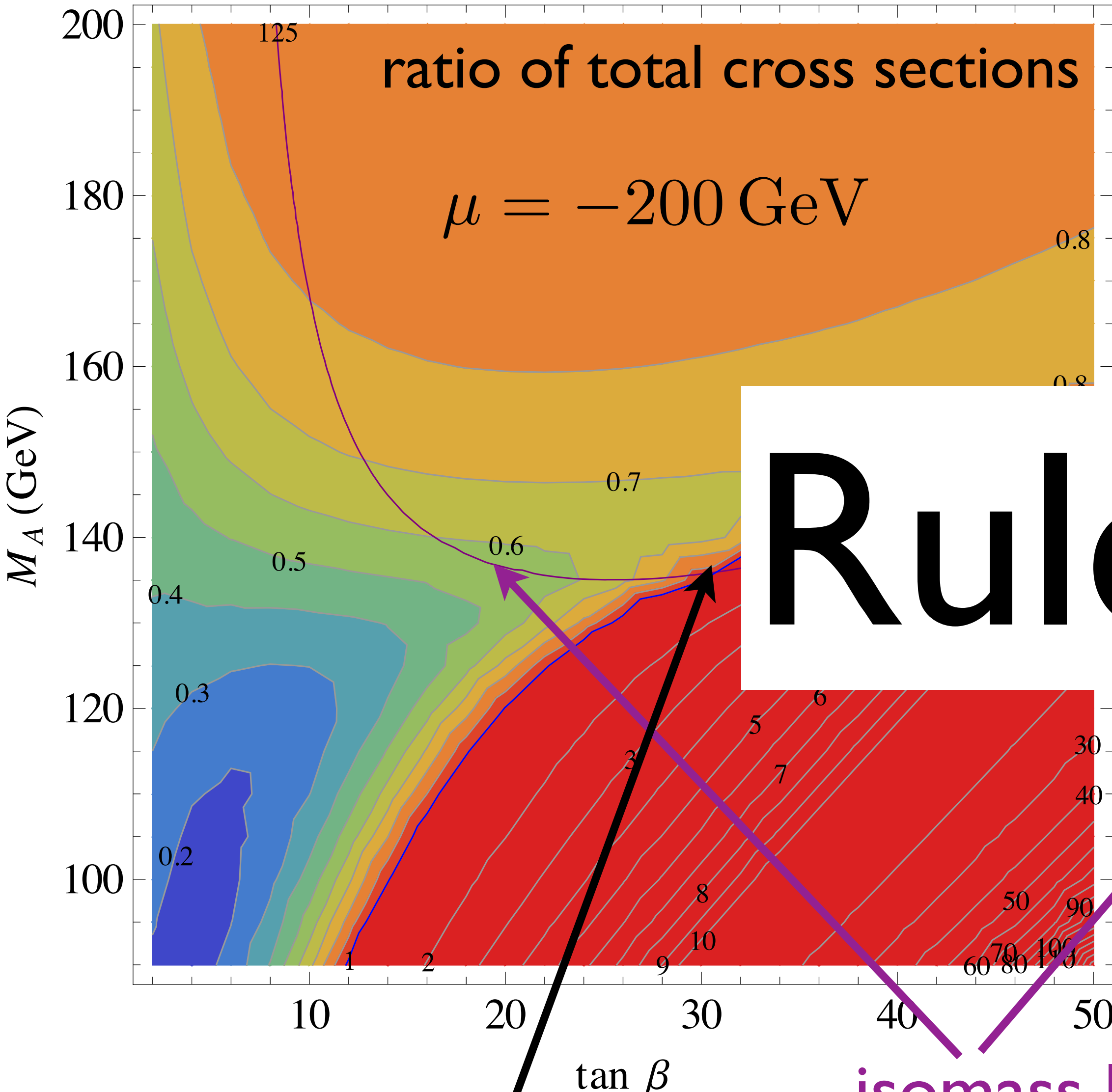


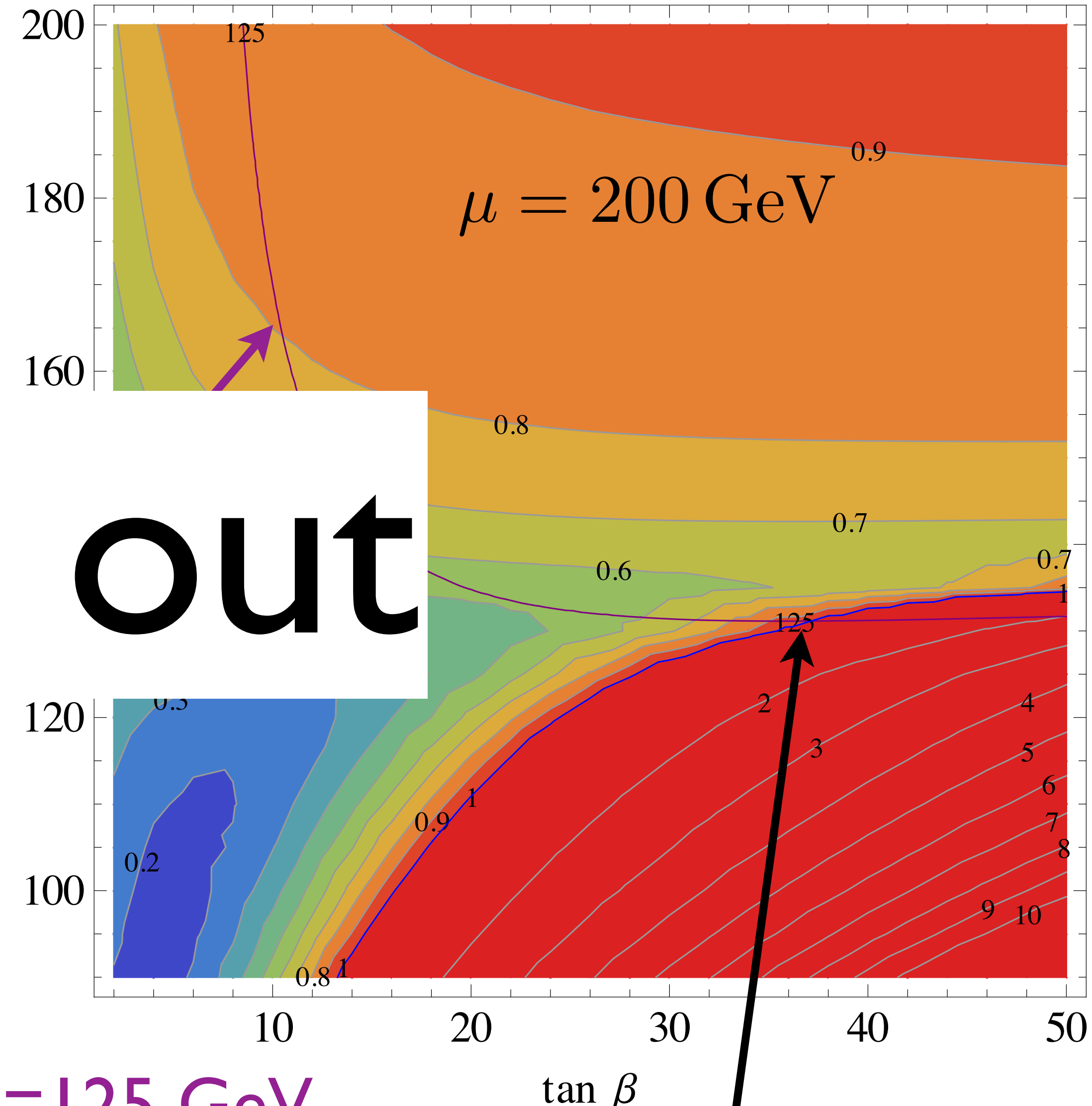
not only the BR
but also the ptH distr
can help to discriminate
between SM and MSSM



Ratios full MSSM/SM, h_0 production

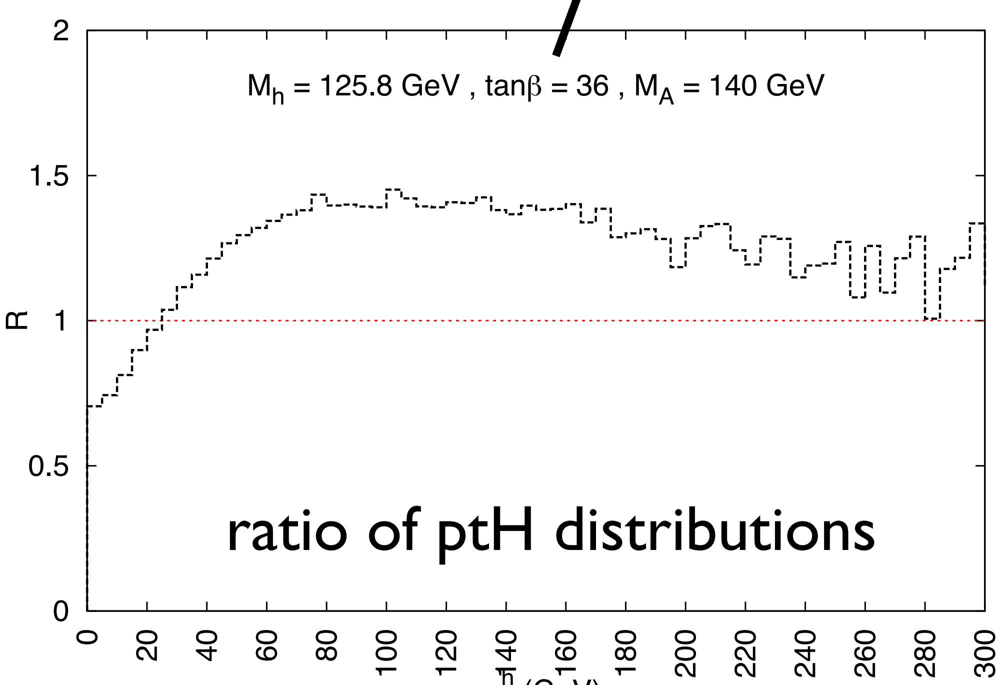
mQ=mU=mD=1000 GeV, X^t=2500 GeV, M_3=800 GeV, M_2=2 M_1=200 GeV



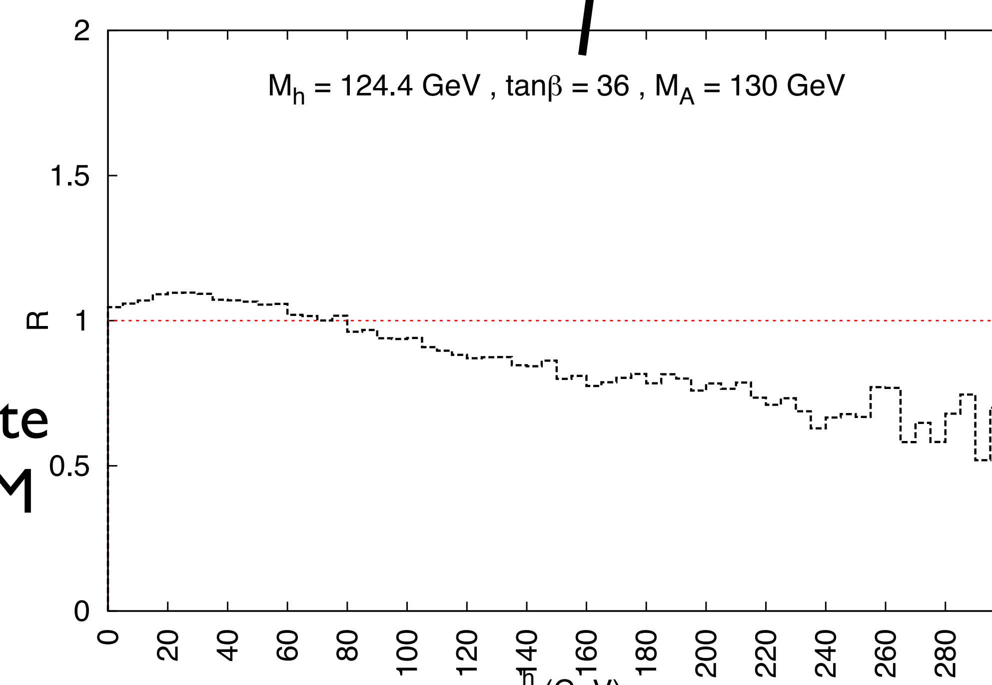


Ruled out

isomass line MH=125 GeV



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



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 tanβ
  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

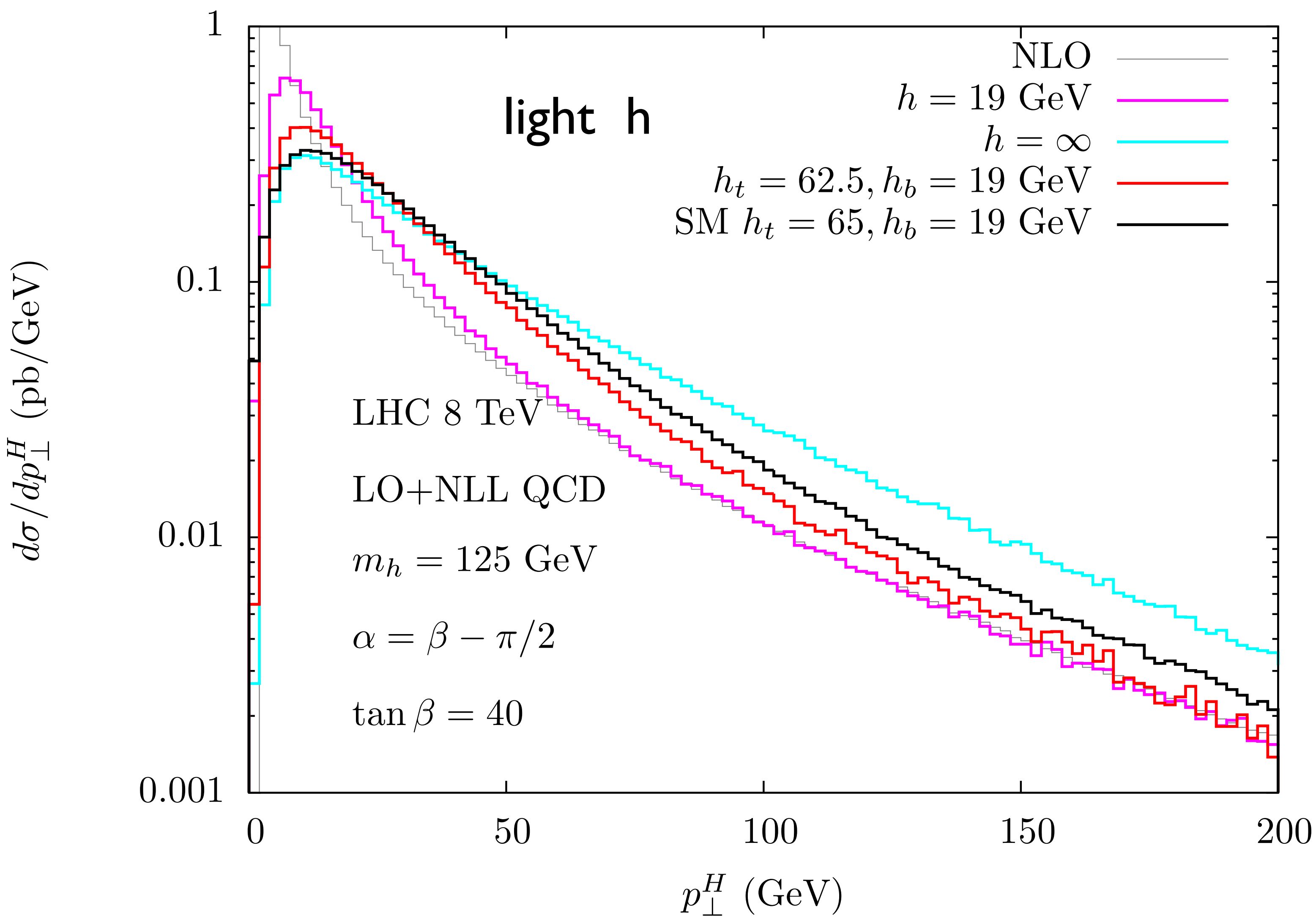
- following a two-scales approach,
  up to which scale can we safely apply the resummation formalism to the top (bottom) contributions ?
  are these scales dependent on MH ?

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

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

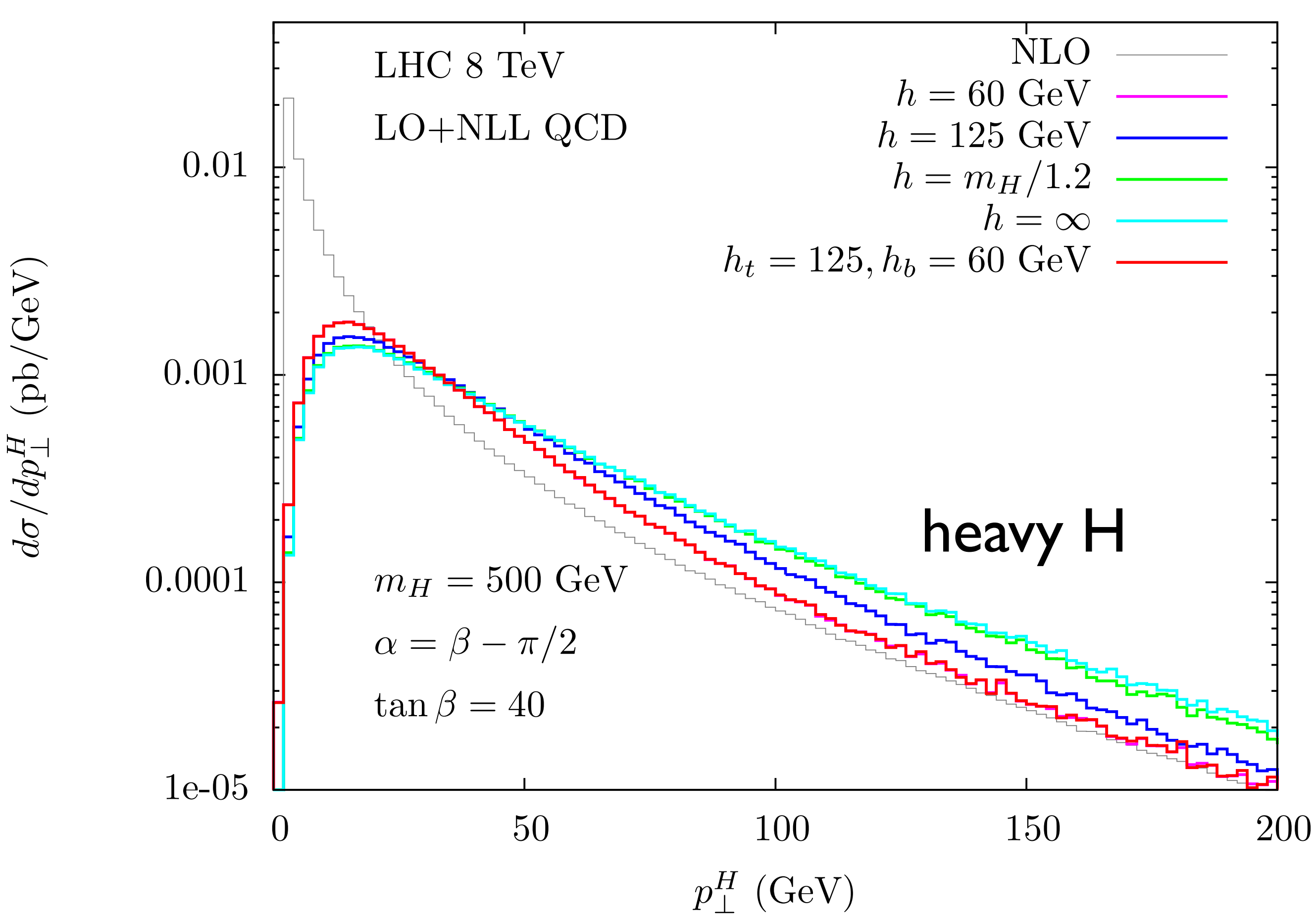
- the couplings of the heavy CP-even scalar H to the fermions instead are tanβ enhanced (down type) or suppressed (up type) w.r.t. the SM ones

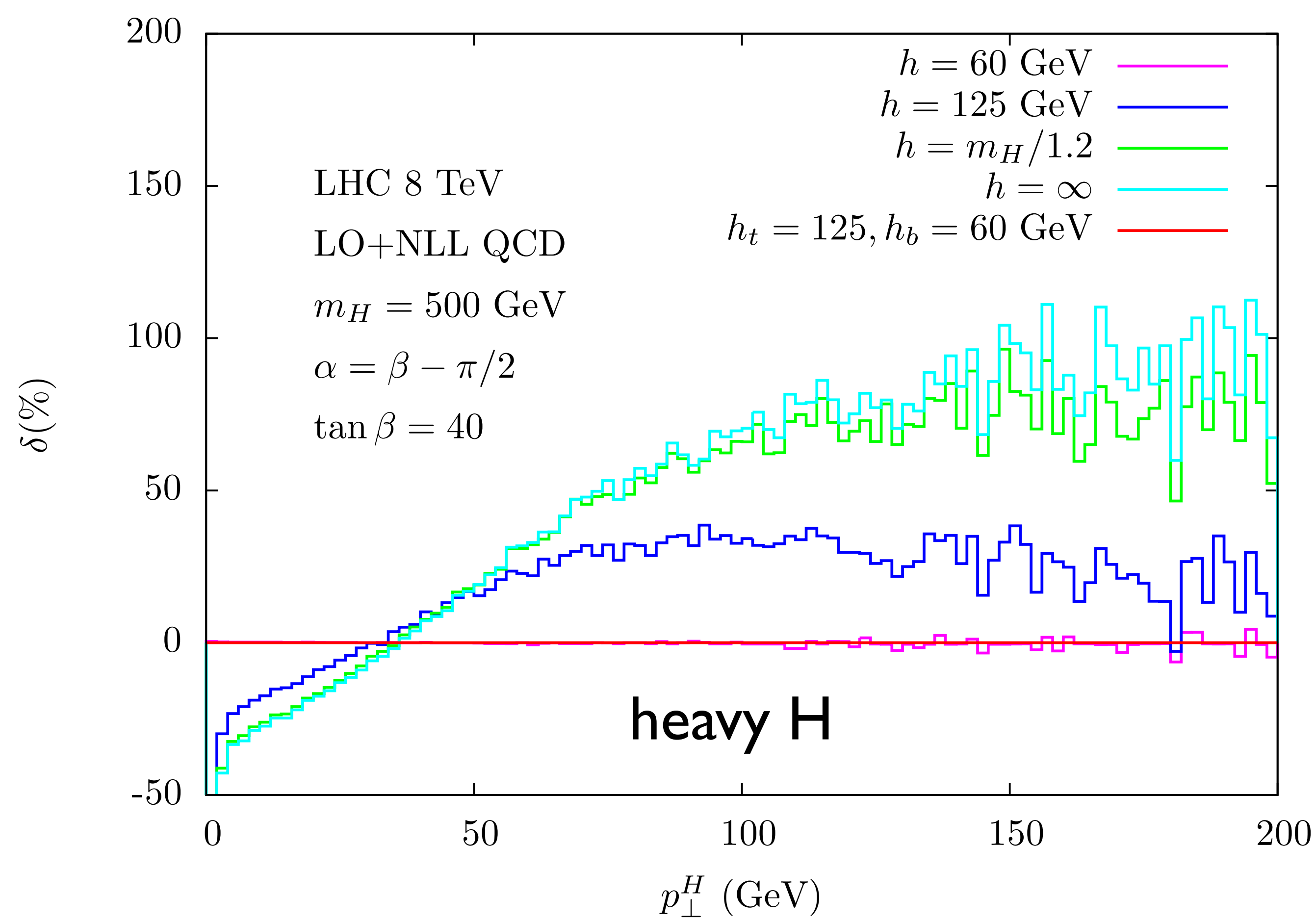


- in this decoupling limit the light CP-even scalar is SM-like (cfr red *vs* black)

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 two scales represents the most conservative recipe developed so far
  in this specific example *ht*=125 GeV and *hb*=60 GeV (red line)
- 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

- the enhanced role of the bottom-quark amplitude requires a two-scale approach to set the resummation scales
  this approach treats in a conservative way the bottom terms in the amplitude

- a one-scale approach may provide a good approximation of the two-scales results:
  in the SM the approximation is, in the worst case, at the 5% level;
  in BSM models the precise value of the 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

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

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

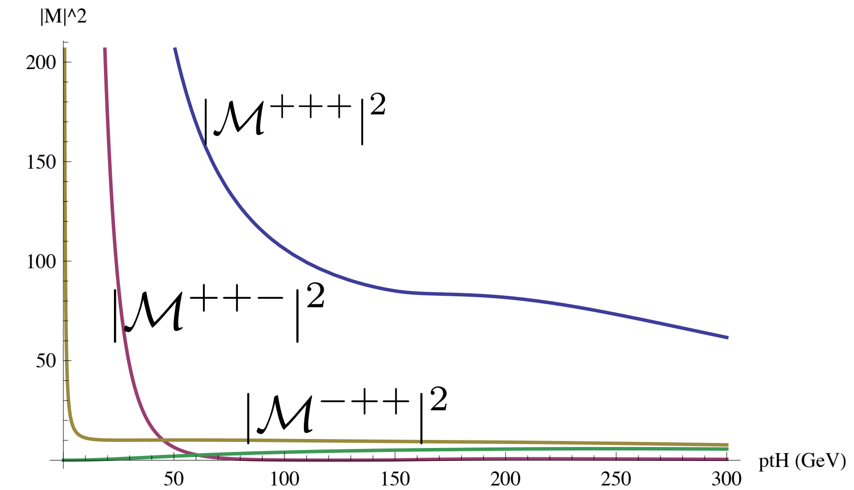
$$C(p_\perp^H) = \frac{|\mathcal{M}_{exact}(p_\perp^H)|^2}{|\mathcal{M}_{div}(p_\perp^H)/p_\perp^H|^2}$$

- 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

- 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

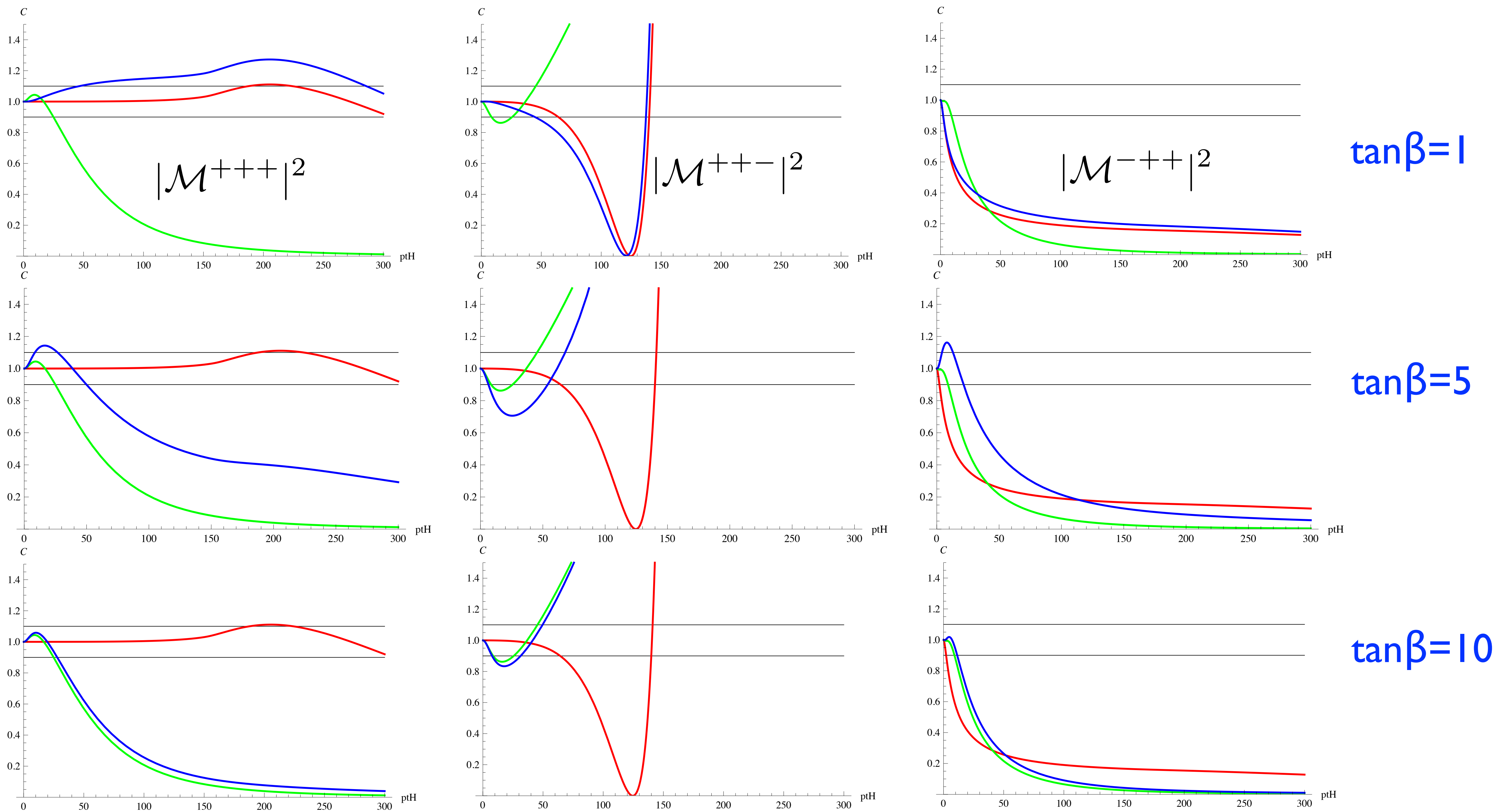


- the results depend on partonic *s*; the choice of the smallest possible *s* allowed value guarantees that the contribution under study has the largest PDF weight at hadron level (small changes when using other choices of *s*)

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

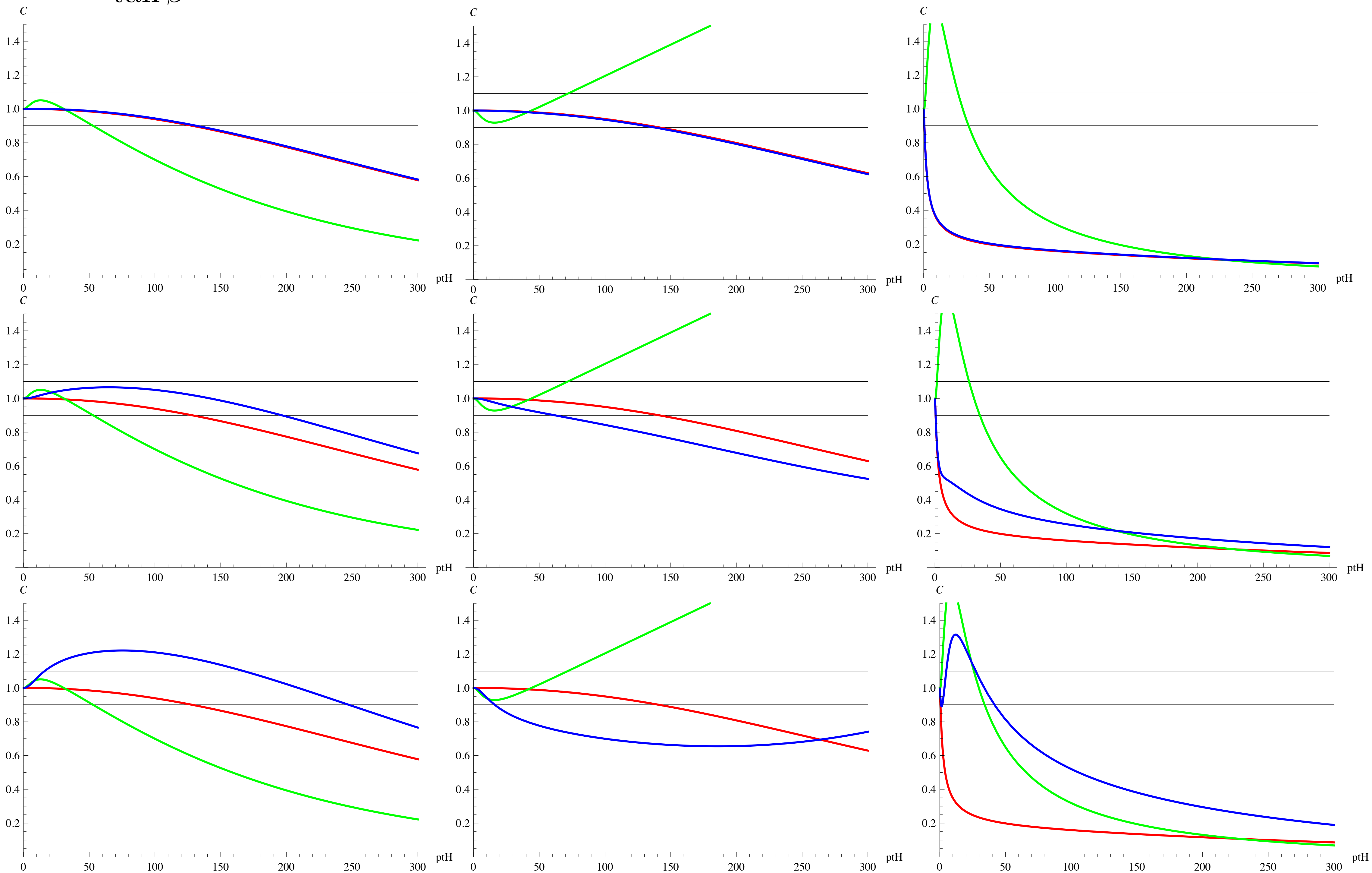


- the single-quark ratios are independent of tanβ
- for the full amplitude, the scale choice at which the collinear approximation fails is dominated by the bottom at large tanβ

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)