Gluons producing Higgs bosons in the SM and in the MSSM

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Beerli, Bucherer, Daleo, Kunszt, CA, ***in preparation***
Beerli, Daleo, CA, arXiv:0803.3065 (accepted in PRL)
Beerli, Daleo, CA, ***JHEP 0705:071,2007***
Beerli, Bucherer, Daleo, Kunszt, CA, ***JHEP 0701:082,2007***

$$M_{HIGGS} = ?$$

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Clinton fights on amid president Obama's first Iraq visit.
Democratic presidential hopeful Hillary Clinton's campaign chief denies she is to concede...

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God's particle found in Geneva
It is a relatively light particle with a mass of 116 GeV.

Just a number away...

- The mass of the Higgs boson may be the only parameter missing to explain everything that we will see at the LHC!
- If the SM is true, this will be the most spectacular triumph of the physicists of the 20th century.

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God's particle found in Geneva. It is not alone!
It is a relatively light particle with a mass of 116 GeV. The top quark is antagonized by mystery particles. It produced only half the expected number of Higgs bosons.

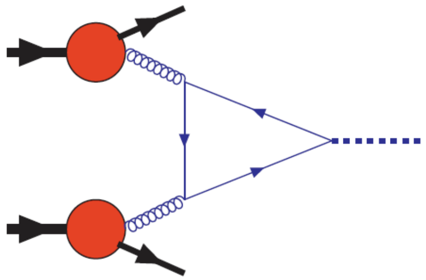
What if
$\sigma_{HIGGS} = 50\% \sigma_{SM}$?

- QCD? Cannot be...two decades long theoretical work must then be all wrong.
- Kaluza-Klein tower of 5-D quark? (Djouadi, Moreau; Falkowski,...)
- “Sweet-spot” supersymmetry? (Kitano, Nomura; Perelstein; Dermisek, Low; Cho;...)
- Higgs dependent Yukawa couplings? (Giudice, Lebedev)
- We shall need to check very many cases!

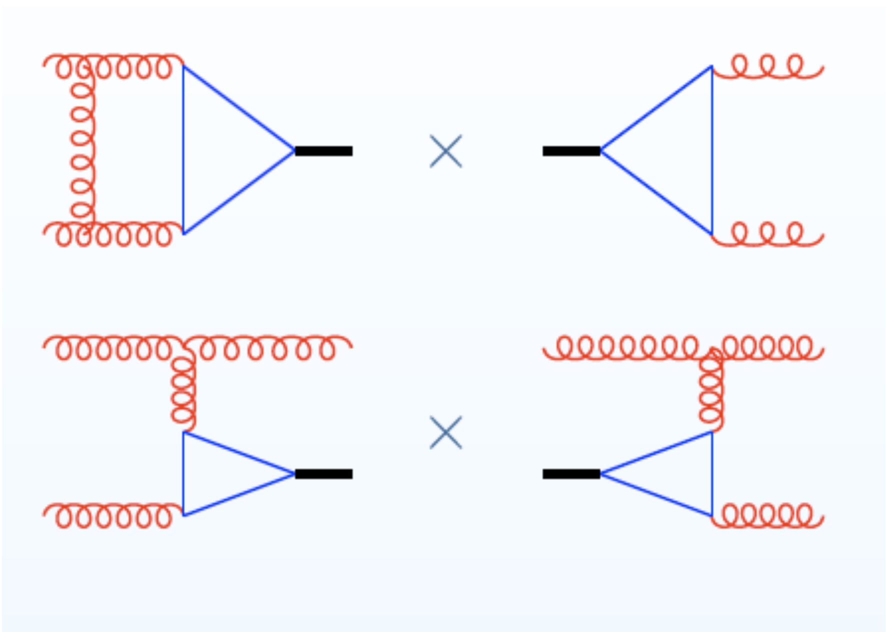
Gluon-fusion cross-section

- A new precision test for ALL models which aspire to explain LHC data...
- If SM cross-section estimate is roughly correct, then it may be measured with a 10-15% precision. Comparable to theory!
- We should be prepared for surprises in the Higgs sector! All SM extensions modify this one way or another! Can we achieve good enough theoretical precision in BSM?

How tough was the SM?



Starting with a loop already at leading order!

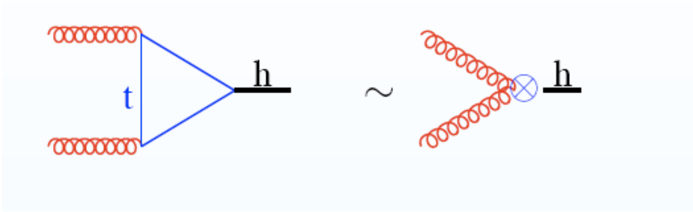


A really tough two-loop calculation at NLO.

Pioneering work by Spira, Djouadi, Gradenz, Zerwas.

Large: (70-100%) x LO (Spira et al, Dawson)

NNLO only in the heavy top approximation (Guenther's talk)



How tough is BSM?

- New coloured and massive particles will circulate in the gluon-fusion loops
- Very heavy ones may decouple (not always)
- For topologically equivalent Feynman diagrams, results can be lifted from (or be computed a la) SM.
- BSM models can though be more complicated....

LHC Olympics...

@ Hoenggerberg!

- Can we compute the the gluon fusion cross-section in the toughest BSM scenario that we can think of?
- Are known multi-loop methods up to the task?
- How well do we understand field theory aspects of new models and their symmetries which are relevant at higher orders? Renormalization?

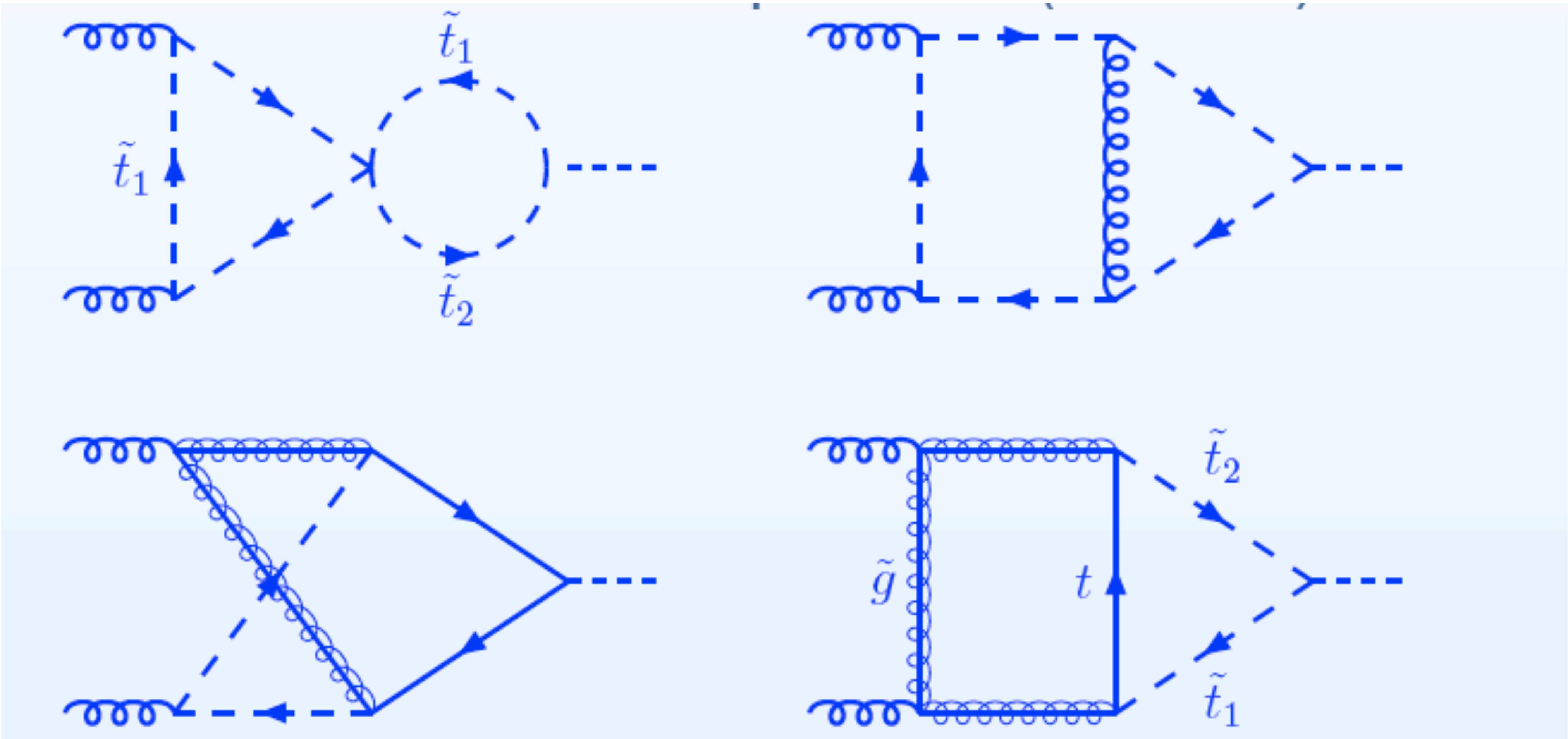
MSSM: a computing nightmare

- QCD corrections should be large
- More than one massive particles may circulate in the loops.
- Consistent regularization/renormalization
- A challenge for any analytic computational method already at NLO
- Disparate mass-scales e,g, Mbottom, Mhiggs, Mgluino

Earlier calculations

- Effective theory for light Higgs boson with respect to quarks, squarks and gluino.
  Harlander, Steinhauser
- No ET for a heavy Higgs, large tanb.
- Two-loop amplitude with squarks and quarks only. CA, Beerli, Bucherer, Daleo, Kunszt; Aglieti, Bonciani, Degrassi, Vicini
- NLO cross-section with squark and quarks only Muhlleitner, Spira; Bonciani, Degrassi, Vicini

The difficult diagrams



Many different masses in propagators...no analytic approach

Recall large mass hierarchy of bottom quark and sparticles

Numerical N...LO fully differential cross-sections

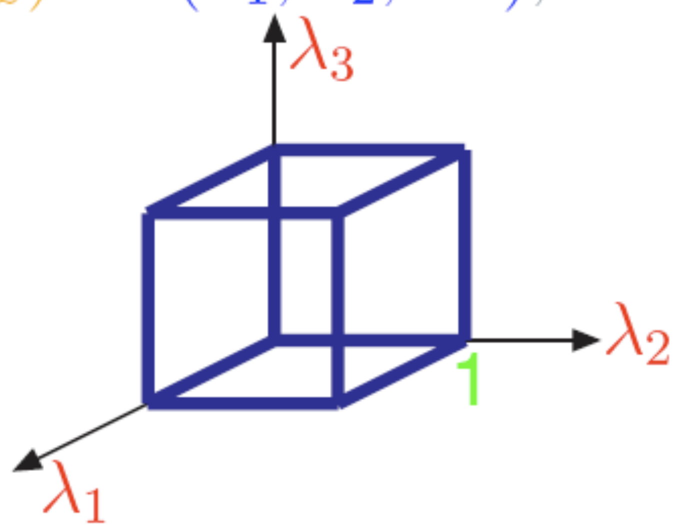
CA, Melnikov, Petriello; Lazopoulos, Melnikov, Petriello; CA, Beerli, Daleo

- Works in dimensional regularization
- Infrared divergences in phase-space integrals are found and simplified automatically. Integration boundaries are arbitrary.
- Loop amplitudes are computed (almost) the same. Automated contour deformation to avoid threshold singularities.
- Blind to the Lagrangian peculiarities

Phase-space integrations

- Singularities have a very complicated form in momentum space (beyond NLO)
- Map phase-space volume to the unit hypercube

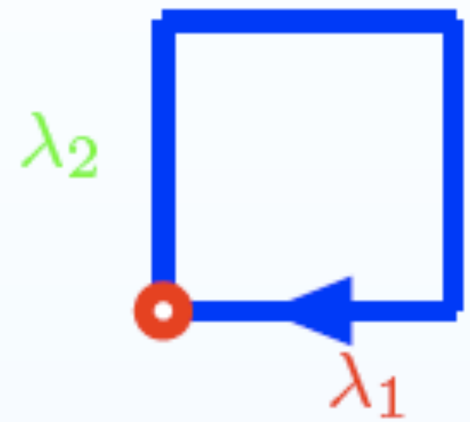
$$(E, p_x, p_y, p_z) \rightarrow (\lambda_1, \lambda_2, \ldots), \quad 0 \leq \lambda_i \leq 1$$



- Simple geometry leads to simple mathematics and automatization
- Easy to spot the singularities (usually at the edges of phase-space)

Factorized singularities

Singularity due to a single variable reaching independently a boundary:

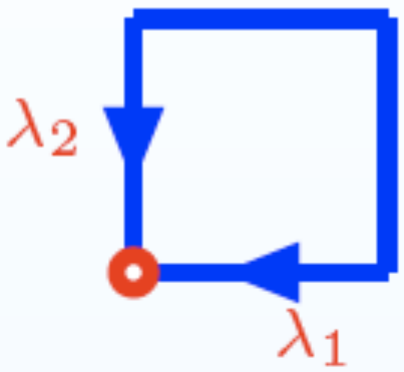


$$: \quad \frac{f(\lambda_1, \lambda_2)}{\lambda_1^{-1+\epsilon}}$$

Can be expanded after a trivial subtraction

$$\begin{aligned}
\int_0^1 d\lambda_1 \frac{f(\lambda_1, \ldots)}{\lambda_1^{1-\epsilon}} &= \int_0^1 d\lambda_1 \frac{f(0, \ldots)}{\lambda_1^{1-\epsilon}} + \int_0^1 d\lambda_1 \lambda_1^{\epsilon} \left[\frac{f(\lambda_1, \ldots) - f(0, \ldots)}{\lambda_1} \right] \\
&= \frac{f(0, \ldots)}{\epsilon} + \int_0^1 d\lambda_1 \lambda_1^{\epsilon} \left[\frac{f(\lambda_1, \ldots) - f(0, \ldots)}{\lambda_1} \right]
\end{aligned}$$

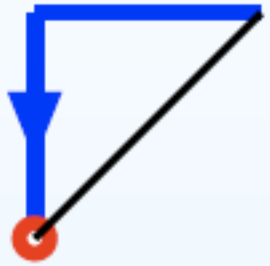
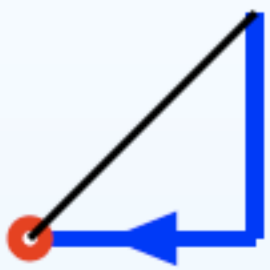
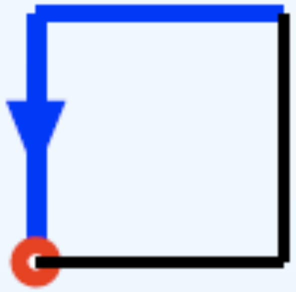
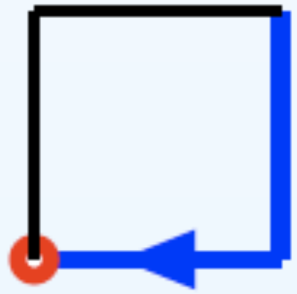
Overlapping singularities



: $\dfrac{\lambda_1^\epsilon \lambda_2^\epsilon}{(\lambda_1+\lambda_2)^2} f(\lambda_1, \lambda_2)$

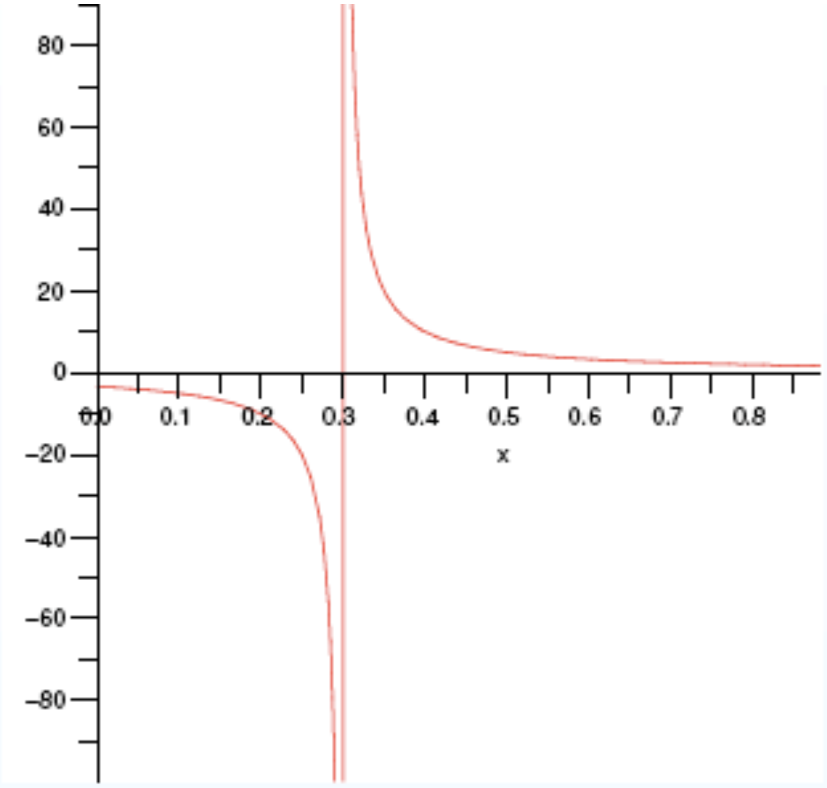
can be factorized

Binoth, Heinrich; Denner, Roth; Hepp

=  +  =  + 

$$= \int_0^1 d\lambda_1 d\lambda_2 \frac{1}{\lambda_1^{-1+\epsilon}} \frac{f(\lambda_1, \lambda_2\lambda_1)}{(1+\lambda_2)^2} + \int_0^1 d\lambda_1 d\lambda_2 \frac{1}{\lambda_2^{-1+\epsilon}} \frac{f(\lambda_1\lambda_2, \lambda_2)}{(1+\lambda_1)^2}$$

Threshold singularities



- Singular inside the integration region; not the edges

$$I = \int_0^1 dx \frac{1}{x - a - i0},$$

- Regulator $i0$ is not good enough for a numerical evaluation.
- Choose a different contour $C : z = x - i\lambda x(1-x)$

$$\begin{aligned} I &= \int_C dz \frac{1}{z-a} = \int_0^1 dx \frac{\partial z}{\partial x} \frac{1}{z-a} \\ &= \int_0^1 dx \left[1 + i\lambda\left(1 - \frac{x}{2}\right)\right] \frac{1}{x - a - i\lambda x(1-x)} \end{aligned}$$

- Suitable for numerical integration!

Contour deformation for Feynman parameters

Nagy, Soper

- For a Feynman integral

$$\int_0^1 \frac{dx_1 \dots dx_n}{[Q(x_i) + i0]^{n+\epsilon}}$$

- choose a path

$$C: \quad z_i = x_i + i\lambda x_i (1 - x_i) \frac{\partial Q}{\partial x_i},$$

- where Q has a positive imaginary part

$$Q(z_i) \quad = \quad Q(x_i) + \left(i\lambda x_i (1 - x_i) \frac{\partial Q}{\partial x_i} \right) \frac{\partial Q}{\partial x_i} + \mathcal{O}(\lambda^2)$$

A "natural" MSSM scenario

Light stop;
Large stop
mass-splitting

$$m_{\tilde{t}_1} = 150\,\mathrm{GeV} \qquad 220\,\mathrm{GeV} < m_{\tilde{t}_2} < 570\,\mathrm{GeV}$$

$$m_{\tilde{b}_1} = 350\,\mathrm{GeV} \qquad m_{\tilde{b}_2} = 370\,\mathrm{GeV}$$

$$m_{\tilde{g}} = 500\,\mathrm{GeV}$$

$$m_h = 115\mathrm{GeV} \qquad 280\mathrm{GeV} < m_H < 450\mathrm{GeV}$$

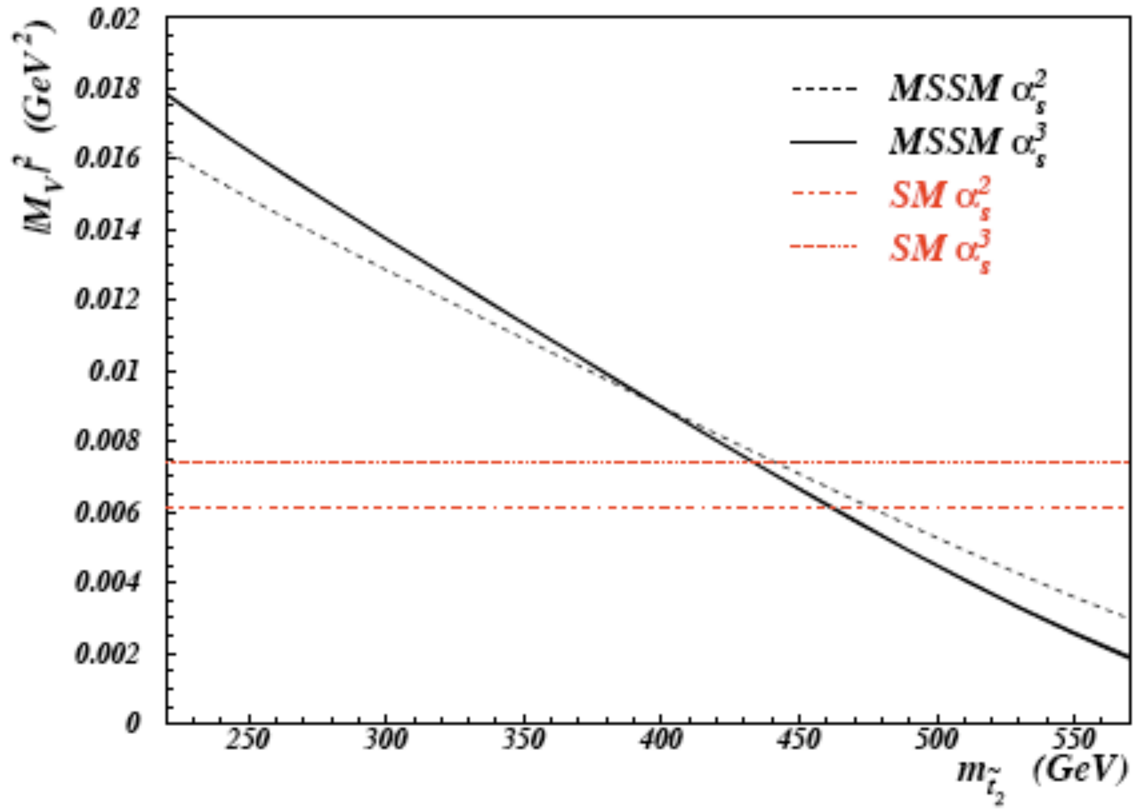
$$\tan\beta = 20 \qquad \mu = 300\,\mathrm{GeV}$$

aka "gluophobic"
Carena et al,
Harlander,
Steinhauser; Spira,
Muhlleitner, Djouadi

Reduced fine-tuning in the MSSM
(Dermisek, Low; Kitano, Nomura; Perelstein; ...)

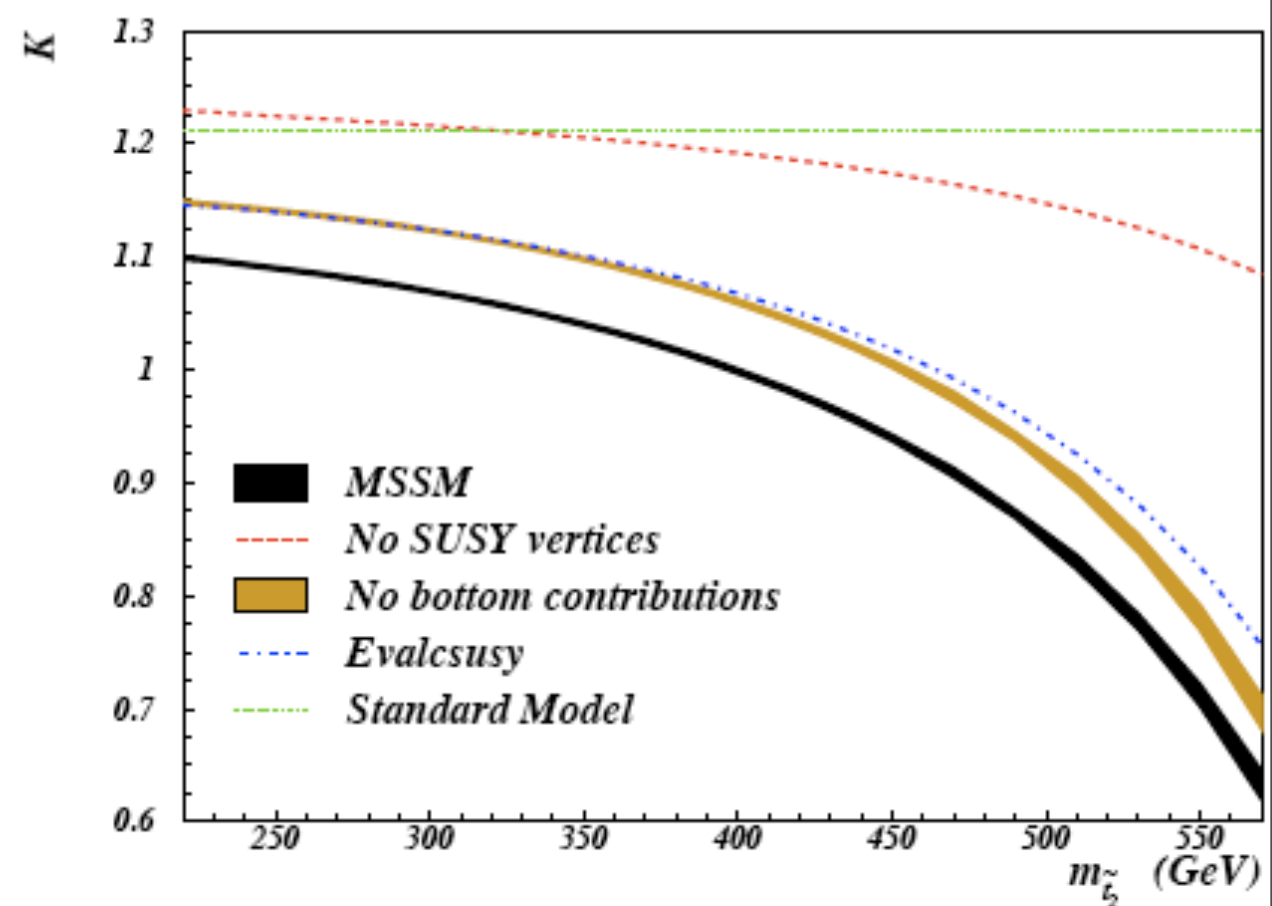
MSSM ggh two-loop amplitude

Beerli, Daleo, CA



Large stop mass splitting decreases the ggh interaction strength

Diagrams with gluinos/ quartic squark couplings cannot be ignored. Very good description from ET



MSSM ggH two-loop amplitude

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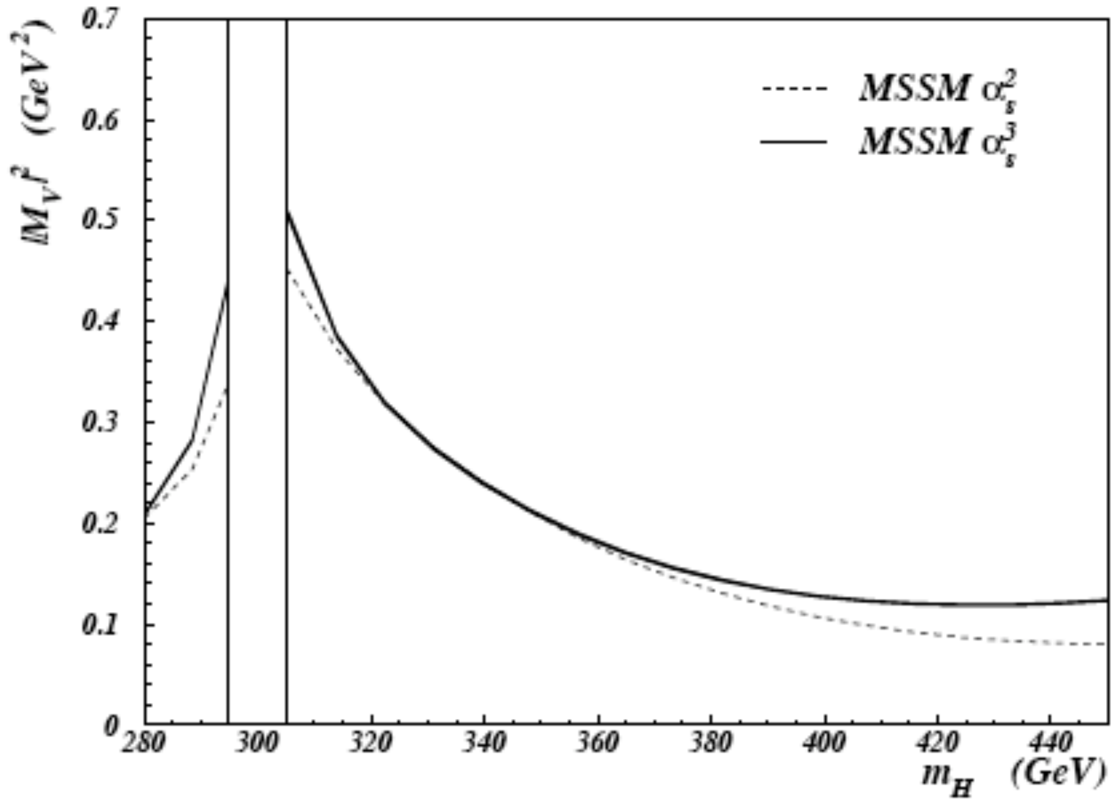
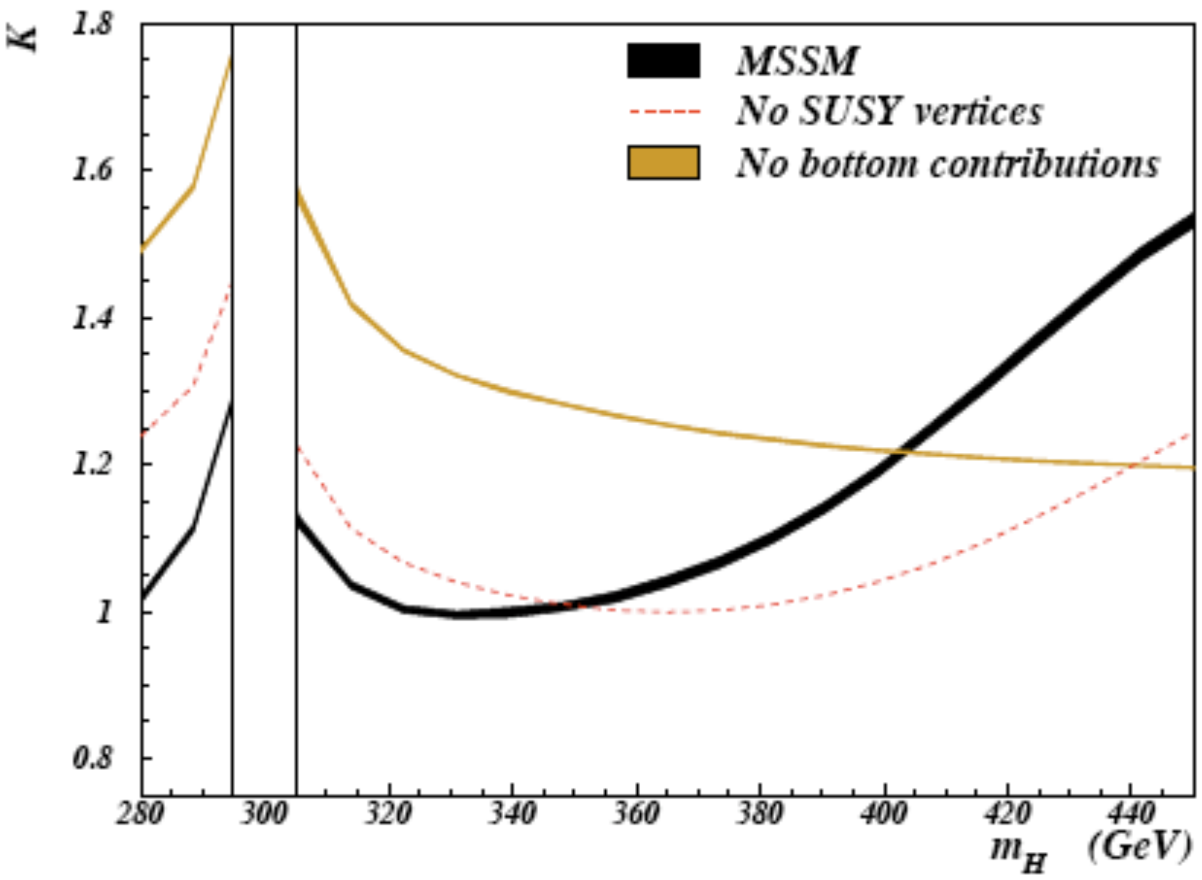


Bottom contributions cannot be ignored

Improved understanding of our numerical method.



Renormalization schemes

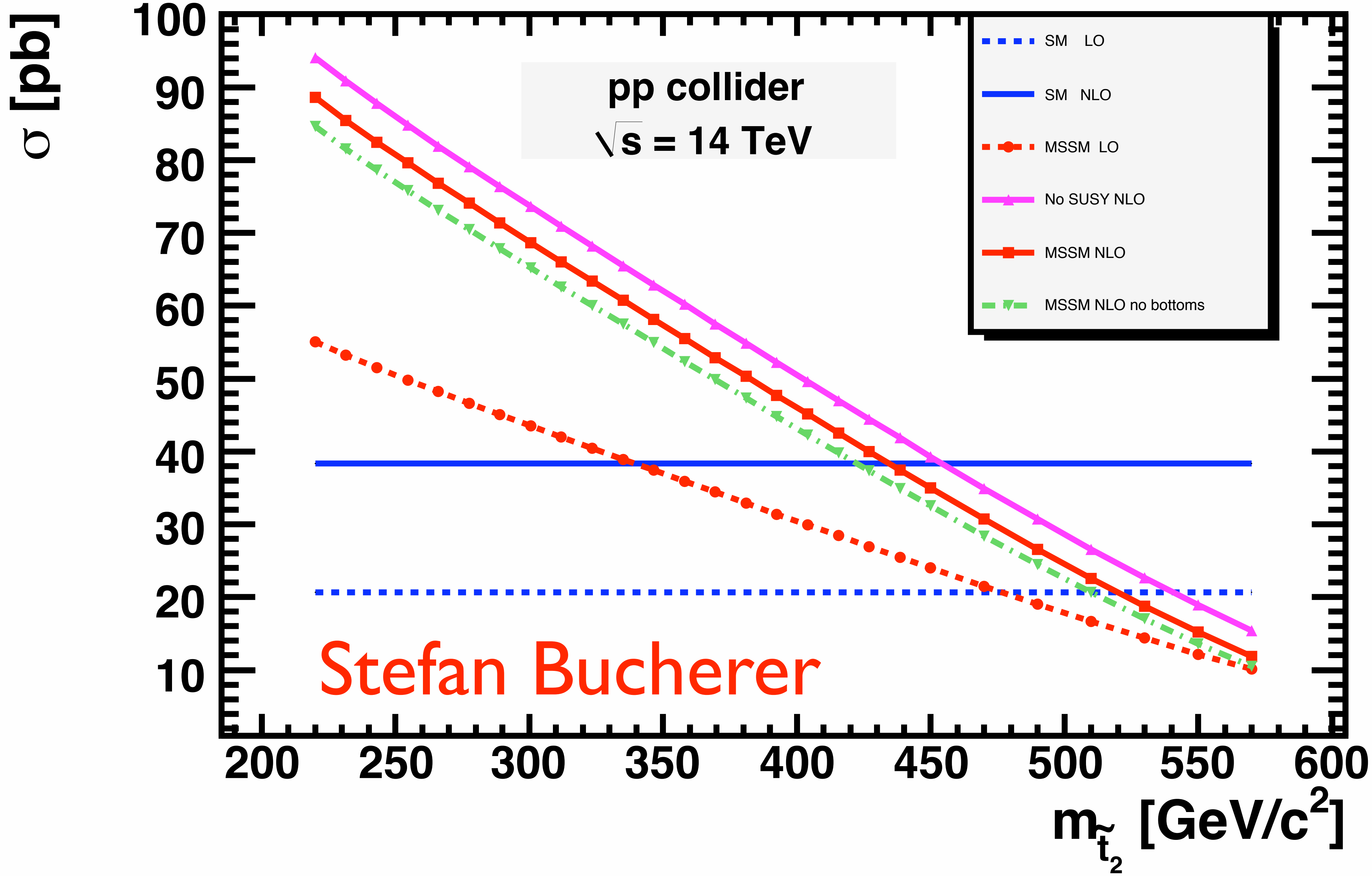
- We used
  dimensional regularization,
  dimensional reduction,
  four dimensional helicity scheme

Dim Red due to A. Daleo with very minor help from the rest of us

- Found universal shift needed in the higgs-squark-squark coupling for dim. reg.
- Encountered new evanescent operator required in less symmetric theories, e.g. the SM
- Inconsistent result for the SM amplitude in FDH.

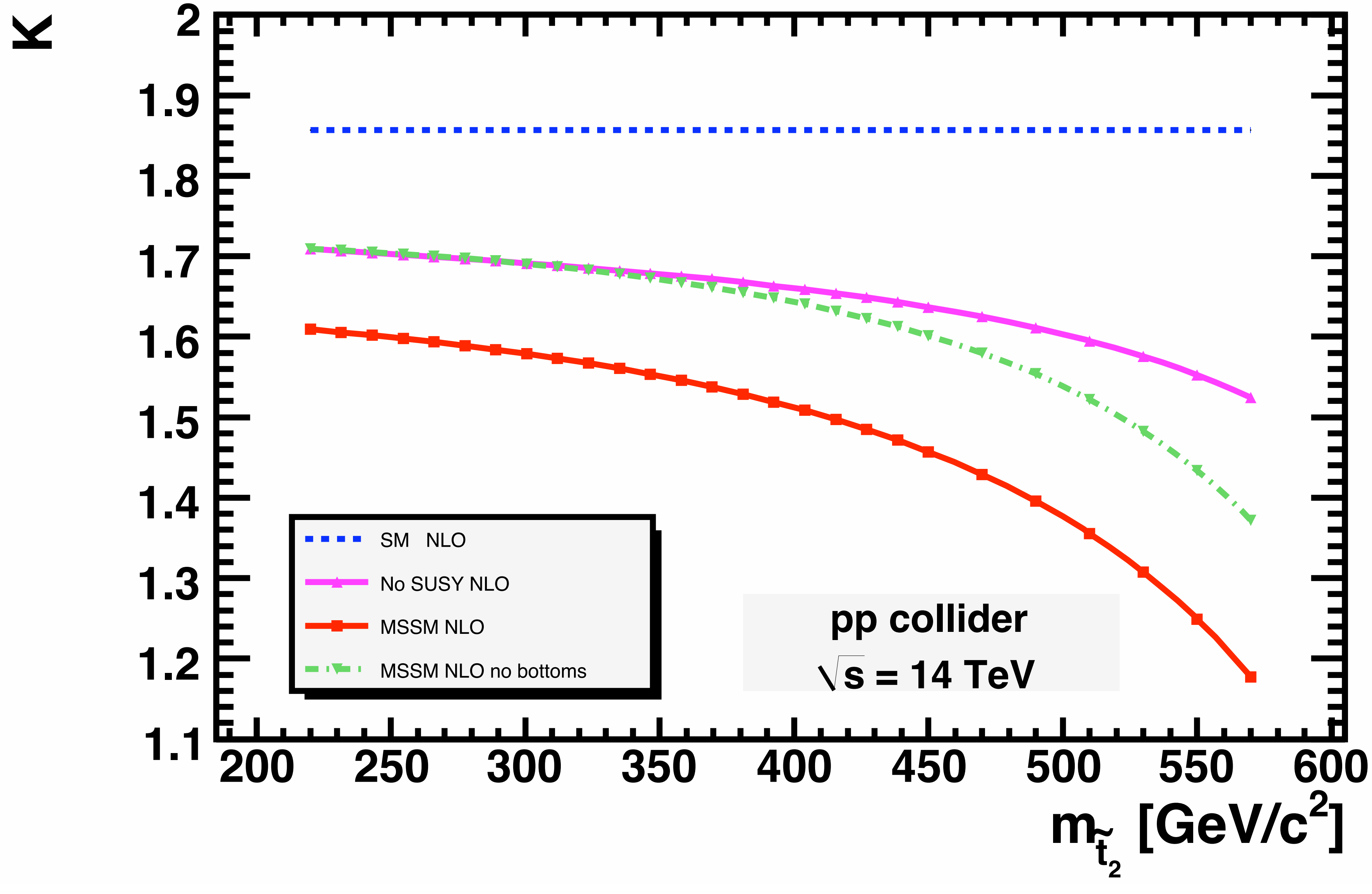
Total NLO cross-section

Preliminary



Inclusive NLO K-factor

Preliminary



Stefan Bucherer

Total NLO cross-section

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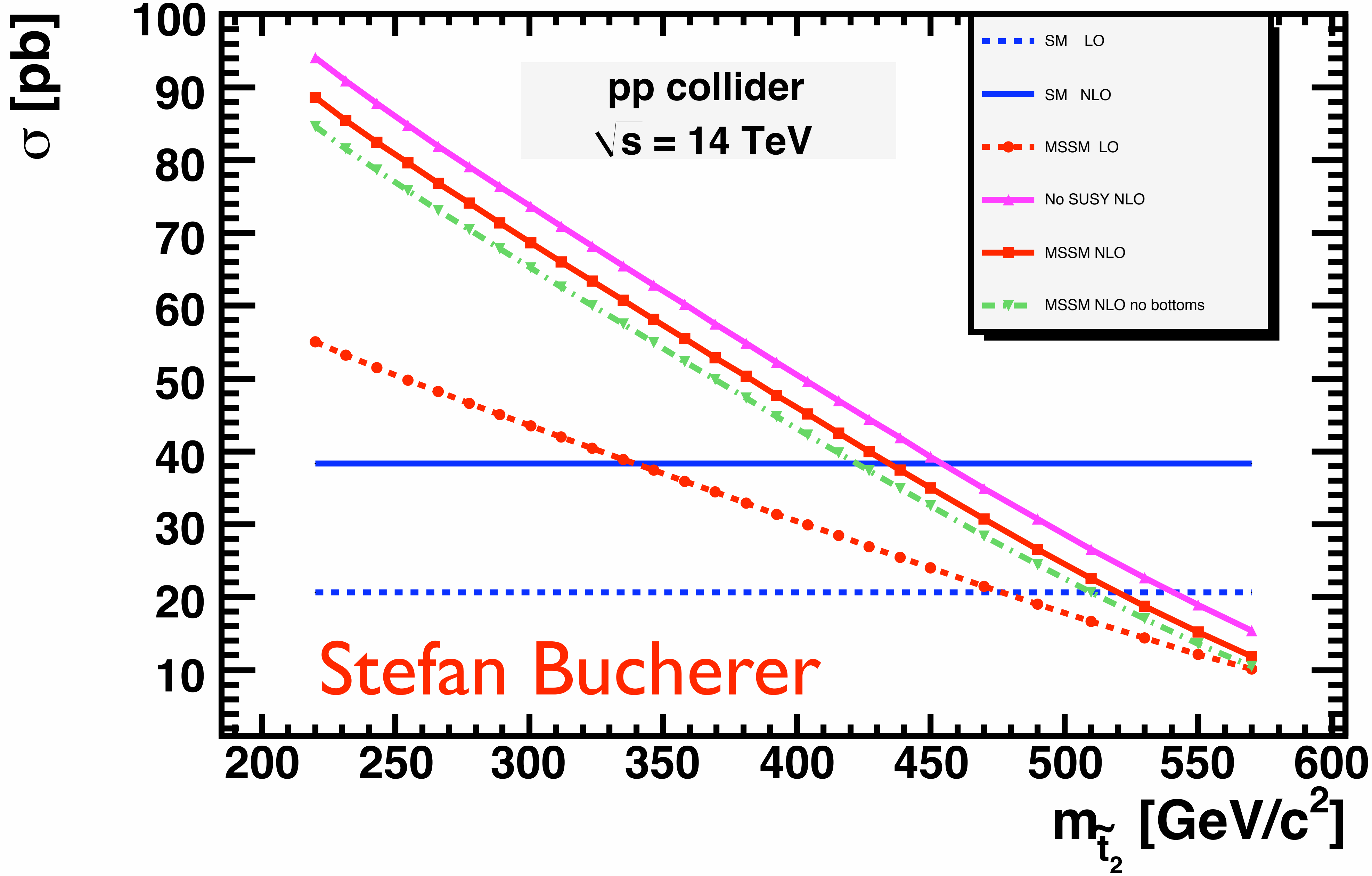
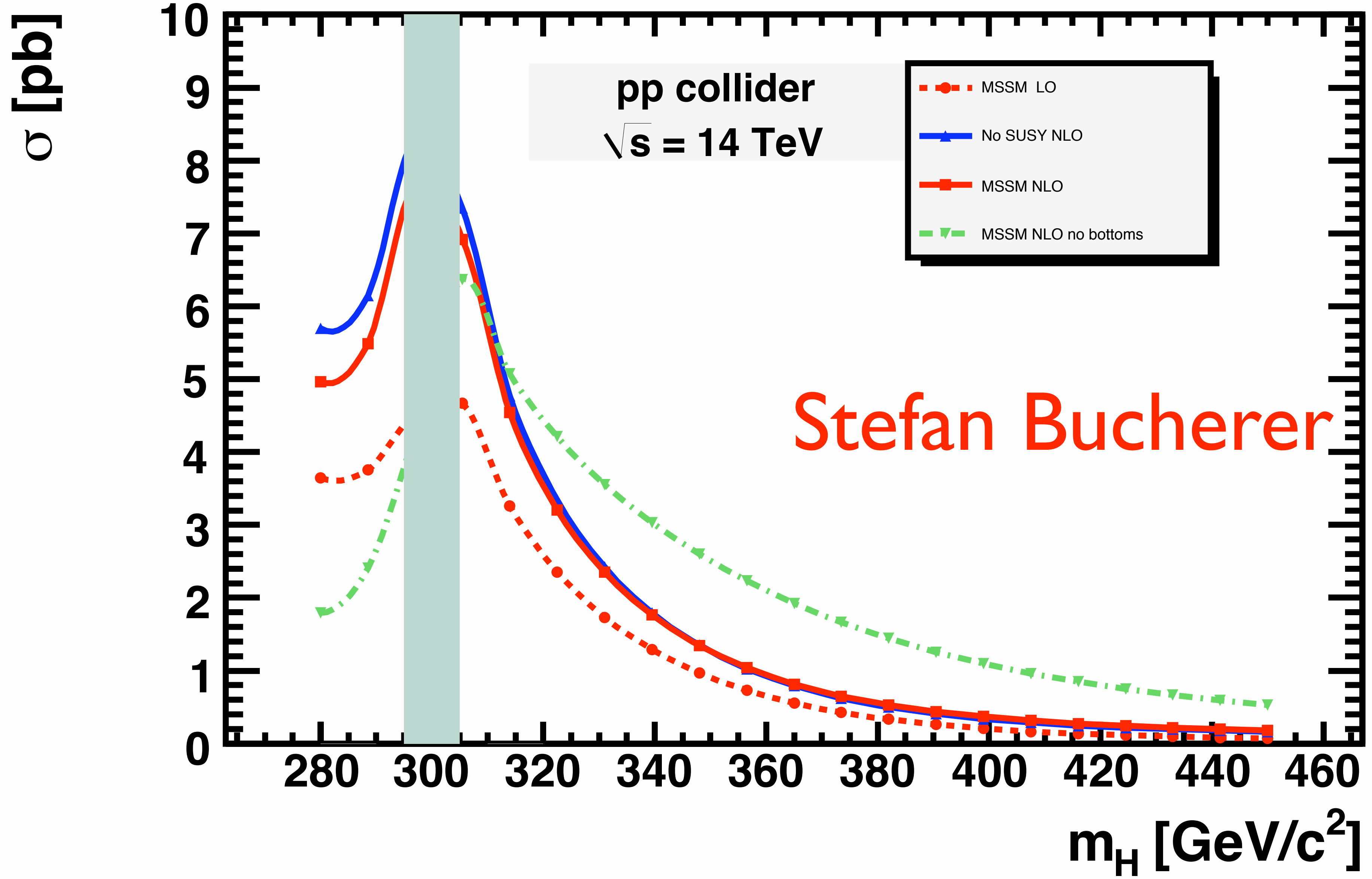


Heavy Higgs total cross-section

Preliminary

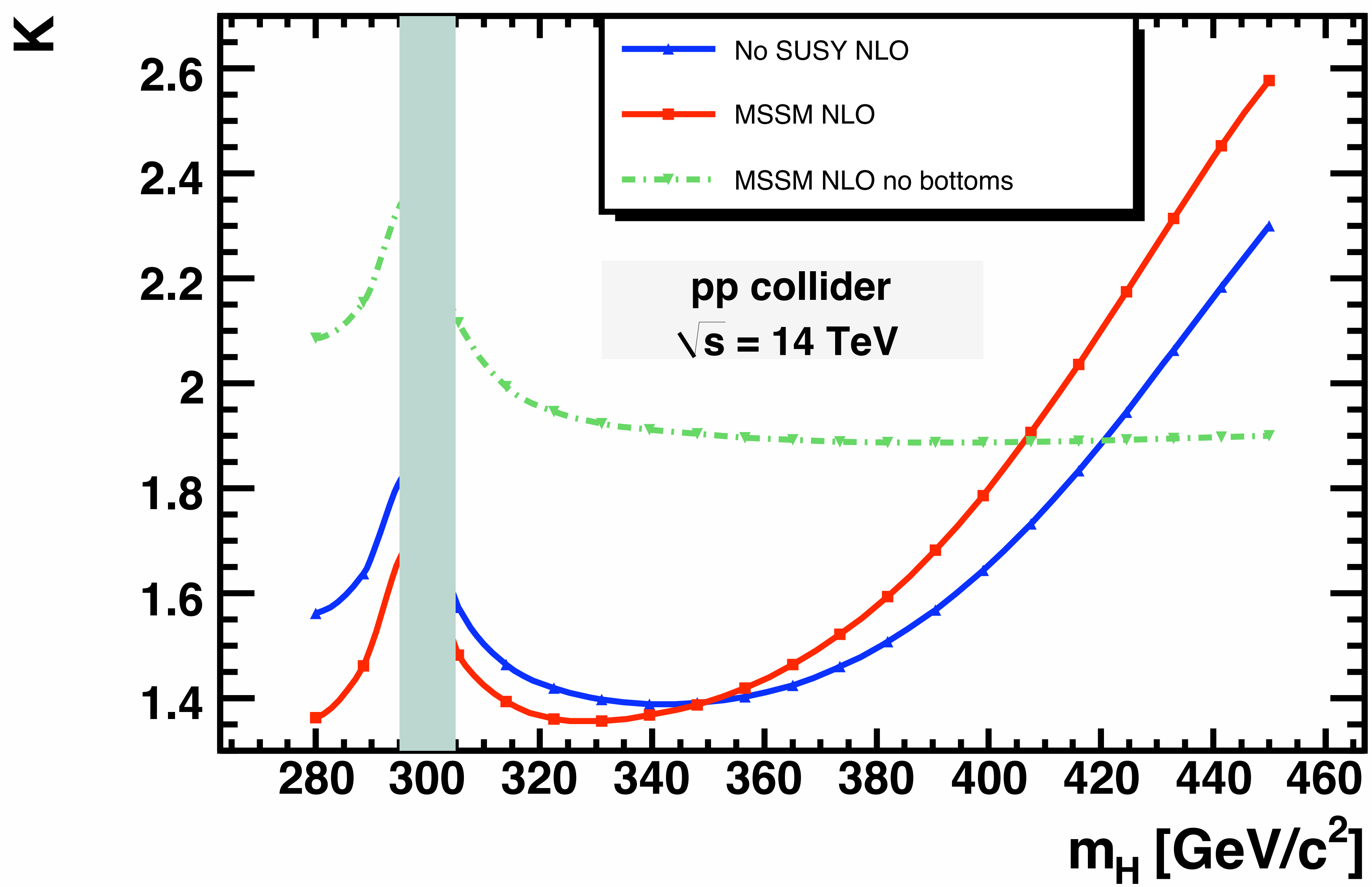


Stefan Bucherer

Heavy Higgs K-factor

Stefan Bucherer

Preliminary



Outlook

- Monte-Carlo with matching to parton shower, and all non-hadronic decay channels (before 14 TeV collisions @ LHC)
- CP-odd+ charged Higgs
- Effective theory @ NNLO
- Further SM applications of our numerical method (2 to 2 processes) at NNLO