Theoretical issues and practical problems in loop calculations of observables in SUSY

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PARTICLEFACE: Case studies of analytical and numerical methods of multiloop calculations for future e+e- colliders, October 3, 2018, Katowice, Poland

in collaboration with P. Dießner, D. Harris, J. Kalinowski, D. Stöckinger

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BSM@NLO for collider physics

Status of automation

- NLO QCD corrections in SM fully automated since few years
- First fully automated NLO EW computations
- BSM automation is just starting:
  - Tree level - many codes claim to have fully automatized tree-level computations. In practice, they will work as long as your BSM model is a simple extension of the SM or the MSSM
  - In principle the community converged to a single standard for specifying models called `UFO` (Universal FeynRules Output). Adopted for example by `MadGraph5`, `Herwig 7` and `Sherpa`. But `UFO` means different things to different people - often incompatible things.
  - Recently, first automation of BSM NLO computations

BSM@NLO

- NLO QCD corrections for squark pair production first calculated in 1997. Some things are still done the same way.

- IR divergences at NLO are simple, e.g. dipoles are universal and depend only on quantum numbers. Dipole subtraction available for arbitrary model.

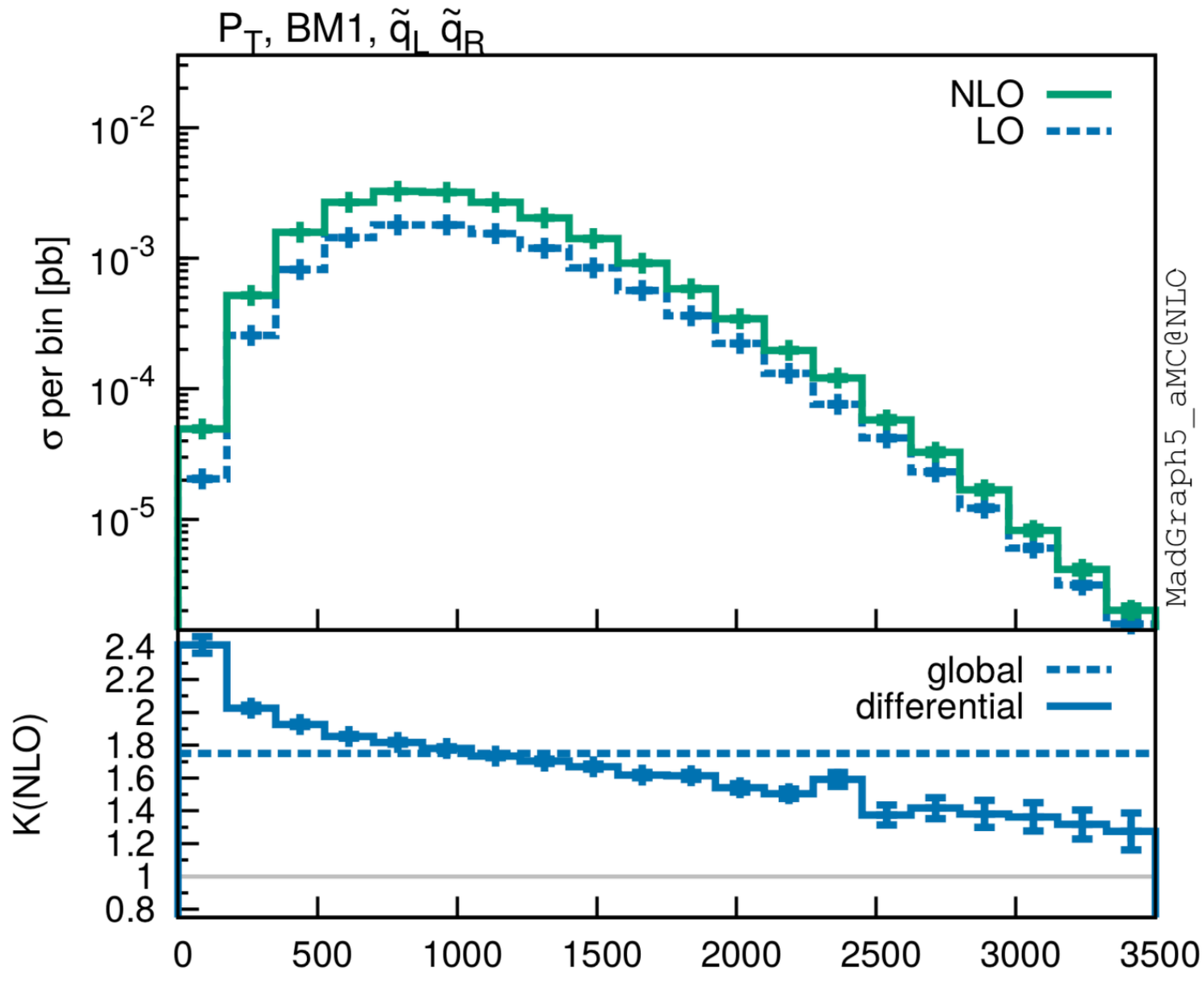
- Renormalization is the problem. One available tool: automated generation of renormalized `UFO` models using `FeynRules` and `NLOCT`

- For now works for simple extensions of the SM: 2HDM, spin 2, MSSM-like SUSY QCD etc.

- Not all models on-shell renormalizable. For non-minimal SUSY models even the SQCD sector might not be on-shell renormalizable (e.g. MRSSM).

Semi-automated calculations

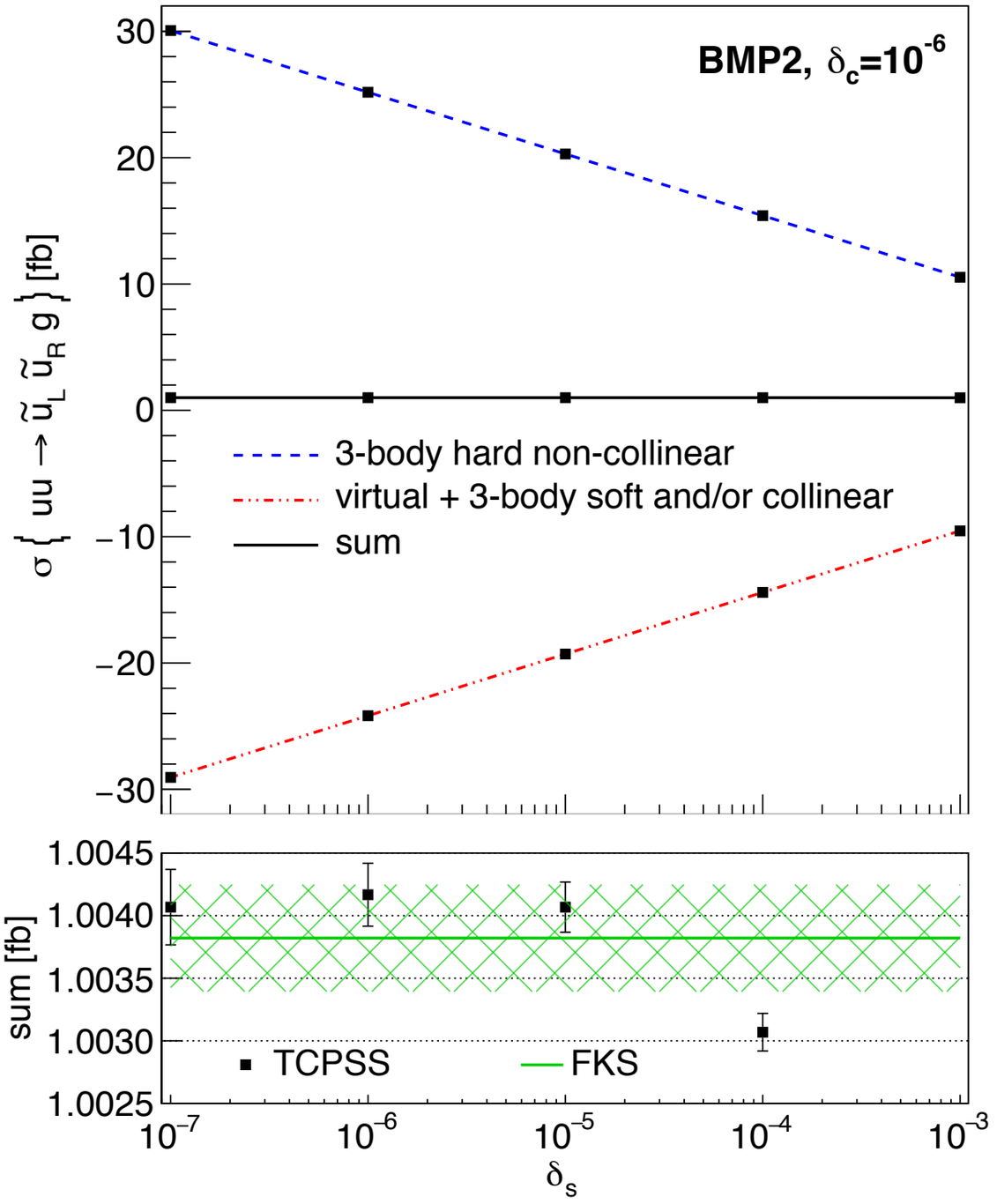
- `UFO` model + `GoSam` + `Madgraph5` with hacked renormalization constants



- The setup works well for squarks, a no-go for Dirac gluinos

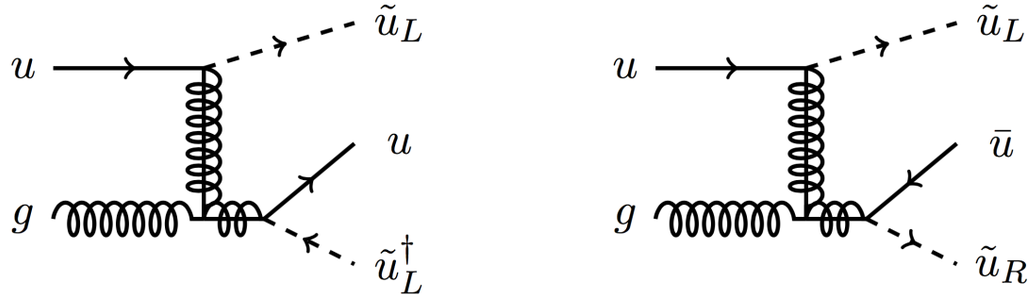
How far can you trust your hacked calculation?

two separate calculations: analytic and MadGraph5_aMC@NLO+GoSam



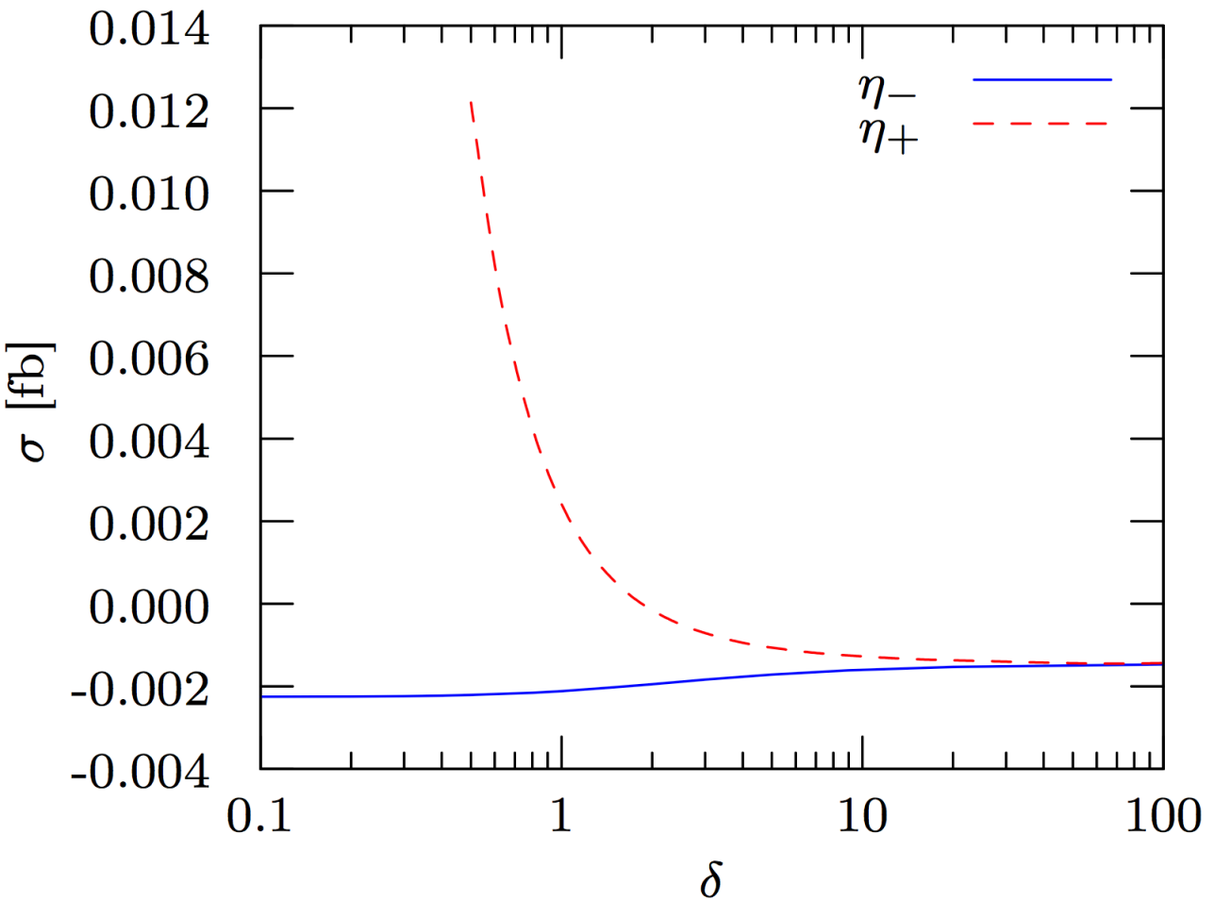
Resonances in real emission diagrams

- appearance of on-shell gluino when $m_{\tilde{g}} \geq m_u + m_{\tilde{u}_i}$



- 2 popular ways of treating them
  - diagram removal (DR)
  - diagram subtraction (DS)
- for DR one needs to carefully choose the gauge
  - DR breaks gauge invariance
  - unphysical gauges break factorization of collinear singularities – use family of light-cone gauges defined by

$$\eta_\pm \equiv (\sqrt{1+\delta^2}, 0, \delta, \pm 1)$$



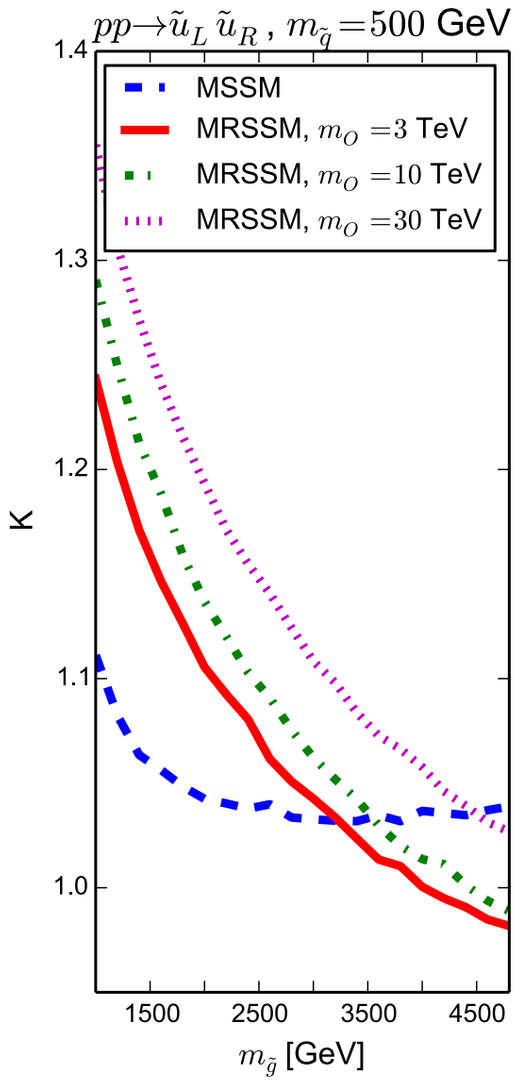
But the effort is worthwhile

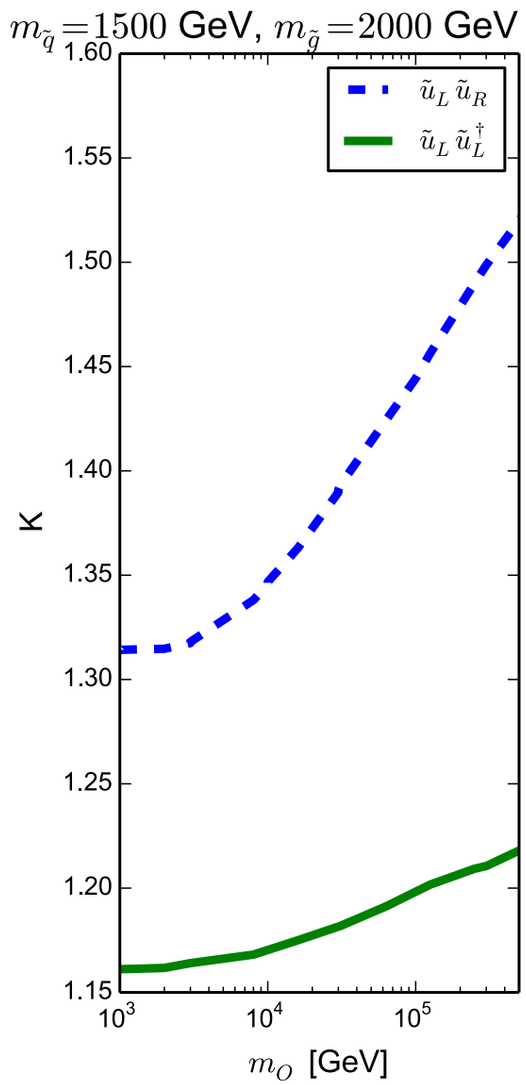
- Effect of Dirac gluinos
  - MSSM contains virtual corrections which grow together with $m_{\tilde{g}}$
  - but no such corrections in the MRSSM
- Non-decoupling of sgluons
  - difference between gauge coupling g and gluino coupling $\hat{g}$

$$\hat{g}_s - g_s = \frac{\alpha_s}{8\pi}\left(\log\frac{m_{O_s}^2}{m_{\tilde{g}}^2} + \log\frac{m_{O_p}^2}{m_{\tilde{g}}^2}\right)$$

  - translates into

$$\sigma^{\text{super-oblique part}}_{pp\to\tilde{u}_L\tilde{u}_R} = \frac{\alpha_s}{2\pi}\left(\log\frac{m_{O_s}^2}{m_{\tilde{g}}^2} + \log\frac{m_{O_p}^2}{m_{\tilde{g}}^2}\right)\sigma^{\text{LO}}_{pp\to\tilde{u}_L\tilde{u}_R}$$





Automation of decay calculations in BSM models

FlexibleDecays

- Phenomenological studies of BSM models require the knowledge of particles' decay chains
- For BSM particles tree-level is enough
- Use modification of SM particles (especially Higgs) width to constrain BSM models

- Common tool in study of BSM physics is a spectrum generator: `SPheno`, `SOFTSUSY`, `Suspect`, `IsaJet`, `SARAH/SPheno`, `FlexibleSUSY`
- **The goal**: Implement (as precise as possible) calculation of Higgs branching ratios in the `FlexibleSUSY` spectrum generator - think `HDECAY` for arbitrary model
- `SARAH/SPheno` already does it. Need for an independent validation. Can we be better?

General strategy

- For the moment, implement leading order computation, i.e. tree-level or 1-loop (depending on the channel)

- Take over known, universal higher order corrections. E.g. for the $H \to b\bar{b}$ that would be 4-loop QCD in leading m_b/m_H expansion.

- For SM, MSSM or THDM the precision should be the same as `HDECAY`

- Treatment of BSM corrections to lower order SM processes, like $H \to b\bar{b}$, is not fully clear yet

Side tour: First idea

- Spectrum generators naturally work with running parameters. No easy access to on-shell parameters other than masses.

- Why not calculate corrections to in scheme $\overline{\rm MS}$ or $\overline{\rm DR}$ scheme?

- Should give the same result as on-shell up to scheme dependent higher order terms

Somehow no-one does calculations of observables in schemes different than on-shell. The closest one gets is expressing result of on-shell calculation through $\overline{\rm MS}$ parameters.

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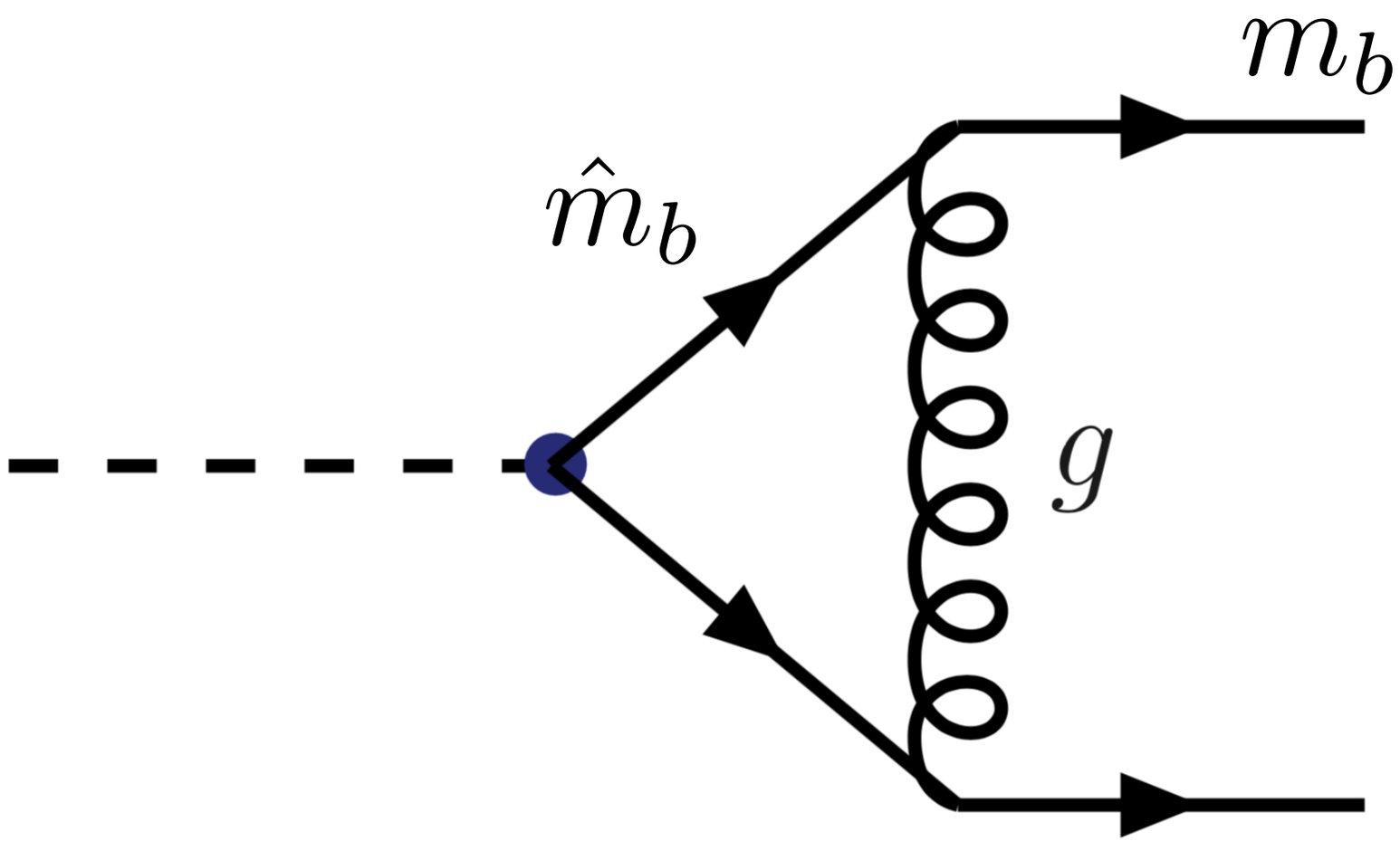
Somehow no-one does calculations of observables in schemes different than on-shell. The closest one gets is expressing result of on-shell calculation through $\overline{\rm MS}$ parameters.

If you know the answer, please don't spoil it for others ;)

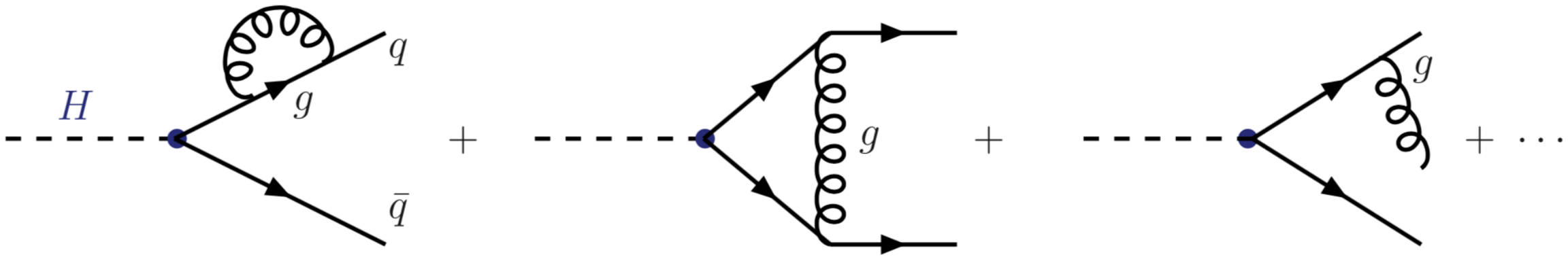
Simplest example: $H \to b\bar{b}$

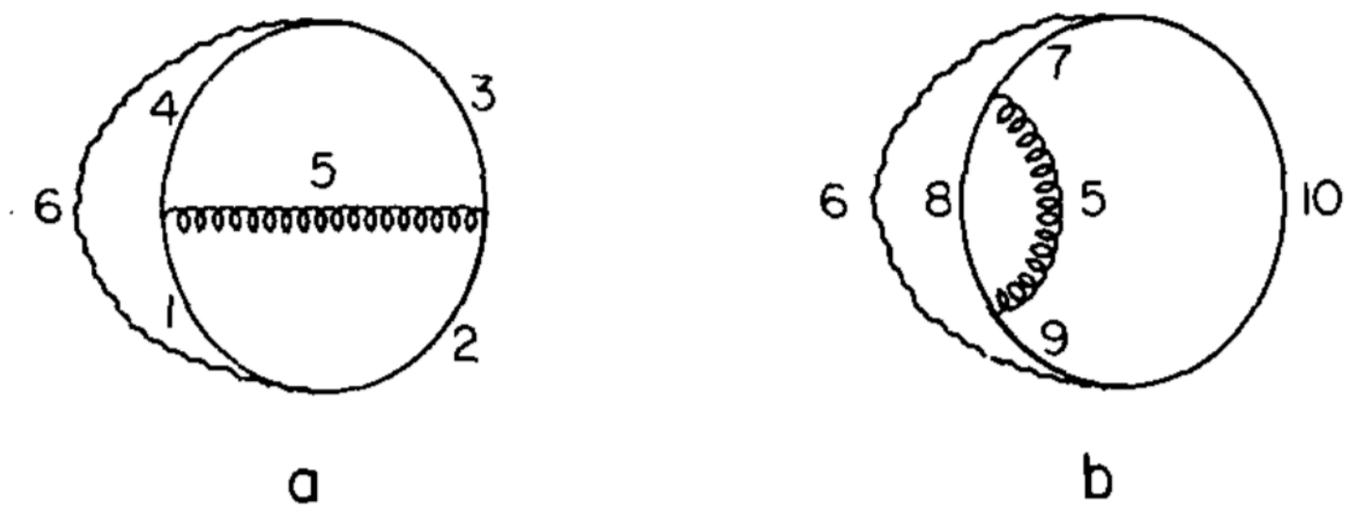


Since the amplitude is technically taken off-shell, there are no IR divergences.

$\delta = m_b - \hat{m}_b$ works like an IR regulator. In the limit $\delta \to 0$ we expect to get back an on-shell result

Kinoshita double cut rules





Explanation

- Known for a long time - see ”How to regularize the infrared and mass singularities in QCD” by Humpert and van Neervan
- Giving mass to gluon will work in this example because there is only one
- The difference is in finite terms, which explains why the limit $\delta \to 0$ exists
- We still want to look into it closer as I’m not satisfied by it. If someone has any comments, there are more than welcome.

Conclusions and prospects:

- BSM automation is far from trivial. Covering all possible models might be next-to-impossible.

- Still, for a broad class of models, the automation is in reach.

- The need for automation in BSM community has a different source than in the SM. In SM N-loop calculations are way to complex to do them „by hand”. In BSM you don’t want to spend 5 years calculating corrections in model which most likely is not realized in nature.

- The problem of the community is lack of testing and lack of clearly stated limitations of codes and even what is understood as SUSY

- On our end the `FlexibleDecays` module will provide (almost) state of the art computation of Higgs decay widths with clearly stated limitations. If your model fails, you will know why and it will make it easier for us to fix it.

- There’s a need for close cooperation between users and developers. We cannot even foreseen all the corner cases. `FlexibleSUSY` development is done in public, on GitHub. If you have a problem, open an issue. Also, if there’s a regression error, you can trace it.