# Computer tools in particle physics

## - Lecture 5 : FlavorKit, odds and ends -

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# Flavor observables in a nutshell

**Step 1:** Consider a lagrangian that includes all the operators relevant for the flavor observable

$$\mathcal{L}_{eff} = \sum_i C_i \mathcal{O}_i$$

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**Step 3:** Plug the results for the Wilson coefficients into a general expression for the flavor observable

# Example: $\mathrm{BR}(\mu \to e\gamma)$

[In the SM extended with Dirac neutrino masses]

**Step 1:** Consider a lagrangian that includes all the operators relevant for the flavor observable

$$\mathcal{L}_{\mu e\gamma} = ie\, m_\mu\, \bar{e}\, \sigma^{\mu\nu} q_\nu \left( K_2^L P_L + K_2^R P_R \right) \mu A_\mu + \mathrm{h.c.}$$

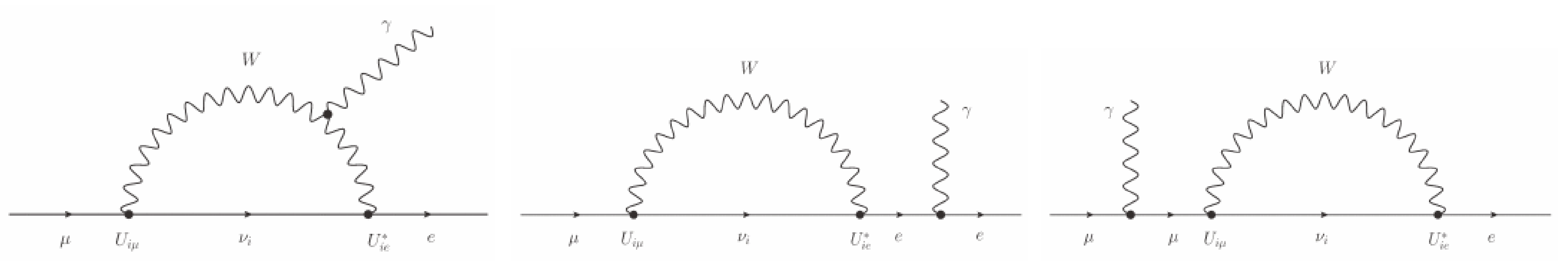
Dipole interaction lagrangian

$K_2^L, K_2^R$ : Wilson coefficients

# Example: $\text{BR}(\mu \to e\gamma)$

[In the SM extended with Dirac neutrino masses]

**Step 2:** Compute the Wilson coefficients at a given loop order




$$K_2^L = \frac{G_F}{2\sqrt{2}\pi^2} m_\mu \sum_i U_{i\mu} U_{ie}^* (F_1 + F_2)$$

$$K_2^R = \frac{G_F}{2\sqrt{2}\pi^2} m_e \sum_i U_{i\mu} U_{ie}^* (F_1 - F_2)$$

[Ma, Pramudita, '81]

# Example: $\mathrm{BR}(\mu \to e\gamma)$

[In the SM extended with Dirac neutrino masses]

**Step 3:** Plug the results for the Wilson coefficients into a general expression for the flavor observable

$$\mathrm{BR}\left(\mu \to e\gamma\right) = \frac{\alpha\, m_\mu^5}{4\,\Gamma_\mu} \left(|K_2^L|^2 + |K_2^R|^2\right)$$

# Flavor observables in a nutshell

**Step 1:** Consider a lagrangian that includes all the operators relevant for the flavor observable

Some freedom. Requires a good understanding of the observable but technically easy

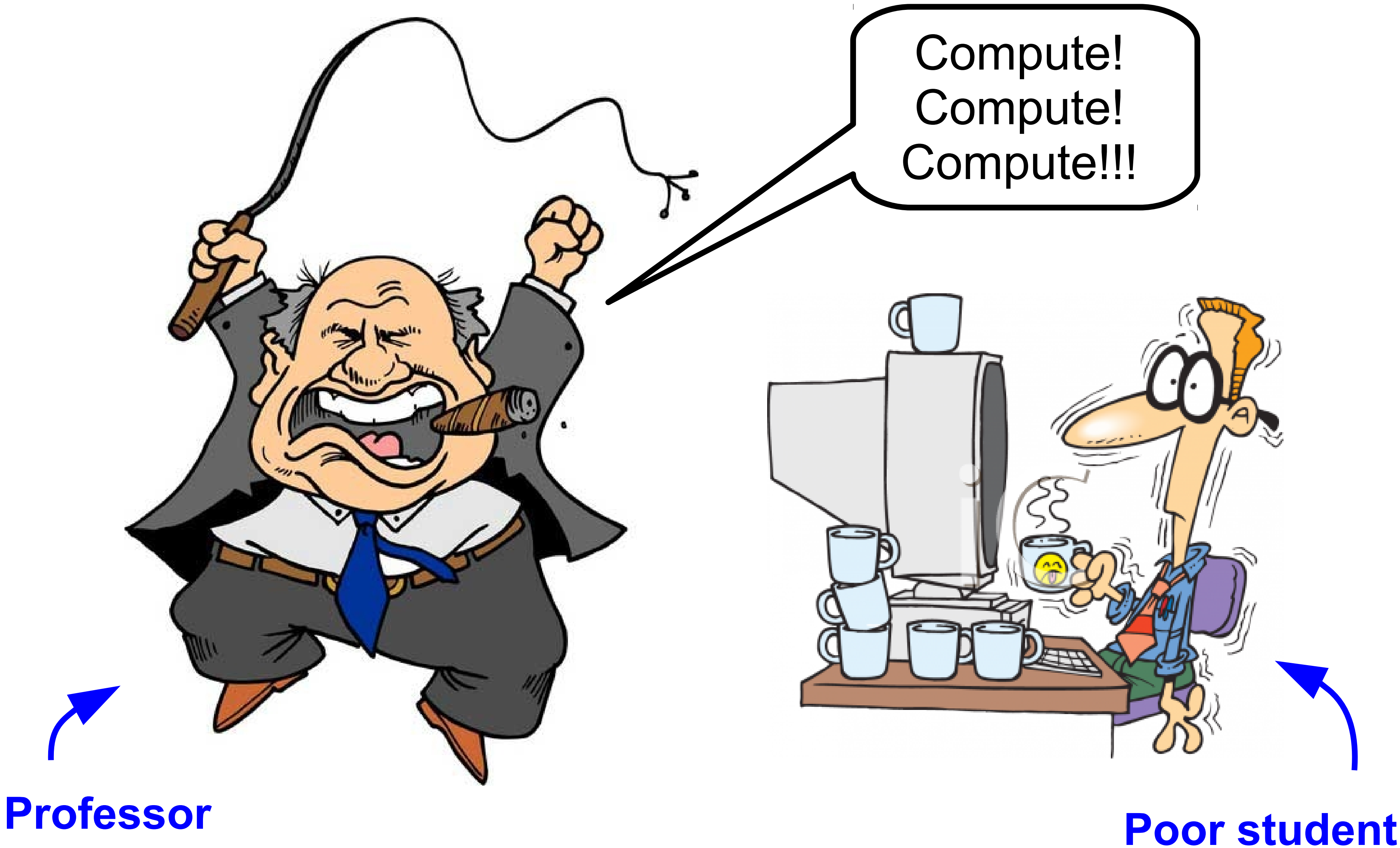
**Step 2:** Compute the Wilson coefficients at a given loop order

Complicated and model dependent part of the computation

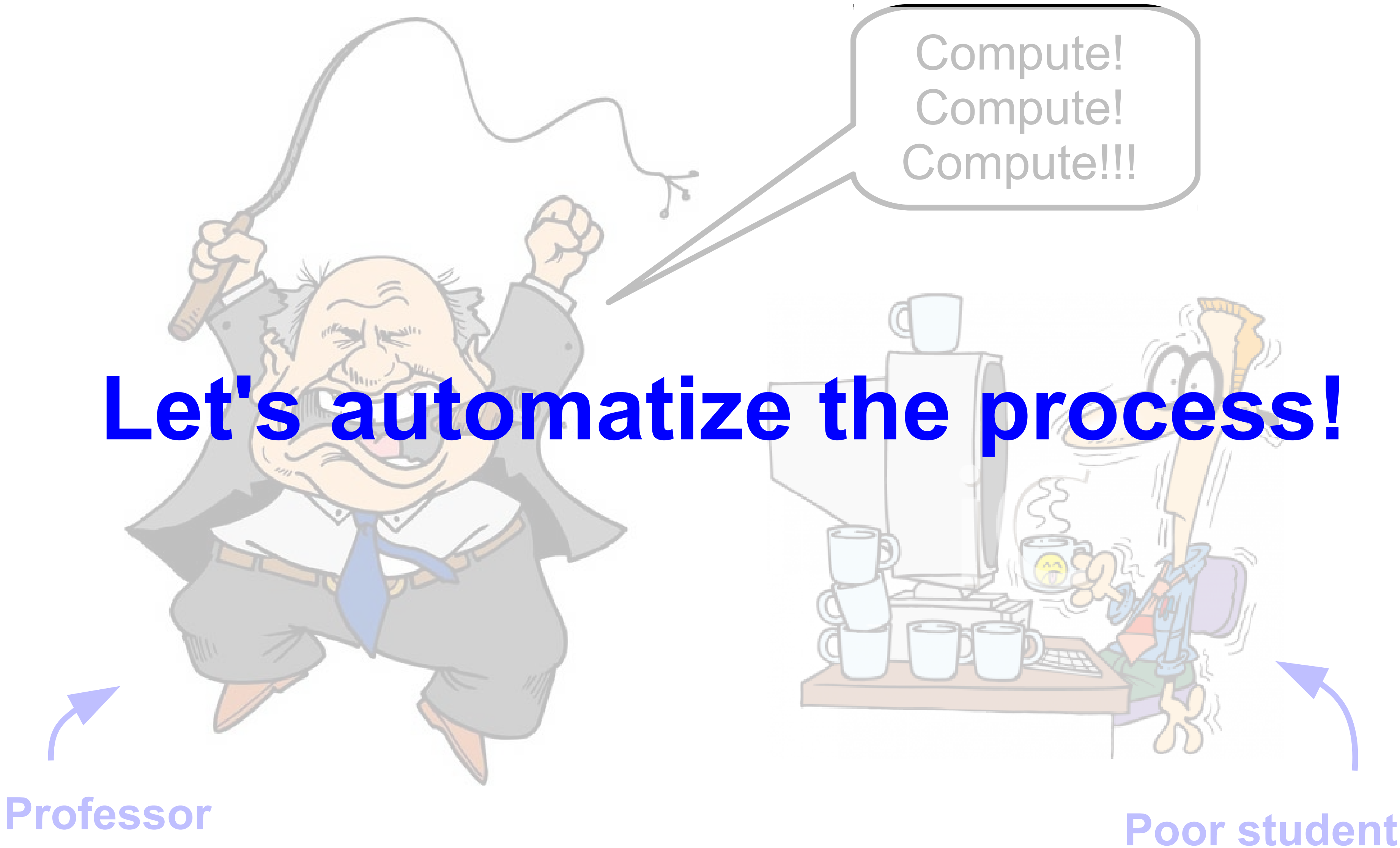
**Step 3:** Plug the results for the Wilson coefficients into a general expression for the flavor observable

Model independent. Can make use of results in the literature

# Usual approach



# Usual approach




**Let's automatize the process!**

**Chuck Norris fact of the day**

*When Chuck Norris does a pushup, he isn’t lifting himself up, he’s pushing the Earth down*

# FlavorKit

W. Porod, F. Staub, A. Vicente

Manual: arXiv:1405.1434
Website: http://sarah.hepforge.org/FlavorKit.html

# FlavorKit

To compute flavor observables one needs:

1) Expressions for all vertices and masses

2) Expressions for the Wilson coefficients

3) Expressions for the observables

4) Numerical evaluation

# FlavorKit

To compute flavor observables one needs:

1) Expressions for all vertices and masses → SARAH

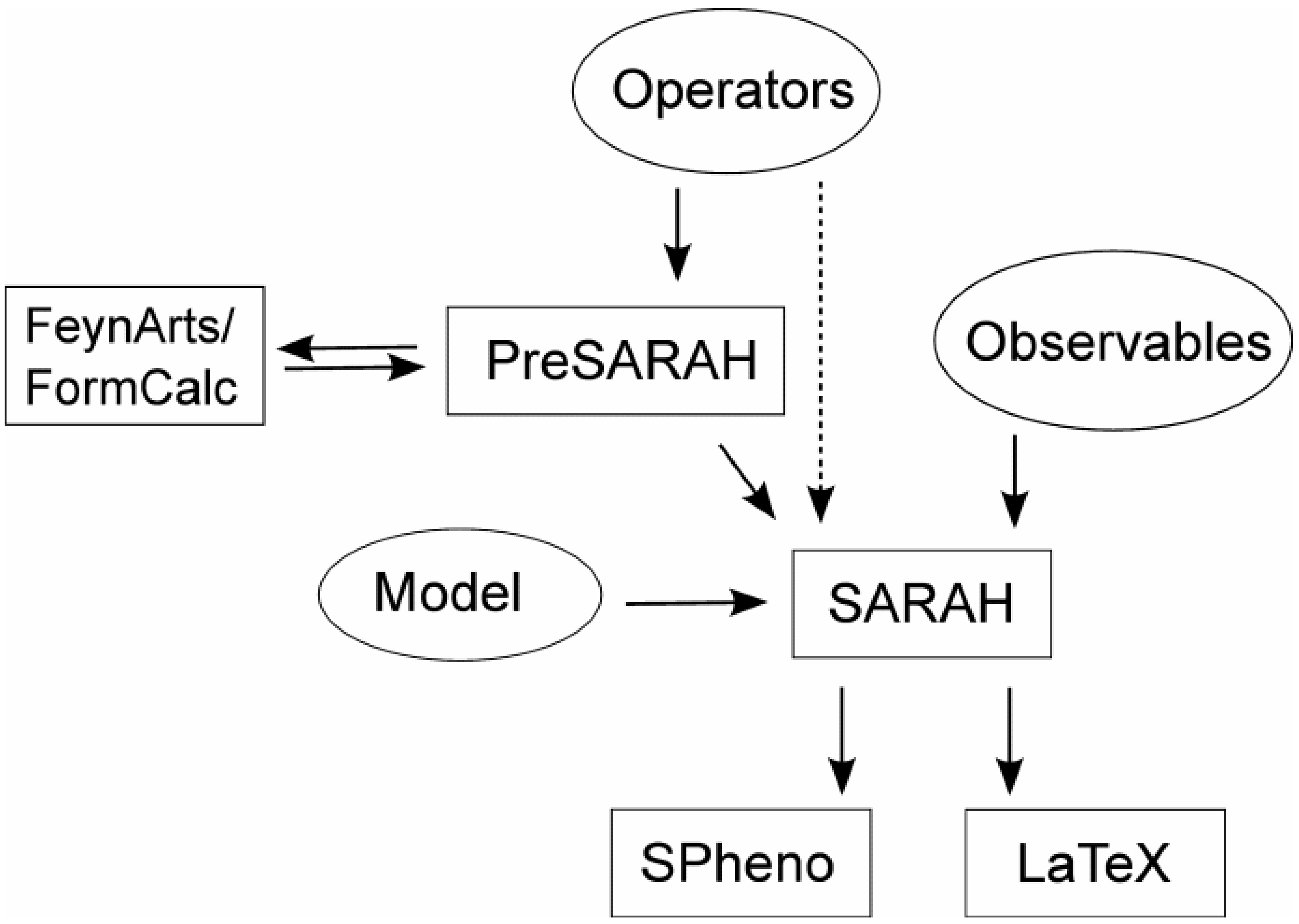
2) Expressions for the Wilson coefficients → FeynArts/ FormCalc

3) Expressions for the observables → Literature

4) Numerical evaluation → SPheno

FlavorKit is the combination of these tools

# FlavorKit


Operators
FeynArts/
FormCalc
PreSARAH
Observables
Model
SARAH
SPheno
LaTeX

# How to use FlavorKit

- **Basic usage**

For those who do not need any operator nor observable beyond what is already implemented in FlavorKit. In this case, FlavorKit reduces to the standard SARAH package.

# Observables already in FlavorKit

| Lepton flavor | Quark flavor |
|---|---|
| $\ell_\alpha \to \ell_\beta \gamma$ | $B^0_{s,d} \to \ell^+ \ell^-$ |
| $\ell_\alpha \to 3\,\ell_\beta$ | $\bar{B} \to X_s \gamma$ |
| $\mu - e$ conversion in nuclei | $\bar{B} \to X_s \ell^+ \ell^-$ |
| $\tau \to P\,\ell$ | $\bar{B} \to X_{d,s} \nu \bar{\nu}$ |
| $h \to \ell_\alpha \ell_\beta$ | $B \to K \ell^+ \ell^-$ |
| $Z \to \ell_\alpha \ell_\beta$ | $K \to \pi \nu \bar{\nu}$ |
| | $\Delta M_{B_{s,d}}$ |
| | $\Delta M_K$ and $\varepsilon_K$ |
| | $P \to \ell \nu$ |

Ready to be computed in your favourite model!

# How to use FlavorKit

## Basic usage

For those who do not need any operator nor observable beyond what is already implemented in FlavorKit. In this case, FlavorKit reduces to the standard SARAH package.

## Advanced usage

For those with further requirements:

- New observables
- New operators

EXTRA

**2nd Chuck Norris fact of the day**

*Chuck Norris can run collider simulations with MadGraph on an abacus*

# New observables

## Implementing a new observable

Two files: steering file “observable.m” + Fortran code “observable.f90”

```
NameProcess = "LLpGamma";
NameObservables = {{muEgamma, 701, "BR(mu->e gamma)"},
                   {tauEgamma, 702, "BR(tau->e gamma)"},
                   {tauMuGamma, 703, "BR(tau->mu gamma)"}};

NeededOperators = {K2L, K2R};

Body = "LLpGamma.f90";
```

Steering file

LLpGamma.m

Reminder:

$$\mathcal{L}_{\mu e\gamma} = ie\, m_\mu\, \bar{e}\, \sigma^{\mu\nu} q_\nu \left( K_2^L P_L + K_2^R P_R \right) \mu A_\mu + \text{h.c.}$$

# New observables

Fortran code
LLpGamma.f90

```
Real(dp) :: width
Integer :: i1, gt1, gt2

Do i1=1,3
If (i1.eq.1) Then         ! mu -> e gamma
      gt1 = 2
      gt2 = 1
Elseif (i1.eq.2) Then
      ...
End if

width = 0.25_dp*mf_l(gt1)**5*(Abs(K2L(gt1,gt2))**2 + Abs(K2R(gt1,gt2))**2)*Alpha

If (i1.eq.1) Then
      muEgamma = width/(width+GammaMu)
Elseif (i1.eq.2) Then
      ...
End if
End do
```

# New operators

## Implementing a new operator

One file: PreSARAH input file "operator.m"

Generic expressions for the Wilson coefficients of new operators can be computed with the help of an additional package (PreSARAH):

- User friendly definition of new operators
- Uses FeynArts/FormCalc [by T. Hahn] to obtain the generic expressions
- Writes all necessary files for SARAH

Example:

$$\mathcal{L}_{2d2\ell} = \sum_{\substack{I=S,V,T \\ X,Y=L,R}} E_{XY}^{I}\, \bar{d}_\beta \Gamma_I P_X d_\alpha\, \bar{\ell}_\gamma\, \Gamma_I P_Y \ell_\gamma + \text{h.c.}$$

$$(\Gamma_{S,V,T} = 1, \gamma_\mu, \sigma_{\mu\nu})$$

# New operators

```
NamePross="2d2L";
```

PreSARAH input file

2d2L.m

```
NameProcess="2d2L";

ConsideredProcess = "4Fermion";
FermionOrderExternal={2,1,4,3};
NeglectMasses={1,2,3,4};


ExternalFields= {DownQuark,bar[DownQuark],ChargedLepton,bar[ChargedLepton]};

CombinationGenerations = {{3,1,1,1}, {3,1,2,2}, {3,1,3,3},{3,2,1,1}, {3,2,2,2}, {3,2,3,3}};


AllOperators={{OddllSLL,Op[7].Op[7]},
              {OddllSRL,Op[6].Op[7]},
              ...,
              {OddllVRR,Op[7,Lor[1]].Op[7,Lor[1]]},
              ...,
              {OddllTLL,Op[-7,Lor[1],Lor[2]].Op[-7,Lor[1],Lor[2]]},
              ...};
```

Note:

$$\mathrm{Op}[7]\ ,\ \mathrm{Op}[6]\ = P_{L,R}$$

$$\mathrm{Lor}[1]\ = \gamma_\mu$$

# Summary

FlavorKit is a combination of computer tools that allow the user to get predictions for his/her favourite flavor observables in the model of his/her choice.

No more lengthy loop computations!

It combines the analytical power of SARAH with the numerical routines of SPheno.

Perfect for phenomenological studies!

Easily extendable: new observables and new operators (thanks to FeynArts/FormCalc).

What are you waiting for? Use FlavorKit!

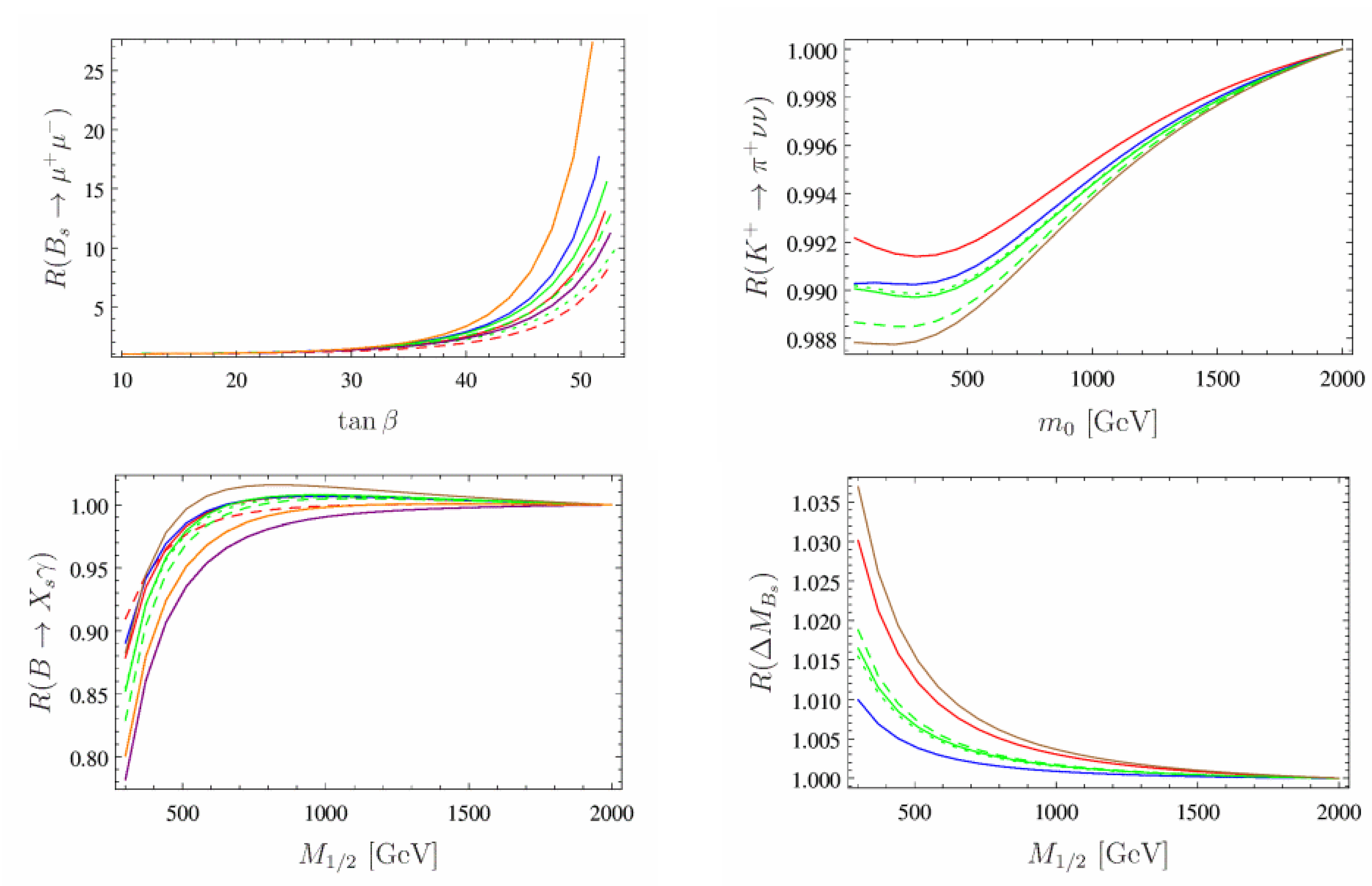
# Backup slides

# Other flavor codes

- **MicrOmegas** [Belanger, Boudjema, Pukhov, Semenov]
- **NMSSM-Tools** [Ellwanger, Hugonie]
- **SPheno** [Porod, Staub]
- **SuperIso** [Mahmoudi]
- **SuSeFLAV** [Chowdhury, Garani, Vempati]
- **SUSY_FLAVOR** [Rosiek, Chankowski, Dedes, Jäger, Tanedo] [Crivellin, Rosiek]
- **...**

Restrictions: Only specific models + hard to extend

# Validation




FlavorKit, SPhenoMSSM (dashed), SPheno 3.3, SUSY Flavor 1, SUSY Flavor 2, MicrOmegas, SuperIso

# Models already in SARAH

## Supersymmetric Models

- MSSM [in several versions]
- NMSSM
- Near-to-minimal SSM (near-MSSM)
- General singlet extended SSM (SMSSM)
- DiracNMSSM
- Triplet extended MSSM/NMSSM
- Several models with R-parity violation
- U(1)-extended MSSM (UMSSM)
- Secluded MSSM
- Several B-L extended models
- Inverse and linear seesaws [several embeddings]
- MSSM/NMSSM with Dirac Gauginos
- Minimal R-Symmetric SSM
- Minimal Dirac Gaugino SSM
- Seesaws I-II-III [SU(5) versions]
- Left-right symmetric model
- Quiver model

## Non-Supersymmetric Models

- Standard Model
- Inert Higgs doublet model
- B-L extended SM
- B-L extended SM with inverse seesaw
- SM extended by a scalar color octet
- Two Higgs doublet model
- Singlet extended SM
- Singlet Scalar DM

**SARAH**

http://sarah.hepforge.org/

# Limitations

**Disclaimer**

FlavorKit is a tool intended to be as general as possible. For this reason, there are some limitations compared to codes which perform specific calculations in a specific model:

- Chiral resummation is not included because of its large model dependence
- Higher order corrections cannot be computed (although they can be included in a parametric way)