Parallel Session Wrap-Up:
Origin of Mass

Hartmut Wittig

PRISMA Cluster of Excellence, Institute for Nuclear Physics and Helmholtz Institute Mainz

Matter and the Universe Programmtag, Helmholtz Institute Mainz
13 December 2016

HELMHOLTZ ASSOCIATION
Helmholtz Institute Mainz

PRISMA

SFB 1044
THE LOW-ENERGY FRONTIER OF THE STANDARD MODEL

Origin of Mass

* **Electroweak symmetry breaking**
  - Mass generation via the Higgs mechanism

Origin of Mass

* **Electroweak symmetry breaking**
  - Mass generation via the Higgs mechanism
  - Measure Higgs couplings ⇒ major LHC activity

Origin of Mass

* **Electroweak symmetry breaking**
  - Mass generation via the Higgs mechanism
  - Measure Higgs couplings $\Rightarrow$ major LHC activity
  - Constrain models for physics beyond the SM

* **Mass generation of visible matter**
  - Strongly coupled QCD
  - Hadron spectrum & resonances from first principles
  - Hadronic uncertainties in precision tests of the SM

Origin of Mass: Programme

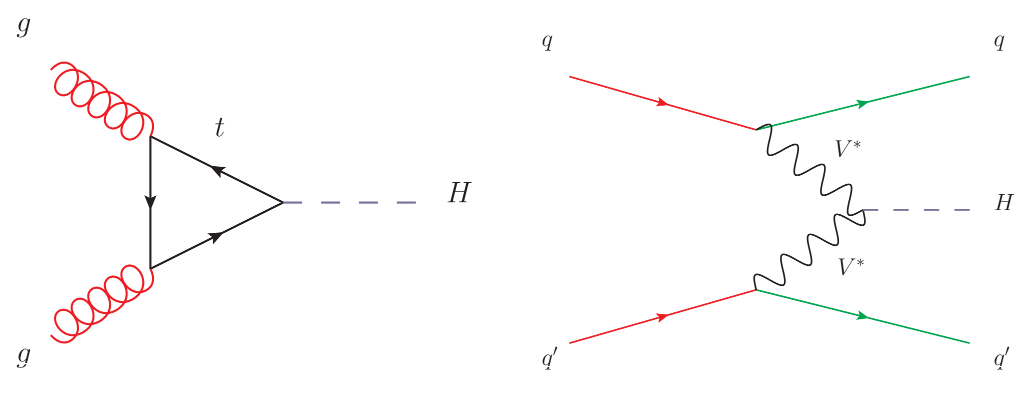
* **Higgs Physics**
  - Emanuele Bagnaschi (DESY): *Higgs mass computation in BSM physics*
  - Florian Staub (KIT): *Generic approach for Higgs mass calculations*

* **Strong QCD**
  - Max Hansen (HIM): *Scattering and resonances from finite-volume calculations*
  - Andreas Nyffeler (JGU): *Theoretical status of the muon g−2*

* **Constraints on BSM physics**
  - Wolfgang G. Hollik (DESY): *Vacuum stability and the origin of mass*
  - Marco Sekulla (KIT): *Unitarization and simplified models for vector boson scattering*

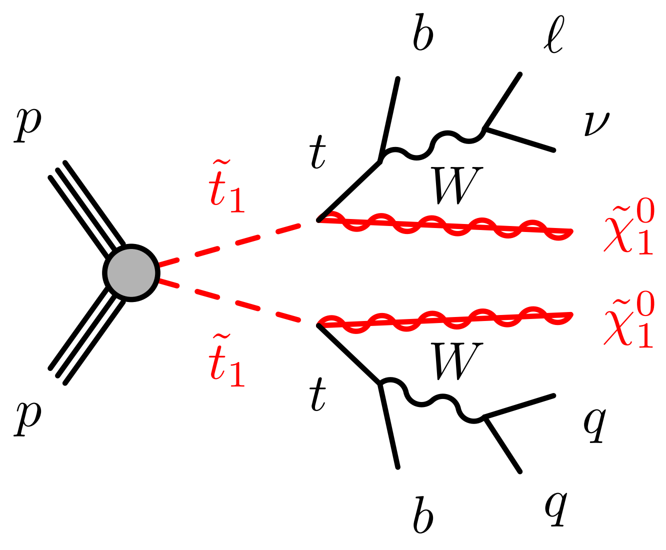
Higgs Physics and BSM models

* **Minimal Supersymmetric Standard Model (MSSM)**
  - solves the hierarchy problem
  - provides a dark matter candidate
  - null result at the LHC
  - Higgs mass too heavy



* Renewed interest in "unnatural" SUSY models: scale for BSM physics far above EW scale

  —> Emanuele Bagnaschi



* Confront MSSM and other BSM model with Higgs mass measurements

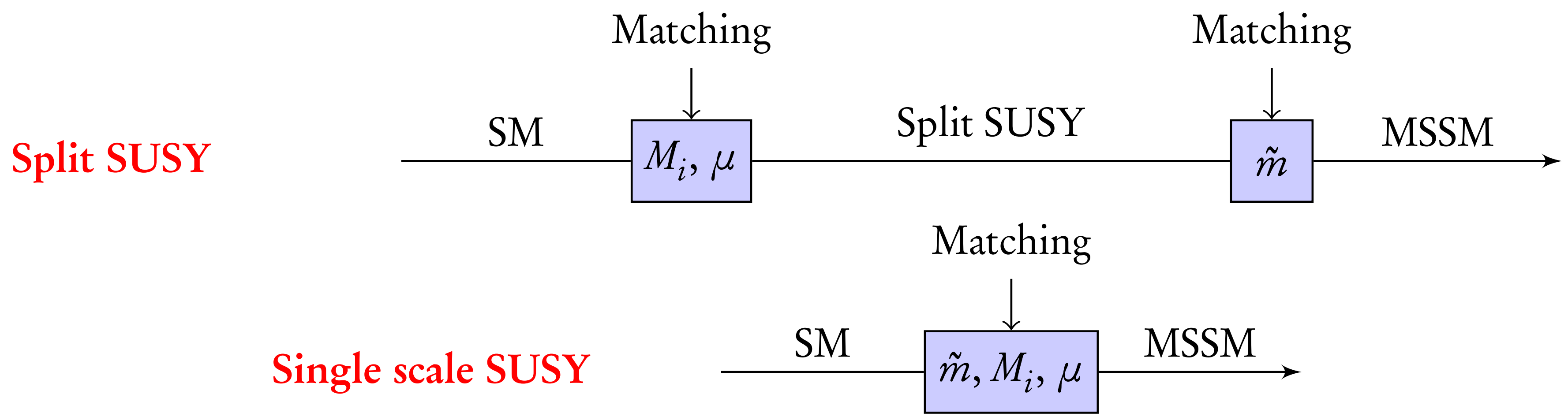
  —> Florian Staub

EFT Approach

* Higher-order corrections to Higgs mass produce large logarithms

⇒ Employ Effective Field Theory approach

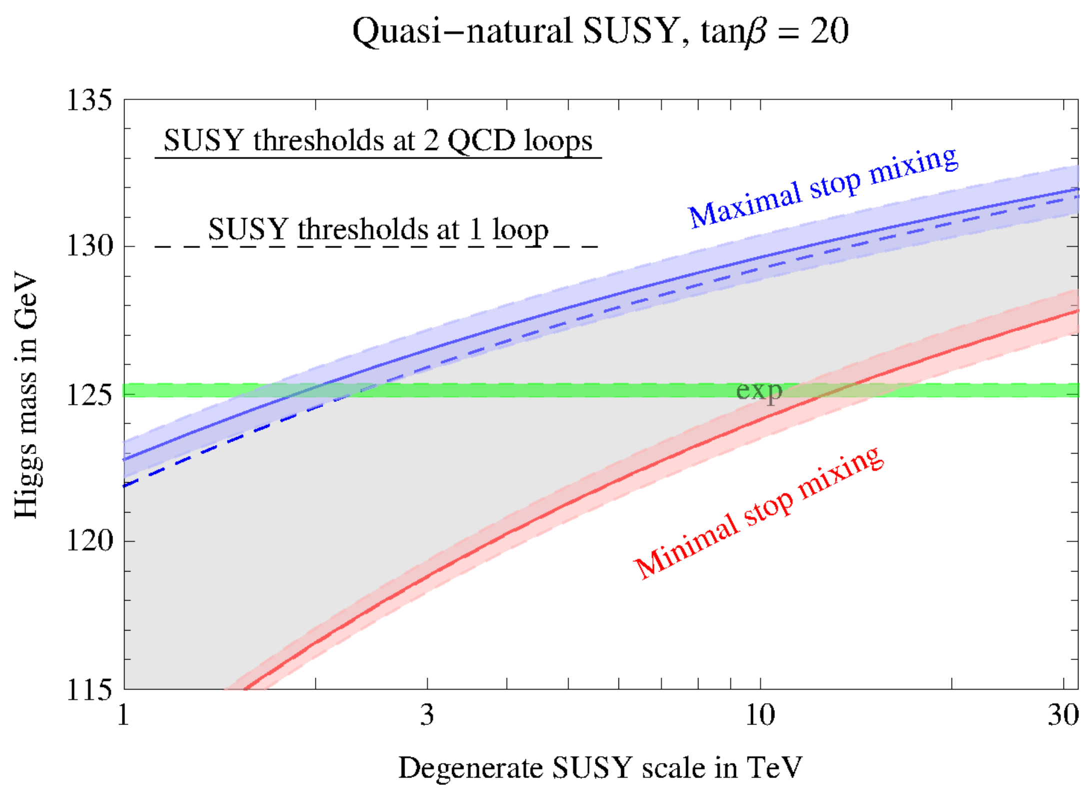
- Problem: mass gap in the physical spectrum makes large logs of the ratio $m_{\rm ew}/\tilde{m}$ appears in the perturbative expressions.
- Solution: For a proper computation these logs have to be resummed.
- Method: define a tower of effective field theories, where the heavy particles are integrated out, and match them at a proper scale. Use RGE to resum the large logarithms.



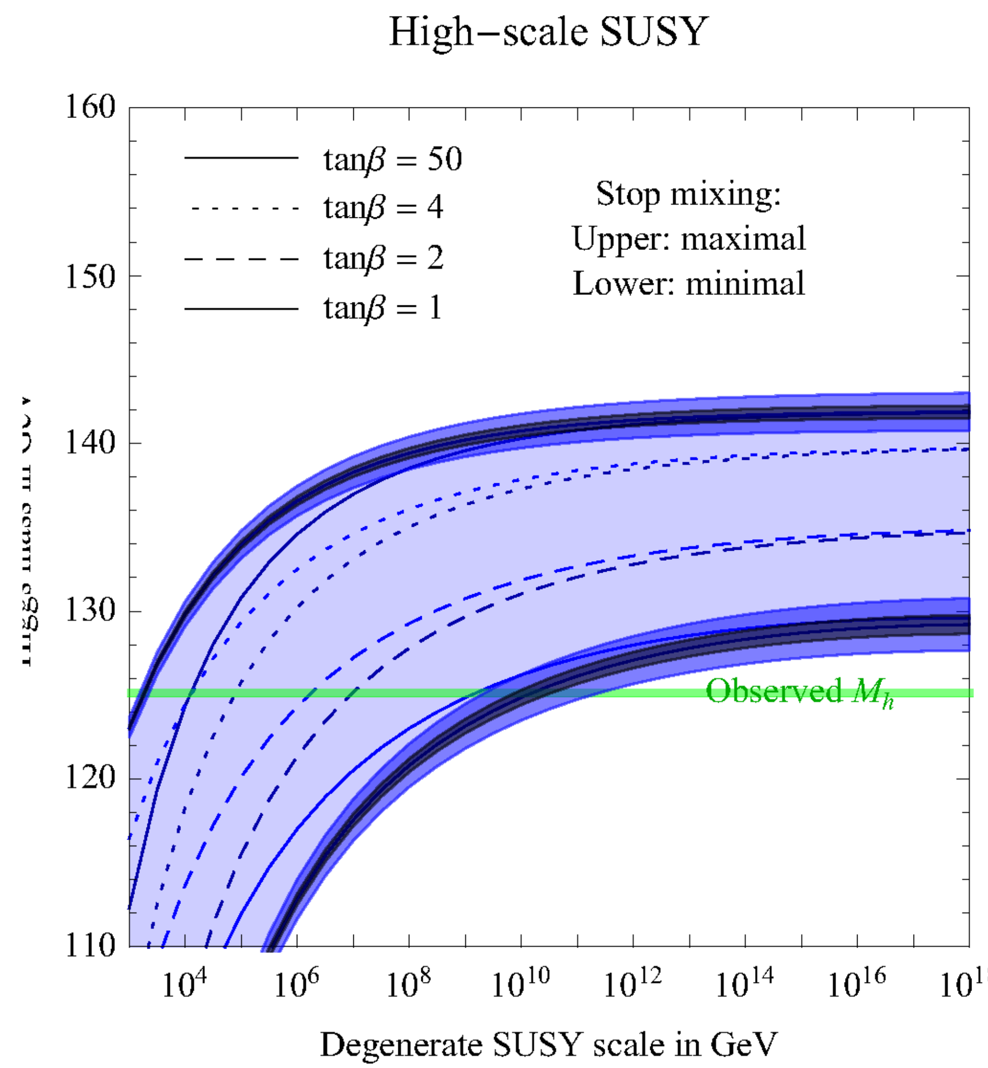
Emanuele Bagnaschi

Higgs mass predictions in SUSY models

Quasi-natural SUSY: superpartners of O(10 TeV)



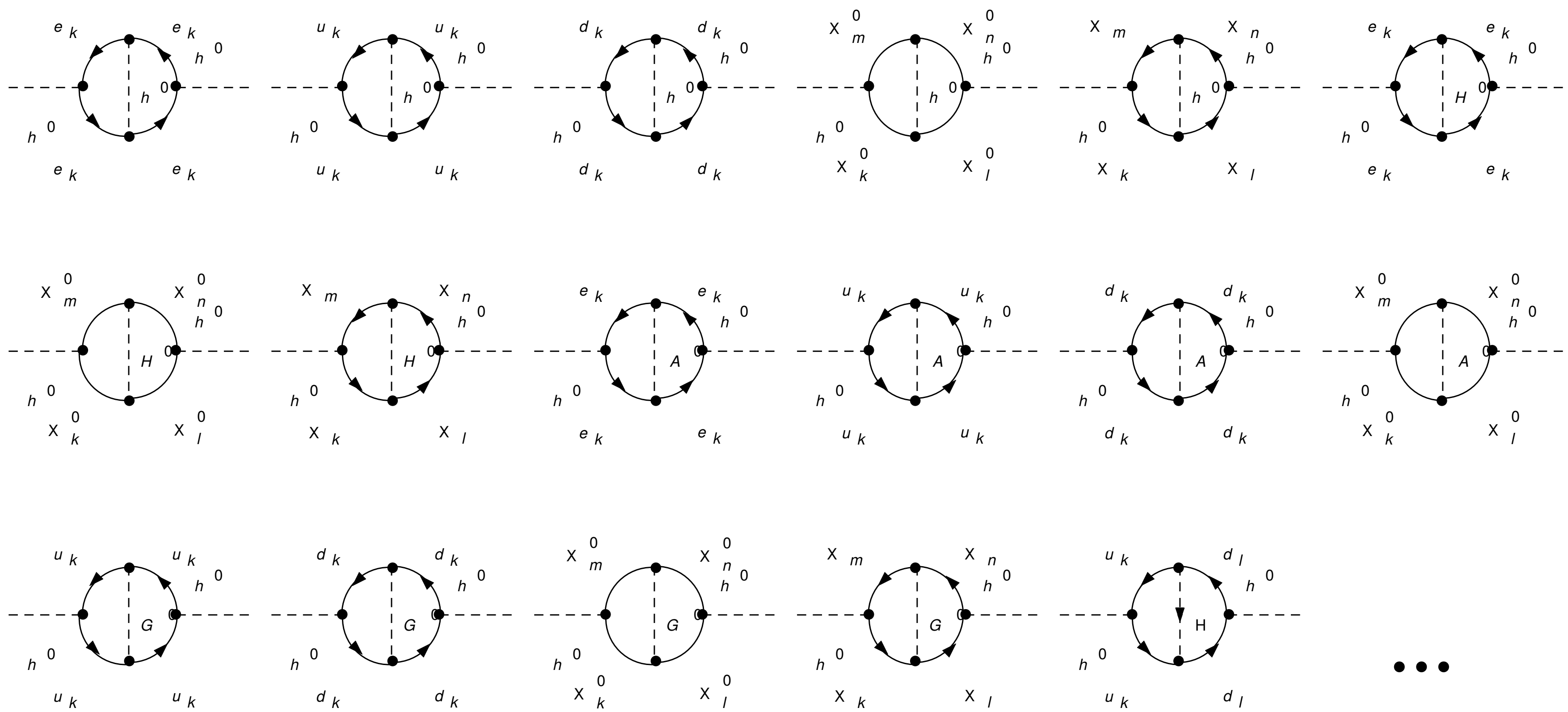
High-scale SUSY: all SUSY particles of $O(\tilde{m}) \gg \mu_{EW}$



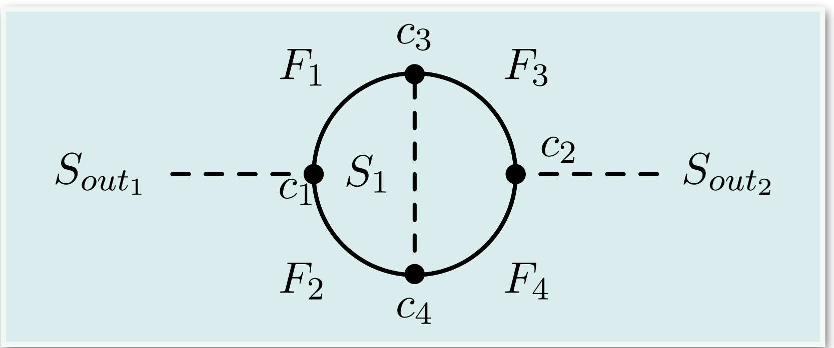
Emanuele Bagnaschi

Precision Higgs mass calculations in BSM

- Generic Higgs mass calculation



- Generic diagram:

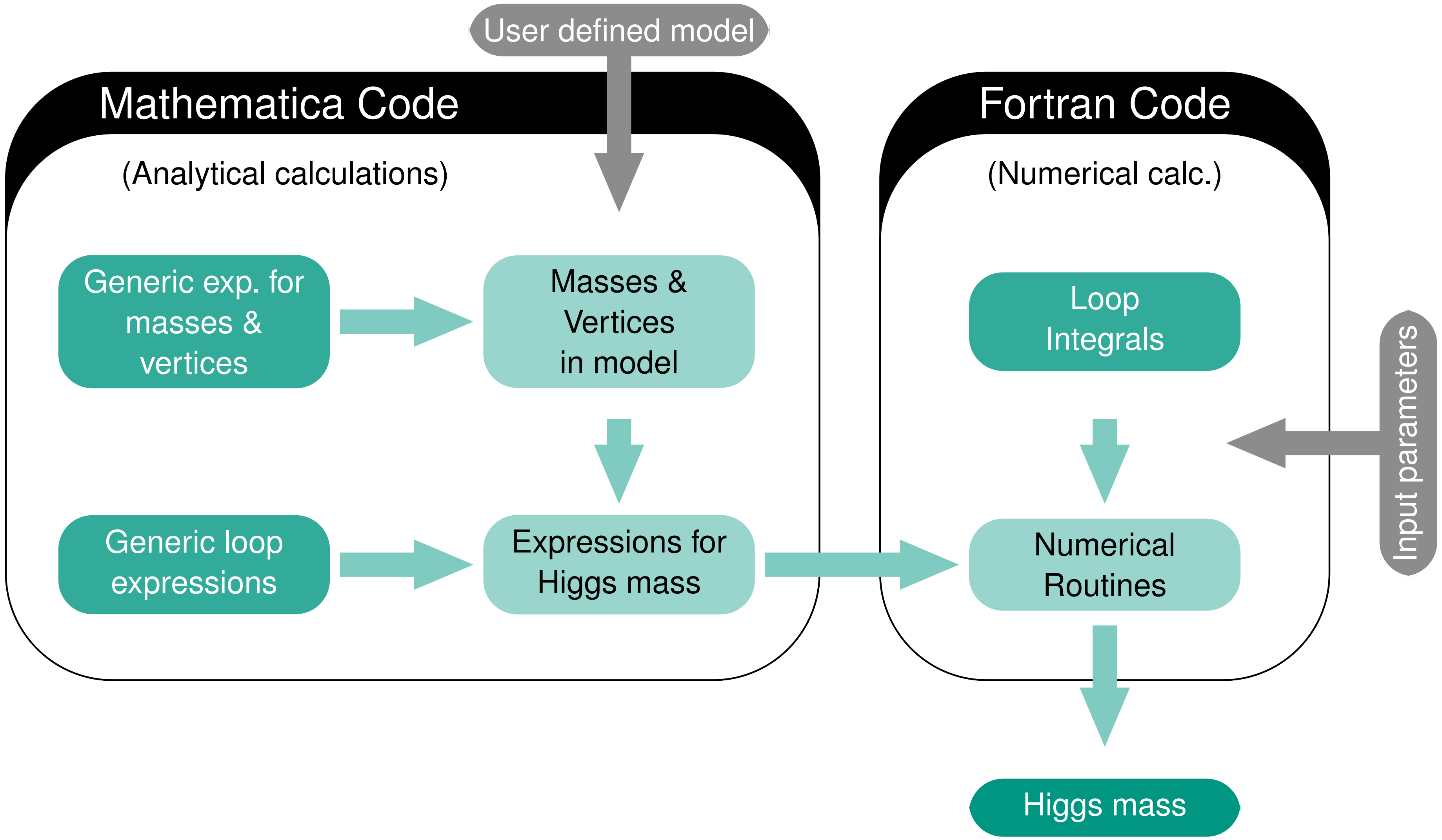


- Valid for any model and any real scalar

Florian Staub

Precision Higgs mass calculations in BSM

* Fully automated two-loop calculations: SARAH/SPheno



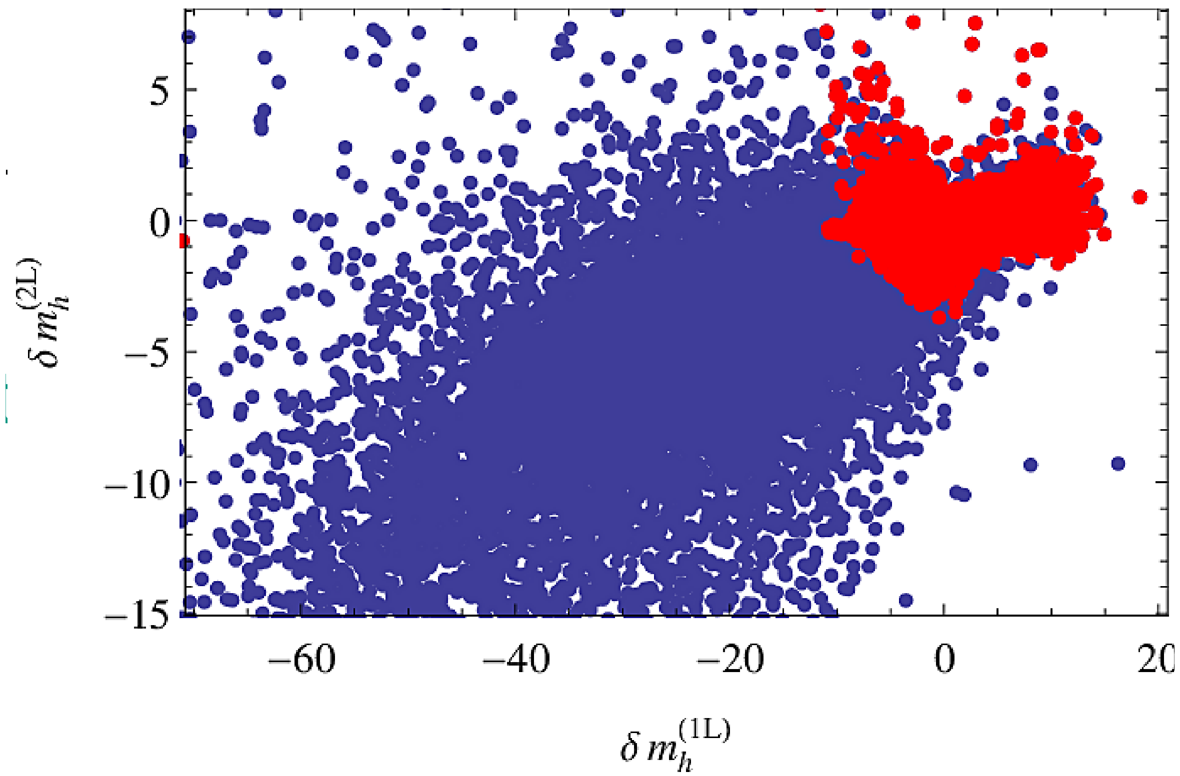
Florian Staub

Precision Higgs mass calculations in BSM

- Study MSSM beyond Minimal Flavour Violation

$$\mathscr{L}_{SB} = \cdots + T_u^{ij}\tilde{u}_i^*\tilde{q}_j H_u + T_d^{ij}\tilde{d}_i^*\tilde{q}_j H_d + T_e^{ij}\tilde{e}_i^*\tilde{l}_j H_d + \text{h.c.}$$

- Constrain couplings T_u^{ij} in the soft-breaking Lagrangian



- Can study NMSSM, vectorlike top partners, Dirac gauginos,…

Florian Staub

Vacuum Stability and Origin of Mass

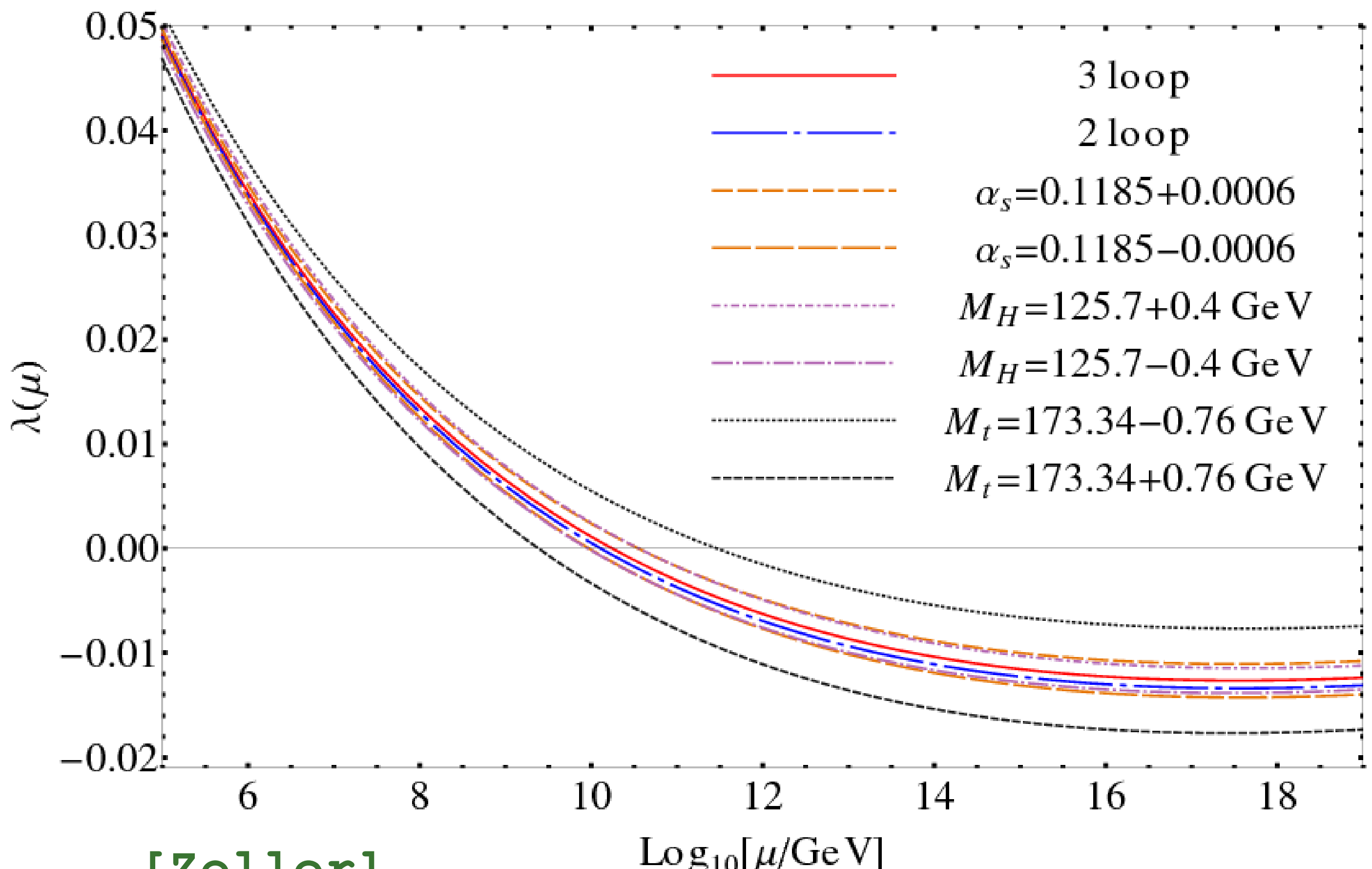
* Higs sector in the SM: —> Wolfgang G. Hollik

$$V_{\rm SM} = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2$$

* BSM: minimum may become unstable

* Running of quartic self-coupling: $\lambda = \lambda(Q)$ $\lambda(Q) \to 0$ for

$$Q \sim H \sim 10^{10}\,\mathrm{GeV}$$



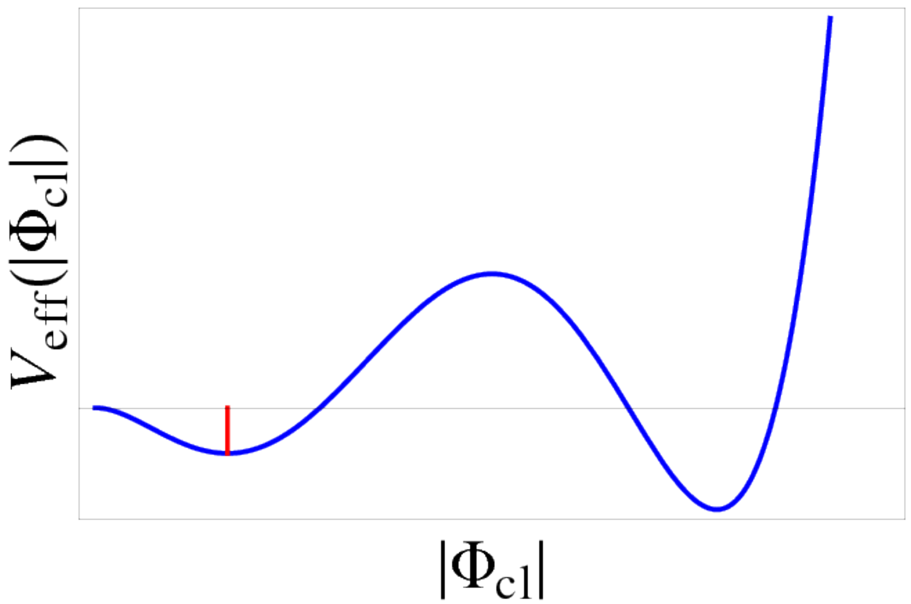
[Zoller]

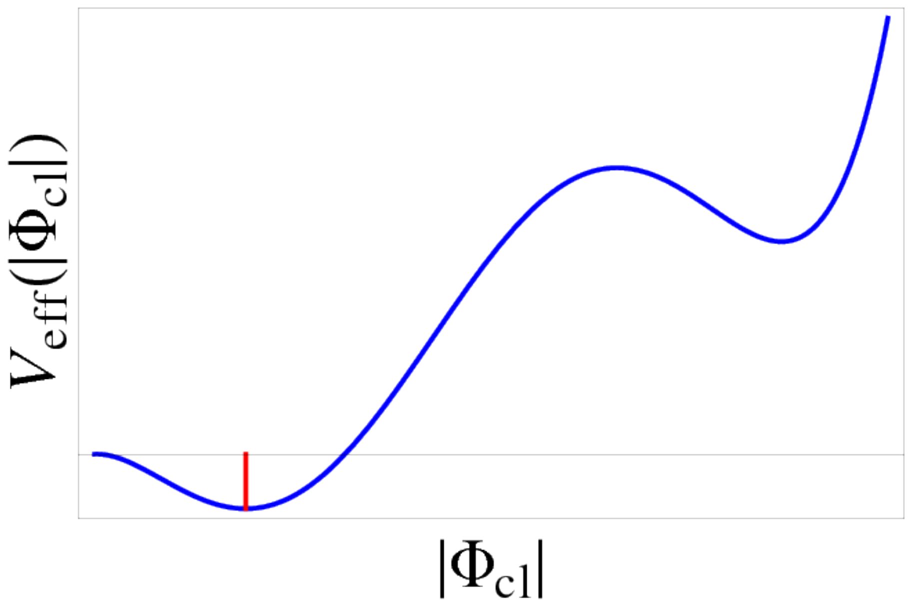
* Main uncertainties:

$$M_{\rm top}, \quad \alpha_s$$

Vacuum Stability and Origin of Mass

- Trans-Planckian VEV





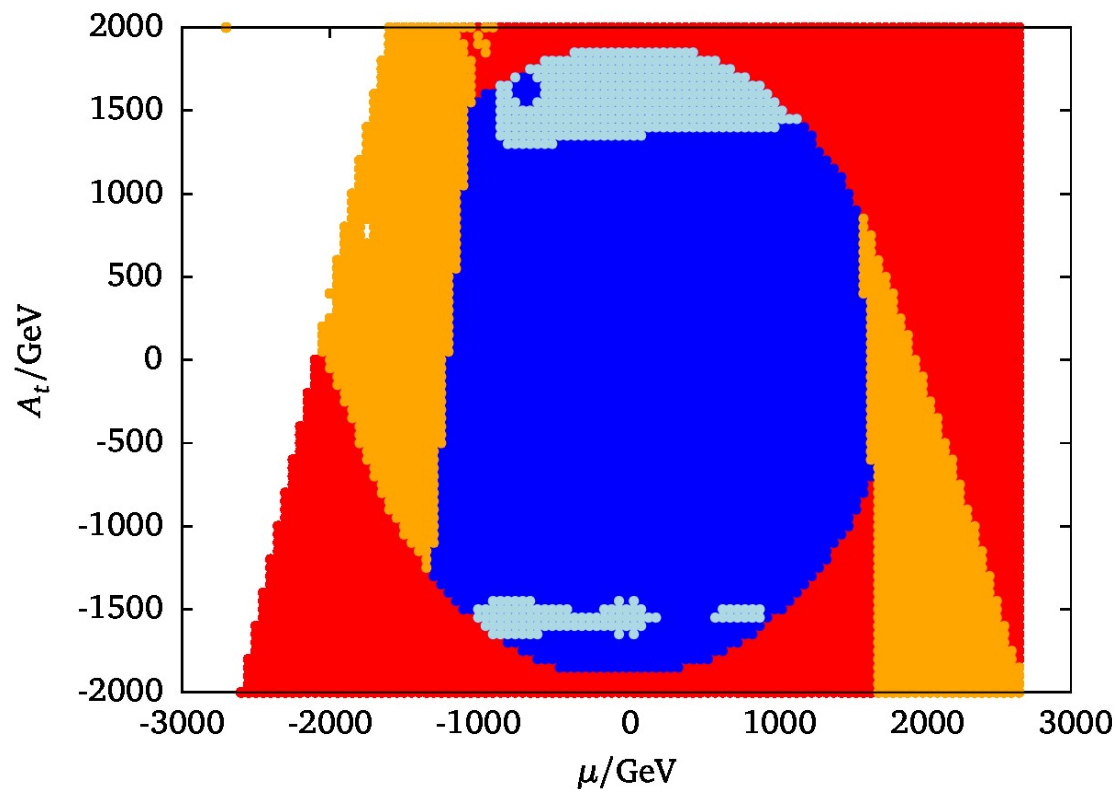
[Zoller]

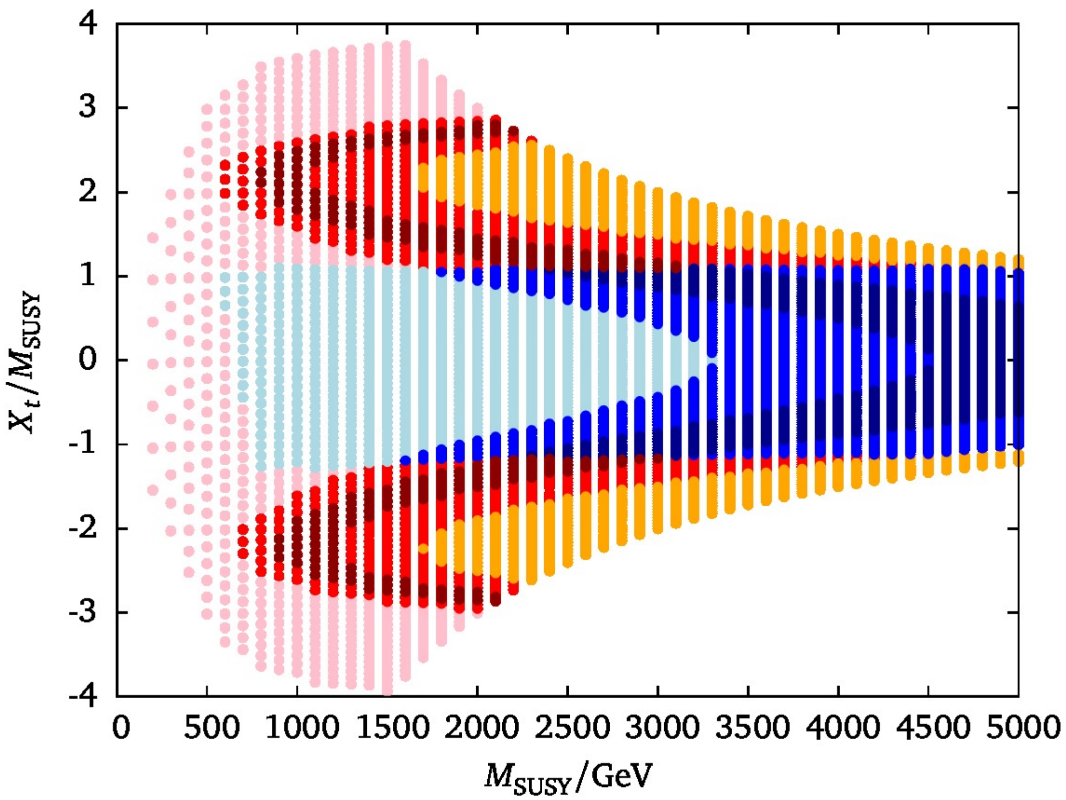
- Vacuum Stability

[Degrassi et al. JHEP 1208 (2012) 098]

Vacuum Stability and Origin of Mass

* BSM model: new particles contribute to the running of λ
* Constrain BSM model parameters:
  require global minimum to coincide with EW minimum

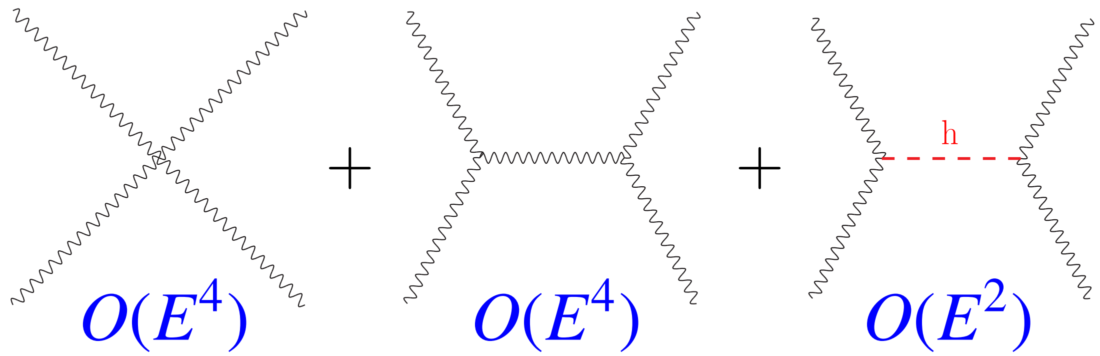




Wolfgang G. Hollik

Vector Boson Scattering

* SM: Higgs exchange cancels energy rise in VBS amplitude



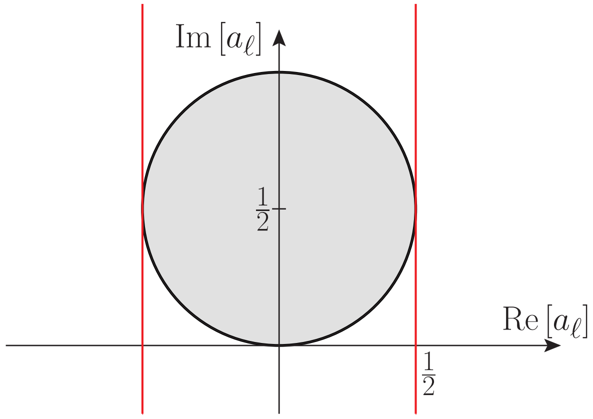
* VBS is sensitive probe for BSM physics: deviation of HVV vertex causes amplitude to grow $\sim O(E^2)$ —> unitarity violations

* EFT approach: new physics contributions via higher-dim. operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \sum_{d\geq 4} \frac{C_i}{\Lambda^{d-4}}\, O_i^d$$

Marco Sekulla

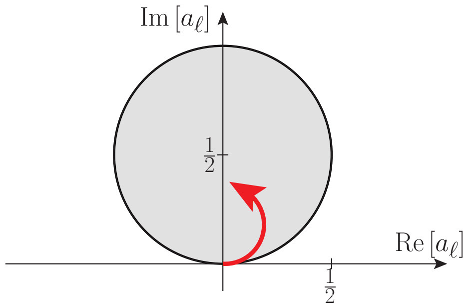
Vector Boson Scattering



* Unitarity implies Argand-circle condition for partial wave amplitude

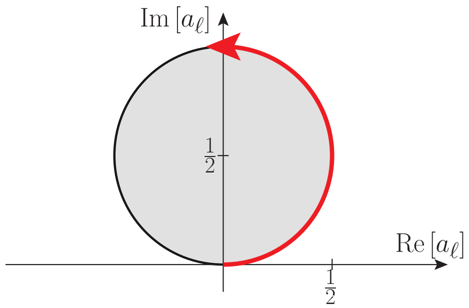
* Scenarios for new physics:

1. Inelastic



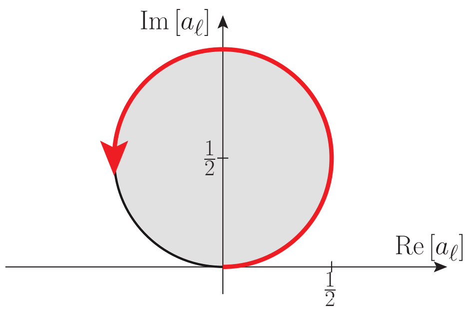
EFT+ Form-factor

2. Saturation



EFT elastic + T-Matrix

3. Resonance

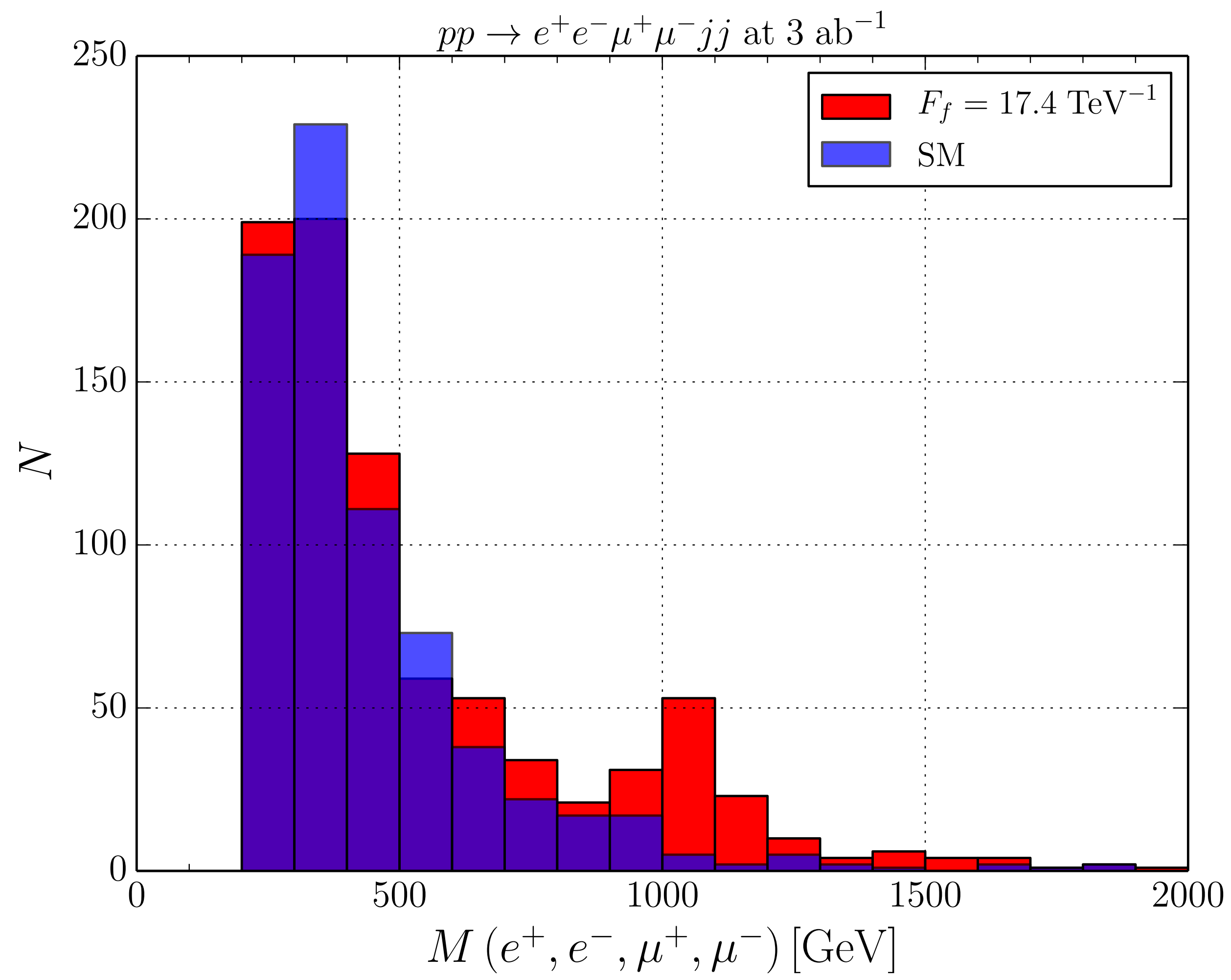


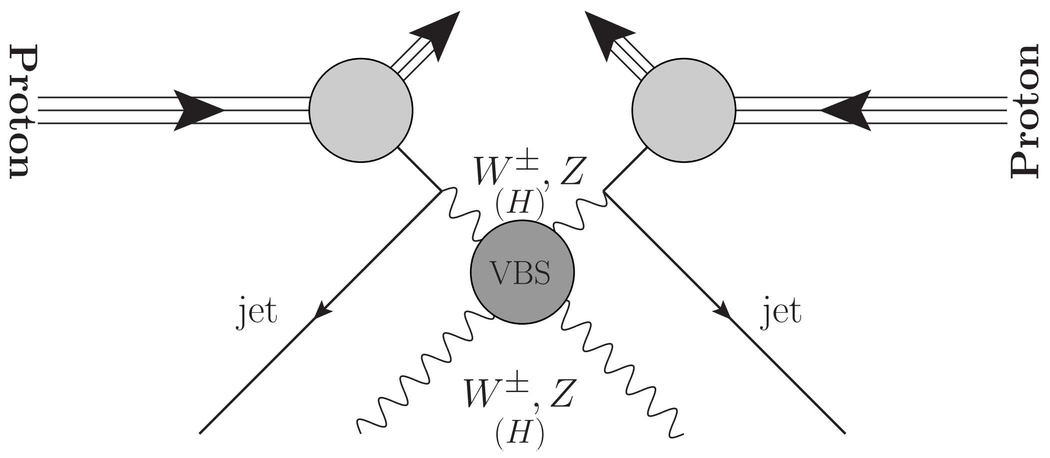
Adding additional resonances

Marco Sekulla

Vector Boson Scattering

- Complete LHC process at 14 TeV in a simplified model with extra tensor resonance:





Marco Sekulla

Theoretical status of the muon $(g-2)$

* Persistent deviation of 3.6 sigma: —> **Andreas Nyffeler**

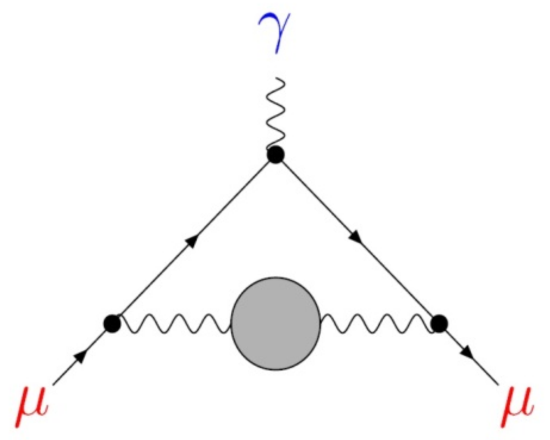
$$a_\mu \equiv \frac{1}{2}(g-2)_\mu = \begin{cases} 116\,592\,080(54)(33)\cdot 10^{-11} & \text{E821 @ BNL} \\ 116\,591\,828(43)(26)(2)\cdot 10^{-11} & \text{SM prediction} \end{cases}$$

$$a_\mu^{\rm SM} = a_\mu^{\rm QED} + a_\mu^{\rm weak} + a_\mu^{\rm had}$$

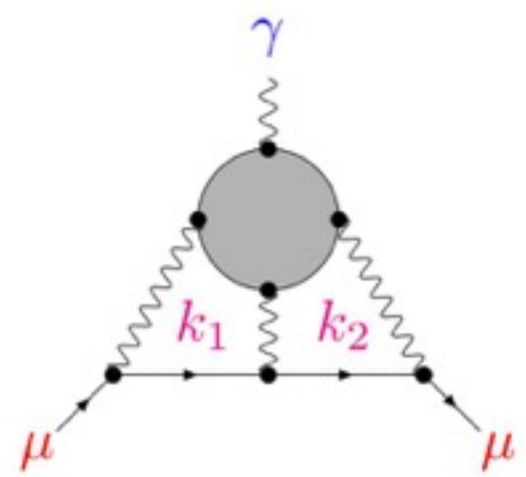
* Theoretical estimate dominated by QED

* Uncertainty of SM prediction dominated by QCD:

Hadronic vacuum polarisation:



Hadronic light-by-light scattering:

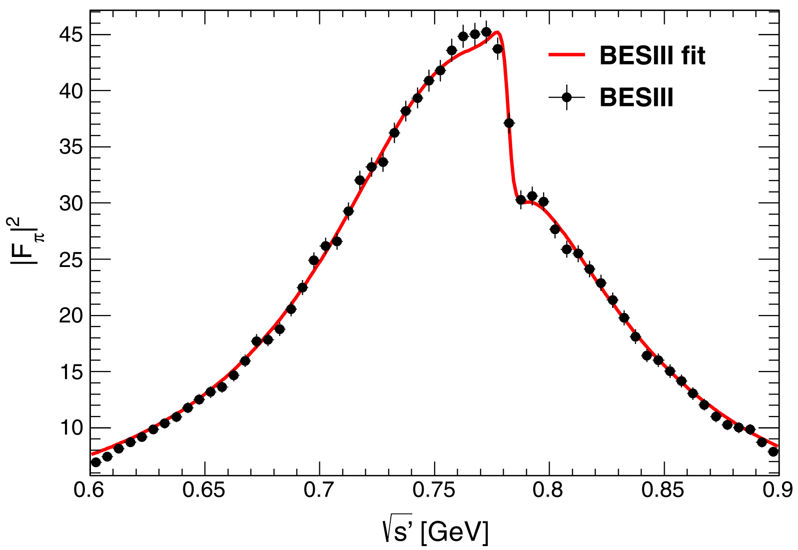


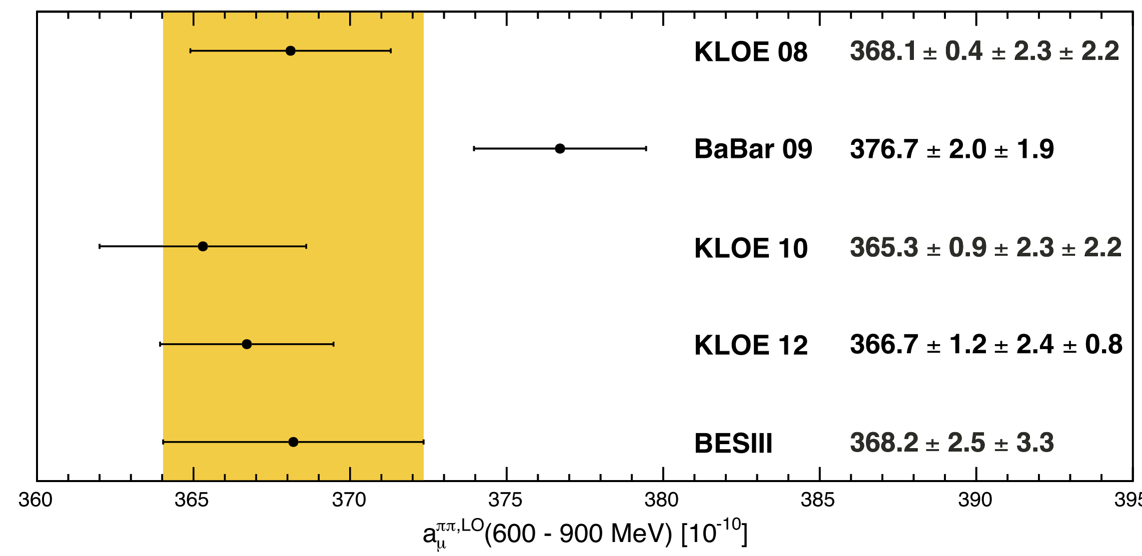
Theoretical status of the muon $(g-2)$

* **Dispersion relations:**

$$a_\mu^{\rm hvp} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \left\{ \int_{m_\pi^2}^{E_{\rm cut}^2} ds\, \frac{R_{\rm had}^{\rm data}(s)\hat{K}(s)}{s^2} + \int_{E_{\rm cut}^2}^{\infty} ds\, \frac{R_{\rm had}^{\rm pQCD}(s)\hat{K}(s)}{s^2} \right\}$$

* Relies on experimental data for hadronic cross section $R_{\rm had}(e^+e^- \to \text{hadrons})$





* New measurements of pion form factor by BESIII confirm 3.6σ tension

* **Lattice QCD:** Major effort in to compute $a_\mu^{\rm hvp}$; Current precision: $O(5\%)$

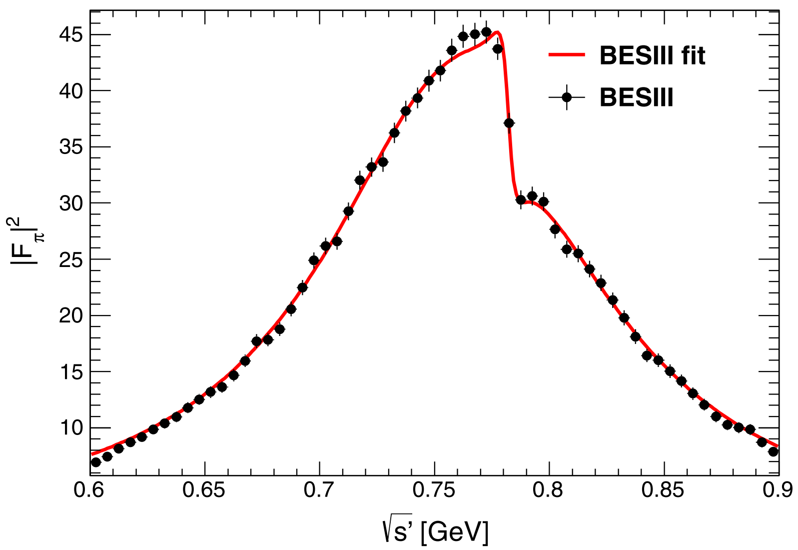
Andreas Nyffeler

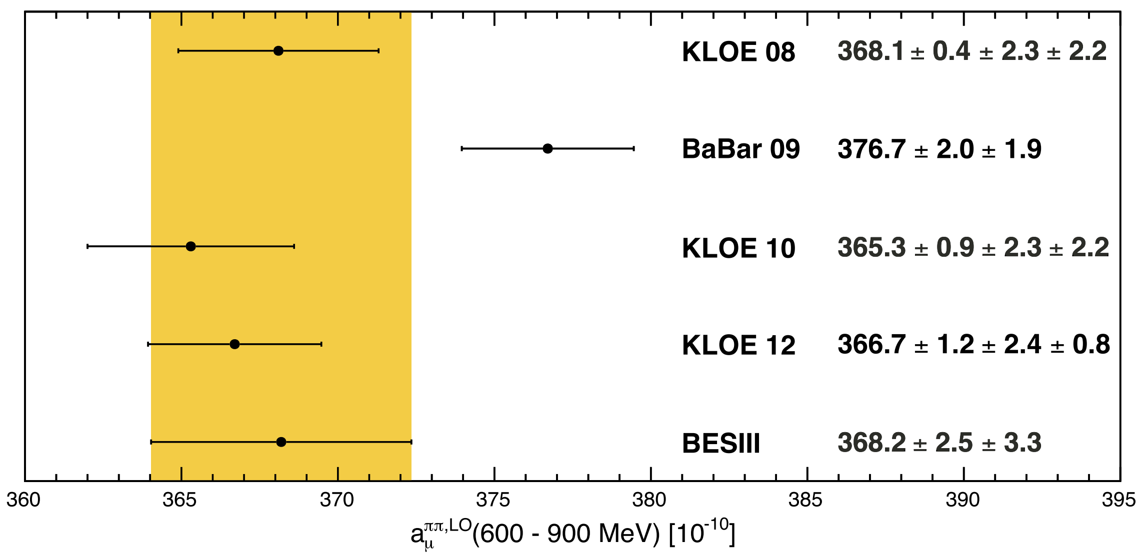
Theoretical status of the muon $(g-2)$

* **Dispersion relations:**

$$a_\mu^{\rm hvp} = \left(\frac{\alpha m_\mu}{3\pi}\right)^2 \left\{ \int_{m_\pi^2}^{E_{\rm cut}^2} ds\, \frac{R_{\rm had}^{\rm data}(s)\hat{K}(s)}{s^2} + \int_{E_{\rm cut}^2}^{\infty} ds\, \frac{R_{\rm had}^{\rm pQCD}(s)\hat{K}(s)}{s^2} \right\}$$

* Relies on experimental data for hadronic cross section $R_{\rm had}(e^+e^- \to \text{hadrons})$



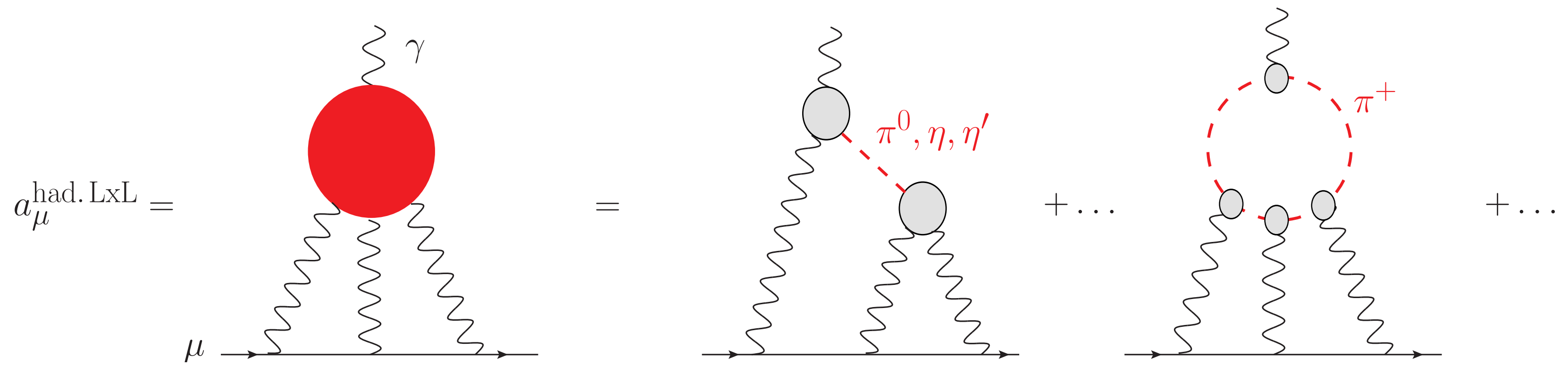


* **Lattice QCD:** Major effort in to compute $a_\mu^{\rm hvp}$; Current precision: $O(5\%)$

Andreas Nyffeler

Theoretical status of the muon (g–2)

Hadronic Light-by-Light Scattering



- ✱ Use hadronic models at low energies; exchange/loop contributions from resonances and dressed quark loops at high energies

- ✱ New approach: **Dispersion relations** to connect dominant light PS contributions to measurable form factors, e.g. $\gamma^*\gamma^* \to \pi^0, \eta, \eta'$

- ✱ **Lattice QCD:** RBC/UKQCD Collab. (2005–2016), Mainz (2015/16)

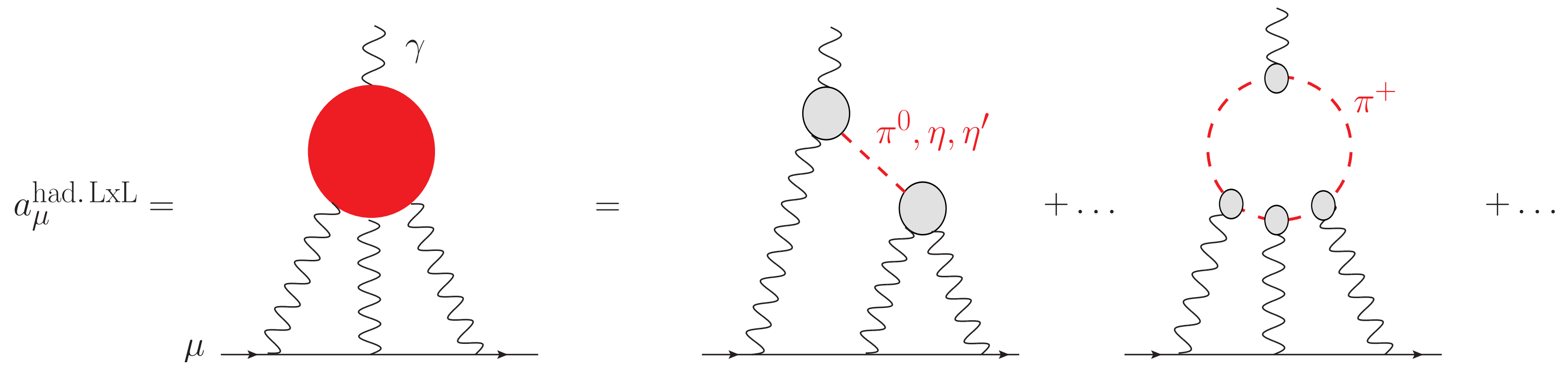
- ✱ Various new physics scenarios to explain $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (290 \pm 90) \cdot 10^{-11}$

  SUSY @ large $\tan\beta$, dark photons,…

Andreas Nyffeler

Theoretical status of the muon (g–2)

Hadronic Light-by-Light Scattering



- New approach: **Dispersion relations** to connect dominant light PS contributions to measurable form factors, e.g. $\gamma^*\gamma^* \to \pi^0, \eta, \eta'$

- **Lattice QCD:** RBC/UKQCD Collab. (2005–2016), Mainz (2015/16)

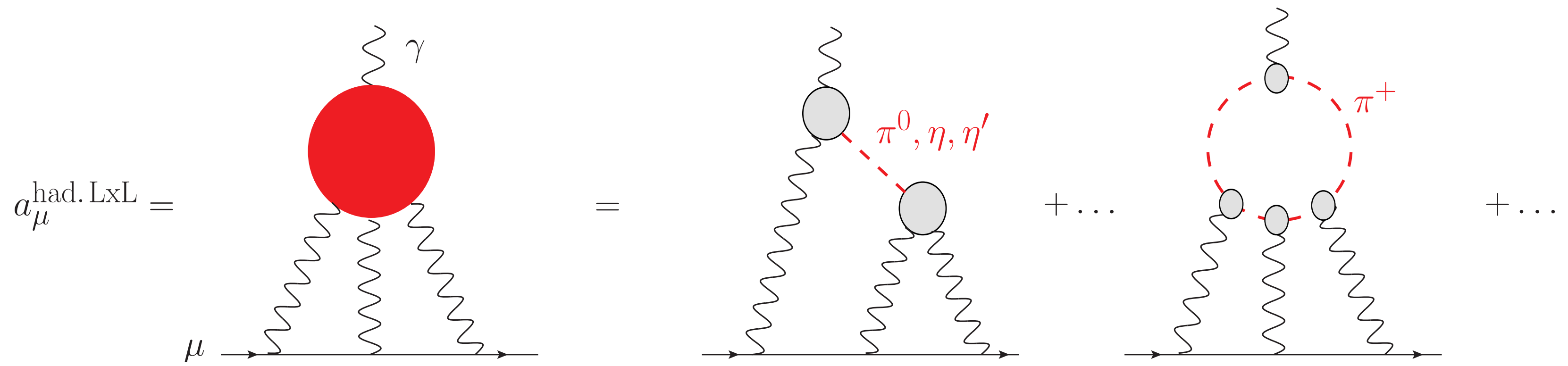
- Various new physics scenarios to explain $a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = (290 \pm 90) \cdot 10^{-11}$

  SUSY @ large $\tan\beta$, dark photons,…

Andreas Nyffeler

Theoretical status of the muon (g–2)

Hadronic Light-by-Light Scattering



- New approach: **Dispersion relations** to connect dominant light PS contributions to measurable form factors, e.g. $\gamma^*\gamma^* \to \pi^0, \eta, \eta'$

- Various new physics scenarios to explain $a_\mu^{\rm exp} - a_\mu^{\rm SM} = (290 \pm 90)\cdot 10^{-11}$

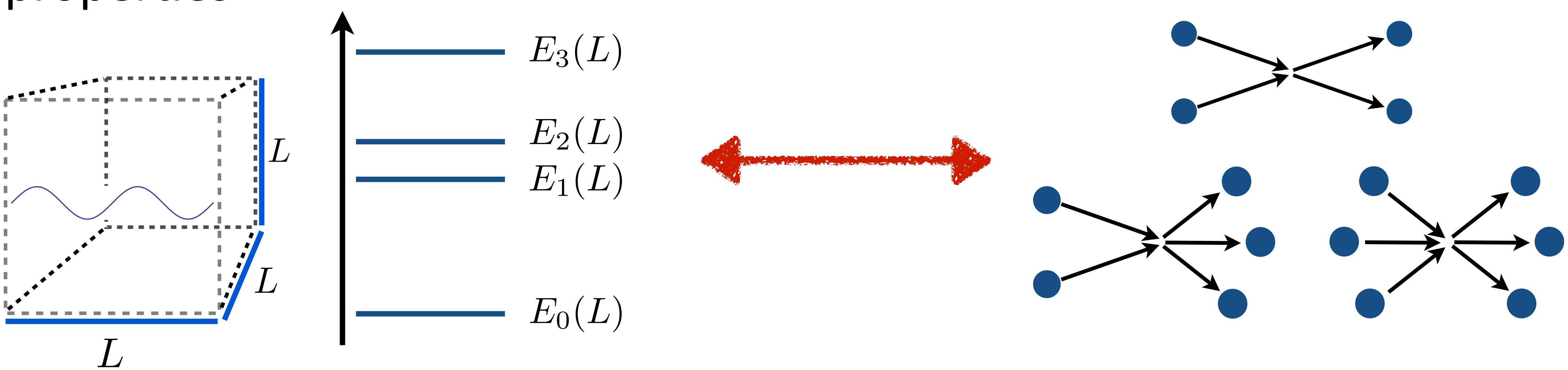
  SUSY @ large $\tan\beta$, dark photons,…

Andreas Nyffeler

Resonances and scattering in LQCD

- Impossible to compute scattering amplitudes directly in Lattice QCD —> **Max Hansen**

- Can obtain energy levels in a finite box —> relation to resonance properties



- (Generalised) Lüscher quantisation condition:

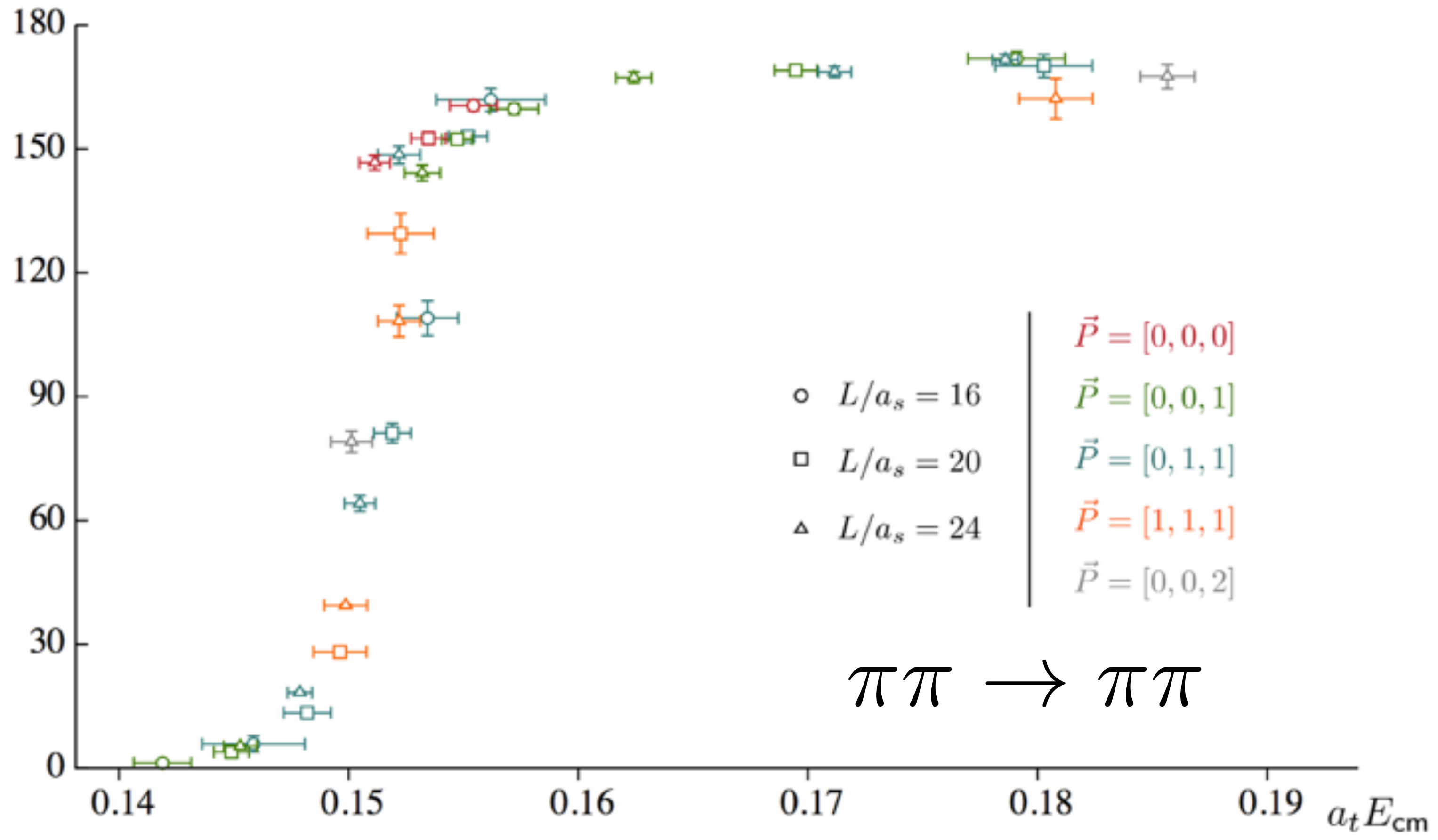
$$\det\left[\mathcal{M}_2^{-1}(E_n^*) + F(E_n, \vec{P}, L)\right] = 0$$

scattering amplitude — known geometric function

Resonances and scattering in LQCD

* Simplest case: 2 —> 2 scattering

$$\cot\delta_{\ell=1}(E_n^*) + \cot\phi(E_n, \vec{P}, L) = 0$$

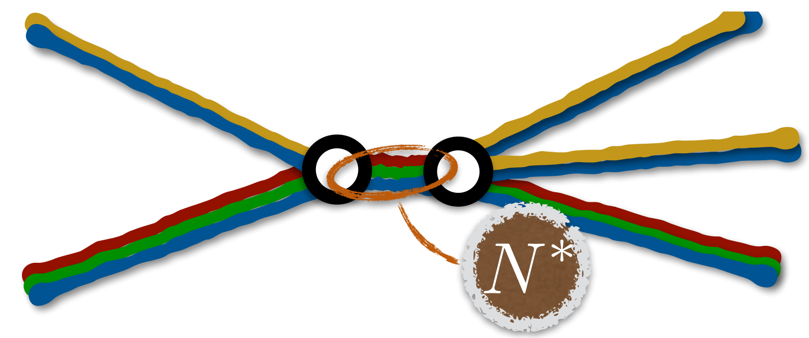


Max Hansen

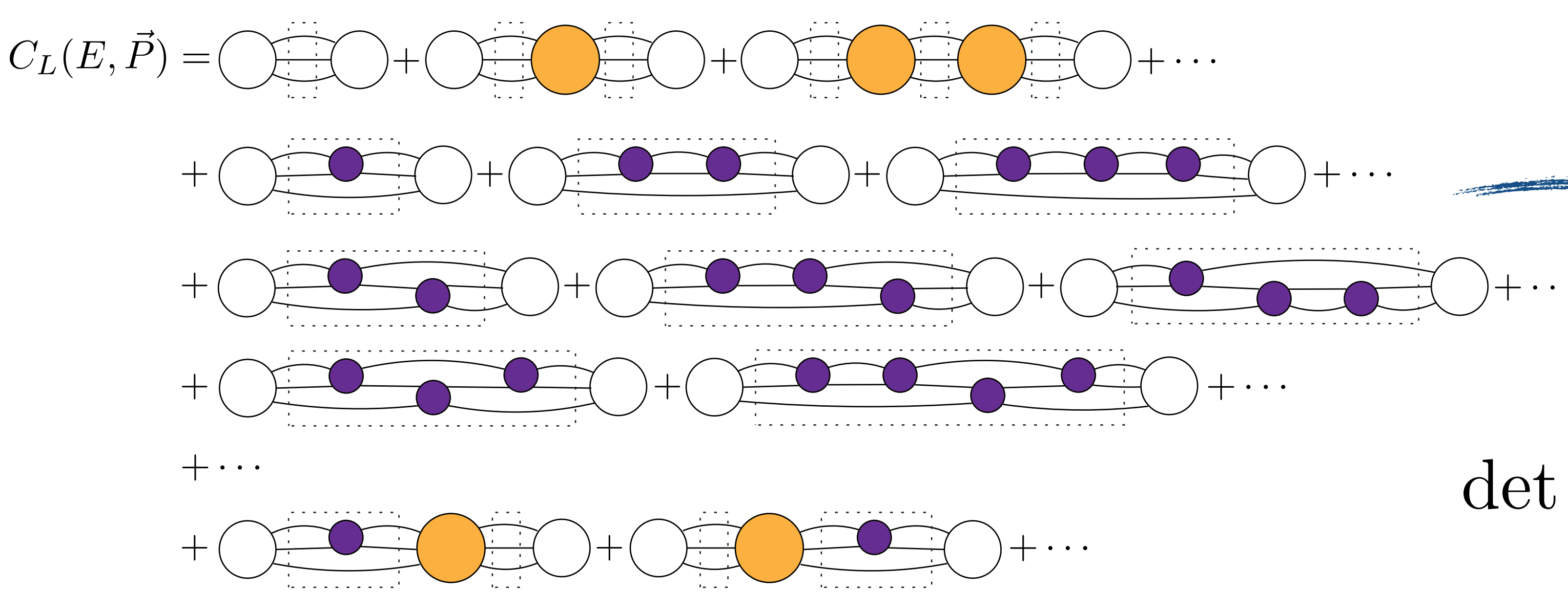
Resonances and scattering in LQCD

* Derive generalisation for arbitrary two- and three-particle systems

* Relevant for 3-particle resonances, weak decay amplitudes $K \longrightarrow \pi\pi\pi$, …



* Formalism complete for simplest three-particle system



$$\det\left[\mathcal{K}_{\mathrm{df},3}^{-1}(E_n^*) + F_3(E_n,\vec{P},L)\right] = 0$$

Max Hansen

Summary

Many efforts to constrain BSM models

- Higgs mass calculations
- Vacuum stability
- Vector boson scattering
- Low-energy precision observables

Methods

- Effective field theories, multi-loop calculations, lattice simulations

Understand hadronic uncertainties

- strong coupling α_s, hadronic contributions to $(g-2)$