# POLXINO: Neutralino, chargino and gluino two-loop pole mass calculator

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# Outline

1. Motivation
   - Challenging experimental accuracy
2. Underlying works
3. Outline of the calc.
   - Tree-level mass matrices
   - Pole mass to two loop order $\mathcal{O}(\alpha\alpha_S, Y^4, \alpha_S Y^2)$
   - The perturbative expansion
   - Automatisms vs. generic calculations
   - Diagrammatics
   - Checks
4. Numerical results
   - Two scenarios
5. Description of Polxino
6. Conclusion & Outlook

# challenging experimental accuracy

- Accuracy at future collider experiments at the ILC and LHC is quite challenging. The physics interplay has been worked out by the LHC/LC study group [G. Weiglein *et al.*, 2004]

accuracy from experiment at LHC + ILC (SPS1a')

| Particle | Mass | "LHC" | "ILC" | "LHC+ILC" |
|---|---|---|---|---|
| $\tilde{\chi}_1^0$ | 97.7 | 4.8 | 0.05 | 0.05 |
| $\tilde{\chi}_2^0$ | 183.9 | 4.7 | 1.2 | 0.08 |
| $\tilde{\chi}_1^\pm$ | 183.7 | | 0.55 | 0.55 |
| $\tilde{q}_R$ | 547.2 | 7 – 12 | – | 5 – 11 |
| $\tilde{q}_L$ | 564.7 | 8.7 | – | 4.9 |
| $\tilde{g}$ | 607.1 | 8.0 | – | 6.5 |

[SPA, J. A. Aguilar-Saavedra *et al.*, 2005 ], all numbers in GeV

- $LHC \sim m^2_{\chi_1^0} - m^2_{\chi_2^0}$, $ILC \sim m_{\chi_1^0}$
- relate observables to $\overline{\mathrm{DR}}$ -input at the two-loop level

# Underlying works

- "Two-loop SUSY QCD corrections to the neutralino masses in the MSSM"
  by R. Schöfbeck and H. Eberl,
  PLB 649 (2007) 67, arXiv:0612276 [hep-ph].
- "Two-loop SUSY QCD corrections to the chargino masses in the MSSM"
  by R. Schöfbeck and H. Eberl,
  EPJC 53 (2008) 621, arXiv:0706.0781 [hep-ph].
- "Leading two-loop Yukawa corrections to the pole masses of SUSY fermions in the MSSM"
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- "Precise predictions for the masses of supersymmetric fermions including two-loop corrections"
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# Outline of the calculation

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# Tree-level mass matrices

## Chargino mass matrix at tree level

$$
\begin{aligned}
X &= \begin{pmatrix} M_2 & \sqrt{2} M_W \sin\beta \\ \sqrt{2} M_W \cos\beta & \mu \end{pmatrix} \\
M_D^{\tilde{\chi}^+} &= U^* X V^\dagger = \mathrm{diag}(m_{\tilde{\chi}_1^+}, m_{\tilde{\chi}_2^+})
\end{aligned}
$$

## Neutralino mass matrix at tree level

$$
\begin{aligned}
Y &= \begin{pmatrix} M_1 & & & \mathrm{sym.} \\ 0 & M_2 & & \\ -M_Z \cos\beta \sin\theta_W & M_Z \cos\beta \cos\theta_W & 0 & \\ M_Z \sin\beta \sin\theta_W & -M_Z \sin\beta \cos\theta_W & -\mu & 0 \end{pmatrix} \\
M_D^{\tilde{\chi}^0} &= N^* Y N^\dagger = \mathrm{diag}(m_{\tilde{\chi}_1^0}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_3^0}, m_{\tilde{\chi}_4^0})
\end{aligned}
$$

# pole mass to two loop order I

## renormalized 2-point function $\Gamma^{(2)\tilde{\chi}\tilde{\chi}}$

$$G^{(2)-1}_{\tilde{\chi}\tilde{\chi}} = -i\Gamma^{(2)\tilde{\chi}\tilde{\chi}} = -i \begin{pmatrix} -M_D + \hat{\Sigma}^L_m(s) & \sigma \cdot k(1 + \hat{\Sigma}^R_k(s)) \\ \bar{\sigma} \cdot k(1 + \hat{\Sigma}^L_k(s)) & -M_D^\dagger + \hat{\Sigma}^R_m(s) \end{pmatrix}$$

$$s = k^2$$

## Pole mass condition

$$0 = \det\left(s - \left(M_D - \hat{\Sigma}^L_m(s)\right) \cdot \left(1 + \hat{\Sigma}^L_k(s)\right)^{-1} \cdot \left(M_D^\dagger - \hat{\Sigma}^R_m(s)\right) \cdot \left(1 + \hat{\Sigma}^R_k(s)\right)^{-1}\right)$$

## Iterative solution to two-loop order

$$s_{i,pole} = |m_{\tilde{\chi}_i}|^2 - \delta m^{2(1)}_{\tilde{\chi}_i} - \delta m^{2(2)}_{\tilde{\chi}_i} \text{with}$$

$$\delta m^{2(1)}_{\tilde{\chi}_i} = \Pi^{(1)}_{ii} \quad \text{and} \quad \delta m^{2(2)}_{\tilde{\chi}_i} = \Pi^{(2)}_{ii} - \Pi^{(1)}_{ii}\frac{\partial \Pi^{(1)}_{ii}}{\partial s} - \sum_{i \neq j} \frac{\Pi^{(1)}_{ij}\Pi^{(1)}_{ji}}{m_i^2 - m_j^2}$$

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$$s = k^2$$

## Pole mass condition

$$0 = \det\left(s - \left(M_D - \hat{\Sigma}^L_m(s)\right)\cdot\left(1+\hat{\Sigma}^L_k(s)\right)^{-1}\cdot\left(M^\dagger_D - \hat{\Sigma}^R_m(s)\right)\cdot\left(1+\hat{\Sigma}^R_k(s)\right)^{-1}\right)$$

## Iterative solution to two-loop order

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# pole mass to two loop order II

$$
\begin{aligned}
\Pi^{(1)}_{ij} &= m_i m_j^\dagger {\hat\Sigma_k^{(1)L}}_{ij} + |m_j|^2 {\hat\Sigma_k^{(1)R}}_{ij} + m_j^\dagger {\hat\Sigma_m^{(1)L}}_{ij} + m_i {\hat\Sigma_m^{(1)R}}_{ij} \\
\Pi^{(2)}_{ii} &= m_i^\dagger {\hat\Sigma_m^{(2)L}}_{ii} + m_i {\hat\Sigma_m^{(2)R}}_{ii} + |m_i|^2 ({\hat\Sigma_k^{(2)L}}_{ii} + {\hat\Sigma_k^{(2)R}}_{ii}) \\
&\quad - \Bigg( |m_i|^2 \left( {\Sigma_k^{(1)R}}_{ij} {\Sigma_k^{(1)R}}_{ji} + {\Sigma_k^{(1)L}}_{ij} {\Sigma_k^{(1)L}}_{ji} \right) + m_i^\dagger ({\Sigma_k^{(1)R}}_{ij} {\Sigma_m^{(1)L}}_{ji} + {\Sigma_m^{(1)L}}_{ij} {\Sigma_k^{(1)L}}_{ji}) \\
&\quad + m_i {\Sigma_k^{(1)L}}_{ij} {\Sigma_m^{(1)R}}_{ji} + m_j {\Sigma_k^{(1)R}}_{ij} {\Sigma_m^{(1)R}}_{ji} + m_i^\dagger m_j {\Sigma_k^{(1)R}}_{ij} {\Sigma_k^{(1)L}}_{ji} + {\Sigma_m^{(1)L}}_{ij} {\Sigma_m^{(1)R}}_{ji} \Bigg) ,
\end{aligned}
$$

with all selfenergies evaluated at $s = |m_i|^2$.

# The perturbative expansion

- regularization: DRED
  gauge fields come with unphysical scalar fields ($\epsilon$-scalars) to restore the counting of DOF for SUSY
- renormalization: $\overline{\mathrm{DR}}\,'$ ($\overline{\mathrm{DR}}$)
  - subtract $1/\epsilon$-piece
  - absorb unphysical $m_\epsilon$ parameter in sfermion mass parameters [Martin '01]
- IR-regulating mass for massless vectors
- EWSB VEVs
  - expand around the loop corrected potential
  - no tadpoles needed
- gauge
  - Landau ($R_{\xi=0}$) gauge for massive vectors
  - Feynman ($R_\xi$) gauge for the gluon

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# A sidenote on the approaches

## How to do tensor reduction best

- use CAS (Mathematica) to design one-for-all tools producing auto-generated code
  - + use for all kinds of particles, not only fermions
  - + no inherent restriction on scheme, gauge, ...
  - + disentangle graphs and counter-term contributions
  - - complicated code
  - - rather slow in compilation and at runtime
- using generic once-and-for-all results
  - + simple code
  - + very fast in programming and execution
  - - a little less flexible
  - + already available "gluinopole.c" [S.P. Martin, '05]

**we did both!**

(and happily, the results agree precisely)

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# A sidenote on the approaches

## How to do tensor reduction best

- use CAS (Mathematica) to design one-for-all tools producing auto-generated code
    - + use for all kinds of particles, not only fermions
    - + no inherent restriction on scheme, gauge, ...
    - + disentangle graphs and counter-term contributions
    - - complicated code
    - - rather slow in compilation and at runtime
- using generic once-and-for-all results
    - + simple code
    - + very fast in programming and execution
    - - a little less flexible
    - + already available "gluinopole.c" [S.P. Martin, '05]

**we did both!**

(and happily, the results agree precisely)

# The hard(er) way

## CAS based approach

- Generation of Diagrams
  - FeynArts 3.2 ($2 \cdot (36 + 128)$ diagrams)[J.Küblbeck, T. Hahn, et. al, '90]
- Analytic simplification
  - conversion to FeynCalc 4.0.2 and evaluation of color and Dirac traces
  - tensor reduction using Tarcer [R. Mertig, R. Scharf, '98]
  - Taylor expansion of Tarcer basis integrals in $d-4$ to scalar basis integrals
- Numerical evaluation
  - auto-creating Fortran code calling TSIL basis integrals [S.P. Martin and D.G. Robertson, '05]
  - use some FormCalc subroutines for calculating the SUSY spectra
  - use two-loop methods also for one-loop integrals by multiplying with some artificial vacuum bubble

⇒ completely independent calculation
up to the evaluation of the basis integrals

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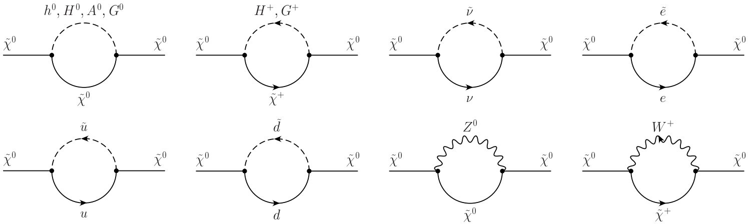
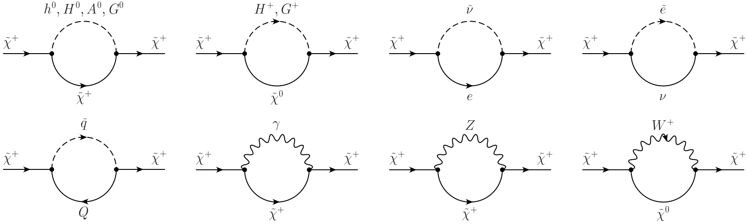
# Generating Amplitudes using FeynArts

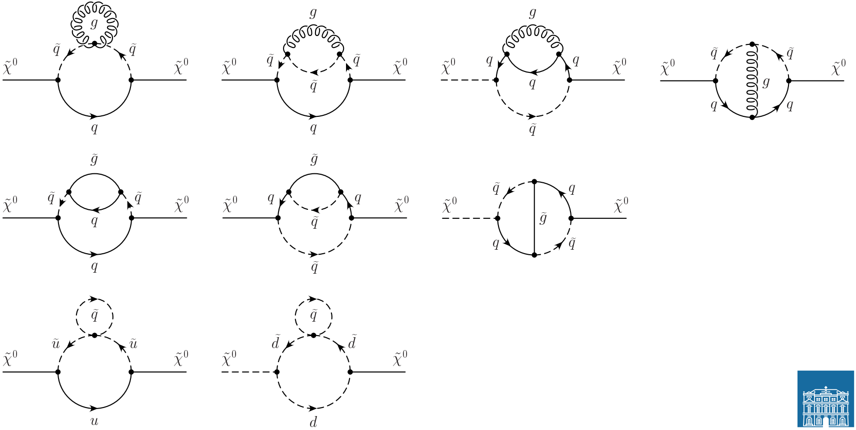
## Neutralinos



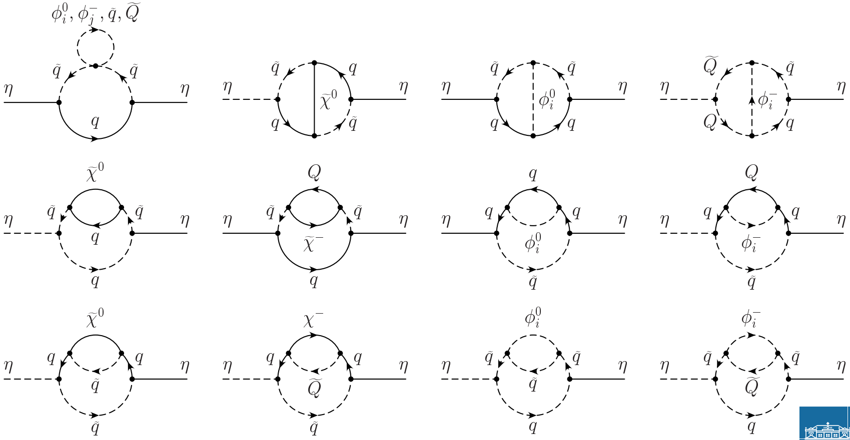
## Charginos



# Two loop SQCD diagrams for neutralinos

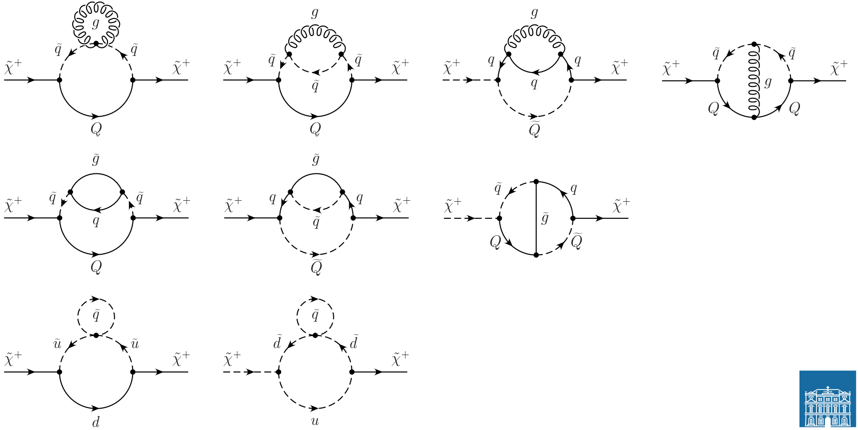


# Two loop Yukawa corr. diagrams for neutralinos



$$\eta = \tilde{\chi}^0$$

# Two loop SQCD diagrams for charginos



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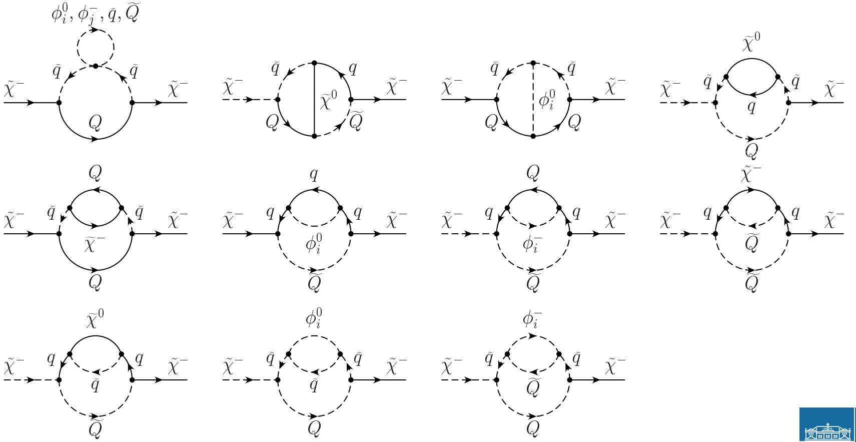

## Checking the Result

### Analytic Checks

- gauge parameter independence of the gluon gauge parameter
- explicit cancellation of $m_\epsilon$ contributions in $\overline{\mathrm{DR}}\,'$
- IR finiteness by extraction of the IR divergent parts in each diagram
- rather non-trivial: RGE check (UV finiteness) on $\mathrm{tr}(Y^\dagger Y) = \mathrm{tr}(M_D^\dagger M_D)$
- one-loop results agree with previous work [W. Öller '03, T. Fritzsche '04]

### Checks on the Numerics

- RGE check of mass shifts $\delta m_{\tilde{\chi}_i}$ against Spheno [W. Porod, '03]

### Check on the whole strategy

- SQCD corrections to the gluino pole mass agree with known result [S.P. Martin, '05]

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# Numerics

# Two scenarios

- Gaugino scenario:
  the SPS1a′ benchmark point J.A. Aguilar-Saavedra '05 *et.al.*, Porod '03
  The $\overline{\mathrm{DR}}$ SUSY Lagrangian parameters at the scale $Q = 1\ \mathrm{TeV}$

| Parameter | SPS1a′ value | Parameter | SPS1a′ value |
|---|---|---|---|
| $g'$ | 0.3636 | $M_1$ | 103.3 |
| $g$ | 0.6479 | $M_2$ | 193.2 |
| $g_s$ | 1.0844 | $M_3$ | 571.7 |
| $Y_\tau$ | 0.1034 | $A_\tau$ | −445.2 |
| $Y_t$ | 0.8678 | $A_t$ | −565.1 |
| $Y_b$ | 0.1354 | $A_b$ | −943.4 |
| $\mu$ | 401.6 | $\tan\beta$ | 10.0 |

- Higgsino scenario:
  $\mu = 130\ \mathrm{GeV}$, $M_2 = 400\ \mathrm{GeV}$, $M_1 = M_2/2$,
  other parameters from SPS1a′

# Gaugino scenario

- Neutralino masses [GeV]

$m_{\tilde{\chi}^0_1} = \ 100.68 \ -3.04 \ \ -0.07 \ +0.00$
$m_{\tilde{\chi}^0_2} = \ 181.32 \ +2.83 \ \ -0.19 \ +0.00$
$m_{\tilde{\chi}^0_3} = \ 407.35 \ -1.65 \ \ +0.16 \ +0.30$
$m_{\tilde{\chi}^0_4} = \ 421.85 \ -3.14 \ \ +0.05 \ +0.83$

- Chargino masses [GeV]

$m_{\tilde{\chi}^+_1} = \ 180.94 \ +2.98 \ \ -0.19 \ +0.00$
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- Gluino mass [GeV]

$m_{\tilde{g}} = \ 572.33 \ +39.14 \ \ +11.06 \ +0.00$

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# Higgsino scenario

- Neutralino masses [GeV]

  $m_{\tilde{\chi}^0_1} = 106.54 \; -8.69 \; -2.19 \; +2.11$
  $m_{\tilde{\chi}^0_2} = 137.22 \; +1.92 \; +1.52 \; -1.36$
  $m_{\tilde{\chi}^0_3} = 212.81 \; -5.66 \; -1.85 \; +1.88$
  $m_{\tilde{\chi}^0_4} = 417.87 \; -3.97 \; -1.90 \; +1.94$

- Chargino masses [GeV]

  $m_{\tilde{\chi}^+_1} = 121.54 \; +8.63 \; -1.42 \; +1.36$
  $m_{\tilde{\chi}^+_2} = 417.75 \; -9.16 \; -1.72 \; +1.74$

- Gluino mass [GeV]

  $m_{\tilde{g}} = 572.33 \; +39.11 \; +11.08 \; -0.15$

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$$m_{\tilde{\chi}^0_1} = 106.54 \; -8.69 \; -2.19 \; +2.11$$
$$m_{\tilde{\chi}^0_2} = 137.22 \; +1.92 \; +1.52 \; -1.36$$
$$m_{\tilde{\chi}^0_3} = 212.81 \; -5.66 \; -1.85 \; +1.88$$
$$m_{\tilde{\chi}^0_4} = 417.87 \; -3.97 \; -1.90 \; +1.94$$

- Chargino masses [GeV]

$$m_{\tilde{\chi}^+_1} = 121.54 \; +8.63 \; -1.42 \; +1.36$$
$$m_{\tilde{\chi}^+_2} = 417.75 \; -9.16 \; -1.72 \; +1.74$$

- Gluino mass [GeV]

$$m_{\tilde{g}} = 572.33 \; +39.11 \; +11.08 \; -0.15$$

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# Description of Polxino

# is a C-program

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## Basic parameters of the struct `MSSM_DATA`

| **MSSM_DATA** member | description |
|---|---|
| **gs, g1, g2** | gauge coupling constants |
| **mue** | $\mu$-parameter |
| **TB** | $\tan\beta$ |
| **VEV** | $\sqrt{v_1^2+v_2^2}$, $v_i$ are the Higgs VEVs |
| **MA02** | squared mass of $A_0$ |
| **MQU[3], MQD[3], MLE[3]** | quark and lepton-masses |
| **M1, M2, M3** | gaugino masses |
| **MSL[3], MSE[3], MSQ[3], MSU[3], MSD[3]** | bilinear soft Susy breaking parameters |
| **Af[4][3]** | trilinear soft Susy breaking parameters |

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# The subroutines
## using generic functions

- generic one- and two-loop functions were extracted from gluinopole.c [S.P.Martin '05]

**getneupole**(⟨int⟩ i, ⟨MSSM_DATA⟩, ⟨POL_REAL*⟩ Mpole1, ⟨POL_REAL*⟩ Gamma1, ⟨POL_REAL*⟩ Mpole2, ⟨POL_REAL*⟩ Gamma2);
**getchpole**(⟨int⟩ i, ⟨MSSM_DATA⟩, ⟨POL_REAL*⟩ Mpole1, ⟨POL_REAL*⟩ Gamma1, ⟨POL_REAL*⟩ Mpole2, ⟨POL_REAL*⟩ Gamma2);
**getgluinopole**(⟨MSSM_DATA⟩, ⟨POL_REAL*⟩ Mpole1, ⟨POL_REAL*⟩ Gamma1, ⟨POL_REAL*⟩ Mpole2, ⟨POL_REAL*⟩ Gamma2);

calculate the one- and two-loop pole masses of chargino (neutralino) *i* or the gluino, stores the one- and two-loop results in the variables **Mpole1** resp. **Mpole2**.

The tree-level and one-loop widths are stored in **Gamma1** and **Gamma2**

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- can be downloaded from `http://wwwhephy.oeaw.ac.at/tools/polxino`

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`Motivation`:

- high precision experiments demand pole mass calculations to two-loop order [LHC/LC Study Group]
- combining existing software packages it was possible to calculate the leading NNLO corrections (SQCD + Yukawas)
- auto-generated code: FeynArts→FeynCalc→Tarcer, Fortran, TSIL, LoopTools
- agrees with Polxino (using generic formulae)

`Results`:

- the remaining renormalization scale dependence is weakened
- For gaugino-like $\tilde{\chi}$'s two-loop SQCD is mandatory
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# Outlook

`Full two-loop calculation`:

- best of two worlds approach
  combine the strength of
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  - well-tested generic results

  to a package capable of doing the full two-loop calculation ($2 \cdot 2500$ diagrams)

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# Thank you for our attention!

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