

# Photonic two-loop corrections to the muon's anomalous magnetic moment $(g - 2)_\mu$ in the MSSM

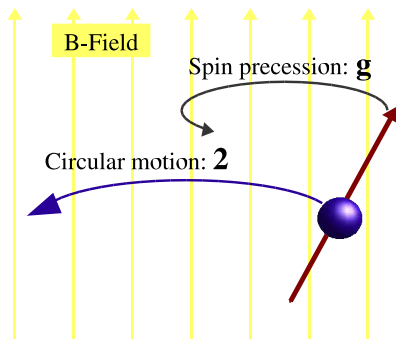
Philipp von Weitershausen

Institut für Kern- und Teilchenphysik  
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9 July 2009

# 3.4 $\sigma$

What's  $g - 2$ ?



$$H_{\text{magn}} = -g \frac{e}{2m} \vec{B} \vec{S}$$

## Why $g - 2$ ?

Simple to measure

e.g.  $(g - 2)_e$  used to measure  $\alpha_{\text{QED}}$

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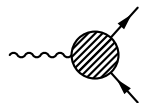
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Sensitive to quantum corrections (birth of QFT)

One of the most precisely measured and computed quantities

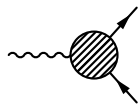
## Computing $g - 2$ in QFT



A Feynman diagram showing a fermion loop (a circle with diagonal hatching) with an incoming wavy line on the left and two outgoing straight lines with arrows on the top and bottom. The diagram is followed by an approximation symbol and a mathematical expression.

$$\sim -ie \bar{u}(p') [\gamma^\mu F_E(q^2) + (p + p')^\mu F_M(q^2) + \dots] u(p)$$

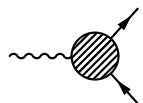
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$$\sim -ie \bar{u}(p') \left[ \gamma^\mu F_E(q^2) + (p + p')^\mu F_M(q^2) + \dots \right] u(p)$$

$$g = 2(1 - 2mF_M(0))$$

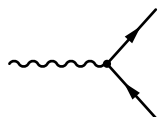
## Computing $g - 2$ in QFT



A Feynman diagram showing a fermion loop (a circle with diagonal hatching) with an incoming wavy photon line on the left and two outgoing fermion lines on the right.

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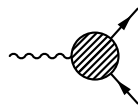
$g - 2 = 0$  on tree level (cf. Dirac eq)



A Feynman diagram showing a tree-level vertex where an incoming wavy photon line splits into two outgoing fermion lines.

$$\sim -ie\gamma^\mu$$

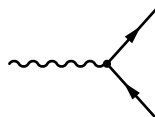
## Computing $g - 2$ in QFT



A Feynman diagram showing a fermion line (wavy) entering a shaded circular loop from the left. Two fermion lines (straight with arrows) exit the loop to the right.

$$\sim -ie \bar{u}(p') [\gamma^\mu F_E(q^2) + (p + p')^\mu F_M(q^2) + \dots] u(p)$$
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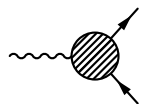


A Feynman diagram showing a fermion line (wavy) entering a vertex from the left. Two fermion lines (straight with arrows) exit the vertex to the right.

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$g - 2 \propto \mathbf{m}$  makes  $(g - 2)_\mu$  interesting

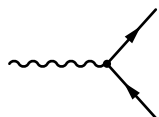
## Computing $g - 2$ in QFT



A Feynman diagram showing a fermion loop (a circle with diagonal hatching) with an incoming wavy photon line from the left and two outgoing fermion lines (arrows) at the top and bottom right.

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A Feynman diagram showing a vertex where a wavy photon line enters from the left and two fermion lines (arrows) exit to the right.

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Loops with heavy particles (mass  $M$ ):

$g - 2 \propto \frac{m^2}{M^2} \Rightarrow$  muon ca. **40,000** times more sensitive

# History: experiment and SM predictions

$\pm$	$a_\mu$	$\sigma_{a_\mu}/a_\mu$	Exp./SM
	$\alpha/2\pi$		'49 Schwinger: QED 1L
	$-1.77 \times 10^{-6}$		'50-'57 QED 2L terms
$\mu^+$	$\pm 0.10$		'57 Nevis
$\mu^+$	$0.001\,13^{+0.000\,16}_{-0.000\,12}$	12.4%	'59 Nevis
$\mu^+$	$0.001\,145(22)$	1.9%	'61 CERN 1(SC)
$\mu^\pm$	$0.001\,166\,16(31)$	265ppm	'68 CERN 2(PS)
	$+5.9 \times 10^{-6}$		'72 QED 2L $\log \frac{m_\mu}{m_e}$ terms
$\mu^\pm$	$0.001\,165\,895(27)$	23ppm	'75 CERN 3(PS)
	$+3 \times 10^{-7}$		'76 QED 3L numerically
	$(4 \pm 2) \times 10^{-9}$		'76 QED 4L leading
	$(6.7 \pm .9) \times 10^{-8}$		'76 hadronic contributions
$\mu^\pm$	$0.001\,165\,911(11)$	7.3ppm	'79 CERN 3(PS)

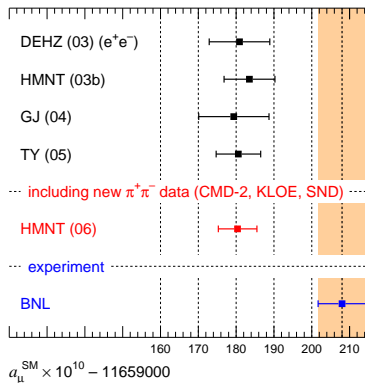
# $(g - 2)_\mu$ experiment in Brookhaven



$$a_\mu^{Exp} = 11\,659\,208.0(6.3) \times 10^{-10}$$

[Phys.Rev.D 2006]

# Experiment vs. SM predictions



3.4  $\sigma$  established

$$(29.5 \pm 8.1) \times 10^{-10}$$

[de Rafael 2008]

# Scenarios

Higher statistical error in experiment

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**New physics!**

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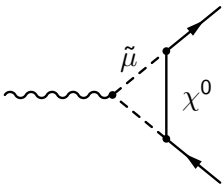
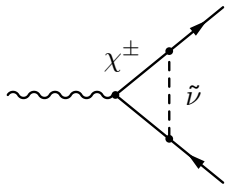
Missing higher orders of SM contributions

Underestimated theory error

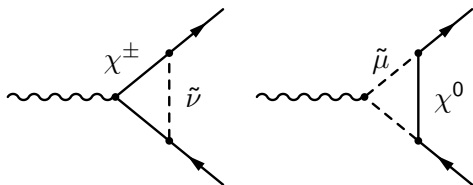
New physics! Supersymmetry (MSSM)

$(g - 2)_\mu$  in the MSSM

# SUSY 1 loop



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$$\propto m_\mu \cdot \tan \beta \cdot \mu$$

complete

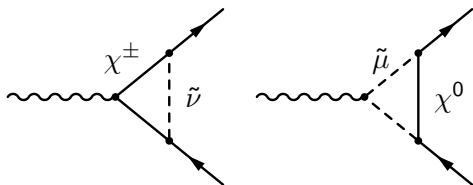
[Fayet '80]

[Kosower et al '83]

[Lopez et al '94]

[Moroi '96]

# SUSY 1 loop



for  $\mu, m_{\tilde{\mu}}, m_{\tilde{\chi}} \approx M_{\text{SUSY}}$

$$a_{\mu}^{\text{SUSY}} \approx 12 \times 10^{-10} \tan \beta \operatorname{sgn}(\mu) \left( \frac{100 \text{ GeV}}{M_{\text{SUSY}}} \right)^2$$

e.g.  $a_{\mu}^{\text{SUSY}} = 24 \times 10^{-10}$  for

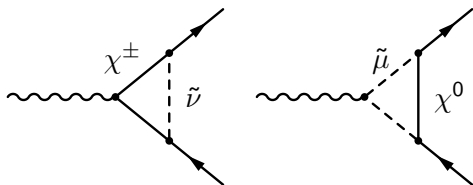
$$\tan \beta = 2, \quad M_{\text{SUSY}} = 100 \text{ GeV}$$

$$\tan \beta = 50, \quad M_{\text{SUSY}} = 500 \text{ GeV}$$

SUSY could account for  $3.4 \sigma$

$g - 2$  constraints MSSM parameters

# SUSY 1 loop



$$a_\mu^{\chi^\pm} = \frac{m_\mu}{16\pi^2} \sum_k \left[ \frac{m_\mu}{12m_{\tilde{\nu}_\mu}^2} (|c_k^L|^2 + |c_k^R|^2) F_1^C(x) + \frac{2m_{\chi^\pm}}{3m_{\tilde{\nu}_\mu}^2} \text{Re}[c_k^L c_k^R] F_2^C(x) \right]$$

$$a_\mu^{\chi^0} = \frac{m_\mu}{16\pi^2} \sum_{i,m} \left[ -\frac{m_\mu}{12m_{\tilde{\mu}}^2} (|n_{im}^L|^2 + |n_{im}^R|^2) F_1^N(x) + \frac{m_{\chi^0}}{3m_{\tilde{\mu}}^2} \text{Re}[n_{im}^L n_{im}^R] F_2^N(x) \right]$$

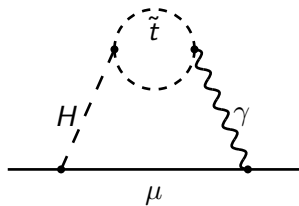
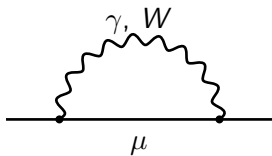
$$F_1^C = \frac{2}{(1-x)^4} (2 + 3x - 6x^2 + x^3 + 6x \log x)$$

$$F_2^C = \frac{3}{2(1-x)^3} (-3 + 4x - x^2 - 2 \log x)$$

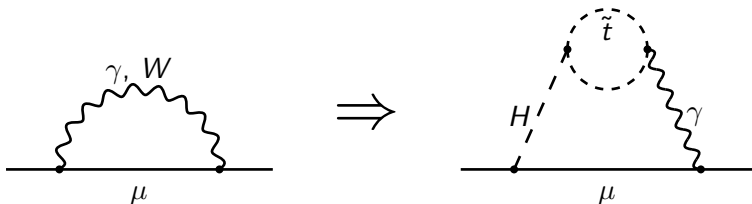
$$F_1^N = \frac{2}{(1-x)^4} (1 - 6x + 3x^2 + 2x^3 - 6x^2 \log x)$$

$$F_2^N = \frac{3}{(1-x)^3} (1 - x^2 + 2x \log x)$$

## 2 loop: SUSY-enhanced SM loop



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$$\propto m_t \cdot \tan \beta \cdot \mu$$

complete

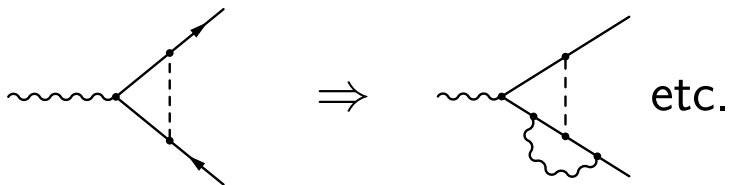
[Chen, Geng '01]

[Arhib, Baek '02]

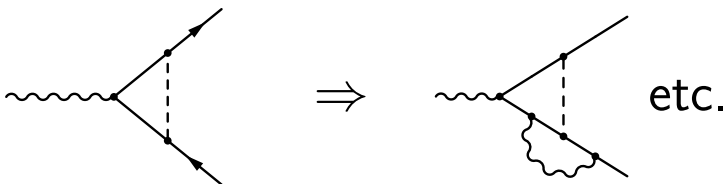
[Stöckinger et al '03]

[Stöckinger et al '04]

## 2 loop: Photon enhanced SUSY loop



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$$\propto \log \frac{M_{\text{SUSY}}}{m_\mu} a_\mu^{1L}$$

leading log

[Degrassi, Giudice '98]

goal: complete

# Methods of computation

## Simplified model

$$\text{QED} + \chi^{\pm} + \chi^0 + \tilde{\mu} + \tilde{\nu}$$

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Chargino and neutralino coupling arbitrary for now:

$$\begin{aligned} \mathcal{L}_{\text{int}} = & \bar{\mu}(\eta_L P_R - \eta_R^* P_L)\chi^0 \tilde{\mu} \\ & + \bar{\mu}(c_L P_R + c_R^* P_L)\chi^- \tilde{\nu} + \text{h.c.} \end{aligned}$$

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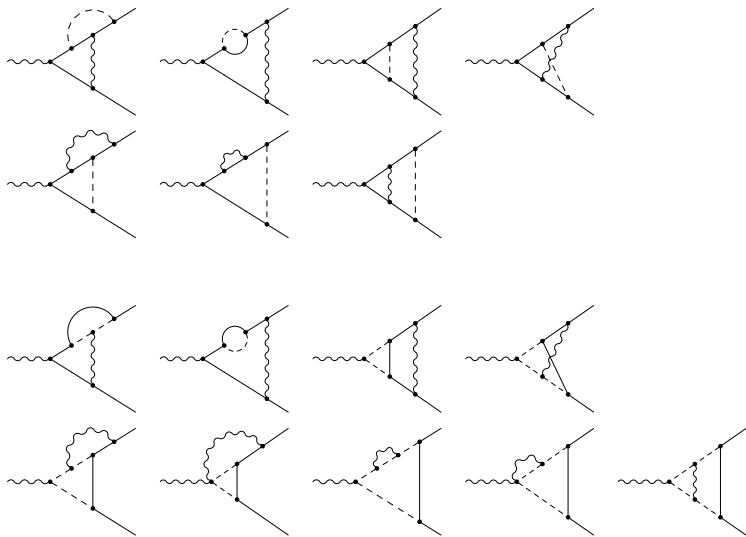
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### Later:

Plug in values from gauge and Yukawa couplings.

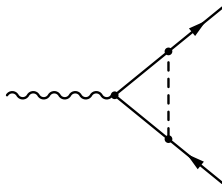
Sum over gauginos and muons in the MSSM.

FeynArts finds 28 unique diagrams  $\propto c^2 e^2, n^2 e^2$



# FeynArts applies Feynman rules

For example:



$$= \int \frac{i(c_R^* P_L + c_L P_R)(\not{k} + \not{q} + m_\chi)(-ie\gamma^\mu)(\not{k} + m_\chi)i(c_L P_L + c_R P_R)}{[k^2 - m_\chi^2][(k+q)^2 - m_\chi^2][(k-p'+q)^2 - m_\nu^2]}$$

## Extract $g - 2$ from diagram amplitude

Idea: use **projector**  $\mathcal{P}$  to extract  $g - 2$  from amplitude:

$$\begin{aligned} a_\mu &= \text{Tr} \left( \mathcal{P} \text{---} \text{---} \text{---} \right) \\ &= c_\mu V^\mu + c_{\mu\nu} T^{\mu\nu} \end{aligned}$$

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$$\begin{aligned} V^\mu &\sim \text{---} \text{---} \text{---} \Big|_{q^2=0} && \sim \text{---} \text{---} \text{---} \\ T^{\mu\nu} &\sim \frac{\partial}{\partial q^\nu} \text{---} \text{---} \text{---} \Big|_{q^2=0} && \sim \text{---} \text{---} \text{---} \end{aligned}$$

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$V^\mu, T^{\mu\nu}$  look like **selfenergies!**

## TwoCalc/OneCalc evaluates selfenergies

Perform Dirac calculus

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Express result in standard integral notation:

$$\int \frac{\dots}{[k_1^2 - m_1^2][k_2^2 - m_2^2][\dots]} \longrightarrow A_0, B_0, T_{123}, Y_{1234}^{12}, \text{ etc.}$$

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Goal: Decompose to **tabulated integrals**

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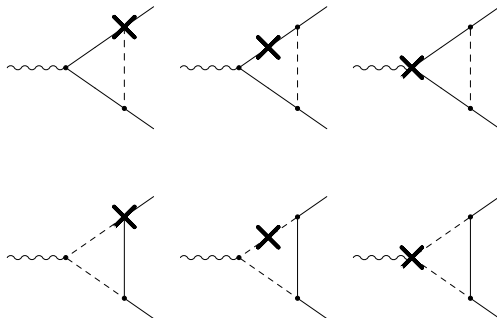
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Solution: only expand loops with **large masses**

The diagram illustrates the large mass expansion of a Feynman diagram. On the left, a tree-level vertex (represented by a wavy line) is connected to two external lines (solid lines with arrows). A loop is formed by a dashed line and a solid line with an arrow. This loop is expanded as a series of terms. The first term is the tree-level vertex multiplied by the Taylor expansion  $\mathcal{T}$  of the loop integral. The second term is the tree-level vertex multiplied by the Taylor expansion  $\mathcal{T}$  of the loop integral, with a correction term  $+ \mathcal{O}(m_\mu^3/M_{\text{SUSY}}^3)$ .

$$\text{Diagram} = \text{Tree-level vertex} \times \mathcal{T}(\text{Loop}) + \mathcal{O}(m_\mu^3/M_{\text{SUSY}}^3)$$

# Renormalization: 10 unique counterterm diagrams



## Renormalization scheme

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Problem:  $c, n$  contain  $m_\mu$  (**large logarithms**), need to account for that:

$$\delta(c_{LCR}) = \frac{\delta m_\mu}{m_\mu} c_{LCR} + \dots$$

$$\delta(n_{LNR}) = \frac{\delta m_\mu}{m_\mu} n_{LNR} + \mathcal{O}(m_\mu^2) + \dots$$

## Analytical result

$$\begin{aligned} a_{2L}^{\chi^\pm} &= \frac{1}{16\pi^2} \frac{e^2}{2\pi^2} \left[ \left( \frac{m_\mu^2}{12m_{\tilde{\nu}}^2} F_1^C \mathcal{A}_C + \frac{2m_\mu m_{\chi^\pm}}{3m_{\tilde{\nu}}^2} F_2^C \mathcal{R}_C \right) \log \frac{m_\mu^2}{m_{\tilde{\nu}}^2} \right. \\ &\quad - \left( \frac{47m_\mu^2}{576m_{\tilde{\nu}}^2} F_3^C \mathcal{A}_C + \frac{61m_\mu m_{\chi^\pm}}{36m_{\tilde{\nu}}^2} F_4^C \mathcal{R}_C \right) \\ &\quad \left. - \left( \frac{m_\mu^2}{16m_{\tilde{\nu}\mu}^2} F_1^C \mathcal{A}_C + \frac{m_\mu m_{\chi^\pm}}{4m_{\tilde{\nu}}^2} F_2^C \mathcal{R}_C \right) L(m_{\tilde{\nu}}^2) \right] \\ a_{2L}^{\chi^0} &= \frac{1}{16\pi^2} \frac{e^2}{2\pi^2} \left[ \left( -\frac{m_\mu^2}{12m_{\tilde{\mu}}^2} F_1^N \mathcal{A}_N + \frac{m_\mu m_{\chi^0}}{3m_{\tilde{\mu}}^2} F_2^N \mathcal{R}_N \right) \log \frac{m_\mu^2}{m_{\tilde{\mu}}^2} \right. \\ &\quad - \left( -\frac{35m_\mu^2}{576m_{\tilde{\mu}}^2} F_3^N \mathcal{A}_N + \frac{2m_\mu m_{\chi^0}}{9m_{\tilde{\mu}}^2} F_4^N \mathcal{R}_N \right) \\ &\quad \left. - \left( \frac{m_\mu^2}{32m_{\tilde{\mu}}^2} F_1^N \mathcal{A}_N \right) L(m_{\tilde{\mu}}^2) \right] \end{aligned}$$

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$$a_{2L}^{\chi^0} = \frac{1}{16\pi^2} \frac{e^2}{2\pi^2} \left[ \left( -\frac{m_\mu^2}{12m_{\tilde{\mu}}^2} F_1^N \mathcal{A}_N + \frac{m_\mu m_{\chi^0}}{3m_{\tilde{\mu}}^2} F_2^N \mathcal{B}_N \right) \log \frac{m_\mu^2}{m_{\tilde{\mu}}^2} \right. \\ \left. - \left( -\frac{35m_\mu^2}{576m_{\tilde{\mu}}^2} F_3^N \mathcal{A}_N + \frac{2m_\mu m_{\chi^0}}{9m_{\tilde{\mu}}^2} F_4^N \mathcal{B}_N \right) \right. \\ \left. - \left( \frac{m_\mu^2}{32m_{\tilde{\mu}}^2} F_1^N \mathcal{A}_N \right) L(m_{\tilde{\mu}}^2) \right]$$

## Analytical result

$$a_{2L}^{\chi^\pm} = \frac{1}{16\pi^2} \frac{e^2}{2\pi^2} \left[ a_{1L}^{\chi^\pm} \log \frac{m_\mu^2}{m_{\tilde{\nu}}^2} - \left( \frac{47m_\mu^2}{576m_{\tilde{\nu}}^2} F_3^C \mathcal{A}_C + \frac{61m_\mu m_{\chi^\pm}}{36m_{\tilde{\nu}}^2} F_4^C \mathcal{R}_C \right) - \left( \frac{m_\mu^2}{16m_{\tilde{\nu}\mu}^2} F_1^C \mathcal{A}_C + \frac{m_\mu m_{\chi^\pm}}{4m_{\tilde{\nu}}^2} F_2^C \mathcal{R}_C \right) L(m_{\tilde{\nu}}^2) \right]$$

$$a_{2L}^{\chi^0} = \frac{1}{16\pi^2} \frac{e^2}{2\pi^2} \left[ a_{1L}^{\chi^\pm} \log \frac{m_\mu^2}{m_{\tilde{\mu}}^2} - \left( -\frac{35m_\mu^2}{576m_{\tilde{\mu}}^2} F_3^N \mathcal{A}_N + \frac{2m_\mu m_{\chi^0}}{9m_{\tilde{\mu}}^2} F_4^N \mathcal{R}_N \right) - \left( \frac{m_\mu^2}{32m_{\tilde{\mu}}^2} F_1^N \mathcal{A}_N \right) L(m_{\tilde{\mu}}^2) \right]$$

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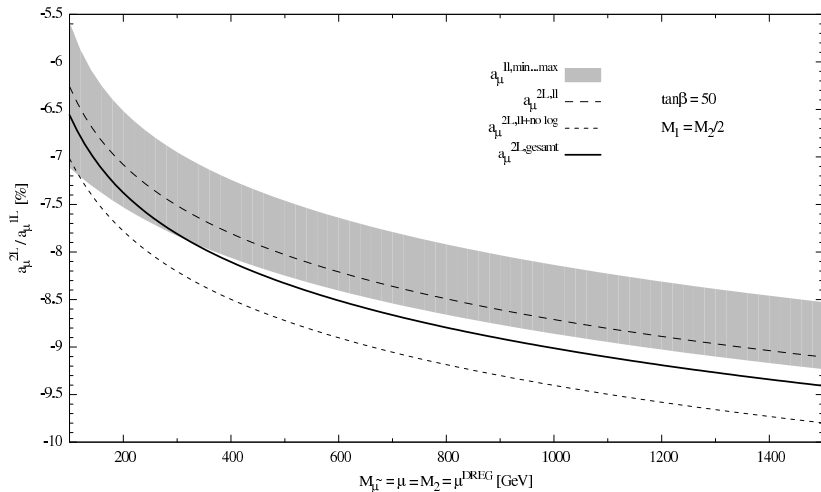
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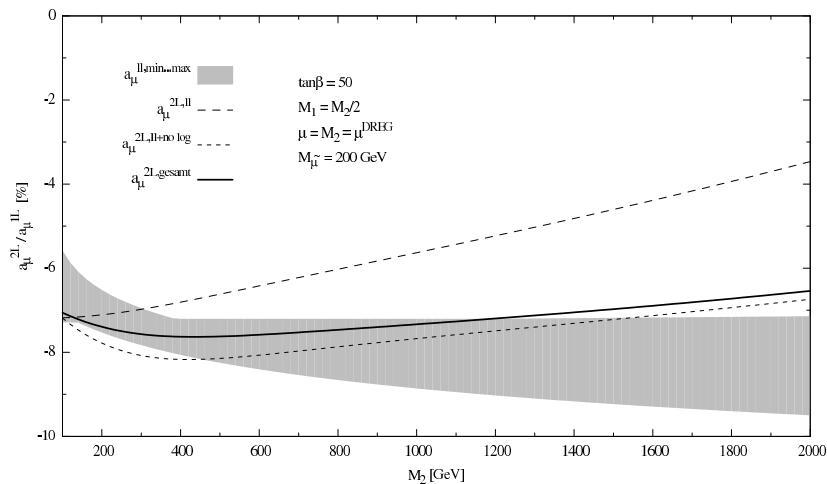
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✓ Non-logarithmic contributions complete

# Numerical evaluation



# Can non-logarithmic contributions be large?



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Non-log contribution amounts to ca. 1% of the one loop result.

Questions?