MSSM Radiative Corrections

to

Neutrino-nucleon Deep-inelastic Scattering

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outline :

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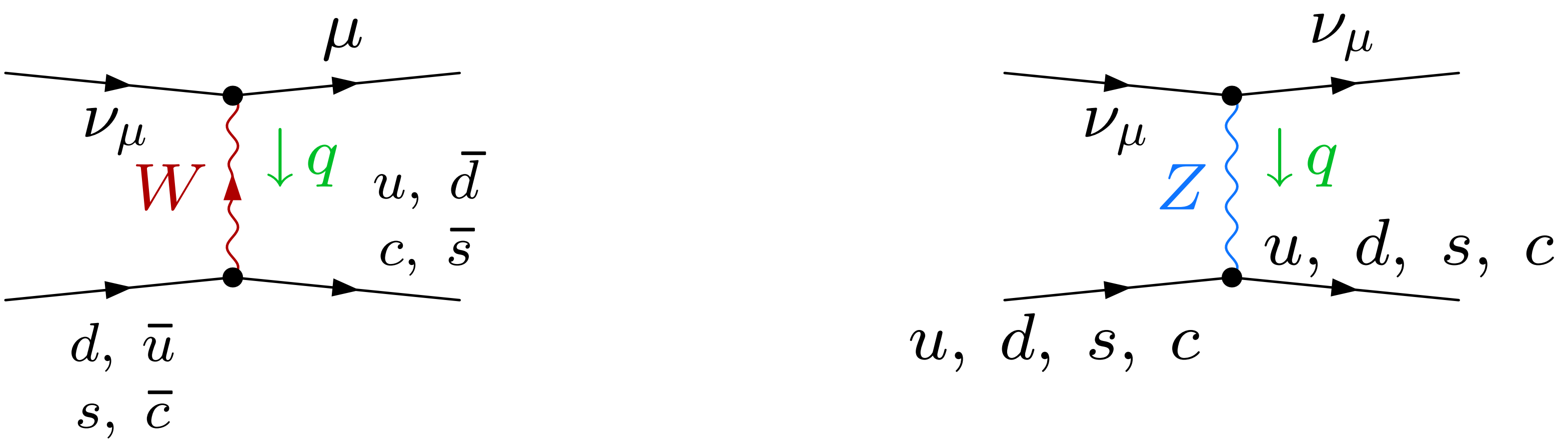
  - possible explanations
- MSSM radiative corrections to $\nu_\mu N$ DIS
  - definition of $\delta R^{\nu,\bar{\nu}} = R^{\nu,\bar{\nu}}_{\text{MSSM}} - R^{\nu,\bar{\nu}}_{\text{SM}}$
  - superpartner loop corrections
  - MSSM-SM Higgs loop difference
- Results for $\delta R^{\nu}, \delta R^{\bar{\nu}}$
  - how to scan over MSSM parameters?
  - MSSM parameter scan

• Introduction

– deep inelastic νN scattering at NuTeV

In the SM neutral (NC) and charged current (CC) neutrino nucleon scattering are described in LO by t-channel W and Z exchange.



At NuTeV ν_μ and $\bar{\nu}_\mu$ beams of a mean energy of 125 GeV were scattered off a target detector and the ratios

$$R^{\nu} = \frac{\sigma^{\nu}_{\text{NC}}}{\sigma^{\nu}_{\text{CC}}}\,, \qquad R^{\bar{\nu}} = \frac{\sigma^{\bar{\nu}}_{\text{NC}}}{\sigma^{\bar{\nu}}_{\text{CC}}}$$

were measured.

NuTeV measured also the weak mixing angle [NuTeV '02].

$$\sin^2\theta_w^{\text{on-shell}} = 0.2277 \pm 0.0013 \pm 0.0009$$

$\rightarrow$ This is about 3σ below the SM prediction !

But the measurement is indirect, using the measurements of $R^\nu, R^{\bar{\nu}}$ and making use of the Paschos-Wolfenstein relation

$$R^- = \frac{R^\nu - rR^{\bar{\nu}}}{1-r} = \frac{1}{2} - \sin^2\theta_w + \cdots\ , \qquad r = \frac{\sigma^{\bar{\nu}}_{\text{CC}}}{\sigma^{\nu}_{\text{CC}}} \approx \frac{1}{2}\,.$$

More precisely, ratios of counting rates

$$R^{\nu}_{\text{exp}} = \frac{\text{\# of NC-like } \nu \text{ events}}{\text{\# of CC-like } \nu \text{ events}} \approx R^{\nu}, \quad R^{\bar{\nu}}_{\text{exp}} = \frac{\text{\# of NC-like } \bar{\nu} \text{ events}}{\text{\# of CC-like } \bar{\nu} \text{ events}} \approx R^{\bar{\nu}}$$

are measured.

$R^{\nu}_{\text{exp}}, R^{\bar{\nu}}_{\text{exp}}$ can be related to $R^{\nu}, R^{\bar{\nu}}$ by a detailed MC physics simulation.

The deviation from the SM in terms of $R^{\nu}_{\text{exp}}, R^{\bar{\nu}}_{\text{exp}}$ are [NuTeV '02]:

$$\Delta R^{\nu} = R^{\nu}_{\text{exp}} - R^{\nu}_{\text{exp}}(SM) = -0.0032 \pm 0.0013 \,,$$
$$\Delta R^{\bar{\nu}} = R^{\bar{\nu}}_{\text{exp}} - R^{\bar{\nu}}_{\text{exp}}(SM) = -0.0016 \pm 0.0028 \,.$$

$\rightarrow$ $\Delta R^{\nu,\bar{\nu}}$: simple starting point for studying MSSM radiative corrections

– possible explanations

- statistical fluctuation, errors underestimated ?
  - $\longrightarrow$ re-analyses of EW rad. corr.

[Diener, Dittmaier, Hollik ’03 & ’05; Arbuzov, Bardin, Kalinovskaya ’03]

- relevant SM effects neglected ?
  - $\longrightarrow$ asymmetry of strange sea-quarks in the nucleon ($s \neq \bar{s}$)
  - $\longrightarrow$ isospin violation ($u_p \neq d_n$)
  - $\longrightarrow$ nuclear effects
  - $\longrightarrow$ etc. . . .

- new physics ?
  - $\longrightarrow$ modified gauge boson interactions (e.g. in extra dimensions)
  - $\longrightarrow$ non-renormalizable operators (suppressed by powers of $\Lambda^{-1}_{\text{new physics}}$)
  - $\longrightarrow$ leptoquarks (e.g. R parity violating SUSY)
  - $\longrightarrow$ SUSY loop effects (e.g. in MSSM)
  - $\longrightarrow$ etc. . . .

Although the NuTeV "anomaly" is far from being settled,
it is interesting, if the MSSM *could* account for such an effect.

Earlier Studies:

- Davidson et al. ['02]
  - rough study in terms of oblique corrections (i.e. momentum transfer $q = 0$)
  - no Parton Distribution Functions (PDFs) used

- Kurylov, Ramsey-Musolf, Su ['04] :
  - detailed parameter dependence studied
  - momentum transfer $q = 0$ approximation
  - no PDFs used

results so far: MSSM not responsible (size ok, but wrong sign)

- our calculation: try to include kinematic effects [OBr, Koch, Hollik]
  - full q^2-dependence
  - use PDFs
  - use NuTeV cuts on hadronic Energy in final state
  - use mean neutrino beam energy (125 GeV)

• MSSM radiative corrections to $\nu_\mu N$ DIS

– definition of $\delta R^{\nu,\bar{\nu}} = R^{\nu,\bar{\nu}}_{\text{MSSM}} - R^{\nu,\bar{\nu}}_{\text{SM}}$

The difference between MSSM and SM prediction, $\delta R^n = R^n_{\text{MSSM}} - R^n_{\text{SM}}$ with $R^n = \sigma^n_{\text{NC}}/\sigma^n_{\text{CC}} (n = \nu, \bar{\nu})$, using

$$(\sigma^n_{\text{NC}})_{\text{NLO}} = (\sigma^n_{\text{NC}})_{\text{LO}} + \delta\sigma^n_{\text{NC}} \quad (n = \nu, \bar{\nu})$$
$$(\sigma^n_{\text{CC}})_{\text{NLO}} = (\sigma^n_{\text{CC}})_{\text{LO}} + \delta\sigma^n_{\text{CC}} \quad (n = \nu, \bar{\nu})$$

can be expanded in $\delta\sigma^n_{\text{NC}}$ and $\delta\sigma^n_{\text{CC}}$

$$\delta R^n = \left(\frac{\sigma^n_{\text{NC}}}{\sigma^n_{\text{CC}}}\right)_{\text{LO}} \left(\frac{(\delta\sigma^n_{\text{NC}})_{\text{MSSM}} - (\delta\sigma^n_{\text{NC}})_{\text{SM}}}{(\sigma^n_{\text{NC}})_{\text{LO}}} - \frac{(\delta\sigma^n_{\text{CC}})_{\text{MSSM}} - (\delta\sigma^n_{\text{CC}})_{\text{SM}}}{(\sigma^n_{\text{CC}})_{\text{LO}}}\right).$$

→ Only differences between MSSM and SM radiative corrections and LO cross sections appear in δR^n.

Because of R parity conservation in the MSSM:

– Born cross section : SM = MSSM (very good approx.)

– real photon emission corrections : SM = MSSM (very good approx.)

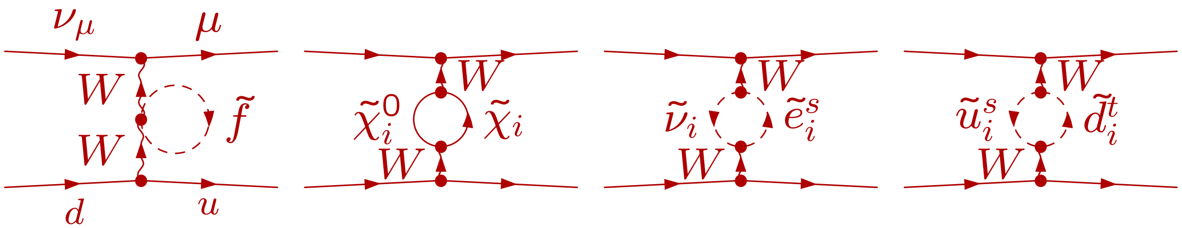
– SM = MSSM for SM-like 1-loop graphs without virtual Higgs

Thus:

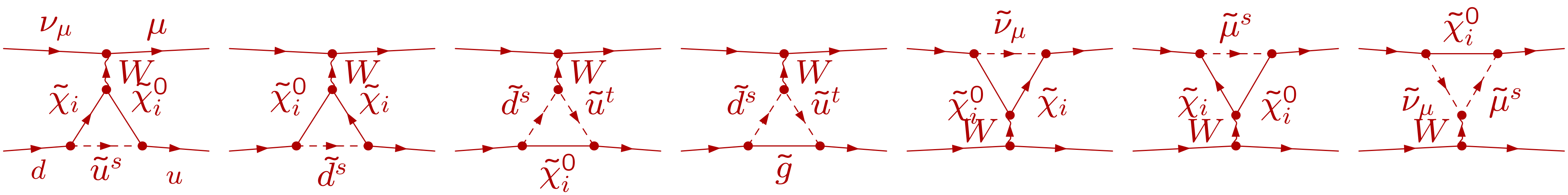
$$\delta\sigma_{\text{MSSM}} - \delta\sigma_{\text{SM}} = \text{const.} \times \Big([\text{superpartner loops}] + [\text{Higgs graphs MSSM} - \text{Higgs graphs SM}] \Big) \,.$$

– superpartner loop corrections

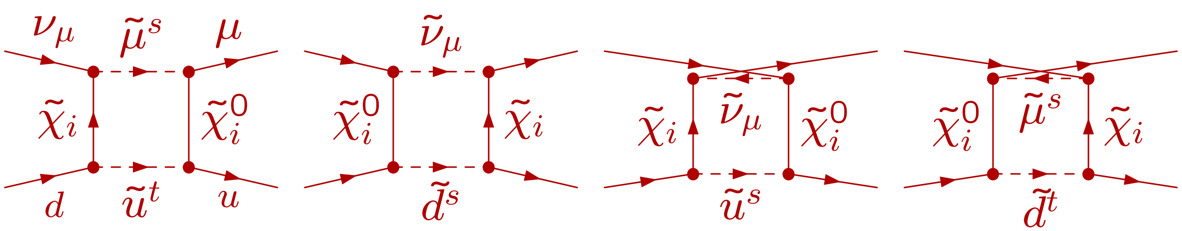
CC self energy insertions



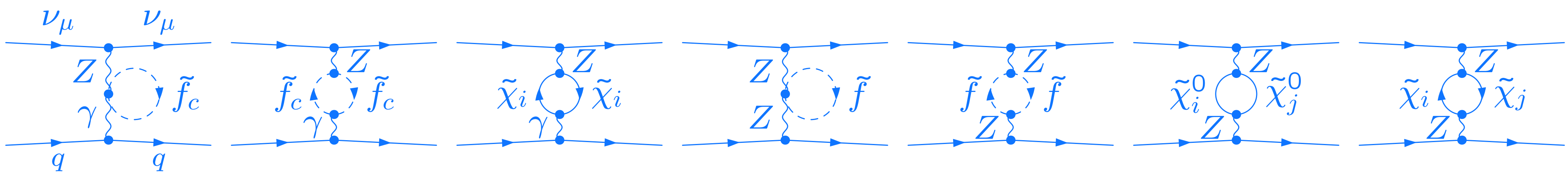
CC vertex corrections



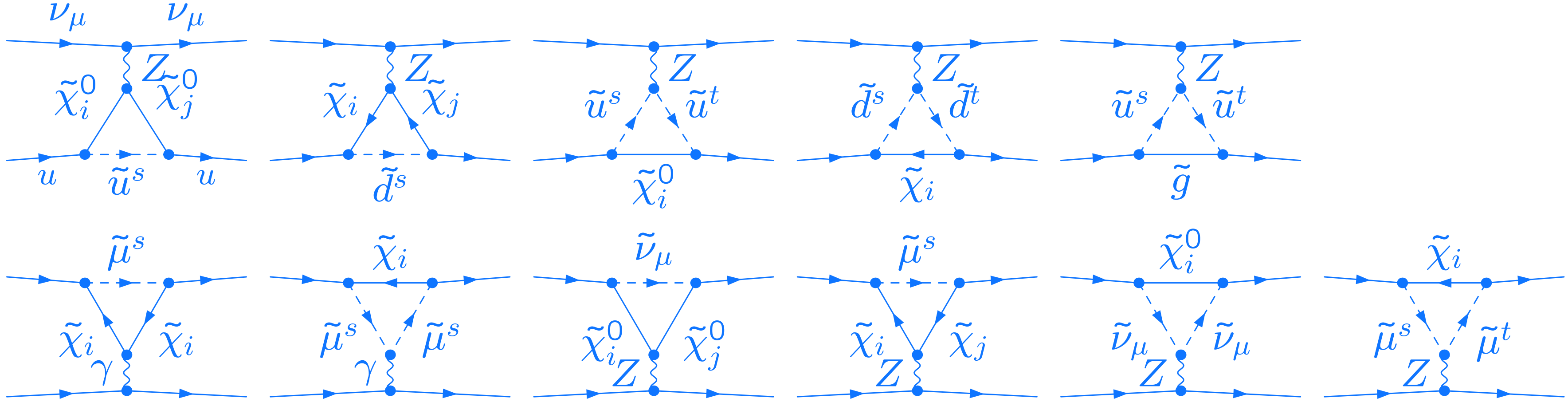
CC box corrections



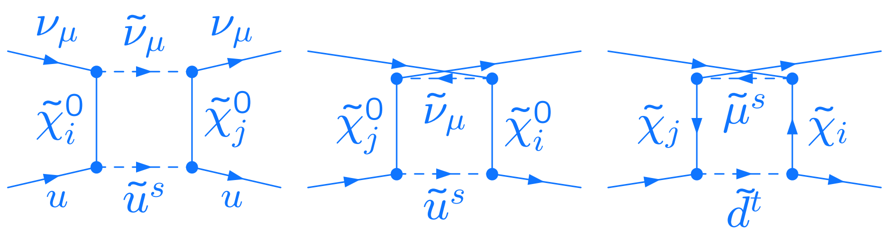
NC self energy insertions



NC vertex corrections

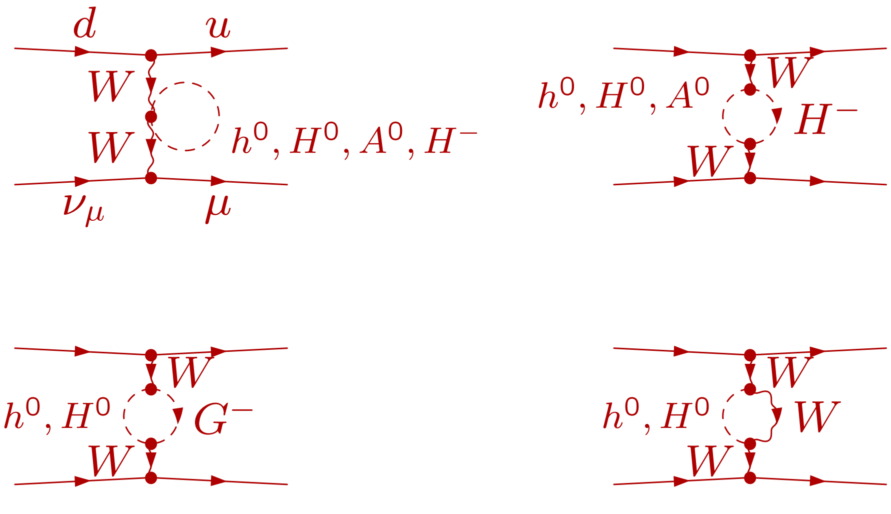


NC box corrections

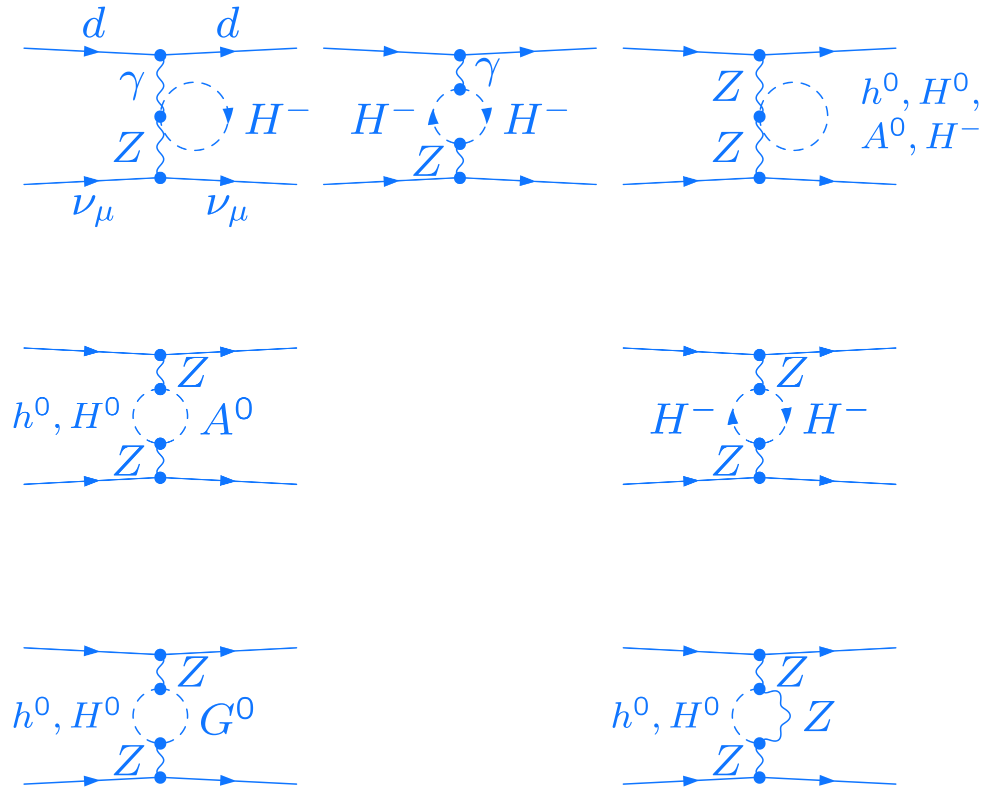


– MSSM-SM Higgs loop difference

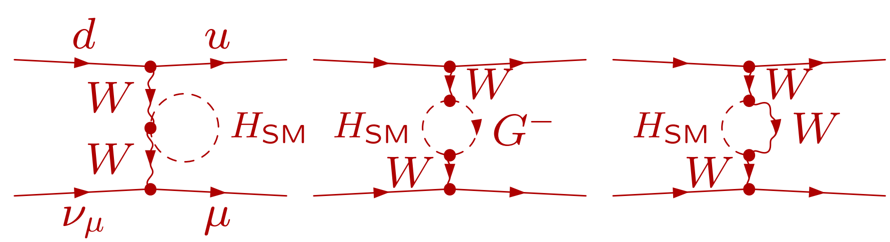
+ CC MSSM Higgs loops



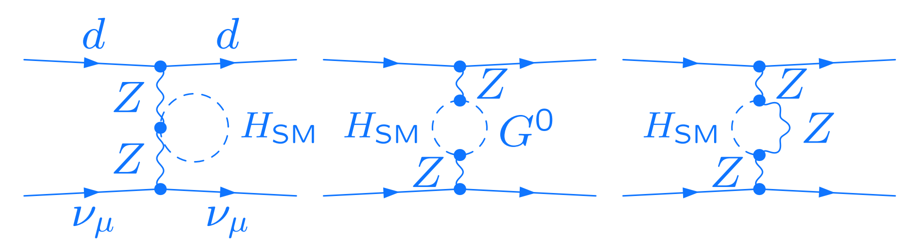
+ NC MSSM Higgs loops



– CC SM Higgs loops



– NC SM Higgs loops



The partonic processes were calculated using FeynArts/FormCalc.

[Küblbeck, Böhm, Denner'90],
[Eck '95], [Hahn, Perez-Victoria '99], [Hahn '01],
[Hahn, Schappacher '02]

see : www.feynarts.de

• Results for $\delta R^{\nu}, \delta R^{\bar{\nu}}$

– how to scan over MSSM parameters?

goal : find regions of parameter space, where the MSSM might explain the NuTeV anomaly.

→ difficult, large dimensionality of MSSM parameter space

scanning strategy : "adaptive scan" [OBr'04]:
→ exploit adaptive integration by importance sampling

method: calculate an approximation to the integral

$$I = \int_{M_1^{\text{min}}}^{M_1^{\text{max}}} dM_1 \cdots \int_{d\tan\beta^{\text{min}}}^{d\tan\beta^{\text{max}}} d\tan\beta \;\; F\Big(\delta R^{\nu(\bar{\nu})}(M_1, \ldots, \tan\beta), M_1, \ldots, \tan\beta\Big)$$

with VEGAS and store the sampled parameter points.

→ automatically, the sample points will be enriched in the regions where $F\Big(\delta R^{\nu(\bar{\nu})}(M_1, \ldots, \tan\beta), M_1, \ldots, \tan\beta\Big)$ is large.

some sample choices of F:

- $F = \begin{cases} 1 & \text{if parameters } (M_1, \ldots, \tan\beta) \text{ not excluded} \\ 0 & \text{elsewhere} \end{cases}$

  $\longrightarrow$ enrich points in allowed region

- $F = \begin{cases} \delta R^{\nu(\bar{\nu})}(M_1, \ldots, \tan\beta) & \text{if parameters } (M_1, \ldots, \tan\beta) \text{ not excluded} \\ 0 & \text{elsewhere} \end{cases}$

  $\longrightarrow$ enrich points where $|\delta R^{\nu(\bar{\nu})}|$ is large in allowed region

- $F = \begin{cases} \sqrt{(\delta R^{\nu}(\ldots))^2 + (\delta R^{\bar{\nu}}(\ldots))^2} & \text{if } \delta R^{\nu} \text{ and } \delta R^{\bar{\nu}} < 0 \\ 0 & \text{elsewhere} \end{cases}$

  $\longrightarrow$ enrich points where $\delta R^{\nu}, \delta R^{\bar{\nu}} < 0$ *and* $\sqrt{\ldots}$ is large

– MSSM parameter scan

restrictions taken into account:

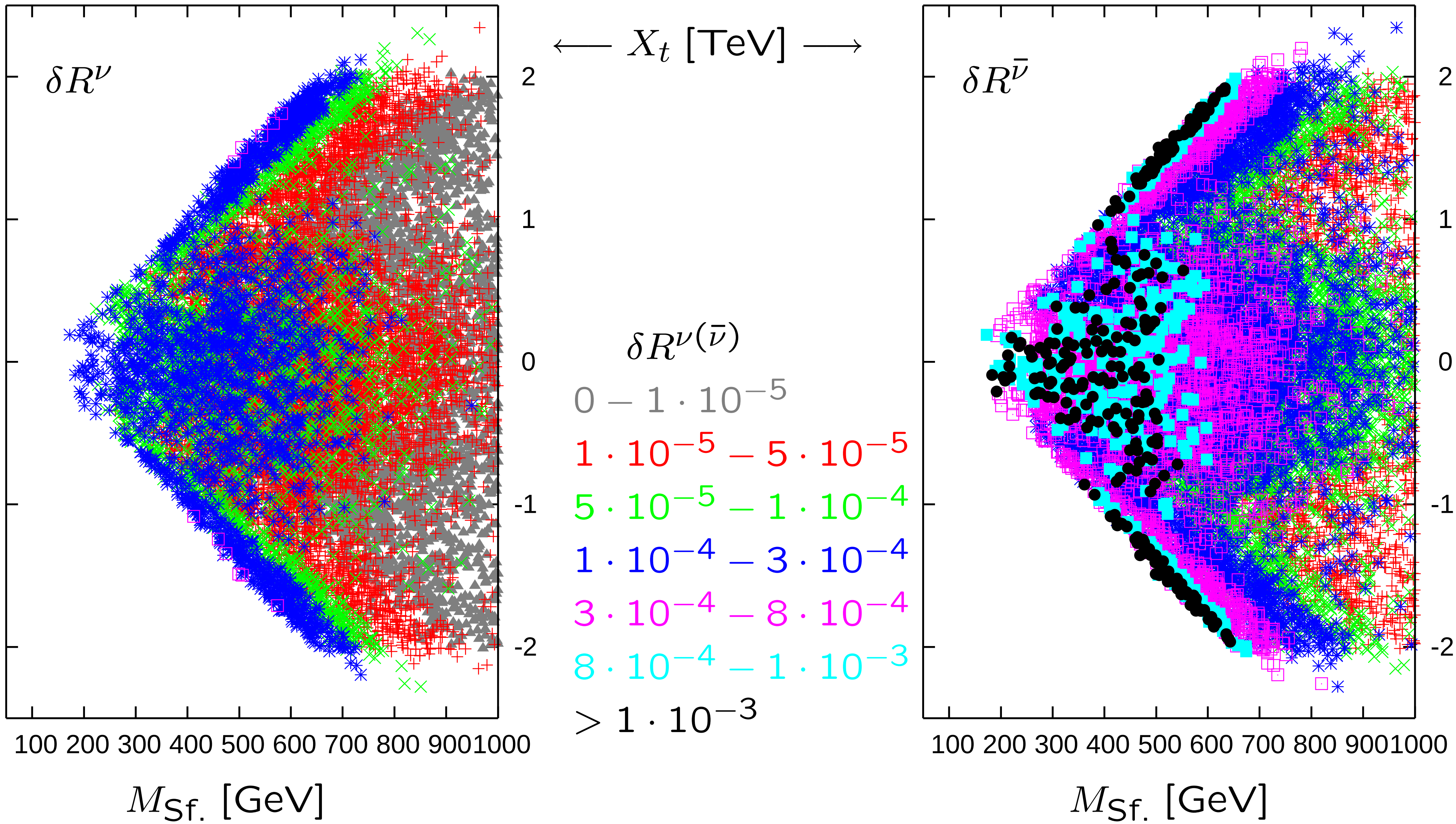
- mass exclusion limits for Higgs bosons and superpartners
- $\Delta\rho$-constraint on sfermion mixing

quantities varied:

$M_1, M_2, M_{\text{gluino}}$	:	$10 \ldots 1000$ GeV	μ	:	$-2000 \ldots 2000$ GeV
$M_{\text{Sf.}}$	:	$10 \ldots 1000$ GeV	A_b, A_t, A_τ	:	$-2000 \ldots 2000$ GeV
m_{A^0}	:	$10 \ldots 1000$ GeV	$\tan\beta$	:	$1 \ldots 50$

[Results for $\delta R^{\nu}, \delta R^{\bar{\nu}}$, MSSM parameter scan]

Scan for large values of $|\delta R^{\nu}|$ and $|\delta R^{\bar{\nu}}|$ with parameter restrictions



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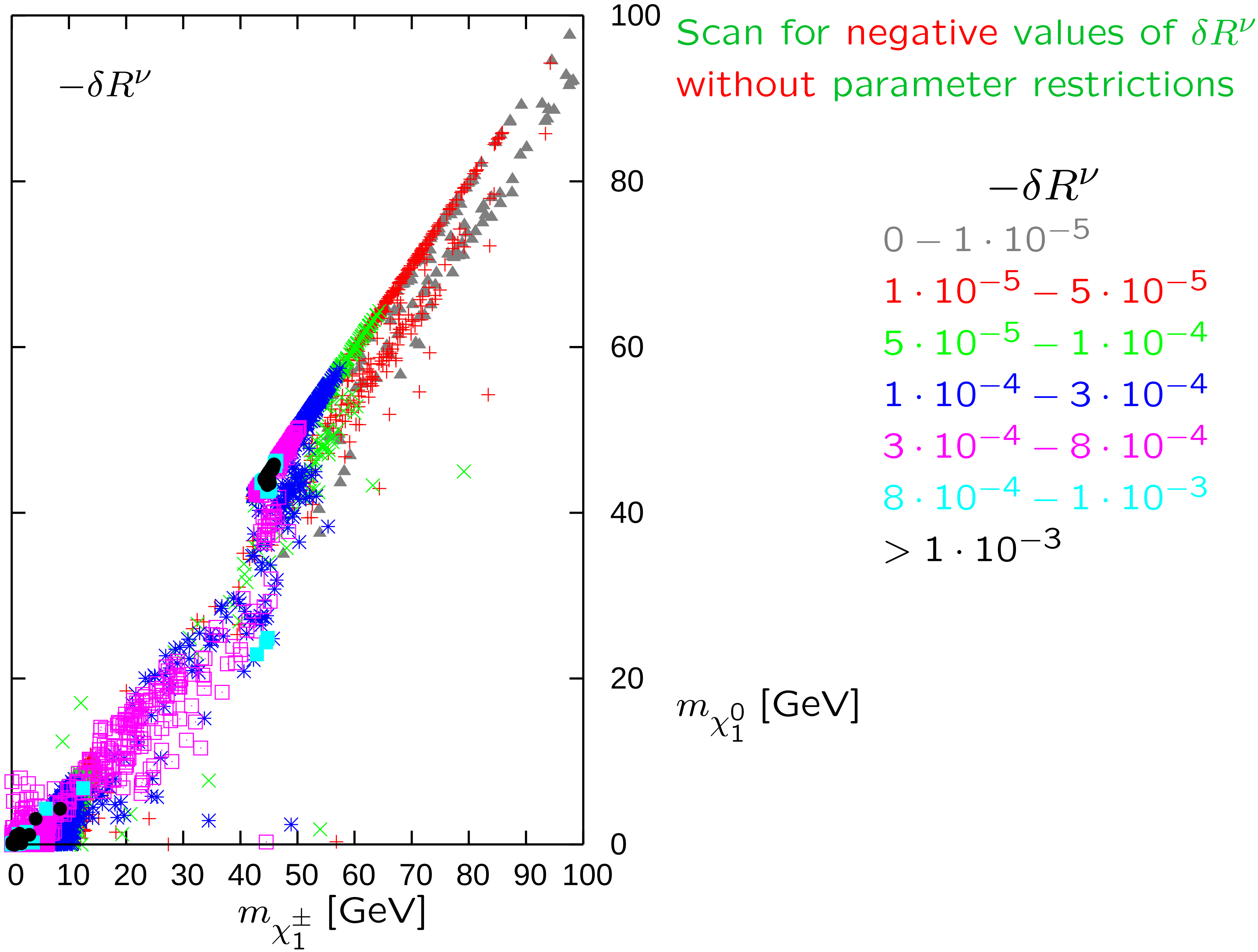

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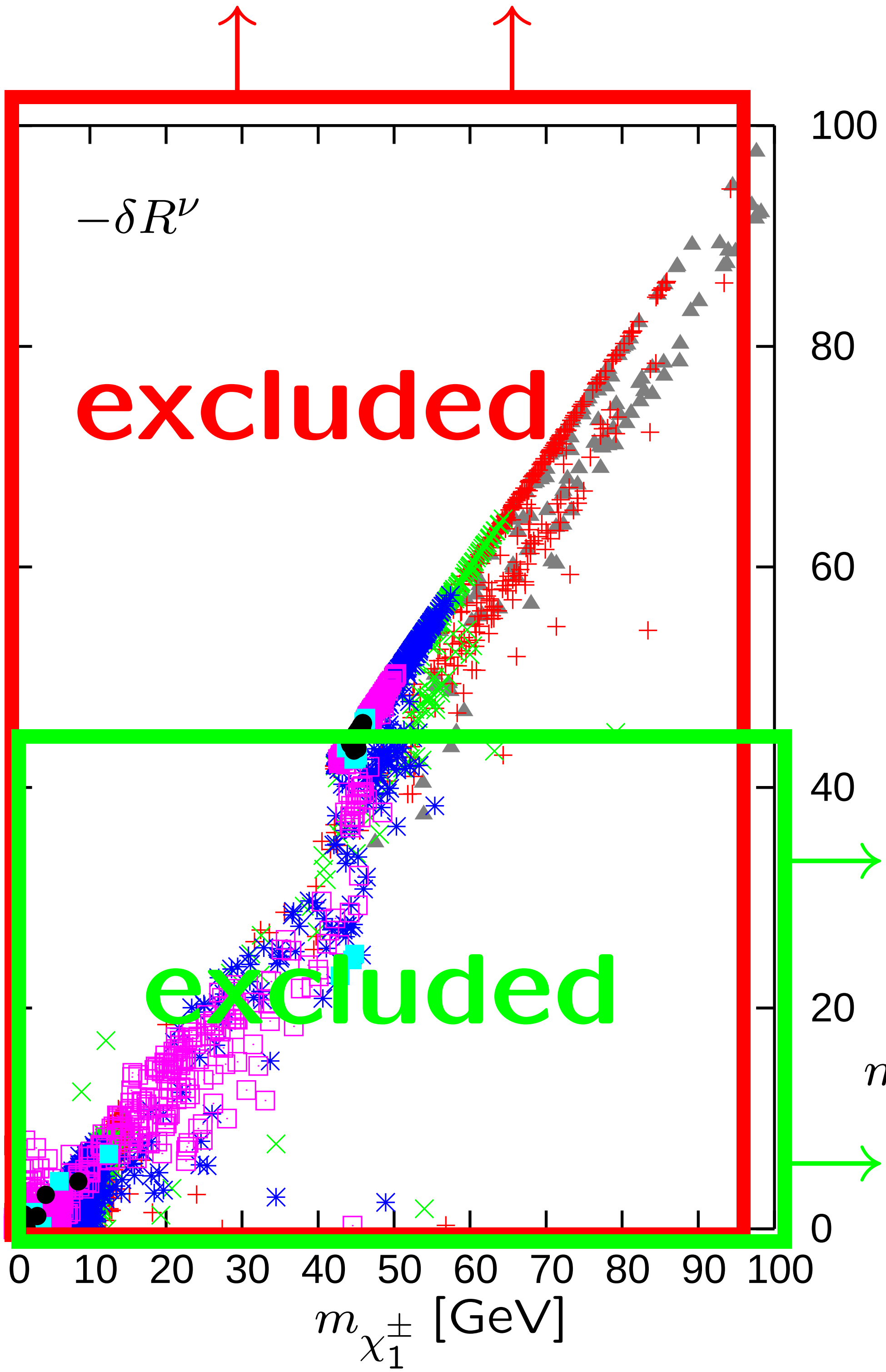


Scan for negative values of δR^{ν} without parameter restrictions

$-\delta R^{\nu}$

$0 - 1 \cdot 10^{-5}$

$1 \cdot 10^{-5} - 5 \cdot 10^{-5}$

$5 \cdot 10^{-5} - 1 \cdot 10^{-4}$

$1 \cdot 10^{-4} - 3 \cdot 10^{-4}$

$3 \cdot 10^{-4} - 8 \cdot 10^{-4}$

$8 \cdot 10^{-4} - 1 \cdot 10^{-3}$

$> 1 \cdot 10^{-3}$

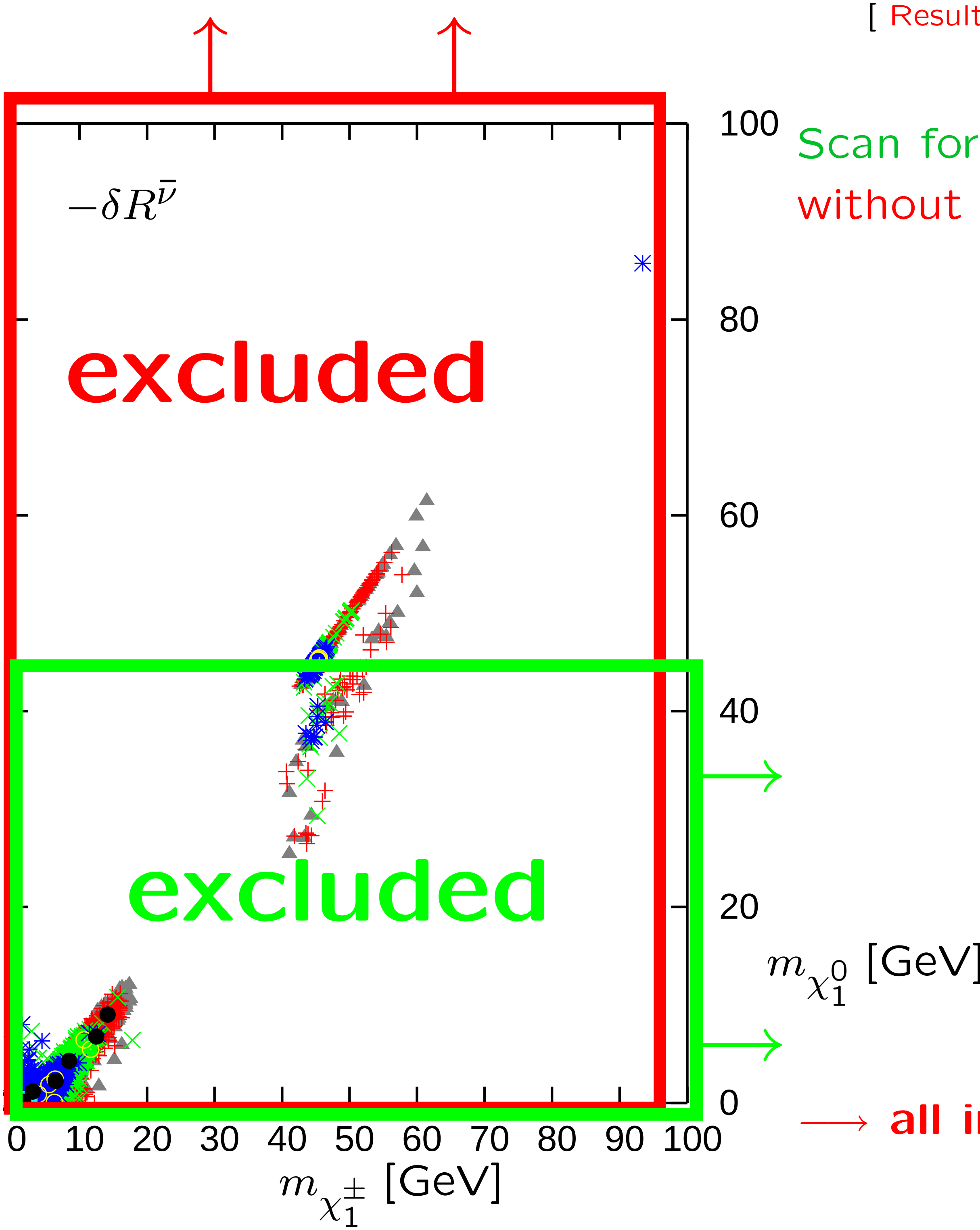
$m_{\chi_1^\pm} > 94$GeV

$m_{\chi_1^0} > 46$GeV

$\longrightarrow$ **all interesting regions excluded**

[Results for $\delta R^{\nu}, \delta R^{\bar{\nu}}$, MSSM parameter scan]

Scan for negative values of $\delta R^{\bar{\nu}}$ without parameter restrictions



$-\delta R^{\bar{\nu}}$

- $0 - 1 \cdot 10^{-5}$
- $1 \cdot 10^{-5} - 5 \cdot 10^{-5}$
- $5 \cdot 10^{-5} - 1 \cdot 10^{-4}$
- $1 \cdot 10^{-4} - 3 \cdot 10^{-4}$
- $3 \cdot 10^{-4} - 8 \cdot 10^{-4}$
- $8 \cdot 10^{-4} - 1 \cdot 10^{-3}$
- $> 1 \cdot 10^{-3}$

$m_{\chi_1^\pm} > 94\,\mathrm{GeV}$

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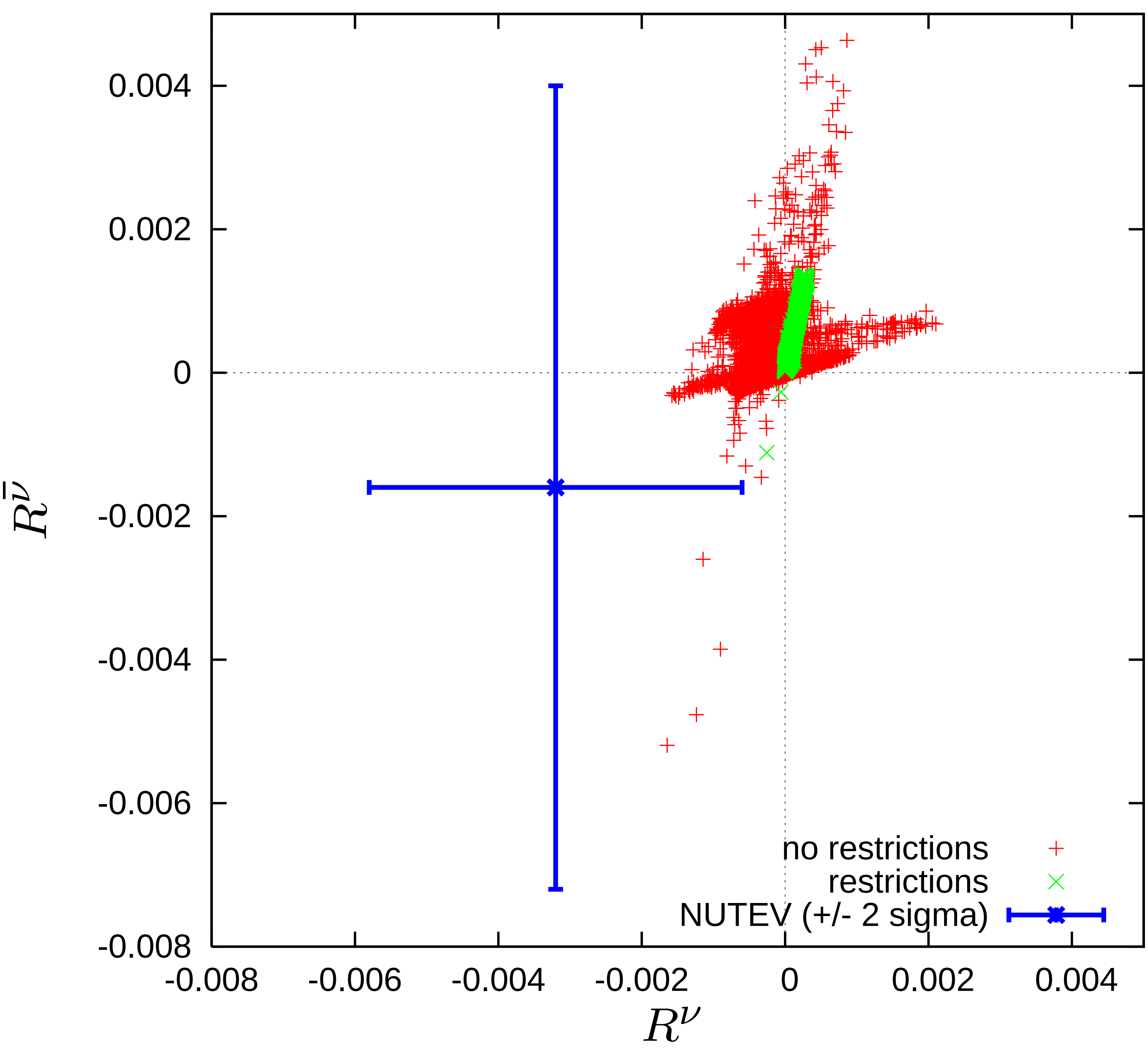
[Results for $\delta R^{\nu}, \delta R^{\bar{\nu}}$, MSSM parameter scan]



Summary

- The NuTeV measurement of $\sin^2\theta_w$ is intriguing
  but has to be further established
  (especially confirmation by other experiment(s) is desirable).

- Loop effects in the MSSM are not capable
  of explaining the NuTeV "anomaly".
  (size can be right, but sign is wrong).

- If the "anomaly" was established,
  the MSSM would be in trouble.

Our result can be easily combined with the one-loop SM result.
$\to$ The complete MSSM one-loop prediction for νN scattering
is available for future analyses.