First results on a search for light pseudoscalar sgoldstino in $K^-$ decays

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Abstract

A search for the light pseudoscalar sgoldstino production in three-body $K^-$ decay $K^- \to \pi^-\pi^0 P$ has been performed with the “ISTRA+” detector exposed to the 25 GeV negative secondary beam of the U-70 proton synchrotron. No signal is seen. Upper limits for the branching ratio $Br(K^- \to \pi^-\pi^0 P)$ at 90% confidence level vary between $2.0 \cdot 10^{-5}$ and $0.5 \cdot 10^{-5}$ in the effective mass $m_P$ range from 0 up to 190 MeV. Our results improve the limits published by the E787 Collaboration in the mass interval between 0 and 120 MeV and are the first ones at higher masses.

1 Introduction

In supersymmetric models with spontaneous supersymmetry breaking superpartners of a Goldstone fermion — goldstino, pseudoscalar $P$ and scalar $S$, should exist. In various versions of gravity mediated and gauge mediated theories one or both of these weakly interacting bosons — sgoldstinos — are light and therefore can be observed in kaon decays. Moreover, if sgoldstino interactions with quarks conserve parity, these constraints result in the following limits on the branching ratio:

$$Br(\pi^-\pi^0 P) \lesssim 1 \times 10^{-6} \div 4 \times 10^{-4}$$

(see Fig. 1 for the diagram of the $K^- \to \pi^-\pi^0 P$ decay). A search for $P$ in charged kaon decays is of particular interest for the case $Re h_{12}^D \simeq 0$, when the corresponding branching ratio of $K_L$ is small.

Light sgoldstino decays into two photons or into a pair of charged leptons, two photon decay dominating almost everywhere in the parameter space. Depending on the parameter $g_\gamma = \frac{\langle m_{\gamma}\rangle}{\langle m_P\rangle}$, where $M_{\gamma}$ is the photino mass, sgoldstino decays either inside or outside the detector. In the present search we assume that sgoldstino decays outside the detector, i.e. is invisible. The existing limits on the branching $Br(K^- \to \pi^-\pi^0 P)$ are at the level of $4 \cdot 10^{-5}$ [2], whereas the limits for the scalar sgoldstino $S$ can be estimated from the studies of the $K^+ \to \pi^+\nu\bar{\nu}$ at the level of $4.7 \cdot 10^{-9}$, see [3] for recent review.

The aim of our present study is to search for invisible pseudoscalar sgoldstino in the decay of $K^-$. Experimental setup and event selection are described in Section 2, the results of the analysis are presented in Section 3 and the conclusions are given in the last Section.

2 Experimental setup and event selection

2.1 Experimental setup

The experiment is performed at the IHEP 70 GeV proton synchrotron U-70. The spectrometer ISTRA+ has been described in some details in our recent papers on $K_{e3}$ [4], $K_{\mu3}$ [5] and $\pi^-\pi^0\pi^0$ decays [6], here we briefly
recall characteristics relevant to our analysis. The 40 m spectrometer ISTRA+ is located in the negative unseparated secondary beam line 4A of U-70. The beam momentum is ~ 25 GeV with $\Delta p/p \sim 2\%$. The admixture of $K^-$ in the beam is ~ 3\%, the beam intensity is ~ $3 \cdot 10^6$ per 1.9 sec U-70 spill. A schematic view of the ISTRA+ setup is shown in Fig. 2. The momentum of a beam particle deflected by the magnet $M_1$ is measured by four proportional chambers $BPC_1$–$BPC_4$ with 1 mm wire steps, the kaon identification is done by three threshold Cerenkov counters $\bar{C}_1$–$\bar{C}_3$. The 9 meter long vacuumated decay volume is surrounded by eight lead glass rings used to veto low energy photons. The same role is played by 72-cell lead glass calorimeter $SP_2$. The decay products deflected in the magnet $M_2$ with 1 Tm field integral are measured with 2 mm step proportional chambers $PC_1$–$PC_3$, with 1 cm cell drift chambers $DC_1$–$DC_3$ and finally with 2 cm diameter drift tubes $DT_1$–$DT_4$. A wide aperture threshold Cerenkov counter $C_4$ is filled with He and used to trigger electrons. $SP_1$ is a 576-cell lead glass calorimeter, followed by HC — a scintillator-iron sampling hadron calorimeter. MH is an 11x11 cell scintillating hodoscope, used to solve ambiguity for multitrack events and improve the time resolution of the tracking system. MuH is a 7x7 cell muon hodoscope.

The trigger is provided by scintillation counters $S_1$–$S_5$, beam Cerenkov counters and by the analog sum of amplitudes from last dinodes of the $SP_1$: $T=S_1 \cdot S_2 \cdot S_3 \cdot \bar{C}_4 \cdot \bar{C}_1 \cdot \bar{C}_2 \cdot \bar{C}_3 \cdot \bar{S}_5 \cdot \Sigma(SP_1)$, here $S_4$ is a scintillation counter with a hole to suppress beam halo, $S_5$ is a counter downstream of the setup at the beam focus, $\Sigma(SP_1)$ — a requirement for the analog sum to be larger than a MIP signal.

During first run in March-April 2001, 363 million of trigger events were logged on DLT’s. During second physics run in November-December 2001 350 million trigger events were collected with higher beam intensity and somewhat stronger trigger requirements. This information is supported by about 100 million MC events generated using Geant3 [7] for dominant $K^-$ decay modes. Signal efficiency for possible sgoldstino production has been estimated using one million generated events for the first run configuration and 0.5 million events for the second run configuration, for each effective mass $m_P$ point in the mass interval from 0 to 200 MeV with a step of 10 MeV. These signal events were weighted using the matrix element given in [1].

2.2 Event selection

Data collected in two runs, Spring 2001, first run, and Winter 2001, second run, are used. Some information on the data processing and reconstruction procedures is given in [4, 5, 6], here we briefly mention the details, relevant for $\pi^-\pi^0 +$ missing energy event selection.

The muon identification (see [5]) is based on the information from the $SP_1$ — a 576-cell lead glass calorimeter and the HC — a scintillation-iron sampling calorimeter. The electron identification (see [4]) is done using $E/p$ ratio — of the energy of the shower associated with charged track and charged track momentum.

A set of cuts is designed in order to suppress various backgrounds to possible sgoldstino production:

0) Events with one reconstructed charged track and with two electromagnetic showers in the electromagnetic calorimeter $SP_1$ are selected. We require the effective mass $m(\gamma\gamma)$ to be within ±40 MeV from $m_{\pi^+}$. The effective two-photon mass distributions for two runs are shown in Fig. 3. Events with vertex inside interval $400 < z < 1650$ cm are selected.

1) Next cut is a "soft" charged pion identification, tracks having electron or muon flag ( as described in [4, 5] ) are rejected.
2) Events with missing energy $E_{beam} - E_{\pi^-} - E_{\pi^+}$ below 3 GeV are rejected. The cut on the missing energy serves to reduce $K_{\pi2}$ contribution. In Fig. 4 missing energy spectra for the second run data, MC background and MC signal with $m_P$ of 90 MeV are compared.
3) Events with $m(\gamma\gamma)$ within ±36 MeV from $m_{\pi^+}+135$ MeV a selected (Tough $\pi^0$ cut).
4) Fourth cut suppresses events with extra photons irradiated by charged particles in a detector material upstream M2-magnet. Such photons have nearly the same $x$ coordinate on the $SP_1$ face as the charged track, i.e event is rejected if at least one photon has $|x_{ch} - x_e| < 10$ cm.
5) Fifth cut removes events having good $K_{e3}$ 2C-fit.
6) The following cut is a restriction on the charged pion momentum $p^*$ in the kaon rest frame: $p^*(\pi^-) < 180$ MeV. It is designed to suppress the tails of the $K_{\pi2}$ decay.
7) Seventh cut is against remaining muon contamination. It is required that the energy in $SP_1$, associated with charged track, should exceed 0.7 GeV. This cut requires "early" hadron shower in $SP_1$ and has , unfortunately,
low signal efficiency. We plan to get rid of it in our final analysis.

8) The following cut is designed to suppress $\pi^-\pi^0\gamma$ contribution: only the events with missing momentum crossing $\text{SP}_1$ transverse plane within $\text{SP}_1$ working aperture are selected.

9) The "Veto" cut uses information from the Guard System GS and the guard electromagnetic calorimeter $\text{SP}_2$: absence of signals above noise threshold is required. The influence of the "Veto" cut on the two-photon effective mass spectrum is illustrated in Fig. 5. No $\pi^0$ signal is seen after the "Veto" cut.

10) As a result of the previous cuts, $\pi^0$-signal practically disappears from the $\gamma\gamma$ mass spectrum. This allows to perform effective linear background subtraction procedure. The interval $\pm 18$ MeV around $m(\pi^0)$ mass value is used as the signal region, remaining events are used for the background estimate.

The data reduction information is given in Table 1 for two runs and is compared in Tables 2,3 with MC-background statistics and with MC-signal statistics for the sgoldstino mass of $m = 90$ MeV.

The influence of the last eight cuts on the missing mass squared spectrum $(P_K - P_\pi - P_{\pi^0})^2$, which is used as the signal "estimator" is is shown in Fig. 6 for the second run data. The left wide bump in Fig. 6 is due to $K_{e3}$ decays, the shift to negative missing mass squared is caused by the use of the pion mass in its calculations. Second peak is caused by $\pi^-\pi^0(\pi^0)$ decay with gammas from second $\pi^0$ escaping detection.

Fig. 7 illustrates the background subtraction procedure: in the first(third) figure the missing mass squared spectrum after cut 10 is shown for the first(second) run (solid curve) together with the normalized back-ground(dashed curve) estimated from the $m(\gamma\gamma)$ spectrum side bands ( 99–117 MeV and 153–171 MeV). The second(forth) figure show signal-background difference for two runs. No sgoldstino signal is observed, the peak around 0.02 GeV$^2$ is due to remaining $\pi^-\pi^0(\pi^0)$ background.

### Table 1: Event reduction statistics for two runs.

| Cut | Events run 1 | $N_i/N_{i+1}$ | Events run 2 | $N_i/N_{i+1}$ |
|-----|--------------|---------------|--------------|---------------|
| (0) $\pi^-$ and $m(\gamma\gamma)$ near $m(\pi^0)$ | 4398982 | 1.13 | 11339975 | 1.29 |
| (1) no $(e, \mu)$ | 978752 | 1.48 | 8762220 | 1.29 |
| (2) $E_{\text{miss}} > 3.0$ GeV | 716830 | 4.16 | 1430781 | 6.12 |
| (3) narrow $m(\gamma\gamma)$ band | 581653 | 1.23 | 1297087 | 1.10 |
| (4) conv. gammas | 322073 | 1.81 | 723248 | 1.79 |
| (5) no $K_{e3}$ fit | 230424 | 1.40 | 487246 | 1.48 |
| (6) $p^0(\pi^-) < 180$ MeV | 150926 | 1.53 | 322298 | 1.51 |
| (7) $E_{\text{SP}} > 700$ MeV | 17101 | 8.83 | 51624 | 6.24 |
| (8) $10 < rr < 60$ cm | 12922 | 1.32 | 40356 | 1.28 |
| (9) Veto | 5255 | 2.46 | 11183 | 3.61 |
| (10) $\pm 18$ meV | 2691 | 1.95 | 6125 | 1.94 |

### 3 Analysis and results

In order to calculate the upper limits we have fitted the residual missing mass distribution by the sum of the background and the signal Gaussian with fixed width of $\sigma = 0.003$ GeV$^2$, as determined from the signal MC.

The signal MC is also used to determine the efficiency of our cuts. The background has been described by two components: the Gaussian for $\pi^-\pi^0(\pi^0)$ peak and a linear background. For the second run an additional wide Gaussian centered at -0.015 has been used. Fit results are illustrated in Fig. 7 for the first and second run, respectively.

The upper limits at the 90% confidence level are calculated from the value

$$N_{UL} = N_{obs} + 1.64 \cdot \sigma,$$

(4)
Table 2: Event reduction statistics for MC data, first run.

| Cut | Events mix MC | \(N_i/N_{i+1}\) | MC signal with \(m=90\) MeV | \(N_i/N_{i+1}\) |
|-----|---------------|-----------------|---------------------------|-----------------|
| (0) 1 \(\pi^-\) and \(m(\gamma\gamma)\) near \(m(\pi^0)\) | 1278382 | 207315 |
| (1) no \((e, \mu)\) | 1156685 | 1.11 | 168179 | 1.21 |
| (2) \(E_{\text{mis}}>3.0\) GeV | 149679 | 1.06 | 165105 | 1.02 |
| (3) narrow \(m(\gamma\gamma)\) band | 91251 | 1.64 | 94503 | 1.75 |
| (4) conv. gammas | 48067 | 1.90 | 68325 | 1.38 |
| (5) no \(K_{e3}\) fit | 32151 | 1.50 | 67528 | 1.01 |
| (6) \(p^+(\pi^-)<180\) MeV | 6880 | 2.34 | 22346 | 3.02 |
| (7) \(E_{SP_1}>700\) MeV | 5283 | 1.30 | 17883 | 1.25 |
| (8) \(10<rr<60\) cm | 2257 | 2.34 | 17770 | 1.01 |
| (9) Veto | 1521 | 1.48 | 15737 | 1.13 |

where \(N_{obs}\) is the number of events in the signal Gaussian. During the fit we impose the constraint that \(N_{obs}\) is nonnegative. Sigma is a non-Gaussian error in \(N_{obs}\). The upper limit \(UL\) is calculated as

\[
UL = \frac{N_{UL} \cdot 0.2116 \cdot 0.98798 \cdot \varepsilon(K_{\pi^2})}{N(K_{\pi^2}) \cdot \varepsilon}
\]

with 0.2116 equal to \(Br(K_{\pi^2})\); with 0.98798 equal to \(Br(\pi^0 \rightarrow \gamma\gamma)\) and \(N(K_{\pi^2})\) equal to the number of reconstructed \(\pi^-\pi^0\) decays found to be 1500000 events for the first run and 4500000 events for the second run.

The values \(\varepsilon\) and \(\varepsilon(K_{\pi^2})\) are respective acceptances for \(K^- \rightarrow \pi^-\pi^0\ P\) and \(K_{\pi^2}\) decays. The acceptance \(\varepsilon(K_{\pi^2})\) is equal to 17.49 % for the first run and 24.92 % for the second run. This acceptance includes both the reconstruction efficiency and geometrical acceptance. The results of the fits are given in Table 4. As the background conditions for the two runs are different, the first run provides better upper limits for some \(m_P\) regions regardless of the lower luminosity. The estimated systematic errors for the upper limits are at the level of 20 %.

The final result obtained using combined statistics of two runs is given in Table 5. The weighted ratio \(\varepsilon(K_{\pi^2})/\varepsilon\) with the weights proportional to the runs statistics has been used for the combined data sample.

Fig. 9 shows a comparison of our result with that published by the E787 collaboration [2].

Special attention should be paid to the region near \(m_{\pi^0}\) mass. If we assume that the sgoldstino mass is exactly equal to that of \(\pi^0\) and that the remaining \(\pi^0\) peak is due to sgoldstino signal, then the upper limit for this point is \(2.8 \cdot 10^{-4}\).

4 Summary and conclusions

A search for a possible pseudoscalar sgoldstino production in the decay \(K^- \rightarrow \pi^-\pi^0\ P\) has been performed. It was assumed that sgoldstino decays outside the setup, i.e is invisible. No signal is seen in the \(m_P\) mass interval between 0 and 200 MeV. The 90% confidence upper limits obtained vary between \(2.0 \cdot 10^{-5}\) and \(0.5 \cdot 10^{-5}\) for the sgoldstino mass range of 0 \(\div\) 190 MeV. These results improve the confidence limits published by the E787 Collaboration.

In future, we plan to extend our search for a sgoldstino signal in the scenario when the decay \(P \rightarrow \gamma\gamma\) happens inside the setup.

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Table 3: Event reduction statistics for MC data, second run.

| Cut                                      | Events mix MC | $N_i/N_{i+1}$ | MC signal with m=90 MeV | $N_i/N_{i+1}$ |
|-------------------------------------------|---------------|---------------|------------------------|---------------|
| (0) 1 $\pi^-$ and m$(\gamma\gamma)$ near m$(\pi^0)$ | 5117109       | 1.11          | 120594                 | 1.01          |
| (1) no (e, $\mu$)                        | 4627156       | 7.48          | 119292                 | 1.22          |
| (2) $E_{\text{miss}} > 3.0$ GeV           | 618446        | 1.09          | 98098                  | 1.02          |
| (3) narrow m$(\gamma\gamma)$ band        | 565772        | 1.63          | 96504                  | 1.78          |
| (4) conv. gammas                          | 346226        | 2.92          | 54206                  | 1.46          |
| (5) no $K_{e3}$ fit                       | 118536        | 3.92          | 37124                  | 1.46          |
| (6) $p^+(\pi^-) < 180$ MeV               | 114160        | 1.04          | 36835                  | 1.01          |
| (7) $E_{\text{SP}} > 700$ MeV            | 21824         | 5.23          | 11800                  | 3.12          |
| (8) 10 < rr < 60 cm                       | 16597         | 1.28          | 9462                   | 1.25          |
| (9) Veto                                  | 7229          | 2.30          | 9407                   | 1.01          |
| (10) $\pm 18$ MeV                        | 5114          | 1.41          | 8541                   | 1.10          |

Table 4: Mass dependence of upper limits UL calculated using two runs separately, left part — first run, right part second run.

| M, MeV | Eff. $\varepsilon$, % | $N_{\text{obs}} \pm \sigma$ | UL | Eff. $\varepsilon$, % | $N_{\text{obs}} \pm \sigma$ | UL |
|--------|------------------------|--------------------------------|----|------------------------|--------------------------------|----|
| 0      | 0.64                   | 0±4.80                         | 1.84 $\cdot 10^{-3}$ | 0.85                   | 0±17.51                         | 2.39 $\cdot 10^{-9}$ |
| 10     | 0.66                   | 0±4.76                         | 1.76 $\cdot 10^{-3}$ | 0.86                   | 0±17.90                         | 2.40 $\cdot 10^{-9}$ |
| 20     | 0.67                   | 0±4.65                         | 1.69 $\cdot 10^{-3}$ | 0.92                   | 0±16.81                         | 2.10 $\cdot 10^{-9}$ |
| 30     | 0.74                   | 0±4.49                         | 1.48 $\cdot 10^{-3}$ | 0.99                   | 0±14.88                         | 1.73 $\cdot 10^{-9}$ |
| 40     | 0.81                   | 0±4.32                         | 1.30 $\cdot 10^{-3}$ | 1.05                   | 0±12.32                         | 1.65 $\cdot 10^{-9}$ |
| 50     | 0.88                   | 0±4.19                         | 1.16 $\cdot 10^{-3}$ | 1.18                   | 0±9.73                          | 1.56 $\cdot 10^{-9}$ |
| 60     | 1.05                   | 0±4.19                         | 0.98 $\cdot 10^{-3}$ | 1.32                   | 0±7.67                          | 1.10 $\cdot 10^{-9}$ |
| 70     | 1.09                   | 0±4.51                         | 1.01 $\cdot 10^{-3}$ | 1.73                   | 0±6.35                          | 0.70 $\cdot 10^{-9}$ |
| 80     | 1.21                   | 0±5.71                         | 1.15 $\cdot 10^{-3}$ | 1.62                   | 0±5.62                          | 0.66 $\cdot 10^{-9}$ |
| 90     | 1.33                   | 0±10.97                        | 2.02 $\cdot 10^{-3}$ | 1.76                   | 0±5.26                          | 0.57 $\cdot 10^{-9}$ |
| 100    | 1.41                   | 0±24.59                        | 4.24 $\cdot 10^{-3}$ | 1.90                   | 0±5.40                          | 0.54 $\cdot 10^{-9}$ |
| 110    | 1.53                   | 10.96±18.16                    | 3.96 $\cdot 10^{-3}$ | 2.09                   | 0±6.86                          | 0.62 $\cdot 10^{-9}$ |
| 120    | 1.60                   | 17.22±15.99                    | 2.24 $\cdot 10^{-3}$ | 2.27                   | 0±12.44                         | 1.04 $\cdot 10^{-9}$ |
| 130    | 1.63                   | 0±25.86                        | 3.86 $\cdot 10^{-3}$ | 2.36                   | 0±28.13                         | 2.26 $\cdot 10^{-9}$ |
| 140    | 1.66                   | 0±25.72                        | 3.79 $\cdot 10^{-3}$ | 2.46                   | 0±27.42                         | 2.12 $\cdot 10^{-9}$ |
| 150    | 1.61                   | 8.27±22.97                     | 4.25 $\cdot 10^{-3}$ | 2.49                   | 0±24.85                         | 1.89 $\cdot 10^{-9}$ |
| 160    | 1.74                   | 0±14.91                        | 2.33 $\cdot 10^{-3}$ | 2.41                   | 0±20.96                         | 1.65 $\cdot 10^{-9}$ |
| 170    | 1.48                   | 0±20.95                        | 3.46 $\cdot 10^{-3}$ | 2.35                   | 0±19.98                         | 1.61 $\cdot 10^{-9}$ |
| 180    | 1.42                   | 0±21.00                        | 3.60 $\cdot 10^{-3}$ | 2.18                   | 15.0±13.35                     | 1.61 $\cdot 10^{-9}$ |
| 190    | 1.27                   | 0±16.19                        | 3.11 $\cdot 10^{-3}$ | 2.01                   | 0±29.29                         | 2.77 $\cdot 10^{-9}$ |
| 200    | 0.85                   | 0±15.89                        | 4.54 $\cdot 10^{-3}$ | 1.26                   | 6.49±15.96                     | 3.00 $\cdot 10^{-9}$ |
Table 5: Mass dependence of upper limits UL calculated using two runs together.

| M, MeV | \(N_{\text{obs}} \pm \sigma\) | UL     |
|--------|-----------------|--------|
| 0      | 0±11.21         | 1.85 \cdot 10^{-8} |
| 10     | 0±11.05         | 1.78 \cdot 10^{-8} |
| 20     | 0±10.56         | 1.61 \cdot 10^{-8} |
| 30     | 0±9.72          | 1.37 \cdot 10^{-8} |
| 40     | 0±8.62          | 1.14 \cdot 10^{-8} |
| 50     | 0±7.42          | 0.88 \cdot 10^{-8}  |
| 60     | 0±6.39          | 0.68 \cdot 10^{-8}  |
| 70     | 0±5.78          | 0.58 \cdot 10^{-8}  |
| 80     | 0±5.69          | 0.49 \cdot 10^{-8}  |
| 90     | 0±6.27          | 0.50 \cdot 10^{-8}  |
| 100    | 0±7.88          | 0.58 \cdot 10^{-8}  |
| 110    | 0±12.59         | 0.85 \cdot 10^{-8}  |
| 120    | 0±25.67         | 1.61 \cdot 10^{-8}  |
| 130    | 0±19.91         | 1.20 \cdot 10^{-8}  |
| 140    | 0±15.51         | 0.91 \cdot 10^{-8}  |
| 150    | 0±14.94         | 0.87 \cdot 10^{-8}  |
| 160    | 0±16.79         | 0.99 \cdot 10^{-8}  |
| 170    | 0±17.07         | 1.03 \cdot 10^{-8}  |
| 180    | 0±20.09         | 1.31 \cdot 10^{-8}  |
| 190    | 0±22.12         | 1.57 \cdot 10^{-8}  |
| 200    | 13.66±19.06     | 3.08 \cdot 10^{-8}  |
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Figure 1: $K^-$ decay into sgoldstino and pions.

Figure 2: Schematic view of the ISTRA+ setup.
Figure 3: Two photon effective mass spectra for events with one charged track and two showers in the SP$_1$. Dashed line — first run data, solid line — second run data.
Figure 4: Missing energy spectra, second run data. Upper histogram — real data, middle histogram — background MC events, lower histogram — signal MC events for $m_P = 90$ MeV.
Figure 5: The influence of the "Veto" cut on the two-photon effective mass spectrum. Left part — second run, right part — first run; solid line — before the "Veto" cut, dashed line — after the "Veto" cut.
Figure 6: Missing mass squared distributions, real data, for successive cuts 3—10 respectively, second run data.
Figure 7: Missing mass squared spectra, background subtraction, first run — upper part, second run — lower part. Solid line shows spectrum for the neutral pion selection within narrow interval, dotted line shows spectrum for tails. Lower histogram in each part shows the difference.
Figure 8: Fit of the missing mass squared spectrum with sgoldstino signal at 120 MeV, first run data, upper part. Lower part — fit of the missing mass squared spectrum with sgoldstino signal at 0 MeV, second run data.
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Figure 9: Mass dependence of the upper limits, calculated using two runs together.