Searches for Signatures from Gauge Mediated SUSY Breaking

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On Behalf of OPAL

Search for Supersymmetric particle

Why do we expect Supersymmetry although the Standard Model (SM) has been verified to high accuracy?

- **Higgs mass becomes stable to radiative corrections.**
- **GUT is possible with Supersymmetric particles.**
- **The lightest Supersymmetric particle (LSP) can be dark matter candidate.**
- **String theory without "tachyon"**

No direct experimental evidence for Supersymmetry (a few indications?).
$\Rightarrow$ **but still attractive**

To verify Supersymmetry
$\Rightarrow$ **must discover at least one Supersymmetric particle.**

This talk will deal with a search for signatures from Gauge Mediated SUSY Breaking (GMSB), which are performed at the OPAL experiment.

♣ *Plan of the talk* ♣

GMSB Supersymmetry

Collider Signature

Analyses and experimental results

Conclusion

Supersymmetry

Supersymmetry must be broken...

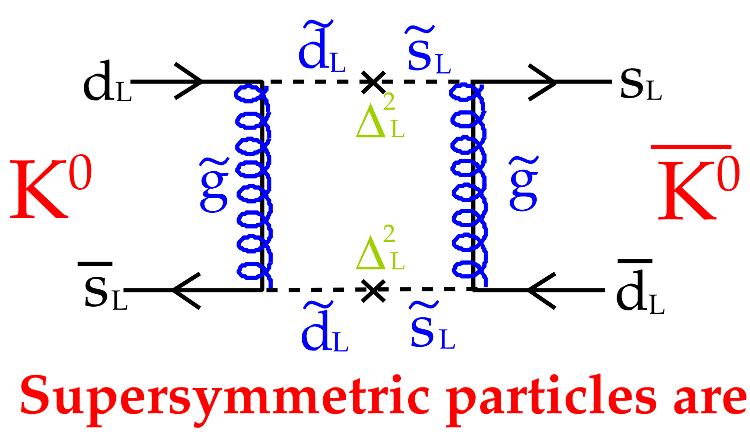
- How is Supersymmetry broken?
  → dynamical Supersymmetry breaking
- How is Supersymmetry breaking communicated to the particles in the MSSM?
  → "mediation" mechanism

♣ Various mediation mechanisms

- Gravity-mediated SUSY Breaking (traditional)
- Gauge-mediated SUSY Breaking
  anomaly, gaugino mediated SUSY Breaking and so on....

♣ Requirements on Supersymmetry theory

Not in conflict with the current experimental results!
One of the most stringent constraints is the flavor changing neutral current (FCNC) suppression.



squark masses-squared can have off-diagonal elements.

Supersymmetric particles are degenerate in mass, especially between 1st and 2nd generations!

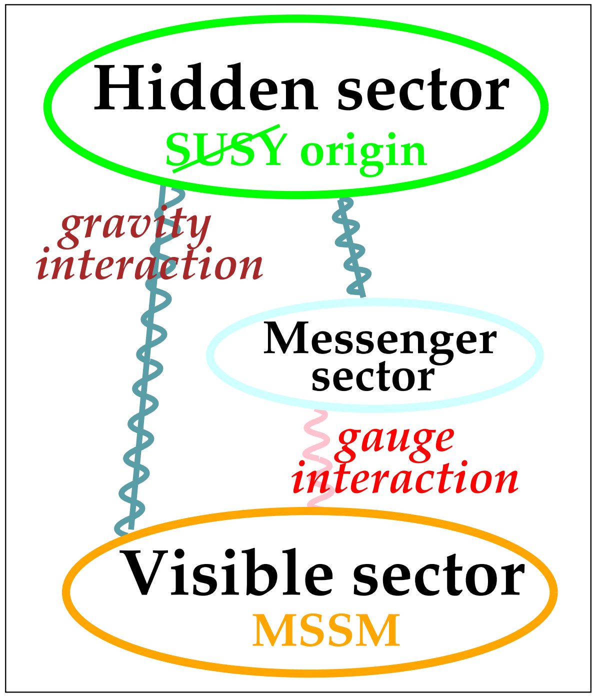
gravity-mediation vs gauge-mediation

Gravity Mediation

$$m_{\rm soft} = \frac{F}{M_{\rm planck}}$$

$$\Downarrow$$

$$\sqrt{F} \sim 10^{10-11}\ \mathrm{GeV}$$



Gauge Mediation

$$m_{\rm soft} = \frac{\alpha_a}{4\pi}\frac{F}{M_{\rm mess}}$$

if $M_{\rm mess} \sim \sqrt{F}$

$$\Downarrow$$

$$\sqrt{F} \sim 10^{4-6}\ \mathrm{GeV}$$

Phenomenology of GMSB

♣ **Gravitino ($\widetilde{G}$) is the LSP**

$$\mathrm{m}_{3/2} = \frac{\sqrt{\mathrm{F}}}{\sqrt{3}\mathrm{M}_{\rm Planck}} = 10^{-2} - 10^{2} \quad \mathrm{eV}$$

♣ **Suppress FCNC**

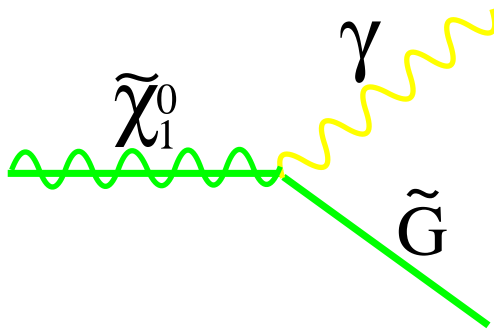
Gauge interaction is flavor blind, and FCNC can be suppressed naturally.

*** For gravity-mediation, this problem is avoided by introducing scalar mass universality (m_0).**

Particle Spectrum

♣ LSP is the Gravitino

If $M_{\rm mess} \ll M_{\rm Planck}$, gravitino becomes super-light.
Gravitino (its longitudinal (goldstino) component) can play an important role in collider physics experiments!



$$\Gamma\,(\tilde{X} \to X\widetilde{G}\,) = \frac{m_{\tilde{X}}}{16\pi}\frac{(m_{\tilde{X}}^2 - m_X^2)^4}{F^2}$$

The expected signature varies according to decay length!

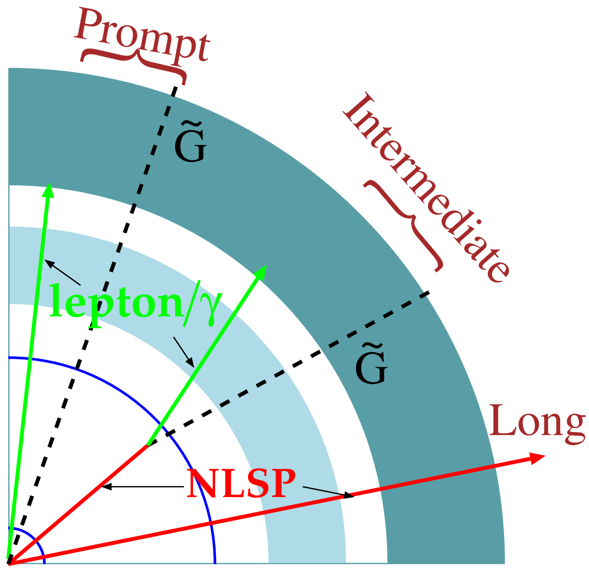
♣ NLSP is the lightest neutralino or slepton(stau)

True in most of the GMSB parameter space.
Characteristics of the NLSP (mass, coupling) are essential for an optimal selection.

	mass-eigenstate		gauge-eigenstate
• neutralino :	$\{\widetilde{\chi}_1^0, \widetilde{\chi}_2^0, \widetilde{\chi}_3^0, \widetilde{\chi}_4^0\}$	=	$\{\widetilde{B}, \widetilde{W}^3, \widetilde{H}_d^0, \widetilde{H}_u^0\}$
• stau :	$\{\tilde{\tau}_1^\pm, \tilde{\tau}_2^\pm\}$	=	$\{\tilde{\tau}_R^\pm, \tilde{\tau}_L^\pm\}$

GMSB Search at OPAL

Various final states are expected according to the gravitino mass and the NLSP type



♣ NLSP production

Good signatures to discover a Supersymmetric particle.

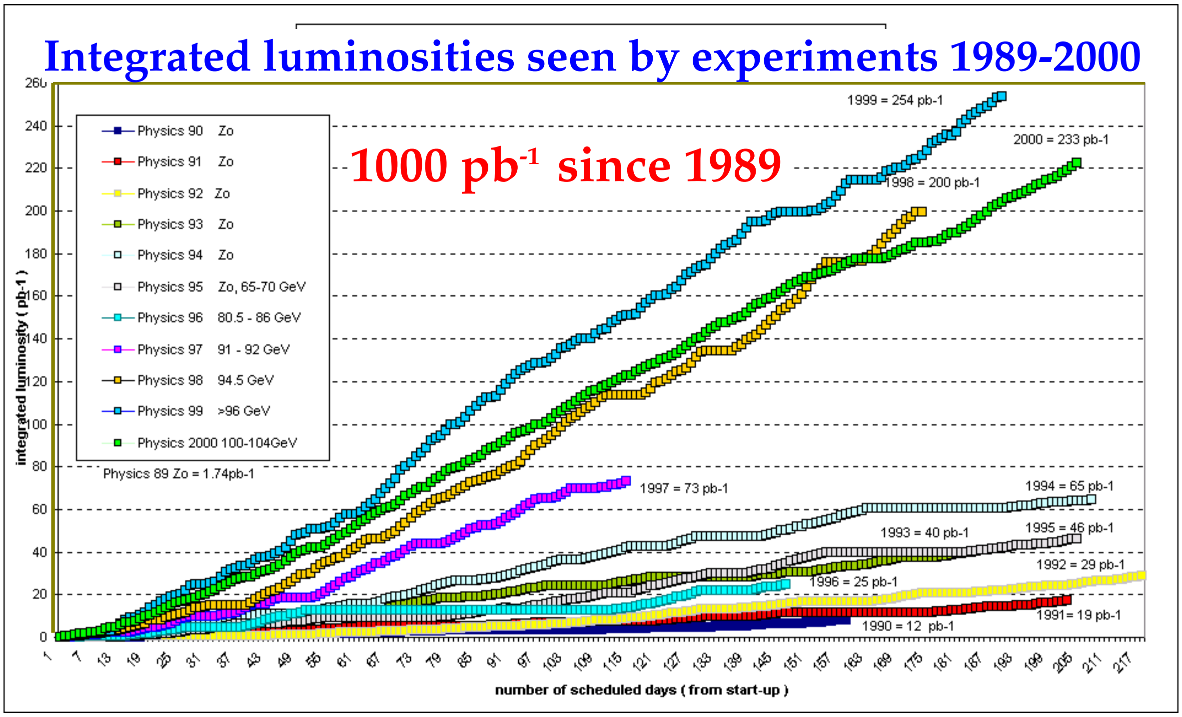
lifetime	$\tilde{\chi}_1^0$ NLSP	Slepton NLSP
short $c\tau \sim 0$	acoplanar photons	acoplanar leptons
medium $0 < c\tau < \infty$	non-pointing photons	kinked track large impact parameter
long $c\tau = \infty$	—	anomalous dE/dx

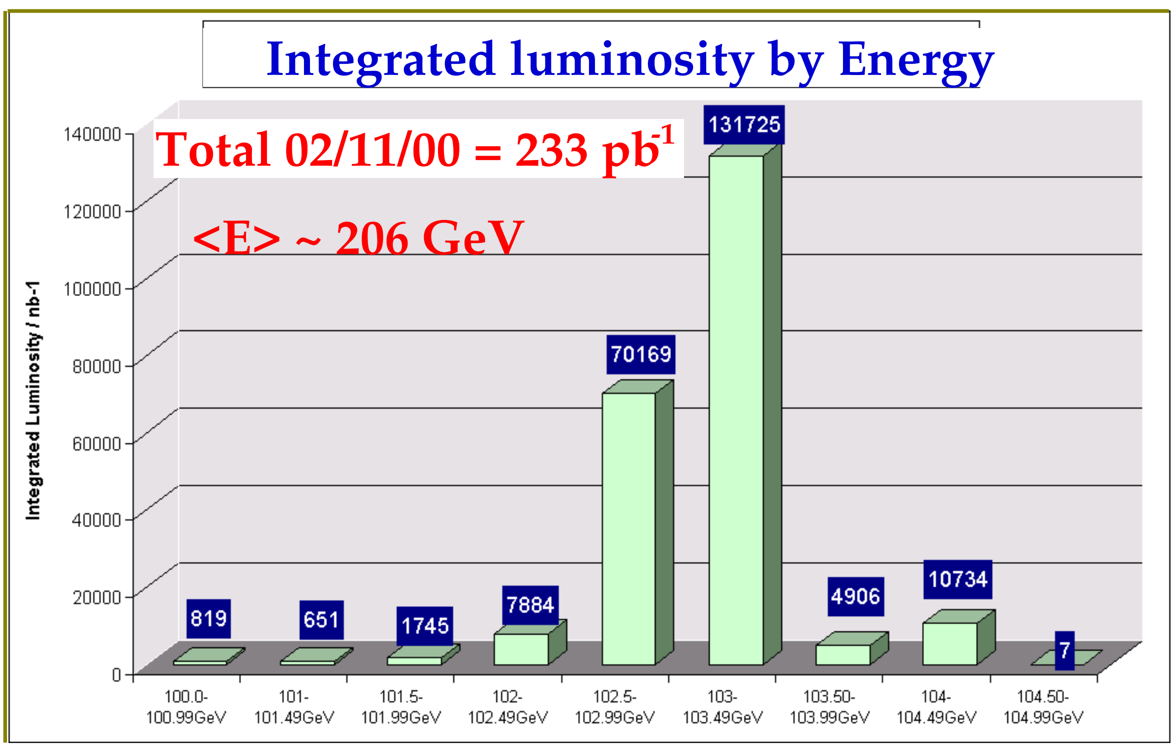
♣ NNLSP production (i.e. cascade decay)

Extend discovery reach beyond NLSP searches. Have low backgrounds and large cross-sections if accessible.

- Photons + X
- Multi-Leptons

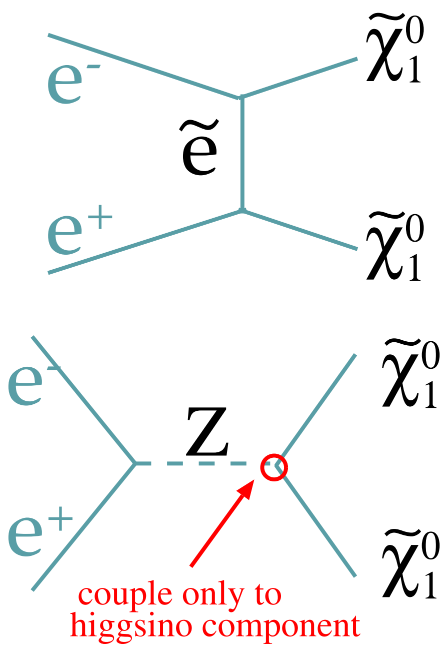
LEP data set

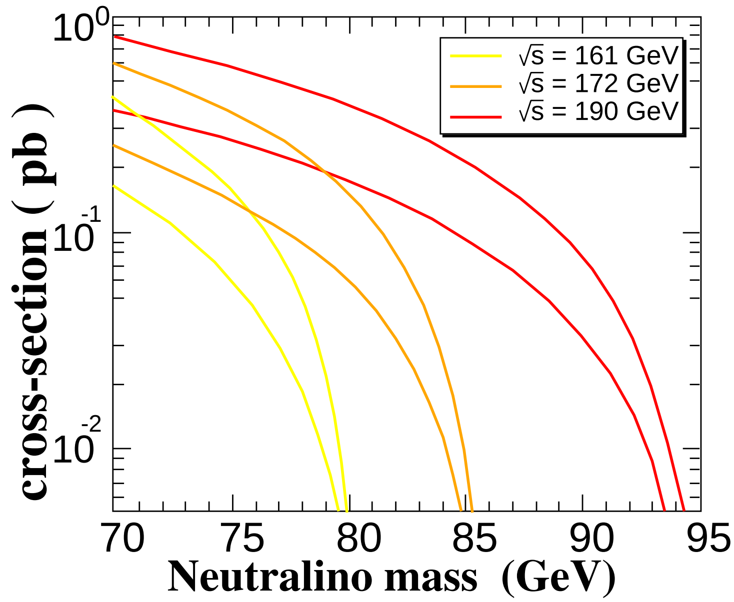

Integrated luminosities seen by experiments 1989-2000
1000 pb-1 since 1989
Physics 90 Zo
Physics 91 Zo
Physics 92 Zo
Physics 93 Zo
Physics 94 Zo
Physics 95 Zo, 65-70 GeV
Physics 96 80.5 - 86 GeV
Physics 97 91 - 92 GeV
Physics 98 94.5 GeV
Physics 99 >96 GeV
Physics 2000 100-104GeV
Physics 89 Zo = 1.74pb-1
1999 = 254 pb-1
2000 = 233 pb-1
1998 = 200 pb-1
1997 = 73 pb-1
1994 = 65 pb-1
1993 = 40 pb-1
1995 = 46 pb-1
1992 = 29 pb-1
1996 = 25 pb-1
1990 = 12 pb-1
1991= 19 pb-1
integrated luminosity (pb-1)
number of scheduled days (from start-up)


Integrated luminosity by Energy
Total 02/11/00 = 233 pb-1
<E> ~ 206 GeV
Integrated Luminosity / nb-1
819
651
1745
7884
70169
131725
4906
10734
7
100.0-100.99GeV
101-101.49GeV
101.5-101.99GeV
102-102.49GeV
102.5-102.99GeV
103-103.49GeV
103.50-103.99GeV
104-104.49GeV
104.50-104.99GeV

Acoplanar photons

♣ Production

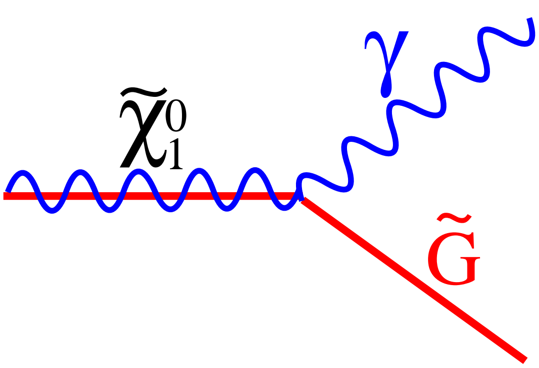




In minimal GMSB case, $\tilde{\chi}_1^0$ is mostly gaugino-like.
Pair-production via t-channel $\tilde{e}^{\pm}$ exchange dominates.

♣ Decay

Expected signature is acoplanar photons with significant missing enegy.
Photon energy is defined by $\tilde{\chi}_1^0$ mass.



$$E_{\rm min}^{\rm max} = \frac{\rm E_{beam}}{2}\left(1 \pm \sqrt{1 - \frac{m_\chi^2}{\rm E_{beam}^2}}\right)$$

Background

$e^+e^- \rightarrow \nu\bar{\nu} + n\gamma$ is dominant.

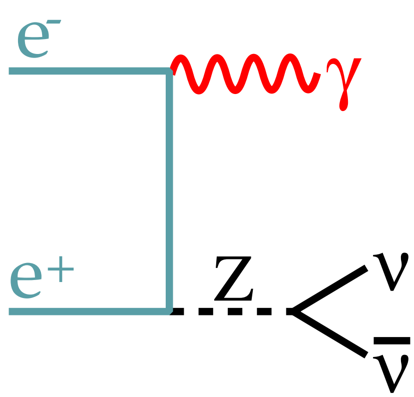
Others : non-SM background (beam-halo , cosmic rays)

Selection : At least two photons + large P_T

(1) $P_T^{\gamma\gamma}/E_{beam}$ >0.05 , E_γ/E_{beam} >0.05 , $|cos\theta| < 0.966$

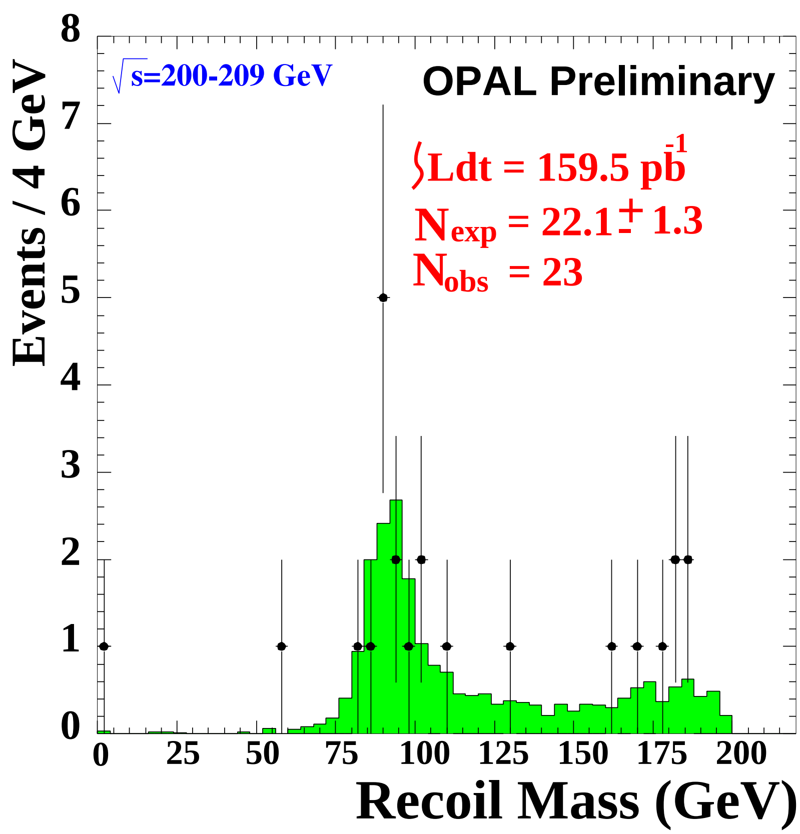
(2) $E_\gamma > 1.75$ GeV and one photon should be $|cos\theta| <$ 0.8 for low energy photons

Radiative return events can be reduced by requiring at least two photons.



$$E_\gamma = \frac{s - m_{Z^0}^2}{2\sqrt{s}}$$

Recoil mass distribution

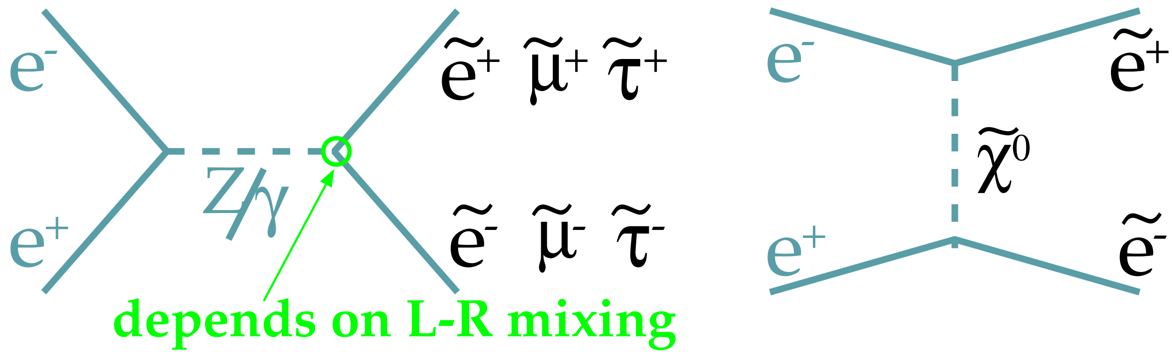


Result with 2000 data ($\sim$ 160 pb^{-1})

	total	$>$ 206.5 GeV	$>$ 207.5 GeV
data	23	12	1
SM bkg.	22.1± 1.3	10.6±0.6	0.9±0.1

Acoplanar leptons

♣ **Production**



Stau and smuon pair production cross-section don't depend on the theoretical parameter so much.

♣ **Irreducible SM background**

$\ell^+\nu\ell^-\bar{\nu}$ mainly comes from W^+W^-

Others ($\sim$ a few %) : $e^+e^-\ell^+\ell^-$ **,** $\ell^+\ell^-(\gamma)$

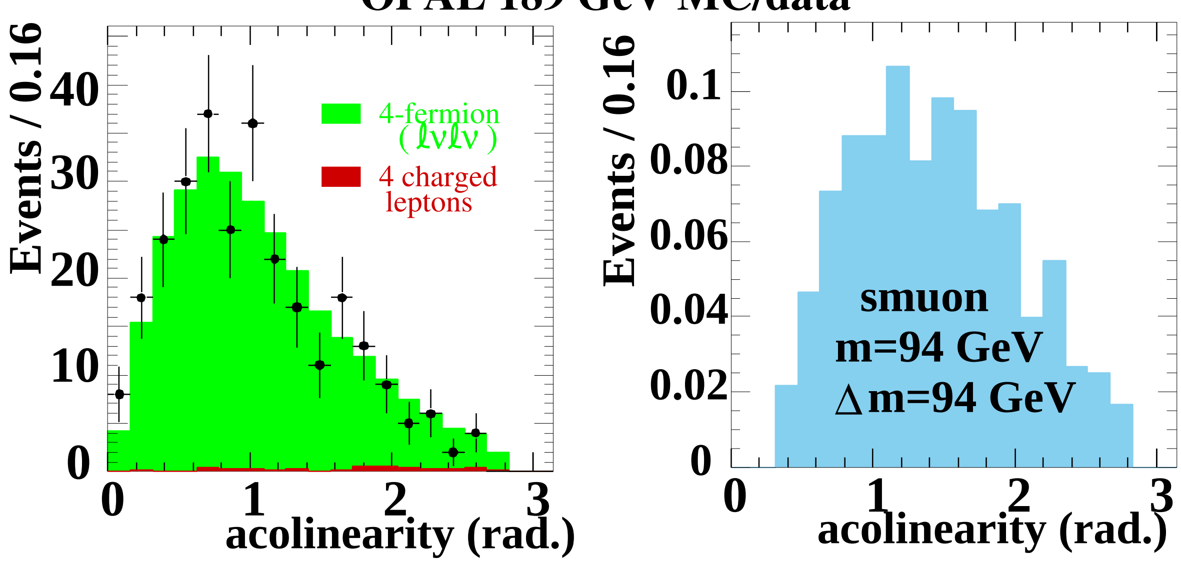
♣ **Important variables are**

acolinearity and transverse momentum.

$m_{\tilde{\ell}} \to \mathrm{E_{beam}}$ **(produced at $\sim$ rest), the event shape becomes more imbalanced.**

$\epsilon =$ **80–90% for** $m_{\tilde{\ell}} > 70$ **GeV** $\Rightarrow$ **good efficiency!**

OPAL 189 GeV MC/data

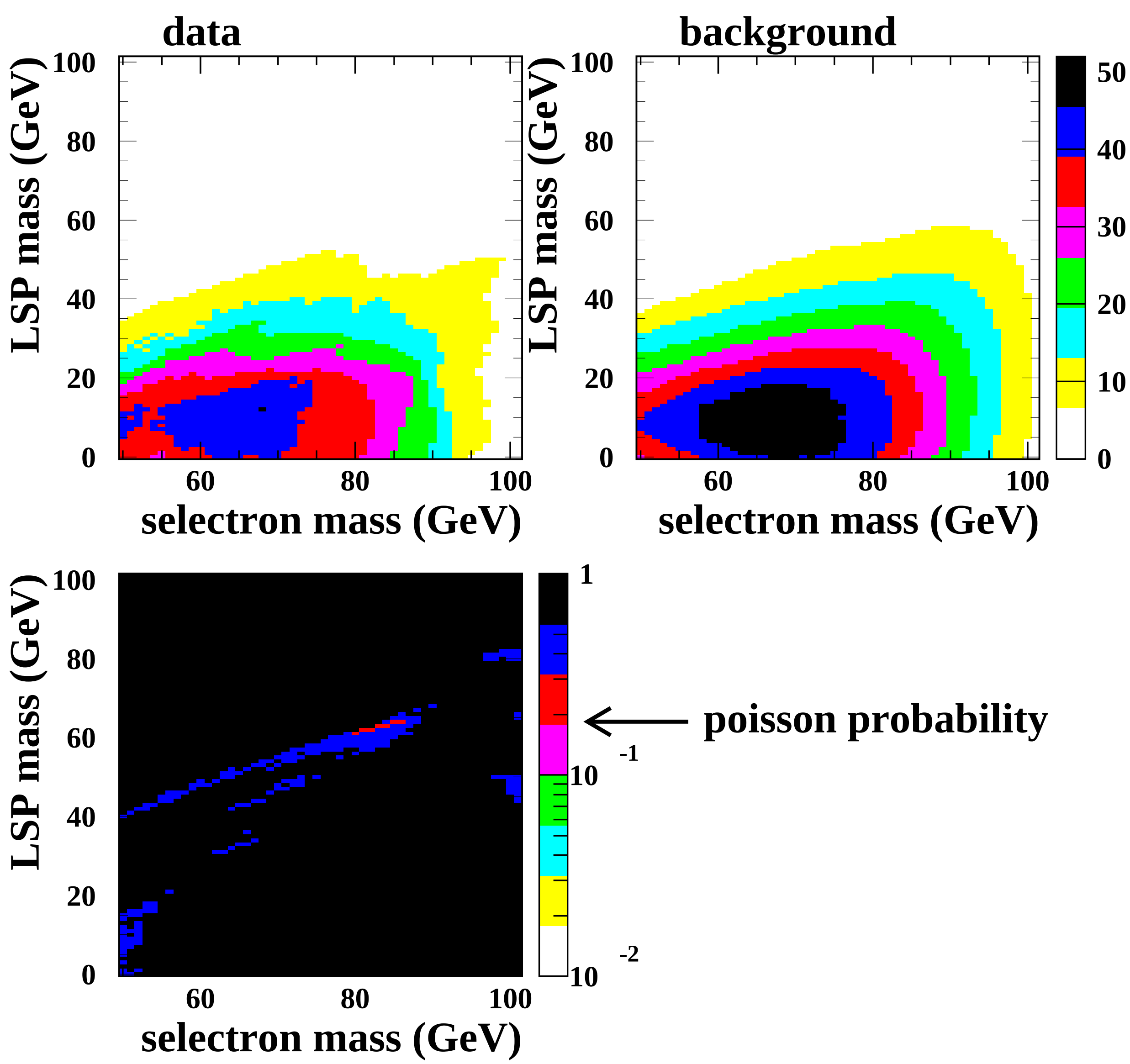


♣ Result with 2000 data ($\sim$ 197 pb^{-1})

ID	total		> 206.5 GeV		> 207.5 GeV	
	data	MC	data	MC	data	MC
ee	45	49.2	23	27.7	3	1.9
$\mu\mu$	55	51.8	35	29.1	3	2.0
hh	24	18.8	16	10.6	1	0.7

♣ Results from Likelihood analysis

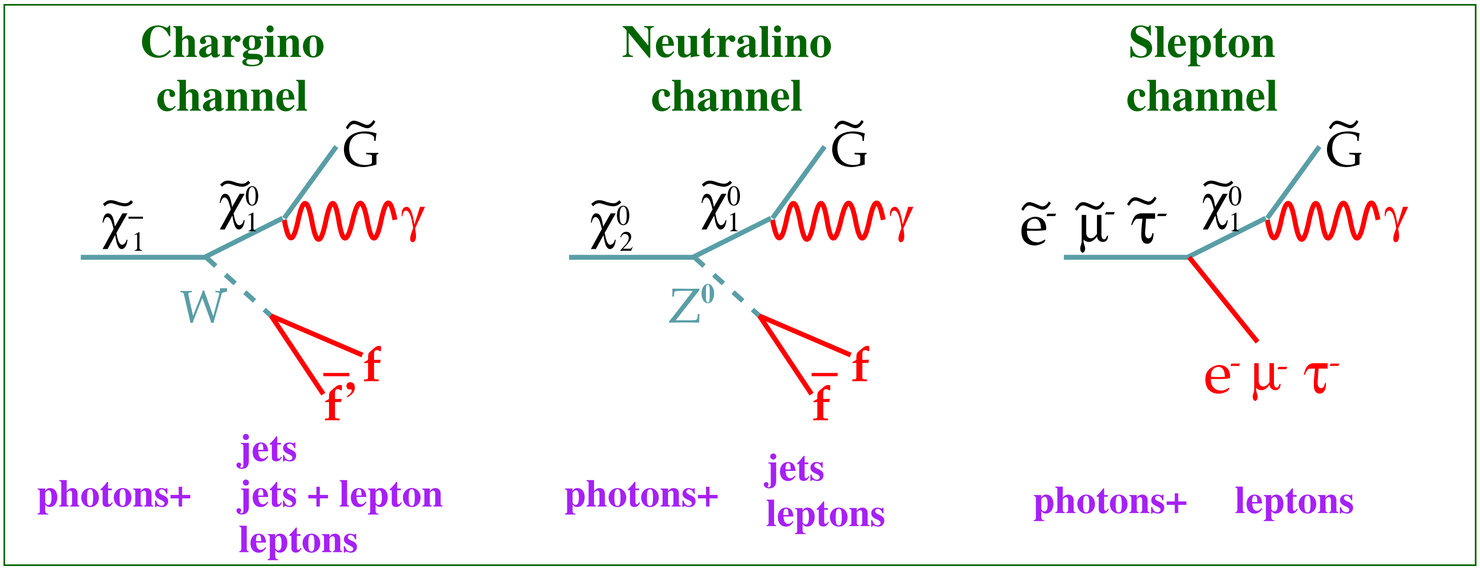
Analysis is optimized for each mass combination using likelihood method.



Photons + X

♣ Topologies from NNLSP Production

- Once NNLSP is produced, the NNLSP tends to decay into the NLSP rather than the gravitino.
- These topologies had not been studied well.



photons + X + missing energy

♣ Event Kinematics

Large Δm $\longrightarrow$ small missing energy

$\Rightarrow$ difficult to distinguish the signal from SM background

Again, **a requirement of at least two photons** is very helpful to reduce the background.

♣ Possible source of second photon

- Initial / Final state radiation
- radiative photon from an electron in a material
- neutral hadron

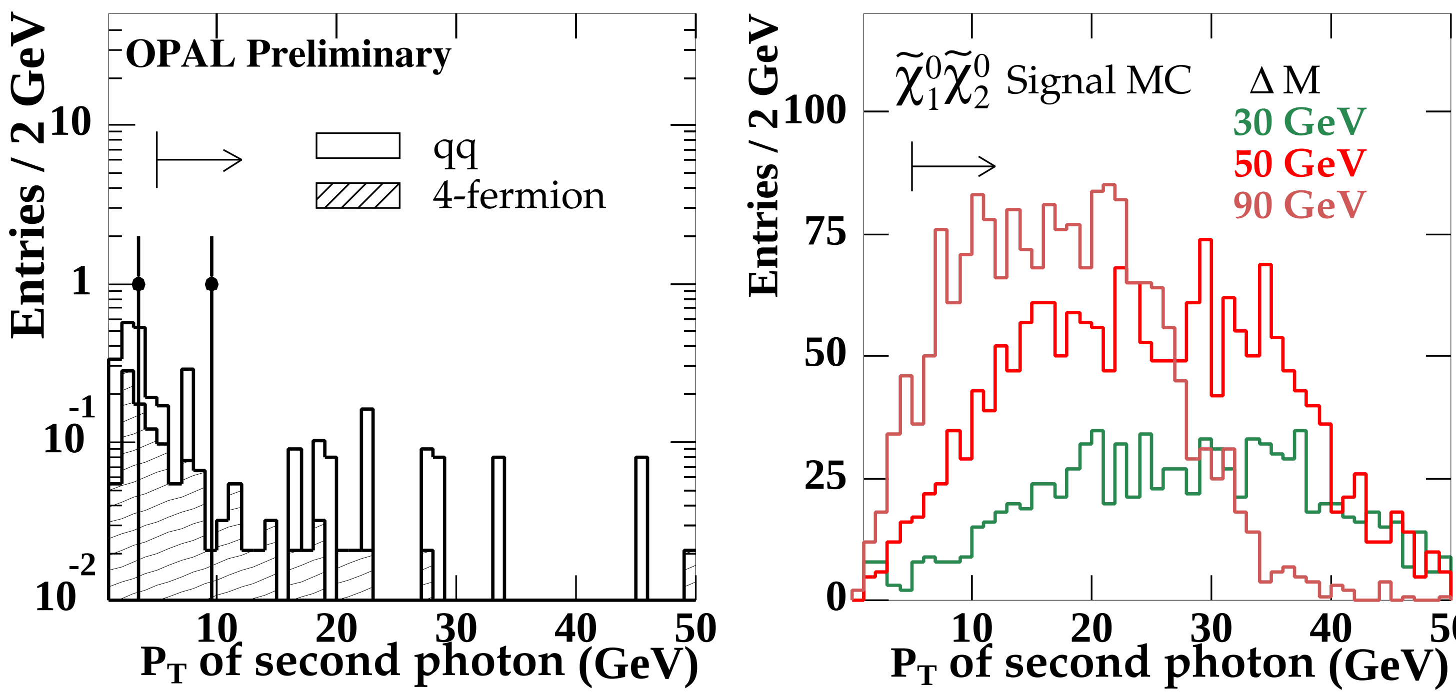
Requirements to reduce background photons :

- Isolation
- P_T w.r.t. the nearest track (jet)

It's also useful to avoid an event with final state soft photons which are not simulated sufficiently in Monte Carlo.

♣ Distribution of second photon's P_T

In High-multiplicity analysis, main background is $q\bar{q}\gamma$ and $q\bar{q}\ell\nu$

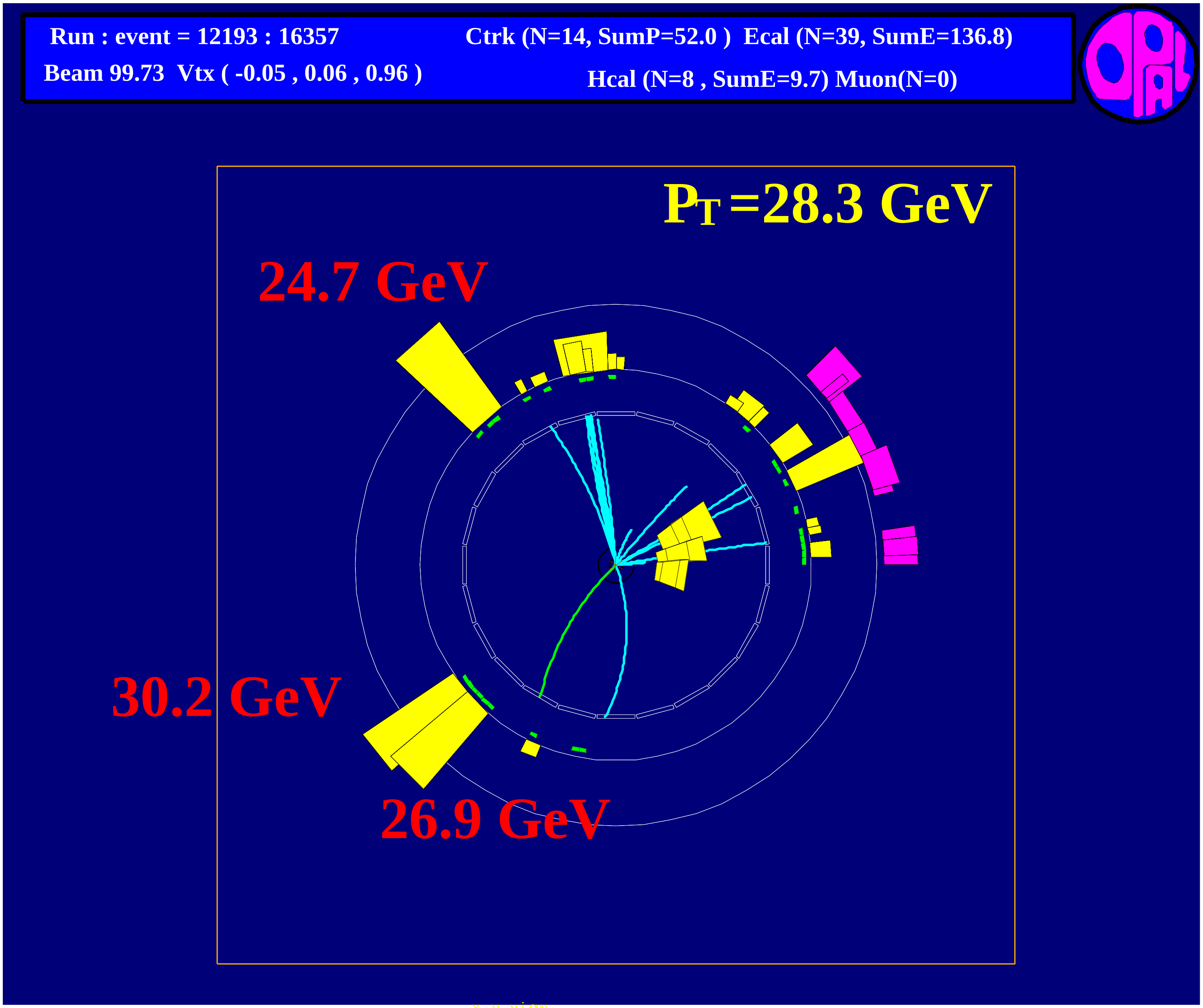


♣ Result with 2000 data ($\sim$ 222 pb^{-1})

	LM	HM (small Δm)	HM(medium Δm, with lepton)
data	3	0	1
SM bkg.	2.89	0.4	0.34

Good Candidate

High-multiplicity event



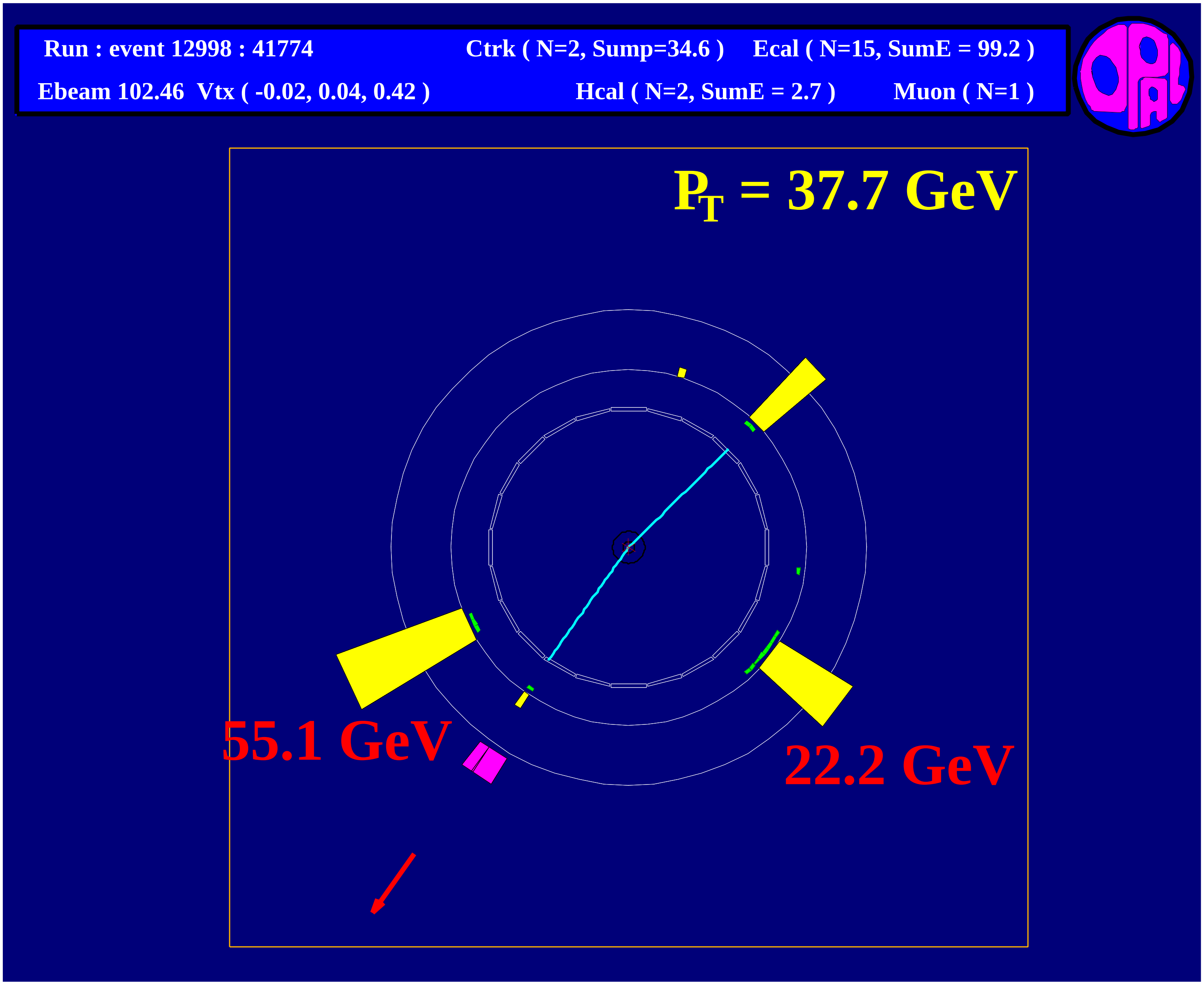
Interpretation within SM

$\mathrm{W^+W^-} \longrightarrow \mathrm{q\bar{q}}\, e^-\nu_e\,\gamma\gamma$

- $M_{\mathrm{q\bar{q}}\gamma} \sim M_W$
- **photon radiated from** e^-

Good Candidate

Low-multiplicity event



Interpretation within SM

$\tau^+\tau^- \longrightarrow e\nu\mu\nu\gamma\gamma$

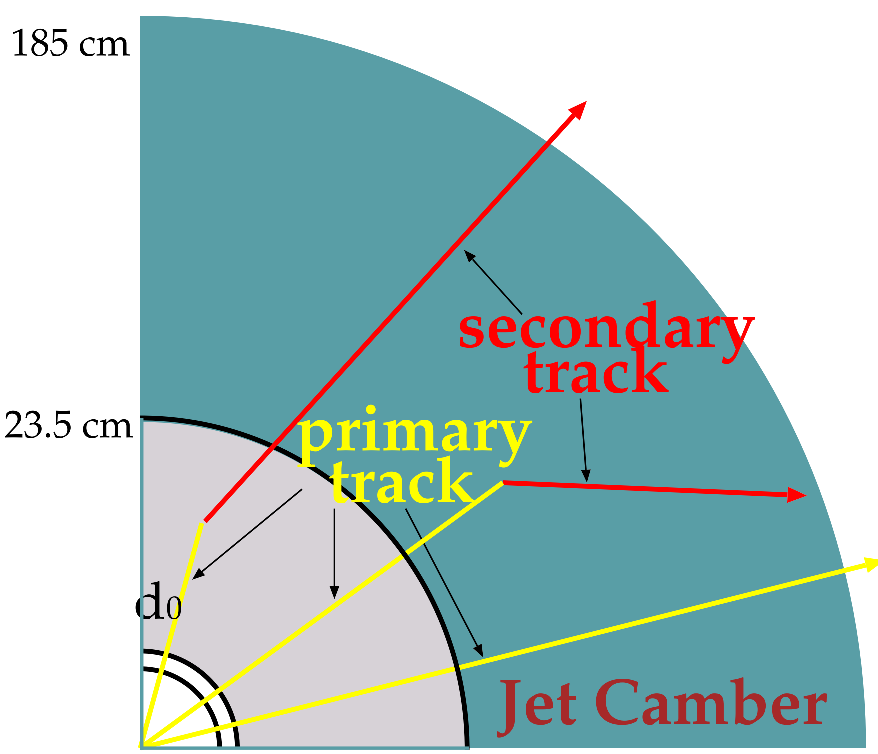
Slepton (NLSP) with observable lifetime

These are very specific signatures in the GMSB scenario and include "SUSY breaking scale" information.

$$L = 0.01\left(\frac{100\ \mathrm{GeV}/c^2}{m_{\tilde{\ell}}}\right)^5\left(\frac{\sqrt{F}}{100\ \mathrm{TeV}}\right)^4\left(\frac{\mathrm{E}^2_{\mathrm{beam}}}{m^2_{\tilde{\ell}}} - 1\right)^{1/2} \quad \mathrm{cm}.$$

♣ Expected signal

	$\beta\gamma\, c\tau$	signal
LIP	1 cm $\sim$ 40 cm	tracks with large impact parameter
KINK	10 cm $\sim$ 2 m	kinked tracks
HSCP	$>$ 2 m	tracks with anomalous dE/dx



Signal

$\tilde{\ell}^+\tilde{\ell}^- \longrightarrow \ell^+\tilde{G}\tilde{\ell}^-\tilde{G}$

with a measurable lifetime

LIP

Only secondary tracks

KINK

Two primary tracks and secondary tracks

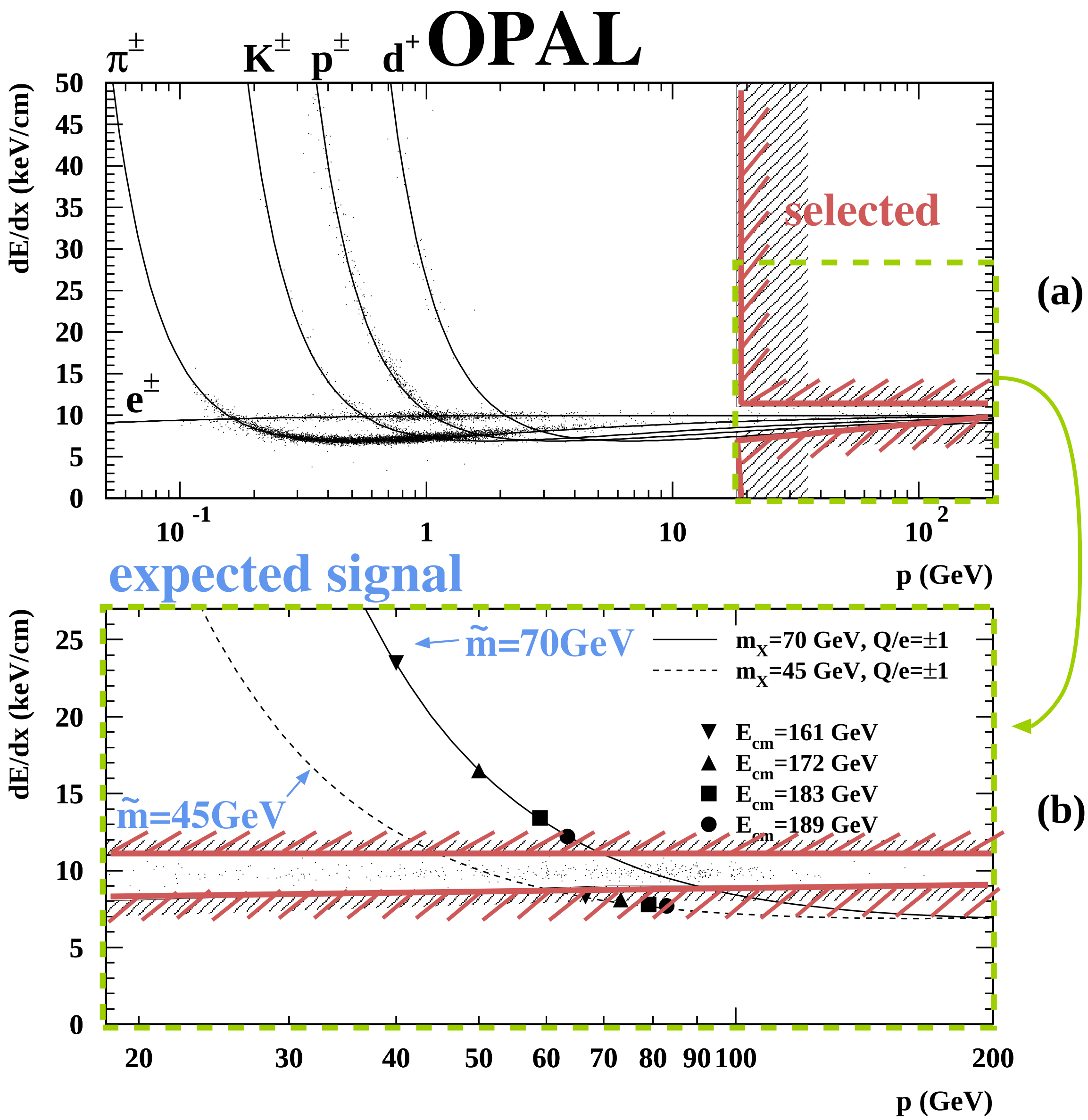
HSCP

Two primary tracks with anomalous dE/dx

Heavy Stable Charged Particles

Sleptons might have long enough lifetimes
to decay outside of the detector

Signal can be separated from SM particles using track's dE/dx energy deposition and their momentum.

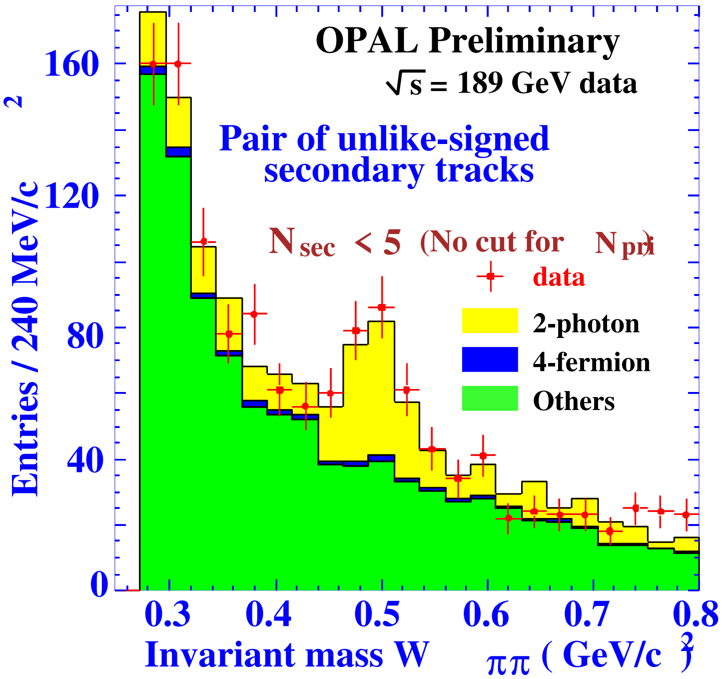


⇒ nearly background free

♣ Result with 2000 data ($\sim 220\ \mathrm{pb}^{-1}$)

0 events observed (0.43 expected)

Large Impact parameter analysis



At least two secondary tracks are required.

Validity check for tracks with LIP

♣ data sample
$\mathrm{K^0_S} \rightarrow \pi^+\pi^-$ $(c\tau \sim 2.7cm)$
$(|d_0| < 5$ cm, $|z_0| < 10$cm$)$

♣ Reducing unmodeled and insufficient-modeled SM background is essential.

- beam gas events, cosmic-ray and hadronic interactions with the detector material.
- 2-photon SM background process

Kinked track analysis

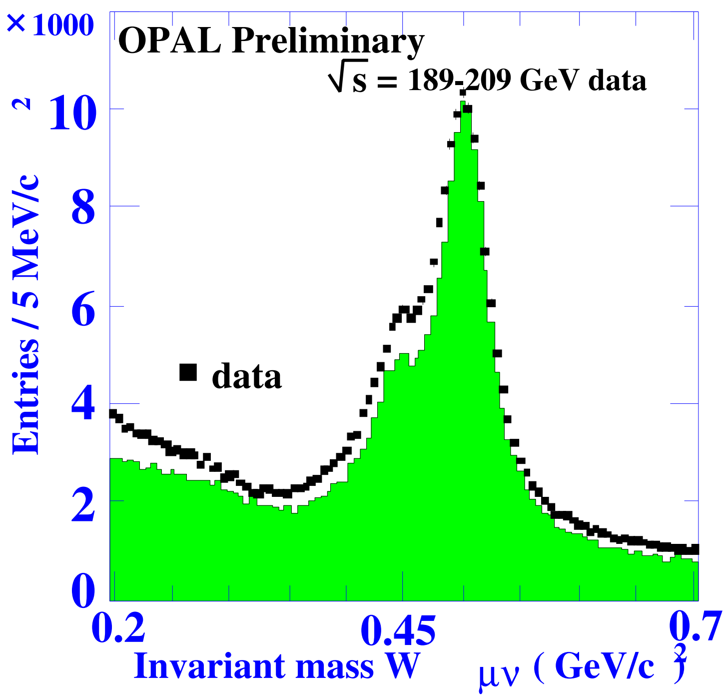
At least one primary track and one secondary track.

♣ Faked secondary track

- hadrons from interaction in the material
- decay products (μ, π) mainly from $\mathrm{K}^\pm$and π^-

They are removed by requiring a large invariant mass of secondaries.

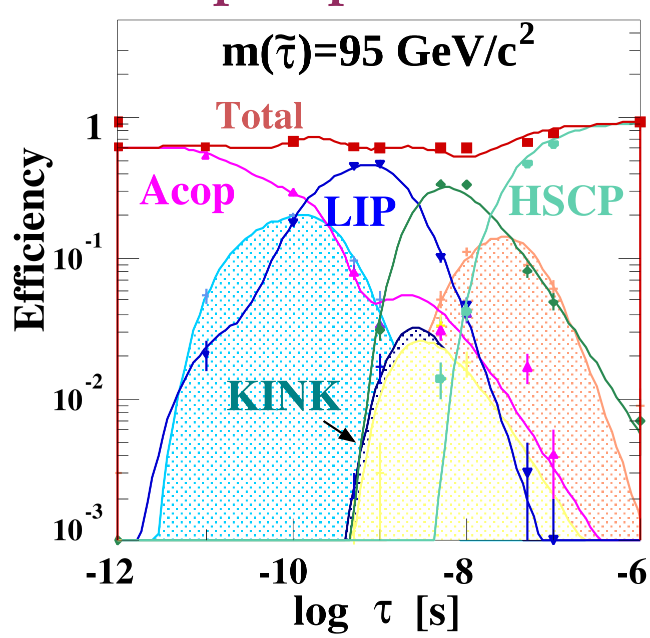
- Selection is studied using Monte Carlo and the validity of selection is checked with real data.



$K^{\pm} \rightarrow \mu^{\pm}\nu, \pi^{\pm}\pi^{0}$
$(c\tau \sim 3.7m)$

$\Delta n_{\rm evt}/n_{\rm evt}$ at peak
$\sim$ 2-3 %.

Stau pair production



- Efficiency

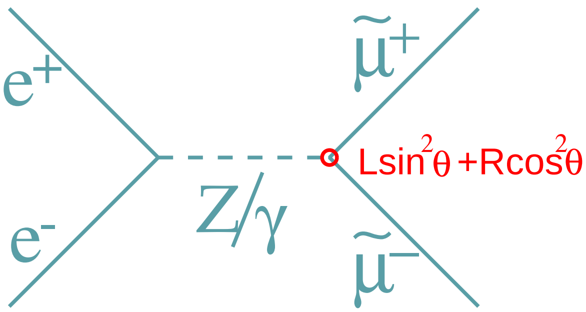
$\epsilon >\sim$ 40 % is kept
for all mass and lifetime,
except
  - near kinematical limit
  - $\tilde{m}/\sqrt{s} \sim 0.3$
    with long lifetime.

- Result with 2000 data ($\sim$ 215 pb^{-1})

	LIP		KINK	
	$\tilde{e}_1^+\tilde{e}_1^-, \tilde{\mu}_1^+\tilde{\mu}_1^-$	$\tilde{\tau}_1^+\tilde{\tau}_1^-$	$\tilde{e}_1^+\tilde{e}_1^-, \tilde{\mu}_1^+\tilde{\mu}_1^-$	$\tilde{\tau}_1^+\tilde{\tau}_1^-$
data	1	2	3	0
SM bkg.	0.64	1.59	3.5	0.6

Result for 2-lepton channel

Concentrate here on model-independent results. Detailed studies in GMSB models ongoing.

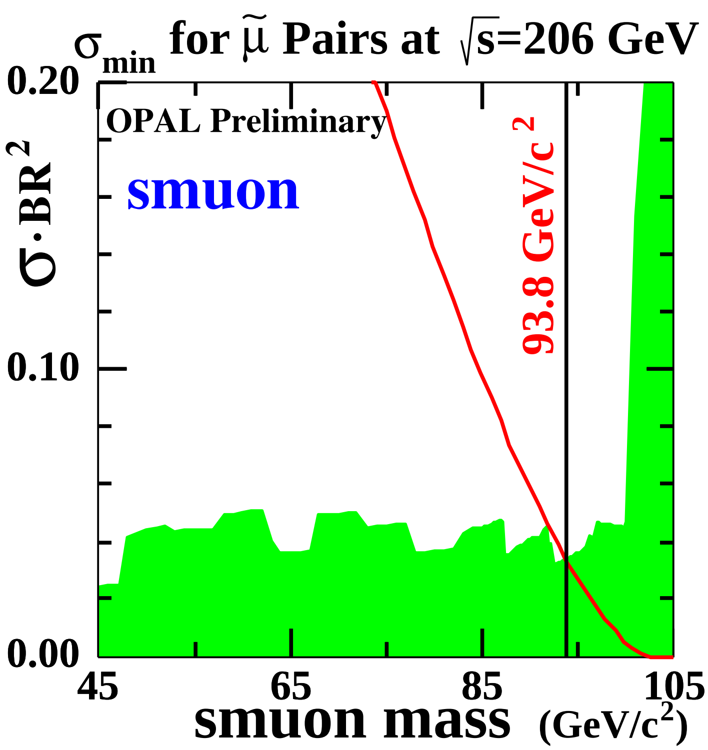


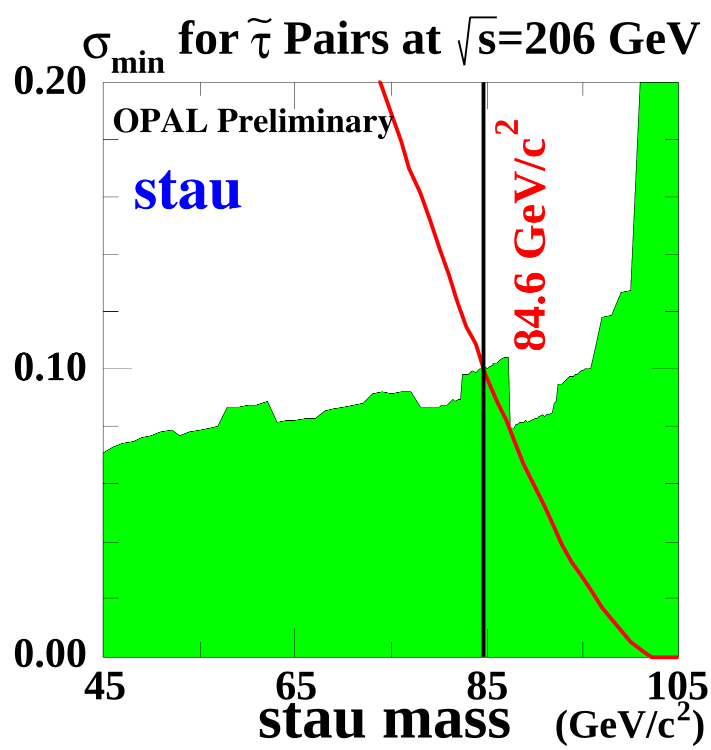
Smuon is almost right handed (negligible Yukawa-coupling)
$\sigma \sim \beta^3/s$ **(γ - exchange)**

$\sigma(\tilde{\mu}\tilde{\mu})$ **= 0.01 - 0.5 pb^{-1}: up to 100 GeV at $\sqrt{s}$ = 206 GeV**

♣ **Model independent mass limits on stau and smuon**

They are valid for any slepton lifetime in case of slepton NLSP.





** **stau mass limit becomes slightly low by tan β**

Conclusion

Signatures expected with GMSB scenario were studied using data taken by the OPAL detector.

♣ Increased LEP centre-of-mass energy gave us an opportunity to search for new physics.

$\int \mathcal{L} \sim 600\ pb^{-1}$ at $\sqrt{s}$ = 189–209 GeV

♣ Possible topologies in GMSB scenario were studied.

- Acoplanar leptons, acoplanar photons
- Photon + X, multi-leptons
- Above processes with visible lifetime
- Heavy stable charged particle

♣ No indication of Supersymmetric particles was observed in any analysis.

♣ We can constrain GMSB parameters as well as sparticle masses with these searches. Detailed studies ongoing, with final results expected summer 2002.