# Experimental Implication for a Linear Collider of SUSY Dark Matter Scenario

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1. Motivation: WMAP ←?→ Small $\Delta M = m_{stau} - m_{\chi}$
2. Detectability of stau/smuon with small $\Delta M$?
   Precision on DM relic density @ a future LC?
   Effect of crossing-angle vs. head-on collisions?
3. Summary

# Motivation

- Current precision on Dark Matter from WMAP: 10%

  or in 2$\sigma$ range: $0.094 < \Omega_{DM} h^2 < 0.129$
- Future precision expected from Planck: 2%

➔ Questions for colliders:

What are these non-baryonic DM?

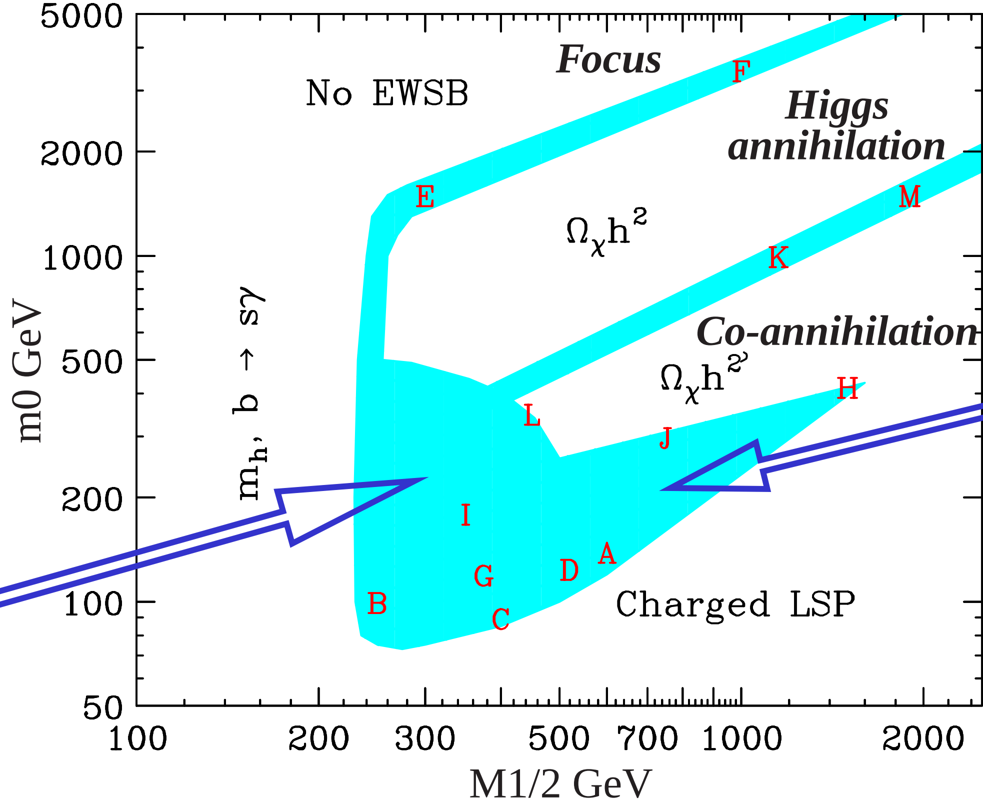
Any connection between DM and $\chi$ LSP in SUSY?

How precise can a LC measure DM relic density?

$$\Omega_{\tilde{\chi}_1^0} h^2 = m_{\tilde{\chi}_1^0} n_{\tilde{\chi}_1^0} \sim \int_0^{x_f} dx (\langle \sigma_{ann} v \rangle)^{-1}$$

# DM vs. mSUGRA SUSY Model

**Benchmark points:**
Battaglia-De Roeck
Ellis-Gianatti-Olive
-Pape,
hep-ph/0306219




$\chi\chi$ pairs annihilation

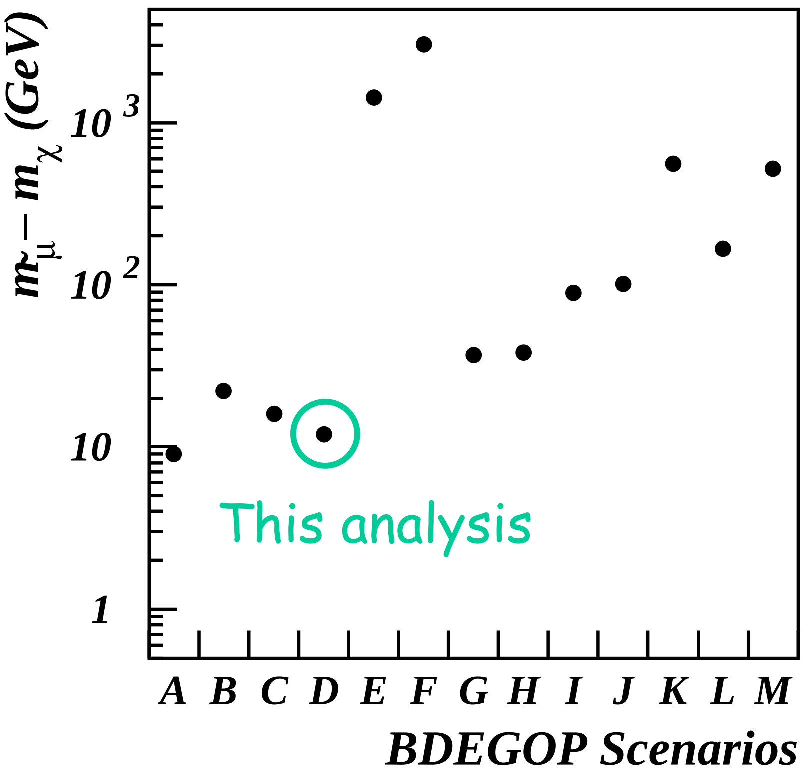
$\chi$ stau ($s\tau$) annihilation

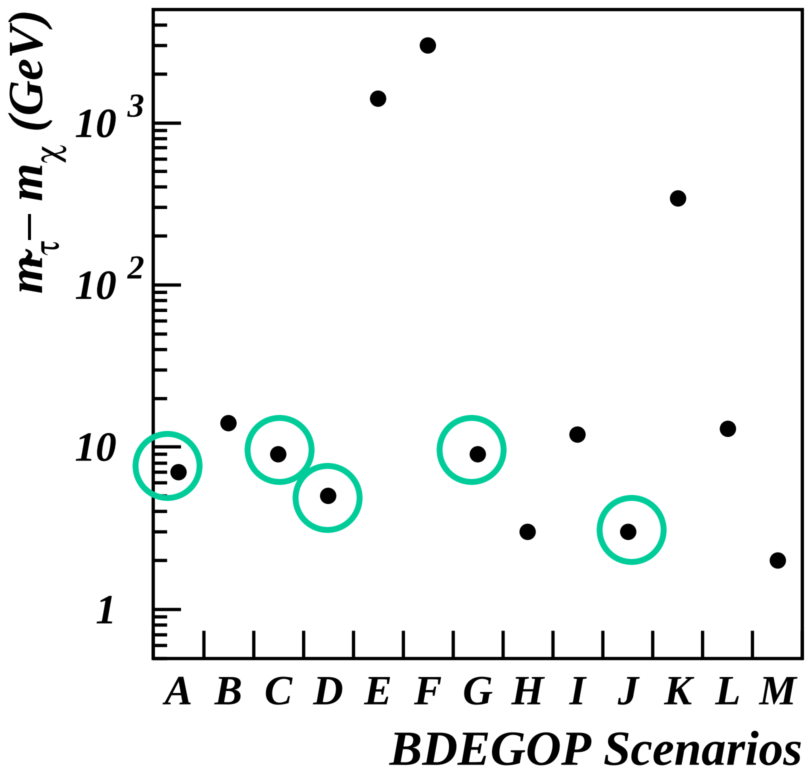
important when $\Delta M = m_{s\tau} - m_\chi$ is small

➔ The precision on SUSY DM prediction depends on $\Delta M$ & thus

$\delta m_\chi$ ➔ Needs smuon (or selectron) analysis
$\delta m_{s\tau}$ ➔ Needs stau analysis

# Smuon, Stau Mass Difference vs. LSP $\chi$




$m_{stau}$-$m_{\chi}$ comparable with intrinsic missing $p_t$ due to crossing-angle !

Impact on the sleption detection & mass measurement?

# LSP & Smuon Mass Measurement Using End-Point Method

**Benchmark D:**

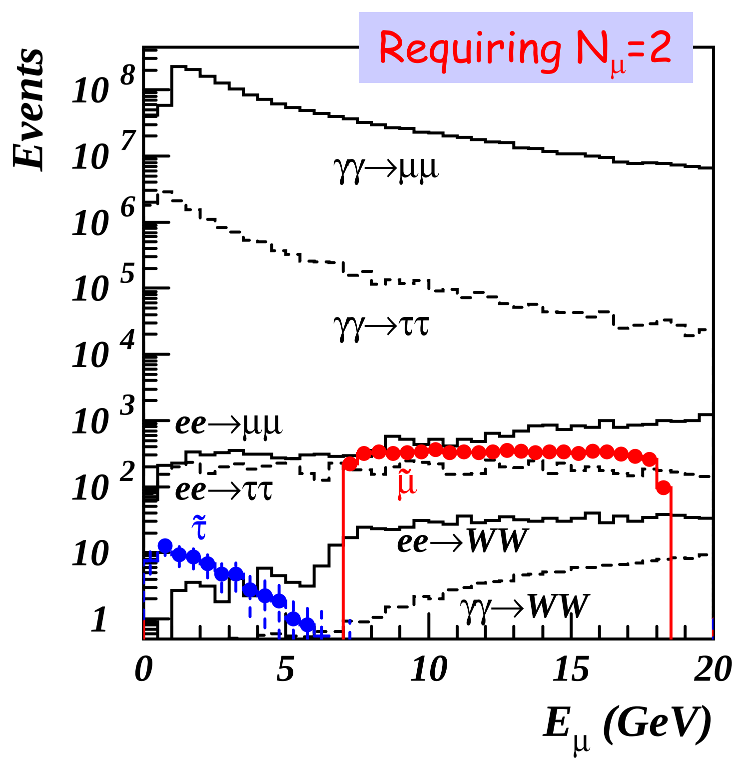
$m_{smu}$=224GeV
$m_{\chi}$ =212GeV
➔ $\Delta M$=12GeV
Ecm=500GeV
L=500pb$^{-1}$

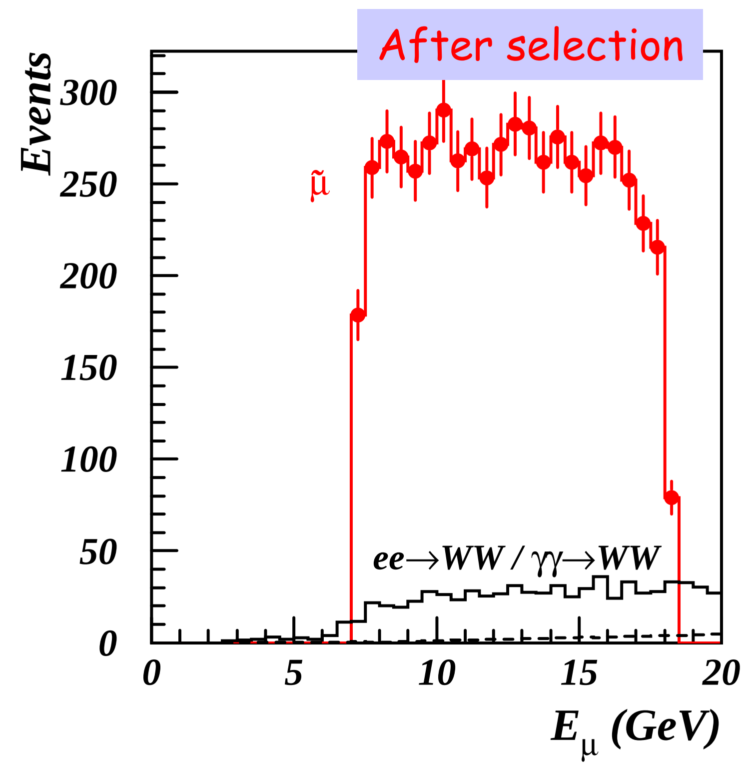
**Signal:**
$\sigma$=7.2fb

**Backgrounds:**
many orders of magnitude larger

**Main cuts:**
veto
$P_{T,miss}$>5GeV

$$E_{\max,\min}=\frac{m_{\tilde{\mu}}}{2}\left(1-\frac{m^2_{\chi 2}}{m^2_{\tilde{\mu}}}\right)\gamma(1\pm\beta) \quad \text{with} \quad \beta=\sqrt{1-\frac{4m^2_{\tilde{\mu}}}{s}},\ \gamma=\frac{1}{\sqrt{1-\beta^2}}$$

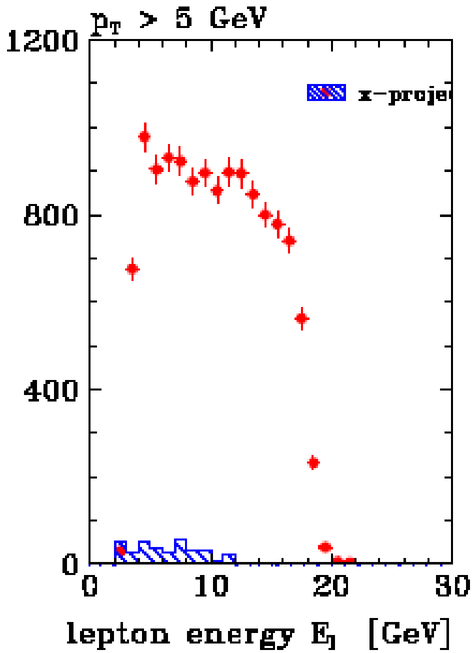


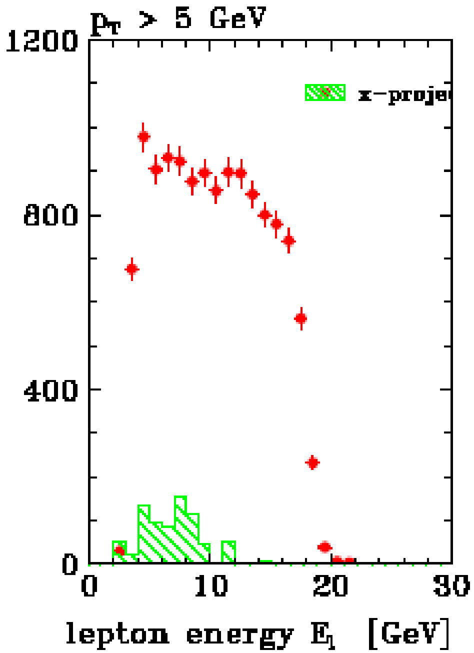
# Precise LSP Mass Measurement from Sleptons

**SPS 1a inspired model:** $m_{smu}$=143GeV, $m_\chi$=96GeV→135GeV → $\Delta$M=8GeV,
(LC-PHSM-2003-071) Ecm=400GeV, L=200pb$^{-1}$, $P_{e-}$=0.8, $P_{e+}$=-0.6, $\sigma$=120fb

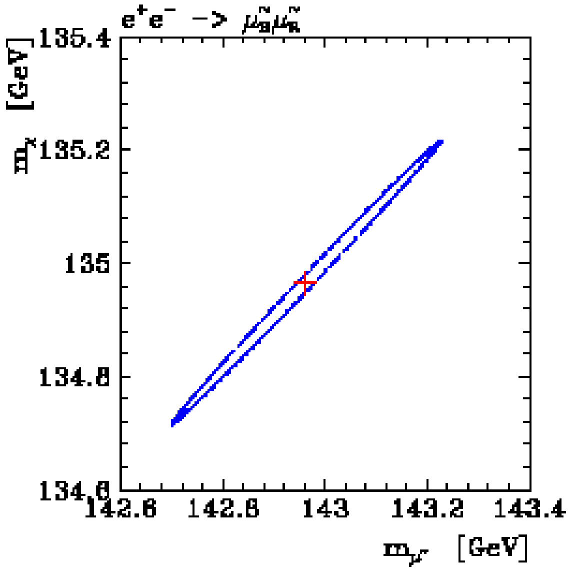
head-on collision




crossed beams




$E_- = 3.270 \pm 0.015$ GeV
$E_+ = 18.48 \pm 0.039$ GeV




**Numerical results:**

| | | |
|---|---|---|
| $\tilde{\mu}_R\tilde{\mu}_R$ | $\delta m_{\tilde{\mu}_R} = 0.18$ GeV | $\delta m_{\tilde{\chi}_1^0} = 0.17$ GeV |
| $\tilde{e}_R\tilde{e}_R$ | $\delta m_{\tilde{e}_R} = 0.09$ GeV | $\delta m_{\tilde{\chi}_1^0} = 0.08$ GeV |

# Stau Analyses

- **Much more difficult than smuon analyses:**
  - → Additional missing energies from neutrinos,
  - → Final state particles very soft: due to small $\Delta M$<10GeV & little Lorentz boost
- **SM backgrounds are many orders of magnitude larger**
  - ➔ Need very efficient veto at low angles
- **Additional complication if crossing-angle collisions**
- **Two different/exclusive strategies:**

Strategy one: when $m_{stau}$~Ecm/2 & signal cross section small
→ event counting (in 1-1,1-3,3-3 prong except eX,$\mu\mu$)

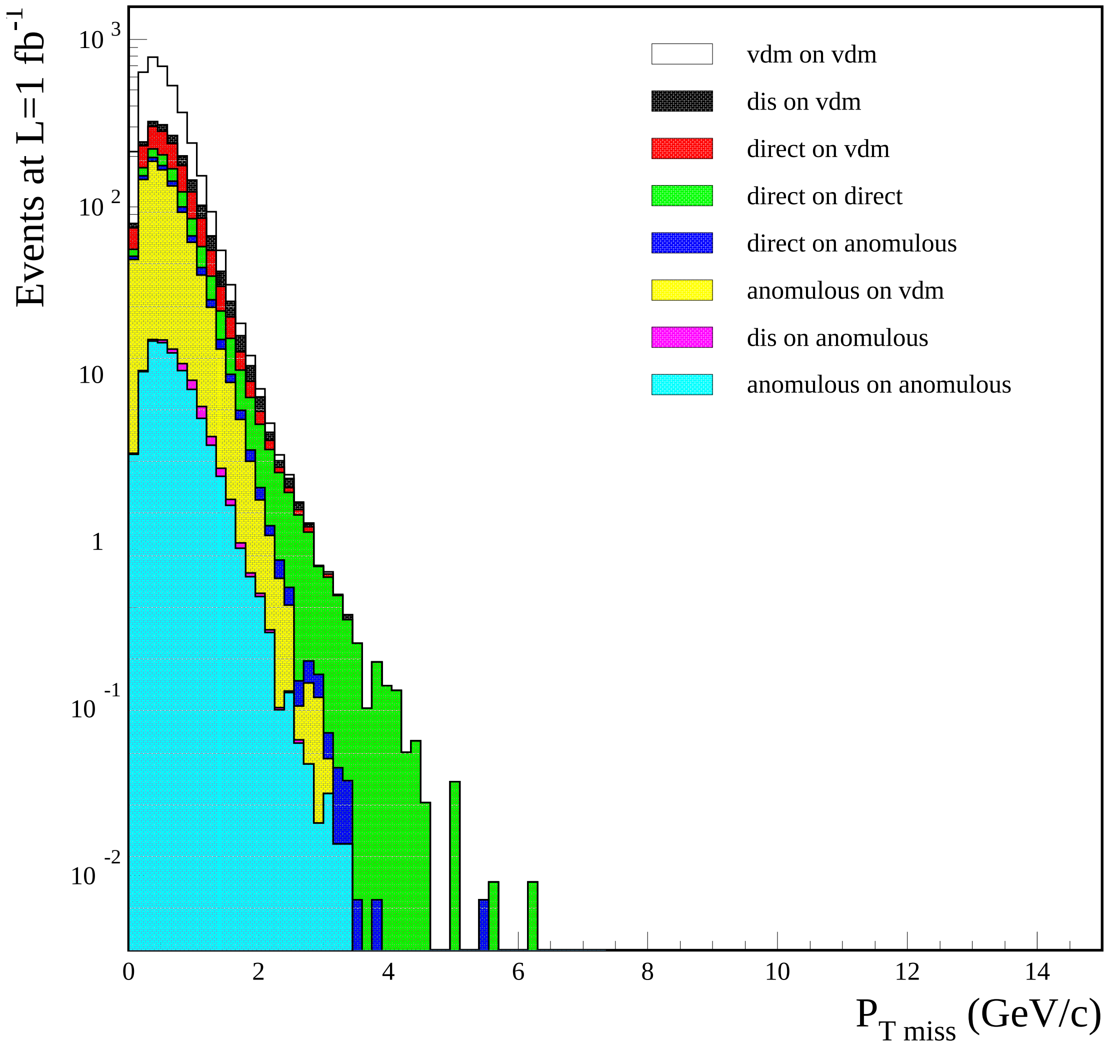
Strategy two: when $m_{stau}$<<Ecm/2 & signal cross section large
→ energy spectrum analysis (in $\pi$, $\rho$, $3\pi$ channels)

# Signal/Background Ratio

e.g. for Benchmark D, $\Delta M=217[m_{stau}]-212[m_{\chi}]=5GeV$, Ecm=500GeV

| | B/S |
|---|---|
| • **Signal** | |
| $e^+e^- \to s\tau^+ s\tau^-$: $\sigma\sim 10fb$ | |
| • **Background processes considered** | |
| $\gamma^*\gamma^* \to \tau^+\tau^-$ $(E_t>4.5GeV)$: $\sigma\sim 4.3\times10^5$ fb | $4.3\times10^4$ |
| $\to \mu^+\mu^-$ $(E_t>2GeV)$: $\sigma\sim 5.2\times10^6$ fb | $5.2\times10^5$ |
| $\to$ hadrons (direct*direct dominant) | |
| ccbar $\sigma\sim 8.2\times10^5$ fb | $8.2\times10^4$ |
| $\to$ WW | |
| $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$: $\sigma\sim 1.0\times10^3$ fb | $1.0\times10^2$ |
| $\to$ WW | |
| $e^+e^- \to s\mu^+ s\mu^-$: $\sigma\sim 7.2fb$ | |

# Comparison of Different Hadronic Subprocesses



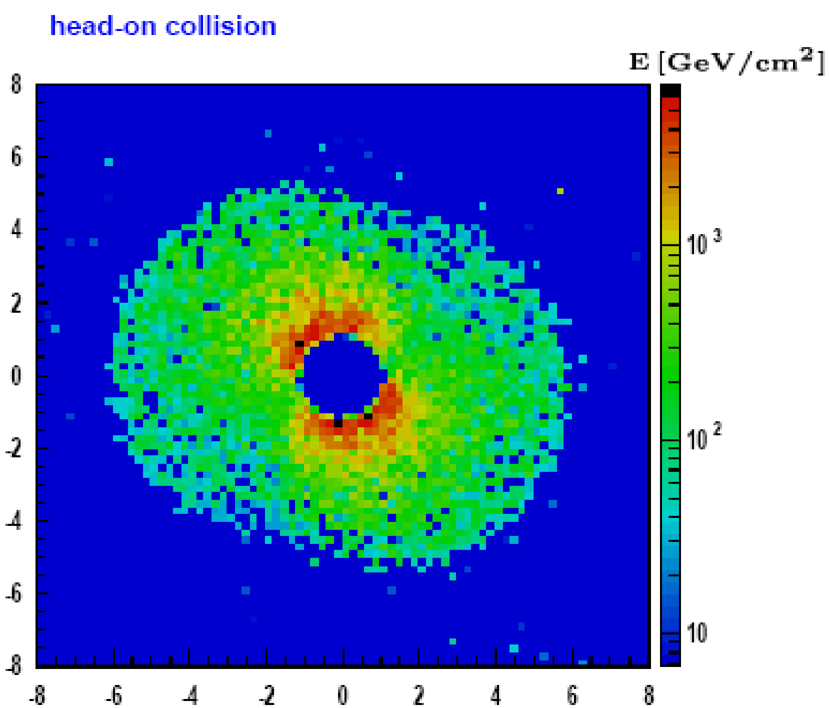

| $\gamma^*\gamma^*$ process: | [s] (pb) |
|---|---|
| VDM*VDM: | 15770 |
| Anom*Anom: | 505 |
| Direct*Direct: | 2370 |
| VDM*Anom: | 5554 |
| VDM*Direct: | 2246 |
| Anom*Direct: | 483 |
| DIS*VDM: | 909 |
| DIS*Anom: | 435 |

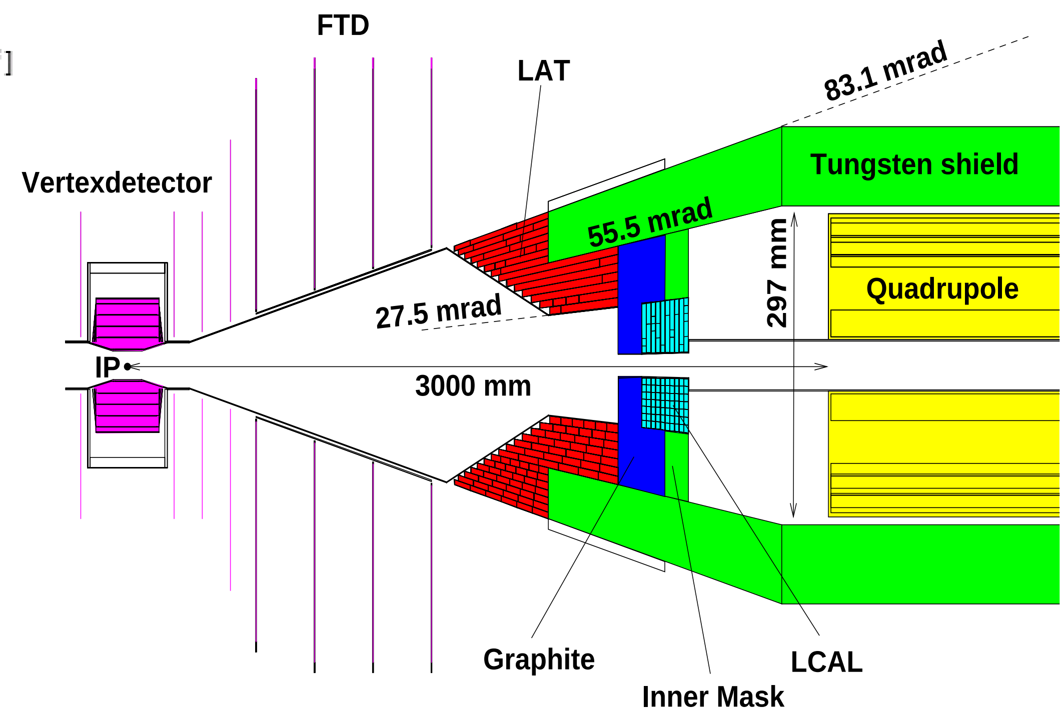
➔ Dominated by Direct*Direct at large $P_{Tmiss}$

# Identify Energetic $e^+/e^-$ from $\gamma\gamma$ out of Huge Number Soft Beamstrahlung Background

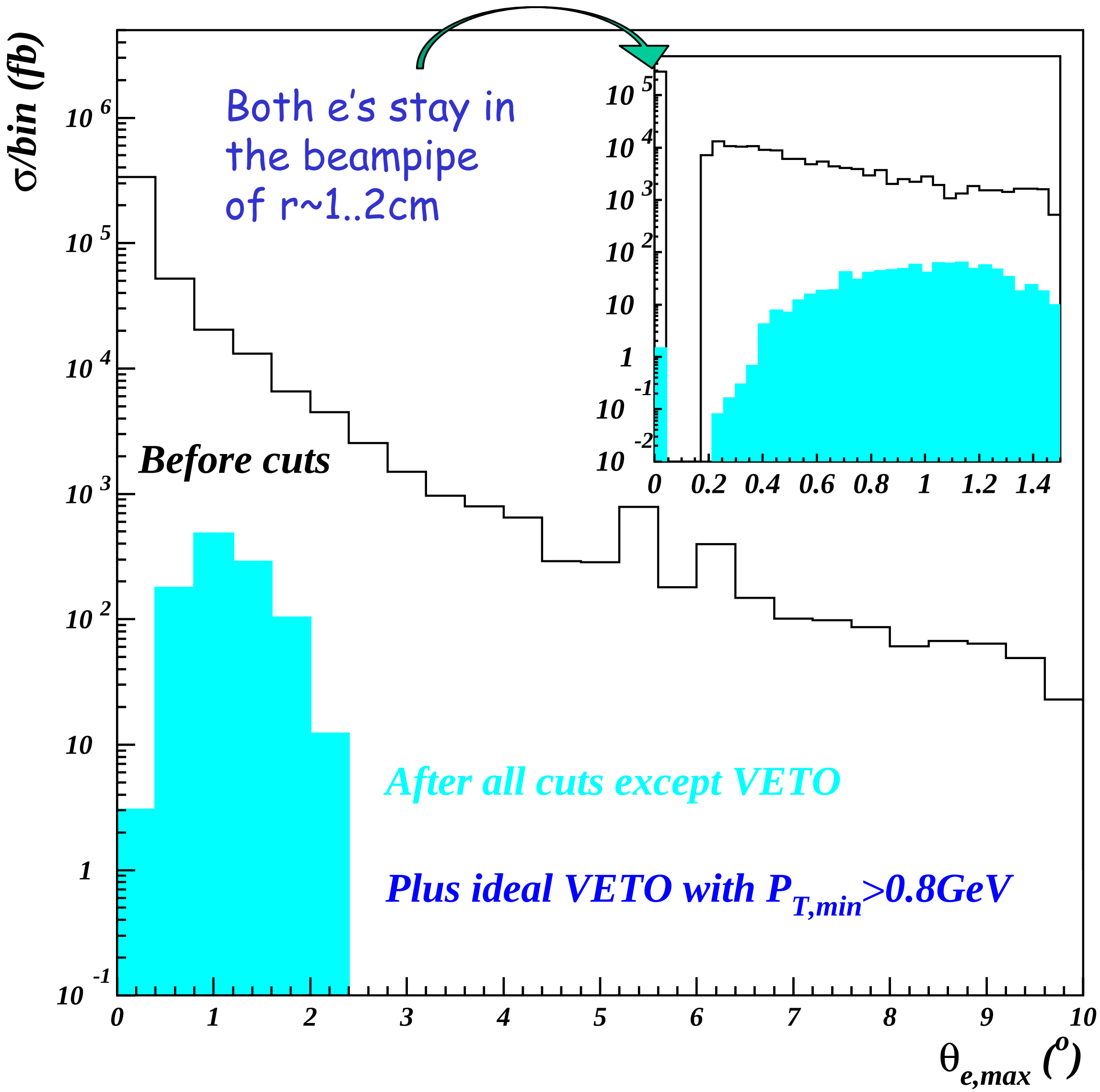
- **$e^+/e^-$ from ee→eeff:** At most 2e/event but energetic
- **Beamstrahlung background:** Huge number e,$\gamma$/event but soft

e.g. the energy density/event in LCAL @ z=3.7m simulated by K. Buesser



# Importance of Low Angle Veto



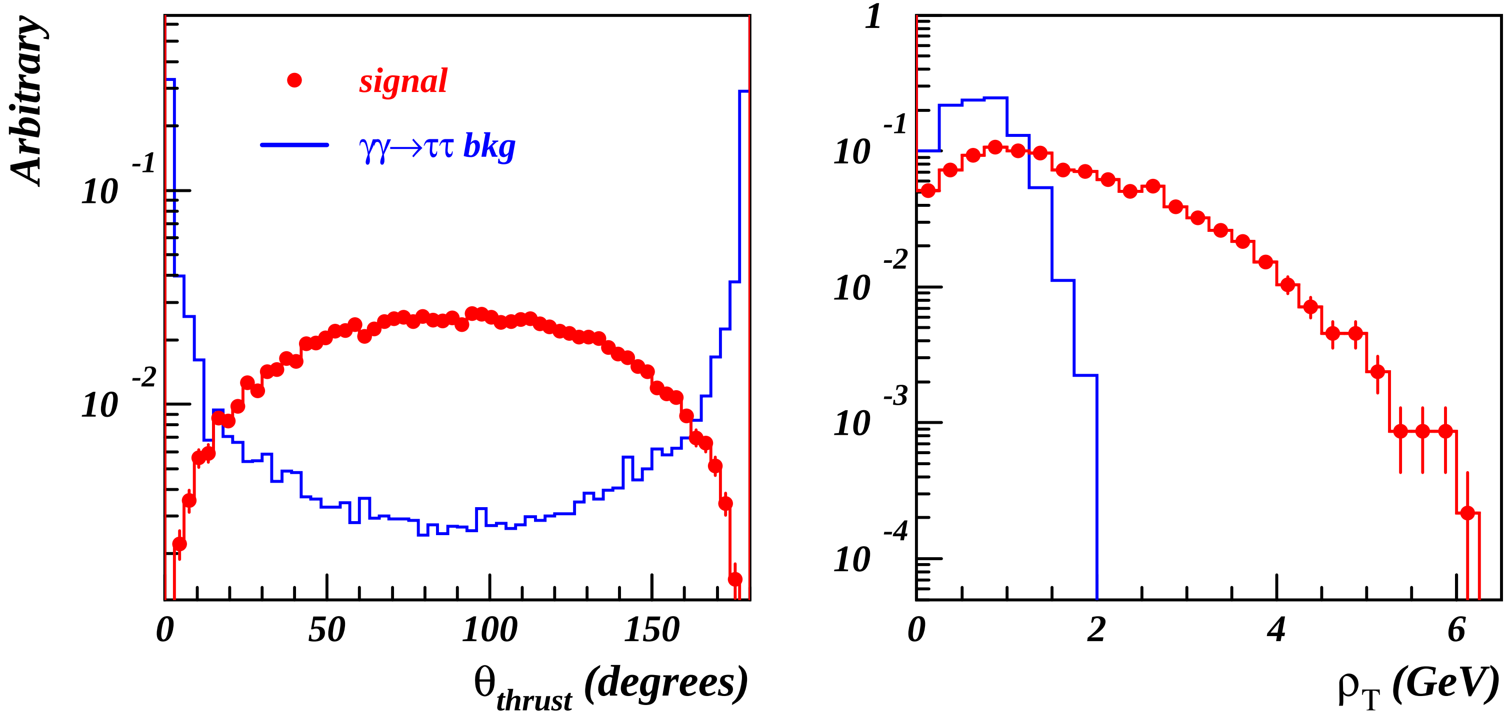

**Angular distribution of the spectator e from $ee \rightarrow ee\tau\tau$**

Total $\sigma \sim 0.43 \times 10^6$ fb of which 3/4 with both e's staying in the beampipe corresponding to the peak at zero in the inset

**Analysis cuts reject most of the background**

**An ideal veto with**
$P_{T,min}$>0.8GeV
is sufficient to suppress all remaining $\gamma\gamma \rightarrow \tau\tau$ background events except those with energetic $\mu/\pi$ at low angles

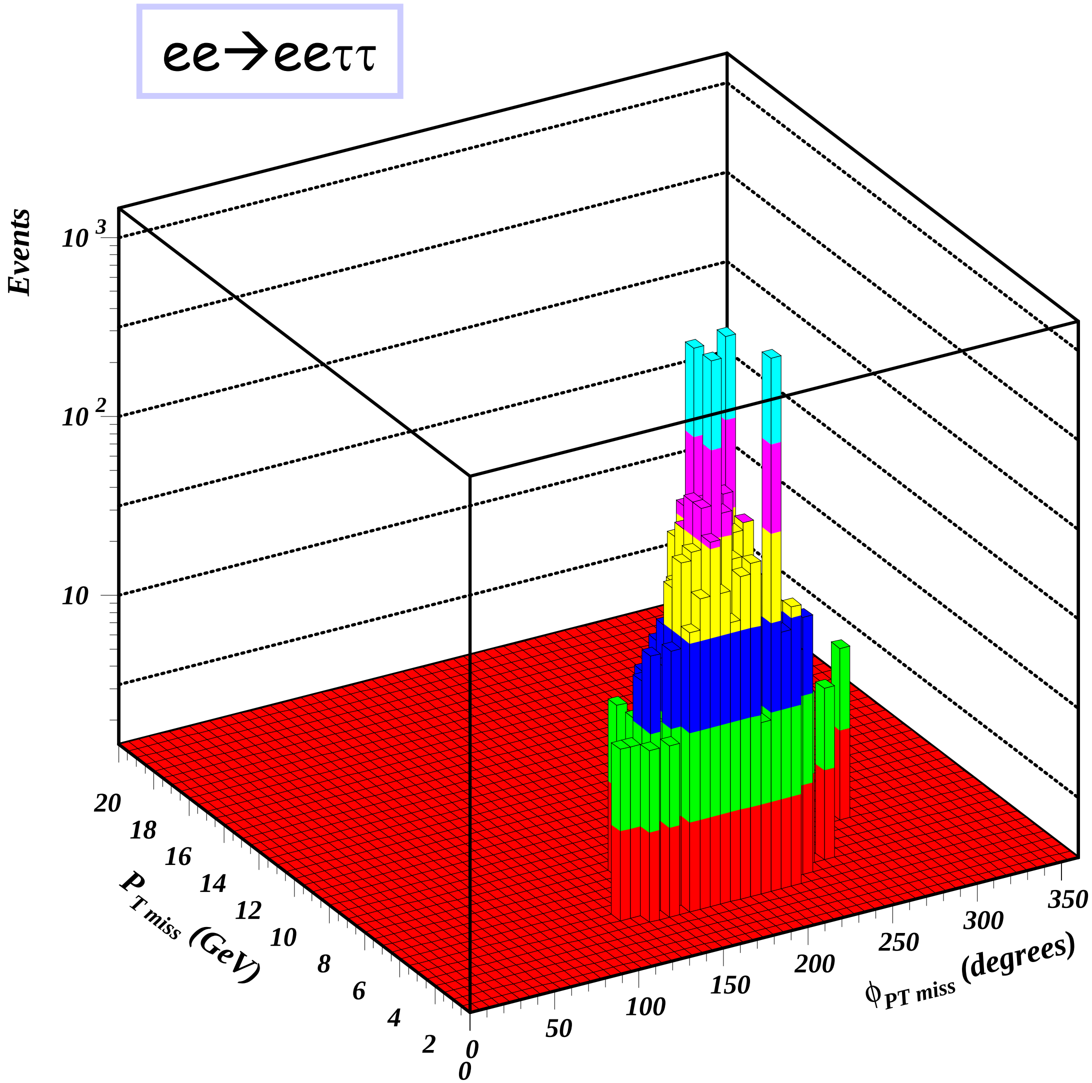
# Examples of Discriminating Variables




Thrust axis angle in 3 dimension:
- Signals mainly centrally distributed
- Backgrounds mostly forward distributed

$P_T$ sum with respect to the thrust axis in the transverse plane to the beam:
- distribution shown after all other cuts except $\rho_T$

# Remaining Background in Cross-Angle Mode




10mrad half crossing angle

For an incoming beam hole of r=1.2cm the probability for a spectator e+/e- to enter the hole is $10^{-3}$.

Remaining background events correspond (mainly) to those with e+/e- goes into the incoming beam hole.

Additional cuts remove essentially all these events.

A price to pay however:
25% efficiency reduction
e.g. for benchmark point D @ Ecm=440GeV
from ~8.5% to ~6.4%

# Strategy One: Optimal Center of Mass Energy for Stau Mass Measurement

Assuming negligible background and given

the integrated luminosity: L

the efficiency: $\varepsilon$

Signal cross section: $\sigma = A\beta^3$ (neglect ISR correction)

with $A \sim 100$, $\beta = (1-4m^2/s)^{1/2}$

➔ Observed events: $N = LA\beta^3\varepsilon$

QED correction: Large but known
Coulomb correction: Known & small
Width effect: small $[\Gamma/M \sim \alpha(\Delta M/M)^2]$

One can easily derive

the relative stau mass precision:

$dm/m = s/12m^2\, [\beta/LA\varepsilon]^{1/2}$

the optimal center of mass energy:

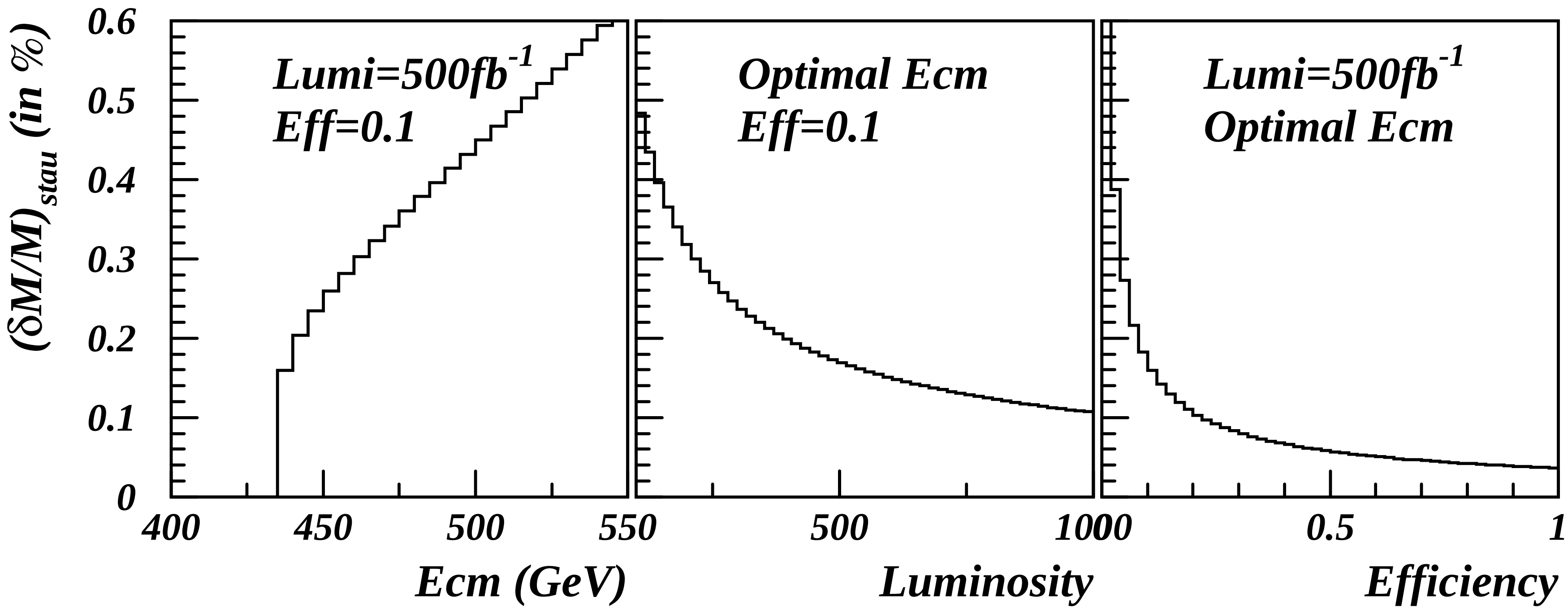
$E_{cm} = s^{1/2} = 2m / [1-(N/LA\varepsilon)^{2/3}]^{1/2}$

**Note: This differs from a threshold scan measurement,**

**➔ Little sensitivity to the $\sigma$ shape & corrections @ threshold**

# Relative Stau Mass Precision

Example with benchmark point D

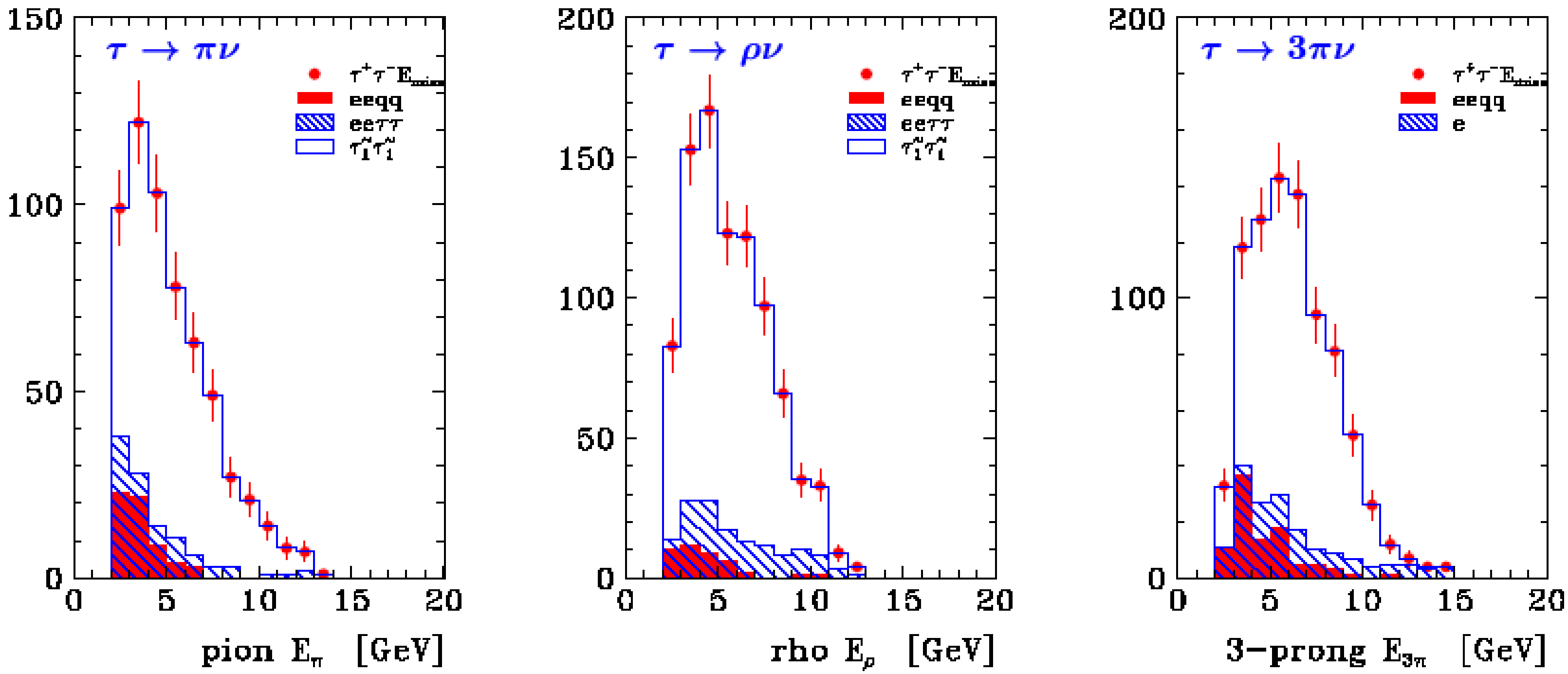



- ➔ Best sensitivity achieved with Ecm~2m: $\delta$M~0.4GeV
- ➔ Higher Ecm does not help
- ➔ Higher integrated luminosity and efficiency do

# Strategy Two: Analyzing Energy Spetra for Stau Mass Measurement

SPA 1a inspired model & Benchmark D (below) studied in $\pi$,$\rho$,3$\pi$ channels

→ Ecm=400 and 600GeV >> $2m_{stau}$ ($m_{stau}$=133, 217GeV)
→ Signal cross section $\sigma$ comfortably large ($\sigma$=140, 50fb) + Polarized beams
→ Background rejection less severe than in the threshold region



# Results on the Stau Mass & Relic DM Density

**Strategy one:** ($L=500fb^{-1}$)

| Scenario | | A | C | D | G | J |
|---|---|---|---|---|---|---|
| $\Delta M$ | (GeV) | 7 | 9 | 5 | 9 | 3 |
| Ecm | (GeV) | 505 | 337 | 440 | 316 | 660 |
| $\sigma$ | (fb) | 0.216 | 0.226 | 0.279 | 0.139 | 1.35 |
| Efficiency | (%) | 13.6 | 17.3 | 8.5 | 17.2 | 1.4 |
| $\delta m_{stau}$ | (GeV) | 0.42 | 0.15 | 0.40 | 0.12 | >1.0 |
| $\delta\Omega h^2$ | (%) | 3.1 | 1.6 | 5.0 | 1.6 | >14* |

**Strategy two:** ($L=200fb^{-1}$ / $300fb^{-1}$)

| Scenario | | SPS 1a | | | D |
|---|---|---|---|---|---|
| $\Delta M$ | (GeV) | 8 | 5 | 3 | 5 |
| Ecm | (GeV) | | 400 | | 600 |
| $\sigma$ | (fb) | | 140 | | 50 |
| Efficiency | (%) | | 18.5 | | 7.6 |
| $\delta m_{stau}$ | (GeV) | 0.14 | 0.22 | 0.28 | 0.15 |
| $\delta\Omega h^2$ | (%) | 1.7* | 4.1* | 6.7* | 1.9 |

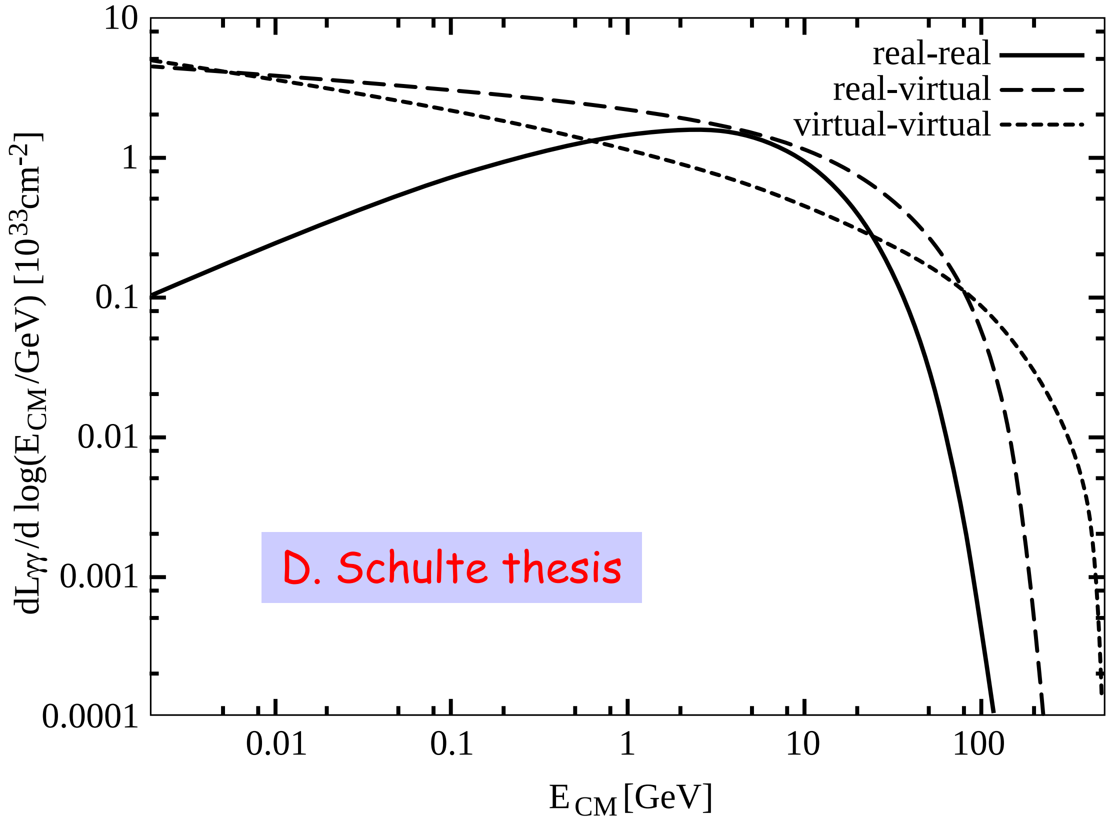
microMegas

Preliminary

*: $\Omega h^2<0.094$(WMAP lower limit)

# Caveat: Background Underestimated?

Additional background from $\gamma\gamma$ and $\gamma\gamma^*$ ?

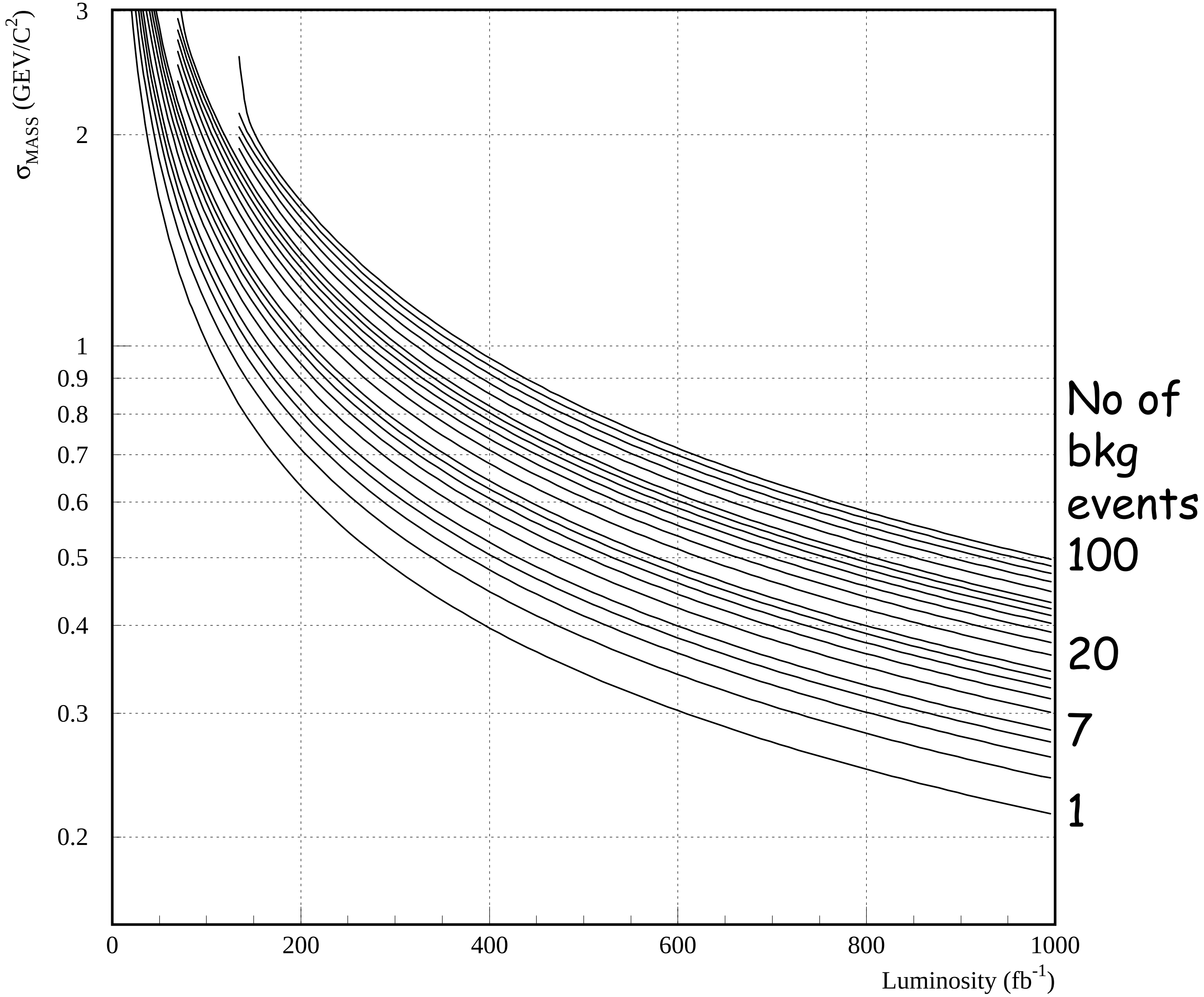



➔ Need to increase the actual $\gamma^*\gamma^*$ bkg statistics by ~10 to be safe

# Summary

- LSP and smuon masses precisely measurable @ small $\Delta M$
- Stau mass measurement @ small $\Delta M$ very challenging
  Two different strategies studied
- Crossing-angle mode possible @ TESLA
  (but lower $\varepsilon$ by 25% in stau analysis)
- $e/\gamma$ veto efficiency to be improved down to 5mrad
  Desirable to have $\mu/\pi$ veto down to 20mrad
  Veto is challenging for warm technology (pile-up)
- Depending on SUSY scenario, DM density precision @ LC can compete with expected precision from e.g. Planck

# Mass Measurement in Case of Background




Mass precision degrades when background contribution increases

Veto efficiency & analysis cuts optimization essential

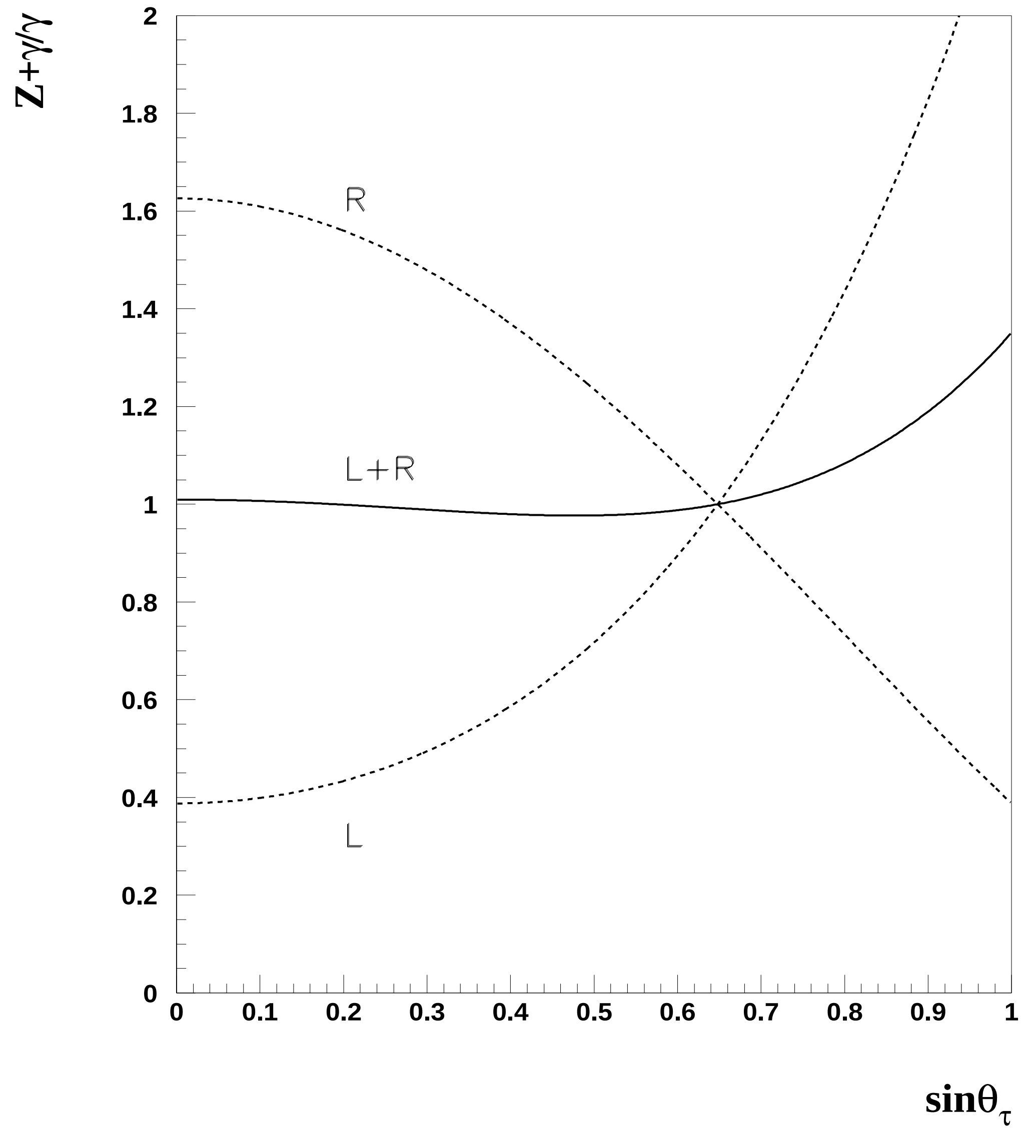
High integrated luminosity will always help

# Mixing Angle and Polarizations

Full cross section ($\gamma$+Z) differs from point-like cross section ($\gamma$) only for polarized beams.

For polarized beams cross section has also strong dependence on the mixing.

If combining L+R polarized data, the net dependence is much reduced.



# Main Selection Cuts for Staus (head-on)

1. Veto (energetic) forward electrons/photons
   against $\gamma\gamma$ and radiative events
2. No of charged tracks: 1 or 3 prongs, no 2 $\mu$'s, charge conservation
   against non-tau decays, against $\mu\mu$ backgrounds
3. $15^o < \theta_{thrust} < 165^o$, acoplanarity angle $< 160^o$
   against $\gamma\gamma$ and 2-fermion events
4. $P_{max} < 7$ GeV, $P_{Tmiss} > 2.5$ GeV
   against smuon and 2-fermion events
5. $\rho_T$: $P_t$ sum w.r.t. the thrust axis in transverse plane to the beam > 2.75 (or 2) GeV ($P_{Tmiss}$ dependent)
   against $\gamma\gamma$

➔ Resulting in an efficiency of ~ 8.5% (ideal detector+SGV acceptance)
no bg events survive (ideal veto)

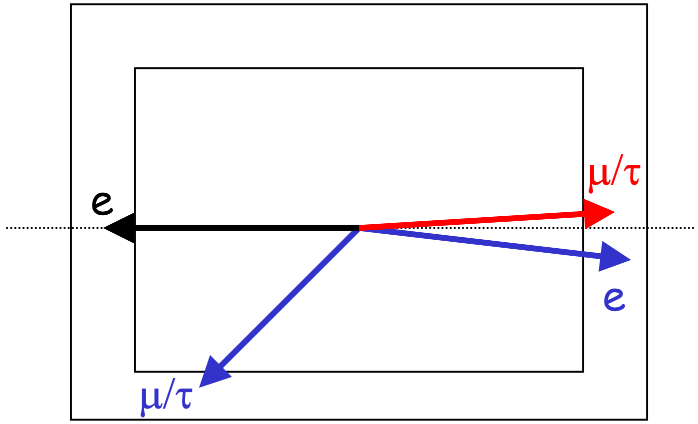
# Vetoing Energetic $\mu/\pi$ Down to 20mrad?

**Background free stau detection needs this capability:**

**$ee \rightarrow ee\mu\mu$, $ee \rightarrow ee\tau\tau$:**

$\mu$+e or $\tau$+e visible in the detector ➔ signal like

Another e in the beam-pipe, another $\mu$ or $\tau \rightarrow \mu/\pi$ (energetic) @ low angle




➔New challenge in forward instrumentation !