Determination of sparicle properties in SUSY scenarios with small mass differences at the ILC

In the light of LHC 7 TeV

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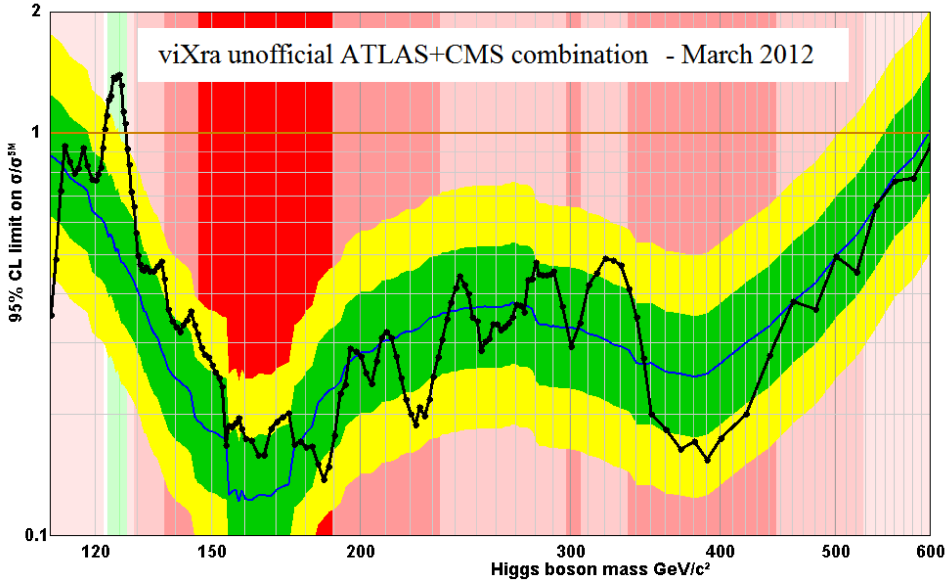
Outline

LHC results

- The Higgs: Extremely in-official theoretician combination from S. Heinemeyer ...
- ... and it's implication for SUSY models (from A. Djouadi).
- Limits in CMSSM (ATLAS)
- Limits in simplified model

Is SUSY under pressure ??



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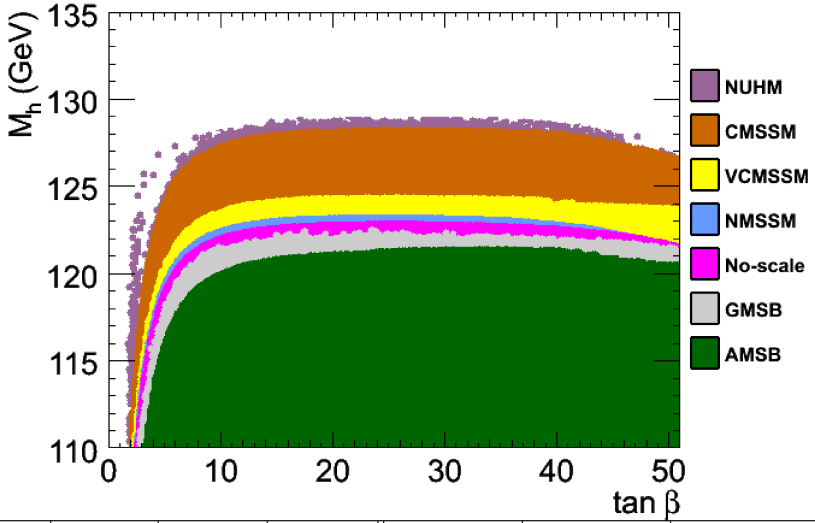

model	amsb	gmsb	sugra	noscale	cnmssm	vcmssm	nuhm
M_h^{max}	120	121	128	123	123	126	128

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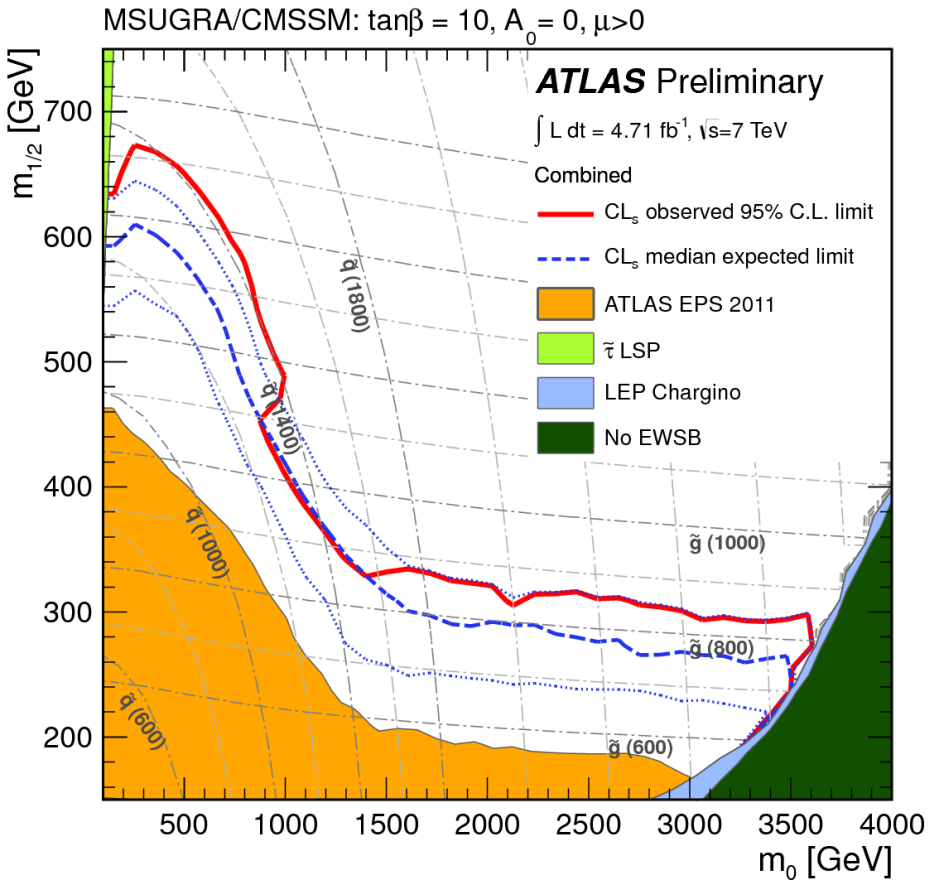

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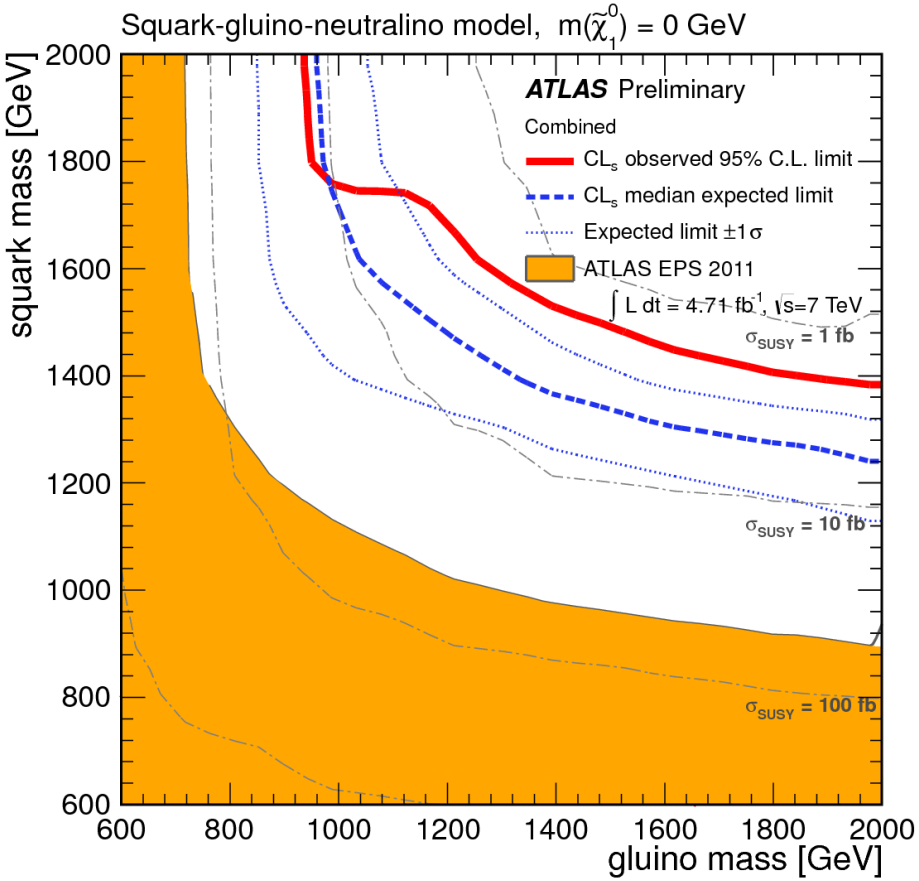

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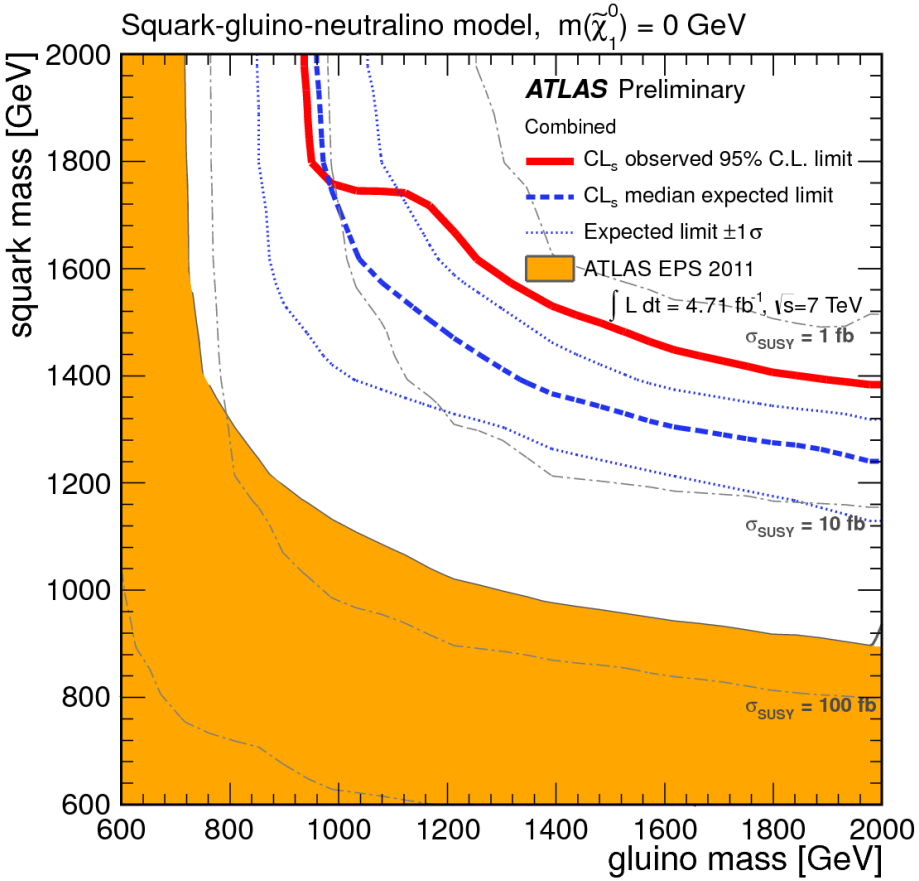
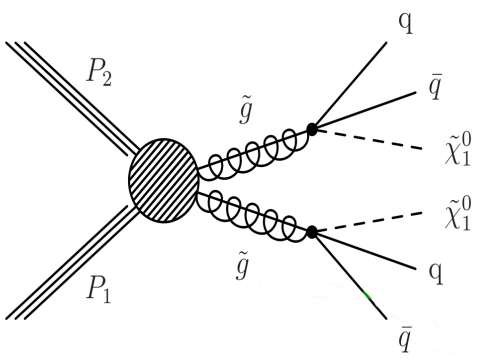
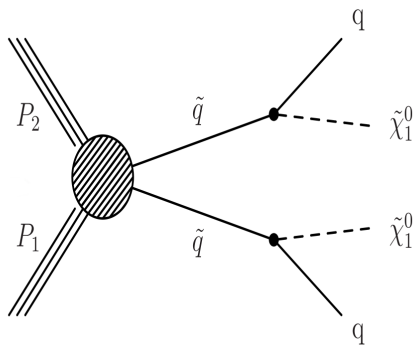


LHC: the fine-print

- Simplified models are (very) special cases: no cascades
- CMSSM is also a (very) special case: coloured sector $\leftrightarrow$ non-coloured sector.
- Production needs a gluino in reach.
- Only generation 1 & 2 squraks (not much t and b in protons !)
- But what matters for naturalness is the third generation:
  - M_H is destabilised by fermion-loops
  - but boson-loops have the same size but opposite sign
  - $\Rightarrow$ Divergences cancel !
  - For this to work: $M_{particle} \approx M_{sparticle}$
  - Higgs coupling $\propto$ Mass $\Rightarrow$ what





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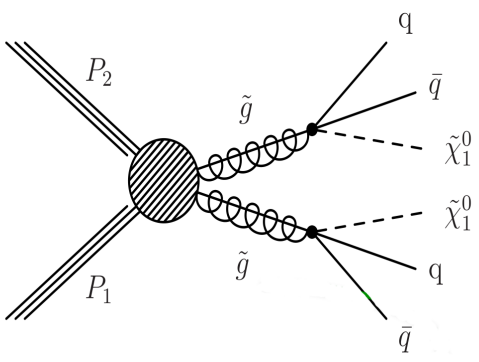

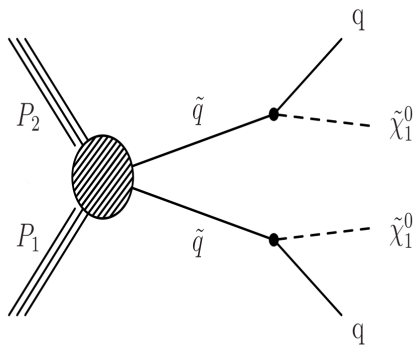

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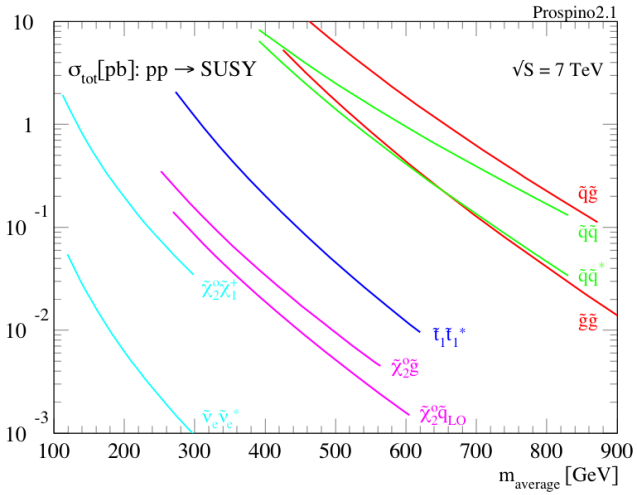

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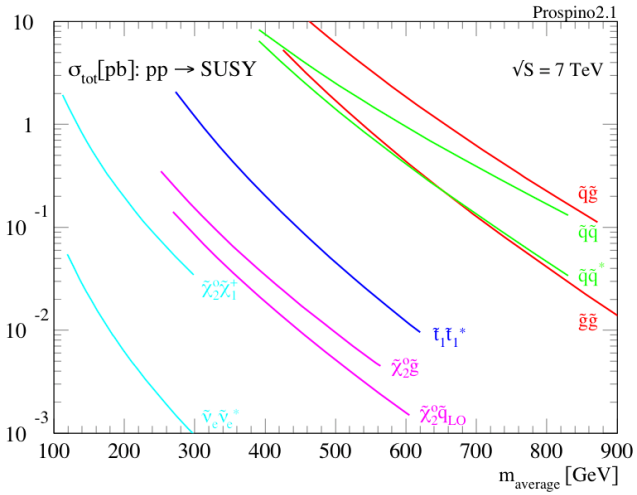

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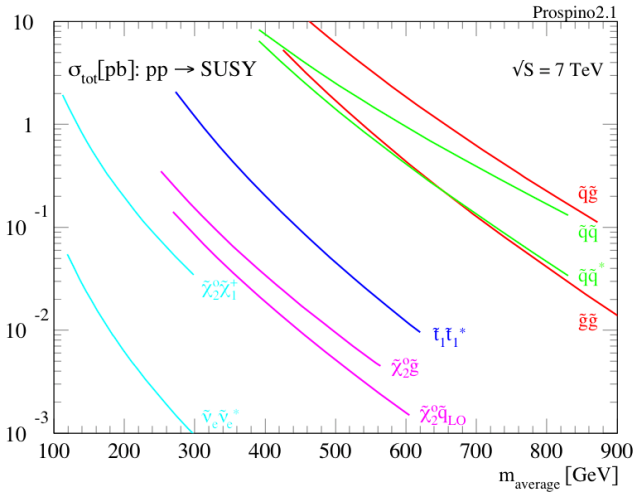

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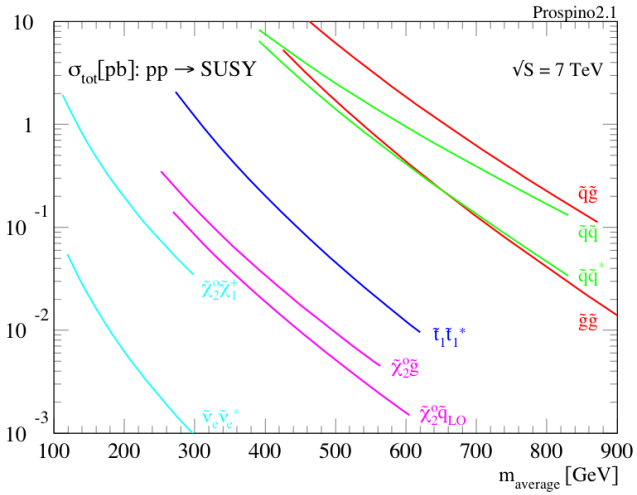

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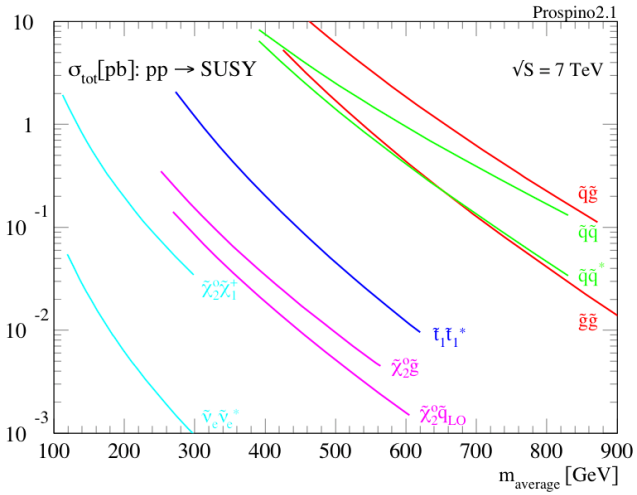

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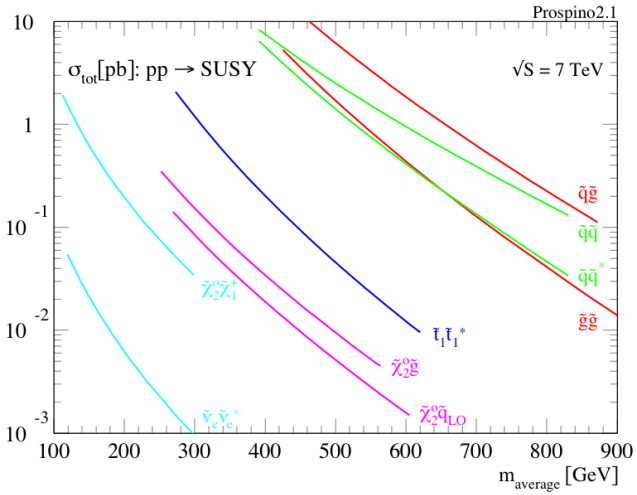

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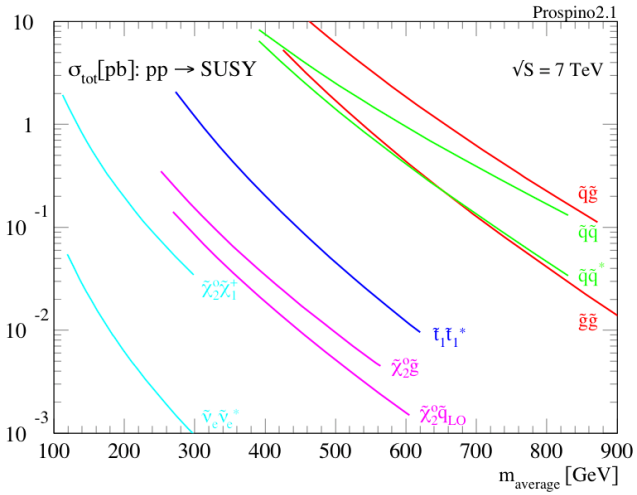

SUSY under pressure ?? No, but simple models are !

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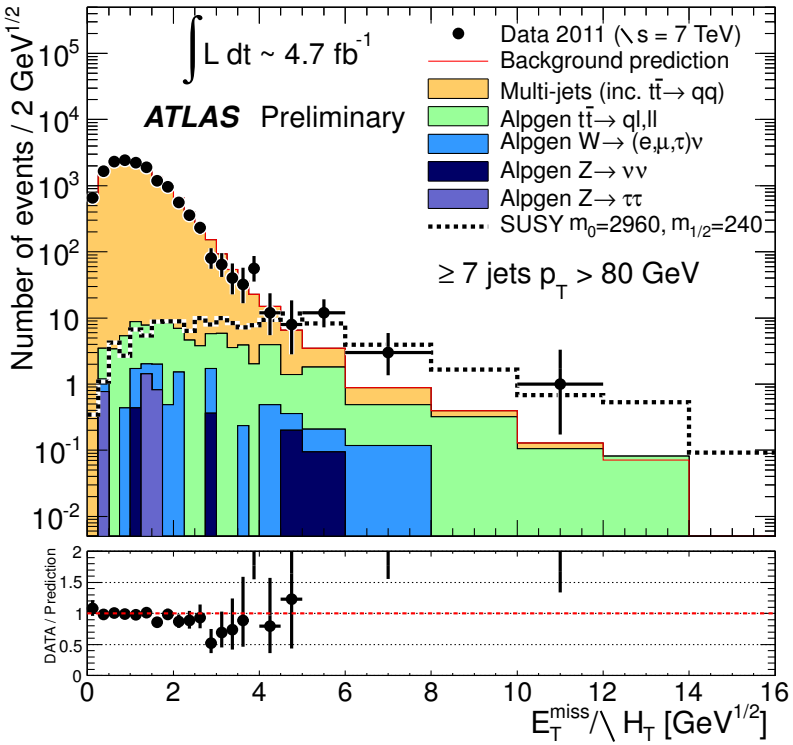
LHC: SUSY hints?

- ATLAS multi-jets: tantalising excess for MET + many jets (starting at 7)
- ATLAS bosinos to Z: 3 leptons+ MET, two leptons from Z: 95 seen, 72 $\pm$ 14 expected. Cascade $\tilde{\chi}_2^0$ or $\tilde{\chi}_1^\pm \to$ IVB ?
- And after all: The Higgs: A 115 to 130:ish Higgs is what SUSY predicts. No Higgs would be a blow for SUSY as well as the SM.



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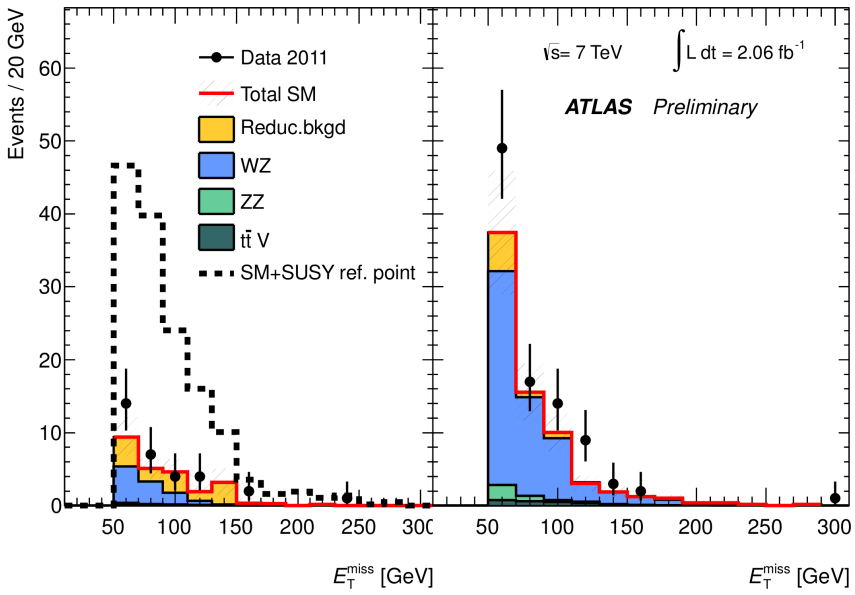

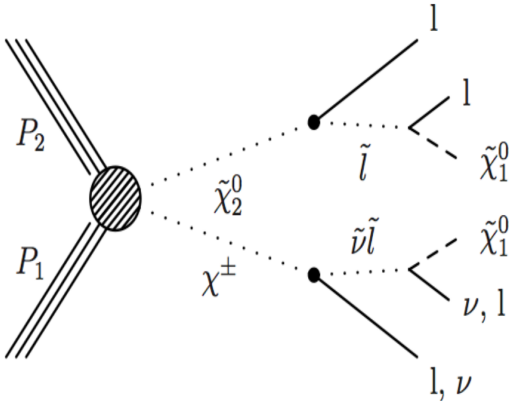

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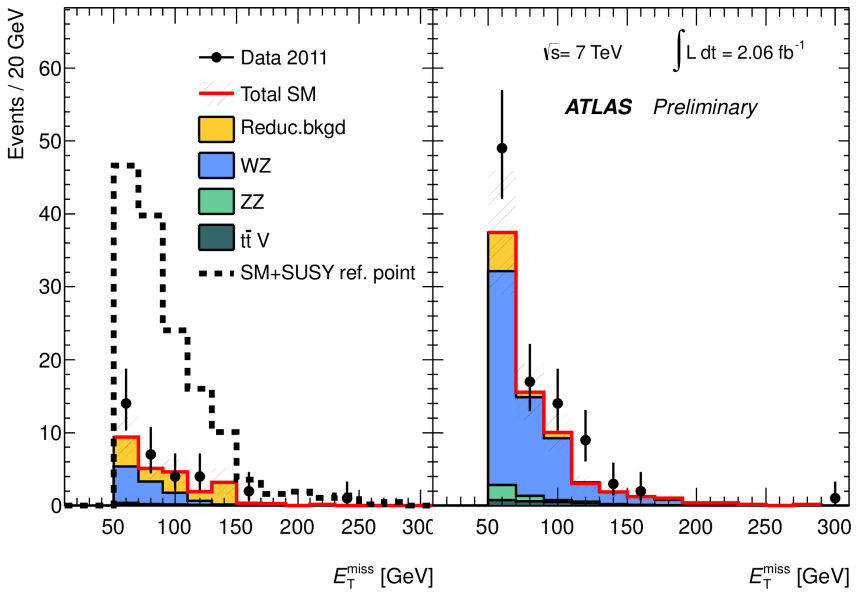

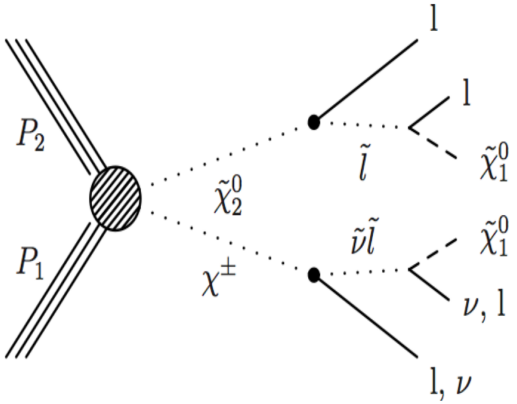

A New bench-mark point

Remember, apart from naturalness:

- Anomaly in $g-2$ of the μ: Would prefer a not-too-heavy smuon.
- Dark matter: A WIMP of ~ 100 GeV would be needed.
- EW symmetry breaking, coupling constant unification: points to NP at or below 1 TeV
- Suppress the SUSY flavour problem (FCNC:s etc): Heavy 1:st & 2:nd generation squarks would be nice ...
- Other low-energy constrains : $b \to s\gamma$,$b \to \mu\mu$, ρ-parameter, $\Gamma(Z)$

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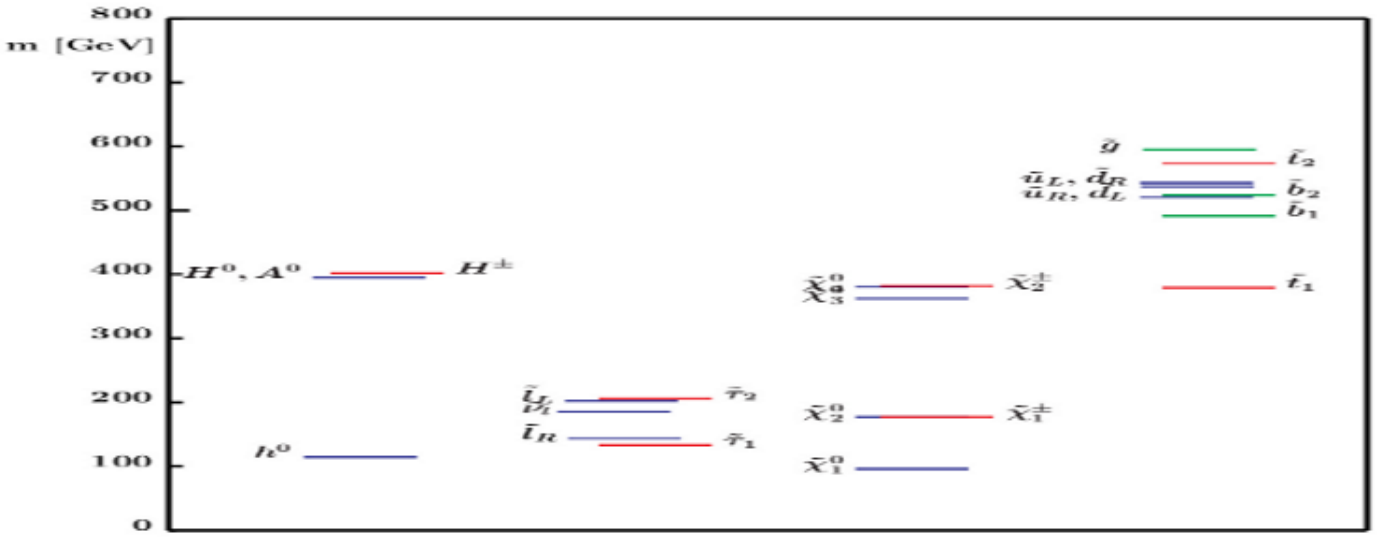

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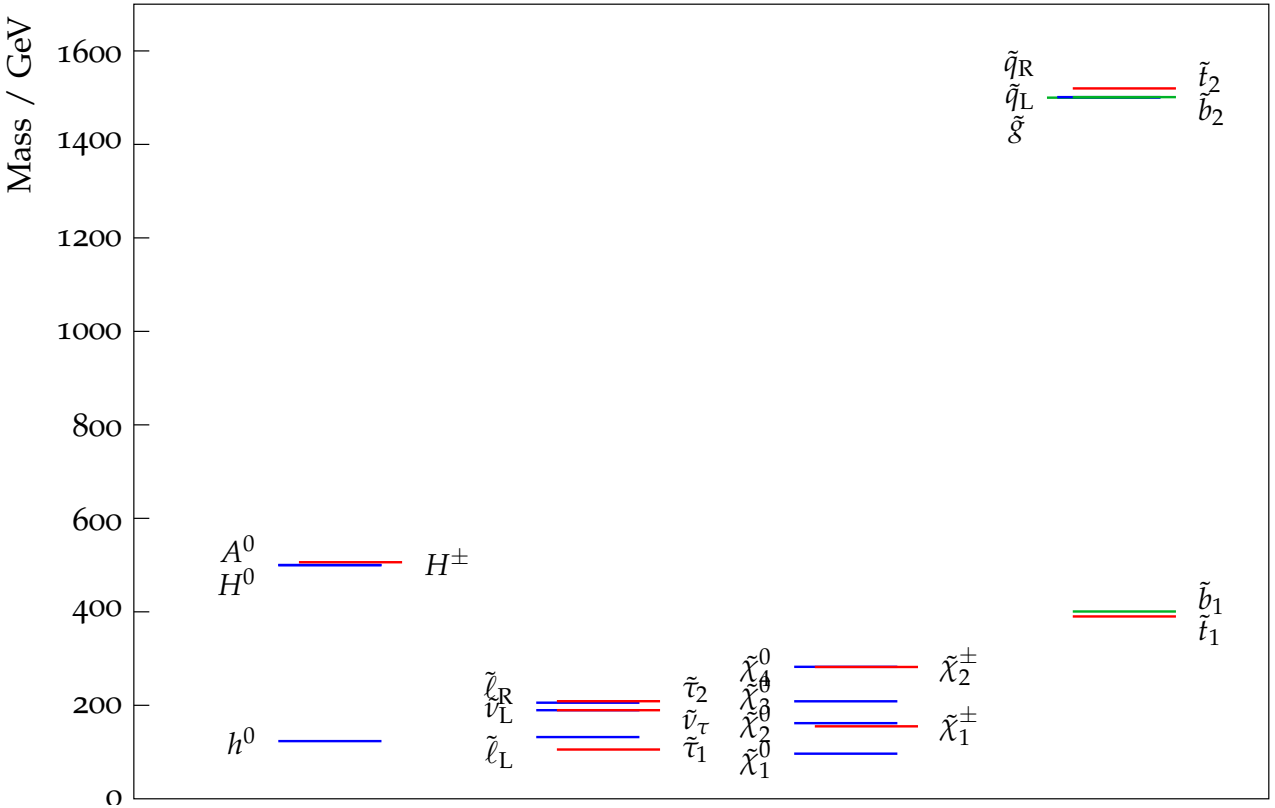

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How?

SPS1a: mSUGRA

- 5 parameters.
- One gaugino parameter
- One scalar parameter

TDR1: natural SUSY

- 11 parameters.
- Separate gluino
- Higgs, un-coloured, and coloured scalar parameters separate

Parameters chosen to deliver all constraints, $\approx$ same ILC accessible spectrum.

Features of SPS1a'/TDR 1-4

- In SPS1a' and the TDR points, the $\tilde{\tau}_1$ is the NLSP.
- For $\tilde{\tau}_1$: $E_{\tau,min} = 2.6\ \mathrm{GeV}$, $E_{\tau,max} = 42.5\ \mathrm{GeV}$: $\gamma\gamma - background \Leftrightarrow pairs - background$.
- For $\tilde{\tau}_2$: $E_{\tau,min} = 35.0\ \mathrm{GeV}$, $E_{\tau,max} = 152.2\ \mathrm{GeV}$: $WW \rightarrow l\nu l\nu$ background $\Leftrightarrow$ *Polarisation*.
- $\tilde{\tau}$ NLSP $\rightarrow \tau$:s in most SUSY decays $\rightarrow$ SUSY is background to SUSY.
- For pol=(-1,1): $\sigma(\tilde{\chi}_2^0\tilde{\chi}_2^0)$ and $\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-)$ = several hundred fb and BR(X$\rightarrow \tilde{\tau}$) $>$ 50 %. For pol=(1,-1): $\sigma(\tilde{\chi}_2^0\tilde{\chi}_2^0)$ and $\sigma(\tilde{\chi}_1^+\tilde{\chi}_1^-) \approx 0$.
- For pol=(-1,1): $\sigma(\tilde{e}_R\tilde{e}_R)$ = 1.3 pb !
- For $\tilde{e}_R$or $\tilde{\mu}_R$: $E_{l,min} = 6.6\ \mathrm{GeV}$, $E_{l,max} = 91.4\ \mathrm{GeV}$: Neither $\gamma\gamma$ nor $WW \rightarrow l\nu l\nu$ background severe.

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Once again: SPS1a' is excluded by LHC, but:

- LHC only excludes 1:st & 2:nd generation squarks. : not visible at ILC anyhow.
- The current LHC limits have no influence at all on the EW sector.
- TDR 1-4 has the'same EW-sector, but heavier gen. 1&2 squarks. Any ILC result on SPS1a' is also good for TDR 1-4

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Extracting the $\tilde{\tau}$ properties

See Phys.Rev.D82:055016,2010

Use polarisation (0.8,-0.22) to reduce bosino background.

From decay kinematics:

- $M_{\tilde{\tau}}$ from end-point of spectrum = $E_{\tau,max}$.
- Other end-point hidden in $\gamma\gamma$ background: Must get $M_{\tilde{\chi}_1^0}$ from other sources. ($\tilde{\mu}$, $\tilde{\mathrm{e}}$ ...)

From cross-section:

- $\sigma_{\tilde{\tau}} = A(\theta_{\tilde{\tau}}, \mathcal{P}_{beam}) \times \beta^3/s$, so
- $M_{\tilde{\tau}} = E_{beam}\sqrt{1-(\sigma s/A)^{2/3}}$: no $M_{\tilde{\chi}_1^0}$!

From decay spectra:

- $\mathcal{P}_\tau$ from exclusive τ decay-mode(s): handle on mixing angles $\theta_{\tilde{\tau}}$ and $\theta_{\tilde{\chi}_1^0}$.

Topology selection

$\tilde{\tau}$ properties:

- Only two τ:s in the final state.
- Large missing energy and momentum.
- High Acolinearity, with little correlation to the energy of the τ decay-products.
- Central production.
- No forward-backward asymmetry.

+ anti $\gamma\gamma$ cuts (see backup)

Select this by:

- Exactly two jets.
- $N_{ch} < 10$
- Vanishing total charge.
- Charge of each jet = ± 1,
- $M_{jet} < 2.5\ \mathrm{GeV}/c^2$,
- $E_{vis} < 300\ \mathrm{GeV}$,
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$\tilde{\tau}_1$ and $\tilde{\tau}_2$ further selections

- $\tilde{\tau}_1$:
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- $\tilde{\tau}_2$:
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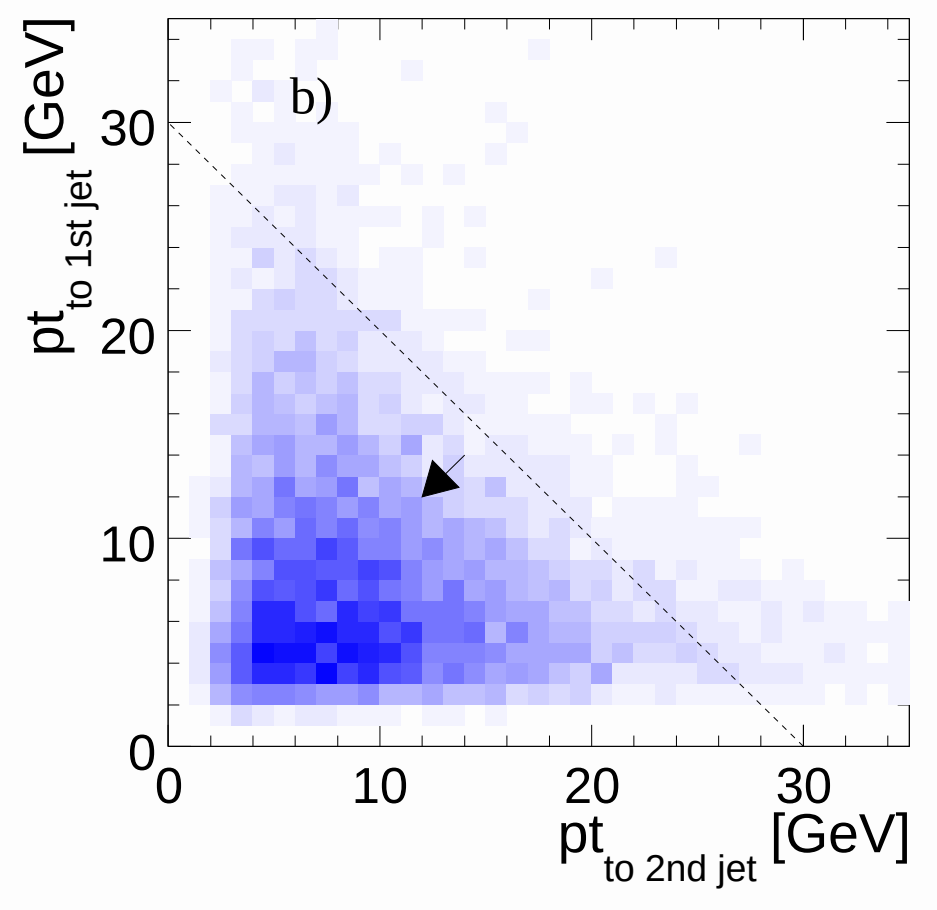
  - Most energetic jet not e or μ
  - Cut on Signal-SM LR of f($q_{jet1} cos\theta_{jet1}$,$q_{jet2} cos\theta_{jet2}$)



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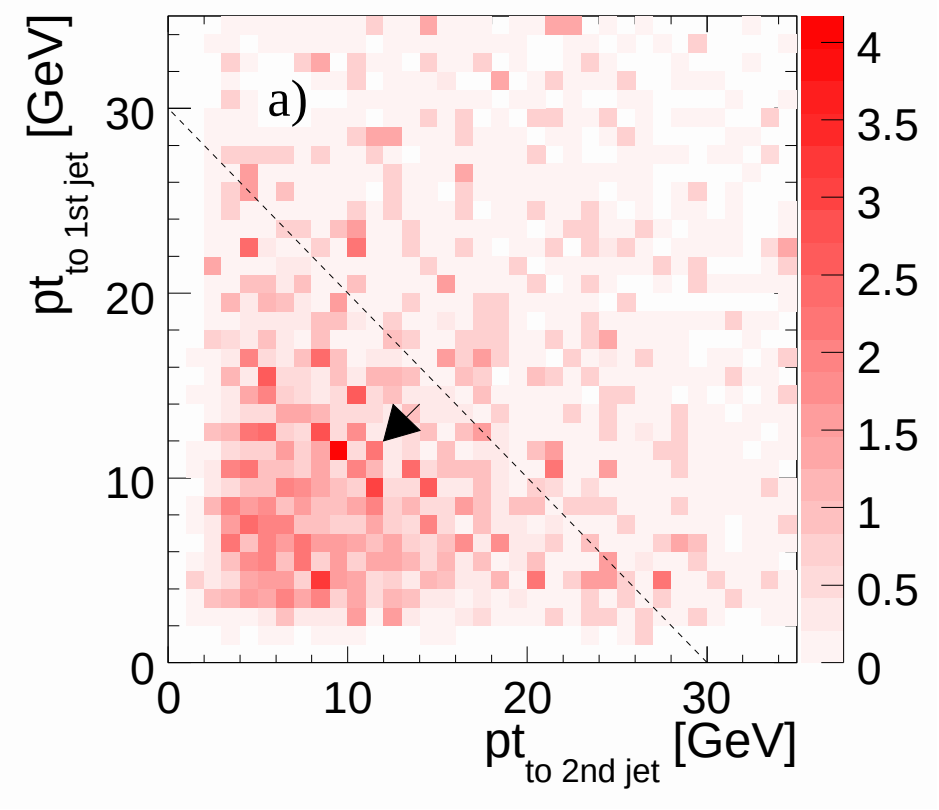

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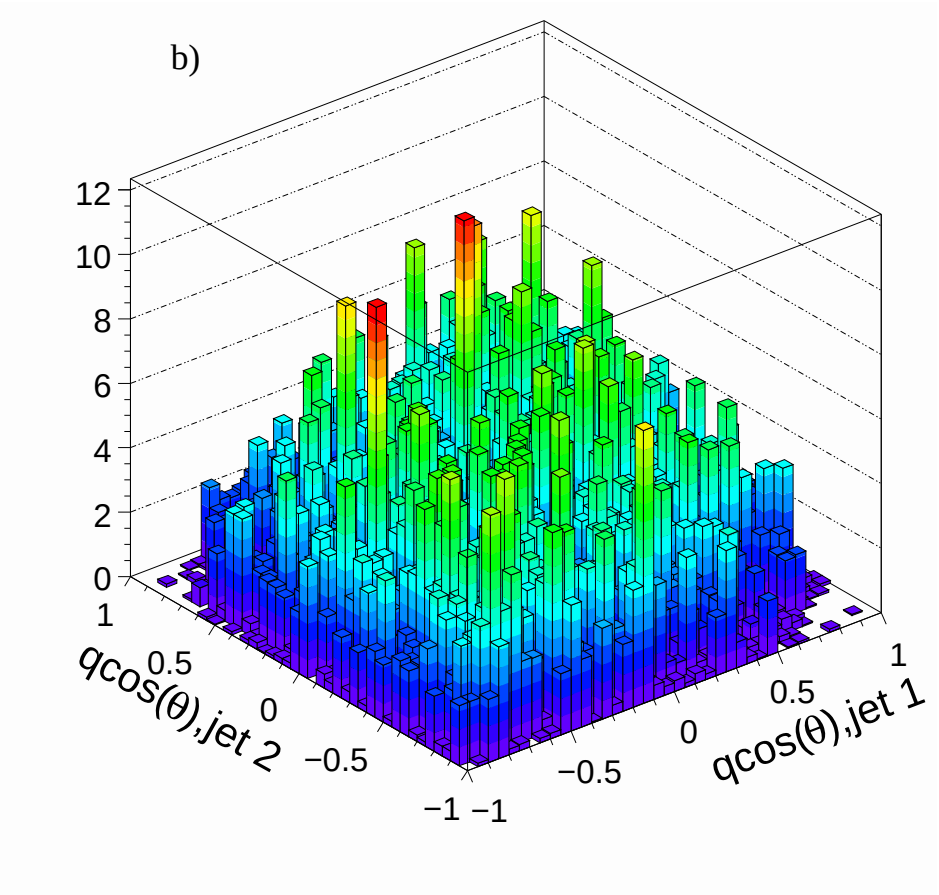

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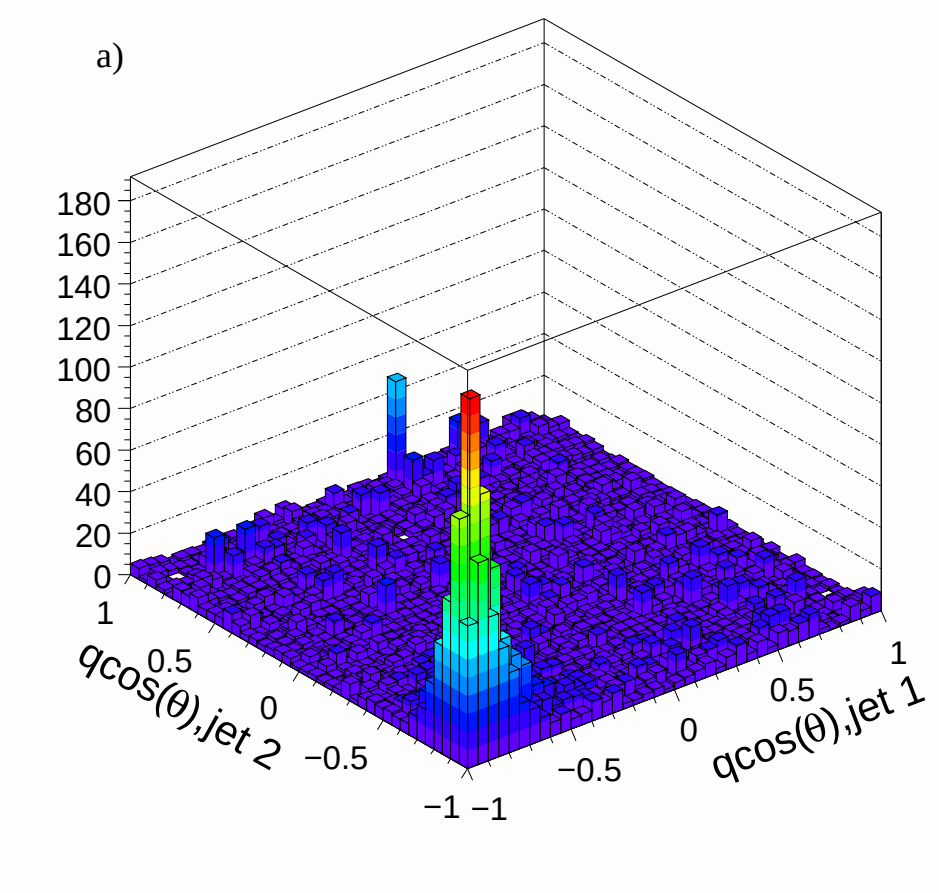

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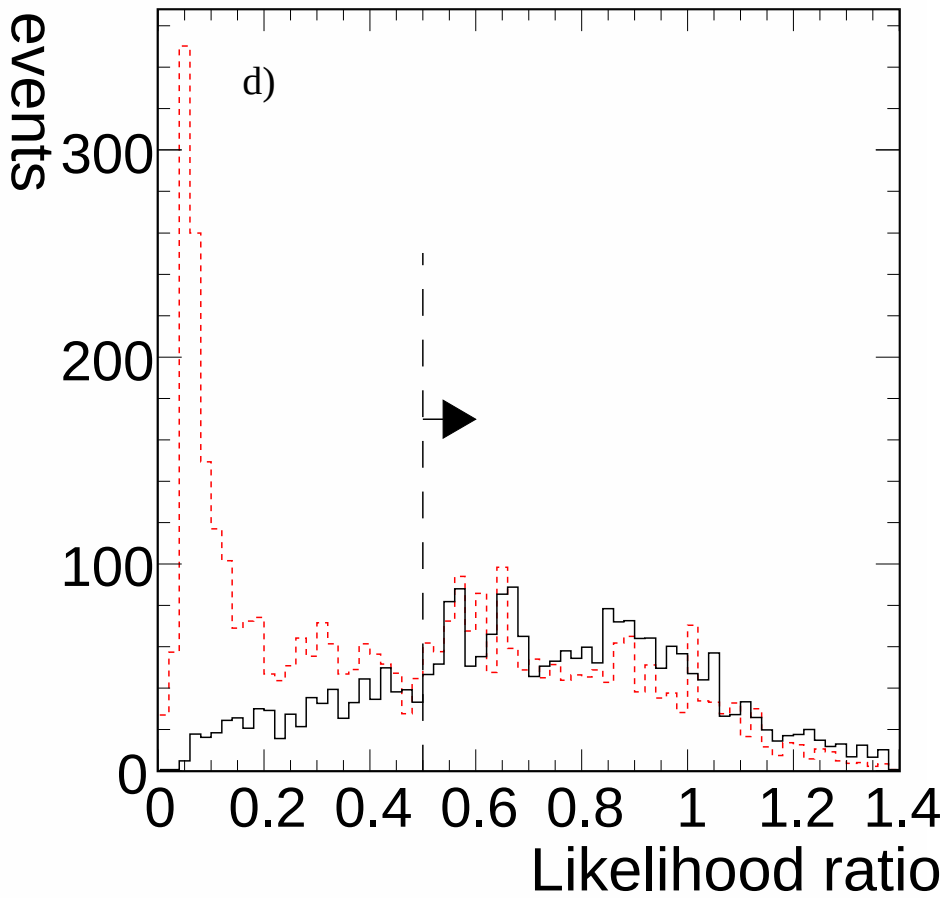

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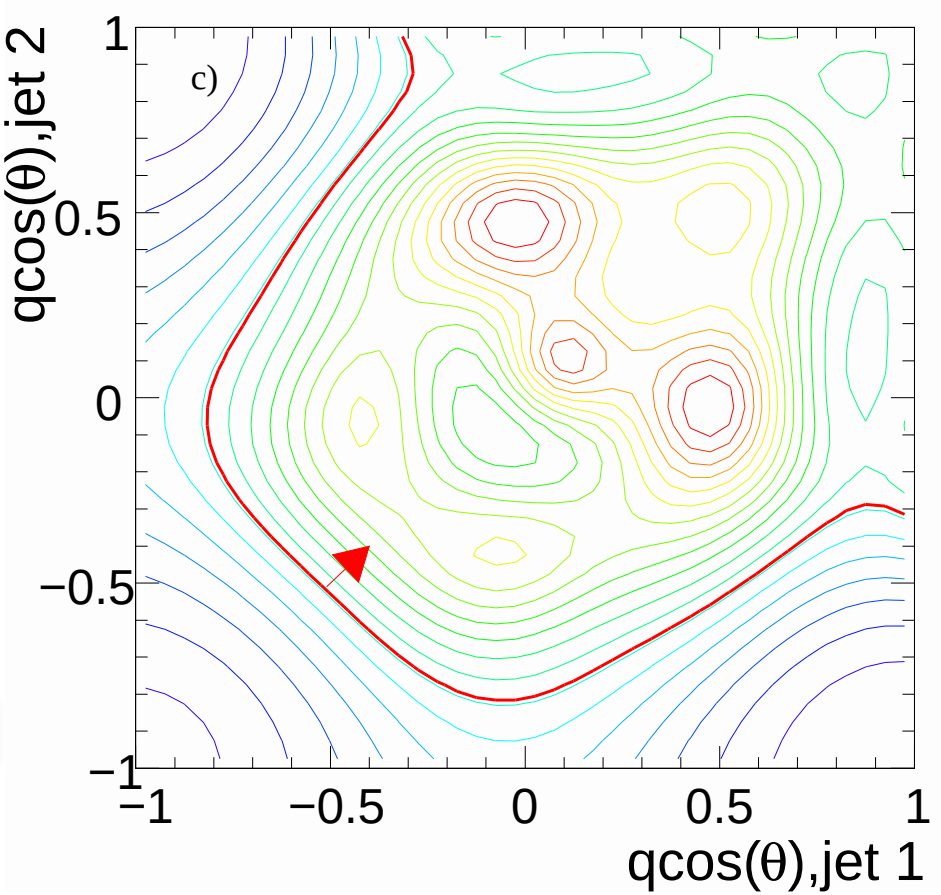

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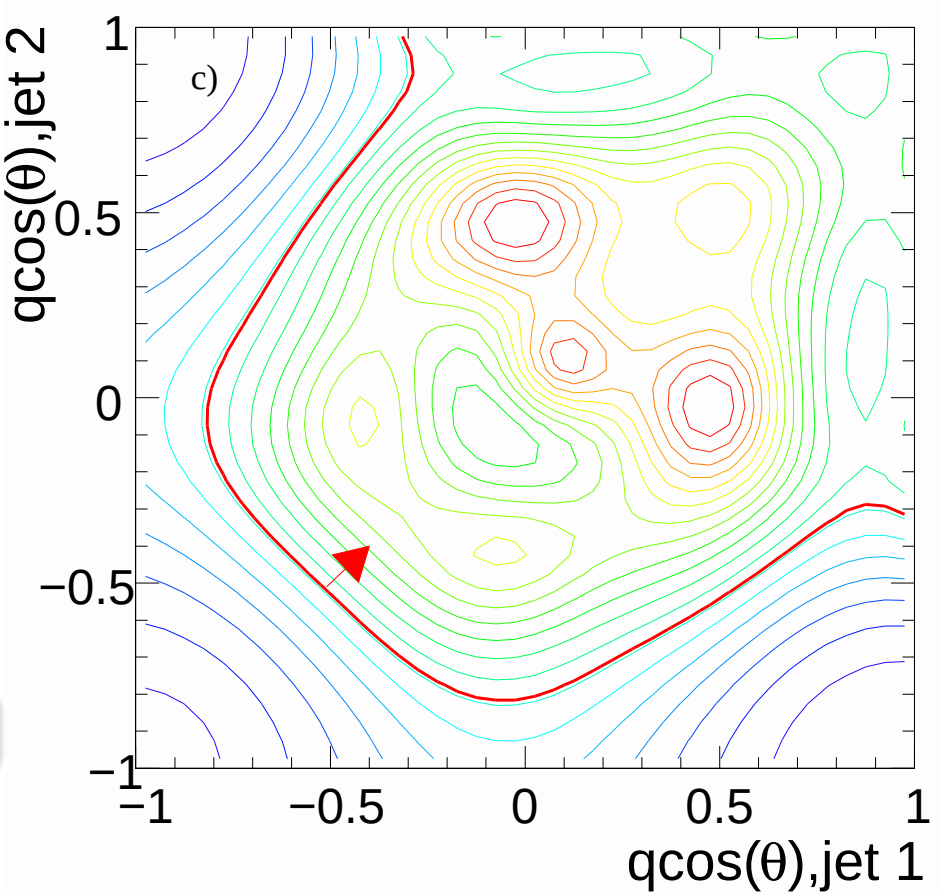

Fitting the $\tilde{\tau}$ mass

- Only the upper end-point is relevant.
- Background subtraction:
  - $\tilde{\tau}_1$: Substantial SUSY background,but region above 45 GeV is signal free. Fit exponential and extrapolate.
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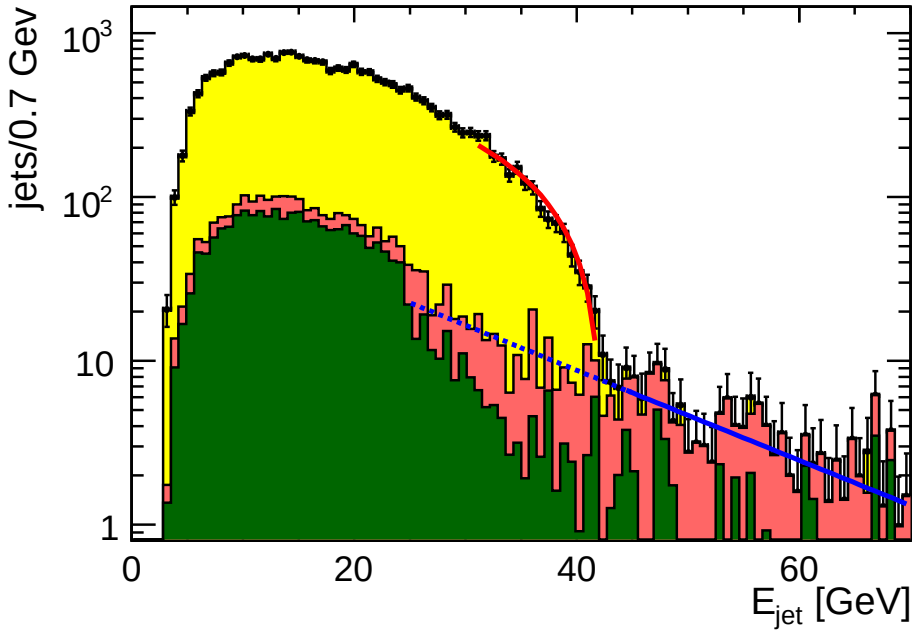

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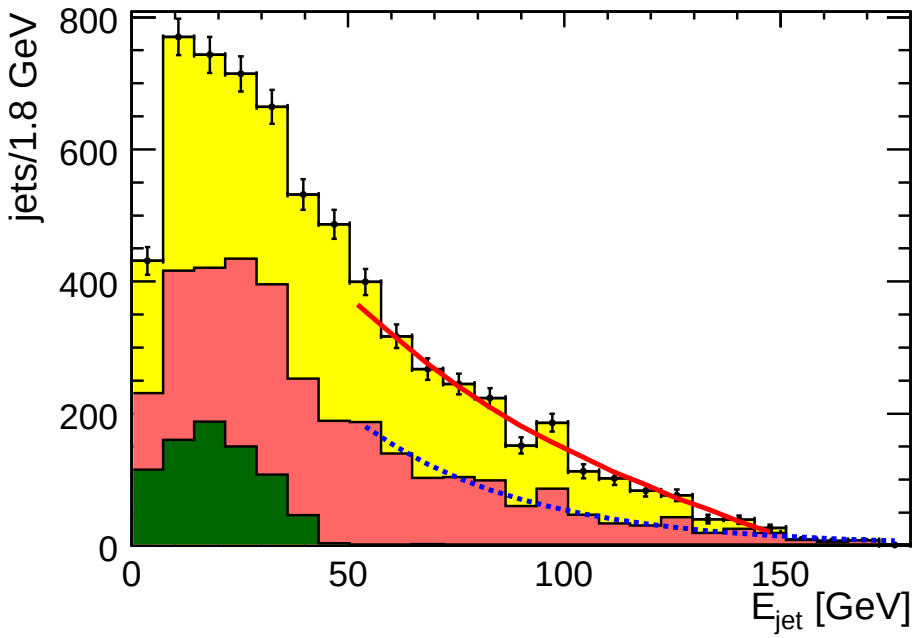

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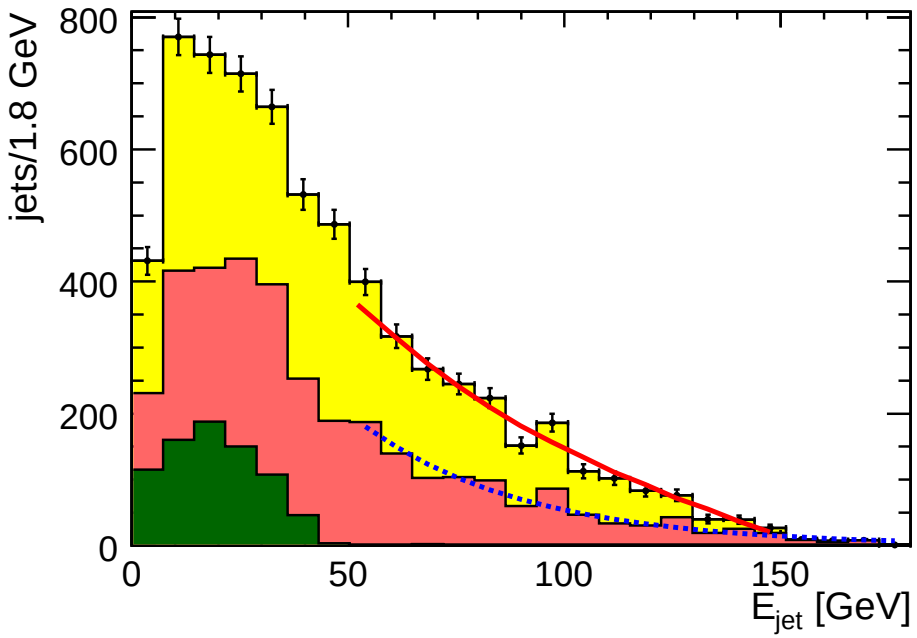


Fitting the $\tilde{\tau}$ mass

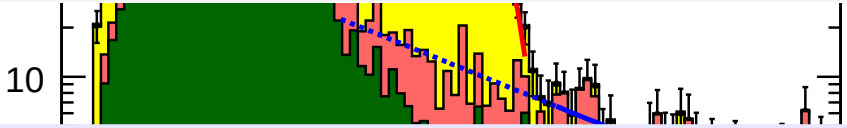
- Only the upper end-point is relevant.

Results for $\tilde{\tau}_1$

$M_{\tilde{\tau}_1} = 107.73^{+0.03}_{-0.05}\ \mathrm{GeV}/c^2 \oplus 1.3\Delta(M_{\tilde{\chi}^0_1})$.
The error from $M_{\tilde{\chi}^0_1}$ largely dominates.

extrapolate.

- $\tilde{\tau}_2$: $\sim$ no SUSY background



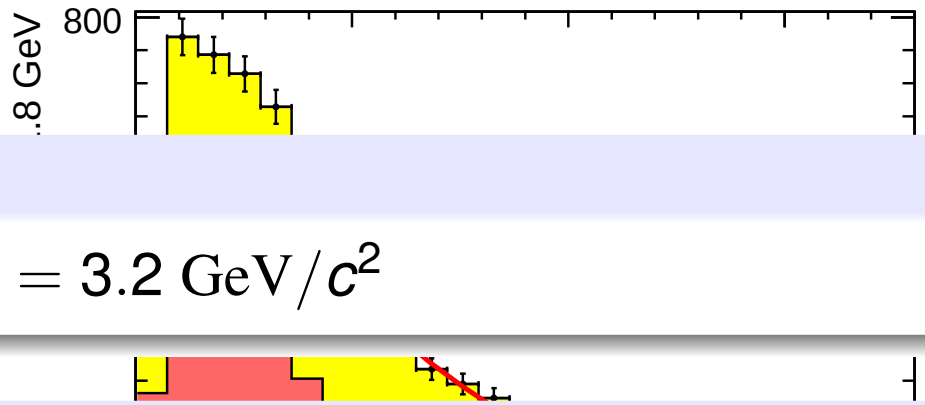
Results for $\tilde{\tau}_2$

$M_{\tilde{\tau}_2} = 183^{+11}_{-5}\ \mathrm{GeV}/c^2 \oplus 18\Delta(M_{\tilde{\chi}^0_1})$.
The error from the endpoint largely dominates.

- Fit line to (data-background fit).

Fitting the $\tilde{\tau}$ mass

- Only the upper end-point is relevant.
- Background subtraction:
  - $\tilde{\tau}_1$: Substantial SUSY background but region



Results from cross-section for $\tilde{\tau}_1$

$$\Delta(N_{signal})/N_{signal} = 3.1\% \rightarrow \Delta(M_{\tilde{\tau}_1}) = 3.2\ \mathrm{GeV}/c^2$$

  - $\tilde{\tau}_2$: no SUSY background

Results from cross-section for $\tilde{\tau}_2$

$$\Delta(N_{signal})/N_{signal} = 4.2\% \rightarrow \Delta(M_{\tilde{\tau}_2}) = 3.6\ \mathrm{GeV}/c^2$$

End-point + Cross-section $\rightarrow \Delta(M_{\tilde{\chi}_1^0}) = 1.7\ \mathrm{GeV}/c^2$

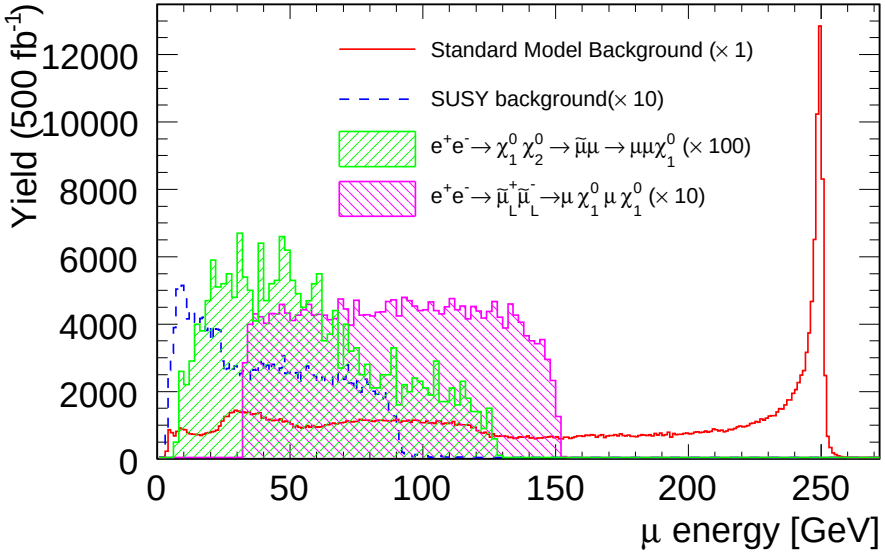
- Fit line to (data-background fit).

μ channels

Use "normal" polarisation (-0.8,0.22).

- $\tilde{\mu}_{\mathrm{L}}\tilde{\mu}_{\mathrm{L}} \rightarrow \mu\mu\tilde{\chi}_1^0\tilde{\chi}_1^0$
- $\tilde{\chi}_1^0\tilde{\chi}_2^0 \rightarrow \mu\tilde{\mu}_{\mathrm{R}}\tilde{\chi}_1^0 \rightarrow \mu\mu\tilde{\chi}_1^0$

- Momentum of μ:s
- E_{miss}
- $M_{\mu\mu}$



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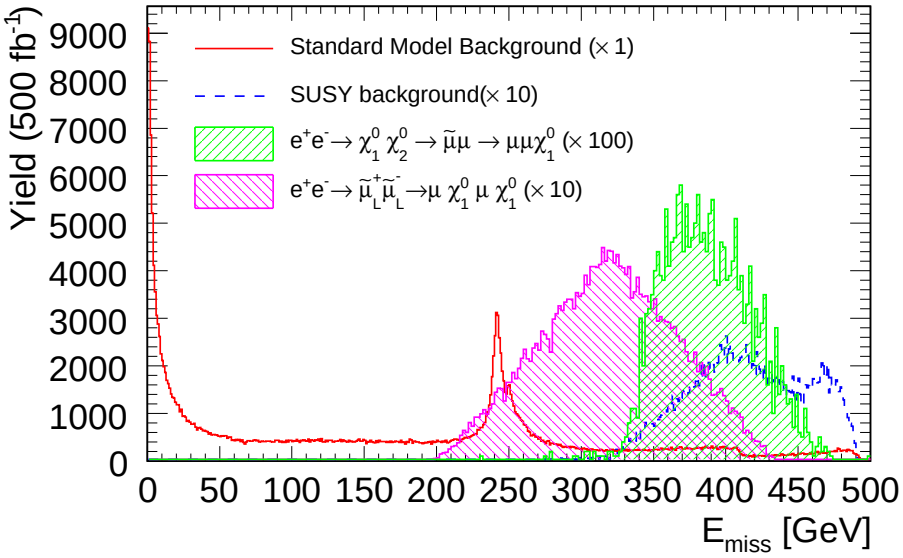

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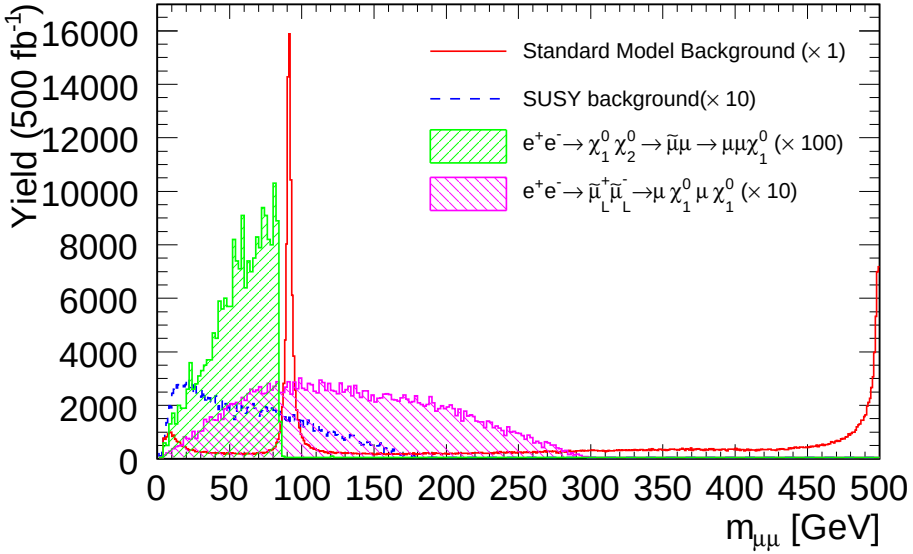
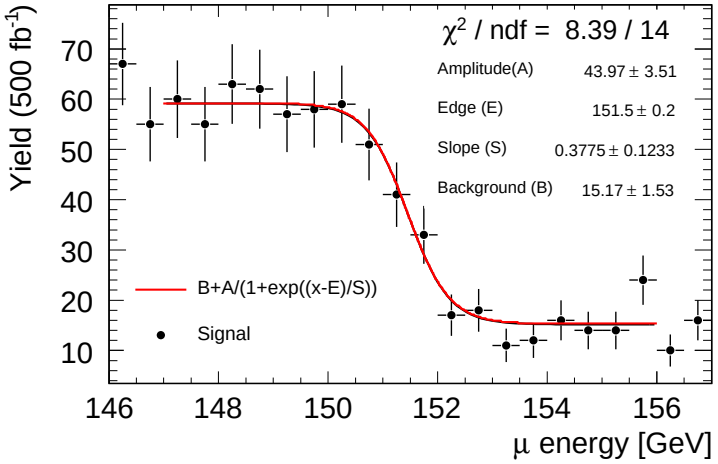


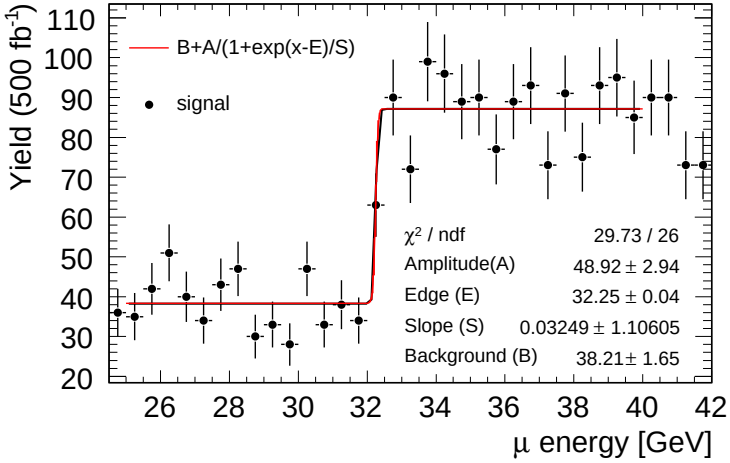
$\tilde{\mu}_L\tilde{\mu}_L$

Selections

- $\theta_{missing\ p} \in [0.1\pi, 0.9\pi]$
- $E_{miss} \in [200, 430]\mathrm{GeV}$
- $M_{\mu\mu} \notin [80, 100]\mathrm{GeV}$ and $> 30\mathrm{GeV}/c^2$

Masses from edges. Beam-energy spread dominates error.





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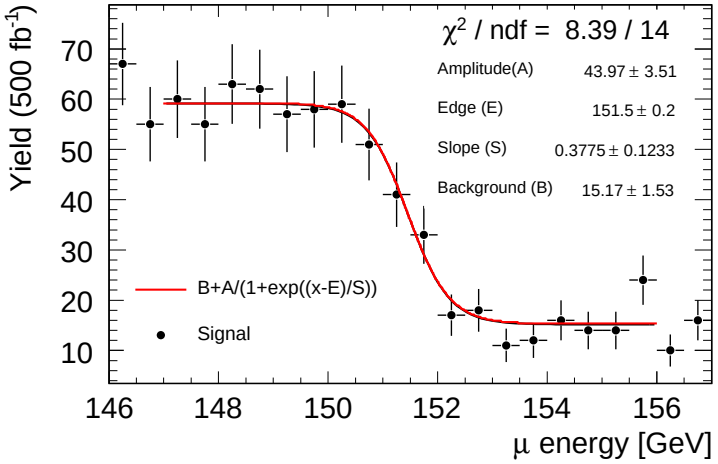
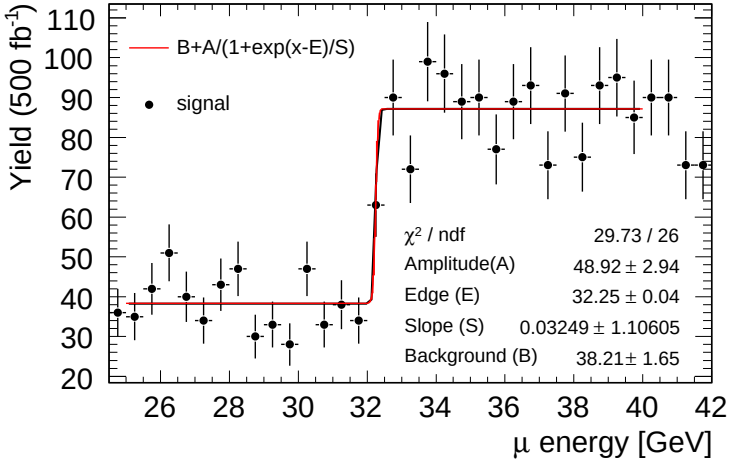
Masses from edges. Beam-energy spread dominates error.

$$\Delta(M_{\tilde{\chi}_1^0}) = 920\mathrm{MeV}/c^2$$
$$\Delta(M_{\tilde{\mu}_L}) = 100\mathrm{MeV}/c^2$$



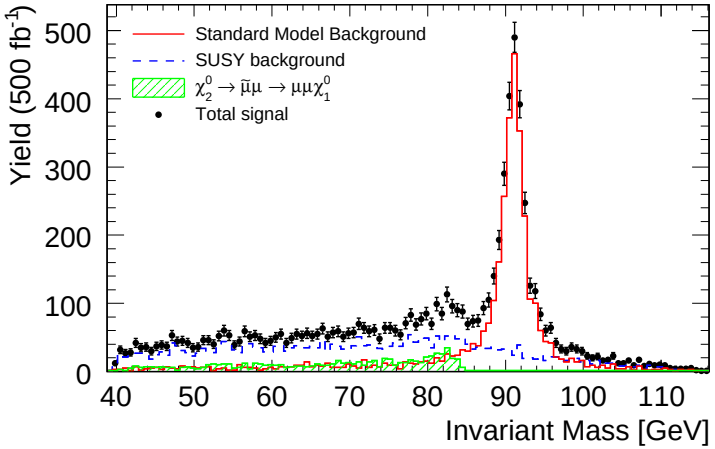


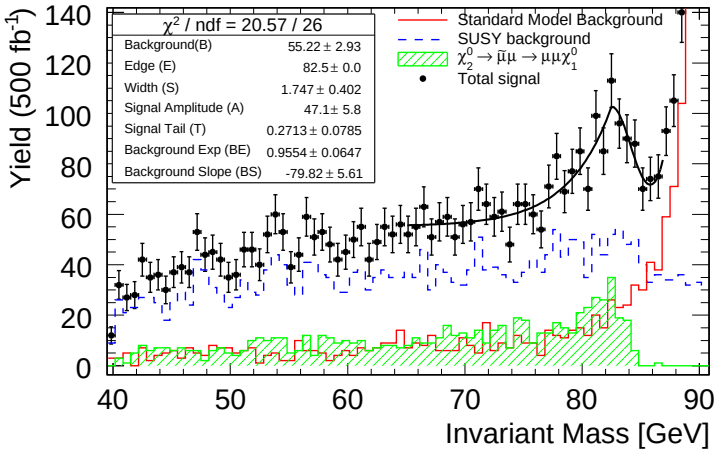
$\tilde{\chi}_1^0\tilde{\chi}_2^0$

Selections

- $\theta_{missing\ p} \in [0.2\pi, 0.8\pi]$
- $p_{Tmiss} > 40\mathrm{GeV}/c$
- β of μ system > 0.6.
- $E_{miss} \in [355, 395]\mathrm{GeV}/c^2$

Mass from fit to invariant mass edge.





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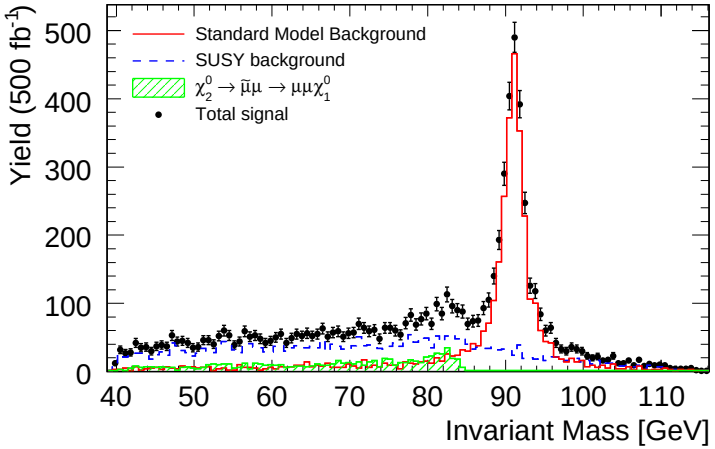
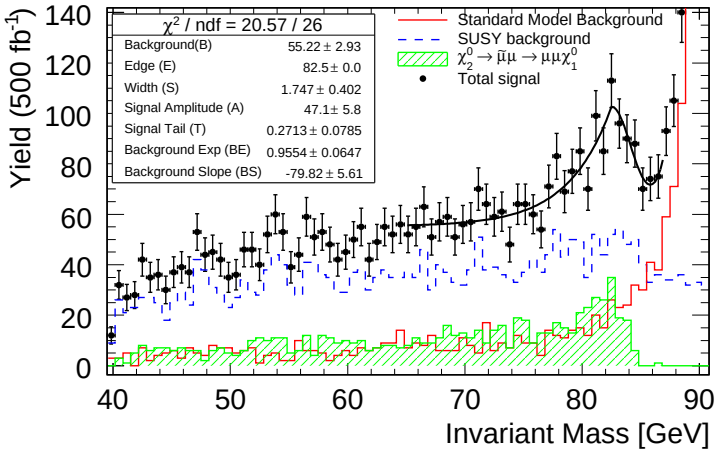
Mass from fit to invariant mass edge.

$$\Delta(M_{\tilde{\chi}_2^0}) = 1.38\mathrm{GeV}/c^2$$





The $\tilde{e}$ channel

$\sigma(\tilde{e}_R\tilde{e}_R)$ = 1.3 pb: Hundreds of thousands of almost background-free events expected.

Most of the reduction of the SM backround can be taken over from the $\tilde{\tau}$ analysis.

Some changes needed:

- $E_{vis} < 170$ GeV (rather than 120).
- $(E_{jet1} + E_{jet2}) \sin\theta_{acop} \in [21, 105]$ GeV. (rather than $\in [0, 30]$ GeV)
- $|\cos\theta_{missing\ momentum}| < 0.95$ (rather than 0.8).
- Both particles should be electron-like (rather than at most one).

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$\tilde{e}_R$ spectrum

- Signal: 227750 events (solid: fullsim, dashed: generator)
- Background: SUSY 1560 events, SM 2219 events.
- Efficiency: 67.8 %.
- Masses:
  - From average and RMS (true: 125.3 & 97.7): $M_{\tilde{e}_R} = 126.5 \pm 0.5\ \mathrm{GeV}/c^2$ and $M_{\tilde{\chi}_1^0} = 99.6 \pm 0.4\ \mathrm{GeV}/c^2$
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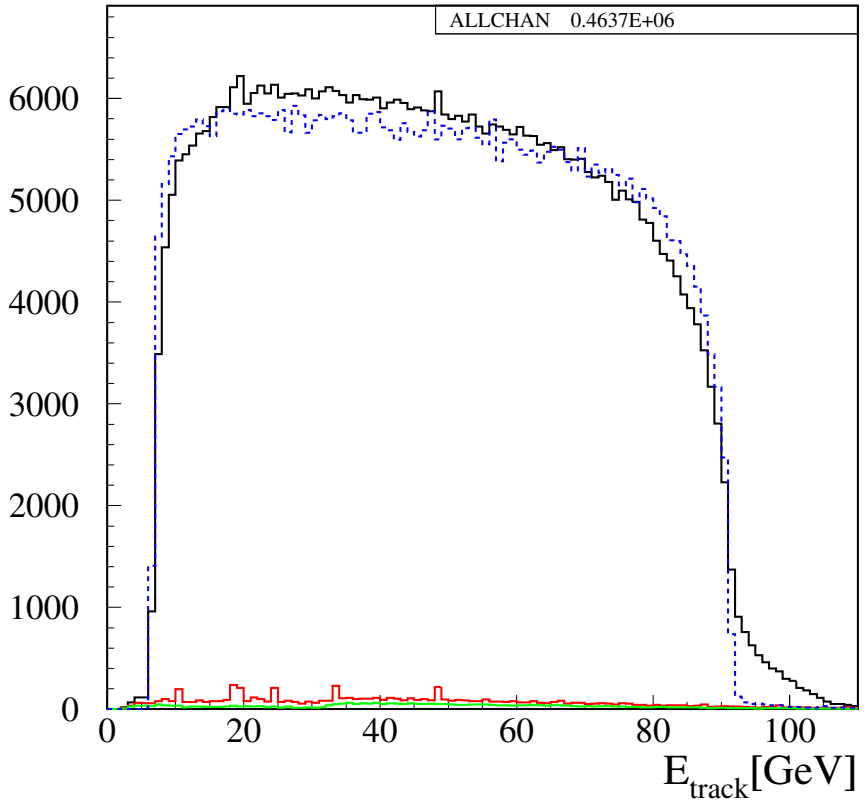

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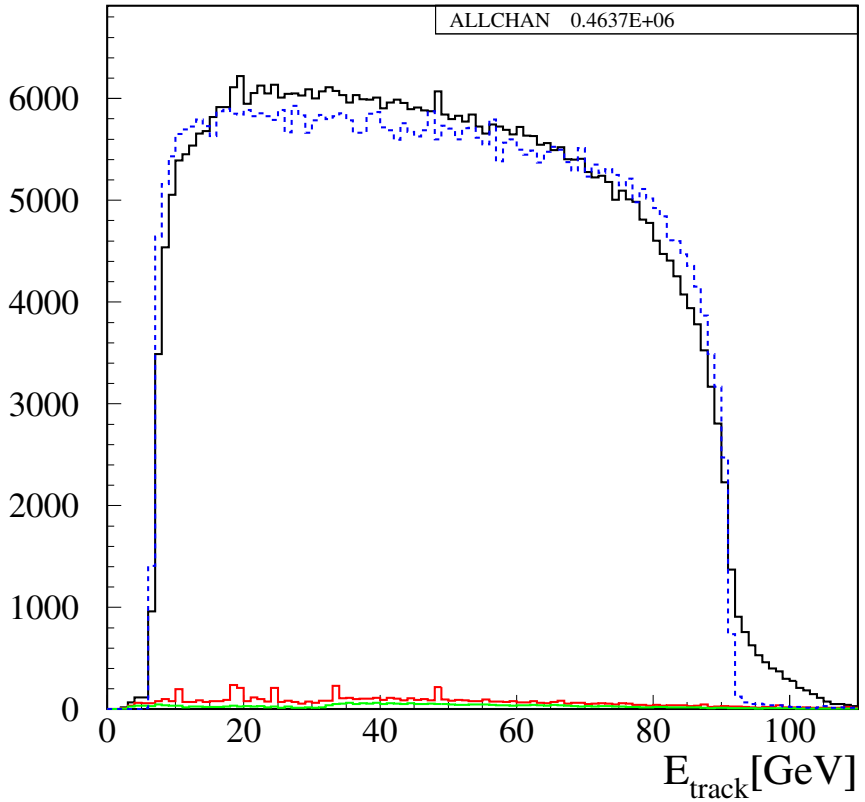

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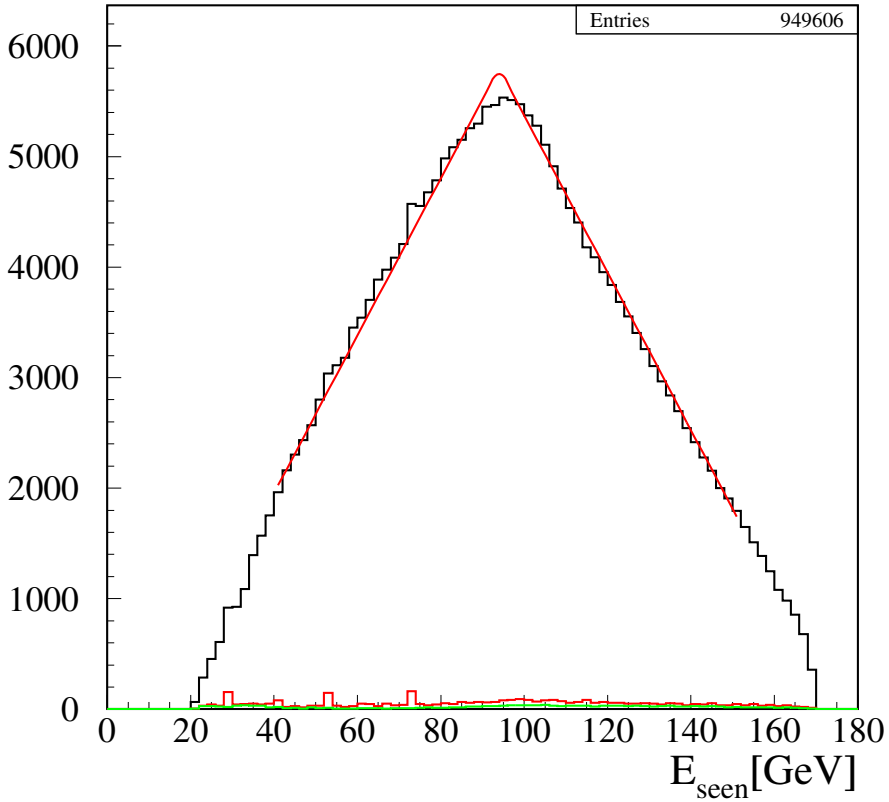
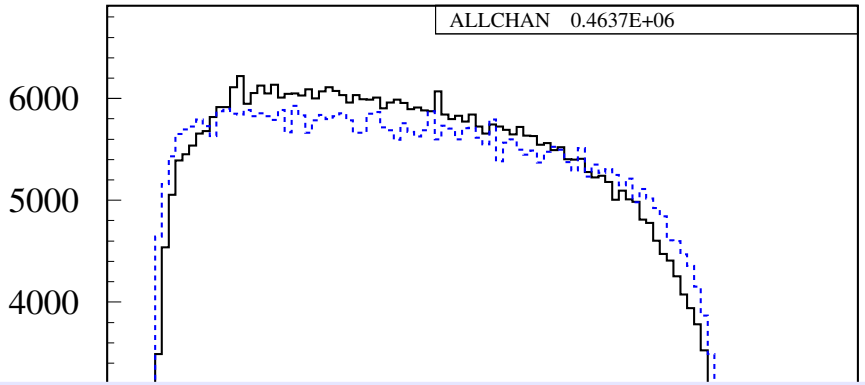


$\tilde{e}_R$ spectrum

- Signal: 227750 events (solid: fullsim, dashed: generator)
- Background: SUSY 1560 events, SM 2219 events.
- Efficiency: 67.8 %.
- Masses:



Comming:

Integration over beam-spectrum and folding in detector-effects.

$M_{\tilde{\chi}_1^0} = 99.6 \pm 0.4\ \mathrm{GeV}/c^2$

- From $E_{vis} \in [40, 150]$ GeV:

  $M_{\tilde{e}_R} = 124.6 \pm 0.5\ \mathrm{GeV}/c^2$ and

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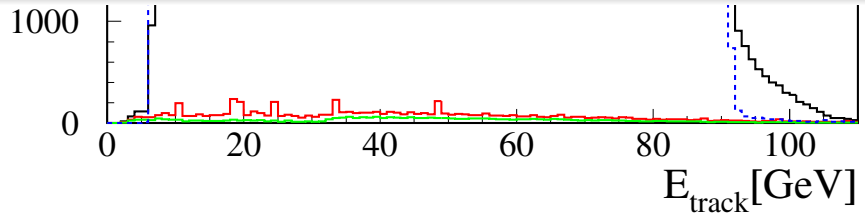

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    - [illegible]
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    - $\Delta(P_{\tau}) \simeq 6$ % (see backup).
    - For $e^+e^- \rightarrow \tilde{\mu}_L\tilde{\mu}_L$, we find: $\Delta(M_{\tilde{\chi}^0_1}) = 920\text{MeV}/c^2$
      $\Delta(M_{\tilde{\mu}_L}) = 100\text{MeV}/c^2$.
    - For $\tilde{\chi}^0_1\tilde{\chi}^0_2 \rightarrow \mu\tilde{\mu}_R\tilde{\chi}^0_1 \rightarrow \mu\mu\tilde{\chi}^0_1\tilde{\chi}^0_1$, we find $\Delta(M_{\tilde{\chi}^0_2}) = 1.38\text{GeV}/c^2$
    - $\Delta(M_{\tilde{\chi}^0_1}) = 400\ \text{MeV}/c^2$ (prospect: 170 MeV/c^2)
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At SPS1a' (TDR 1) there are

- 10 (11) masses
- Cross-sections for 13 (18) channels
- >100 branching ratios
- Several mixing angles

to measure at a 500 GeV ILC.

We intend to study TDR points

- At different E_{CMS}
- With different beam-polarisations
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- Main tool: Fast simulation tuned to full-simulation

We are also studying other (cosmo-inspired) "LHC nightmare points":

- All sfermions at > 10 TeV.
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People involved:

N. d'Ascenzo, J. List, S. Caiazza, K. Rolbiecki, H. Sert, M.B.

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Thanks to:

P. Schade, P. Bechtle, R. Wilkinson, G. Moortgat-Pick, G. Weiglein, H. Baer, S. Heinemeyer, W. Buchmüller

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THANK YOU !

Backup

BACKUP SLIDES

$\gamma\gamma$ suppression

$\Delta(M) = 10.2\ \mathrm{GeV}/c^2 \rightarrow \gamma\gamma$ background ...

- Correlated cut in ρ and θ_{acop}: $\rho > 2.7 \sin\theta_{acop} + 1.8$. ($\rho = P_T$ of jets wrt. thrust axis, in x-y projection.)
- no significant activity in the BeamCal
- $\phi_{p\ miss}$ not in the direction of the incoming beam-pipe.

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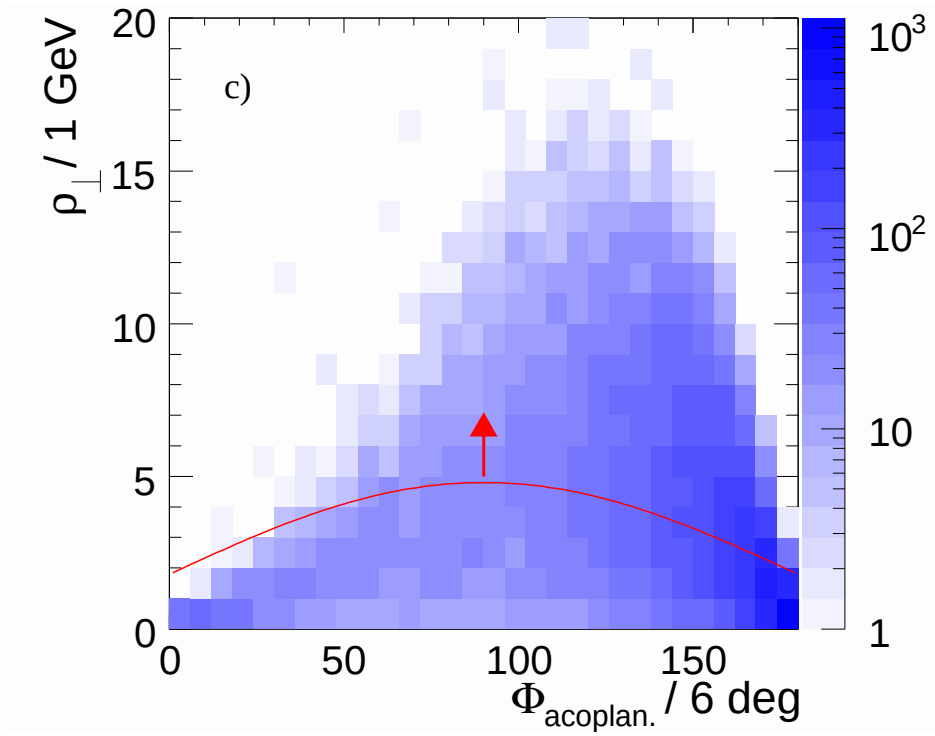

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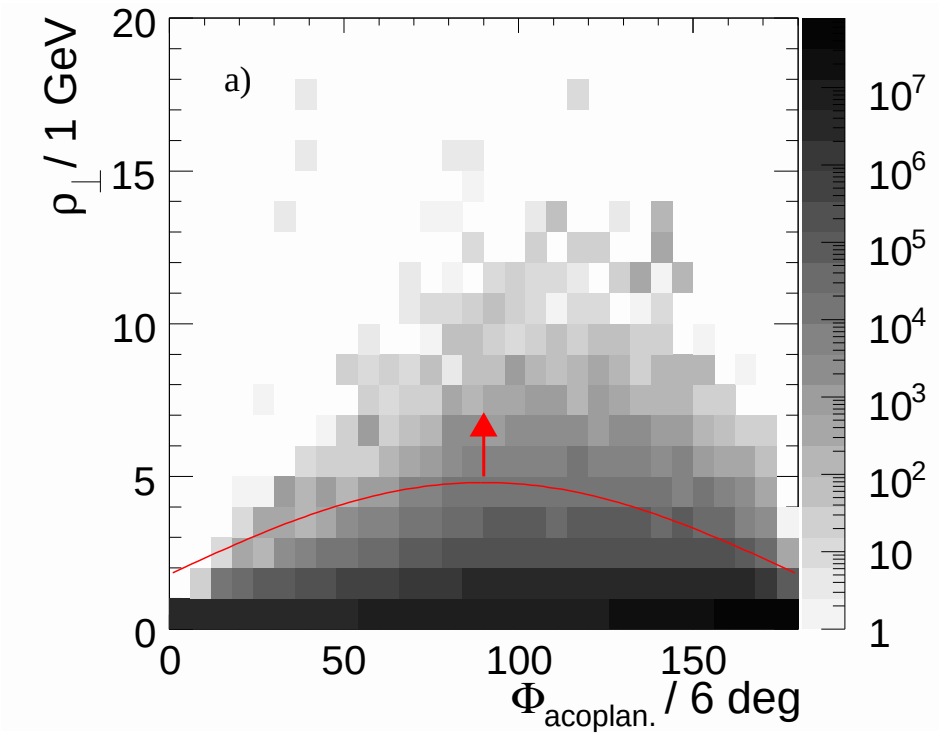

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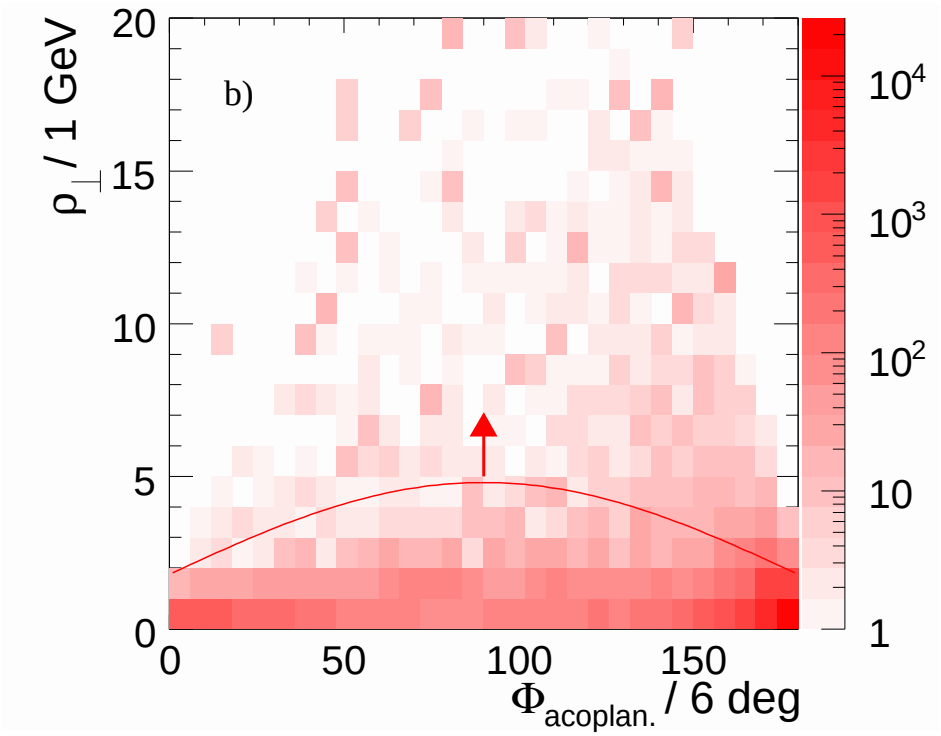

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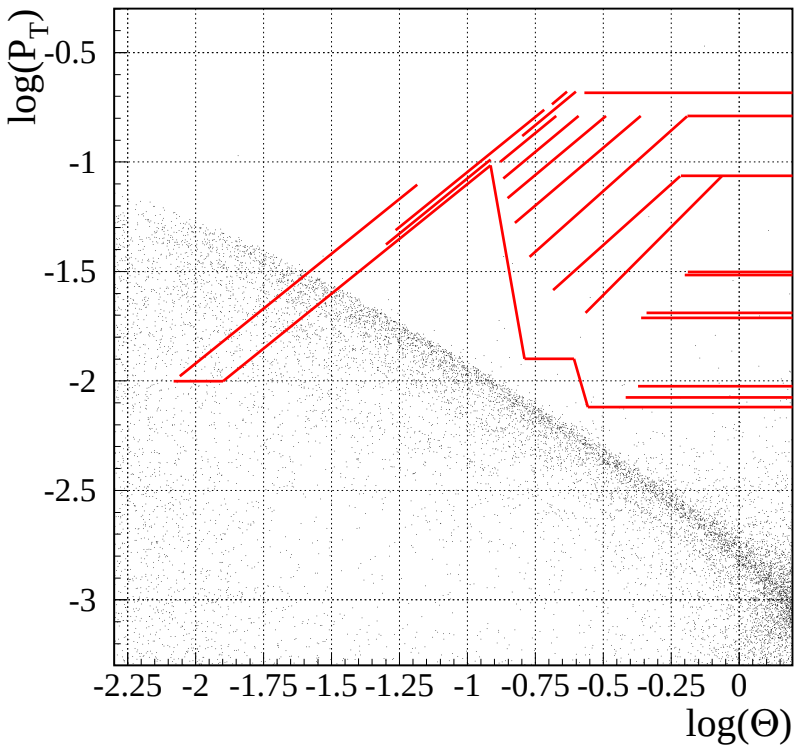

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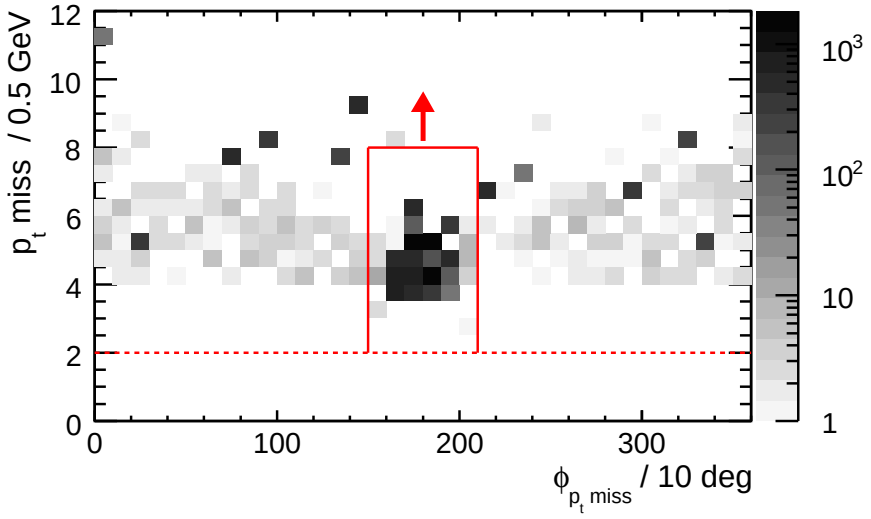

End-point and cross-section

Additional cuts against $\gamma\gamma$ (not needed for polarisation, due to PID requirements):

- $|\cos\theta_{\textit{missing momentum}}| < 0.8$
- Low fraction of "Rest-of-Event" energy at low angles.

From now on: Different cuts for $\tilde{\tau}_1$ ($\gamma\gamma$ background), and $\tilde{\tau}_2$ (*WW* background).

Fitting the $\tilde{\tau}$ mass: Cross-section

- Poorly known SUSY background is most important contribution to uncertainty.
- Select region where is is as low as possible.

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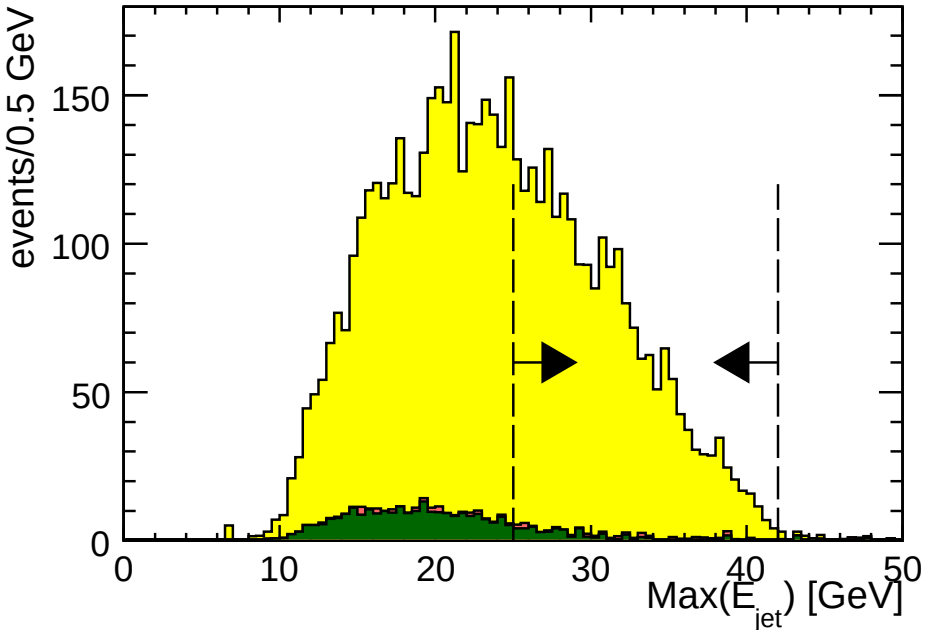

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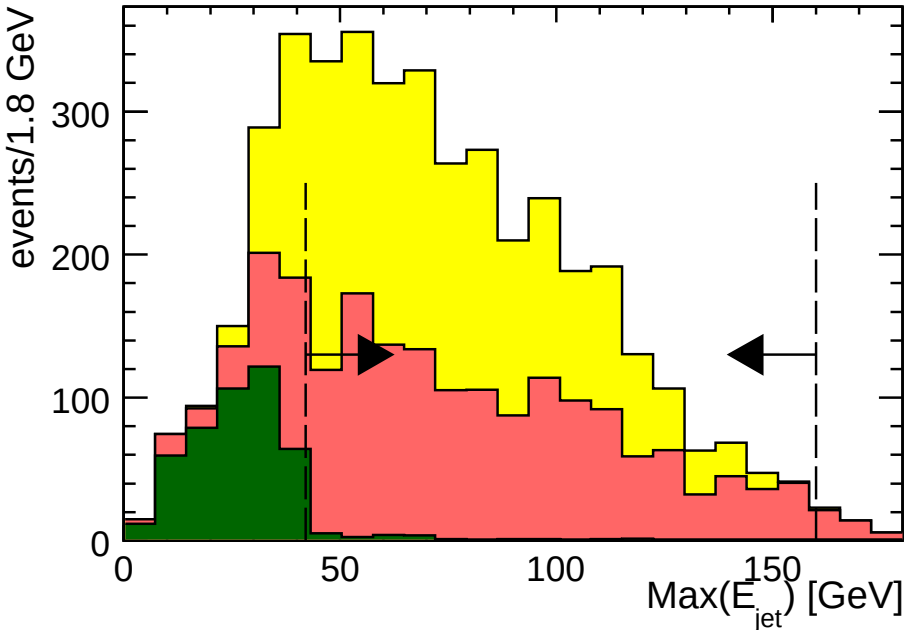

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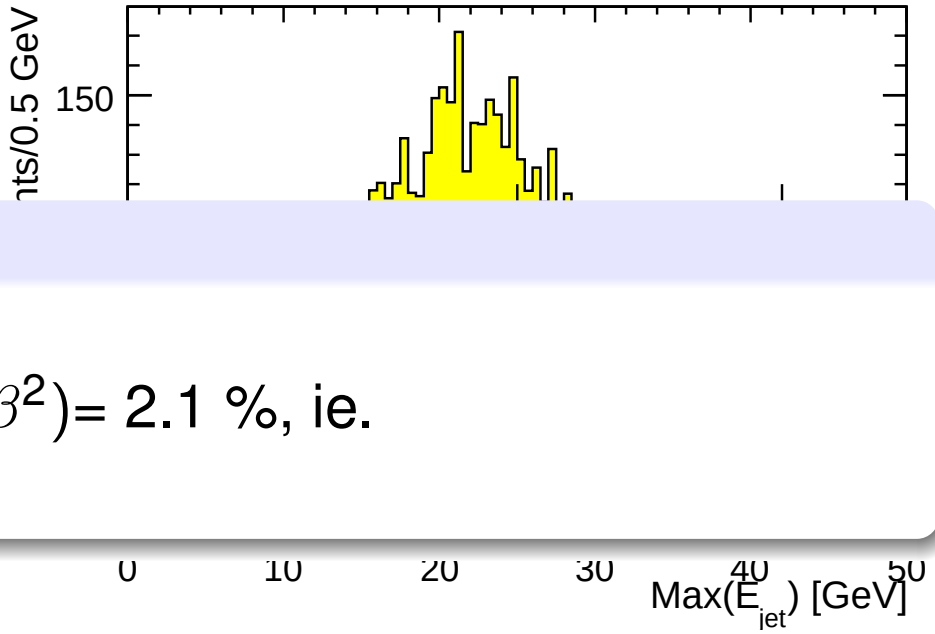

Results for $\tilde{\tau}_1$

$\Delta(N_{signal})/N_{signal} = 3.1\%$
$\Delta(M_{\tilde{\tau}_1})/M_{\tilde{\tau}_1} = (\Delta(\sigma)/\sigma)(\beta^2)/3(1-\beta^2)$= 2.1 %, ie.
$\Delta(M_{\tilde{\tau}_1}) = 3.2\ \mathrm{GeV}/c^2$

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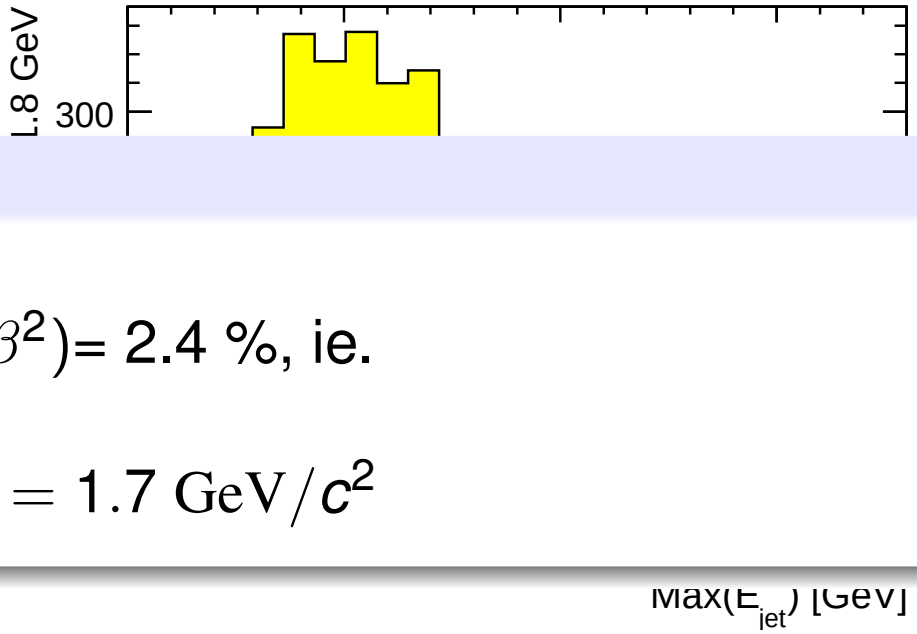


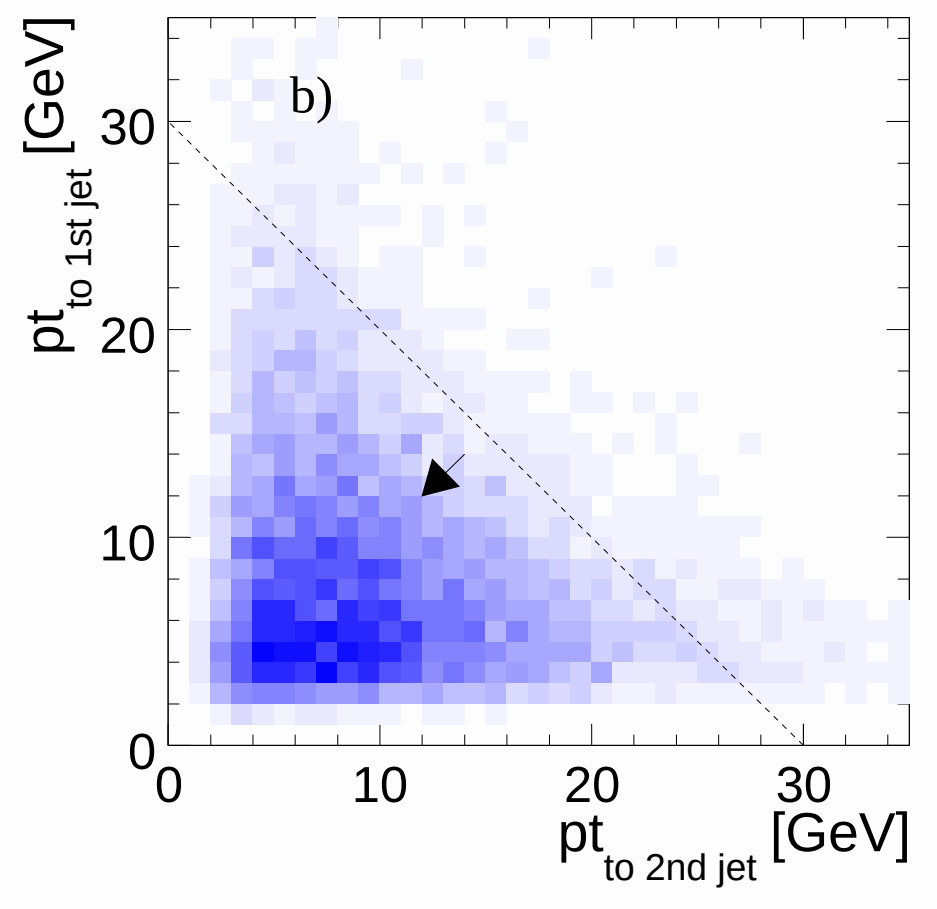
Results for $\tilde{\tau}_2$

$\Delta(N_{signal})/N_{signal} = 4.2\%$
$\Delta(M_{\tilde{\tau}_2})/M_{\tilde{\tau}_2} = (\Delta(\sigma)/\sigma)(\beta^2)/3(1-\beta^2)$= 2.4 %, ie.
$\Delta(M_{\tilde{\tau}_2}) = 3.6\ \mathrm{GeV}/c^2$
End-point + Cros-section $\rightarrow \Delta(M_{\tilde{\chi}_1^0}) = 1.7\ \mathrm{GeV}/c^2$

$\tilde{\tau}_1$ End-point and cross-section

- $E_{vis} < 120$ GeV,
- $|\cos\theta_{jet}| < 0.9$ for both jets,
- $\theta_{acop} > 85°$,
- $(E_{jet1} + E_{jet2})\sin\theta_{acop} < 30$ GeV.
- $M_{vis} > 20$ GeV$/c^2$.

Efficiency 14.9 %



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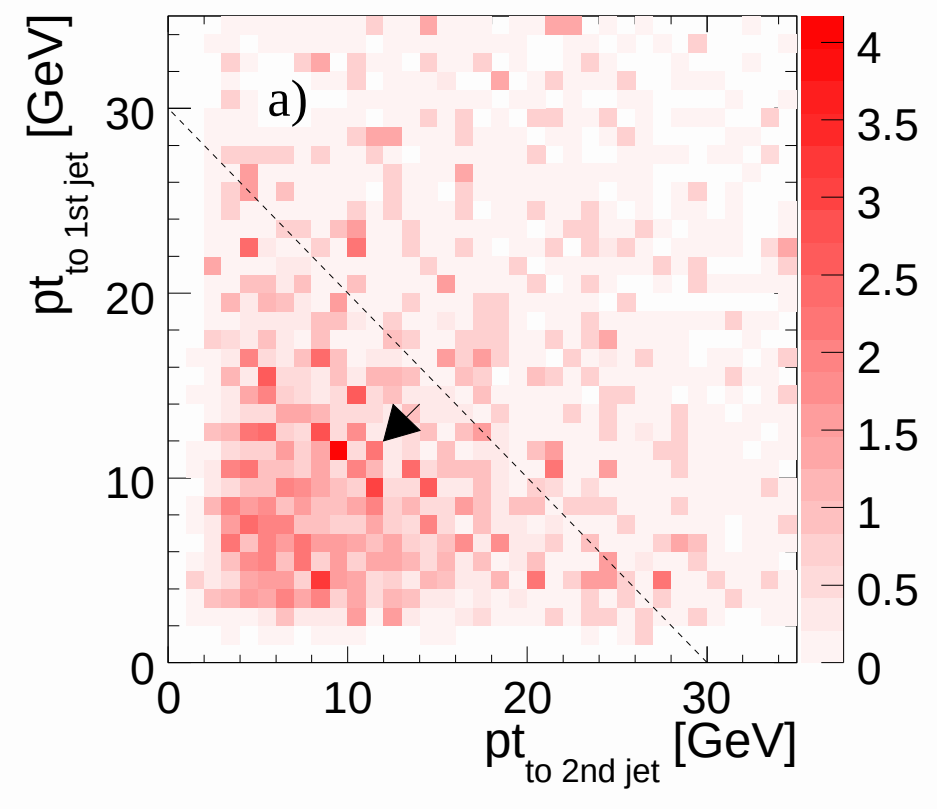

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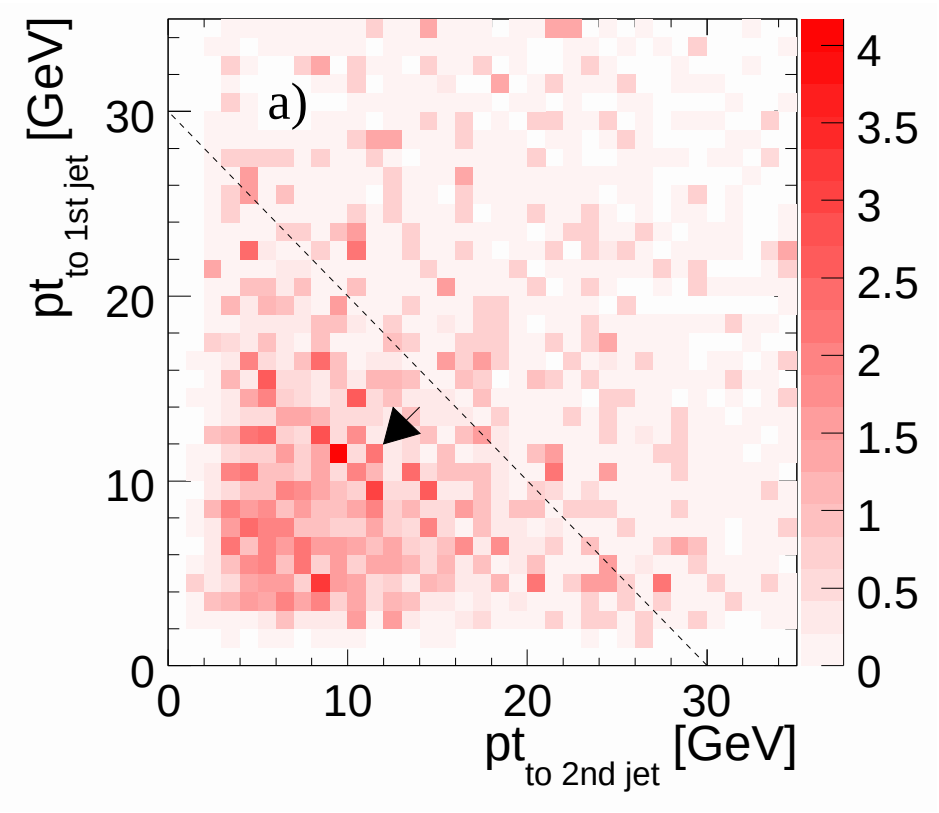
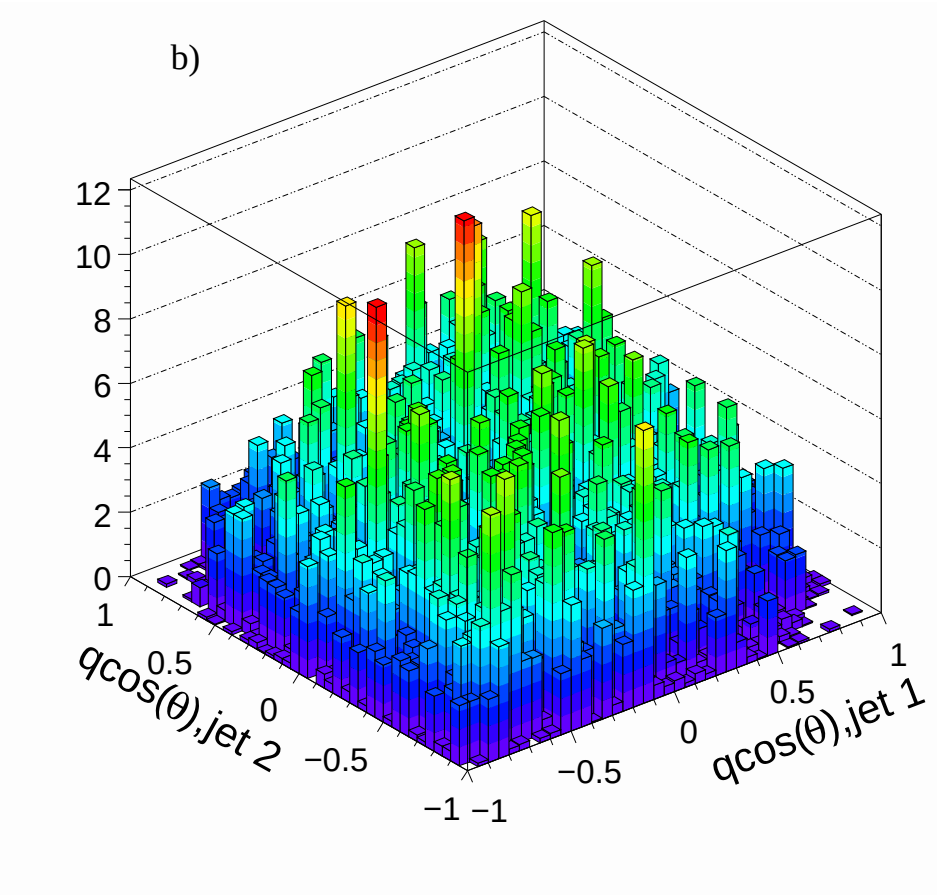


$\tilde{\tau}_2$ End-point and cross-section

- $E_{vis} > 50$ GeV.
- $\theta_{acop} < 155°$.
- Other side jet not e or μ
- Most energetic jet not e or μ
- Cut on Signal-SM LR of f($q_{jet1} cos\theta_{jet1}$,$q_{jet2} cos\theta_{jet2}$)

Efficiency 22.3 %



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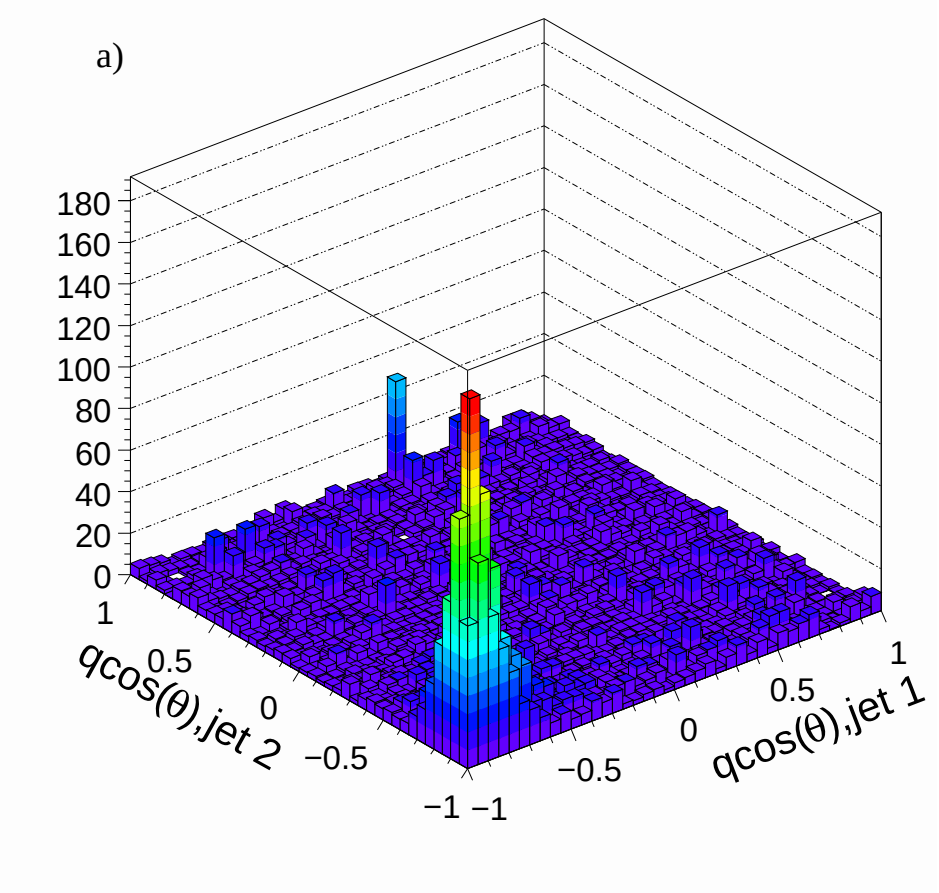

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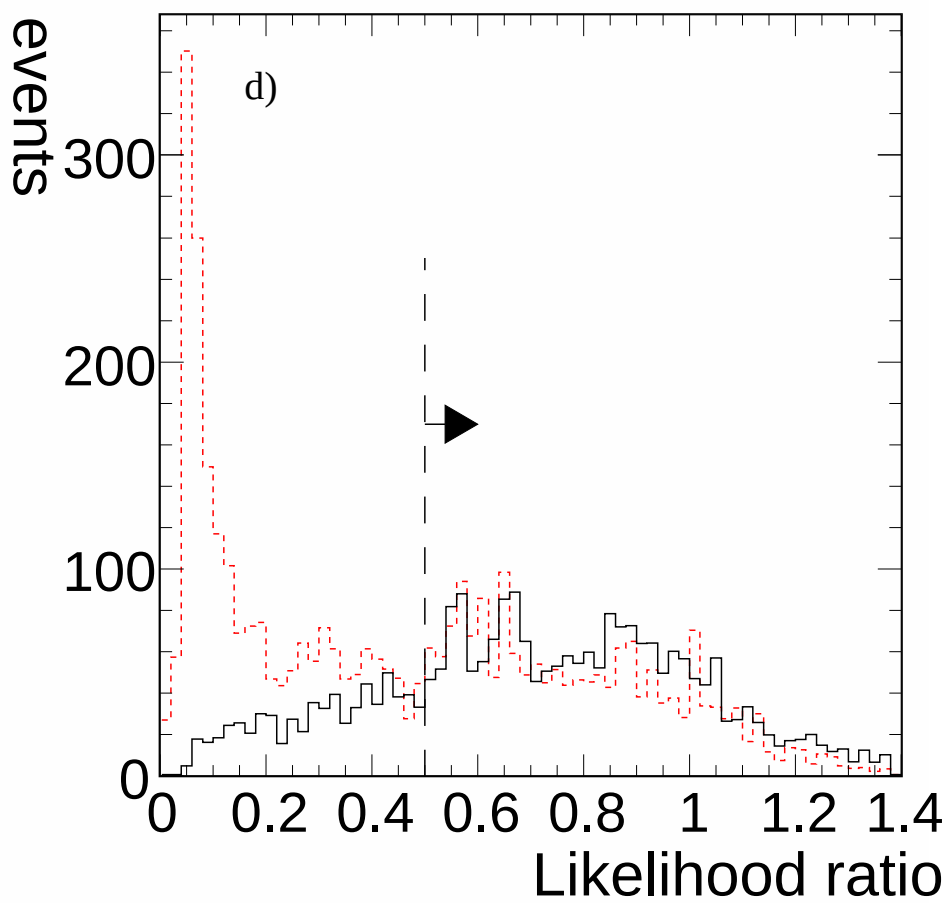

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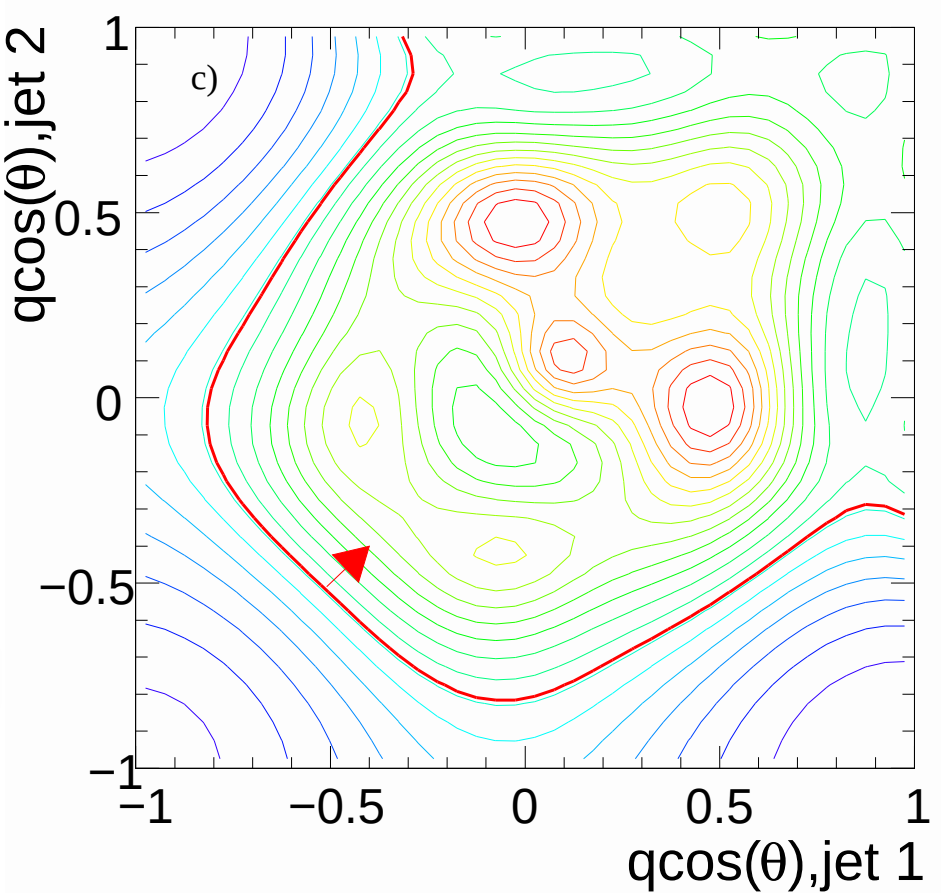

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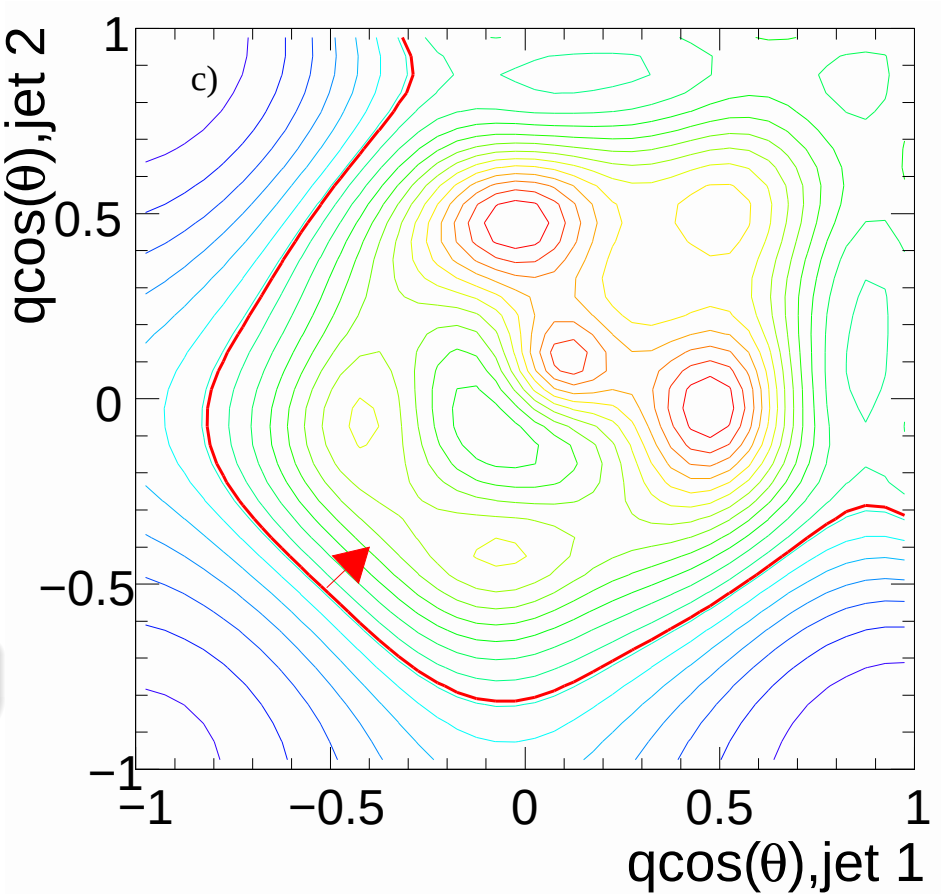
- Cut on Signal-SM LR of f($q_{jet1} cos\theta_{jet1}$,$q_{jet2} cos\theta_{jet2}$)

Efficiency 22.3 %



τ Polarisation: formulae and corrections

Spectrum of π:s in $\tau \to \pi^{+-}\nu_\tau$:

$$\frac{1}{\sigma}\frac{d\sigma}{dy_\pi} \sim \begin{cases} (1-P_\tau)\log\frac{P_{\tilde{\tau},max}}{P_{\tilde{\tau},min}} + 2P_\tau y_\pi\left(\frac{1}{P_{\tilde{\tau},min}} - \frac{1}{P_{\tilde{\tau},max}}\right) & \text{for } y_\pi < P_{\tilde{\tau},min} \\ (1-P_\tau)\log\frac{P_{\tilde{\tau},max}}{y_\pi} + 2P_\tau\left(1 - \frac{y_\pi}{P_{\tilde{\tau},max}}\right) & \text{for } Y_\pi > P_{\tilde{\tau},min} \end{cases}$$

Analysers:

- π-channel: P_π
- ρ-channel: $E_\pi/(E_\pi + E_{\gamma:s})$

Note the importance of the region with $Y_\pi < P_{\tilde{\tau},min}$!

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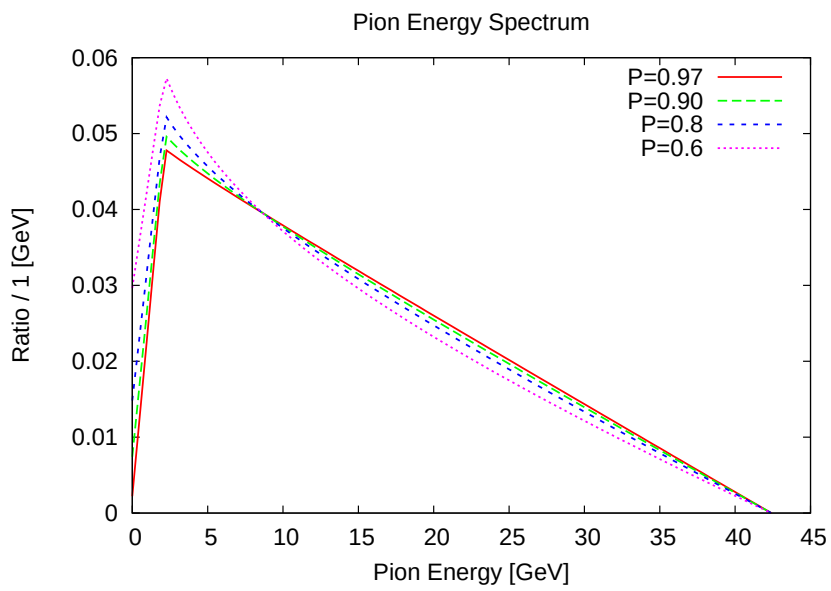

τ Polarisation from π: background and signal fit

Method to extract the polarisation:

- Fit background MC.
- Subtract this background estimate.
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- Fit $\mathcal{P}_\tau$, with normalisation from cross-section determination.
- Repeat fit with randomly modified background.
- Determine effect from $\Delta(M_{\tilde{\chi}_1^0})$ and $\Delta(M_{\tilde{\tau}_1})$ numerically.

$$\mathcal{P}_\tau = 93 \pm 6 \pm 5(\text{bkg}) \pm 3(\text{SUSY masses})\%$$

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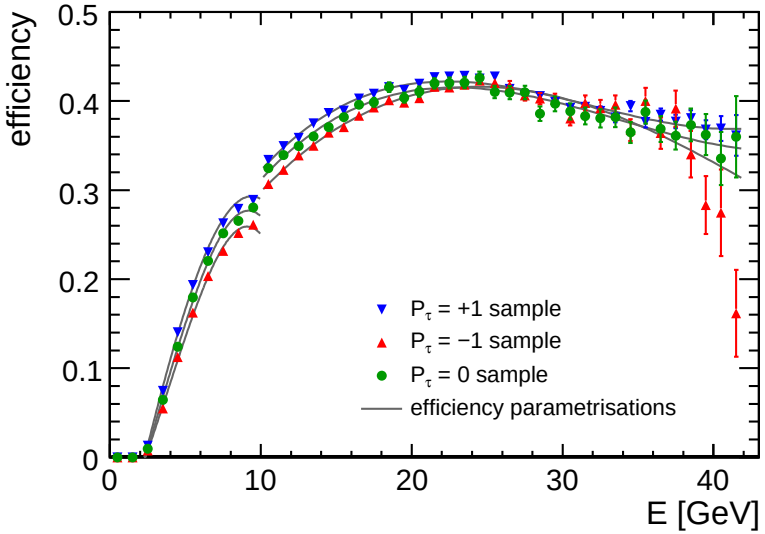

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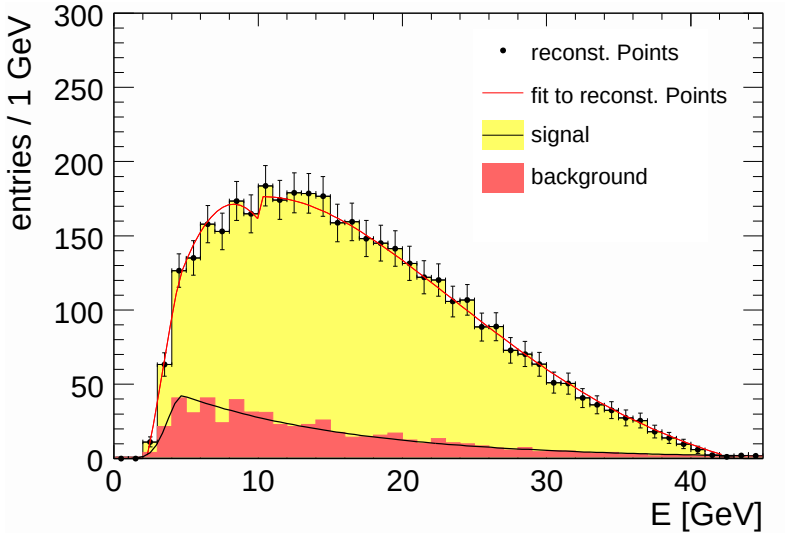

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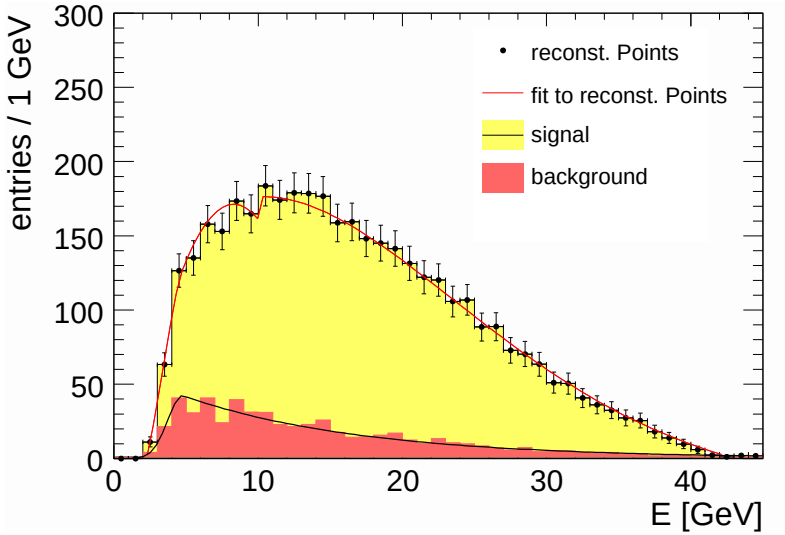

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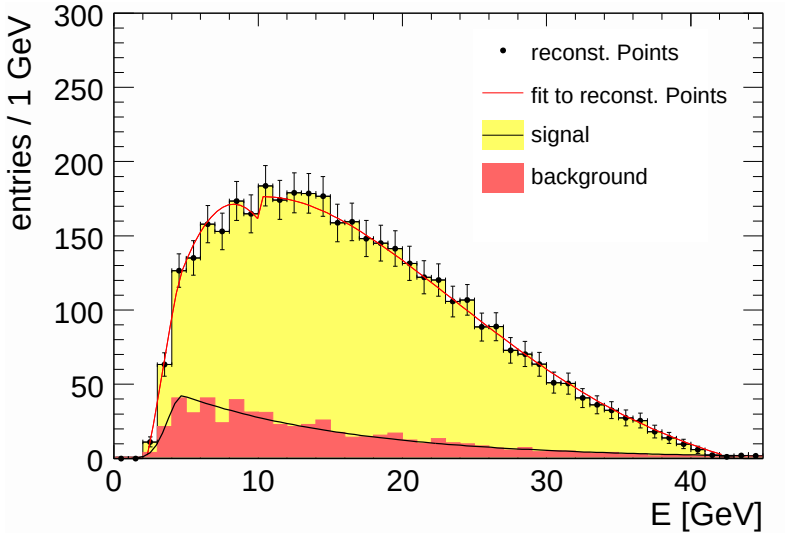

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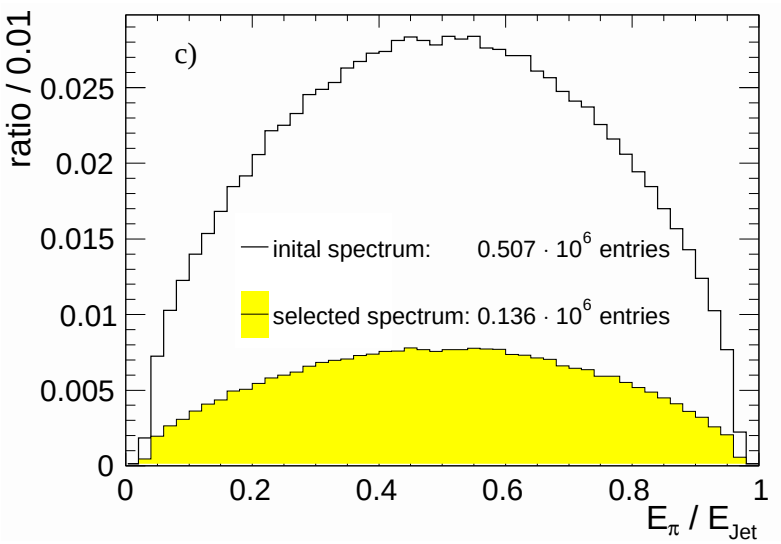

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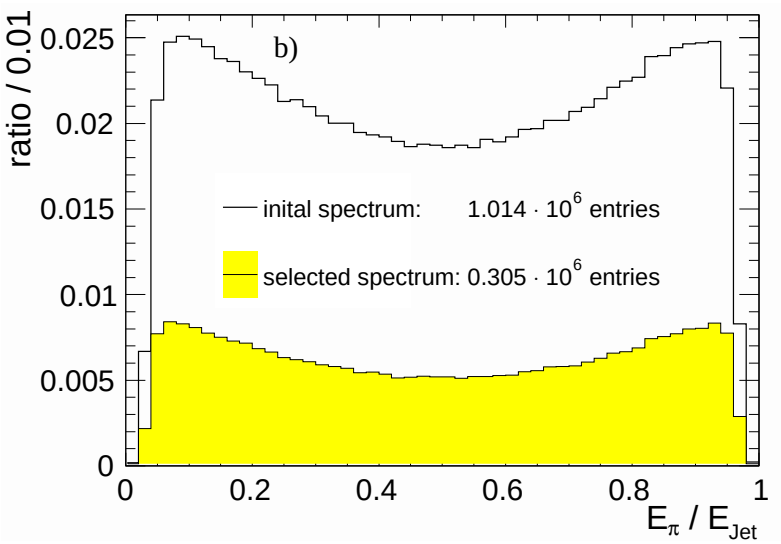

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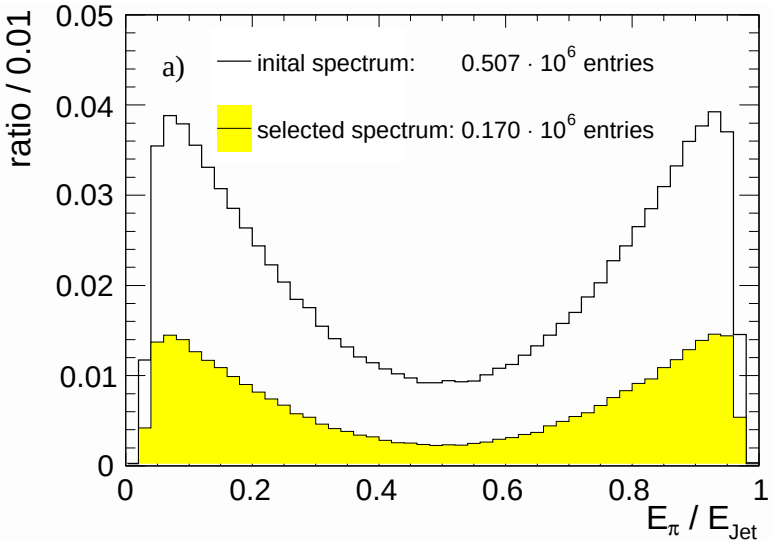

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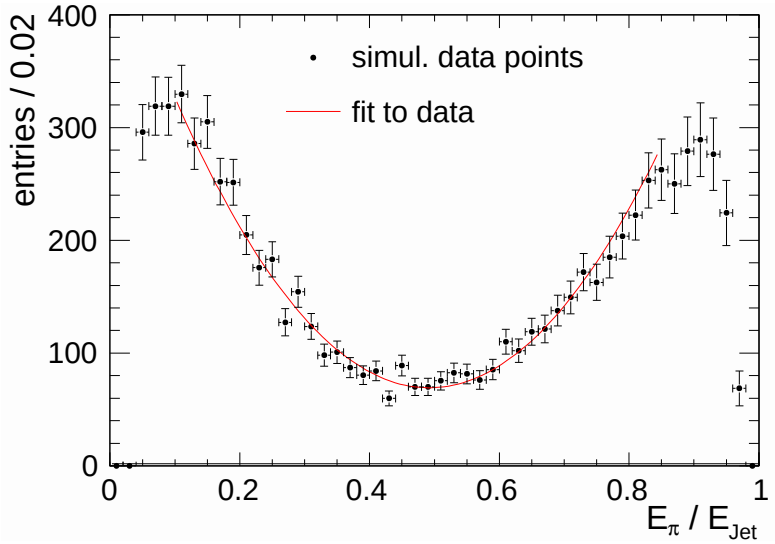

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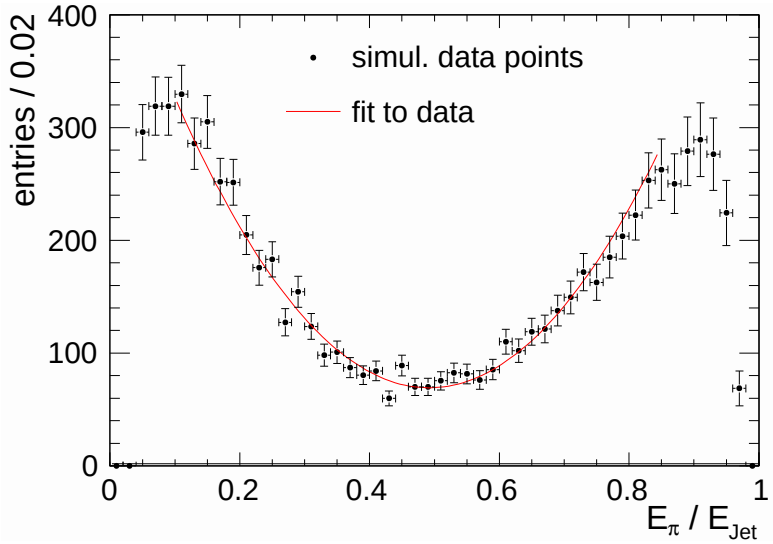

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Correct for the spread in E_{beam}:

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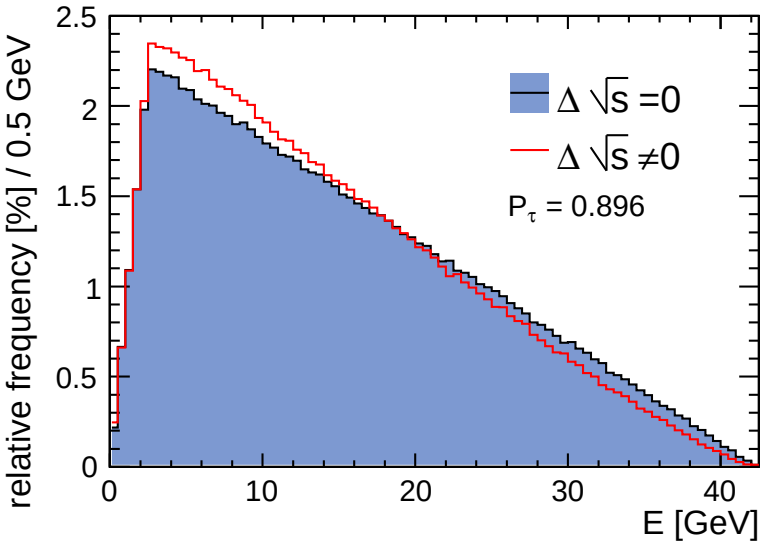

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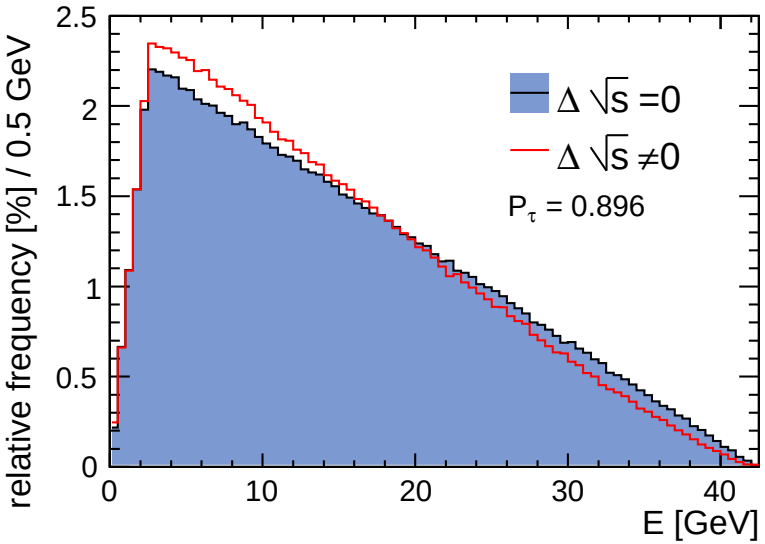

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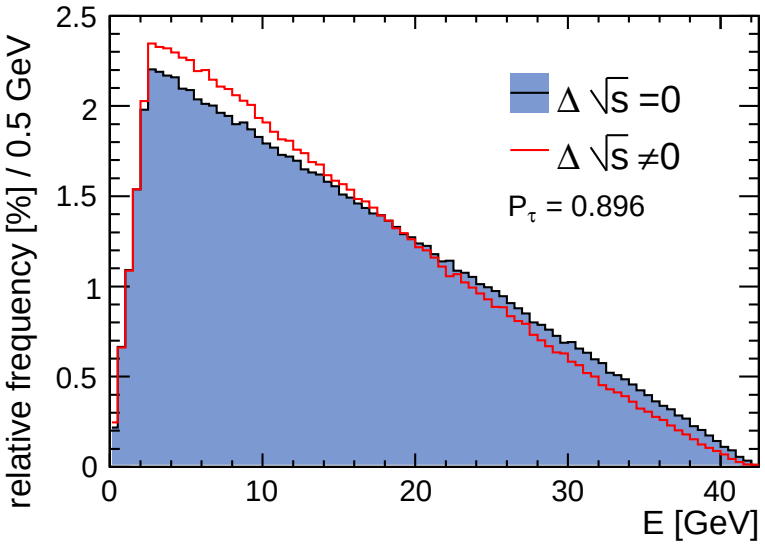

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Extract the $\tau \to \pi^{+-}\nu_\tau$ signal.

- The events should pass the anti-$\gamma\gamma$ cut.
- $E_{vis} < 90\ \mathrm{GeV}$.
- No jet with $E > 60\ \mathrm{GeV}$
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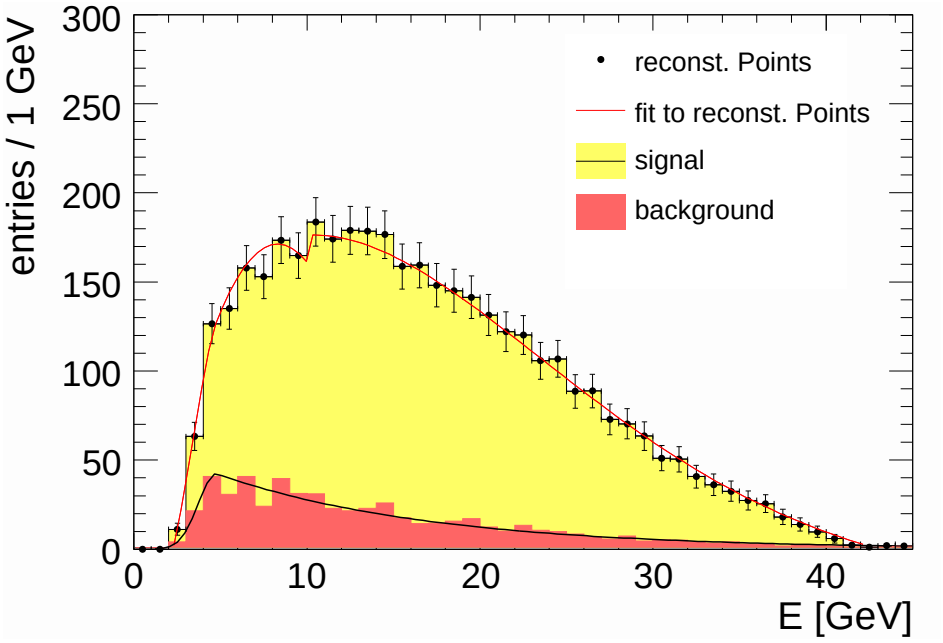

τ Polarisation from ρ: Select the signal process

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- No jet with $E > 43\ \mathrm{GeV}$
- Tighter ρ cut:$\rho > 3.5 \sin\theta_{acop} + 2$.
- At least one jets should contain one charged particle, and at least two neutrals.
- The single particle should have a π-id (dE/dx only).
- Mass of this jet close to M_ρ:$M_{jet} \in [0.4, 1.1]\mathrm{GeV}/c^2$.

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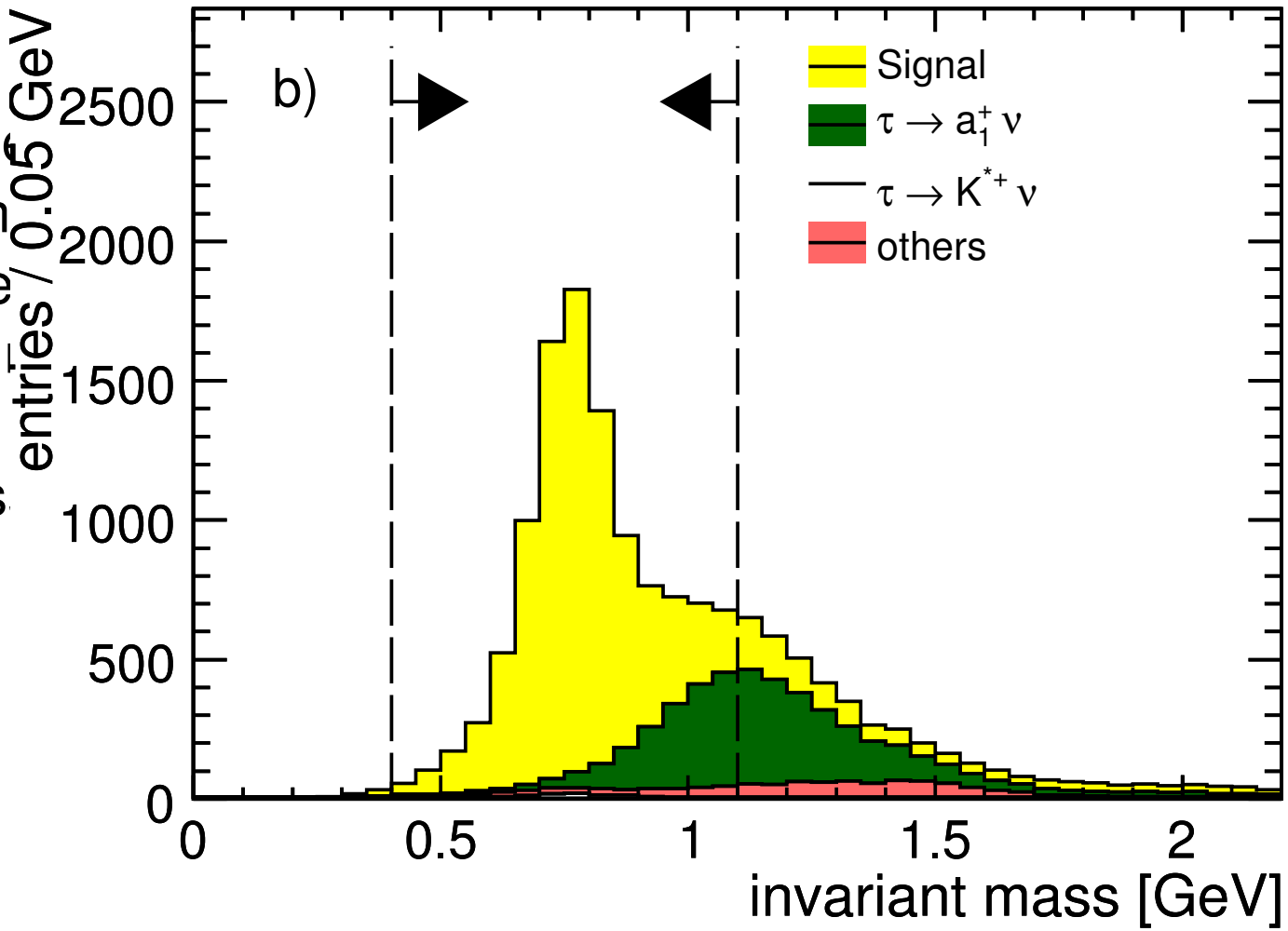

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Near Degenerate $\tilde{e}$

Background and efficiency from Full-sim SPS1a' sample, kinematics from Whizard simulation of the model.

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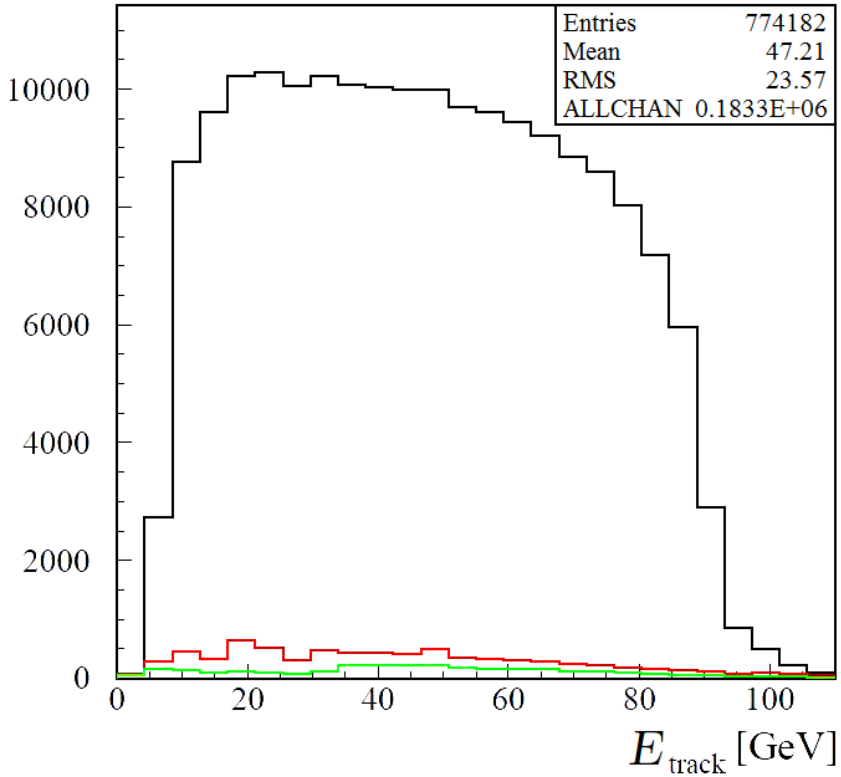

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For the signal:

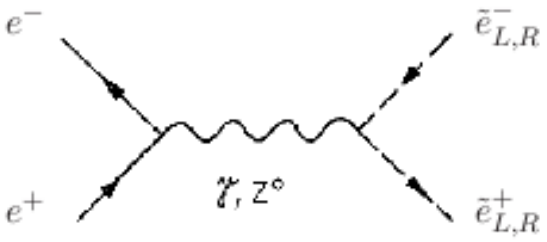
- Generate (with Whizard 1.95) the modified model.
- Apply the kinematic cuts used for the full simulation analysis.
- Scale down the over-all event-weight so that the efficiency agrees with the full simulation.

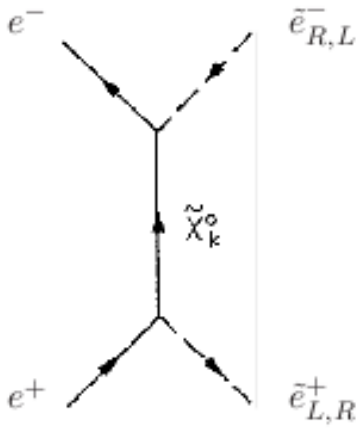
Near Degenerate $\tilde{e}$ and polarisation

(Preliminary work by M.B., G. Moortgat-Pick)

SUSY associates scalars to chiral (anti)fermions

$$e^-_{L,R} \leftrightarrow \tilde{e}^-_{L,R} \quad \text{and} \quad e^+_{L,R} \leftrightarrow \tilde{e}^+_{R,L}. \tag{1}$$





$\tilde{e}$:s with same chirality

Chirality for $\tilde{e}^\pm$ same as $e^\pm$

What if $M_{\tilde{e}_L} \approx M_{\tilde{e}_R}$, so that thresholds can't separate $e^+e^- \to \tilde{e}_L\tilde{e}_L, \tilde{e}_R\tilde{e}_R$ and $\tilde{e}_R\tilde{e}_L$?

Near Degenerate $\tilde{e}$ and polarisation

Model: SPS1a' like, but:

$M_{\tilde{e}_L}$ = 200 GeV and $M_{\tilde{e}_R}$ = 195 GeV. Both decay 100 % to $\tilde{\chi}_1^0$ e.

Background and efficiency from Full-sim SPS1a' sample, kinematics from Whizard simulation of the model.

Even with $P_{e^-} \geq +90\%$: No separation of $\tilde{e}_L^+ \tilde{e}_R^-$ and $\tilde{e}_R^+ \tilde{e}_R^-$: Ratio of the cross sections $\approx$ constant.

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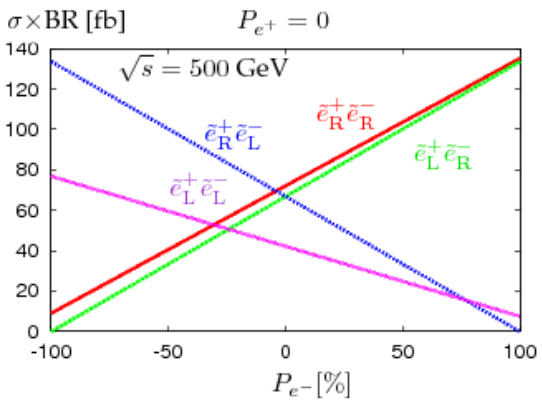

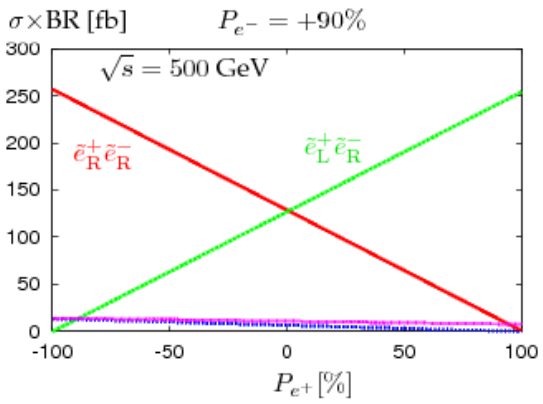

Near Degenerate $\tilde{e}$ and polarisation

The handle:
Opposite polarisation beams produces $\tilde{e}$:s in both s- and t-channel.
Same polarisation produces $\tilde{e}$:s in t-channel only $\Rightarrow$

Modification of Θ distribution with changed positron polarisation

However, the effect is small since t-channel always dominates !
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Reconstruct $\Theta_{\tilde{e}}$ event-by-event assuming $M_{\tilde{e}}$ and $M_{\tilde{\chi}_1^0}$ known.

- P(e^-)= +80 % and ..
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- P(e^-)= +80 % and ..
- P(e^+) = $\pm$ 22 % ...
- P(e^+) = $\pm$ 30 % ...
- P(e^+) = $\pm$ 60 % ...
- ... and for P(e^-)= $\pm$ 80 %
  P(e^+) = 0

Near Degenerate $\tilde{e}$ and polarisation

The handle: Opposite polarisation beams produces $\tilde{e}$:s in both s- and t-channel.
Same polarisation produces $\tilde{e}$:s in t-channel only $\Rightarrow$

Modification of Θ distribution with changed positron polarisation

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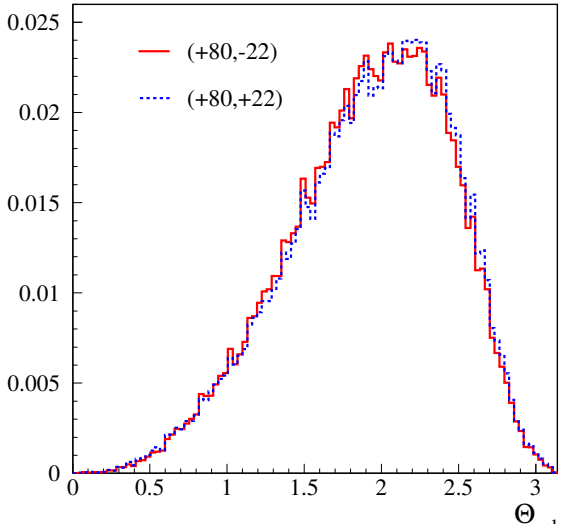

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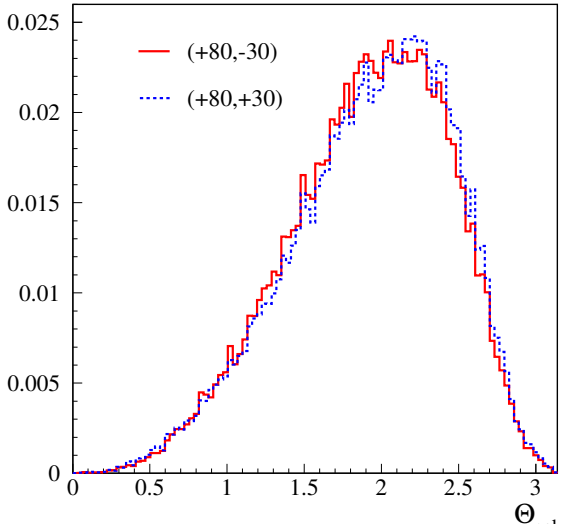

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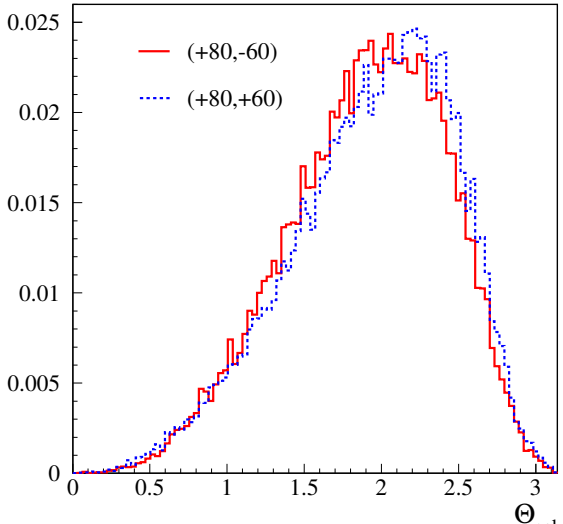

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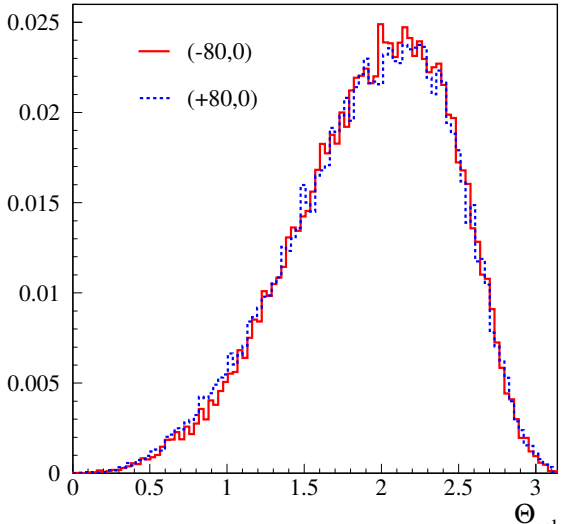

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$\lvert P(e^+)\rvert$ (%)	significance of shift (σ)	Title of paper
22	2.4	"Limit on ..."
30	3.5	"Evidence for ..."
60	6.6	"Observation of ..."

- $P(e^+) = \pm 60$ % ...
- ... and for $P(e^-) = \pm 80$ % $P(e^+) = 0$