# Part 3: SUSY parameter measurement

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# Establishing SUSY experimentally

Assume an excess seen in inclusive analyses: how does one verify whether it is actually SUSY? Need to demonstrate that:

- Every particle has a superpartner
- Their spin differ by $1/2$
- Their gauge quantum numbers are the same
- Their couplings are identical
- Mass relations predicted by SUSY hold

Available observables:

- Sparticle masses,
- Production cross-sections,
- BR's of cascade decays
- Angular decay distributions

Precise measurements of such observables requires development of ad-hoc techniques at the LHC: develop a strategy based on detailed MC study of reasonable candidate models

# Measurement of model parameters: LHC strategy

The problem is the presence of a very complex spectroscopy due to long decay chains, with crowded final states.

Many concurrent signatures obscuring each other

## General strategy:

- Select signatures identifying well defined decay chains
- Extract constraints on masses, couplings, spin from decay kinematics/rates
- Try to match emerging pattern to template models, SUSY or anything else
- Having adjusted template models to measurements, try to find additional signatures to discriminate different options

In last ten years developed techniques for mass and spin measurements in complex SUSY decay kinematics

Focus today on most promising techniques for mass and spin measurements

Show in detail application to an "easy" model point

# Typical starting point: $\tilde{\chi}_2^0$ decays

QCD Background: need decay chains involving leptons (e,$\mu$), $b$'s, $\tau$'s

$\tilde{\chi}_2^0$ is a mixing of $Z, \gamma$ and higgsino, always some BR into recognizable chain

- $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z^*$ ($6\%$ BR to $(e, \mu)\tilde{\chi}_1^0$ non–resonant)
- $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$ ($6\%$ BR to $(e, \mu)\tilde{\chi}_1^0$ resonant)
- $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 h \to \tilde{\chi}_1^0 \bar{b}b$
- $\tilde{\chi}_2^0 \to \tilde{\ell}^{\pm(*)}\ell^{\mp} \to \tilde{\chi}_1^0 \ell^+\ell^-$ ($\ell$ mostly $\tilde{\tau}_1$ at high $\tan\beta$)

One or more of these decays present in all mSUGRA Points considered

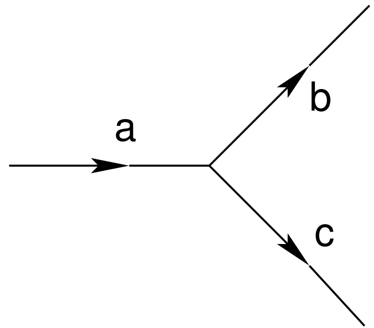
Abundantly produced: BR($\tilde{q}_L \to q\tilde{\chi}_2^0$) typically 30% in mSUGRA

R-parity conservation $\Rightarrow$ two undetected LSP's per event

$\Rightarrow$ no mass peaks, constraints from edges and endpoints in kinematic distributions

Key result: If a chain of at least three two-body decays can be isolated, can measure masses and momenta of involved particles in model-independent way.

# Two-body kinematics




### 4-momentum conservation

$$m_a^2 = (E_b + E_c)^2 - (\vec{p_b} + \vec{p_c})^2 \qquad E_{b(c)}^2 = m_{b(c)}^2 + |\vec{p_b}|^2$$

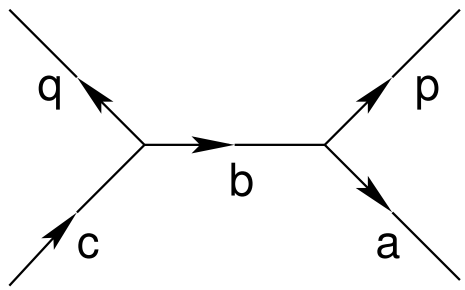
In rest frame of $a$: $\quad \vec{p_b} + \vec{p_c} = 0 \Rightarrow |\vec{p_b}| = |\vec{p_c}| = |\vec{p}|$

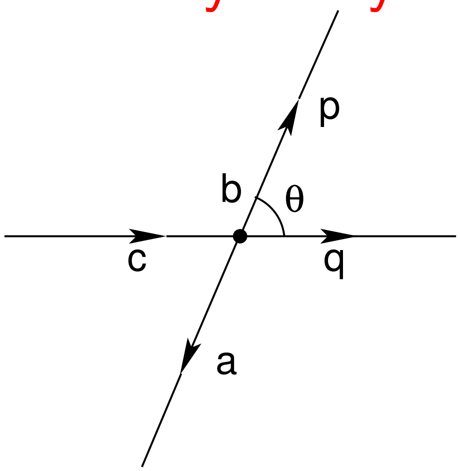
$$m_a^2 = (E_b + E_c)^2 \qquad m_a^2 = m_b^2 + m_c^2 + 2\,|\vec{p}|^2 + 2\,\sqrt{m_b^2 + |\vec{p}|^2}\,\sqrt{m_c^2 + |\vec{p}|^2}$$

Solve for $|\vec{p}|$: $\quad |\vec{p}|^2 = [m_b^2, m_a^2, m_c^2] \quad$ where

$$[x, y, z] \equiv \frac{x^2 + y^2 + z^2 - 2(xy + xz + yz)}{4y} \tag{1}$$

# Cascade of successive two-body decays




Go to rest system of intermediate particle $b$:

$$|\vec{p}_p|^2 = |\vec{p}_a|^2 = [m_p^2, m_b^2, m_a^2] \qquad |\vec{p}_q|^2 = |\vec{p}_c|^2 = [m_q^2, m_b^2, m_c^2] \tag{2}$$

We are interested in the invariant mass of the two visible particles: $m_{pq}^2$:

$$m_{pq}^2 = (E_p + E_q)^2 - (\vec{p_q} + \vec{p_q})^2 = m_p^2 + m_q^2 + 2(E_pE_q - |\vec{p_p}||\vec{p_q}|cos\theta)$$

$m_{pq}$ has maximum or minimum value when $p$ or $q$ are back-to-back or collinear in rest frame of $b$:

$$(m_{pq}^{max})^2 = m_p^2 + m_q^2 + 2(E_pE_q + |\vec{p_p}||\vec{p_q}|) \tag{3}$$

Let us specialize to the decay:

$$\begin{array}{llll} \tilde{q}_L \longrightarrow & \tilde{\chi}_2^0 \quad q & & \\ & \lfloor\!\!\longrightarrow \tilde{\ell}_R^{\pm} \quad \ell^{\mp} & & \\ & & \lfloor\!\!\longrightarrow \tilde{\chi}_1^0 \quad \ell^{\pm} & \end{array}$$

By substituting into Equation 3 $p, q \longrightarrow \ell^+\ell^-$, $c \longrightarrow \tilde{\chi}_2^0$, $b \longrightarrow \tilde{\ell}_R$, $a \longrightarrow \tilde{\chi}_1^0$, and by treating the leptons as massless, we obtain:

$$(m_{\ell\ell}^{max})^2 = 4|\vec{p}||\vec{q}| = 4\sqrt{[0, m^2_{\tilde{\ell}_R}, m^2_{\tilde{\chi}_1^0}]}\sqrt{[0, m^2_{\tilde{\ell}_R}, m^2_{\tilde{\chi}_2^0}]}$$

By substituting the formula for $[x, y, z]$ we obtain the desired result:

$$(m_{\ell\ell}^{max})^2 = \frac{(m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\ell}_R})(m^2_{\tilde{\ell}_R} - m^2_{\tilde{\chi}_1^0})}{m^2_{\tilde{\ell}_R}}$$

# Invariant mass distribution

If the spin of the intermediate particle $b$ is zero, the decay distribution is:

$$\frac{dP}{d\cos\theta} = \frac{1}{2}$$

Where $\cos\theta$ is the angle between the two visible particles in the rest frame of $b$

If the two visible particles $p$, $q$ are massless:

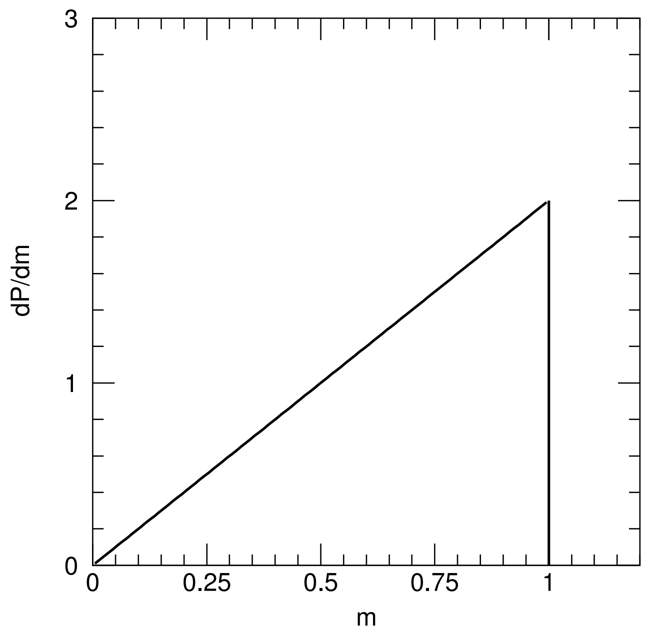
$$m_{pq}^2 = 2|\vec{p_p}||\vec{p_q}|(1-\cos\theta) \quad \text{and} \quad (m_{pq}^{max})^2 = 4|\vec{p_p}||\vec{p_q}|$$

We can thus define the dimensionless variable:

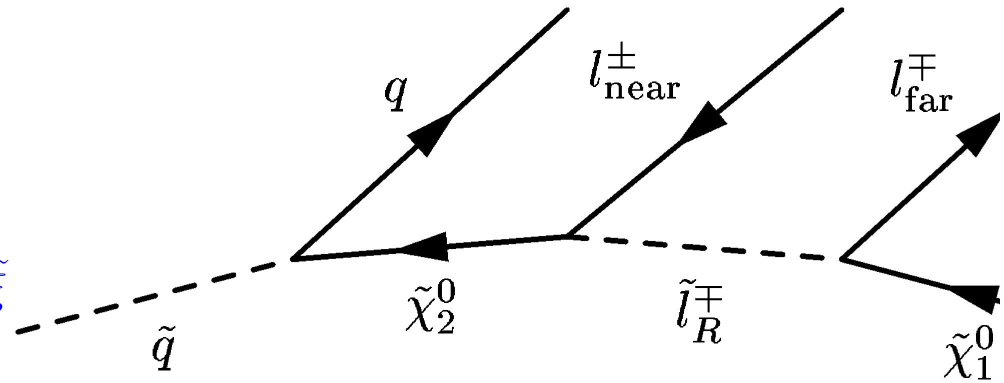
$$\hat{m}^2 = \frac{m_{pq}^2}{(m_{pq}^{max})^2} = \frac{1}{2}(1-\cos\theta) = \sin^2\frac{\theta}{2}$$

By a changement of variable:

$$\frac{dP}{d\hat{m}} = 2\hat{m}$$



## Complete results for $\tilde{q}_L \to \tilde{\ell}\ell$ decay chain: (Allanach et al. hep-ph/0007009)




$l^+l^-$ edge $\quad (m_{ll}^{\rm max})^2 = (\tilde{\xi}-\tilde{l})(\tilde{l}-\tilde{\chi})/\tilde{l}$

$l^+l^-q$ edge $\quad (m_{llq}^{\rm max})^2 = (\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi})/\tilde{\xi}$

$l^+l^-q$ thresh $\quad (m_{llq}^{\rm min})^2 = \begin{cases} [\ 2\tilde{l}(\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{\chi}) \\ +(\tilde{q}+\tilde{\xi})(\tilde{\xi}-\tilde{l})(\tilde{l}-\tilde{\chi}) \\ \quad -(\tilde{q}-\tilde{\xi})\sqrt{(\tilde{\xi}+\tilde{l})^2(\tilde{l}+\tilde{\chi})^2-16\tilde{\xi}\tilde{l}^2\tilde{\chi}}\ \ ] \\ /(4\tilde{l}\tilde{\xi}) \end{cases}$

$l^{\pm}_{\rm near}q$ edge $\quad (m_{l_{\rm near}q}^{\rm max})^2 = (\tilde{q}-\tilde{\xi})(\tilde{\xi}-\tilde{l})/\tilde{\xi}$

$l^{\pm}_{\rm far}q$ edge $\quad (m_{l_{\rm far}q}^{\rm max})^2 = (\tilde{q}-\tilde{\xi})(\tilde{l}-\tilde{\chi})/\tilde{l}$

With $\quad \tilde{\chi} = m^2_{\tilde{\chi}^0_1}, \qquad \tilde{l} = m^2_{\tilde{l}_R}, \qquad \tilde{\xi} = m^2_{\tilde{\chi}^0_2}, \qquad \tilde{q} = m^2_{\tilde{q}}$

All these formulas worked out in detail in the thesis of Chris Lester (Cambridge)

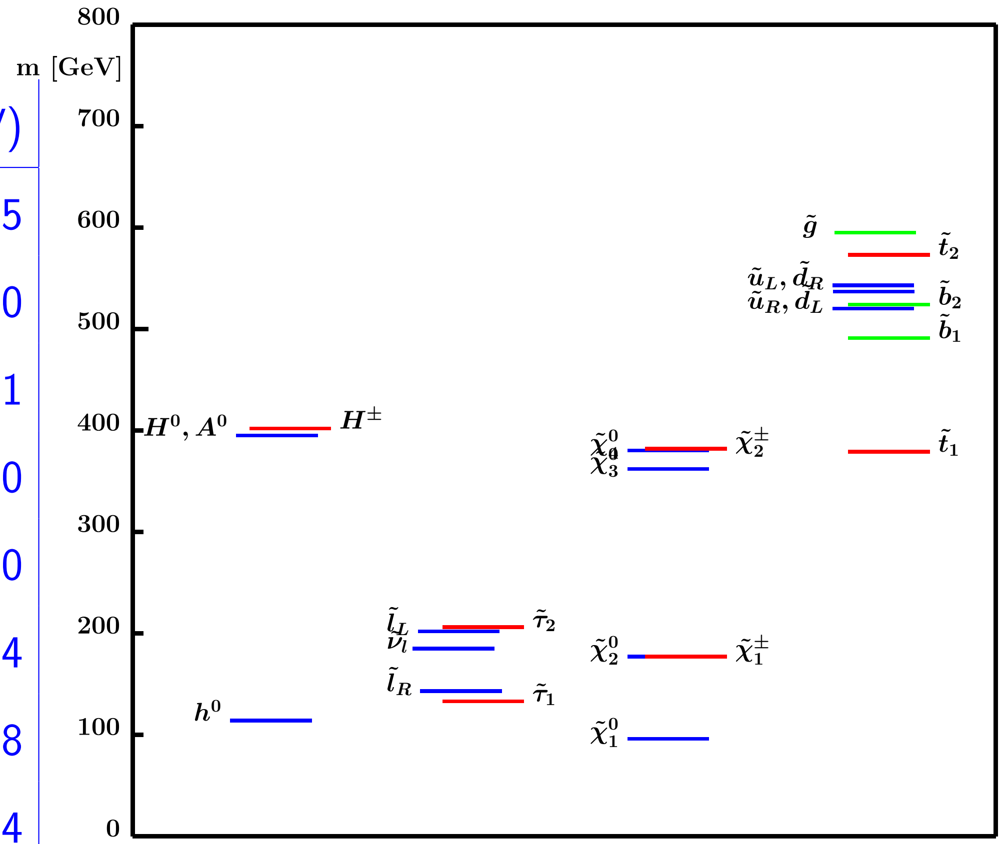
# Example: Point SPS1a

$m_0 = 100$ GeV, $m_{1/2} = 250$ GeV, $A = -100$ GeV, $\tan\beta = 10$, $\mu > 0$

Chosen friendly to a 1 TeV linear Collider, with appropriate Dark Matter density

## Mass spectrum

| Particle | Mass (GeV) | Particle | Mass (GeV) |
|---|---|---|---|
| $\tilde{g}$ | 595.5 | $\tilde{u}_R$ | 520.5 |
| $\tilde{u}_L$ | 537.3 | $\tilde{d}_L$ | 543.0 |
| $\tilde{b}_1$ | 491.9 | $\tilde{t}_1$ | 379.1 |
| $\tilde{e}_L$ | 202.1 | $\tilde{e}_R$ | 143.0 |
| $\tilde{\tau}_1$ | 133.4 | $\tilde{\tau}_2$ | 206.0 |
| $\tilde{\chi}^0_1$ | 96.5 | $\tilde{\chi}^\pm_1$ | 176.4 |
| $\tilde{\chi}^0_2$ | 176.8 | $\tilde{\chi}^0_4$ | 377.8 |
| $h$ | 114.0 | $A$ | 394.4 |



# Point SPS1a

Total cross-section: ~55 pb, $\sigma(\tilde{g}\tilde{g}) \sim 8$ pb, $\sigma(\tilde{q}\tilde{g}) \sim 30$ pb, $\sigma(\tilde{q}\tilde{q}) \sim 16$ pb

Branching Ratios:

| | | |
|---|---|---|
| BR($\tilde{g} \to \tilde{q}_L q$) ~25% | BR($\tilde{g} \to \tilde{q}_R q$) ~40% | BR($\tilde{g} \to \tilde{b}_1 b$) ~17% |
| BR($\tilde{q}_L \to \tilde{\chi}_2^0 q$) ~30% | BR($\tilde{q}_L \to \tilde{\chi}^{\pm} q'$) ~60% | BR($\tilde{q}_R \to \tilde{\chi}_1^0 q$) ~100% |
| BR($\tilde{\chi}_2^0 \to \tilde{\ell}_R \ell$)=12.6% | BR($\tilde{\chi}_2^0 \to \tilde{\tau}_1 \tau$)=87% | BR($\tilde{\chi}_1^{\pm} \to \tilde{\tau}_1 \nu_\tau$)$\sim 100\%$ |

- In most events end up with a $\tilde{q}\tilde{q}$ pair
- $m(\tilde{q}) - m(\tilde{\chi}^0_{2(1)}) > 250$ GeV $\Rightarrow$ each event 2 high $p_T$ jets from $\tilde{q} \to q\tilde{\chi}^0_{2(1)}(\tilde{\chi}_1^{\pm})$
- $m(\tilde{g}) - m(\tilde{q}) > 250 \sim 50$ GeV: two highest $p_T$ jets mostly from $\tilde{q}$ decay

# Promising chains

$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\ell}^{\pm} q \ell^{\mp} \to \tilde{\chi}_1^0 q \ell^{\pm} \ell^{\mp}$$

BR~4%: final state with two OS-SF leptons, 1 high $p_T$ het, $\not{E}_T$

Start with measuring $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\ell}_R}$, $m_{\tilde{\chi}_2^0}$, $m_{\tilde{q}_L}$ from this chain

$$\tilde{q}_L \to \tilde{\chi}_2^0 q \to \tilde{\tau}_1^{\pm} q \tau_2^{\mp} \to \tilde{\chi}_1^0 q \tau_1^{\pm} \tau_2^{\mp}$$

BR=72%. Final state with two $\tau$'s 1 high $p_T$ jet, $\not{E}_T$

Very high statistics, but experimental issue of $\tau$ identification

$\tau$ decays into neutrinos, less clear kinematics

$$\tilde{g} \to \tilde{b}_1 b \to \tilde{\chi}_2^0 bb \to \tilde{\ell} bb\ell \to \tilde{\chi}_1^0 bb\ell\ell$$

BR=0.8% of gluino production. Two OS-SF leptons, 1 hard $b$-jet, 1 soft $b$-jet

Very well defined chain, gives clean measurement of gluino and sbottom

Relies on $b$-tagging and $b$-jet energy measurement

$$pp \to \tilde{q}_R \tilde{q}_R \to qq\tilde{\chi}_1^0 \tilde{\chi}_1^0$$

BR: 100%. Very simple signature, 2 high $p_T$ jets, high $\not{E}_T$

Of course in real life we do not know which decay chains, will actually exist.

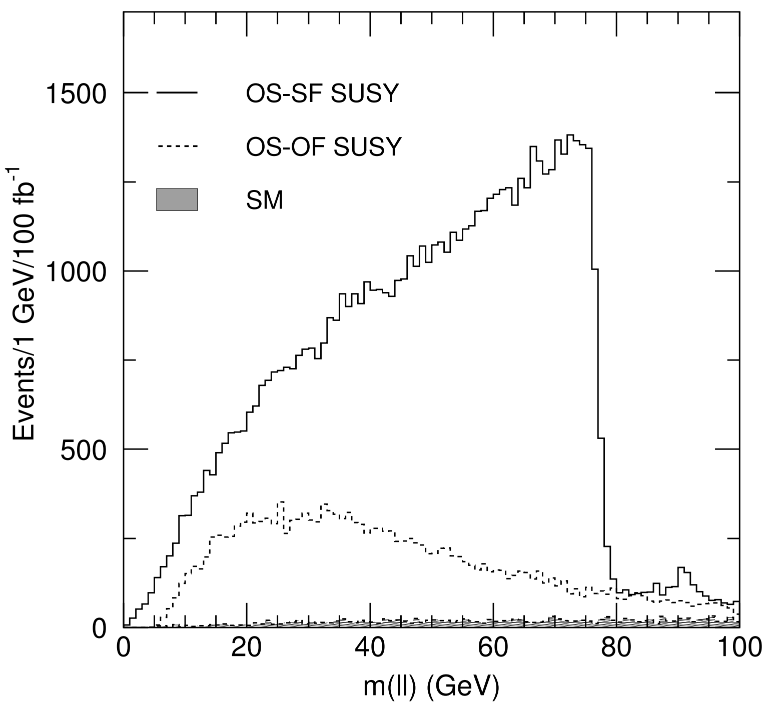
Extended to various sample models, exercise useful to identify topologies we may want to investigate once SUSY is discovered

Isolate SUSY signal by requiring:

- At least four jets: $p_{T,1} > 150$ GeV, $p_{T,2} > 100$ GeV, $p_{T,3} > 50$ GeV.
- $M_{\text{eff}} \equiv E_{T,\text{miss}} + p_{T,1} + p_{T,2} + p_{T,3} + p_{T,4} > 600$ GeV, $E_{T,\text{miss}} > \max(100\text{ GeV}, 0.2M_{\text{eff}})$
- Exactly two opposite-sign same-flavour $e, \mu$ (OSSF) with $p_T(l) > 20$ GeV and $p_T(l) > 10$ GeV

$W$ and $Z$ suppressed by jet requirements, and $\bar{t}t$ by hard kinematics

Build lepton-lepton invariant mass for selected events



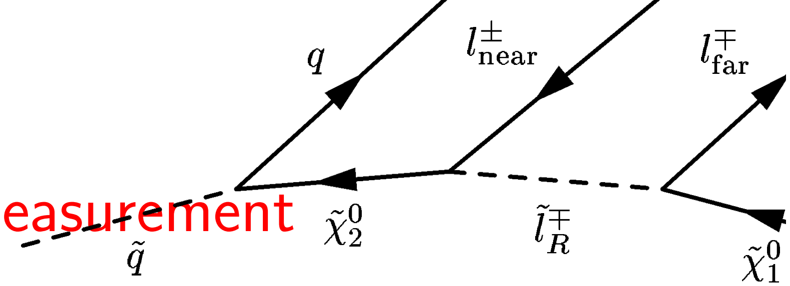

SM background almost negligible

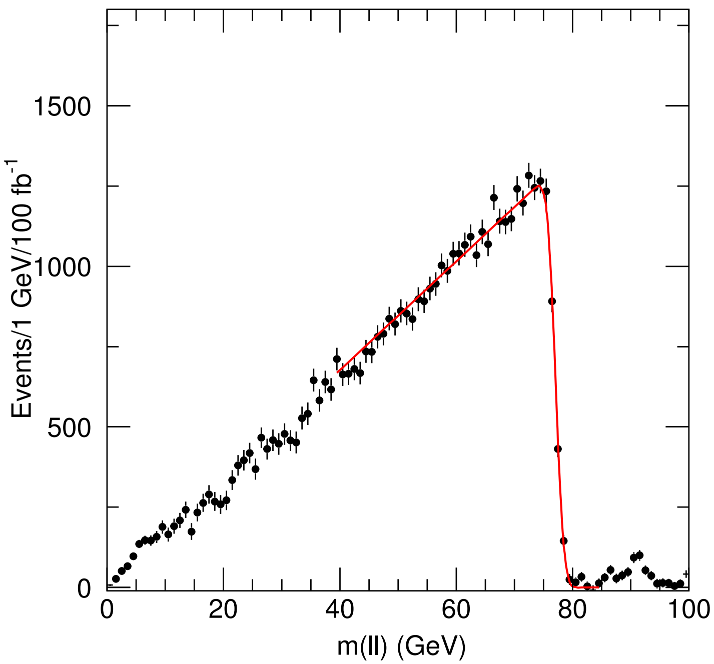
SUSY background mostly uncorrelated $\tilde{\chi}_1^{\pm}$ decays

Subtract SUSY and SM background using flavour correlation:

$$e^+e^- + \mu^+\mu^- - e^{\pm}\mu^{\mp}$$

# Lepton-lepton edge measurement




$m_{\ell^+\ell^-}$ after flavour subtraction

Fit to sharp edge shape smeared by gaussian resolution

For 100 fb$^{-1}$ statistical error on the fit comparable to 0.1$\%$ uncertainty on lepton energy scale

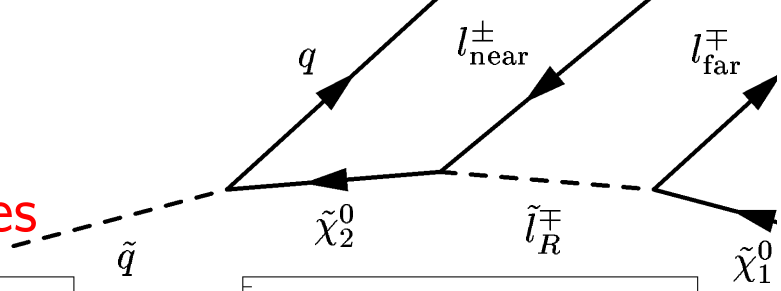
High precision measurement as for $W$ mass.

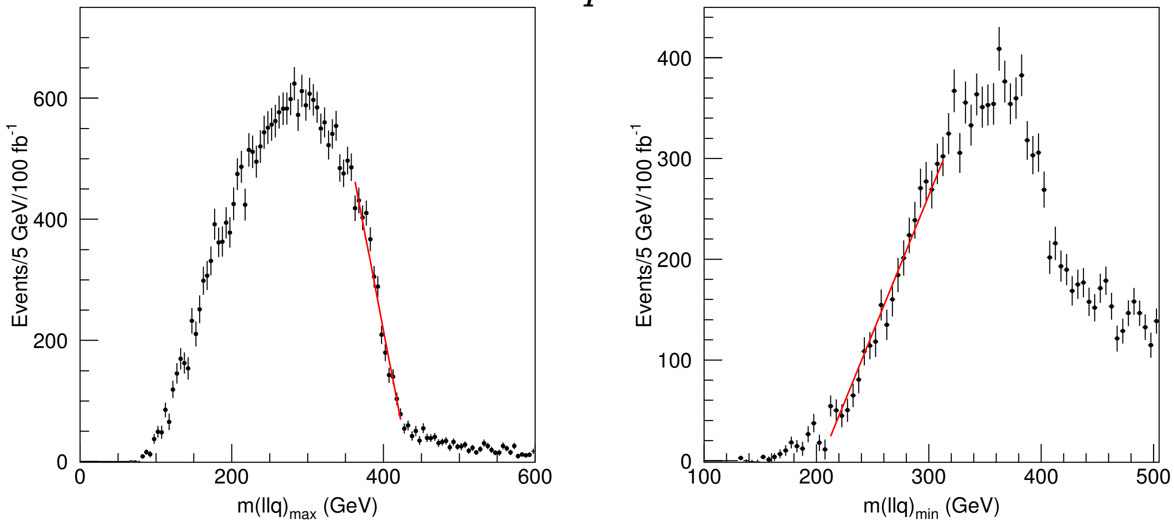
Final precision dominated by systematics of modelling $\tilde{\ell}$ production

Fit result (300 fb$^{-1}$):

$$m_{l^+l^-}^{max} = m_{\tilde{\chi}^0_2}\sqrt{1-\frac{m^2_{\tilde{\ell}_R}}{m^2_{\tilde{\chi}^0_2}}}\sqrt{1-\frac{m^2_{\tilde{\chi}^0_1}}{m^2_{\tilde{\ell}_R}}} = 77.077 \pm 0.03 \text{ (stat)} \pm 0.08 \text{ (E scale) GeV}$$

## Lepton-lepton-jet edges




Pick right jet in eventi: for SPS1a, jet from $\tilde{q}_L$ decay is one of two leading jets

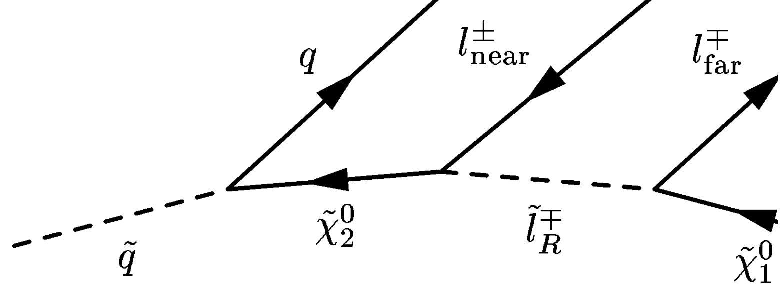
Plot min$(m_{\ell\ell j_1}, m_{\ell\ell j_2})$ (left), max$(m_{\ell\ell j_1}, m_{\ell\ell j_2})$ (right)

min$(m_{\ell\ell j_1}, m_{\ell\ell j_2})$ lower than $m^{max}_{llq}$, max$(m_{\ell\ell j_1}, m_{\ell\ell j_2})$ higher than $m^{min}_{llq}$

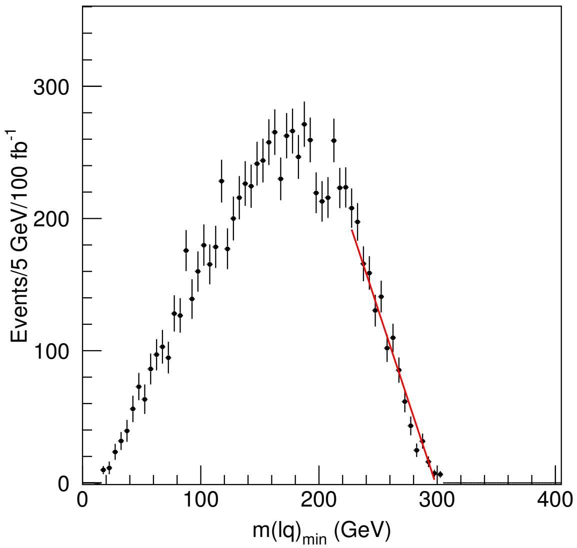
Distributions fall $\sim$ linearly to end (threshold) point.

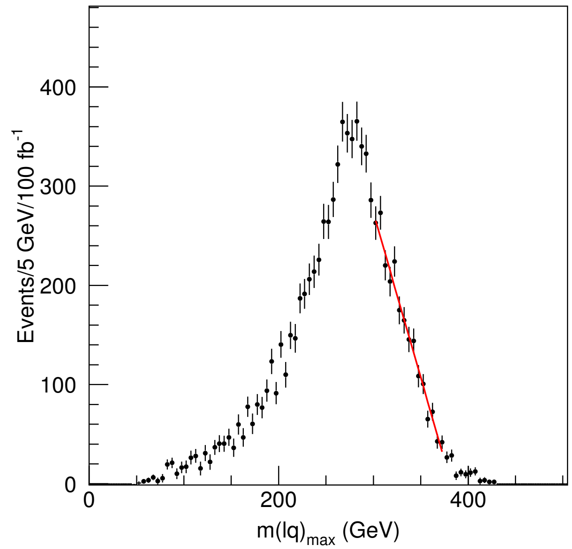
Statistical uncertainty from simple linear fit $\sim 1.5$ GeV for 300 fb$^{-1}$

Linear slope only approximation, need to fit to more complex shape. $\Rightarrow$ significant systematic uncertainty form modelling of experimental distortions




# Lepton-jet edges




Require $m_{\ell\ell}$ below edge, $m_{\ell\ell j} < 600$ GeV, choose jet giving minimum $m_{\ell\ell j}$

Define: $m_{lq(\text{high})} = \max\left(m_{l^+q}, m_{l^-q}\right)$ $\quad m_{lq(\text{low})} = \min\left(m_{l^+q}, m_{l^-q}\right)$

For 300 fb$^{-1}$ ~1 GeV statistical error, larger edge error from energy scale $0.5\%$

5 edge constraints: generate MC experiments as sets of edge measurements normal distributed according to estimated errors

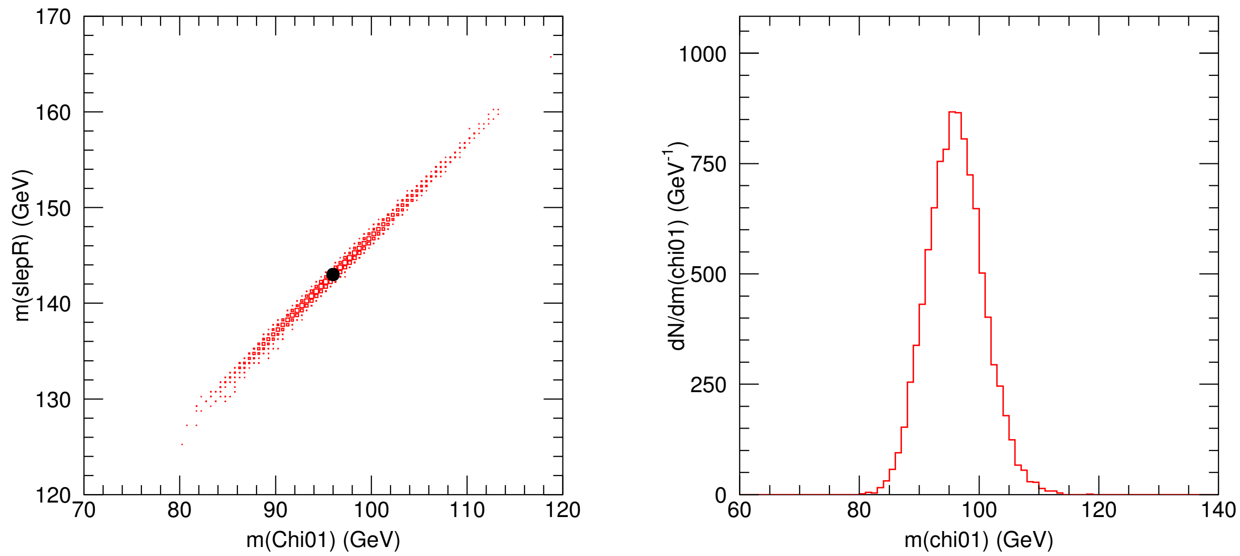
For each set solve numerically system of equations for sparticle masses.

# Sparticle mass results

Strong correlation, kinematic constraints of the form $(m_a^2 - m_b^2)(m_b^2 - m_c^2)/m_b^2$,

measure mass differences rather than absolute scale

Large impact of threshold measurement with different functional form




Probability distributions for reconstructed masses $\sim$ gaussian

$\sigma$ for $\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\ell}_R$ masses $\sim 5$ GeV , for $\tilde{q}_L$ mass $\sim 9$ GeV (300 fb$^{-1}$)

Mass differences measured to $\sim 250$ MeV Statistical and E-scale errors only

# Alternate approach: mass relation method

Limitations of method based on kinematic edges:

- Only events near end-point are used
- Need statistics to observe end-point
- Unknown systematics from shape of edge distribution

Alternate approach: start from chain of 4 two-body decays: e.g

$$\tilde{g} \to \tilde{q} q_2 \to \tilde{\chi}_2^0 q_1 q_2 \to \tilde{\ell} q_1 q_2 \ell_2 \to \tilde{\chi}_1^0 q_1 q_2 \ell_1 \ell_2 .$$

5 constraints from mass-shell conditions of 5 sparticles:

$$\begin{aligned} m^2_{\tilde{\chi}_1^0} &= p^2_{\tilde{\chi}_1^0}, \\ m^2_{\tilde{\ell}} &= (p_{\tilde{\chi}_1^0} + p_{\ell_1})^2, \\ m^2_{\tilde{\chi}_2^0} &= (p_{\tilde{\chi}_1^0} + p_{\ell_1} + p_{\ell_2})^2, \\ m^2_{\tilde{b}} &= (p_{\tilde{\chi}_1^0} + p_{\ell_1} + p_{\ell_2} + p_{b_1})^2, \\ m^2_{\tilde{g}} &= (p_{\tilde{\chi}_1^0} + p_{\ell_1} + p_{\ell_2} + p_{b_1} + p_{b_2})^2. \end{aligned} \tag{4}$$

9 Unknowns: 4-mom of $\tilde{\chi}_1^0$ (different event by event)+5 masses (common among events)

For each event solve the system by eliminating the $\tilde{\chi}_1^0$ 4-momentum

Solution is quadratic form in the space of sparticle masses:

$$f(m_{\tilde{g}}, m_{\tilde{q}}, m_{\tilde{\chi}_2^0}, m_{\tilde{\ell}_R}, m_{\tilde{\chi}_1^0}) = 0$$

Coefficients of quadratic form are functions of 4-momenta $q_1, q_2, \ell_1, \ell_2$

Intersection of 5 quadratic forms: point in 5-dim mass space

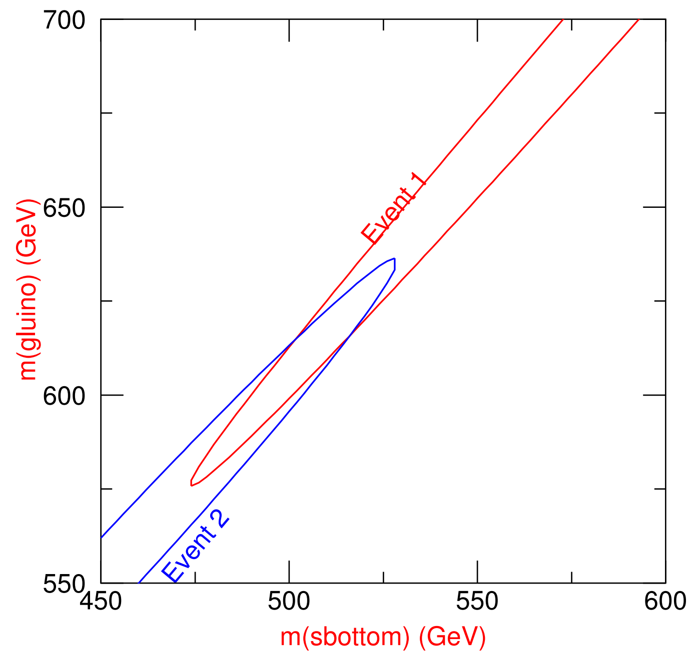
5 events enough in principle to measure masses of 5 sparticles

Consider simple case in which all the sparticle masses are known except 2: $m_{\tilde{g}}, m_{\tilde{q}}$

Quadratic form is a parabola in $(m_{\tilde{g}}, m_{\tilde{q}})$ plane

With two events have two parabolas

Intersection of two parabolas gives two points, measurement of masses with twofold ambiguity



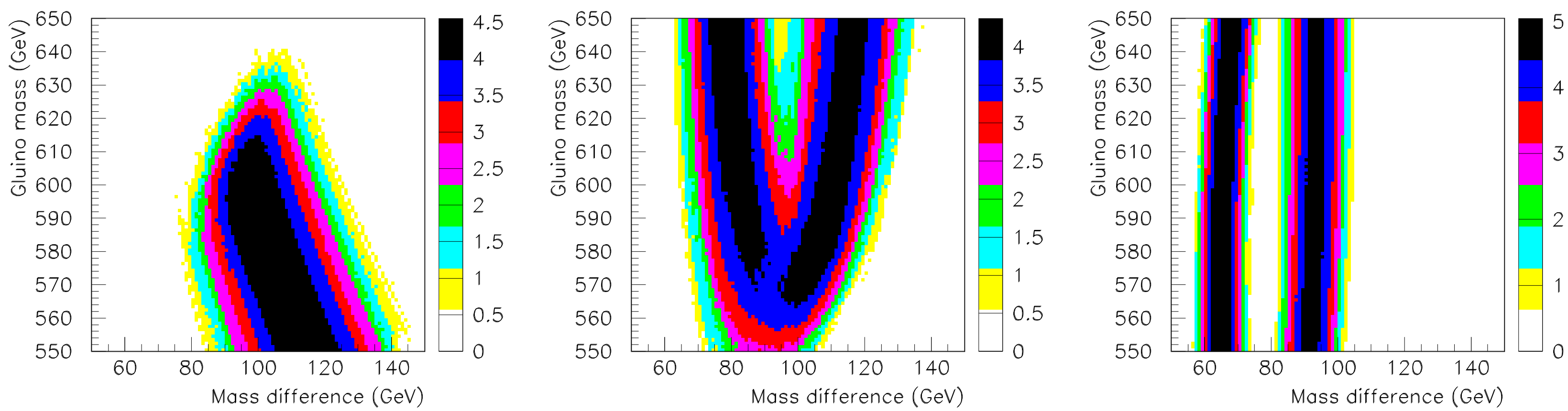
# Practical application

Apply technique to measurement of gluino and sbottom mass in SPS1a

Challenging situation as $\tilde{g}$ decays to two $\tilde{b}$: $\tilde{b}_1$, $\tilde{b}_2$ and $m_{\tilde{b}_2} - m_{\tilde{b}_1} \sim 35$ GeV

Take into account smearing of measurement of momenta of $b$-partons: represent each event not as parabola, but as a probability density function in the ($m_{\tilde{g}}$, $m_{\tilde{b}_1}$) plane: $\mathcal{L}(m_{\tilde{g}}, m_{\tilde{b}_1})$

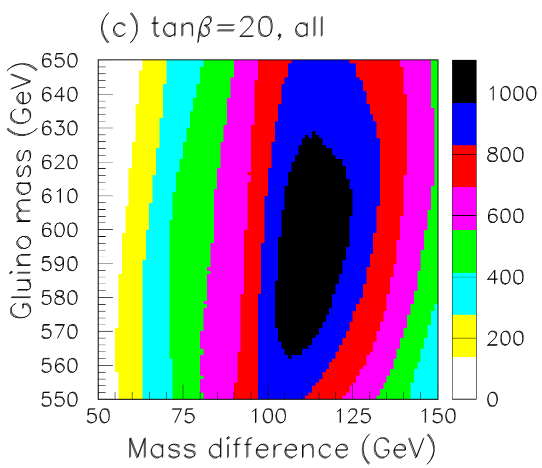
Main ingredient: knowledge of the response function of ATLAS detector to $b$ partons

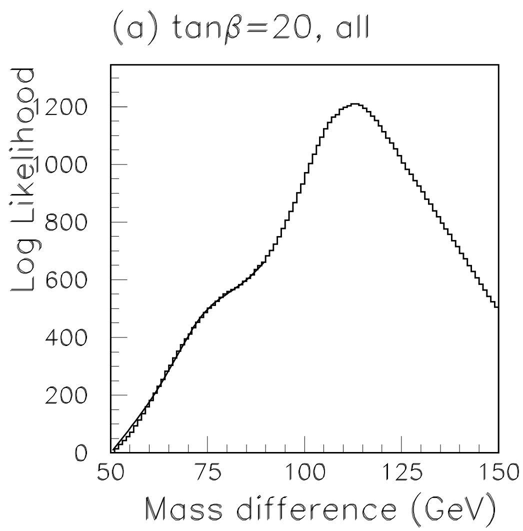



Examples of $\mathcal{L}$ functions in $(m_{\tilde{g}}, m_{\tilde{g}} - m_{\tilde{b}_1})$ plane for 3 random events

Combine likelihoods for all the events as:

$$\log \mathcal{L}_{\text{comb}}(m_{\tilde{g}}, m_{\tilde{b}}) \equiv \sum_{\text{events}} \log \mathcal{L}(m_{\tilde{g}}, m_{\tilde{b}})$$




Achieve excellent power in combined measurement of $m_{\tilde{g}}$ and $m_{\tilde{b}}$ even for low statistics $\tan\beta = 20$ case

Search for maximum probability rejects multiple solutions

Possibly a hint for the presence of shoulder from $\tilde{b}_2$ production. Need excellent understanding of detector response systematics to disentangle possible signal

# Interpretation of results

The measurements do not depend a priori on a special choice of the model

For instance, we can state that in the data appear the decays:

$$
\begin{array}{llll}
a \rightarrow b & q & & \\
& \hookrightarrow c & \ell^{\mp} & \\
& & \hookrightarrow d & \ell^{\pm}
\end{array}
$$

$$
\begin{array}{llll}
a \rightarrow b & q & & \\
& \hookrightarrow e & \tau\mp & \\
& & \hookrightarrow d & \tau^{\pm}
\end{array}
$$

Where we know the masses of $a$, $b$, $c$, $d$, $e$, and we might conjecture that $a$, $b$, $d$ appearing in both decays are the same having the same masses

So we have a mass hierarchy, some of the decays related these particles and, perhaps, the relative rates

Having decay chains help restricting the possibilities, if one imposes some conservations, e.g. charges or quantum numbers

Model dependence enters when we try to give a name to the particles, and match them to a template decay chain

Among the models proposed to solve the hierarchy problem, various options providing a full spectrum of new particles, with cascade decays:

- Universal extra-dimensions: first KK excitation of each of the SM fields
- Little Higgs with $T$ parity

Special feature of SUSY: if one identifies the heavy partners through their quantum numbers, the spins of all of them are wrong by $1/2$

Worth investigating if exploiting the identified chains one can obtain information on the sparticle spins

# Sparticle spins in squark decay chain

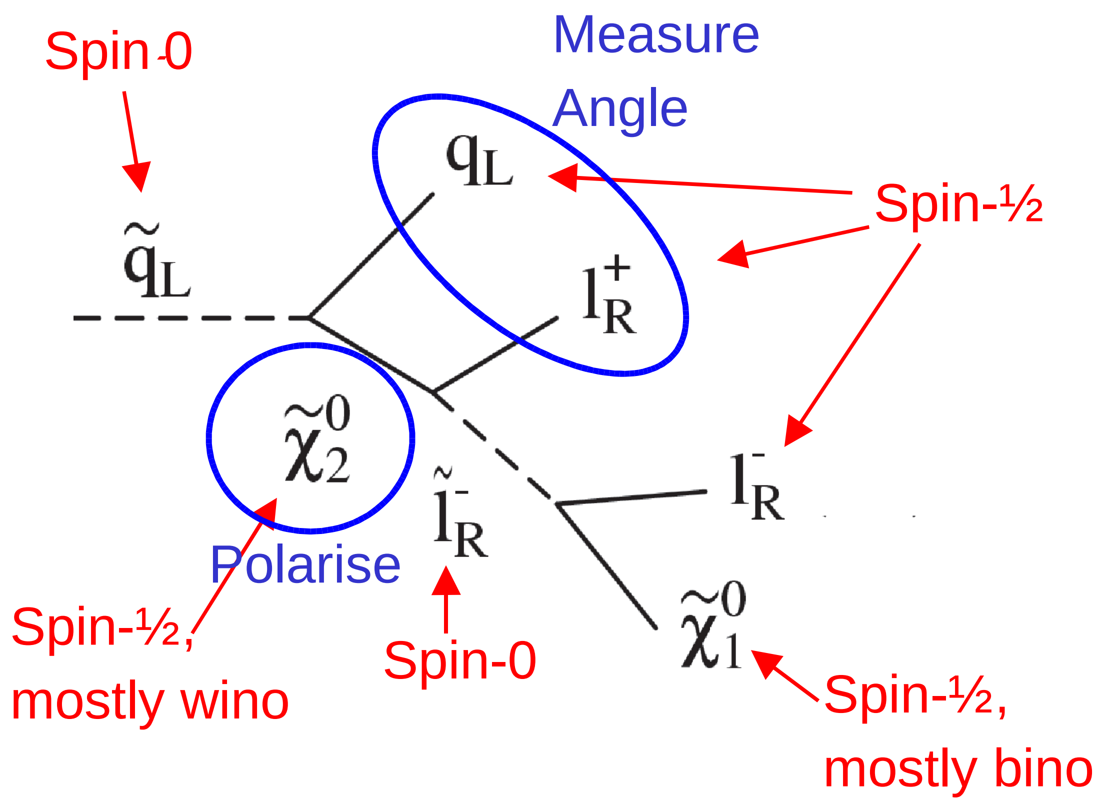
Technique proposed by A. Barr

Consider usual squark decay chain in SPS1a point

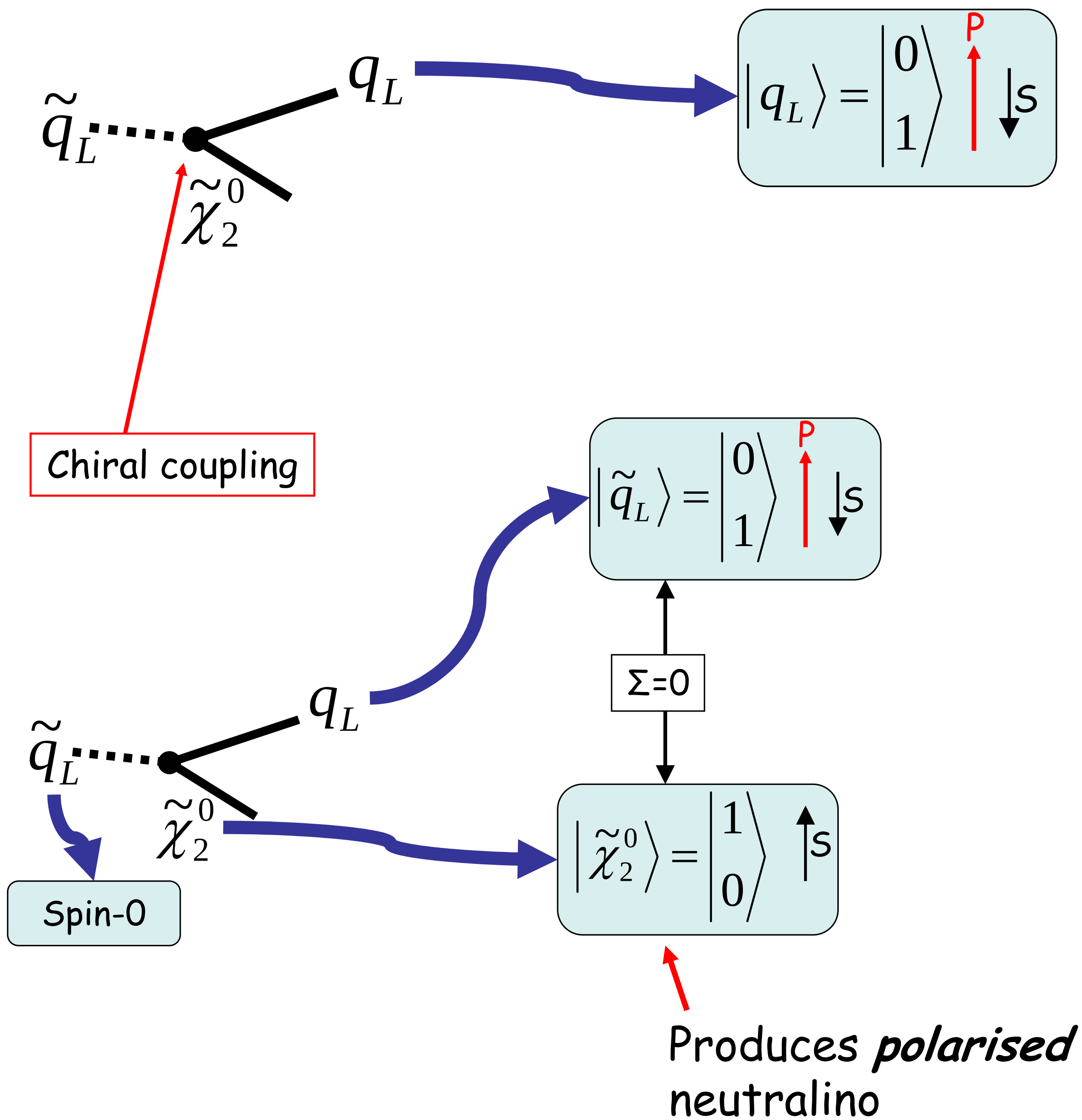
Three visible particles in final state: 1 jet, two leptons

Spin analyser is the angle between the quark and the lepton from $\tilde{\chi}_2^0$ decay

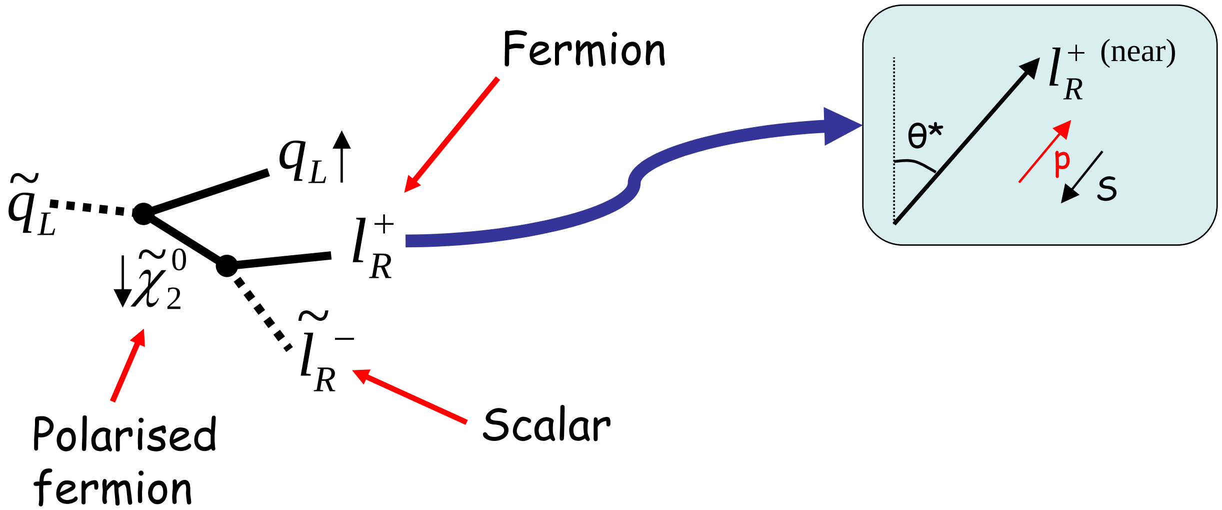
No dynamic information from angle between two leptons, as $\tilde{\ell}_R$ is spin zero

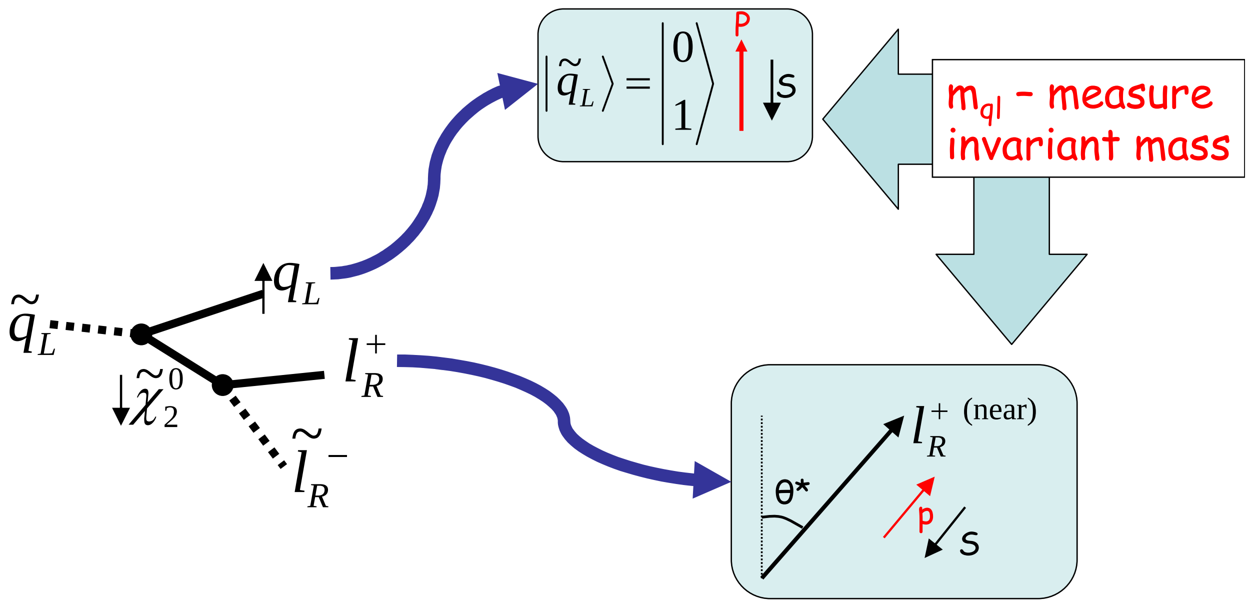


# Spin projection factors (1)

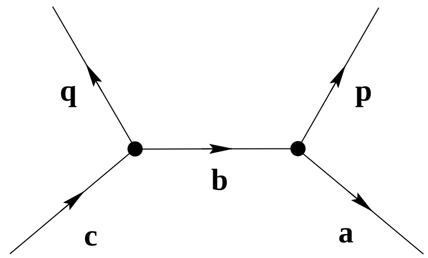


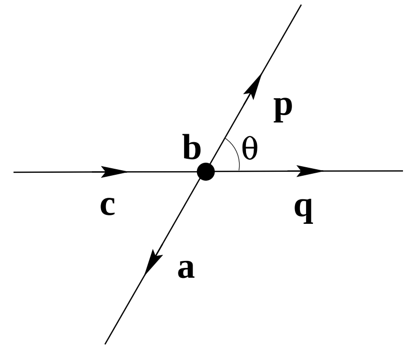
# Spin projection factors (2)

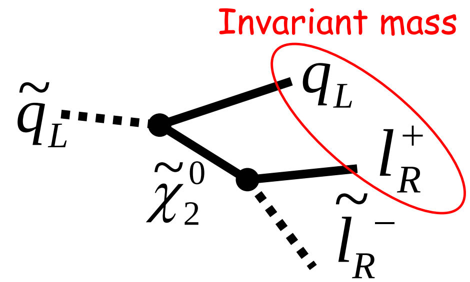


# Invariant mass distribution for visible particles




The angle $\theta$ between the two visible particles in rest frame of $b$ related to $m_{pq}$ as:

$$m_{pq}^2 = 2|\vec{p_p}||\vec{p_q}|(1-\cos\theta) \quad \text{and} \quad (m_{pq}^{max})^2 = 4|\vec{p_p}||\vec{p_q}|$$

for $p$, $q$ massless

We can thus define the dimensionless variable:

$$\hat{m}^2 = \frac{m_{pq}^2}{(m_{pq}^{max})^2} = \frac{1}{2}(1-\cos\theta) = \sin^2\frac{\theta}{2}$$

For intermediate particle with spin zero:

$$\frac{dP}{d\cos\theta} = \frac{1}{2} \quad \Rightarrow \frac{dP}{d\hat{m}} = 2\hat{m}$$

Spin 1/2: two cases:

- Lepton same helicity as quark:

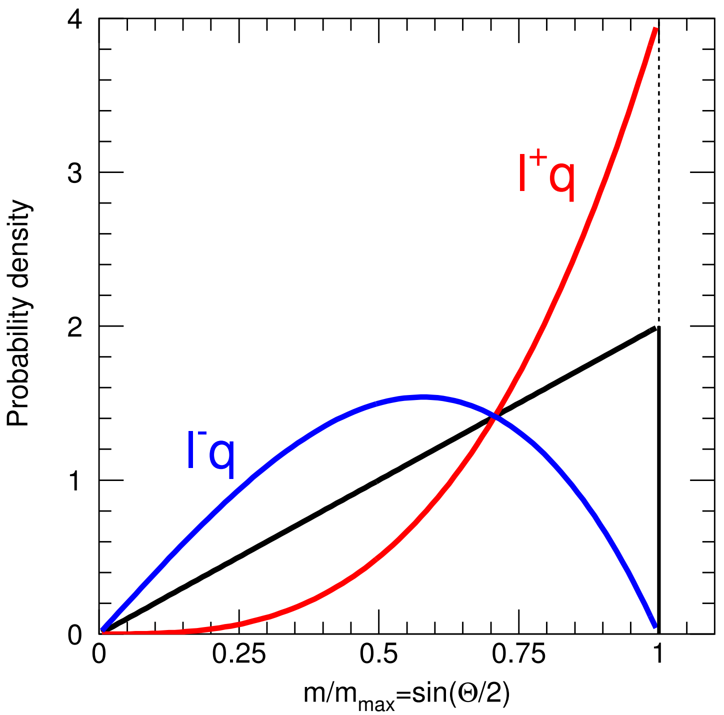
  $l^+q$, $l^-\bar{q}$ for $\tilde{q}_L$, $\tilde{\ell}_R$

  $$\frac{dP}{d\cos\theta} = \frac{1}{2}(1-\cos\theta) \quad \Rightarrow \frac{dP}{d\hat{m}} = 4\hat{m}^3$$

- Lepton opposite helicity to quark:

  $l^-q$, $l^+\bar{q}$ for $\tilde{q}_L$, $\tilde{\ell}_R$

  $$\frac{dP}{d\cos\theta} = \frac{1}{2}(1+\cos\theta) \quad \Rightarrow \frac{dP}{d\hat{m}} = 4\hat{m}(1-\hat{m}^2)$$



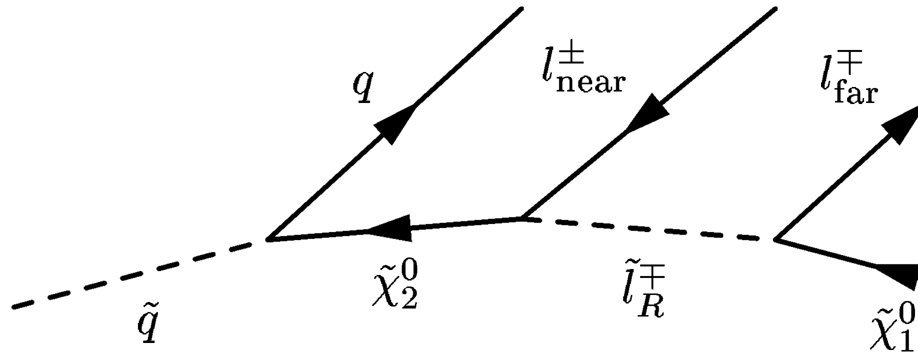

Difference in shape of $m_{\ell^+q}$ and $m_{\ell^-q}$: indication for $\tilde{\chi}_2^0$ spin $1/2$

# Experimental measurement

$\ell^{near}q$ shows nice charge asymmetry:

$\Rightarrow$ Excellent probe of $\tilde{\chi}_2^0$ spin

Experimental problems in measurement:

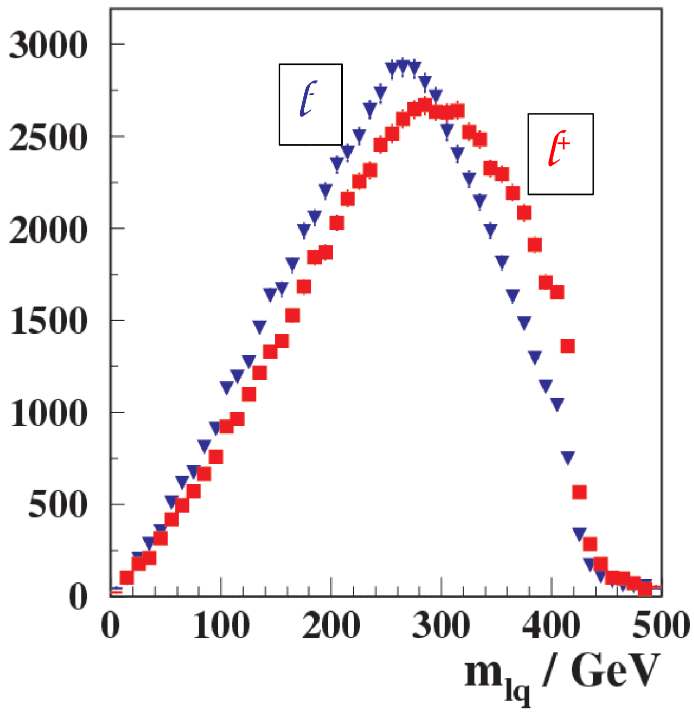


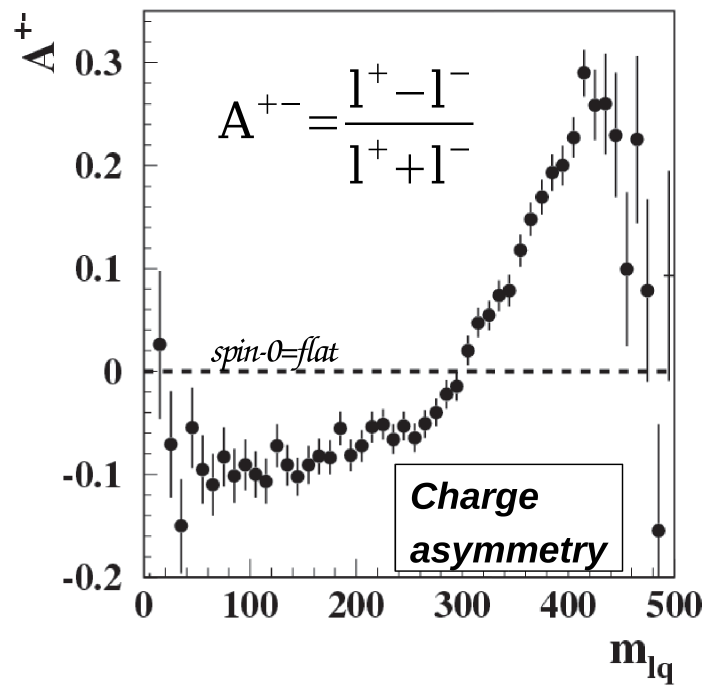

- $\ell^+ q = \ell^- \bar{q}$ and can't tell quark jet from anti-quark jet
  - $q$ ($\bar{q}$) in decay chain come from squark (antisquark)
  - $pp$ Collider $\longrightarrow$ PDF favour production of squarks over anti-squarks, excess of quarks in decay chain
- Two leptons in the event, a priori indistinguishable
  - We are only interested in the first (near) lepton (from neutralino decay)
  - Second (far) lepton comes from the decay of a spin-0 particle, $\tilde{\ell}$ : expect almost no distortion of asymmetry from invariant mass of jet with far lepton

# Parton level

We now build at parton level on simulated events the lepton-jet invariant mass, and take the bin-by-bin asymmetry of $\ell^+$ and $\ell^-$ distributions

Experimentally measurable: both $q$ and $\bar{q}$ in plot, both near and far lepton

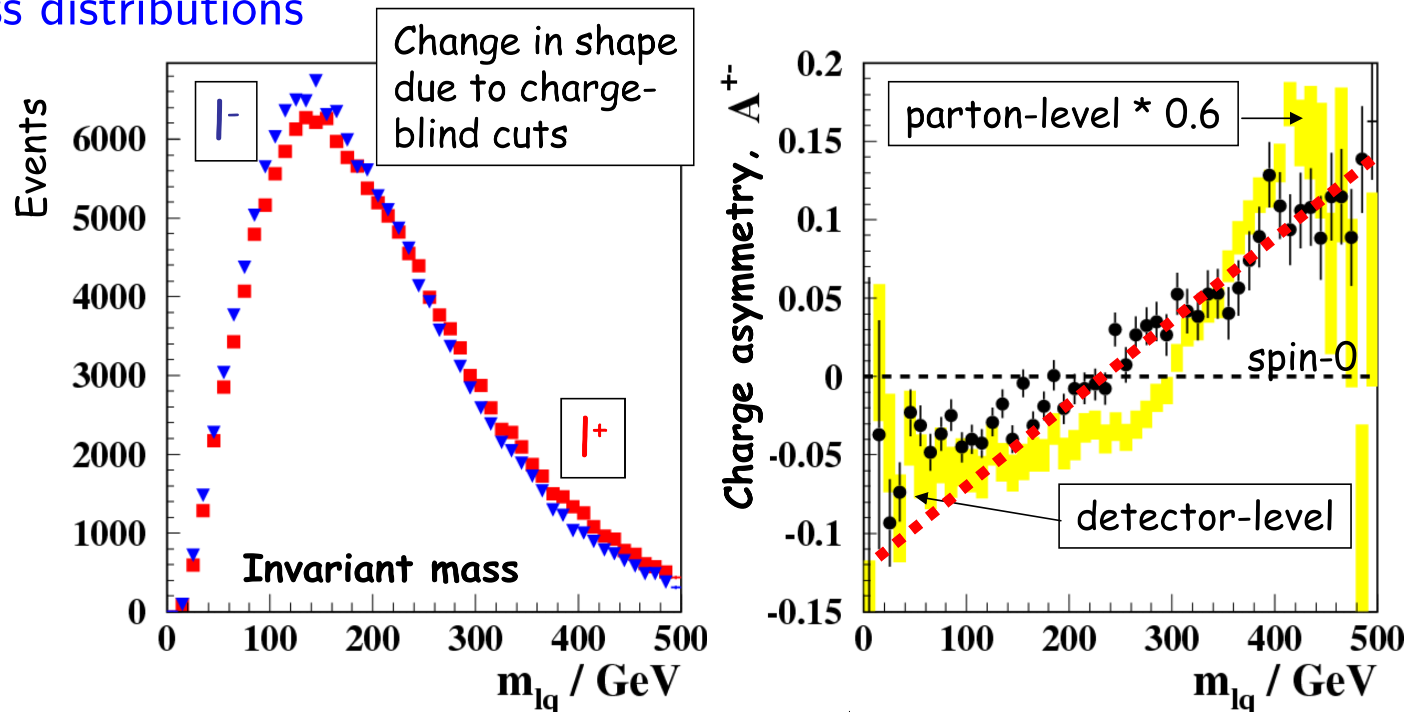



Shape shows clear deviation from what expected for spin-zero $\tilde{\chi}_2^0$

# Experimental asymmetry

From a sample of events in parametrised simulation build $\ell^+ j$ and $\ell^- j$ invariant mass distributions




Build bin-by bin charge asymmetry: $A = \frac{\ell^+ - \ell^-}{\ell^+ + \ell -}$

Strong dilution through detector smearing and background effects

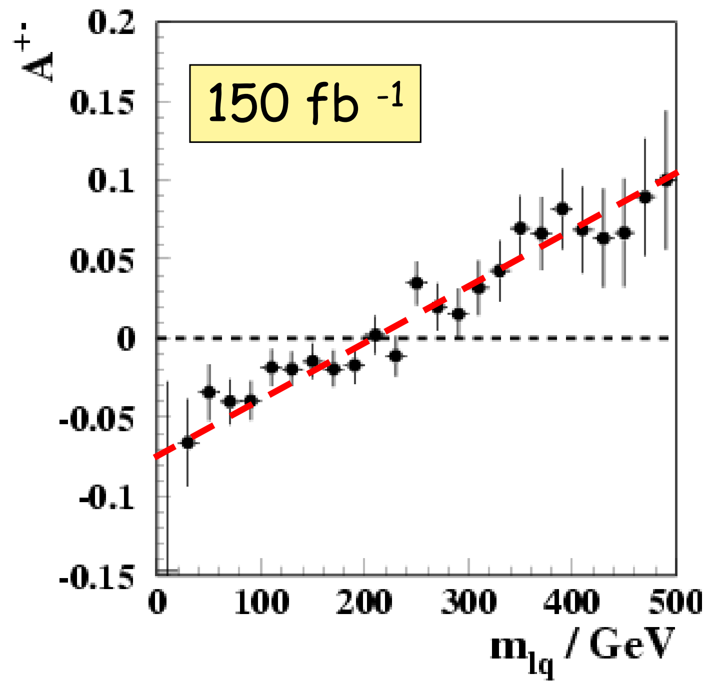
Effect still observable, with similar shape for asymmetry as at parton level

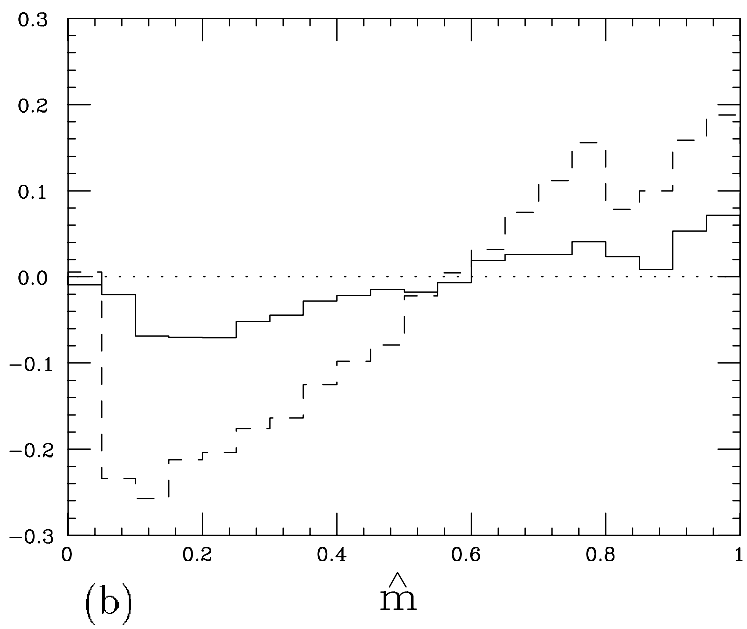
Checked that when spin correlations turned off no asymmetry observed

Required statistics:

In the considered model 150 fb$^{-1}$ sufficient

to observe the asymmetry effect




Comparison with spin 1 (Smillie, Webber)

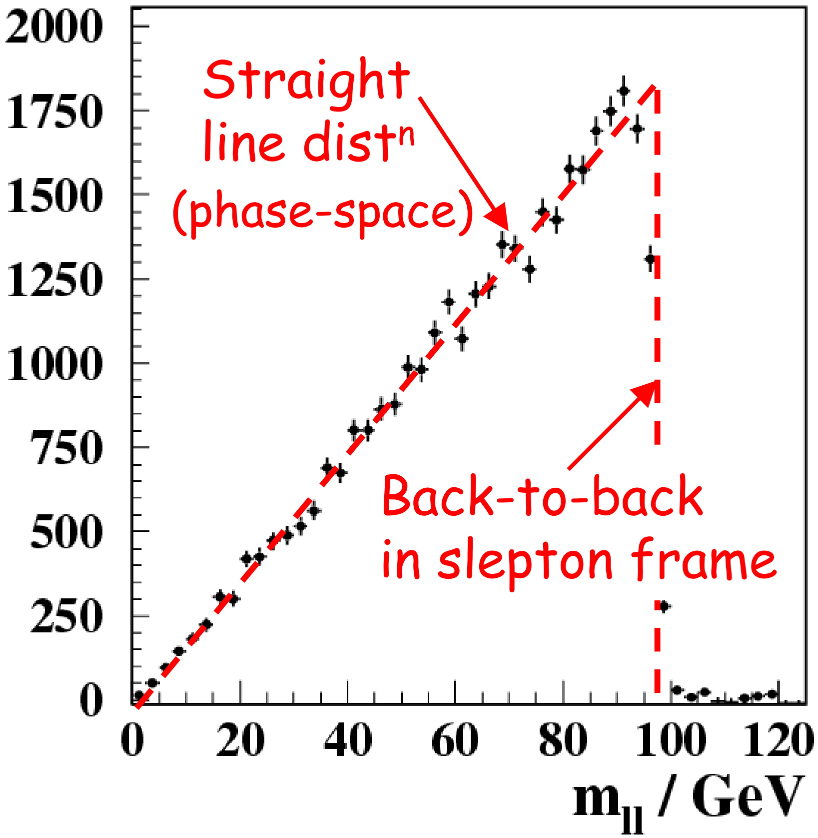
In alternate models, $Z$ partner has spin 1, need to discriminate spin $1/2$ from spin 1

Two spin assignments:

SM-like (solid lines), SUSY (dashed lines)

Excellent discrimination also against spin one case, but function of degeneracy of sparticle spectrum

# Further evidence: slepton spin




Dilepton invariant mass

- Right-handed slepton
- $\ell^+$ and $\ell^-$ are right-handed
- might expect pronounced spin effects
- none because slepton is scalar

Scalar particle carrying lepton number

# Next step: go for soft SUSY breaking parameters

Assume we measure masses and we see a spin/helicity pattern such as:

$$a \rightarrow b \quad q \qquad \text{spin(b)} = 1/2 \quad \text{from asymmetry plot}$$
$$\hookrightarrow c \quad \ell^{\mp} \qquad \text{spin(c)} = 0 \quad \text{from triangular shape of m}(\ell\ell) \text{ plot}$$
$$\hookrightarrow d \quad \ell^{\pm}$$

Helicity of coupling of $a$ is opposite to the one of $c$ (slope of asymmetry plot)

$\Rightarrow$ matches SUSY assignment: $a = \tilde{q}_L$, $b = \tilde{\chi}^0_2$, $c = \tilde{\ell}_R$, $d = \tilde{\chi}^0_1$

From measured neutralino/chargino masses constrain gaugino mixing matrix: weak-scale parameters

$M_1$, $M_2$, $\mu$, $\tan\beta$

For info on $\tan\beta$, have to use measurements in higgs sector

Typically not enough info to fully fix matrix, multiple ($M_1$, $M_2$, $\mu$) solutions

For each solution can predict $BR$ of gaugino decays

Use relative rates of identified decay chains to discriminate solutions: experimentally challenging

Complicated constraints, need global fit programs: SFitter, Fittino or Markov chain

multi-dimensional parameter scans

# Usages of measured soft SUSY breaking parameters

- Constrain cosmology-related observables. Examples:
  - Neutralino relic density
  - Cross-section for neutralino direct detection
- Constrain low-energy observables. Examples:
  - $BR(B \to \mu\mu)$
  - $BR(B \to X_s\gamma)$
  - $g_\mu$-2
- Constrain SUSY breaking from pattern of soft parameters
  - Compare observed pattern to given breaking models: mSUGRA, GMSB, ...
  - Backward evolution of soft parameters

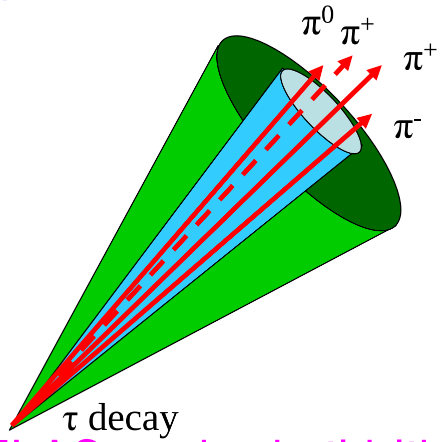
Ambitious program, work in progress to develop the tools to carry it out

A surprisingly large part of it can be carried out with LHC data, and we are still learning how to use LHC measurements, but data from ILC needed to complete it

Backup

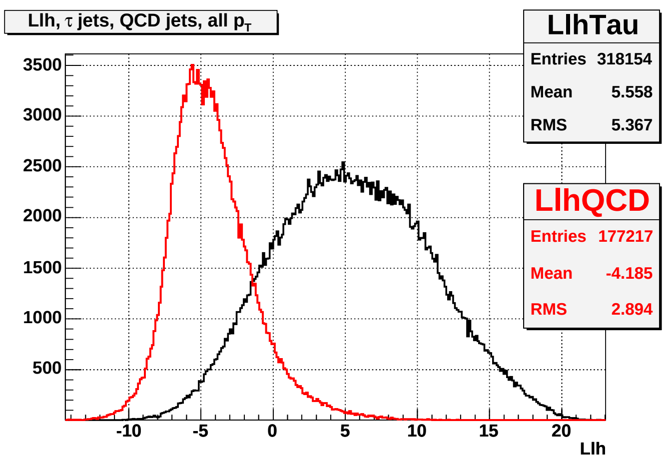
# Identification of $\tau$ hadronic decays

Exploit difference between hadronic decays of $\tau$'s and QCD jets:

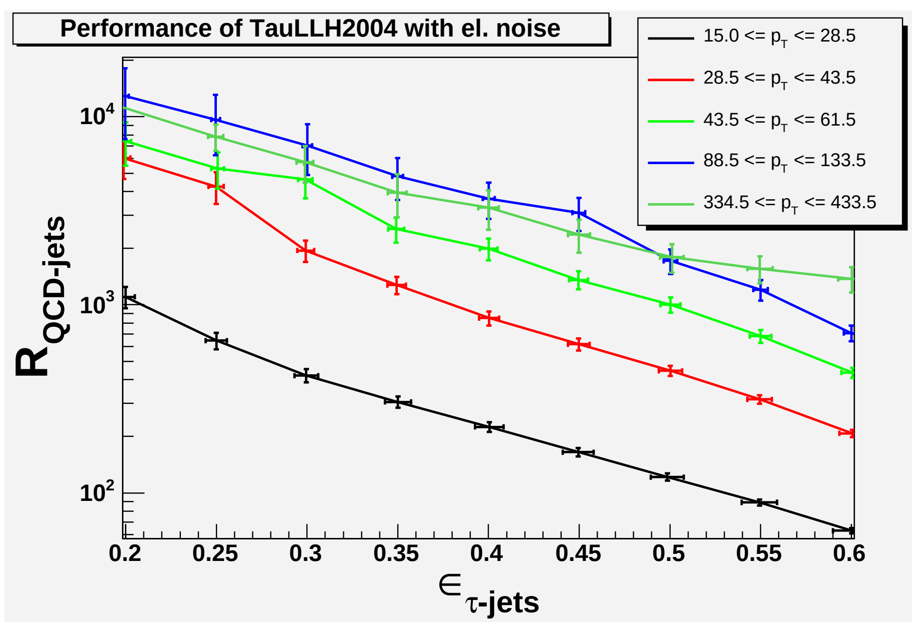



- Low track multiplicity ($1 < N_{tr} < 3$), charge
- Narrow jet in calo (Radius in EM calo, Number of strips in presampler)
- Impact parameter

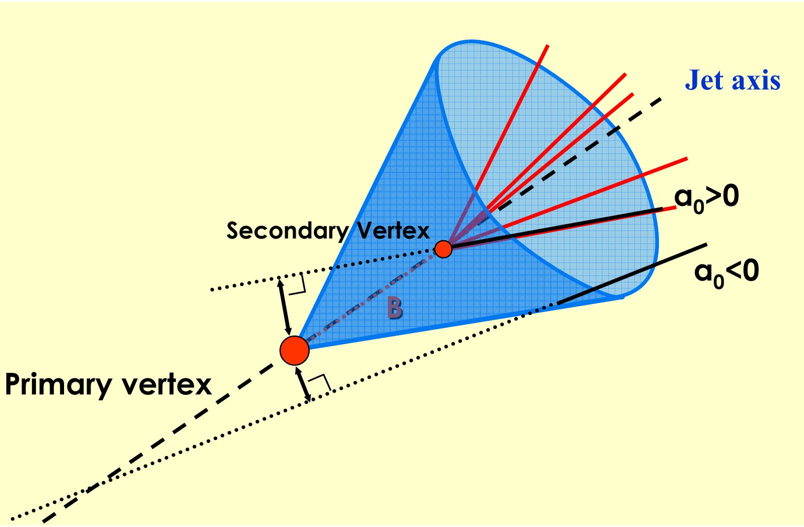
ATLAS study: build likelihood function in bins of jet $P_T$ ($15 < P_T < 600$ GeV)




ATLAS preliminary



# B-tagging

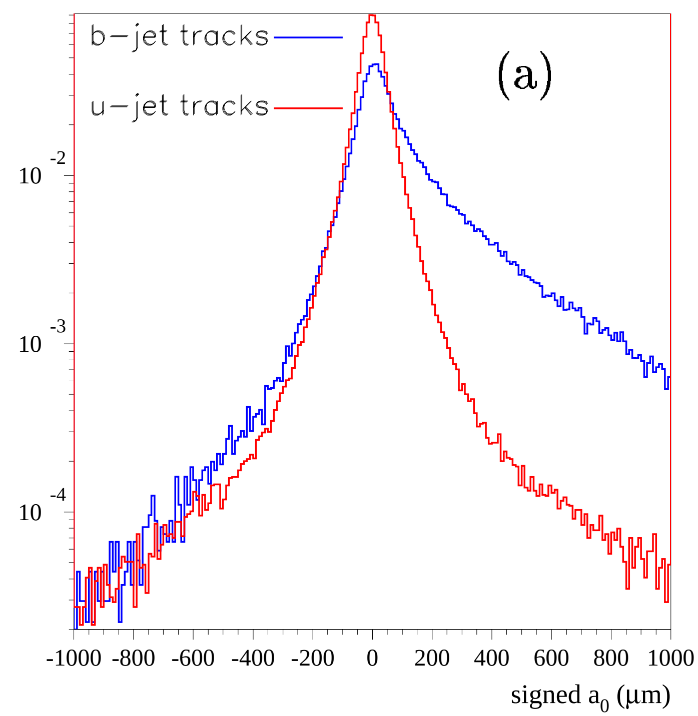



b-hadrons decay a a few mm away from interaction vertex

Measure decay path of b-hadrons through impact parameter: minimum distance from primary vertex

Distribution of impact parameter symmetric for tracks from fragmentation of light quarks

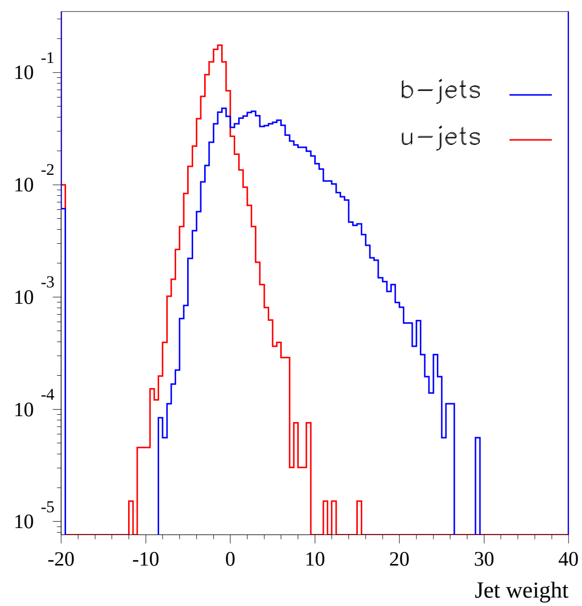
Significant enhancement of positive impact parameters for tracks from $b$-hadron decays

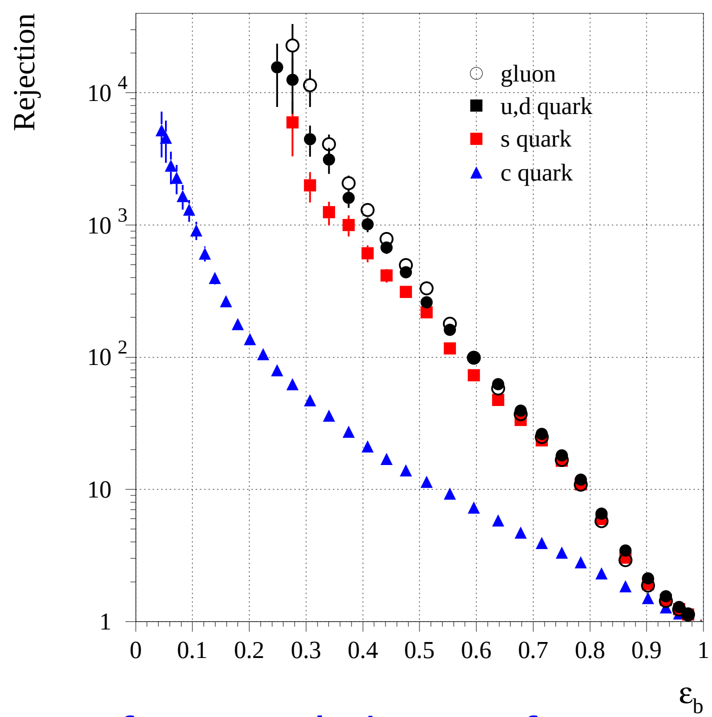


# B-tagging (cont)

For a jet, build likelihood function from the impact parameter of the tracks associated to it

ATLAS: Study samples of fully simulated $WH$, $ttH$, $\bar{t}t$ events




ATLAS TDR: rejection factor of 100 on light jets for $\epsilon_b = 60\%$