Mass and Spin at the LHC

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Press Release

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CERN announces start-up date for LHC

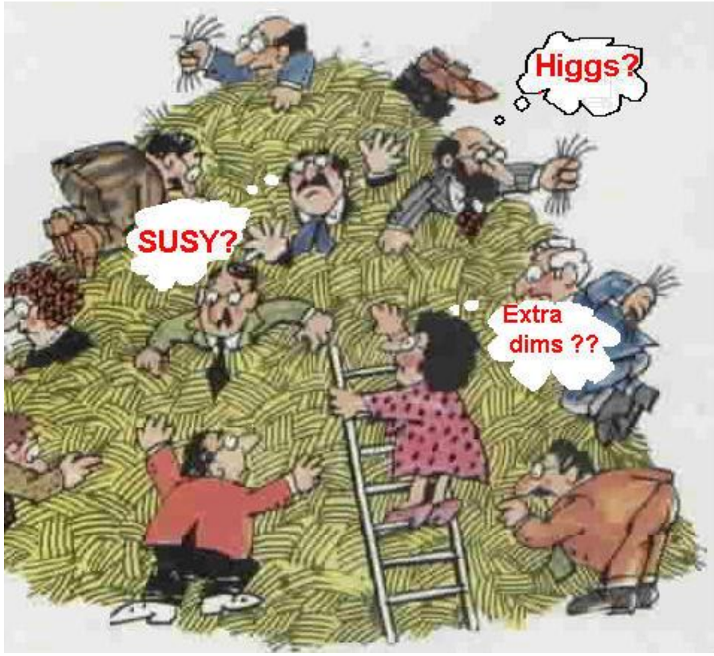
Geneva, 7 August 2008,
CERN has today announced that the first attempt to circulatea beam in the Large Hadron Collider (LHC) will be made on 10 September. This news comes as the cool down phase of commissioning CERN's new particle accelerator reaches a successful conclusion. Television coverage of the start-up will be made available through Eurovision.

The CERN Control Center,
from where the LHC be operated

We are entering exciting period in particle physics.

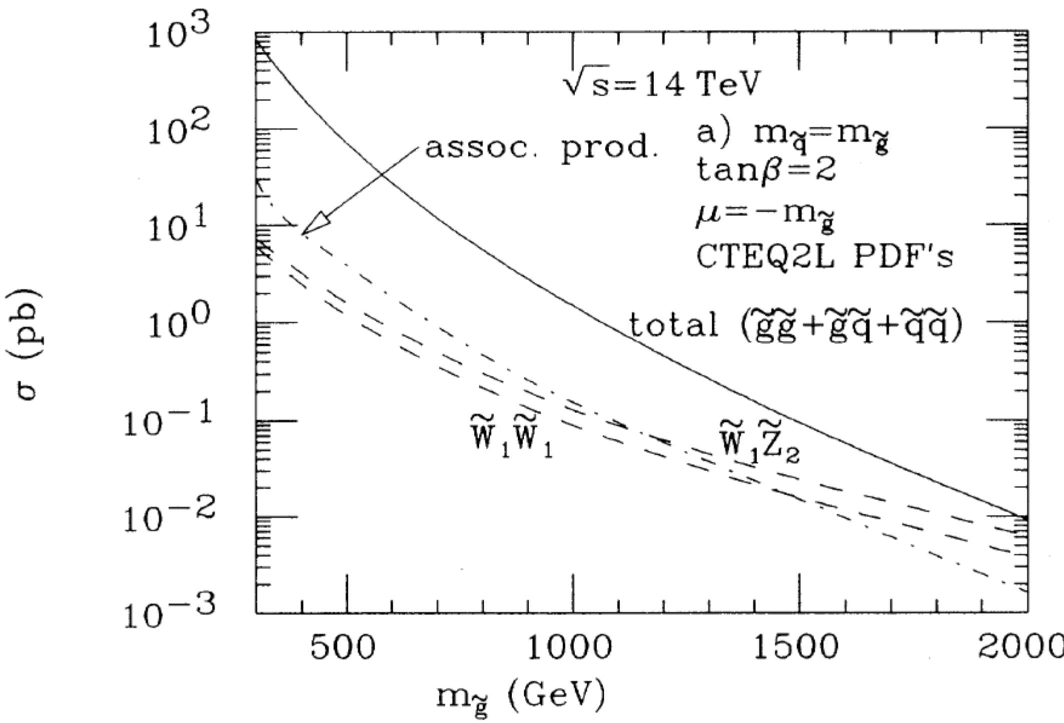
The LHC is about to explore for the first time
the TeV energy scale.

The origin of EWSB ?
The nature of dark matter ?
Supersymmetry ?
Extra dimensions ?



General features for SUSY at the LHC

- SUSY production is dominated by gluinos and squarks, unless they are too heavy



(Baer etal. 1995)

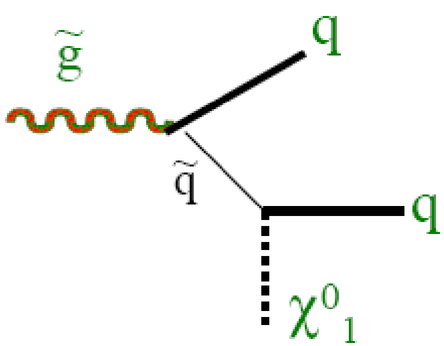
Squark and gluino production rates

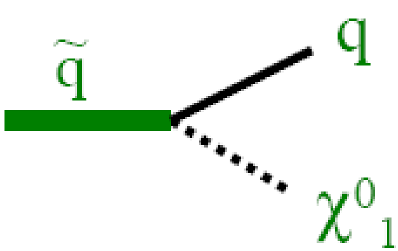
−determined by strong interaction, and the squark and gluino masses,

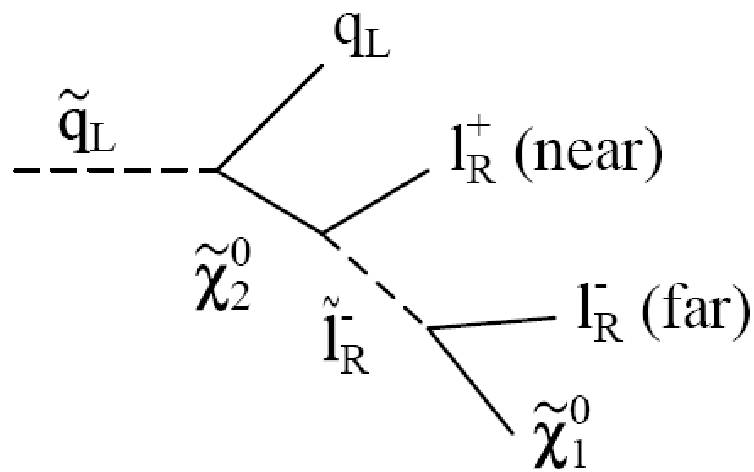
−do not depend on the details of model

~50 pb for m_gluino~500 GeV
~ 1 pb for m_gluino~1000 GeV

- The gluinos and squarks cascade down, generally in several steps, to the final states including multi-jets (and/or leptons) and two invisible LSPs







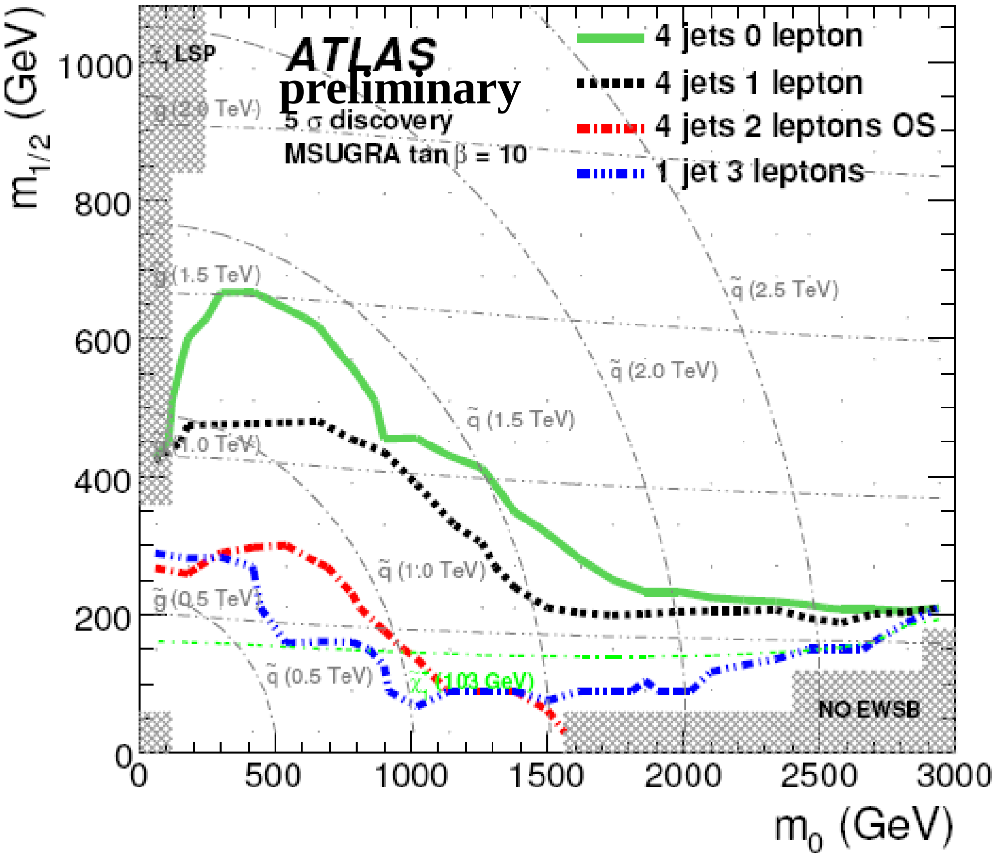
Characteristic signals of SUSY with R_p

- Invisible LSPs
  - → Large Missing Transverse Energy
- Decays of squarks and gluinos
  - → Large multiplicity of hadronic jets

and/or

- Decays of sleptons and gauginos
  - → Isolated leptons

Discovery potential



5σ evidence after 1 fb^{-1} (including systematics) expected if squarks lighter than 1300 GeV

0-lepton and 1-lepton best modes for mSUGRA

No attempt to combine channels yet

(Taken from T.Lari's talk in LHC focus week at IPMU)

Discovery of Supersymmetry

↓

Mass measurements

↓

Measurements of spin, couplings

Mass measurement

The Mass measurement is Not an easy task at the LHC !

- Final state momentum in beam direction is unknown a priori, due to our ignorance of initial partonic center of mass frame

- SUSY events always contain two invisible LSPs

→ No masses can be reconstructed directly

- Several approaches (and variants) of mass measurements proposed

  - **Invariant mass Edge method**

    Hinchliffe, Paige, Shapiro, Soderqvist, Yao ;
    Allanach, Lester, Parker, Webber

  - **Mass relation method**

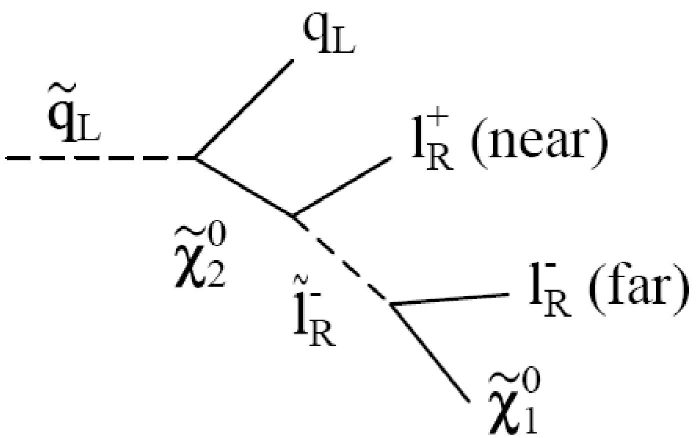
    Kawagoe, Nojiri, Polesello ;
    Cheng, Gunion, Han, Marandellea, McElrath

  - **Transverse mass (M_{T2}) kink method**

    Cho, Choi, YGK, Park ;
    Barr, Lester, Gripaios ;
    Ross, Serna;
    Nojiri, Shimizu, Okada, Kawagoe

Invariant mass edge method

Hinchliffe, Paige, etal. (1997)



- Basic idea

  → Identify a particular long decay chain and measure kinematic endpoints of various invariant mass distributions with visible particles

  → The endpoints are given by functions of SUSY particle masses

If a long enough decay chain is identified,
It would be possible to measure sparticle masses in a model independent way

$$(m_{ll}^2)^{\rm edge} = \frac{(m_{\tilde\chi_2^0}^2 - m_{\tilde l_R}^2)(m_{\tilde l_R}^2 - m_{\tilde\chi_1^0}^2)}{m_{\tilde l_R}^2},$$

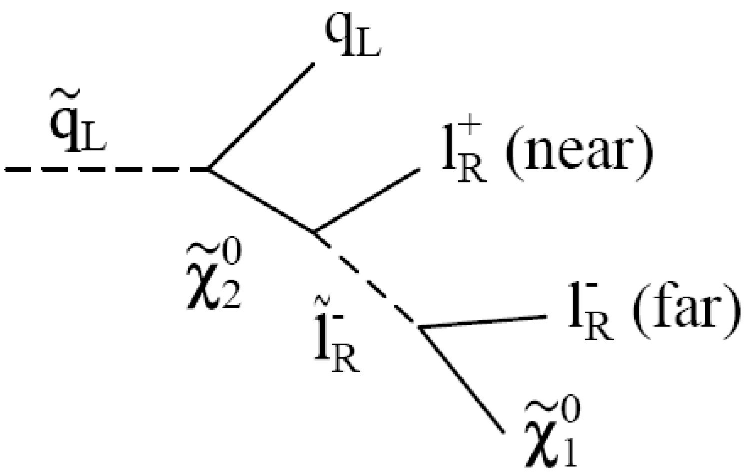
$$(m_{qll}^2)^{\rm edge} = \frac{(m_{\tilde q_L}^2 - m_{\tilde\chi_2^0}^2)(m_{\tilde\chi_2^0}^2 - m_{\tilde\chi_1^0}^2)}{m_{\tilde\chi_2^0}^2},$$

$$(m_{ql}^2)^{\rm edge}_{\rm min} = \frac{(m_{\tilde q_L}^2 - m_{\tilde\chi_2^0}^2)(m_{\tilde\chi_2^0}^2 - m_{\tilde l_R}^2)}{m_{\tilde\chi_2^0}^2},$$

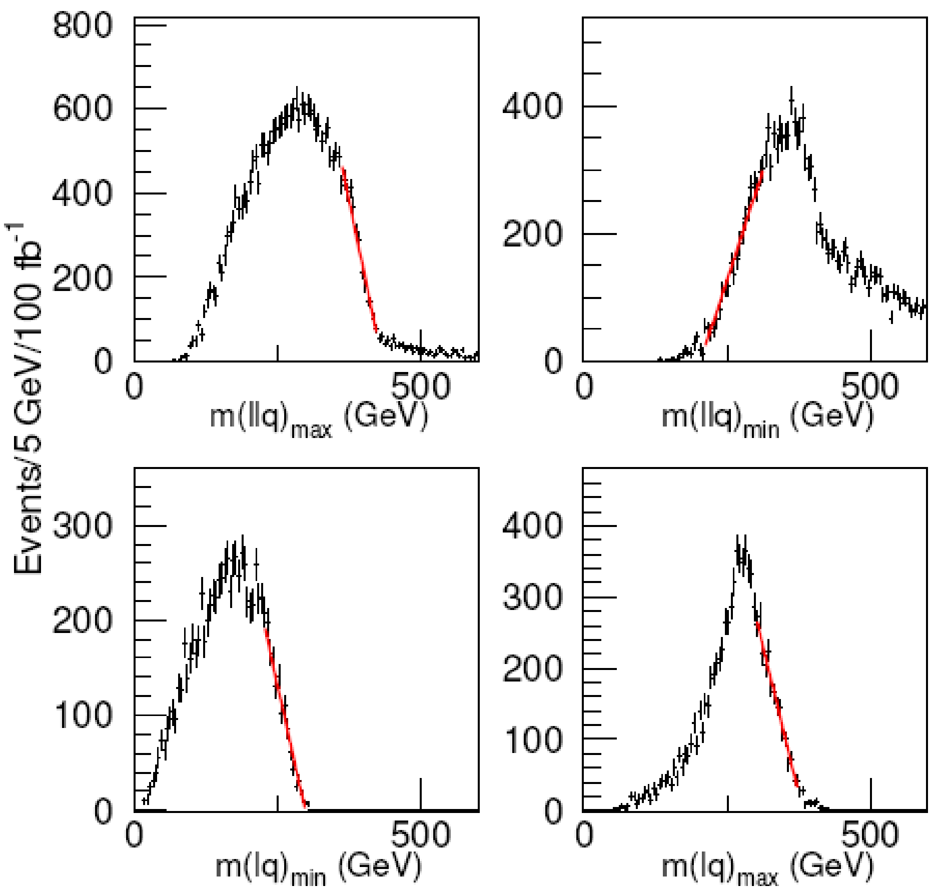
$$(m_{ql}^2)^{\rm edge}_{\rm max} = \frac{(m_{\tilde q_L}^2 - m_{\tilde\chi_2^0}^2)(m_{\tilde l_R}^2 - m_{\tilde\chi_1^0}^2)}{m_{\tilde l_R}^2},$$

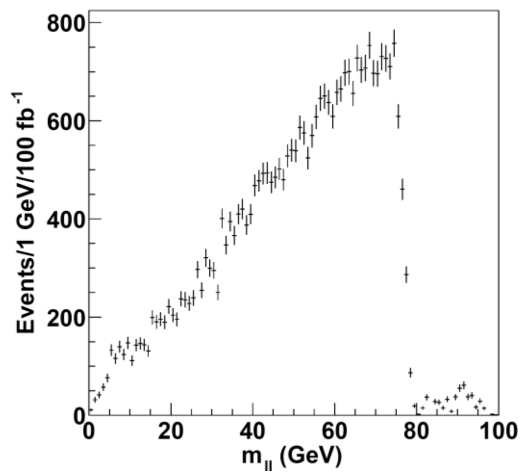
$$\begin{aligned}(m_{qll}^2)^{\rm thres} = \Big[&(m_{\tilde q_L}^2 + m_{\tilde\chi_2^0}^2)(m_{\tilde\chi_2^0}^2 - m_{\tilde l_R}^2)(m_{\tilde l_R}^2 - m_{\tilde\chi_1^0}^2)\\ &- (m_{\tilde q_L}^2 - m_{\tilde\chi_2^0}^2)\sqrt{(m_{\tilde\chi_2^0}^2 + m_{\tilde l_R}^2)^2(m_{\tilde l_R}^2 + m_{\tilde\chi_1^0}^2)^2 - 16 m_{\tilde\chi_2^0}^2 m_{\tilde l_R}^4 m_{\tilde\chi_1^0}^2}\\ &+ 2m_{\tilde l_R}^2(m_{\tilde q_L}^2 - m_{\tilde\chi_2^0}^2)(m_{\tilde\chi_2^0}^2 - m_{\tilde\chi_1^0}^2)\Big] / (4 m_{\tilde l_R}^2 m_{\tilde\chi_2^0}^2),\end{aligned}$$

3 step two-body decays



Invariant mass edges





In total, five endpoint measurements

⇓

Four invovled sparticle masses can be obtained

$\tilde{\chi}_1^0$, $\tilde{\chi}_2^0$, $\tilde{\ell}_R$ masses reconstructed with ~ 5 GeV ,

$\tilde{q}_L$ mass with ~ 9 GeV (300 fb^{-1}) for SPS1a point

Mass relation method

Kawagoe, Nojiri, Polesello (2004)

- Consider the following cascade decay chain (4 step two-body decays)

$$\tilde{g} \to \tilde{b} b_2 \to \tilde{\chi}_2^0 b_1 b_2 \to \tilde{\ell} b_1 b_2 \ell_2 \to \tilde{\chi}_1^0 b_1 b_2 \ell_1 \ell_2$$

- Completely solve the kinematics of the cascade decay by using mass shell conditions of the sparticles

- One can write five mass shell conditions

$$m_{\tilde{\chi}_1^0}^2 = p_{\tilde{\chi}_1^0}^2, \qquad m_{\tilde{\ell}}^2 = (p_{\tilde{\chi}_1^0} + p_{\ell_1})^2,$$

$$m_{\tilde{\chi}_2^0}^2 = (p_{\tilde{\chi}_1^0} + p_{\ell_1} + p_{\ell_2})^2,$$

$$m_{\tilde{b}}^2 = (p_{\tilde{\chi}_1^0} + p_{\ell_1} + p_{\ell_2} + p_{b_1})^2,$$

$$m_{\tilde{g}}^2 = (p_{\tilde{\chi}_1^0} + p_{\ell_1} + p_{\ell_2} + p_{b_1} + p_{b_2})^2.$$

which contain 4 unknown d.o.f of LSP momentum

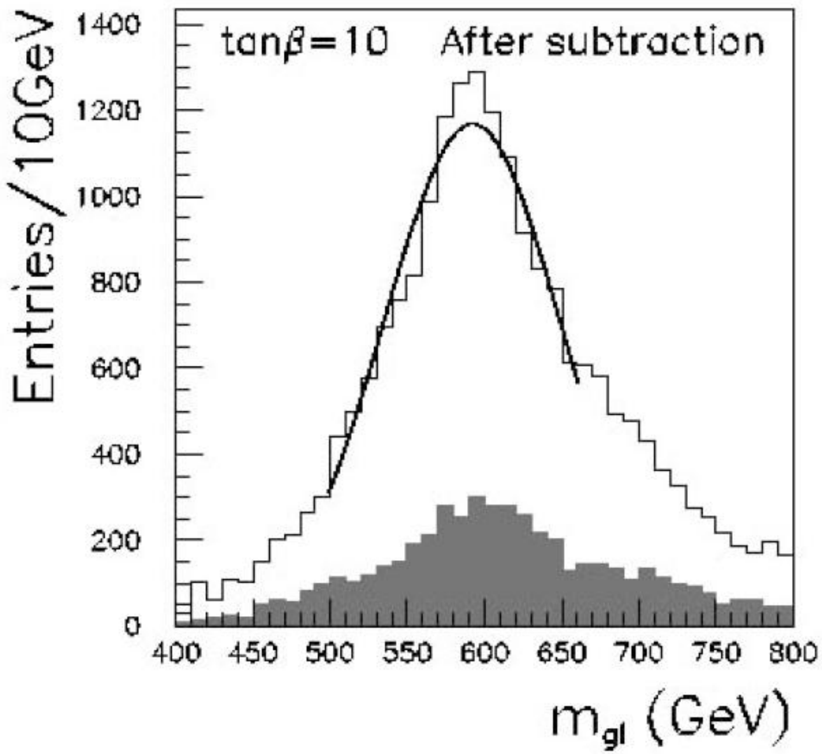
→ Each event describes a 4-dim. hypersurface in 5-dim. mass space, and the hypersurfcae differs event by event

→ Many events determine a solution for masses through intersections of hypersurfaces

▪ Measurements of gluino and sbottom masses

(assuming that the masses of two neutralinos and slepton are already known) in SPS 1a point

Kawagoe, Nojiri, Polesello (2004)



In this case, each event corresponds to a different line in $(m_{\tilde{g}}, m_{\tilde{b}})$ plane

Two events are enough to solve the gluino and sbottom masses altogether

Build all possible event pairs (with some conditions)

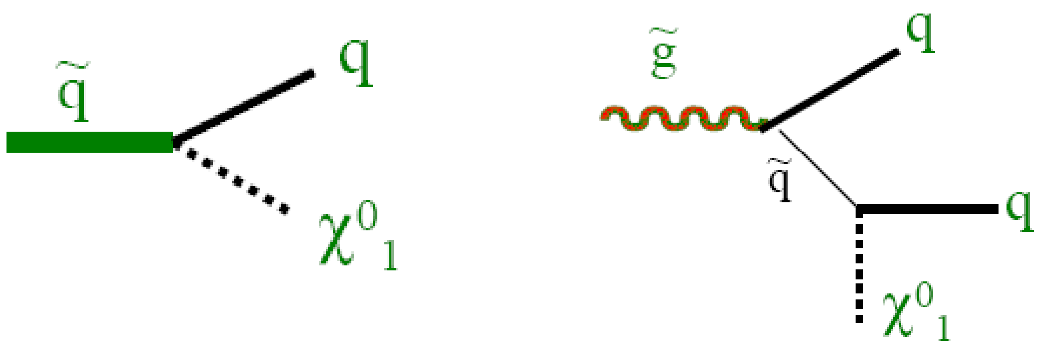
m_gluino ~ 592 GeV

(300 fb^{-1})

Gluino mass distribution with event pair analysis

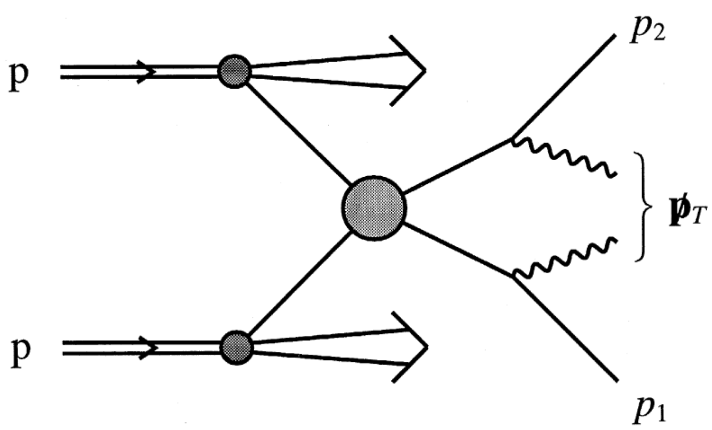
- Both the Edge method and the Mass relation method rely on a long decay chain to determine sparticle masses

- What if we don't have long enough decay chain but only short one ?



- In such case, M_{T2} variable would be useful to get information on sparticle masses

• Cambridge m_{T2} (Lester and Summers, 1999)



Massive particles pair produced

Each decays to one visible and one invisible particle.

For example,

$$pp \to X + \tilde{l}_R^+ \tilde{l}_R^- \to X + l^+ l^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$$

For the decay, $\tilde{l} \to l \tilde{\chi}$

$$m_{\tilde{l}}^2 \geq m_T^2(\boldsymbol{p}_{Tl}, \boldsymbol{p}_{T\tilde{\chi}})$$

$$\equiv m_l^2 + m_{\tilde{\chi}}^2 + 2\left(E_{Tl} E_{T\tilde{\chi}} - \boldsymbol{p}_{Tl} \cdot \boldsymbol{p}_{T\tilde{\chi}}\right)$$

(where $E_T = \sqrt{\boldsymbol{p}_T^2 + m^2}$)

If $\boldsymbol{p}_{T\tilde{\chi}_a}$ and $\boldsymbol{p}_{T\tilde{\chi}_b}$ were obtainable,

$$m_{\tilde{l}}^2 \geq \max\left\{m_T^2(\boldsymbol{p}_{Tl^-}, \boldsymbol{p}_{T\tilde{\chi}_a}), m_T^2(\boldsymbol{p}_{Tl^+}, \boldsymbol{p}_{T\tilde{\chi}_b})\right\}$$

($\not{\boldsymbol{p}}_T = \boldsymbol{p}_{T\tilde{\chi}_a} + \boldsymbol{p}_{T\tilde{\chi}_b}$: total MET vector in the event)

However, not knowing the form of the MET vector splitting, the best we can say is that :

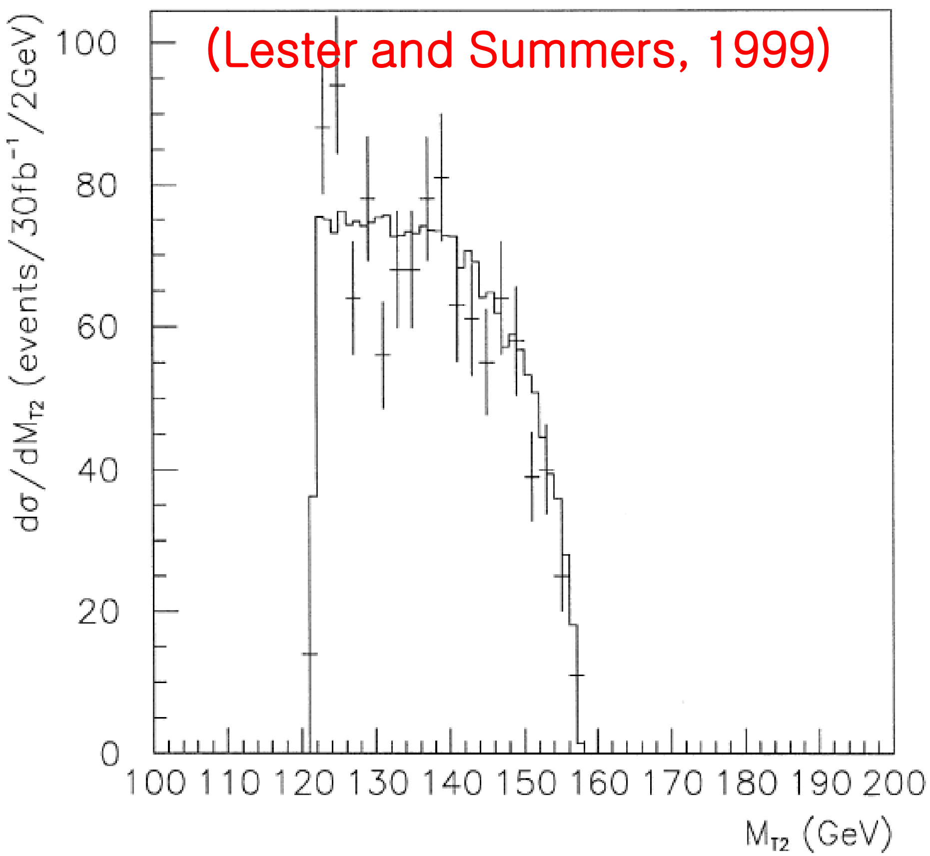
$$m_{\tilde{l}}^2 \geq M_{T2}^2$$
$$\equiv \min_{\not{\boldsymbol{p}}_1 + \not{\boldsymbol{p}}_2 = \not{\boldsymbol{p}}_T} \left[\max\left\{m_T^2(\boldsymbol{p}_{Tl^-}, \not{\boldsymbol{p}}_1), m_T^2(\boldsymbol{p}_{Tl^+}, \not{\boldsymbol{p}}_2)\right\}\right]$$

with minimization over all possible trial LSP momenta

❖ M_{T2} distribution for $pp \to X + \tilde{l}_R^+ \tilde{l}_R^- \to X + l^+ l^- \tilde{\chi}_1^0 \tilde{\chi}_1^0$

LHC point 5, with 30 fb^{-1},

$$m_{\tilde{l}_R} = 157.1\,\mathrm{GeV}\,, \quad m_{\tilde{\chi}_1^0} = 121.5\,\mathrm{GeV}\,.$$



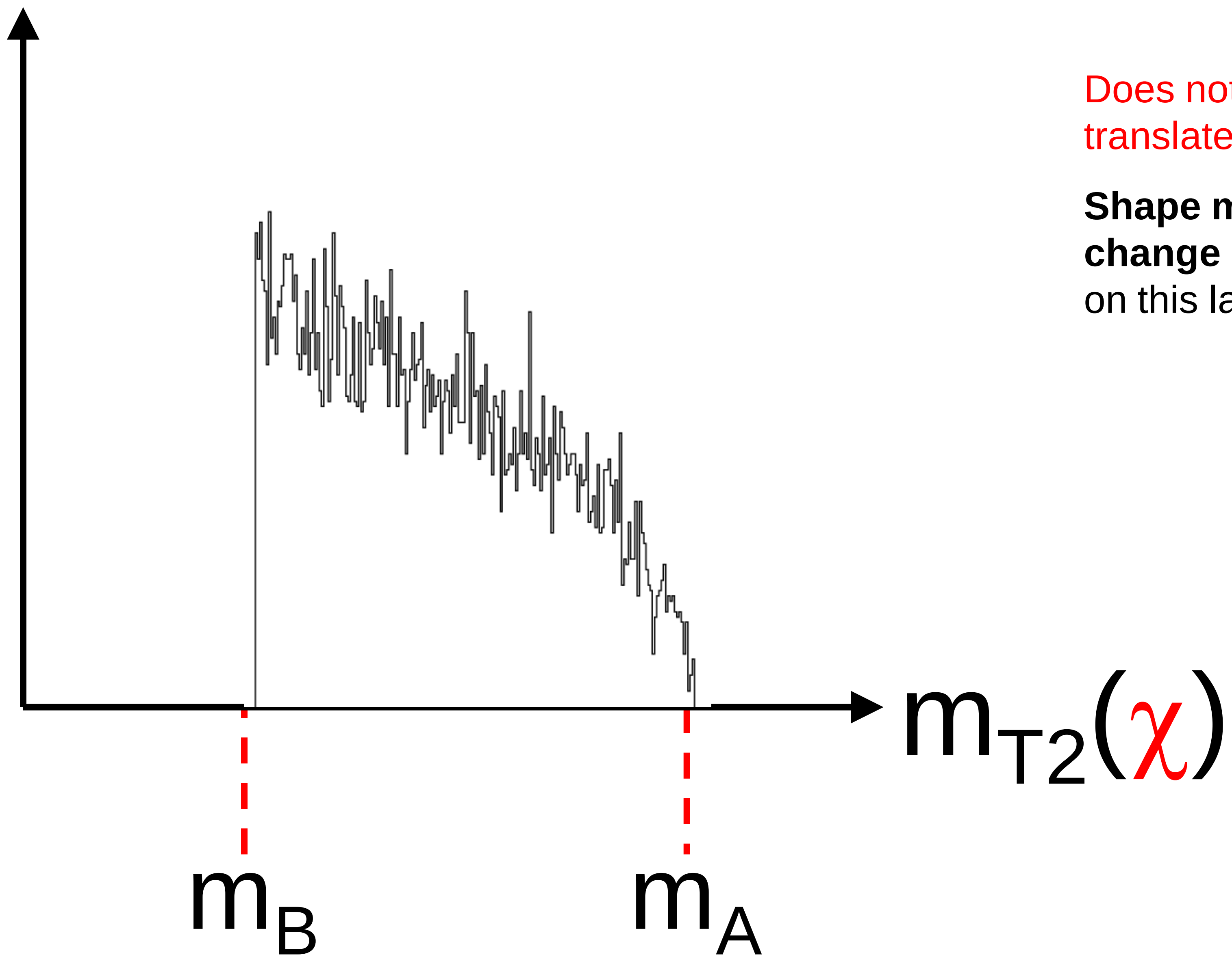
Endpoint measurement of m_{T2} distribution determines the mother particle mass

$$m_{T2}^{\max} \simeq 157\ \mathrm{GeV}$$

(with $m_{\tilde{\chi}_1^0} = 121.5\ \mathrm{GeV}$)

Varying "χ" …

(Taken from Lester's talk in the LHC focus week at IPMU)



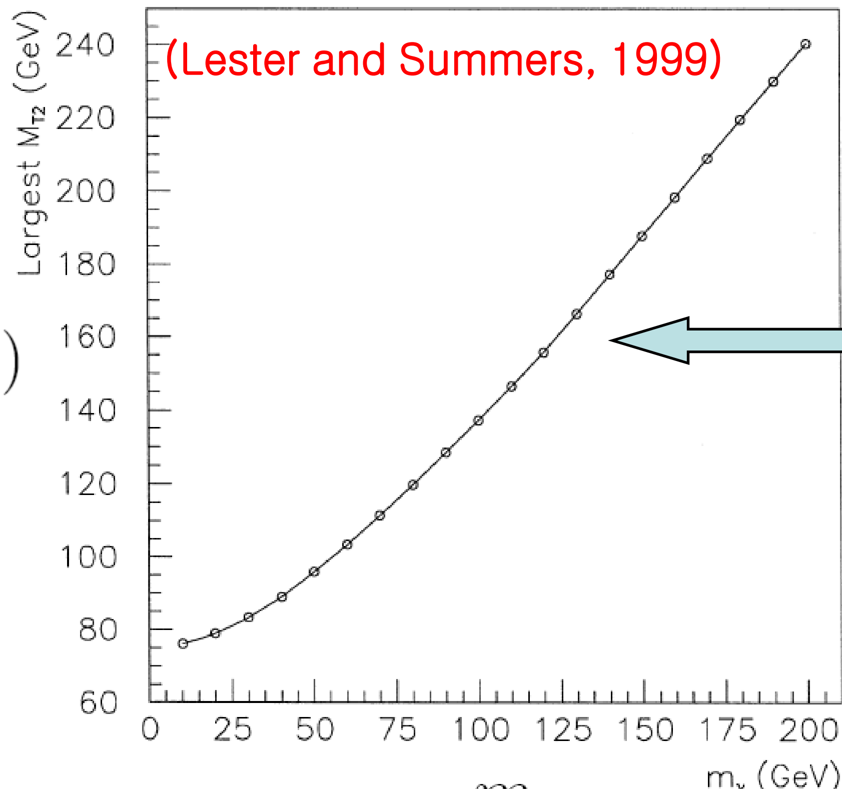
Does not just translate …

Shape may also change … more on this later.

The LSP mass is needed as an input for m_{T2} calculation
But it might not be known in advance

m_{T2} depends on a trial LSP mass m_χ
Maximum of m_{T2} as a function of the trial LSP mass

$m_{T2}^{\max}(m_\chi)$



m_χ

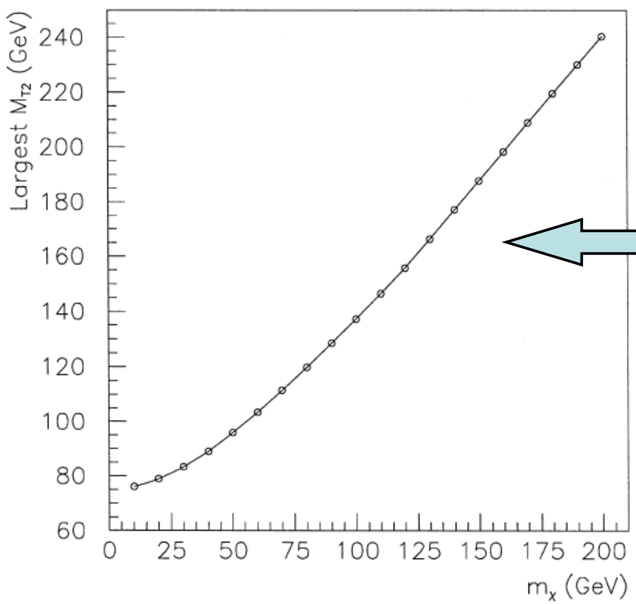
The correlation from a numerical calculation can be expressed by an analytic formula in terms of true sparticle masses

The maximum of the squark m_{T2} as a function of m_chi

(Cho, Choi, YGK and Park, 2007)

$$m_{T2}^{\max}(m_\chi) = \frac{m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2}{2m_{\tilde{q}}} + \sqrt{\left(\frac{m_{\tilde{q}}^2 - m_{\tilde{\chi}_1^0}^2}{2m_{\tilde{q}}}\right)^2 + m_\chi^2}$$

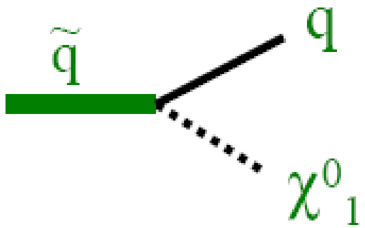
- $m_{T2}^{\max}(m_\chi) = m_{\tilde{q}} \quad \text{if } m_\chi = m_{\tilde{\chi}_1^0}$



Well described by the above Analytic expression with true Squark mass and true LSP mass

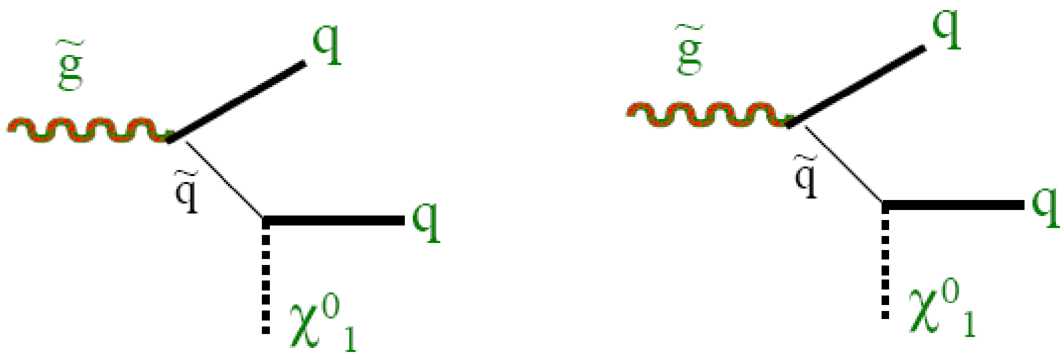
✓ Squark and LSP masses are Not determined separately

- We considered 'Squark' m_{T2}

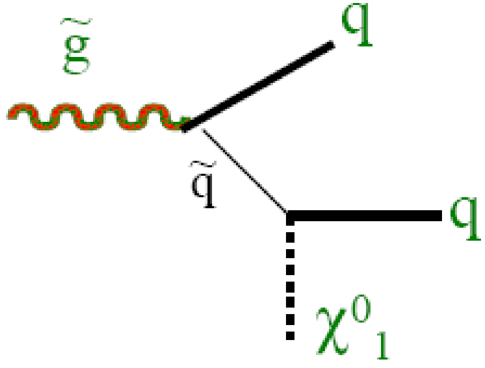


- Now consider 'Gluino' m_{T2}

(Cho, Choi, YGK and Park, 2007)

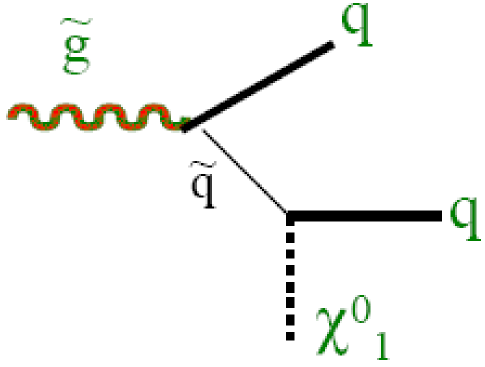


Each mother particle produces
one invisible LSP
and more than one visible particle

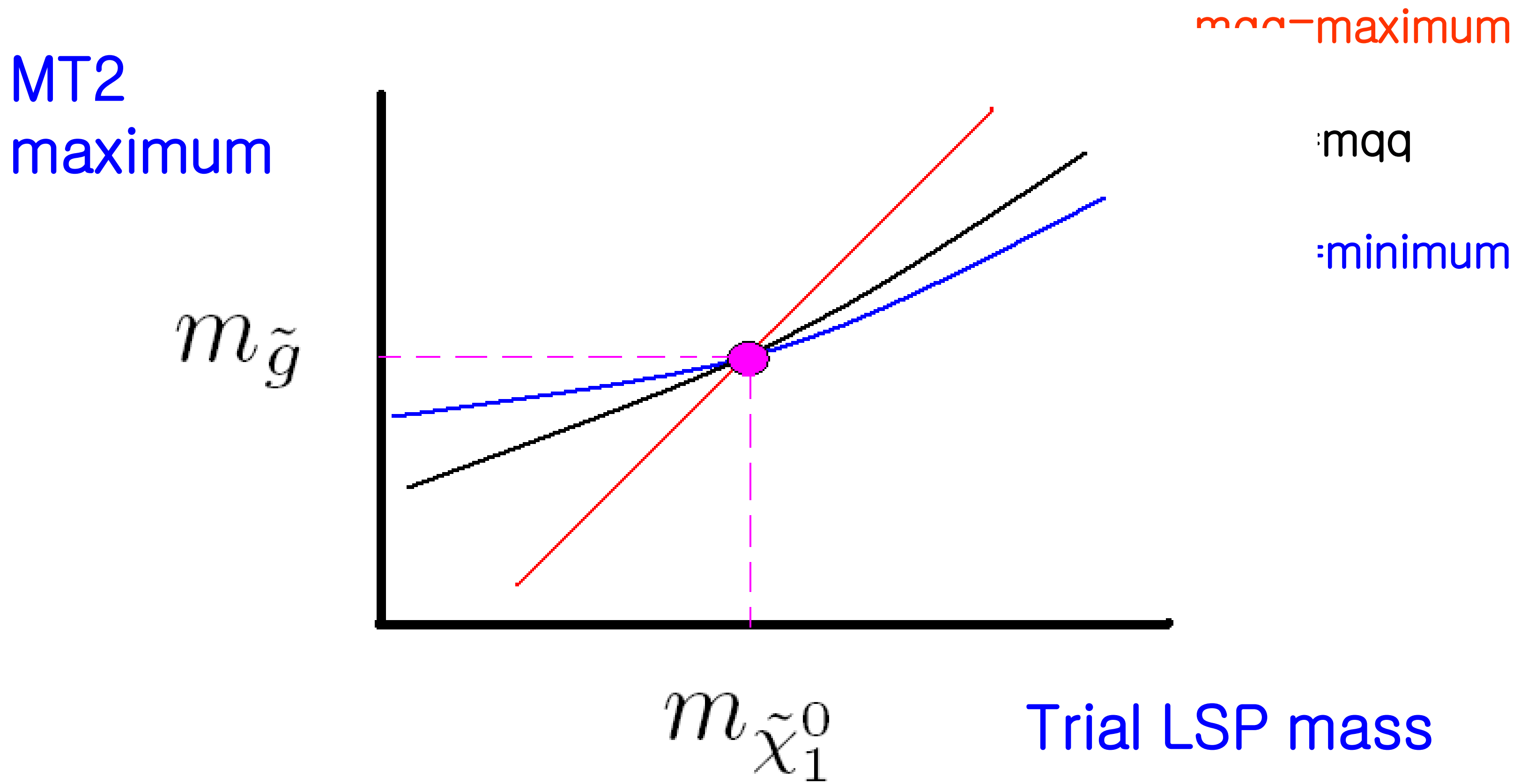


m_{qq} value for
three body gluino decay

$$0 \leq m_{qq} \leq m_{\tilde{g}} - m_{\tilde{\chi}_1^0}$$



- MT2 maximum as a function of trial LSP mass depends on di-quark invariant mass (mqq)



(Assume mqq (1) = mqq (2), for simplicity)

Experimental feasibility

An example (a point in mAMSB)

$$m_{\tilde{g}} = 780.3\ \mathrm{GeV},\ \ m_{\tilde{\chi}_1^0} = 97.9\ \mathrm{GeV},$$

with a few TeV sfermion masses
(gluino undergoes three body decay)

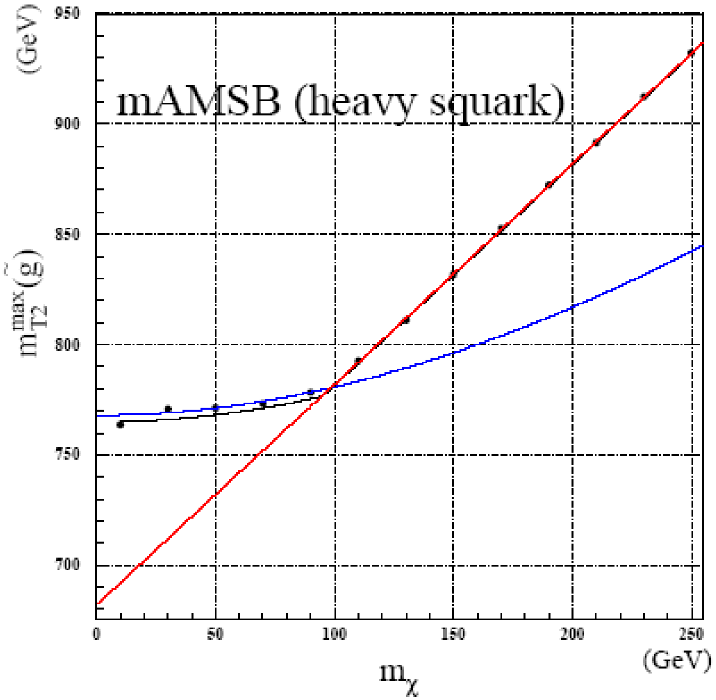
$\sigma(\tilde{g}\tilde{g}) \sim 1.1\mathrm{pb}$ $\quad B(\tilde{g} \to \tilde{\chi}_1^0 qq) \sim 32\%,$

Wino LSP $\quad B(\tilde{g} \to \tilde{\chi}_1^{\pm} qq') \sim 64\%.$

We have generated a MC sample of SUSY events,
which corresponds to 300 fb^{-1} by PYTHIA

The generated events further processed with PGS detector simulation,
which approximates an ATLAS or CMS-like detector

- $m_{T2}^{\max}$ as a function of the trial LSP mass for a benchmark point



$$m_{T2}^{\max}(m_\chi) = \left(m_{\tilde{g}} - m_{\tilde{\chi}_1^0}\right) + m_\chi$$

$$m_{T2}^{\max}(m_\chi) = \frac{m_{\tilde{g}}^2 - m_{\tilde{\chi}_1^0}^2}{2m_{\tilde{g}}} + \sqrt{\left(\frac{m_{\tilde{g}}^2 - m_{\tilde{\chi}_1^0}^2}{2m_{\tilde{g}}}\right)^2 + m_\chi^2}$$

Fitting the data points with the above two theoretical curves, we obtain

$$m_{\tilde{g}} = 776.5 \pm 1.0 \text{ GeV}$$

$$m_{\tilde{\chi}_1^0} = 94.9 \pm 1.4 \text{ GeV}$$

The true values are

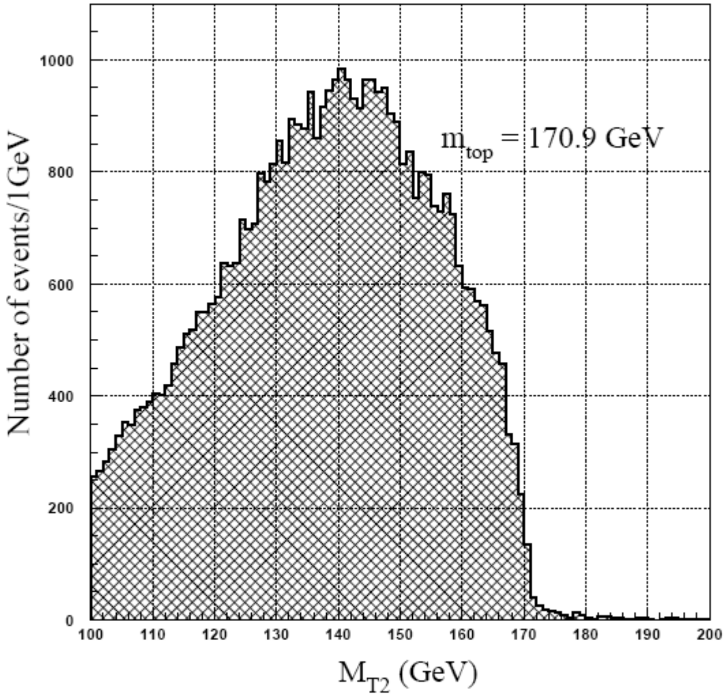
$$m_{\tilde{g}} = 780.3 \text{ GeV}, \ m_{\tilde{\chi}_1^0} = 97.9 \text{ GeV},$$

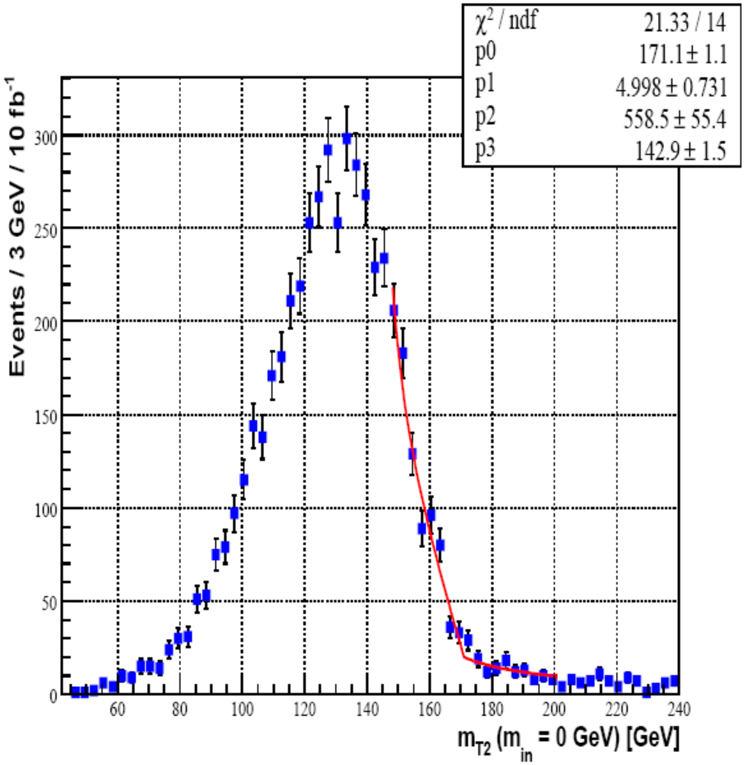
Measuring the top quark mass with m_{T2} at the LHC

(Cho, Choi, YGK, Park, arXiv:0804.2185)

$$t\bar{t} \longrightarrow b l^+ \nu \bar{b} l^- \nu$$

Standard Candle for MT2 study

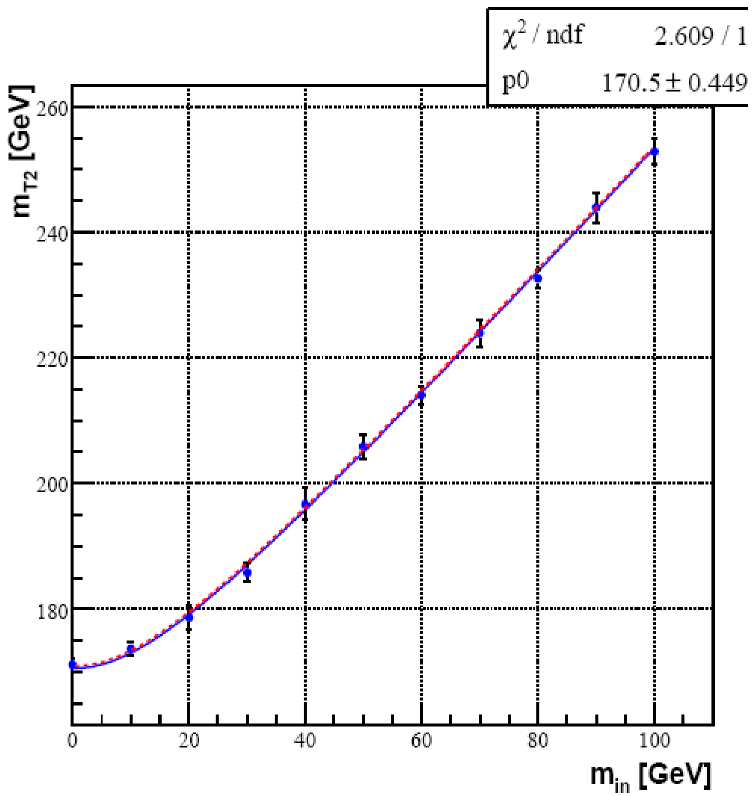




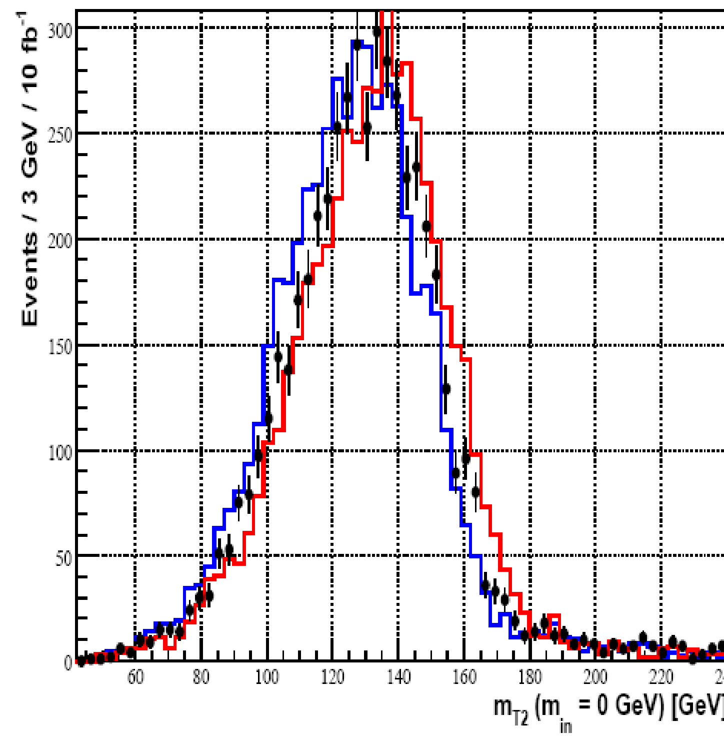
Top quark mT2 distribution with m_nu = 0

Standard Candle for MT2 study

mT2 max vs. trial neutrino mass



Shape of mT2 distribution

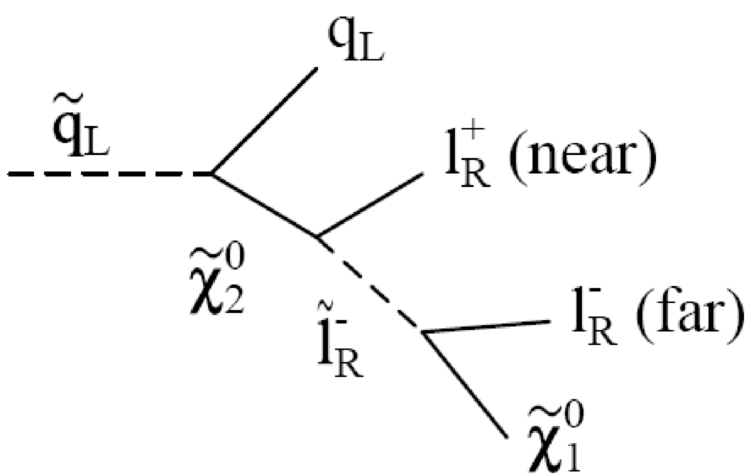


The di-leptonic channel will provide a good playground for mT2 excercise

Spin effects in decays

Determining the spin of supersymmetric particles at the LHC using lepton charge asymmetry.

A.J. Barr (2004)

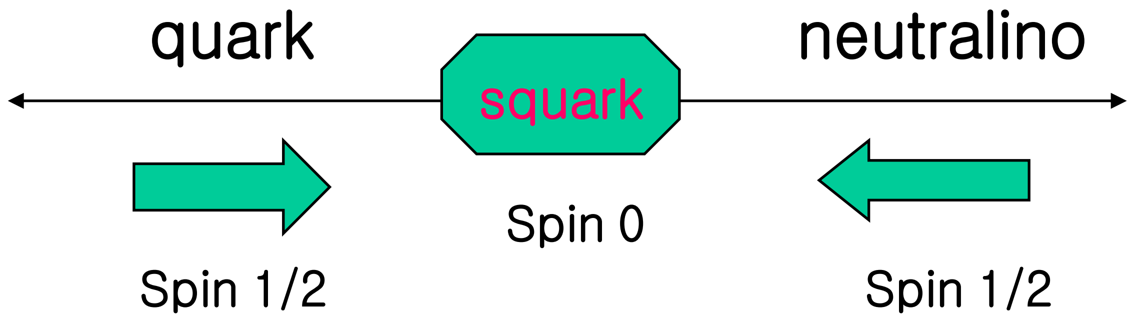


Decay chain
under investigation

Spin correlations can play a significant role in the kinematics of the emitted SM particles

Consider invariant mass of quark and (near) lepton

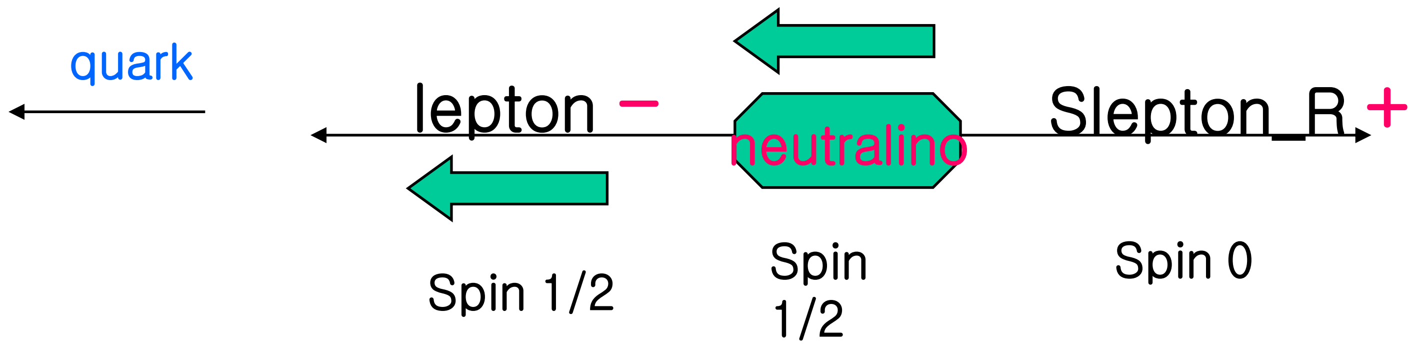
$$\tilde{q}_L \longrightarrow q + \tilde{\chi}_2^0$$ decay



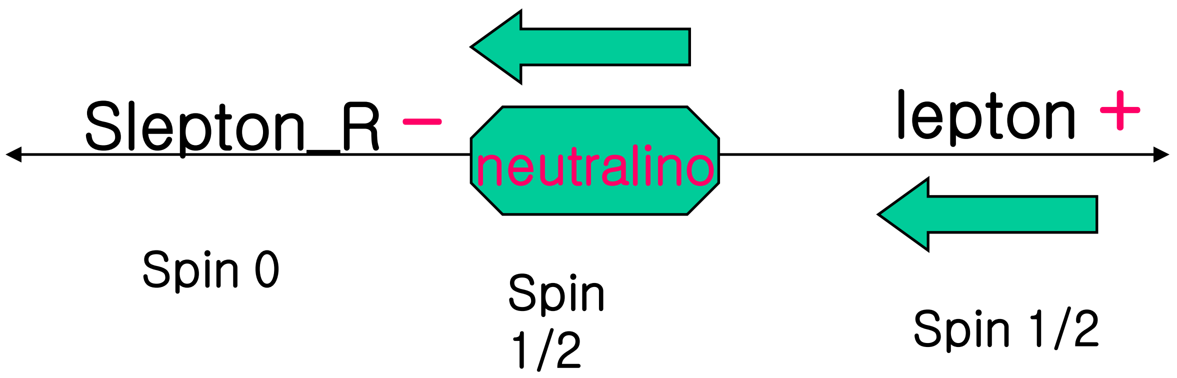
It is assumed that neutralino $\tilde{\chi}_2^0$ is largely Wino, so the branching ratios $\tilde{q}_R \longrightarrow \tilde{\chi}_2^0 q$ are highly suppressed compared to the above decays

Polarized $\tilde{\chi}_2^0 \rightarrow \tilde{l}_R^{\pm} + l^{\mp}$ decay

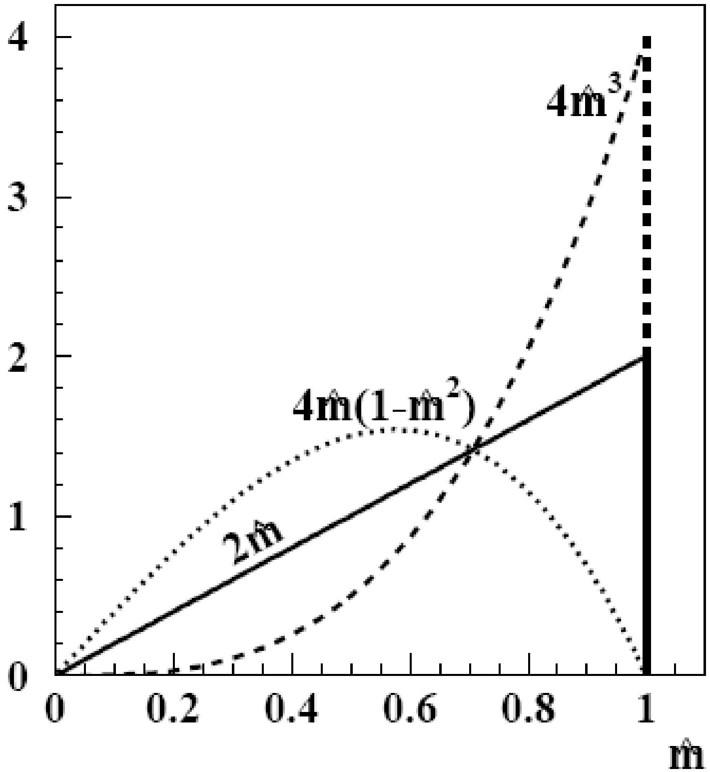
Right-handed lepton goes the same direction to the quark direction



Right-handed anti-lepton goes the opposite to the quark direction



Near lepton + quark invariant mass distribution



$$\frac{dP_1}{d\hat{m}} = 4\sin^3(\theta^*/2) = 4\hat{m}^3$$

$$\text{for } l^+q \text{ or } l^-\bar{q}$$

$$\frac{dP_2}{d\hat{m}} = 4\sin(\theta^*/2)\cos^2(\theta^*/2) = 4\hat{m}(1-\hat{m}^2)$$

$$\text{for } l^-q \text{ or } l^+\bar{q}$$

θ^* : angle between quark and lepton in neutralino rest frame

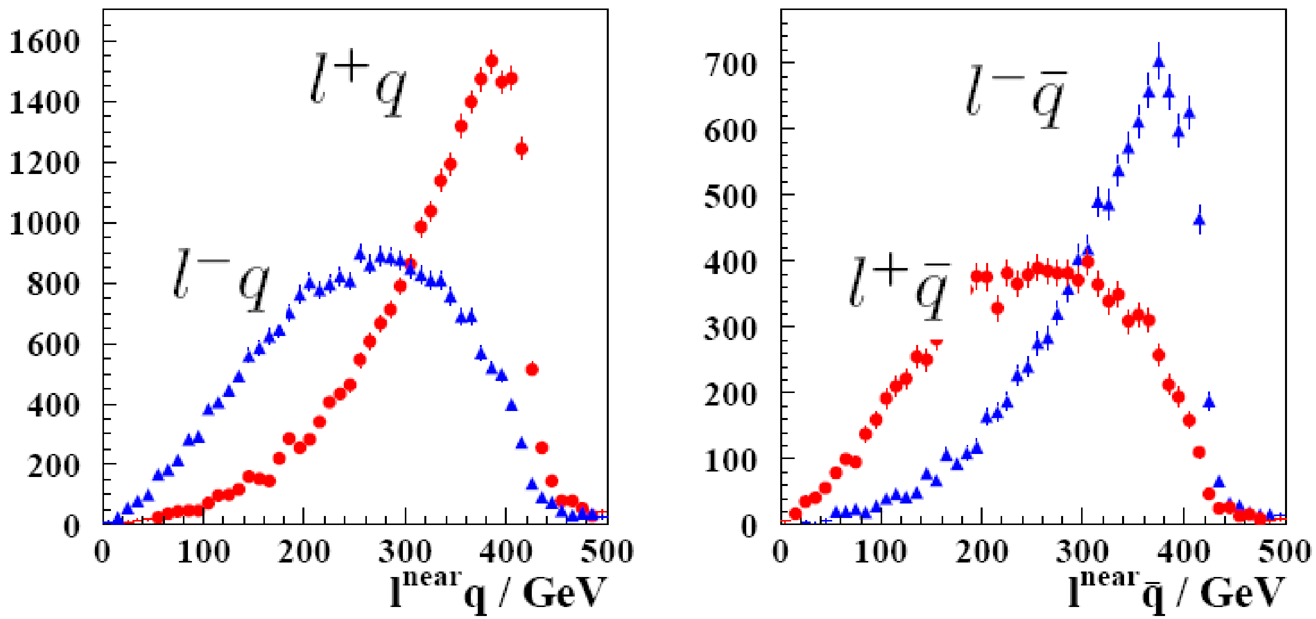
$$\left(m_{lq}^{\rm near}\right)^2 = 2|\mathbf{p}_l||\mathbf{p}_q|(1-\cos\theta^*) = \left(m_{lq}^{\rm near}\right)^2_{\rm max}\sin^2(\theta^*/2)$$

$$\hat{m} \equiv m_{lq}^{\rm near}/\left(m_{lq}^{\rm near}\right)_{\rm max} = \sin(\theta^*/2) \qquad \frac{dP_{\rm PS}}{d\hat{m}} = 2\sin(\theta^*/2) = 2\hat{m}$$

- Invariant mass distribution of quark + (near) lepton at parton level MC simulation for a test point

$\tilde{g}$	$\tilde{\chi}_1^0$	$\tilde{\chi}_2^0$	$\tilde{u}_L$	$\tilde{d}_L$	$\tilde{e}_R$	$\tilde{e}_L$
717	116	213	631	634	153	229

(mSUGRA point with m_0=100 GeV, $m_{1/2}$=300 GeV, A_0=300 GeV)



shows nice charge asymmetry !

(caused by spin correlations carried by the spin ½ neutralino)

- **Experimental difficulties** in making such a measurement

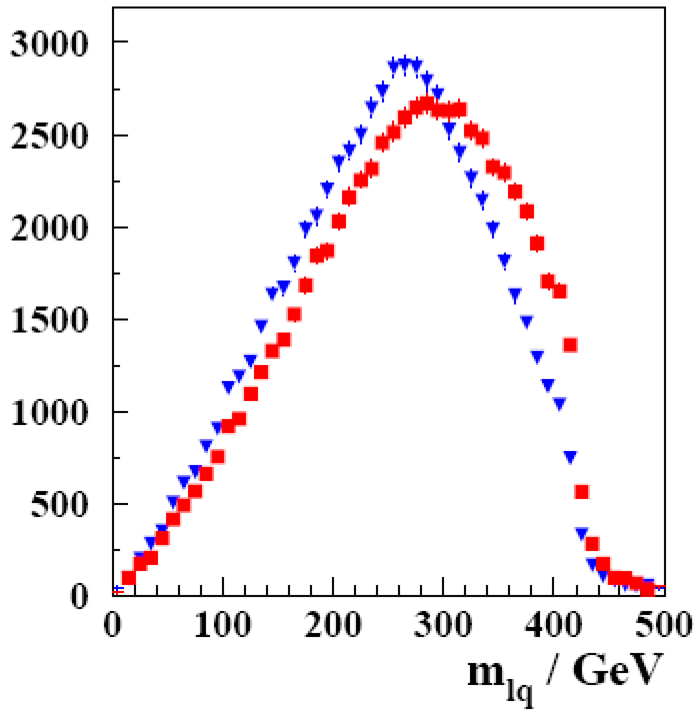
  - In anti-squark decay the asymmetry in the lepton charge distribution is in the opposite sense to that from squark decays

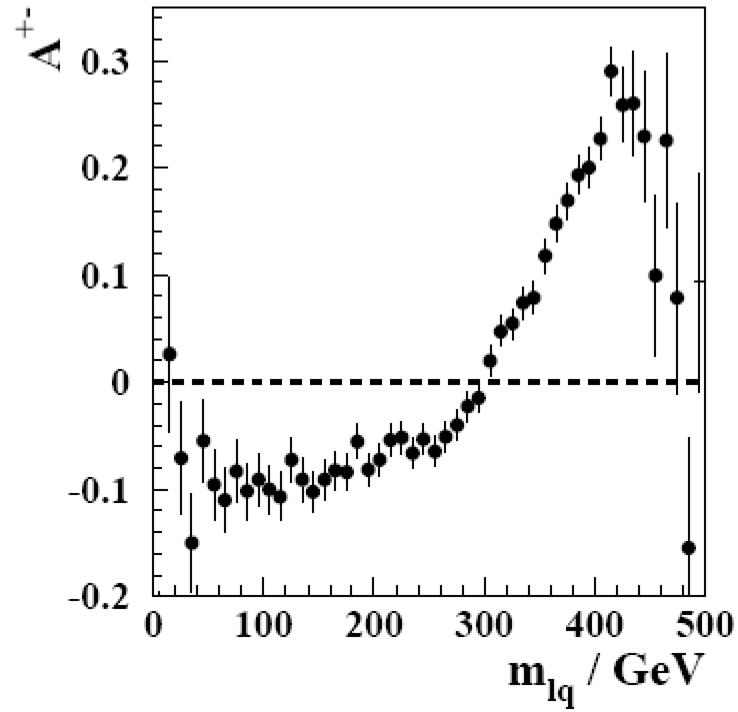
    If equal numbers of squarks and anti-squarks were produced, no spin information could be obtained

  - It will not be possible to distinguish the near lepton from the far lepton on an event-by-event basis

❖ The l^-q and l^+q distributions (parton-level)

from both near and far leptons, and from squark and anti-squark

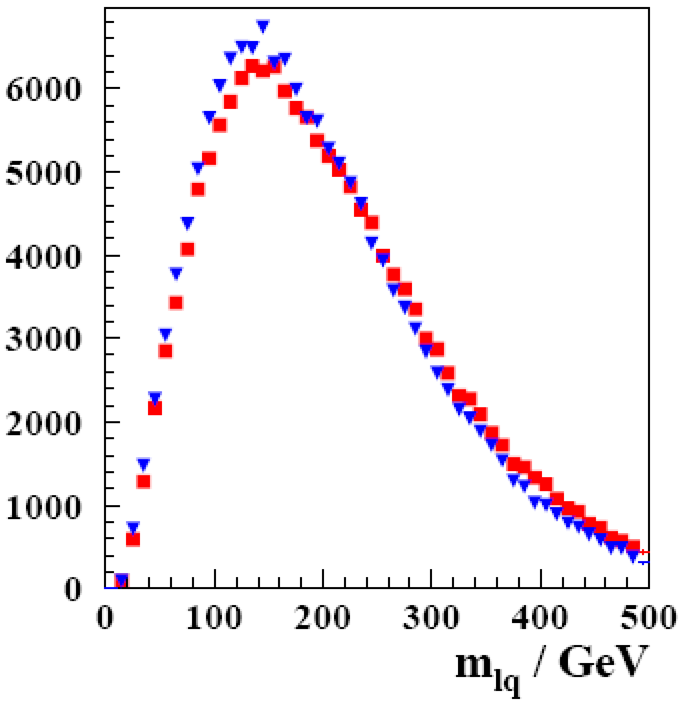


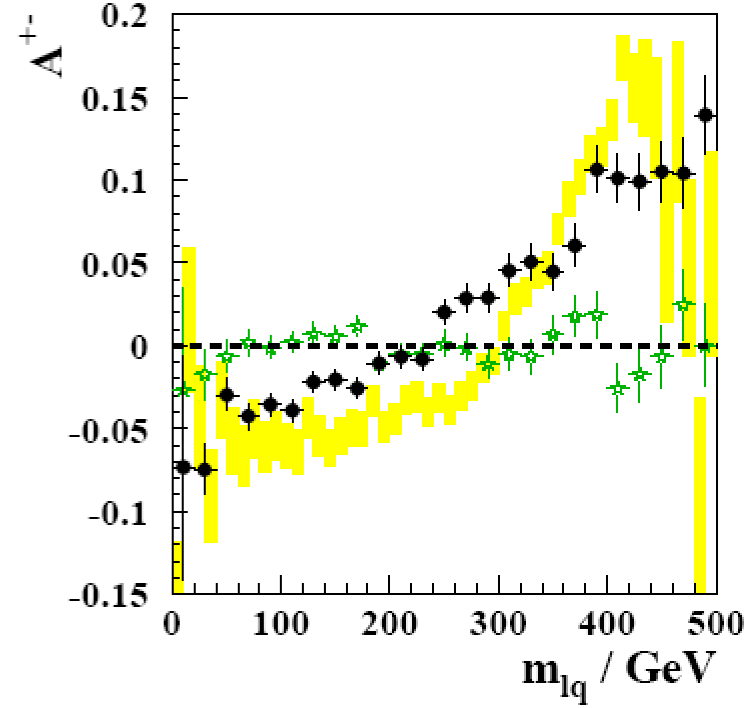


Charge asymmetry

$$A^{+-} \equiv \frac{s^+ - s^-}{s^+ + s^-}, \quad \text{where} \quad s^\pm = \frac{d\sigma}{d(m_{l^\pm q})} .$$

Including Detector Simulation and exp. cuts

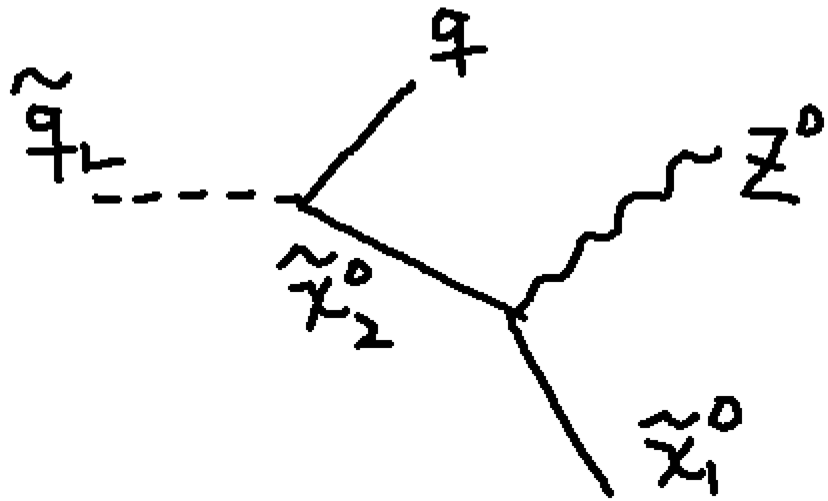




The charge asymmetry survives, and favors a spin-½ $\tilde{\chi}_2^0$

(black dots : with spin correlations,
green dots : switched off the spin correlations
yellow : parton-level asymmetry * 0.6)

- What if $\tilde{q}_L \rightarrow q\tilde{\chi}_2^0 \rightarrow qZ\tilde{\chi}_1^0.$?



Dominant decay mode if chi_2^0 is lighter than slepton.

Any useful spin correlation ?

Polarized neutralino decay

$$\tilde{\chi}_i^0(p, \hat{n}) \to \tilde{\chi}_j^0(q) + Z(k)$$

(YGK 2007)

Matrix element squared

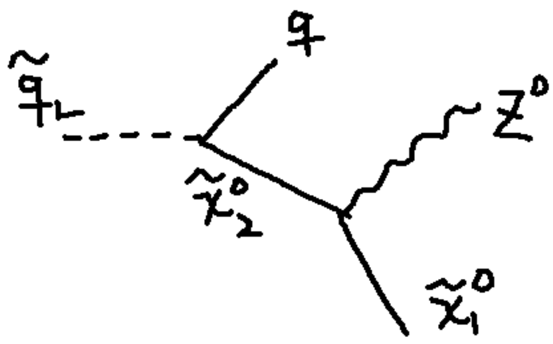
$$\sum_{\lambda=\pm,0} |\mathcal{M}|^2 \propto (|V|^2 + |A|^2)\left(q \cdot p + \frac{2}{m_Z^2}(k \cdot p)(k \cdot q)\right)$$
$$+ (|V|^2 - |A|^2)(-3m_j m_i)$$
$$+ 2\,\mathrm{Re}(VA^*)m_i\left((q \cdot n) + \frac{2}{m_Z^2}(k \cdot n)(k \cdot q)\right).$$

Vector coupling V is pure imaginary and axial-vector coupling A is pure real, due to Majorana nature of neutralinos.

$$\mathrm{Re}(VA^*) = 0$$

Flat angular distribution of Z boson w.r.t the polarization vector of neutralino
(Choi, Drees, Song 2006)

Wang and Yavin (2006)



" This could be a potentially golden channel considering the leptonic decay of the Z.

Unfortunately, there are no angular correlations since the neutralio–neutralino–Z is not even partially chiral. "

Z polarization can be reconstructed via leptonic angular distribution in Z → $l^+ l^-$

- Differential decay widths with explicit helicity of Z boson

(YGK 2007)

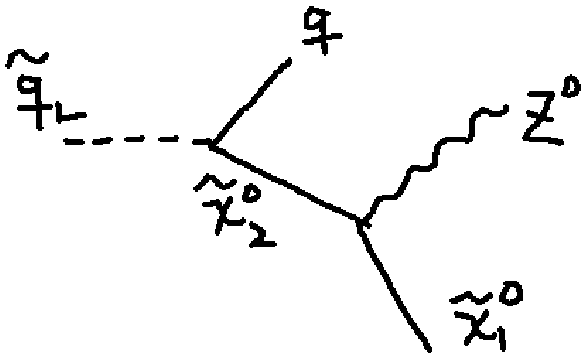
$$\frac{d\Gamma[\tilde{\chi}_i^0(\hat{n}) \to \tilde{\chi}_j^0 Z(\pm)]}{d\cos\theta} = \frac{g_Z^2 \lambda_Z^{1/2}}{64\pi m_i^3}[(|V|^2 + |A|^2) \times (m_i^2 + m_j^2 - m_Z^2) + (|V|^2 - |A|^2) \times (-2m_i m_j)](1 \pm \cos\theta), \qquad (3)$$

for transverse Z

$$\cos\theta \equiv \hat{\mathrm{k}} \cdot \hat{\mathrm{n}}$$

$$\frac{d\Gamma[\tilde{\chi}_i^0(\hat{n}) \to \tilde{\chi}_j^0 Z(0)]}{d\cos\theta} = \frac{g_Z^2 \lambda_Z^{1/2}}{64\pi m_i^3}\left[(|V|^2 + |A|^2) \times \left(m_i^2 + m_j^2 - m_Z^2 + \frac{\lambda_Z}{m_Z^2}\right) + (|V|^2 - |A|^2)(-2m_i m_j)\right], \qquad (4)$$

for longitudinal Z



$$\tilde{q}_L \to q\tilde{\chi}_2^0 \to qZ\tilde{\chi}_1^0.$$

(YGK 2007)

❖ Quark + Z boson invariant mass distributions

$$\frac{d\hat{\Gamma}(-)}{d\hat{m}} = \frac{4}{(1-\hat{m}_{\min}^2)^2}\hat{m}(\hat{m}^2 - \hat{m}_{\min}^2) \quad \text{for } Z(\lambda = -),$$

$$\frac{d\hat{\Gamma}(+)}{d\hat{m}} = \frac{4}{(1-\hat{m}_{\min}^2)^2}\hat{m}(1 - \hat{m}^2) \quad \text{for } Z(\lambda = +),$$

Can we see the polarization asymmetry at the LHC ?

Challenging…

Lepton angular distribution in Z → l+ l− (in Z rest frame)

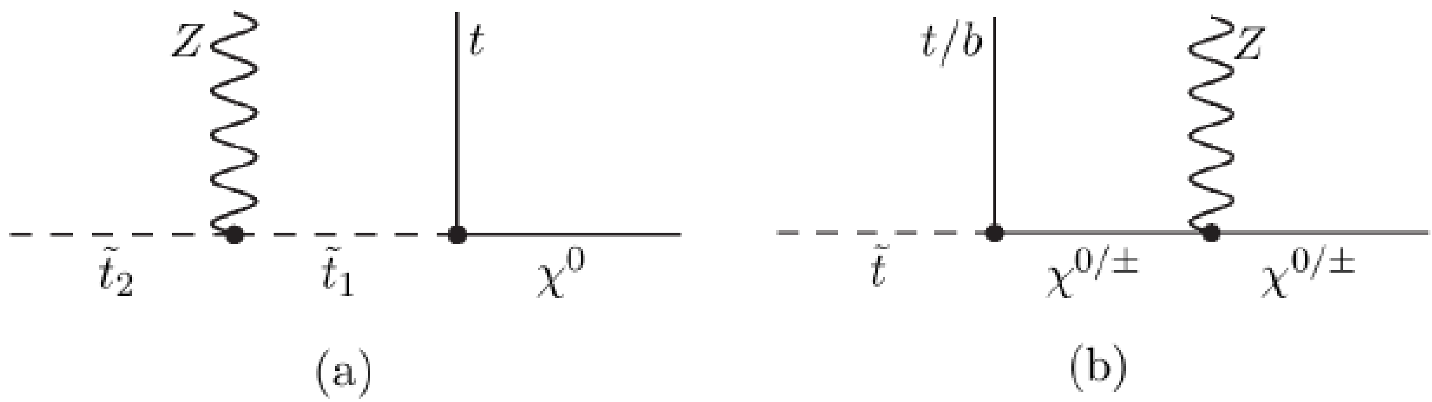
$$\frac{1}{\Gamma[Z \to l^+ l^-]} \frac{d\Gamma[Z(\pm) \to l^+ l^-]}{d\cos\theta_l} = \frac{3}{8}\left[1 + \cos^2\theta_l \pm 2\,\xi_l \cos\theta_l\right]$$

$$\frac{1}{\Gamma[Z \to l^+ l^-]} \frac{d\Gamma[Z(0) \to l^+ l^-]}{d\cos\theta_l} = \frac{3}{4}\,\sin^2\theta_l\,,$$

$$\xi_l = 2 v_l a_l / (v_l^2 + a_l^2) \simeq -0.147$$

Distinguishing decay chain with Z polarization (work in progress)

(Perelstein and Spethmann 2007)



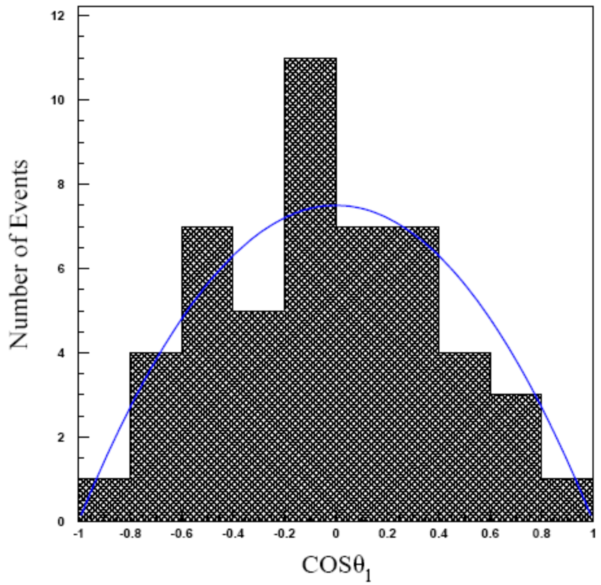
(a) Decay chain of SUSY golden region (b) An alternative chain

Two confusing chains.. However, notice that

Stop2 → stop1 + Z N2 → N1 + Z

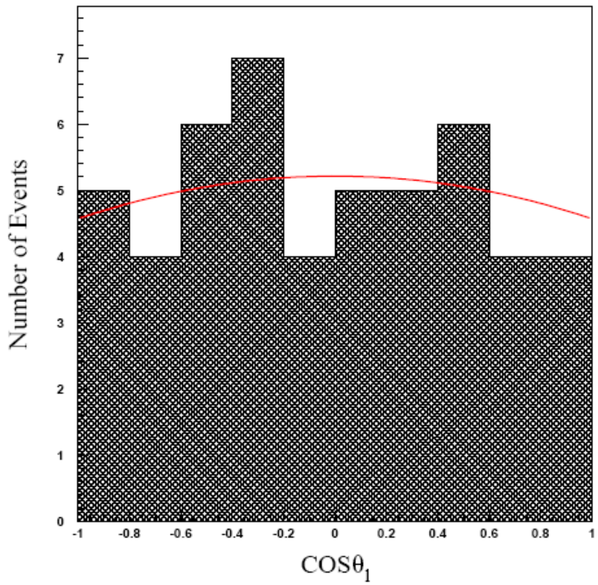
(only longitudinal Z possible) (Both transverse and longitudianl Z)

Leptonic angular distribution of Z → $l^+ l^-$ in Z rest frame
(Partonic-level, no selection cut etc.)



for stop2 → stop1 + Z

(m_t2=700GeV, m_t1=400 GeV)



for N2 → N1 + Z

(m_N2=220 GeV, m_N1=120 GeV)

Two decay chains exhibit distinctive angular distribution
So that they may be clearly distinguished experimentally.

Z polarization as a model-independent spin analyzer (work in progress)

Two body decay of a new state A into a new state B and Z boson

$$A \to B\,Z \to B\,\ell^+\ell^-$$

For each spin assignment of A and B, ABZ vertex structure

$$\boxed{\mathrm{S\,S}} \;:\; (p+q)^\mu$$

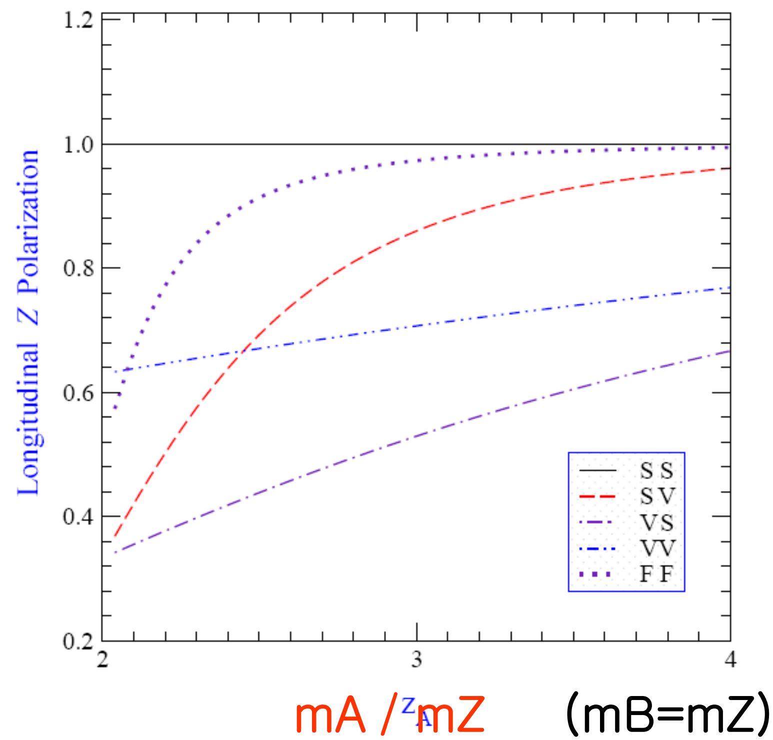
$$\boxed{\mathrm{S\,V}} \;:\; g^{\mu\nu}$$

$$\boxed{\mathrm{V\,S}} \;:\; g^{\lambda\nu}$$

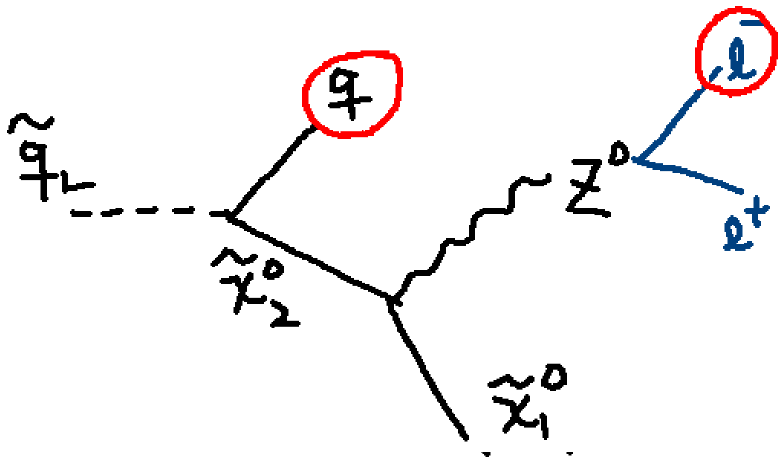
$$\boxed{\mathrm{V\,V}} \;:\; g^{\mu\nu}(k-q)^\lambda + (q+p)^\mu g^{\nu\lambda} - g^{\mu\lambda}(p+k)^\nu$$

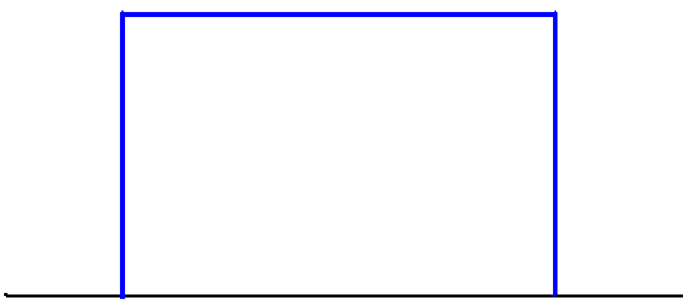
$$\boxed{\mathrm{F\,F}} \;:\; \gamma^\mu(v+a\gamma_5)$$

Degree of longitudinal Z polarization in the A particle rest frame



Mass determination in $\tilde{q}_L \to q\tilde{\chi}_2^0 \to qZ\tilde{\chi}_1^0$.





$$m^2_{qZ_{\min}} = \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}_2^0})}{2m^2_{\tilde{\chi}_2^0}}((m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_1^0} + m^2_Z) - \lambda_Z^{1/2}) + m^2_Z,$$

$$m^2_{qZ_{\max}} = \frac{(m^2_{\tilde{q}_L} - m^2_{\tilde{\chi}_2^0})}{2m^2_{\tilde{\chi}_2^0}}((m^2_{\tilde{\chi}_2^0} - m^2_{\tilde{\chi}_1^0} + m^2_Z) + \lambda_Z^{1/2}) + m^2_Z.$$

➢ Invariant mass distribution of quark and lepton

$$m_{ql}^2 \propto \gamma_Z(1-\cos\theta_q\cos\theta_l^*)+\gamma_Z\beta_Z(\cos\theta_l^*-\cos\theta_q)-\sin\theta_q\sin\theta_l^*\cos\phi_l^*$$

$$\gamma_Z = \frac{m_{\tilde{\chi}_2^0}^2 - m_{\tilde{\chi}_1^0}^2 - m_Z^2}{2m_{\tilde{\chi}_2^0}m_Z}$$: boost factor for Z boson in N2 rest frame

theta_q : the opening angle between q and Z in N2 rest frame

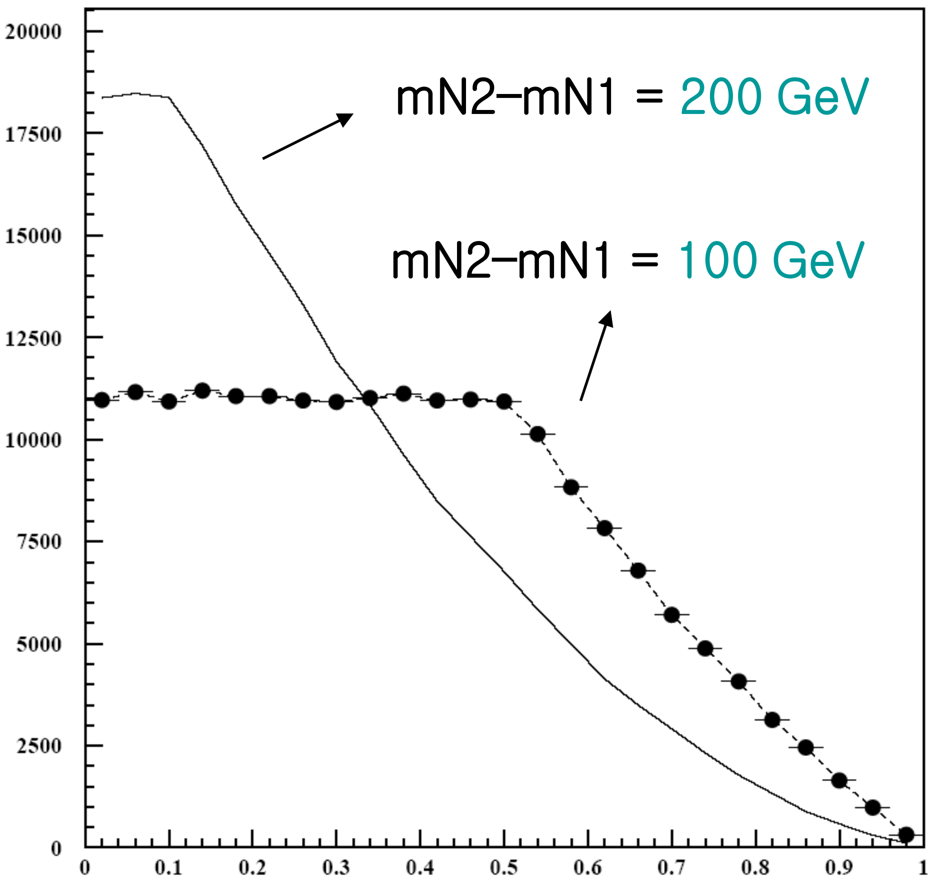
theta*_l : the lepton polar angle w.r.t. Z mom. in Z rest frame

phi*_l : the angle between the qZ and dilepton plane

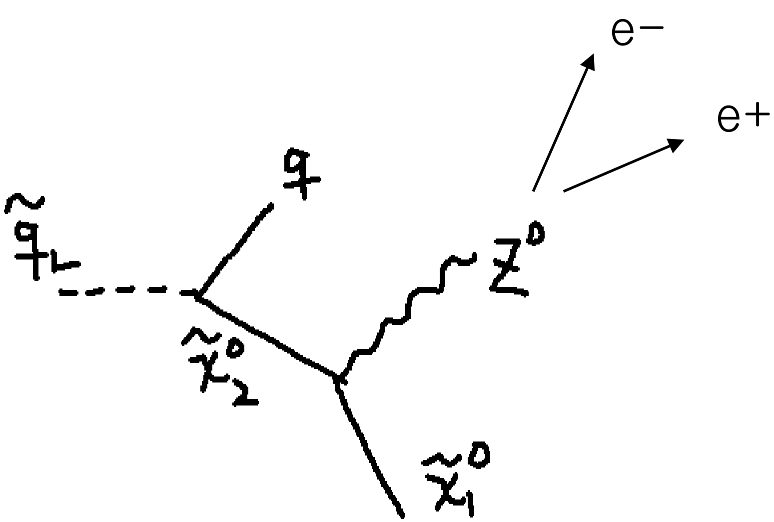
The shape of the invariant mass distribution depends on the boost and the polarization of Z boson in N2 rest frame, therefore determined by m_N2 – m_N1

Normalized invariant mass of quark and lepton

(work in progress)

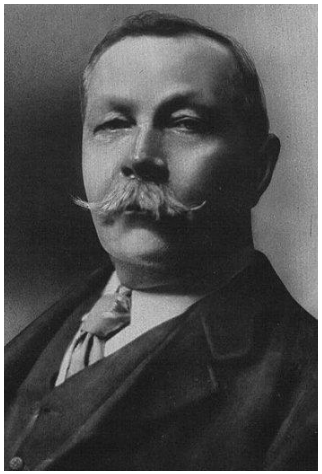


(m_ql)^2

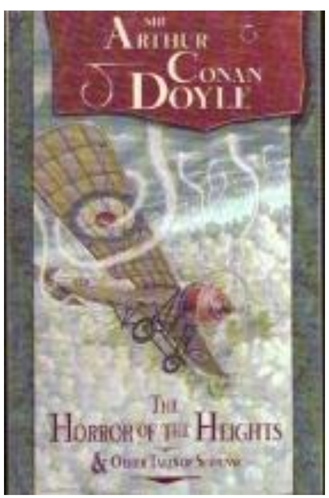


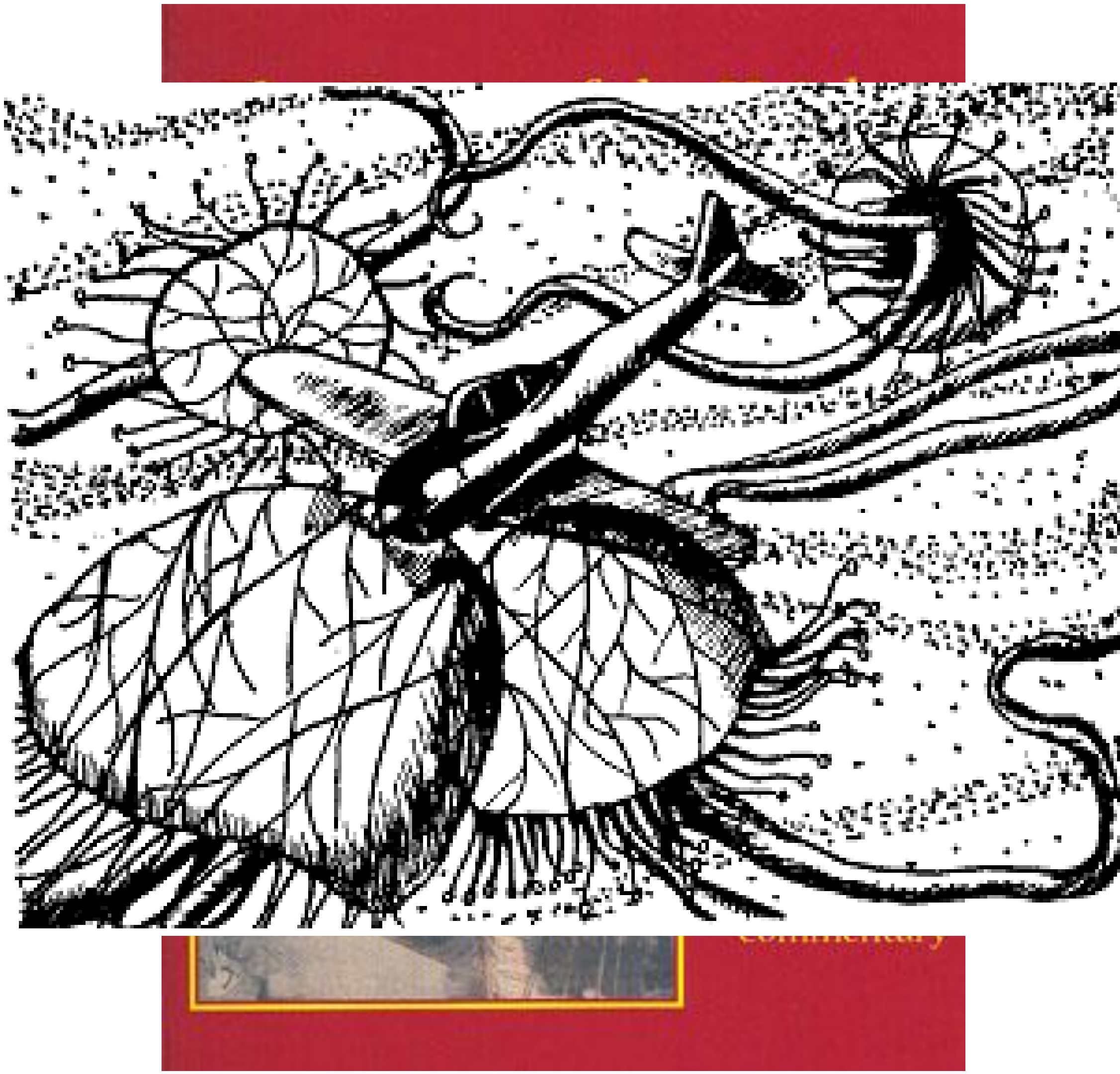
In this talk, I discussed
mass measurements at the LHC
and also showed
what I'm thinking of these days
mainly with Z boson.

The Horror of the Heights (1913)

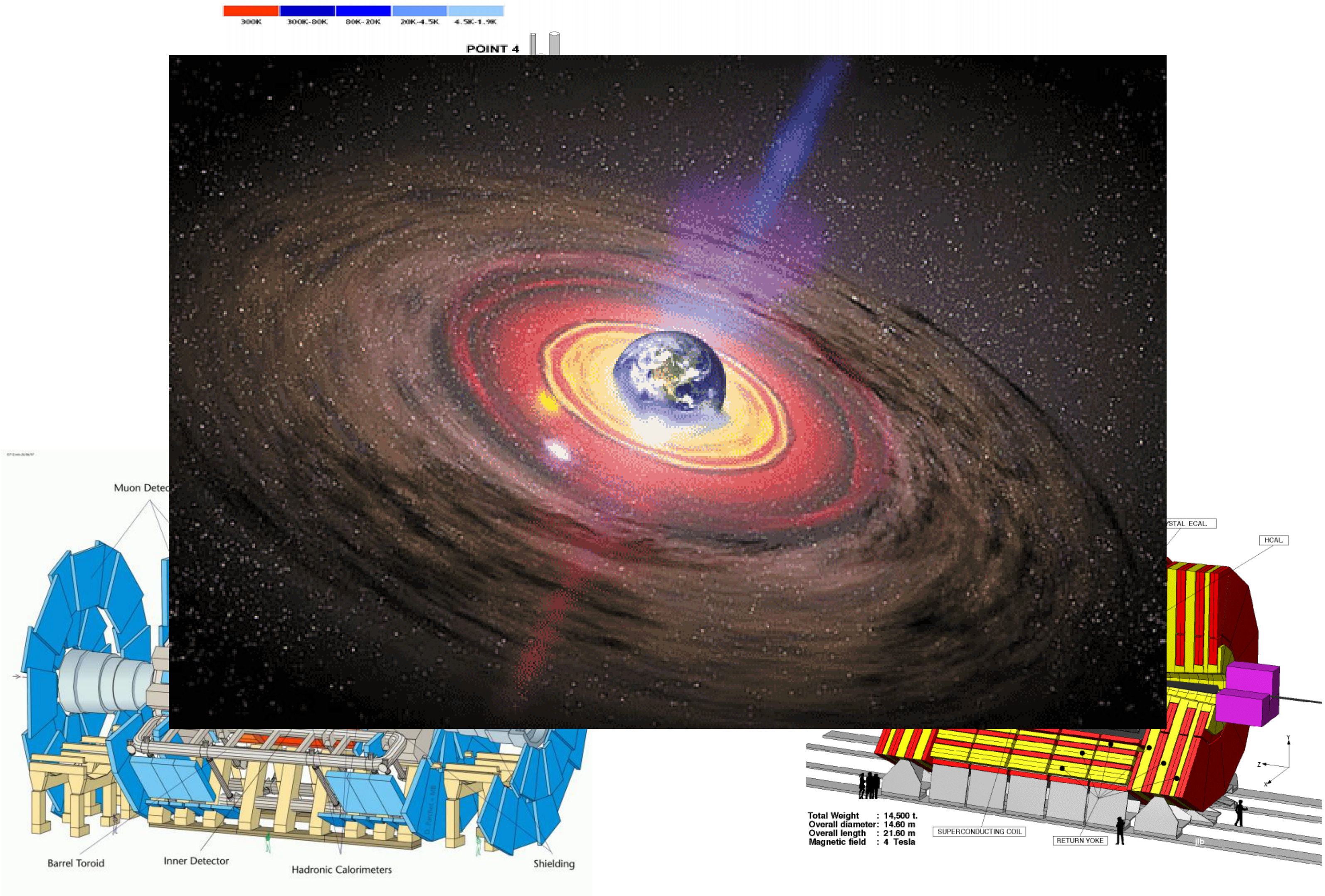


Arther Conan Doyle

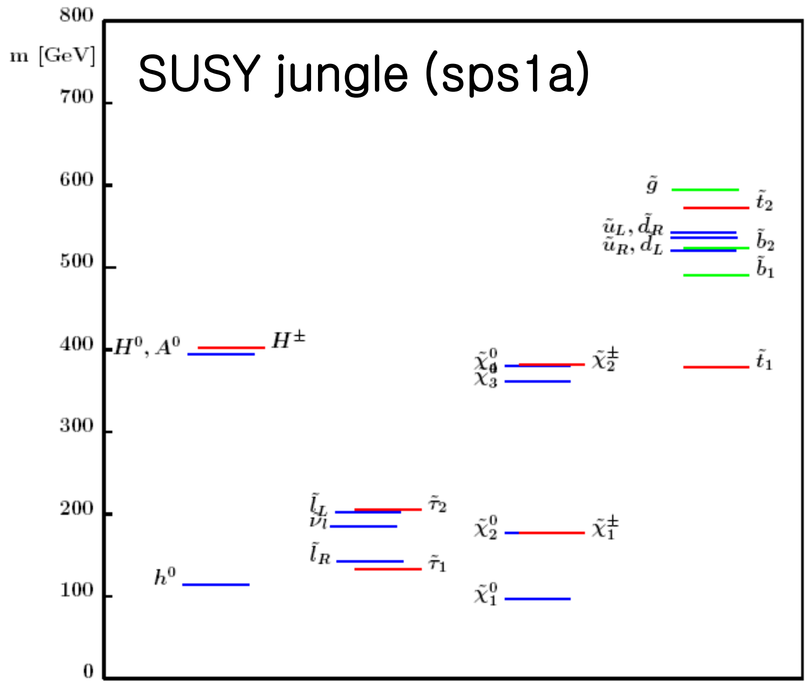




The Horror of the Heights (2008–)



● The Hope of the Heights (2008–)



“ There are jungles of the upper air,
and there are worse things than tigers which inhabit them.
I believe in time they will map these jungles accurately out “

– Armstrong in ‘the Horror of the Height’