# Collider probes of SUSY

Where do we go now with SUSY searches?

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Happening at the Pre SUSY school at SUSY 2014, Manchester.

Let us continue with the case where the new particle decays into various standard model particles including $W/Z$ etc.

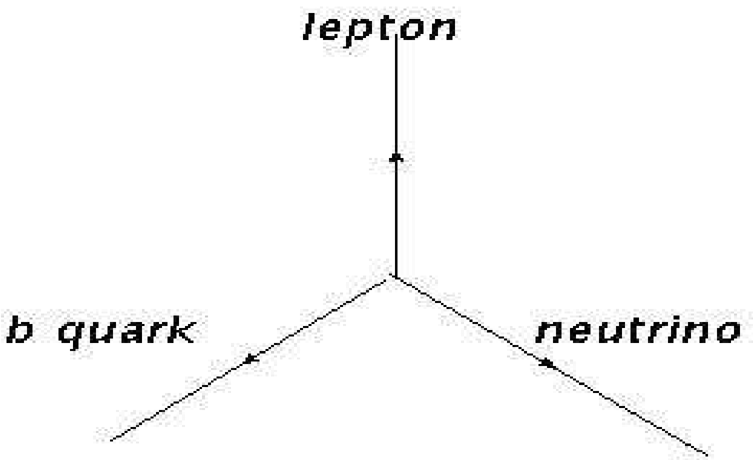
1)Isolation criterion

2)VBF kinematics

3)Jet substructure analysis

Phys. Rev. Lett. 50, 1529, 1983 (R.Godbole, D.P. Roy, S. Pakvasa)

The decay was $Q \to l + \nu + X, X$ being hadron and $Q$ being $D, B$ or $T$. Our observation: Heavier the quark the more 'isolated' the lepton from the 'hadronic' activity! Why did we expect it? Consider the rest frame decay of the $Q$



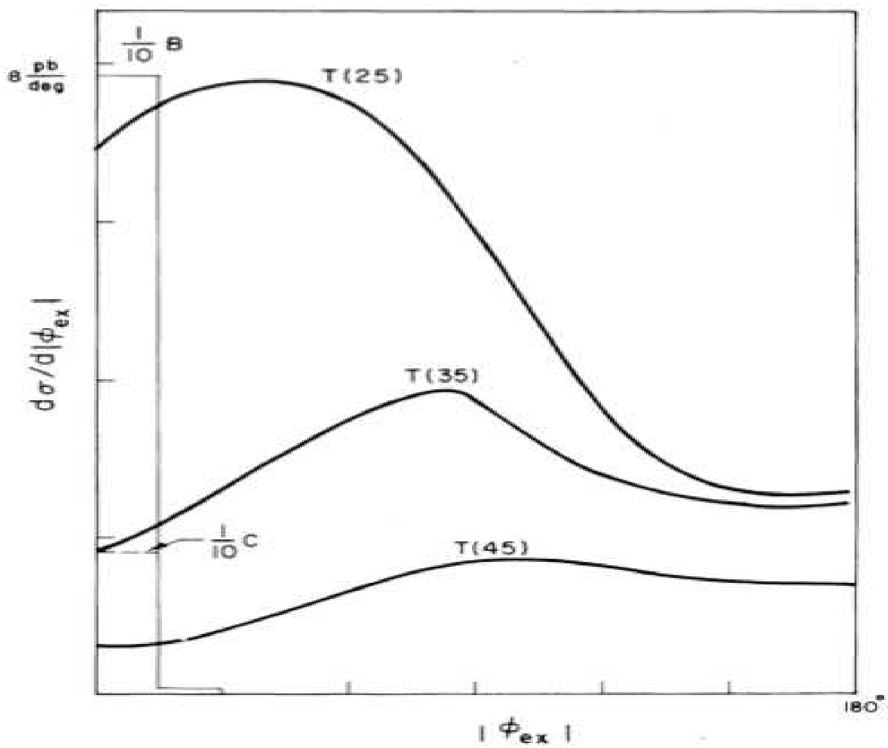

The most likely configuration is this Merceds-Benz star!

In the rest frame the maximum value of $p_T^l = m_Q/3$.

For the lepton to have a large enough $p_T$ to pass the cuts, one needs a larger boost for the lighter quark than for the heavier quark while going to the lab frame.

Larger boosts will coalesce the decay products and reduce the angular separation between the lepton and $X$. The lepton will be 'less' isolated.

**I took this example as this also will relate to the top jet-substructure analysis later!**



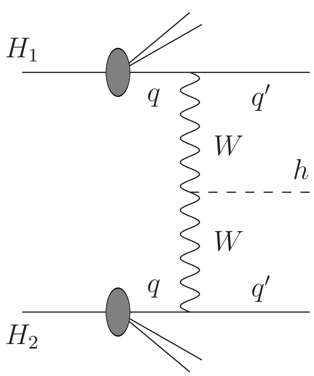

All the high energy leptons from $W/Z/t$ decay are always isolated. Isolation is always used to get good leptons!

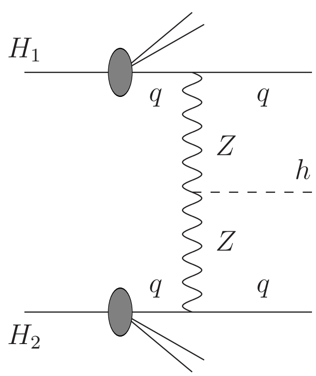
Separation between two particles is measured in terms of: $\Delta R = \sqrt{(\Delta\eta^2 + \Delta\Phi^2)}$

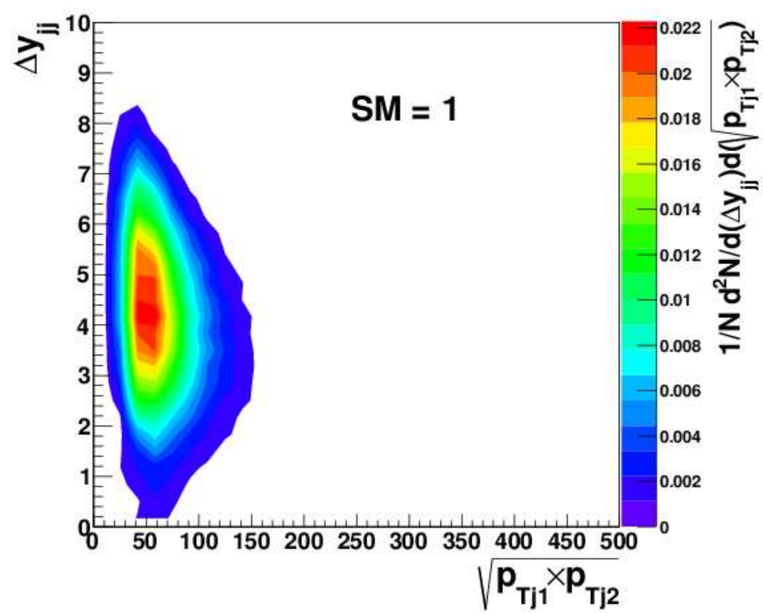
Example of a specific kinematic configuration: large $\Delta\eta$: Rapidity gaps!

Initially suggested by Barger, Han and then studied by Zeppenfeld and collaborators to determine $CP$ property of the Higgs!.

Idea: the two tagging jets will have no hadronic activity between them!



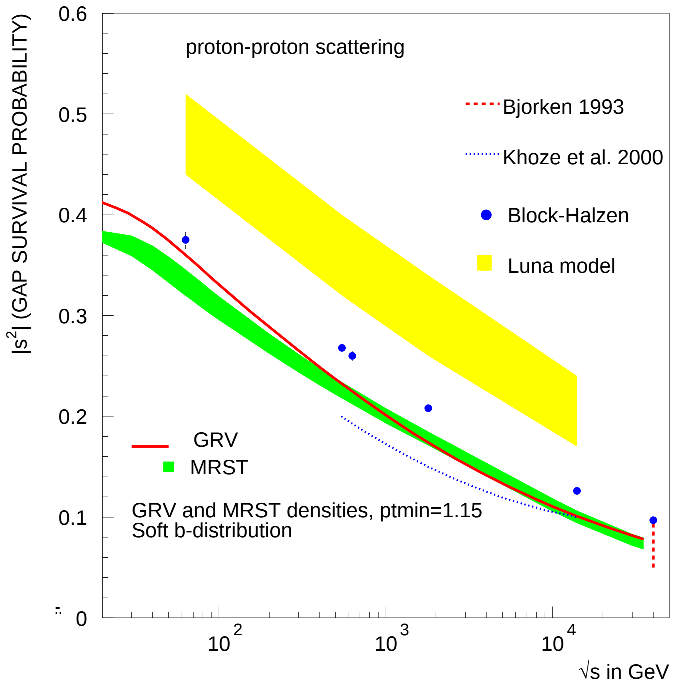
Consider Higgs production via WW fusion processes.

Usually one demands that the the two 'forward' jets have very little hadronic activity among them.

These are called 'large rapidity gap' events.

**Question: How do we decide that the the underlying event does not fill the gap?**

This depends on the models for multi parton interactions in a given collision.




From G. Pancheri, RG et al

In fact more detailed MC simulations show nicely that the large rapidity gap' survives.

We will see how we will use this technique for SUSY searches in the last lecture!

So in general:

To be able to now dig the signal from beneath the bkgd you need accurate calculations of distributions! The MC@NLO, POWHEG... contribute by big progress in this direction too!

Demanding leptons reduces rates. Can one use the hadronic decays of particles? $W \to qq'$, $h \to b\bar{b}$?

This uses an idea initially proposed by M. Seymore and J. Foreshaw in the context of $h \to W^+W^- \to W(\to q\bar{q}')W(\to qq')$.

Idea: In the rest frame of a heavy particle the decay products $q, \bar{q}$ will be well separated and energy shared symmetrically!

If the particle is boosted then they would all coalesce and appear as a fat jet!

**This fat jet will be different from the usual QCD jet.**

QCD jet:

A hard parton produced in the process emits more patrons and all of them appear as a jet of particles!

The process of emission has divergences due to soft and collinear emissions.

Have to identify jets in an infra red safe way! Clustering algorithms.

The energy sharing among the constituents of the QCD jets decided by the QCD splitting function and can be computed in perturbative QCD.

QCD jets different from 'fat' jet coming from hadronic decay of a boosted particle.

How?

The Invariant mass of the 'fat' jet coming from the decay of a heavy particle will be large and when one tries to unwind the fat jet, the constituents of this fat jet will be 'massless'. **Energy sharing between the constituents of the fat jet will be symmetric**

For QCD the constituents of the jets are produced by QCD splitting, energy sharing can not be symmetric AND the drop in the 'jet invariant mass' as one unravels the jets is gradual!

This technology is developing.

Many issues need to be considered:

Effect of multiple parton interactions, effect of underlying events, the particular jet clustering algorithm ....!

Shown by Butterworth and collaborators to work (using MC) for the

$pp \to h + X \to h(\to b\bar{b}) + X$.

I.e QCD background can be killed!

The loss in rate by demanding large $p_T$ of the $h$ is made up by much bigger reduction in QCD background!

Will allow to use hadronic decays of the decay products like $t, W, Z$ and $h$, all of which can be produced with high $P_T$ at higher energies!

Relevance for SUSY searches?

1)R parity violating SUSY: use multi jet final states

2)Use the hadronic decays of $t, W, Z$ to increase the statistics and hence the reach!

**Understanding of QCD and MC development played an extremely important role in developing this variable which is now become an important phenomenological tool!**

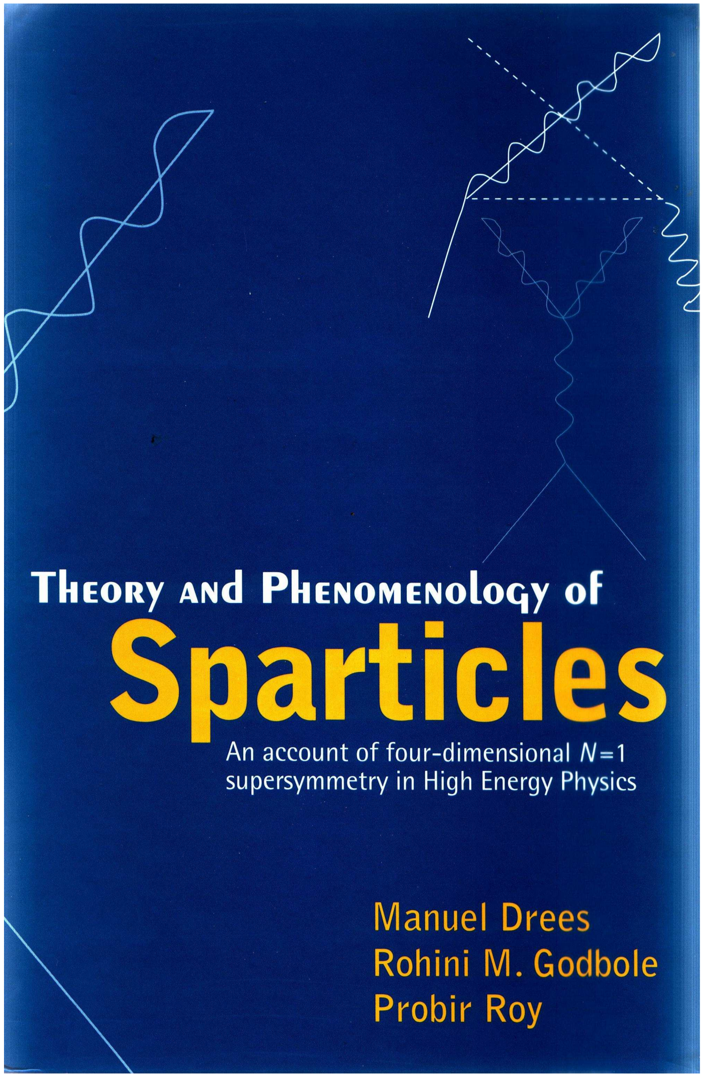
So far we discussed what is to be done if the decay products are high energy leptons, photons OR jets! All visible in the detector!

Now we discuss techniques of 'classic' SUSY phenomenology!

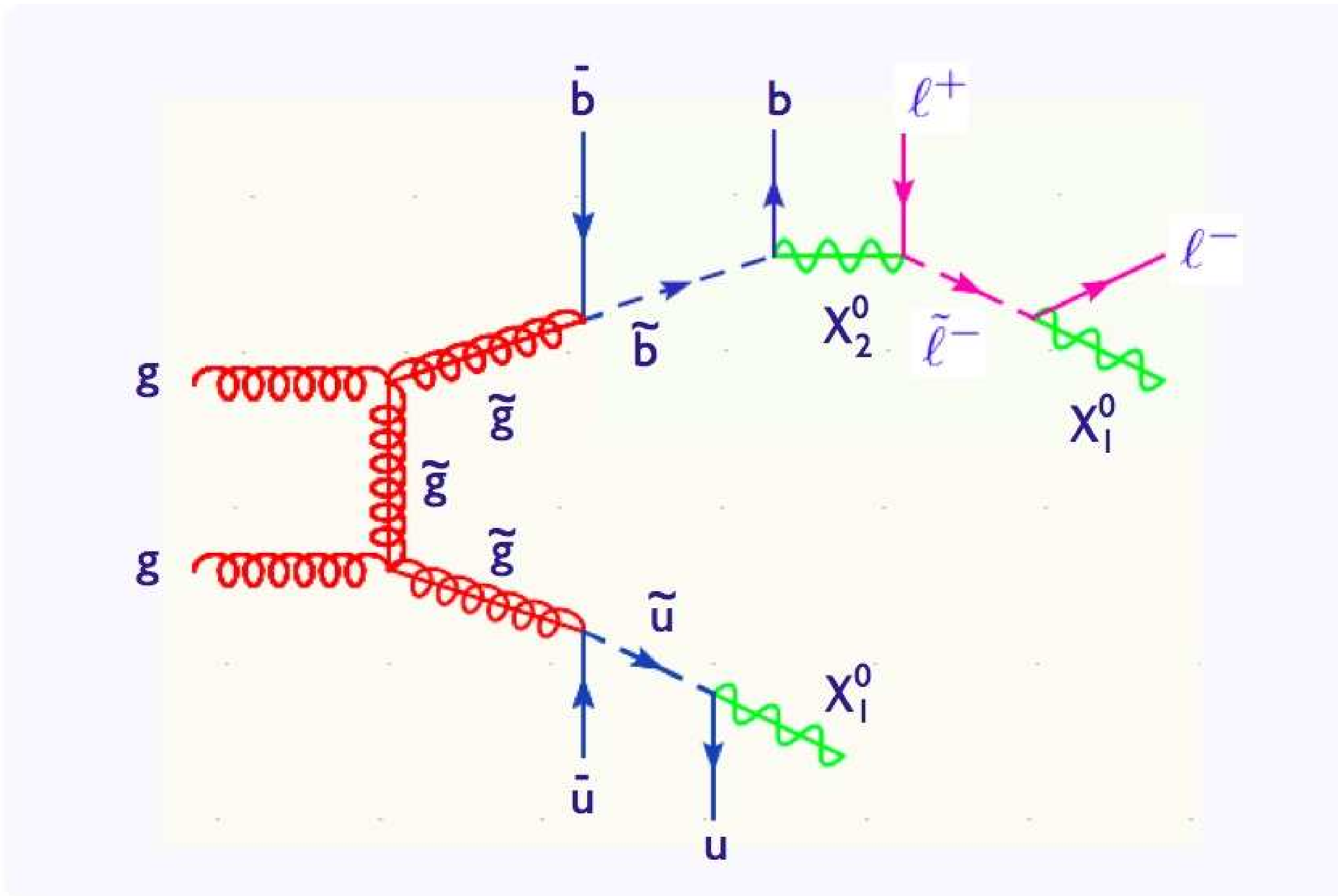
Two aspects:

- Search strategies using the fact that in $R$-parity conserving scenarios LSP is stable and does not decay in the detector!
- How to determine masses of parent gluino/squark when discovered!

Here we will discuss more interesting and recent stuff than in Chapter 15 of Sparticles!



Consider the decay chain:



Since the $\nu$ and the stable LSP will not deposit energy in the detector, there will be missing energy; the amount depending on mass differences $\Delta M = m_{\tilde{g}} - m_{\tilde{q}}$ !

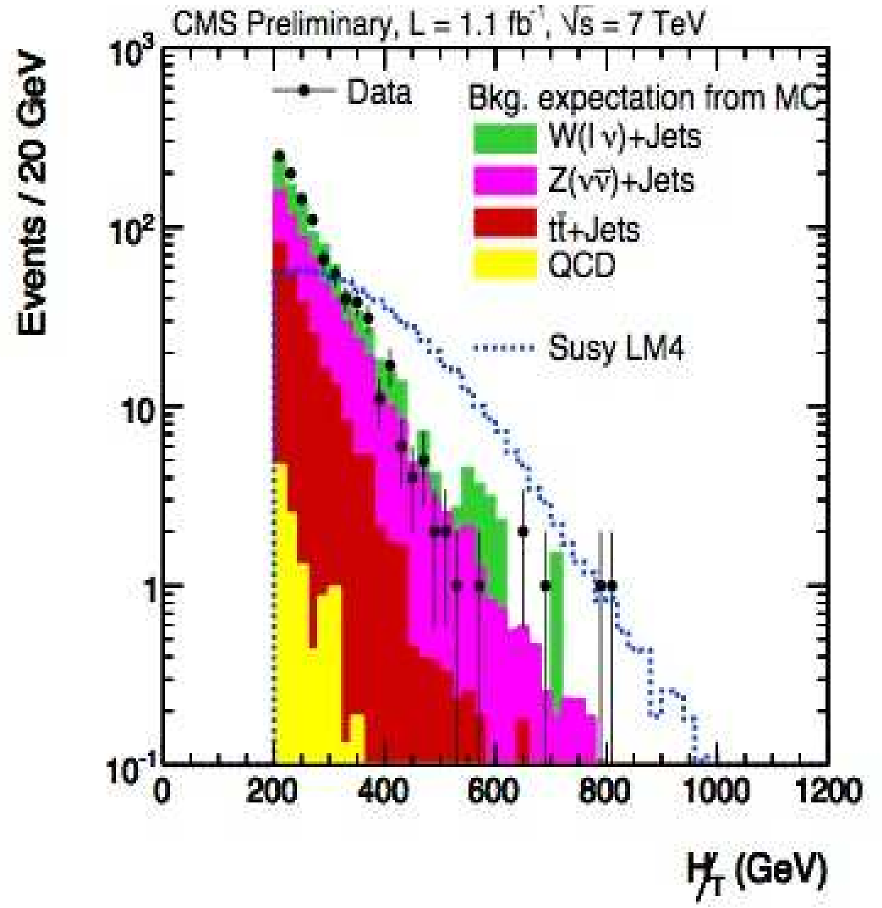
For universal gaugino masses at high scale, $\Delta M$ is always large!

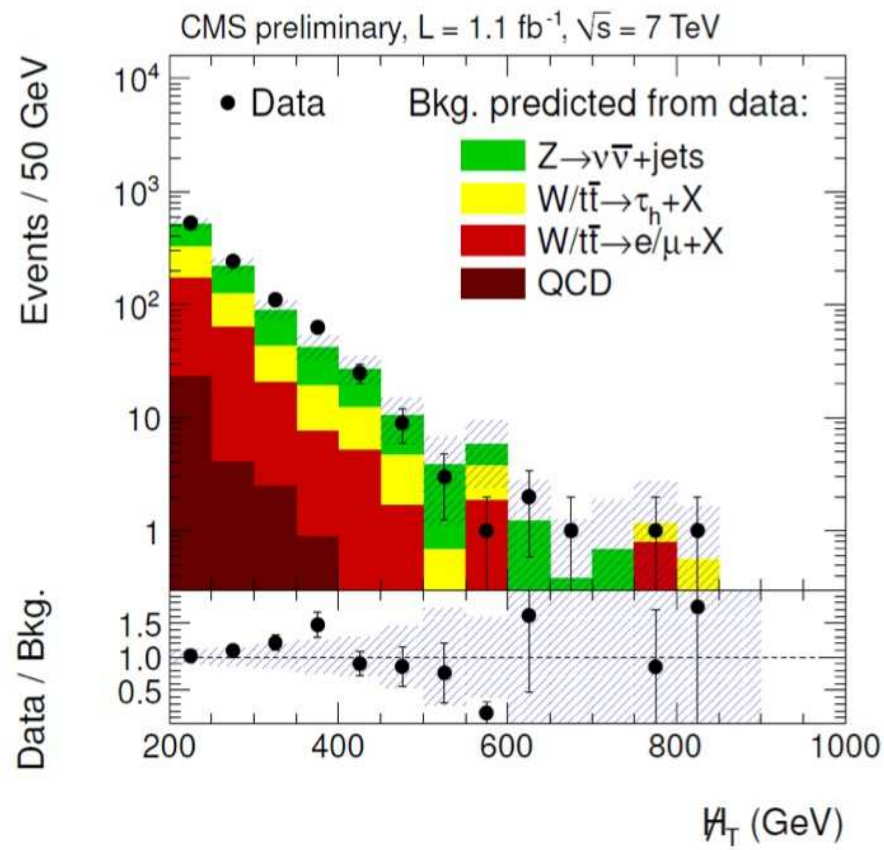
We don't know the longitudinal boost of the initial parton frame. But we do know that transverse momentum $p_T$ is zero!

Define $H_T = \sum |p_T^{vis}|$ ; $\not{H}_T = | - \sum \vec{p}_T^{vis}|$

Look for an excess above the SM expectations.

Consider events where everything decays hadronically to increase the signal event rate! (at first go).

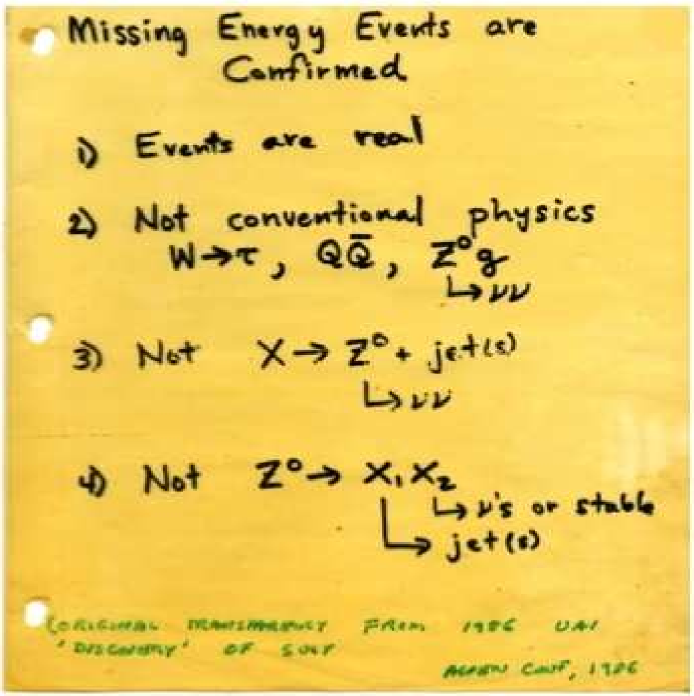



(CMS-SUS-PAS-004)

# Irreducible backgrounds: An historical example

In the 80's the UA1 experiment performed a search for Events with a single jet and Etmiss>40 GeV




They found a number of events In excess of SM expectations

This was interpreted as the Possible sign for the production of a 40 GeV gluino

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# The Altarelli Cocktail (S.Ellis, Kleiss, Stirling)

cuts. We are thus able to sum the contributions of MANY SMALL sources which were absent in previous studies and which can, in the sum, yield a sizeable result. These are the "many roads" of the title. [This concern, that many small numbers can yield a large sum, was colourfully voiced at the meeting by G. Altarelli who described his vision of a mixture of small effects -- the Altarelli cocktail -- leading to the observed signal.] Before proceeding to the

Table

all event selection cuts.

Data

| Process | Events (total) | Events with $L_\tau<0$ | Events with $L_\tau<0$ and $E_T^{jet}<40$ GeV |
|---|---|---|---|
| $W\to e\nu$<br>$W\to\mu\nu$<br>$W\to\tau\nu\to$ leptons | 3.6 | 2.0 | 1.4 |
| $W\to\tau\nu$, $\tau\to\nu\bar{\nu}$ + hadrons | 36.7 | 8.0 | 7.1 |
| $W\to c\bar{s}$ | <0.1 | <0.1 | <0.1 |
| $Z^0\to\tau^+\tau^-$ | 0.5 | 0.1 | 0.1 |
| $Z^0\to\nu\bar{\nu}$ (3 neutrino species) | 7.4 | 7.1 | 5.6 |
| $Z^0\to c\bar{c}$ and $b\bar{b}$ | <0.1 | <0.1 | <0.1 |
| $c\bar{c}$ and $b\bar{b}$ (direct production) | 0.2 | 0.2 | 0.2 |
| Jet fluctuations (fake missing energy) | 3.8 | 3.4 | 3.4 |
| Data | 56 | 24 | |
| TOTAL | 52.2 | 20.8 ± 5.1 ± 1.0 | 17.8 ± 3.7 ± 1.0 |

Lesson: before claiming new Physics

- Be sure that you have considered everything in your background estimate
- Validate theoretical predictions using your data

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# Performing estimates

## Still Ellis Kleiss and Stirling

The processes $p+\bar{p} \rightarrow W^{\mp}, Z^{\circ} + 0,1,2$ jets are studied in the context of the observation of events with large missing $E_T$ at the CERN $p\bar{p}$ collider. The conclusion is that vector bosons which decay into undetected or unidentified leptons can constitute a non-negligible source of such events. By correlating these unidentified decays with those in which the leptons are identified we can, in principle, eliminate the theoretical uncertainties in such perturbative QCD calculations.

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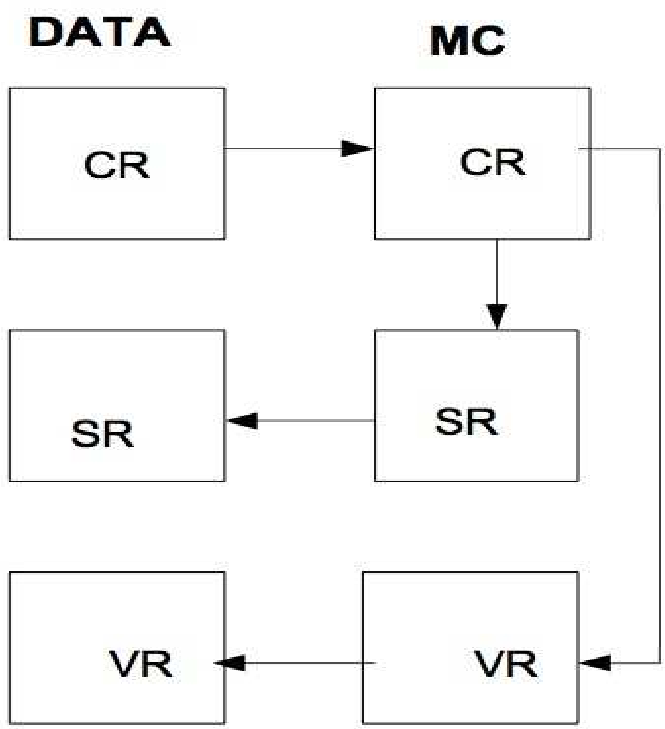
# Background predictions: CR method




Control Region: CR
No signal expected

Signal Region: SR
Where signal is expected

Validation Region (VR)
No signal expected

Transfer factor (TF)=

N(MC,SR)*/N(MC,CR)

N(DATA,SR)=N(DATA,CR)*TF

**Key is clever Choice of CR**

**Estimate relies on the MC to predict TF correctly**
**Use VR to give you confidence on prediction**

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The background can be from $Z \to \nu\bar{\nu}$ + jets

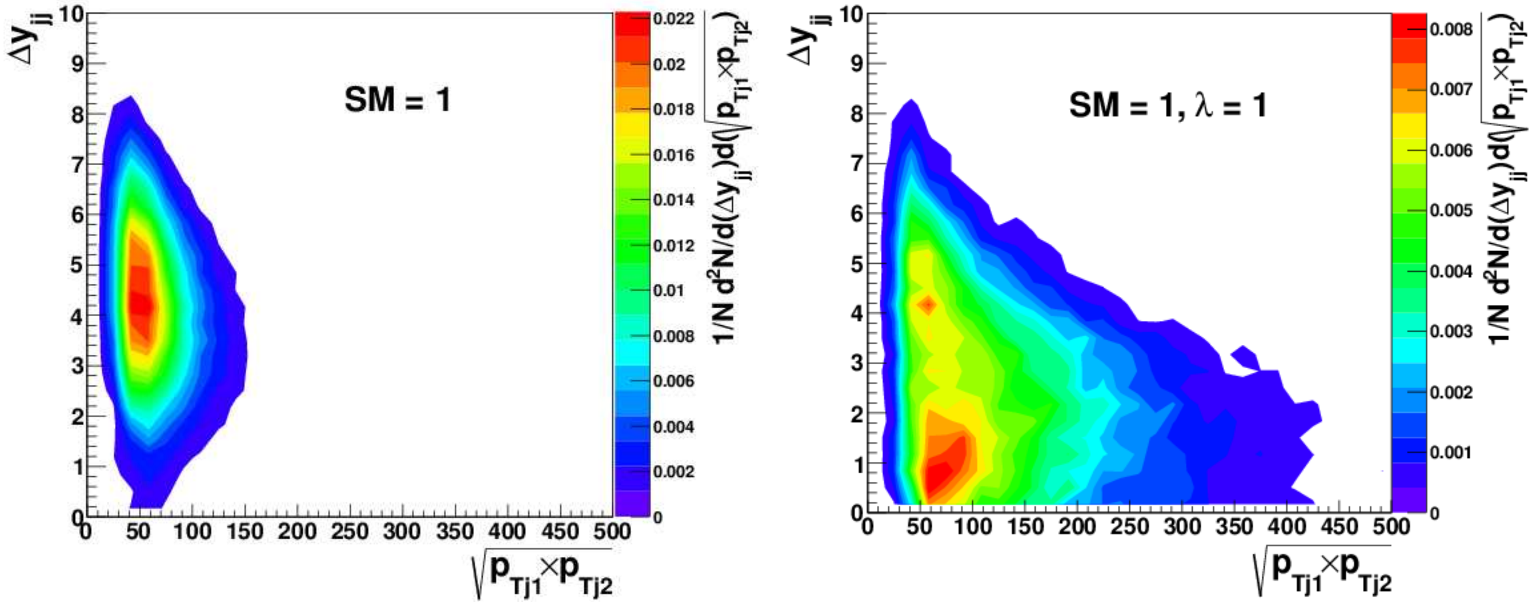
Idea: measure $Z + jets$ events where $Z \to l^+l^-$ with similar kinematics of jets, remove the leptons from the events and calculate missing $E_T$.

Use this to now estimate the background, rather than the calculation.

Warning: Number of events of $Z \to l^+l^-$ is much smaller than those for $\nu\bar{\nu}$.

Why: BR $(Z \to \nu\bar{\nu}) \sim 3\times$ BR $(Z \to l^+l^-)$ $(l = e, \mu)$ AND leptons will suffer from detection efficiencies.

Existence of new physics may have modified the control distributions! I give an example from Higgs physics:




LHS: Expectations from the SM

RHS: If the Higgs had anomalous couplings. If we use the region at low $\Delta y_{jj}$ as control region and it was populated by a nonstandard contribution? Do we background away new physics?

Do both:

use the SM calculations to calculate the background in the signal region

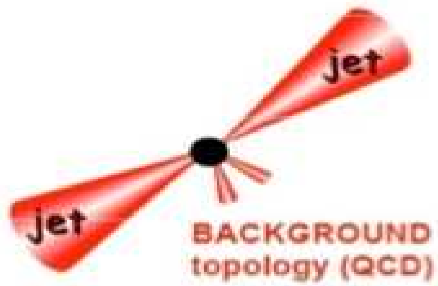
Use data driven background estimates.

That is what is meant by validation.

See talk by Isabell Melzer Pelleman (CMS) at Pre SUSY 2010 Talk by G. Polesello, Lectures given at school in ICTP.

## $\alpha_T$

$$\alpha_{\rm T} = \frac{p_{\rm T}^{j2}}{\sqrt{H_{\rm T}^2 - \not{H}_{\rm T}^2}} \qquad H_{\rm T} = \sum_j |\overrightarrow{p_{\rm T}}| \qquad \not{H}_{\rm T} = |\sum_j \overrightarrow{p_{\rm T}}|$$




Jets are back-to-back in $\phi$

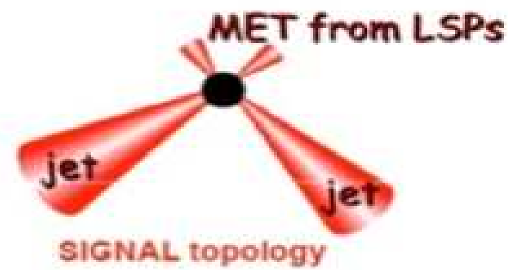
$$\alpha_{\rm T} = 0.5$$

in the case of an imbalance in the measured $p_{\rm T}$s of back-to-back jets

$$\alpha_{\rm T} < 0.5$$

when the two jets are not back-to-back and balancing genuine MET

$$\alpha_{\rm T} > 0.5$$

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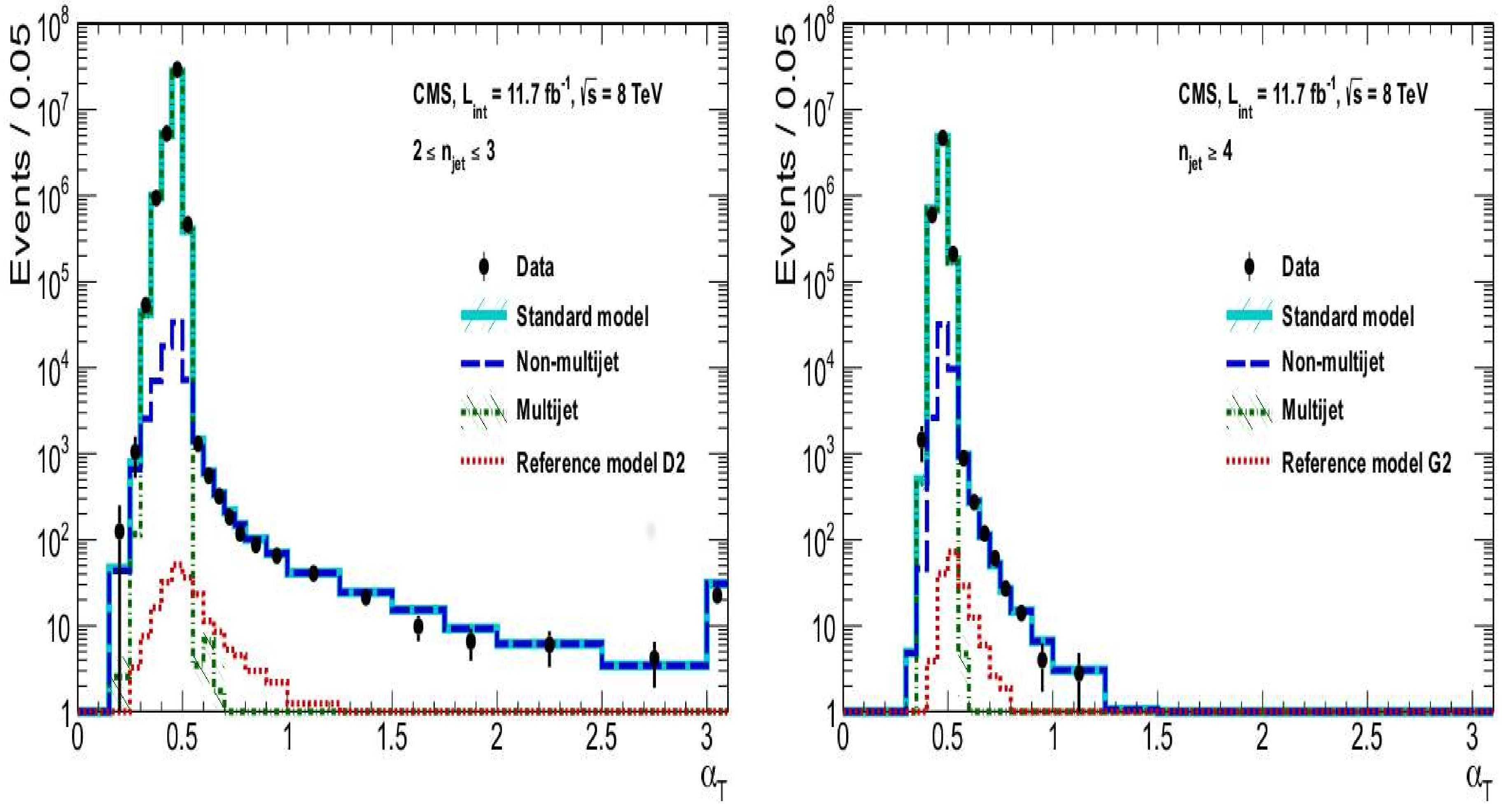



Idea extended to multijet. Works! (1303.2985)

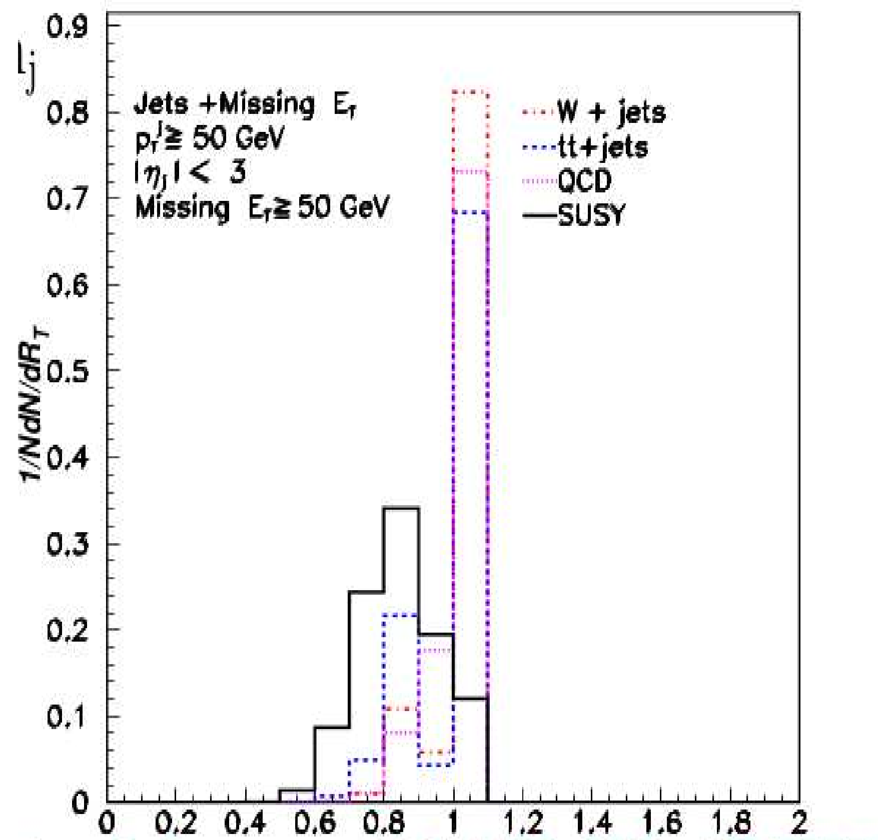
$$T_T = max_{\vec{n}_T} \frac{\Sigma_i |\vec{p}_{T,i}.\vec{n}_T|}{\Sigma_i |\vec{p}_{T,i}|}$$

For pencil like or back to back events(QCD): $\hat{n}$ lies along the jet axis $T(\tau = 1 - T) \sim 1(0)$

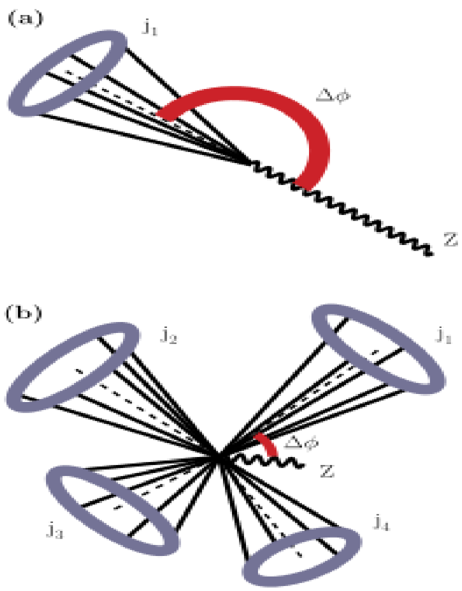
Isotropic configurations $T(\tau) << 1$(Predominant in SUSY processes).

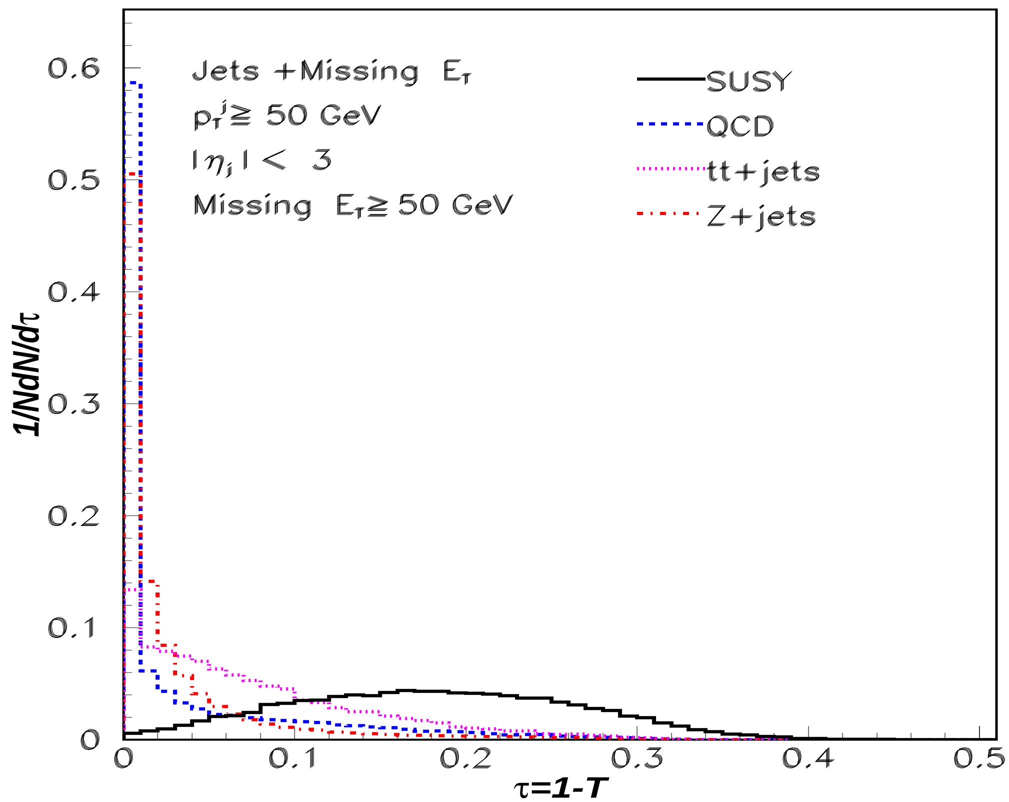
Infrared safe.

M. Guchait, D. Sengupta, R. Chatterjee: 1206.5770



Transverse Thrust: To Suppress QCD, Z($\rightarrow \nu\bar{\nu}$)+1,2 jet, $W(\rightarrow l\nu)$ +1,2 jet.



1) Measurement of production cross-section. Use accurate theoretical prediction for it and determine the mass.

model dependent!

2)Kinematically. For example

a) $t \rightarrow bW \rightarrow bq\bar{q}'$ . Invariant mass of the all the final state decay particles will give $m_t$.

b) $R \rightarrow l^+l^-$.

model independent

If $R \to l^+ l^-$ then it is easy.

What for $pp \to X + W(\to e\nu_e)$?

$m^2_{e\nu}$ is the invariant mass of the $e\nu$ system $(p_e + p_\nu)^2 = m^2_{\nu e}$. $\hat{\sigma}$ will have a the Breit-Wigner propagator $\frac{1}{(m^2_W - m^2_{e\nu})^2 + \Gamma^2_W m^2_W}$.

$\vec{p}_W = \vec{p}_e + \vec{p}_\nu$ We measure only $p_e$ (also $\mu$).

$W$ produced at the collider, subprocess $q + \bar{q}' \to W \to e\nu_e$

Means $\vec{p}_{Te\nu} = 0$.

Define what is called transverse mass. Call $\vec{\not p}_T = \vec{p}_T^{\nu}$, then

$\vec{\not p}_T = -\sum \vec{p}_T^{vis}$

Define $m_{e\nu T}^2 \simeq 2 E_{eT} \not E_T (1 - cos\phi_{e\nu})$

$E_{eT}, E_{\nu T}$ are defined using only the transverse momenta given by $E_{eT} = \sqrt{p_{eT}^2 + m_e^2}$ etc.

1)This observable is bounded by the real mass of the $M_W$ (see on the next slide)

2)The distribution has a peak near $M_W$.

The distribution then has a sharp end point at $m_W$ and a peak. This happens due to the propagator in the subprocess $q\overline{q}' \to W \to \nu_e e$ also simple jacobean of transformation.

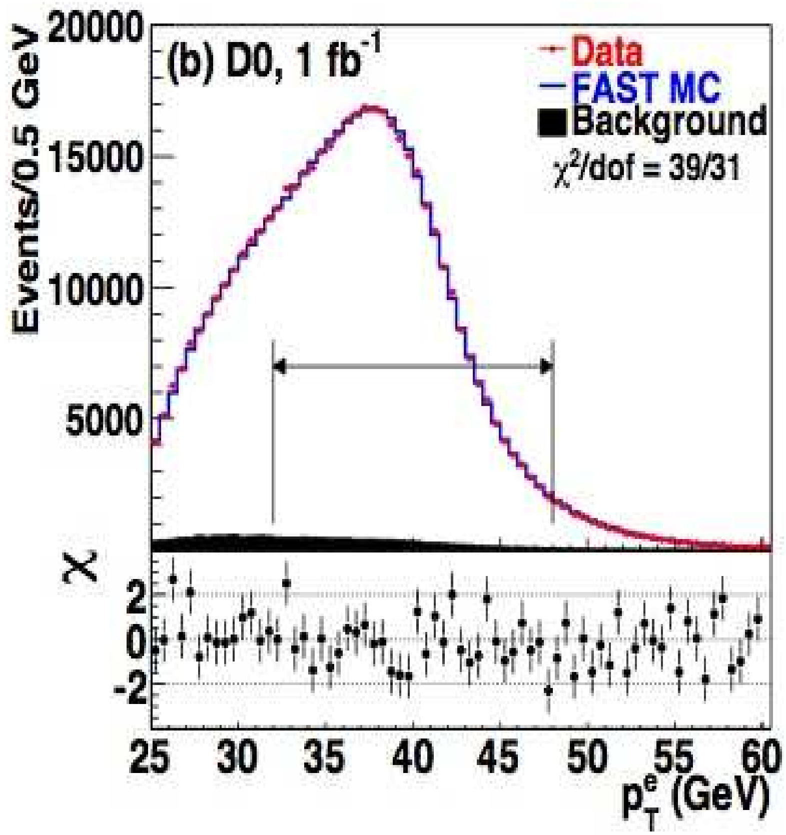
$$\frac{d\hat{\sigma}}{dm^2_{e\nu T}dm^2_{e\nu}} \propto \frac{1}{\sqrt{m^2_{e\nu} - m^2_{e\nu T}}}$$

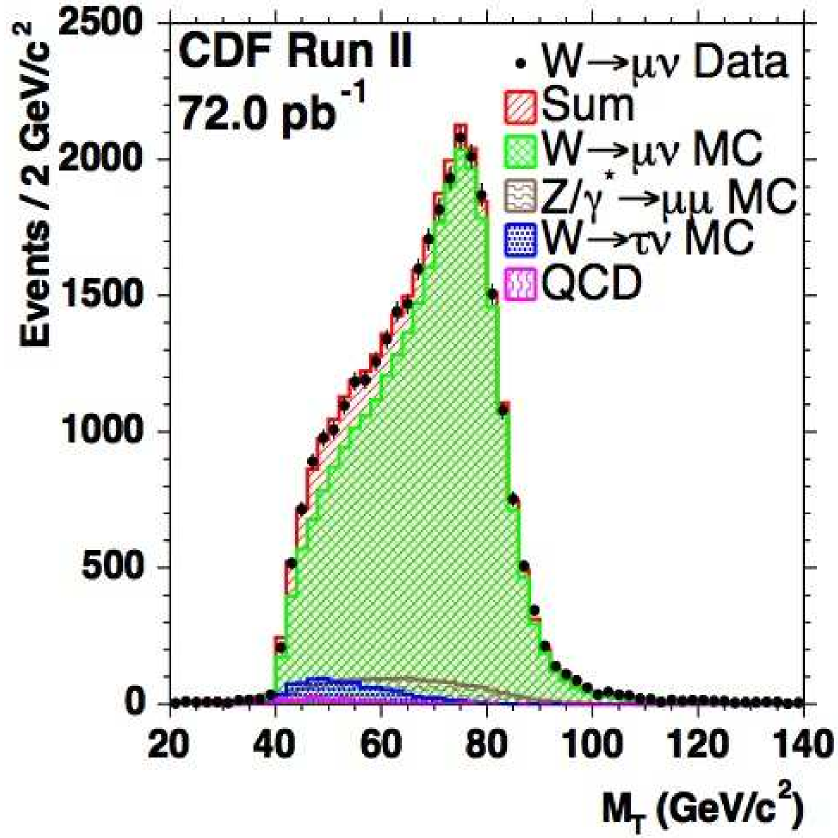
By studying the $m_{e\nu T}$ distribution one can then determine $M_W$.

One can also use $p_{eT}$ distribution. Peak of that distribution depends on $m_W$. However, the measurement is model dependent as the $p_{eT}$ distribution gets affected by transverse motion of the $W$. So some model dependence.

Use of $m_{e\nu T}$ distribution is model independent as it can only shift the distribution downwards!

Both used at the Tevatron!


(b) D0, 1 fb$^{-1}$
Data
FAST MC
Background
$\chi^2$/dof = 39/31
Events/0.5 GeV
χ
$p_T^e$ (GeV)


CDF Run II
72.0 pb$^{-1}$
W→μν Data
Sum
W→μν MC
Z/γ*→μμ MC
W→τν MC
QCD
Events / 2 GeV/c$^2$
$M_T$ (GeV/c$^2$)

# $\mathbf{M_{T2}}$

Let us define $m_T$ first : Consider the decay $A \rightarrow B\,\tilde{\chi}$

$$m_A^2 = m_B^2 + m_{\tilde{\chi}}^2 + 2(E_{TA}E_{T\tilde{\chi}}\cosh(\Delta\eta) - \mathbf{p}_{TB}\cdot\mathbf{p}_{T\tilde{\chi}})$$

$$\eta = \frac{1}{2}\ln[(E+p_z)/(E-p_z)]$$

$$E_T = \sqrt{\mathbf{p}_T^2 + m^2}$$

$\cosh(\Delta\eta) \geq 1$ ⇓

$$m_A^2 \geq m_B^2 + m_{\tilde{\chi}}^2 + 2(E_{TA}E_{T\tilde{\chi}} - \mathbf{p}_{TB}\cdot\mathbf{p}_{T\tilde{\chi}})$$

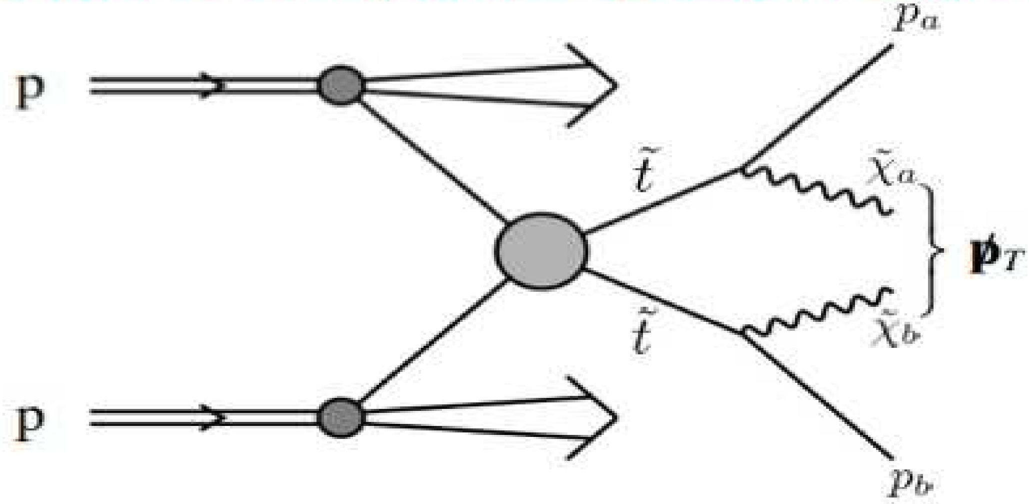
⇓

$$m_A \geq \underbrace{\sqrt{m_B^2 + m_{\tilde{\chi}}^2 + 2(E_{TA}E_{T\tilde{\chi}} - \mathbf{p}_{TB}\cdot\mathbf{p}_{T\tilde{\chi}})}}_{m_T(\mathbf{p}_{TB},\,\mathbf{p}_{T\tilde{\chi}})}$$

for given $m_B$, $m_{\tilde{\chi}}$

2

**Now consider a decay with two sources of missing energy :**

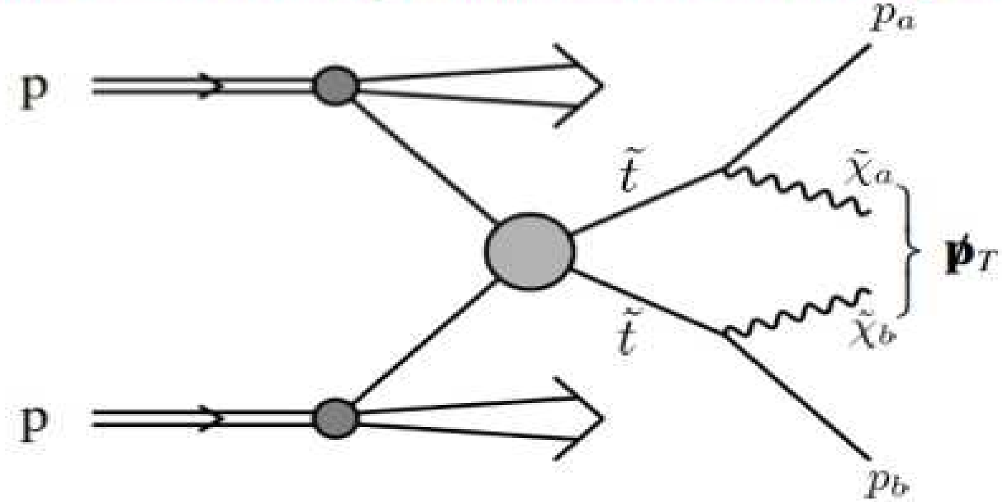



C. G. Lester and D. J. Summers, 1999

$$\not{\mathbf{p}}_T = \mathbf{p}_{T\tilde{\chi}_a} + \mathbf{p}_{T\tilde{\chi}_b}$$

**Now consider a decay with two sources of missing energy :**

C. G. Lester and D. J. Summers, 1999

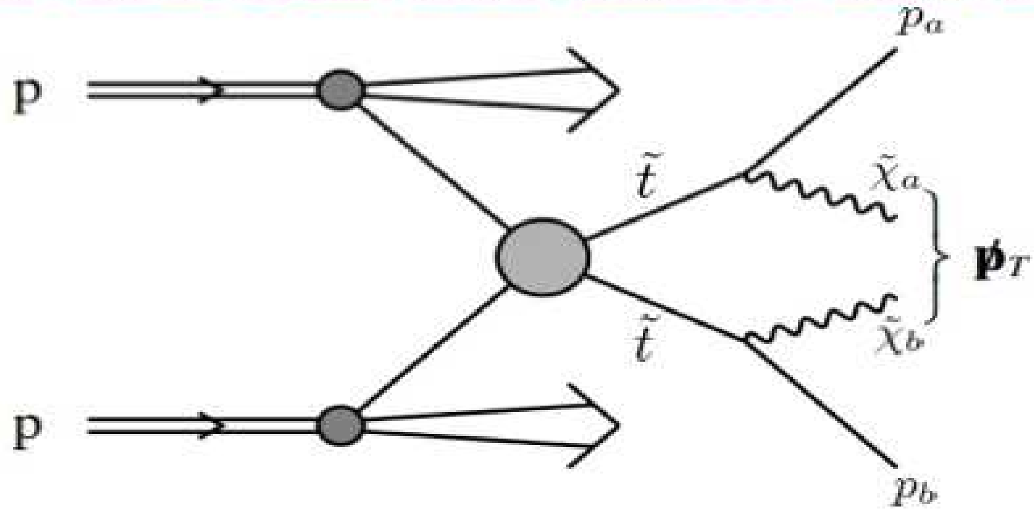



$$\not{\mathbf{p}}_T = \mathbf{p}_{T\tilde{\chi}_a} + \mathbf{p}_{T\tilde{\chi}_b}$$

$$m_{\tilde{t}} \geq \qquad m_T(\mathbf{p}_{Ta}, \mathbf{p}_{T\tilde{\chi}_a})$$

4

**Now consider a decay with two sources of missing energy :**

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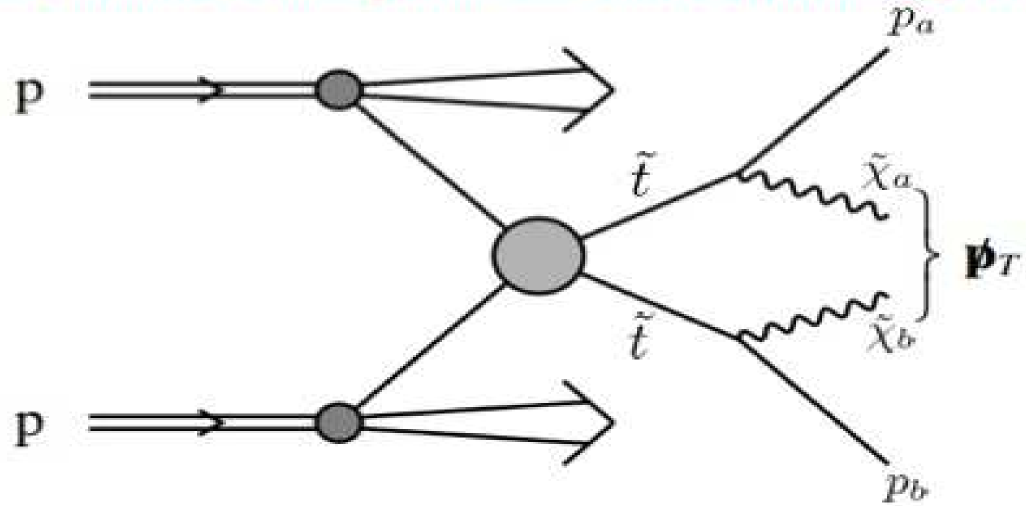
$$\not{\mathbf{p}}_T = \mathbf{p}_{T\tilde{\chi}_a} + \mathbf{p}_{T\tilde{\chi}_b}$$

$$m_{\tilde{t}} \geq \quad \{m_T(\mathbf{p}_{Ta}, \mathbf{p}_{T\tilde{\chi}_a}), m_T(\mathbf{p}_{Tb}, \mathbf{p}_{T\tilde{\chi}_b})\}$$

**Now consider a decay with two sources of missing energy :**

C. G. Lester and D. J. Summers, 1999

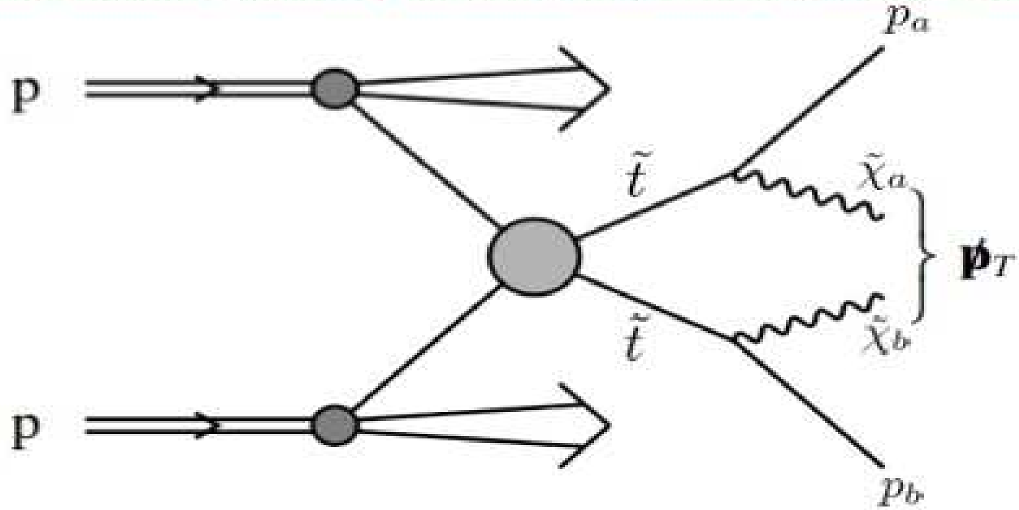



$$\not{\mathbf{p}}_T = \mathbf{p}_{T\tilde{\chi}_a} + \mathbf{p}_{T\tilde{\chi}_b}$$

$$m_{\tilde{t}} \geq \max\{m_T(\mathbf{p}_{Ta}, \mathbf{p}_{T\tilde{\chi}_a}), m_T(\mathbf{p}_{Tb}, \mathbf{p}_{T\tilde{\chi}_b})\}$$

6

**Now consider a decay with two sources of missing energy :**




C. G. Lester and D. J. Summers, 1999

$$\not{\mathbf{p}}_T = \mathbf{p}_{T\tilde{\chi}_a} + \mathbf{p}_{T\tilde{\chi}_b}$$

$$m_{\tilde{t}} \geq \max\{m_T(\mathbf{p}_{Ta}, \mathbf{p}_{T\tilde{\chi}_a}), m_T(\mathbf{p}_{Tb}, \mathbf{p}_{T\tilde{\chi}_b})\}$$

$$m_{\tilde{t}} \geq \underbrace{\min_{\not{\mathbf{p}}_T = \not{\mathbf{p}}_{T1} + \not{\mathbf{p}}_{T2}} \left[\max\{m_T(\mathbf{p}_{Ta}, \not{\mathbf{p}}_{T1}), m_T(\mathbf{p}_{Tb}, \not{\mathbf{p}}_{T2})\}\right]}_{M_{T2}(\mathbf{p}_{Ta}, \mathbf{p}_{Tb}, \not{\mathbf{p}}_T)}$$

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Of course we hope it can be used to determine the mass once we find the SUSY particle.

But for now it is still useful to reduce the background!

For example one can reduce the $t\bar{t}$ background as the variable for the background would have an upper limit at a known value and one could cut that region out!

# BACKUP

Older story: Time 1979:

$b$ quark had been found. Big effort to make sure that it was part of a doublet as it aught to be if anomalies had to cancel.

Look for the $t$ quark at the $p\bar{p}$ collider through a large $p_T$ lepton produced in the three body decay of $t \to b\nu e^-$

Note at this point it was not even known that $t$ is so heavy that it decays before hadronisation and that there is no $T$meson.

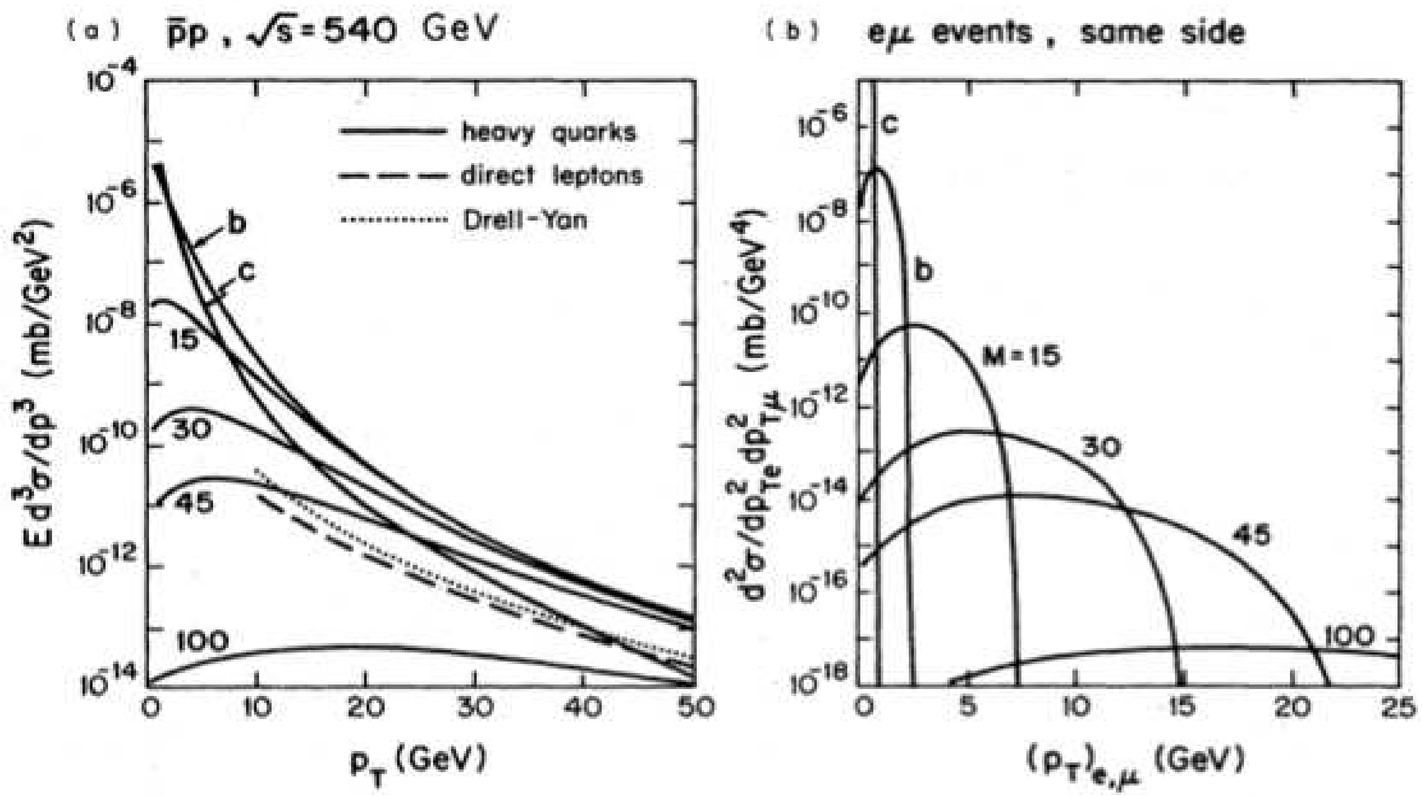
At a hadronic collider one could produce $t\bar{t}$ pair via $q\bar{q}$ and $gg$ collisions.

Halzen et al: (Phys. Rev. D 20, 1979)

**"as almost any high-pt lepton originating from the semi-leptonic decay of a heavy quark can be simulated by the semi-leptonic decay of a ligther quark produced with a relatively larger transverse momentum. In lowest-order perturbative QCD the two keep matching each other's cross sections**."

In simple words the backgrounds from the lighter 'heavy quarks' will always make it difficult to find the signal from $T$ and hence perhaps one should look for 'dileptons'

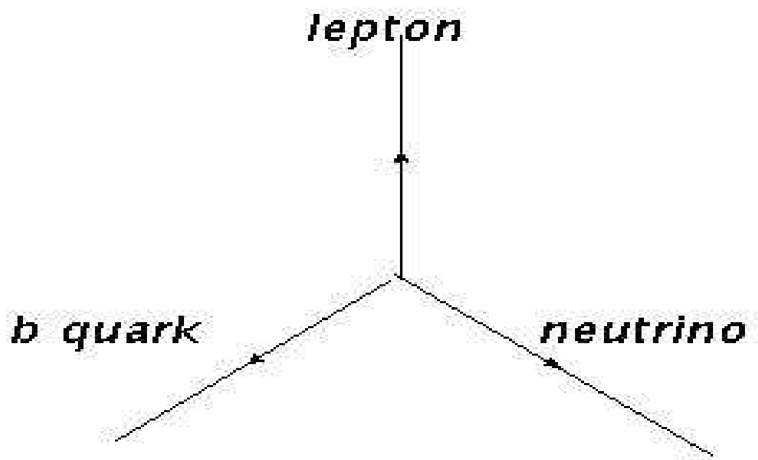
From the branching ratios one knows the rates for 'dileptons' differ by a factor of about a factor 5 to 6.




The predictions were for the S$p\bar{p}$ S which actually 'discovered' the $W, Z$. Conclusion: choosing a lepton and large $p_T$ was not enough. You had to increase the number of leptons to reduce background!

Phys. Rev. Lett. 50, 1529, 1983 (R.Godbole, D.P. Roy, S. Pakvasa)

The decay was $Q \to l\nu + X, X$ begin hadron and $Q$ being $D, B$ or $T$. Our observation: Heavier the quark the more 'isolated' the lepton from the 'hadronic' activity! Why did we expect it? Consider the rest frame decay of the $Q$



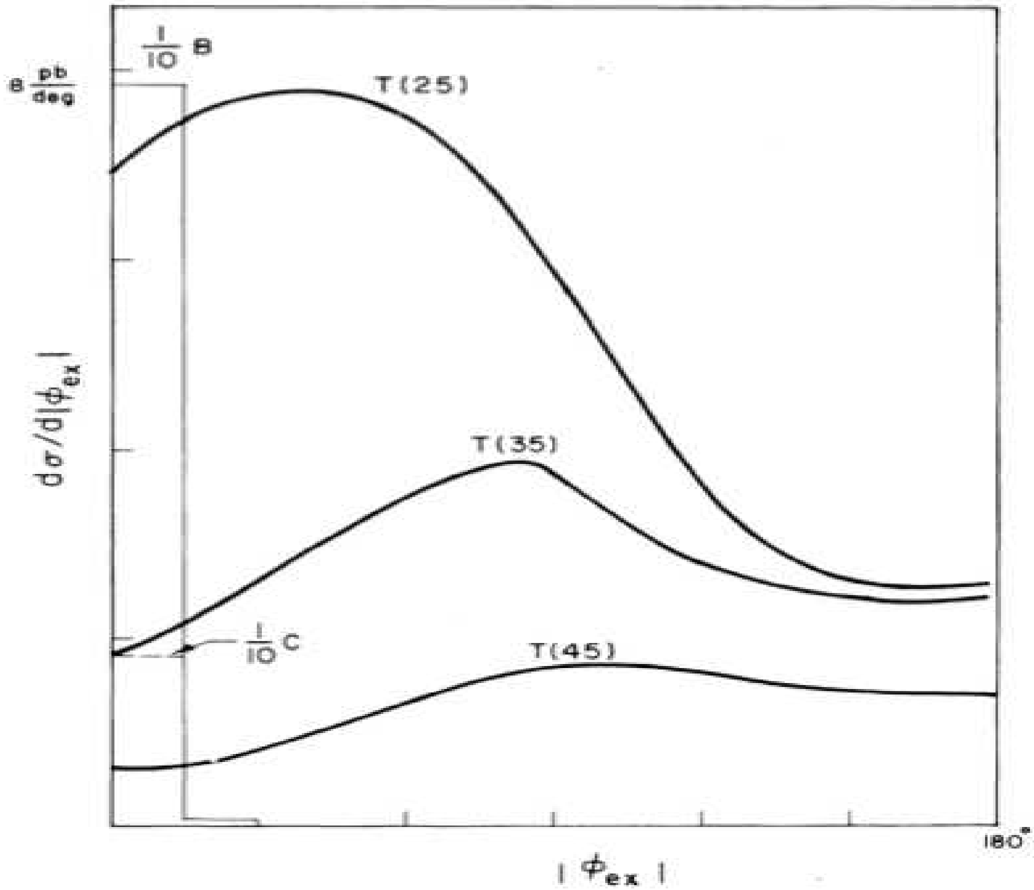

The most likely configuration is this Merceds-Benz star!

In the rest frame the maximum value of $p_T^l = m_Q/3$.

For the lepton to have a large enough $p_T$ to pass the cuts, one needs a larger boost for the lighter quark than for the heavier quark while going to the lab frame.

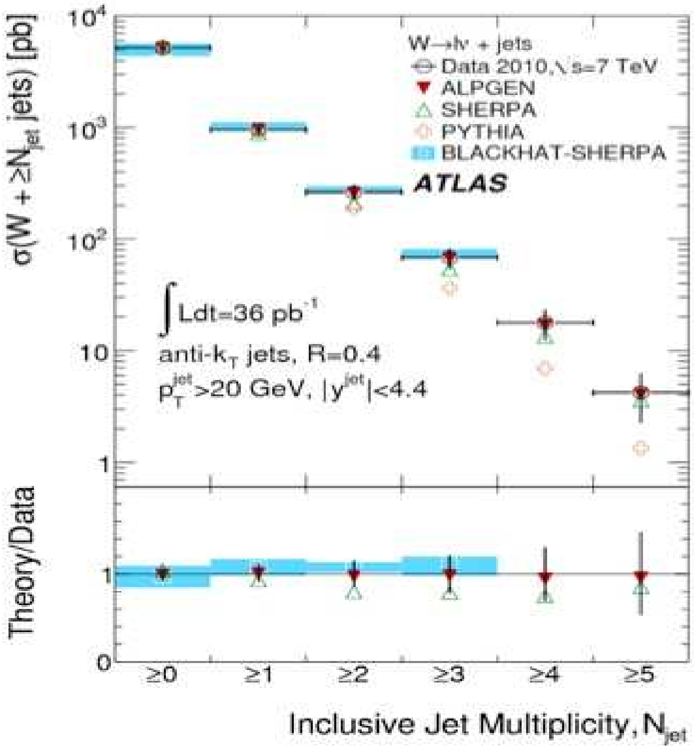
Larger boosts will coalesce the decay products and reduce the angular separation between the lepton and $X$. The lepton will be 'less' isolated.

**I took this example as this also will relate to the top jet-substructure analysis later!**




Now that now a days all the leptons are from $W/Z/t$ decay they are always isolated. Any way isolation is always used to get good leptons!

# V+JETS AT THE LHC




Working amazingly well!

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