Performing a SUSY Analysis
(from the experimentalist's point of view)

Isabell-A. Melzer-Pellmann

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Bonn

DESY

HELMHOLTZ | GEMEINSCHAFT

UHH

Overview

- Search for Supersymmetry – a recipe:
  - Do we search for a certain model? (Is it important for the analysis?)
  - Event selection – In which channels do we perform the search? (Choose your favorite final states!)
  - What are the interesting observables to isolate SUSY signals?
  - Do we understand the remaining background? (This is the worst/interesting part…)
  - How can we stay model independent?
  - Do we understand our systematic uncertainties?

Outline

SUSY models

- Event selection
- Interesting observables
- Background determination
- Model independent searches
- Systematic uncertainties

Which Model do we look for?

- Is it important? – YES!
  - Different masses – different phase space – different search region – different final state particles to search for…
- Do theorists like experimentalists using models? – NO!
  - In general theorists prefer to see the plain observation of deviations from SM (if any!) and draw their own conclusions concerning their favorite model
- But:
  - We need some model for our Monte Carlo Simulations (e.g. for acceptance calculations)
  - If we don't see anything, we (the experimentalists) also like to set limits, and limits can only be set on certain models…
- Model independent analysis?
  → possible if we compare many distributions to SM expectation

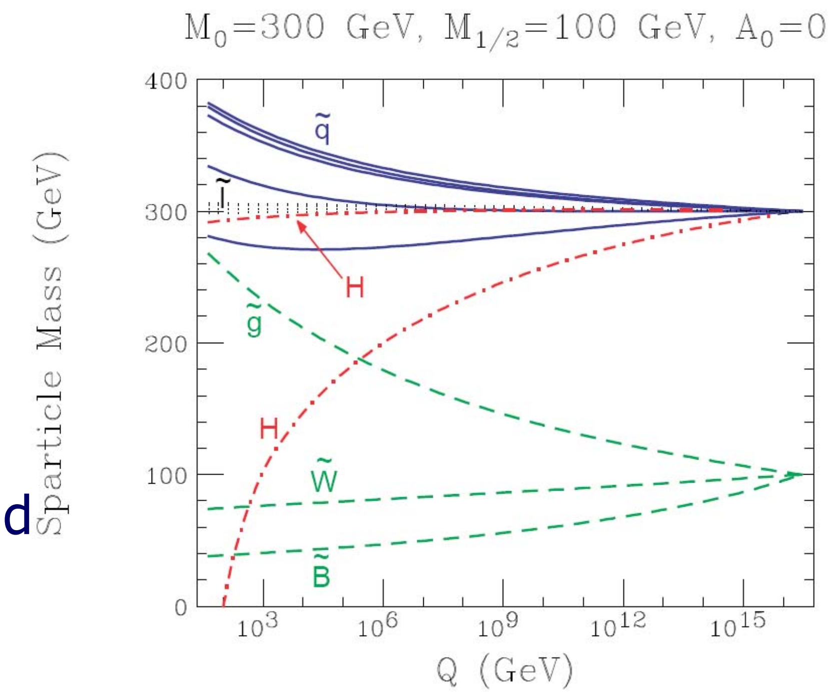
Minimal SuperSymmetric Model

MSSM: no particular SUSY breaking mechanism assumed, parametrisation of possible soft SUSY-breaking terms

- relations between dimensionless couplings unchanged
- cancellation of large quantum numbers preserved

Most general case: 105 new parameters!

- Difficult to predict due to the large number of free parameters
- Try to reduce number of parameters, e.g. by putting universal boundary conditions at GUT scale (running masses equal to running coupling constants) – CMSSM
- Impose R-Parity conservation to forbid proton decays and other problems



R-Parity

R-parity is defined as:

$R = (-1)^{2S+3B+L}$ with S: Spin, B: baryon number, L: lepton number

R=1: SM particle

R=-1: SUSY particle

If R-parity is conserved

→ Single SUSY particle cannot decay into just SM particles

→ Lightest SUSY particle (LSP) absolutely stable

→ LSP candidates are: lightest neutralino, lightest sneutrino, gravitino

→ Important for your analysis: LSP carries away energy from the detector

→ Missing transverse energy signature!

SUSY breaking scenarios

We know SUSY is a broken symmetry – but how?
Different theories about the hidden sector on the market:

Hidden sector	→	Visible sector
SUSY breaking	→	MSSM

- SUGRA:
  - mediating interactions are gravitational
- GMSB:
  - mediating interactions are ordinary electroweak and QCD gauge interactions
- AMSB, Gaugino-mediation:
  - SUSY breaking happens on different brane in a higher-dimensional theory
- ... (many more models, that I will unfortunately not cover)

Let's have a closer look at these different scenarios and possible signatures to search for…

SUGRA

Mediating interactions are gravitational ⇔ connection of gravity and electroweak physics

- SUGRA with universality assumptions → mSUGRA

  → Lightest SUSY particle (LSP) is usually the lightest neutralino

  → Neutralino escapes unseen → missing energy signature

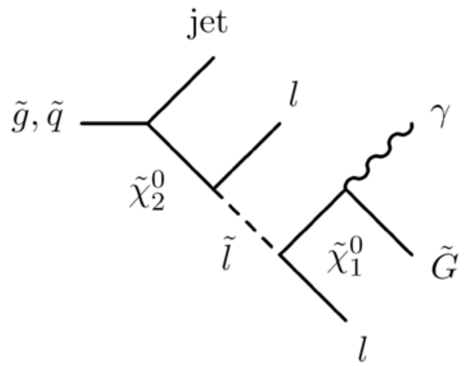
GMSB

Gauge-mediated symmetry breaking: mediating interactions are ordinary electroweak and QCD gauge interactions

- Gravitino is always the LSP, neutralino or $\tilde{\tau}$ NLSP (possibly long-living if masses are degenerate)
  - If neutralino is NLSP, decay modes are
  - $\tilde{\chi}^0 \rightarrow \gamma\, \tilde{G}$, $\tilde{\chi}^0 \rightarrow h\tilde{G}$ or $\tilde{\chi}^0 \rightarrow Z\tilde{G}$

    NLSP might decay into LSP inside or even outside(!) detector

  → look for photons (if you have a good calorimeter, like ATLAS, check if they are not pointing to primary vertex)



- If $\tilde{\tau}$ is NLSP

  → $\tilde{\tau}$ could be long-lived charged particle, with $\tilde{\tau} \rightarrow \tau\, \tilde{G}$

  → interesting signature (searches for heavy stable charged particles)

AMSB

- Anomaly-mediated symmetry breaking: SUSY breaking happens on a different brane in a higher-dimensional theory
- Typical scenario is mass degeneracy between lightest neutralino and chargino
- LSP could be neutralino or sneutrino
- Decays can be
  - Chargino → pion and neutralino (if accessible, otherwise large lifetime possible, could even reach muon chambers)
  - Chargino → lepton and sneutrino

Which Model-Parameters to choose?

Idea:

→ Choose a set of benchmark points that are representative of a range of topologies and areas of phase space

Good starting point were the Snowmass Points and Slopes (SPS) 2001/02:

- Set of benchmark points and parameter lines in the MSSM parameter space corresponding to different scenarios
- Agreed upon as a consensus based on different existing proposals for post-LEP benchmarks

arXiv:hep-ph/0202233v1

2004 an improved determination of the allowable range of the cold dark matter density obtained by combining WMAP and other cosmological data lead to different benchmark points

arXiv:hep-ph/0306219

CMS and ATLAS traditionally looked mainly into benchmark points in mSUGRA (of course not all with the same parameters, but surprisingly they share one common point!)

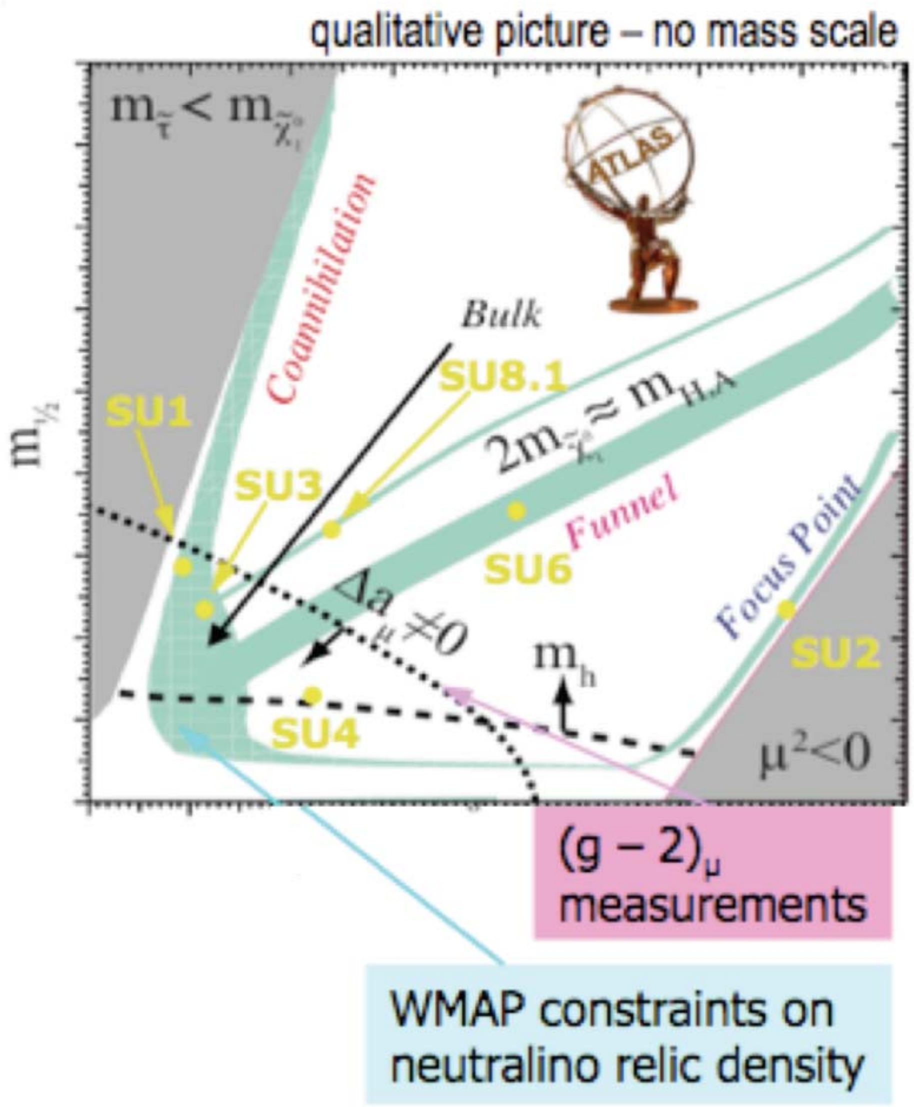
Reminder: mSUGRA

- In mSUGRA the MSSM parameters are reduced to 4 parameters and 1 sign:
- $m_{1/2}$: universal gaugino mass
- m_0: universal scalar mass
- A_0: universal soft breaking trilinear coupling constant (higgs-sfermion-sfermion)
- $\tan\beta$: ratio of the VEVs of the two Higgs doublets
- sign μ: sign of the Higgsino mass parameter (bilinear higgsino coupling constant)

ATLAS Benchmark Points

- ATLAS points in mSUGRA are chosen to be roughly consistent with observed cold dark matter density

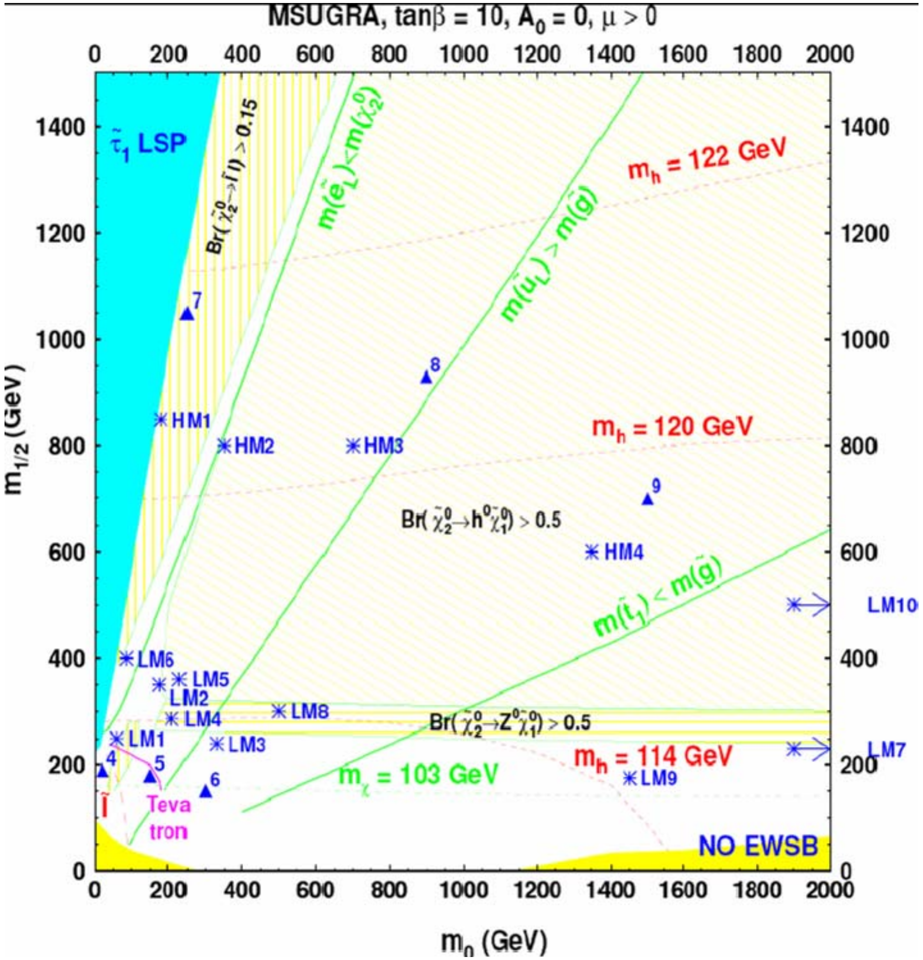
- SU1: Coannihilation region with nearly degenerate neutralino and slepton
- SU2: Focus point region near boundary where $\mu^2<0$, so light Higgsinos which annihilate efficiently
- SU3: Bulk region: relatively light sleptons enhance LSP annihilation
- SU4: Low mass point close to TeVatron bound



CMS Benchmark Points

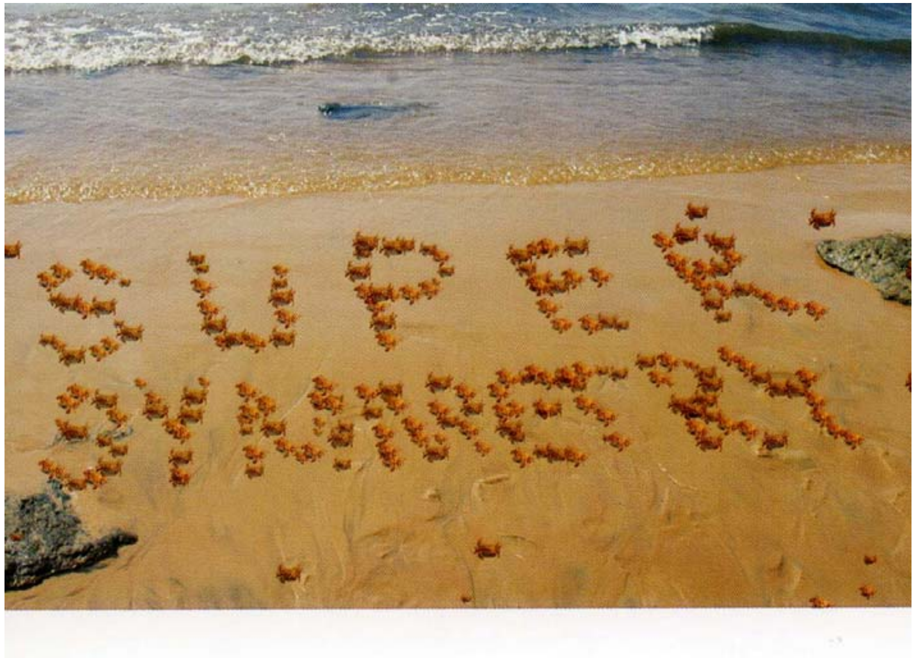
Interesting for our nearer future are the Low Mass (LM points)
The High Mass (HM) points are close to the ultimate LHC reach…

Model	Cross Section (pb)	m_0 (GeV)	$m_{1/2}$ (GeV)	A_0	$\tan\beta$
LM0	110	200	160	-400	10
LM1	16.06	60	250	0	10
LM2	2.42	185	350	0	35
LM3	11.79	330	240	0	20
LM4	6.70	210	285	0	10
LM5	1.94	230	360	0	10
LM6	1.28	85	400	0	10
LM7	2.90	3000	230	0	10
LM8	2.86	500	300	-300	10
LM9	11.58	1450	175	0	50



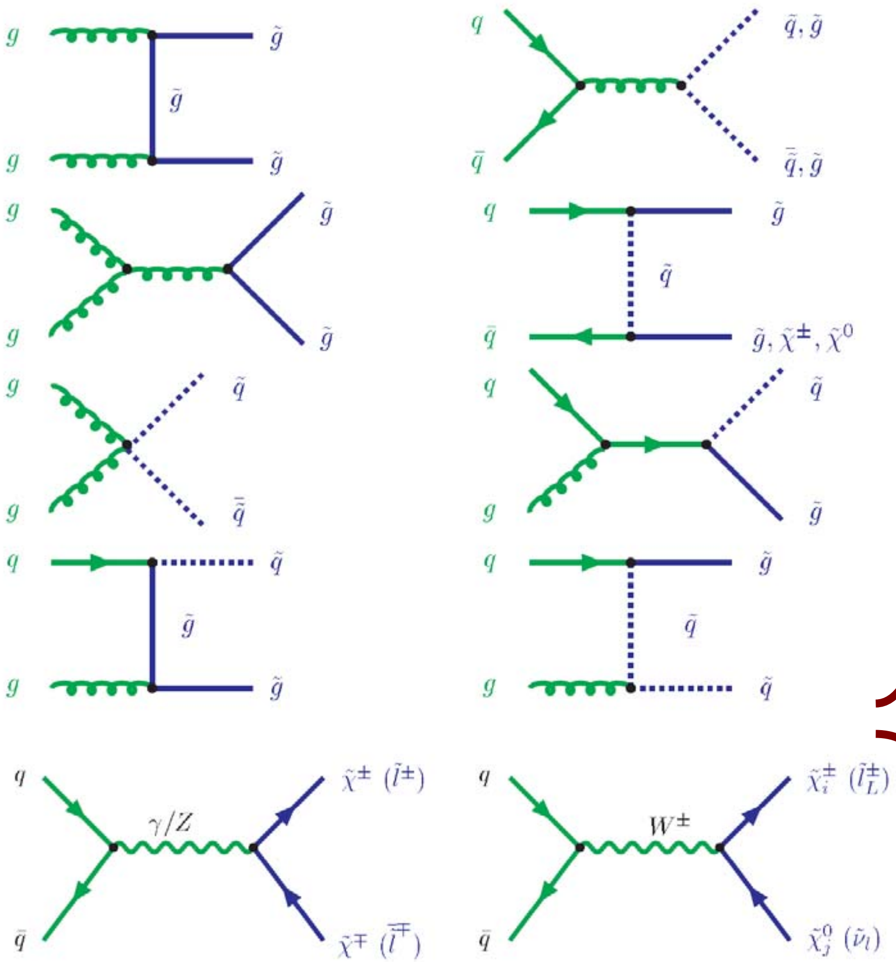
Where we are…

- SUSY models
- **Event selection**
  - SUSY signatures
  - Detectors
  - Typical selection cuts
- Interesting observables
- Background determination
- Model independent searches
- Systematic uncertainties



Sparticle Production at LHC

- Main production processes at LHC energies:



Gluon fusion, quark anti-quark and quark-gluon scattering

Annihilation (similar to e^+e^- channels)

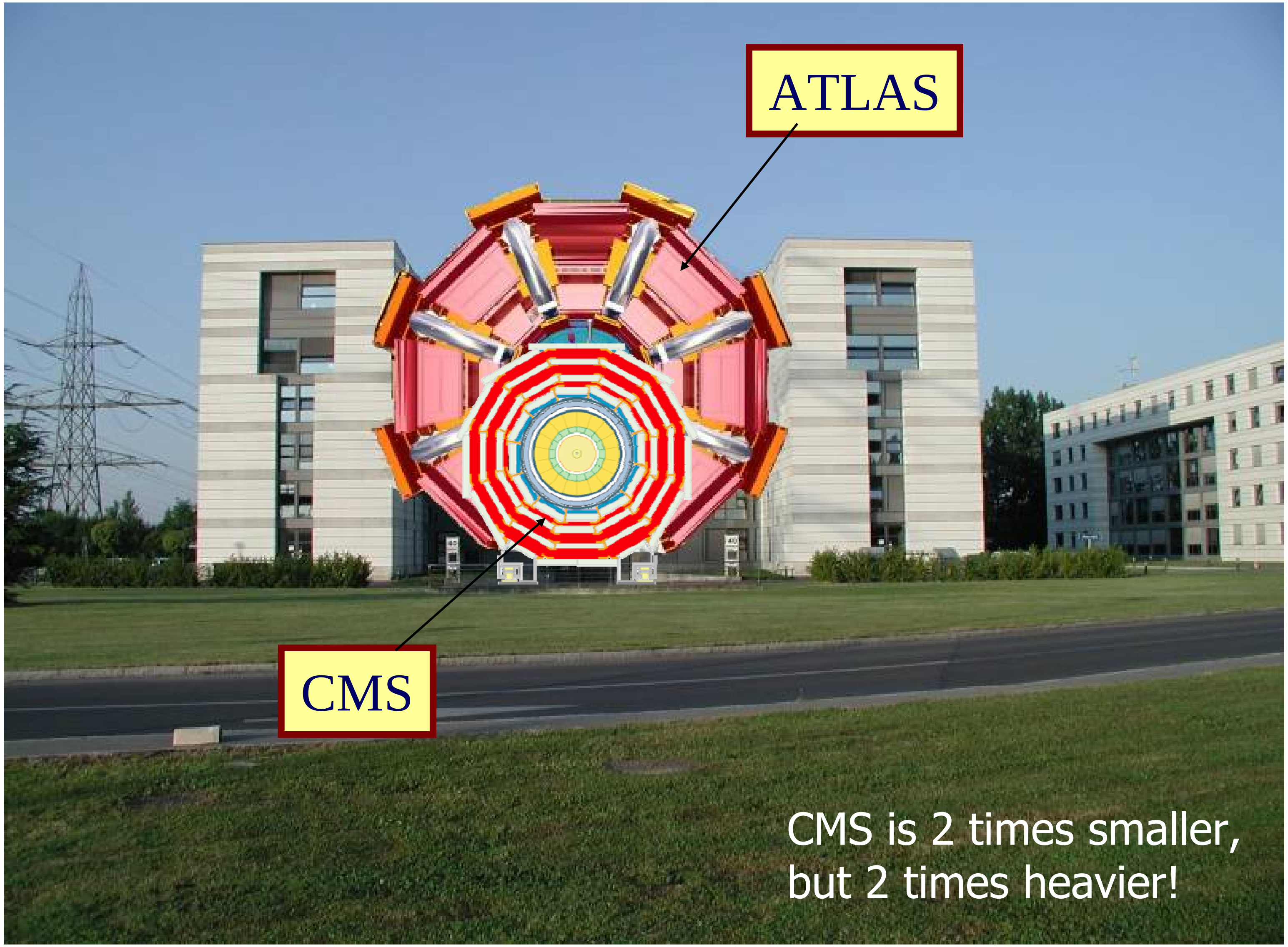
Feynman diagrams from D.I. Kazakov

Sparticle Key Decay Modes

Production	Key Decay Modes	Signatures
$\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{g}\tilde{q}$	$\left.\begin{array}{l}\tilde{g} \to q\bar{q}\tilde{\chi}_1^0 \\ \quad q\bar{q}'\tilde{\chi}_1^\pm \\ \quad g\tilde{\chi}_1^0\end{array}\right\} m_{\tilde{q}} > m_{\tilde{g}}$ $\left.\begin{array}{l}\tilde{q} \to q\tilde{\chi}_i^0 \\ \tilde{q} \to q'\tilde{\chi}_i^\pm\end{array}\right\} m_{\tilde{g}} > m_{\tilde{q}}$	$\not{E}_T$ + multijets (+leptons)
$\tilde{\chi}_1^\pm\tilde{\chi}_2^0$	$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu,\ \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ll$ $\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}', \tilde{\chi}_2^0 \to \tilde{\chi}_1^0 ll,$	Trilepton + $\not{E}_T$ Dilepton + jet + $\not{E}_T$
$\tilde{\chi}_1^+\tilde{\chi}_1^-$	$\tilde{\chi}_1^+ \to l\tilde{\chi}_1^0 l^\pm \nu$	Dilepton + $\not{E}_T$
$\tilde{\chi}_i^0\tilde{\chi}_i^0$	$\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X, \tilde{\chi}_i^0 \to \tilde{\chi}_1^0 X'$	$\not{E}_T$ + Dilepton + (jets) + (leptons)
$\tilde{t}_1\tilde{t}_1$	$\tilde{t}_1 \to c\tilde{\chi}_1^0$ $\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q}'$ $\tilde{t}_1 \to b\tilde{\chi}_1^\pm, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu, \tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 l^\pm \nu$	2 acollinear jets + $\not{E}_T$ single lepton + $\not{E}_T$ + $b's$ Dilepton + $\not{E}_T$ + $b's$
$\tilde{l}\tilde{l}, \tilde{l}\tilde{\nu}, \tilde{n}u\tilde{\nu}$	$\tilde{l}^\pm \to l \pm \tilde{\chi}_i^0, \tilde{l}^\pm \to \nu_l \tilde{\chi}_i^\pm$ $\tilde{\nu} \to \nu\tilde{\chi}_1^0$	Dilepton + $\not{E}_T$ Single lepton + $\not{E}_T$ + $(jets)$ $\not{E}_T$

D.I. Kazakov

ATLAS and CMS

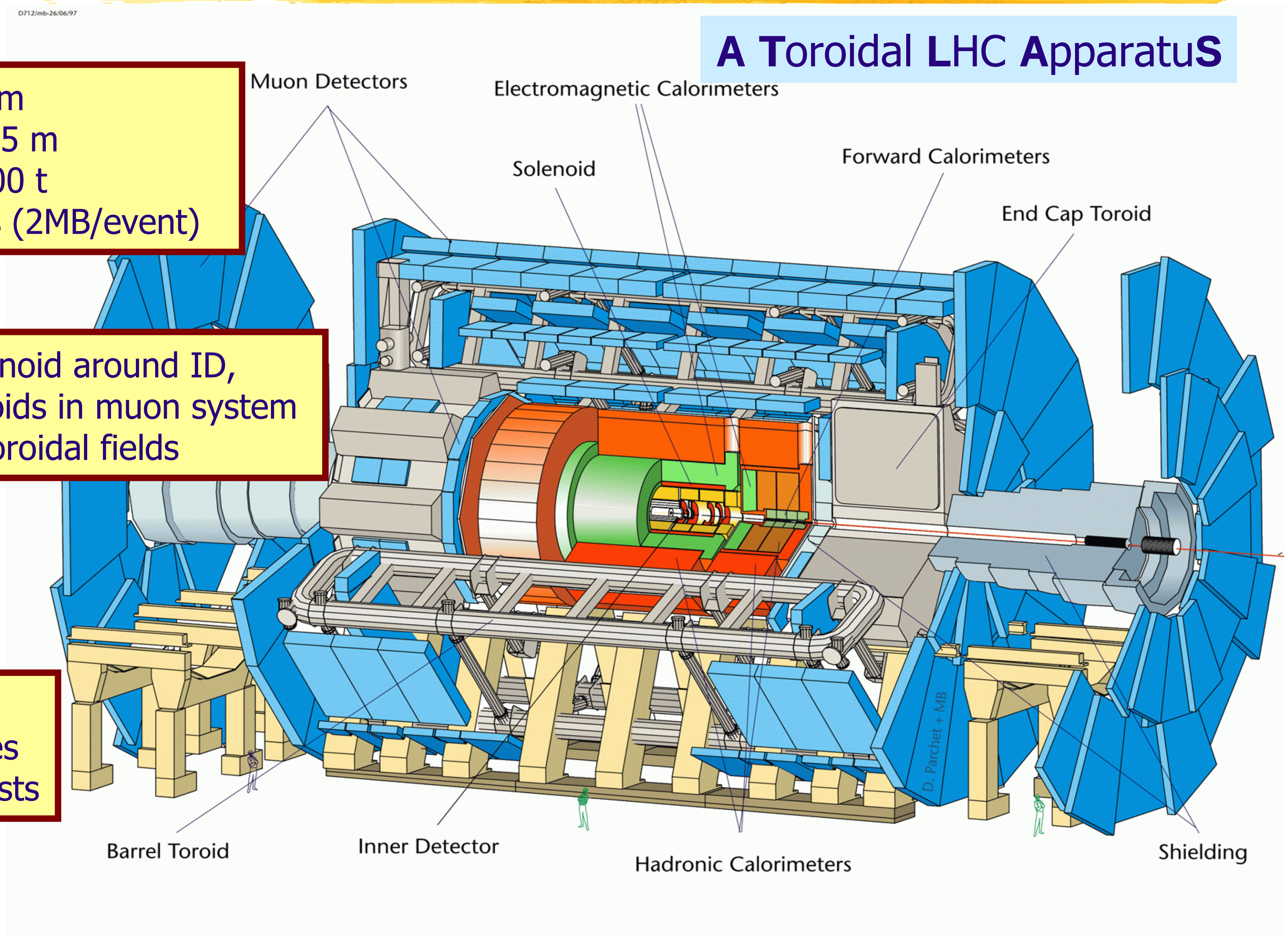


ATLAS

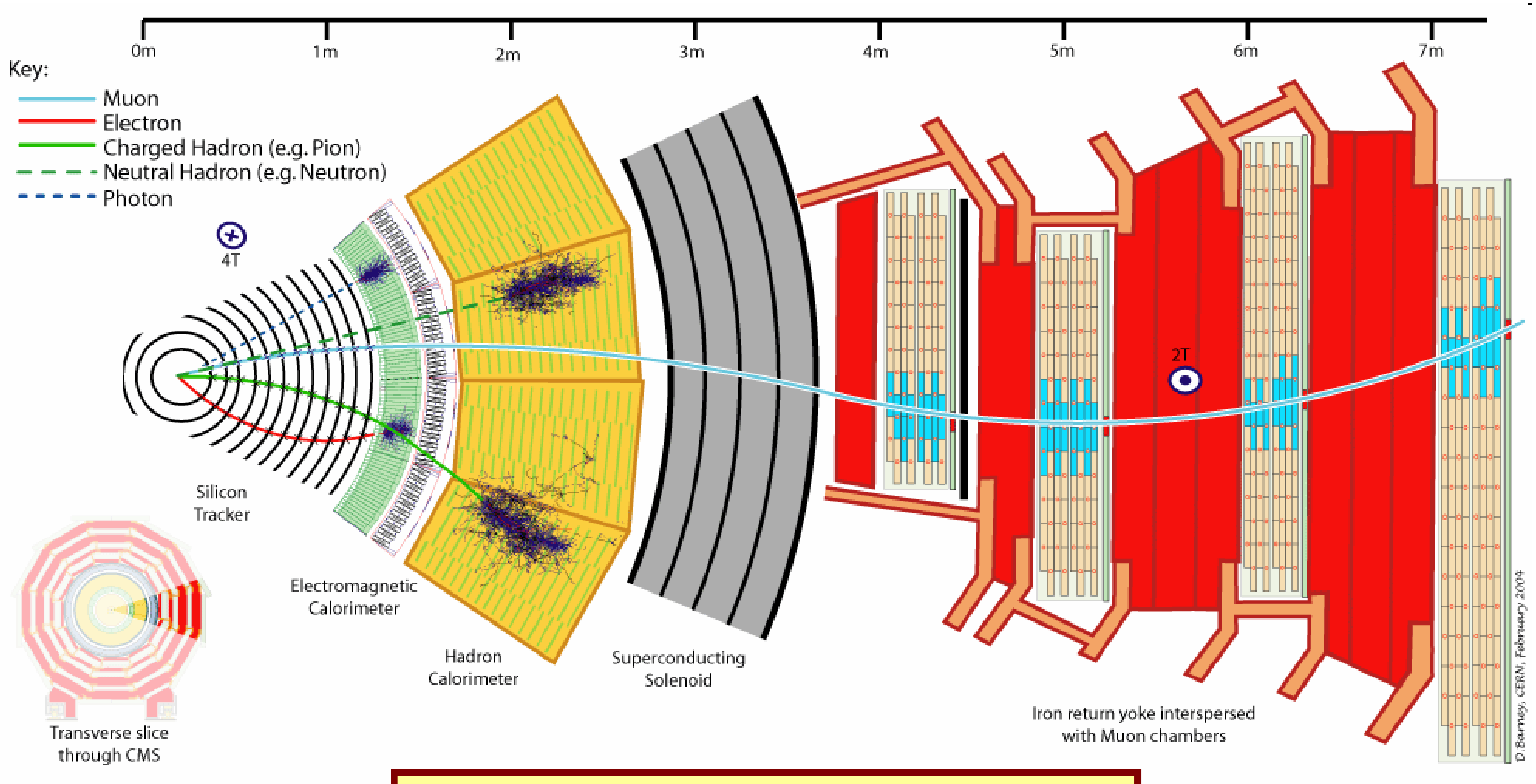
- Length ~40 m
- Diameter ~25 m
- Weight ~7000 t
- 10^8 channels (2MB/event)

- Central: solenoid around ID,
  Toroids in muon system
- End caps: Toroidal fields

~40 Nations
~150 Institutes
~2000 physicists



Compact Muon Solenoid (CMS)



CMS: Calorimeters inside solenoid magnet
ATLAS: solenoid between tracker and ECAL

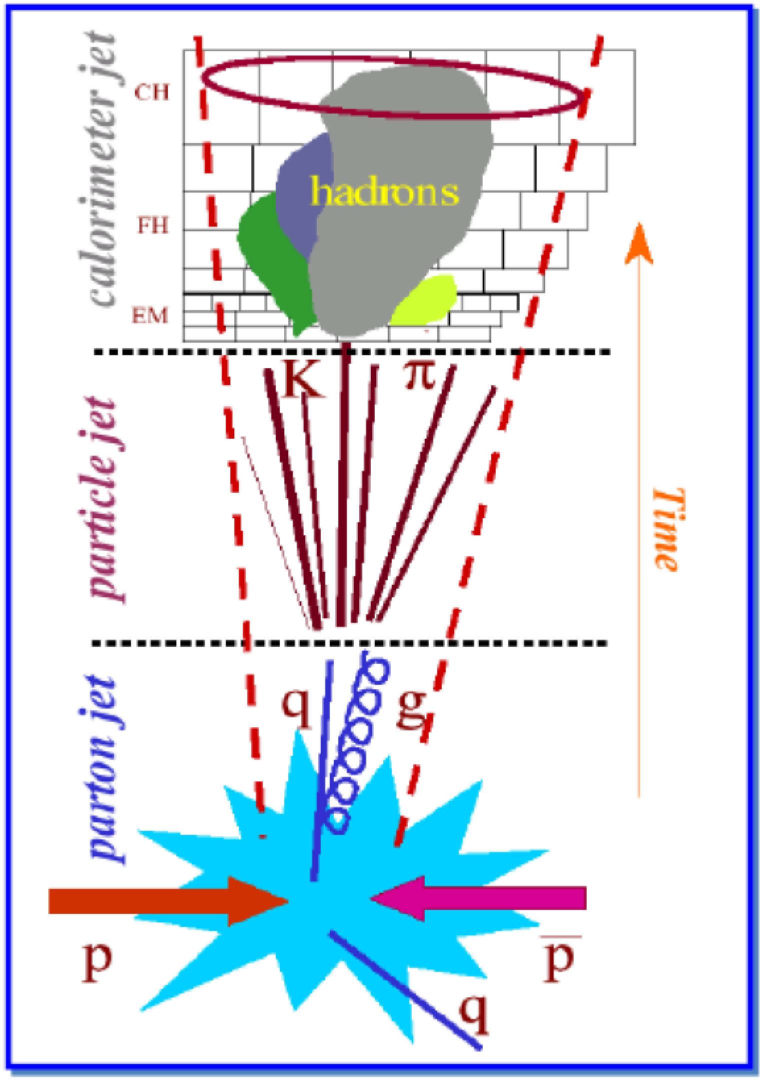
Reconstructed Objects

- You can reconstruct so called “physics objects”:
  - Photons: no track but energy in el-m (and not in the hadronic) calorimeter
  - Electrons: track and energy in el-m (and not in the hadronic) calorimeter
  - Muons: track in inner tracker and muon chamber
  - Jets: cluster in hadronic calorimeter
  - Missing transverse energy (if transverse energy sum is not 0)

- Of course reconstruction is not always simple
- Different reconstruction algorithms for each object are on the market – need to choose the best one for each analysis

- Based on these objects we can select our SUSY events…

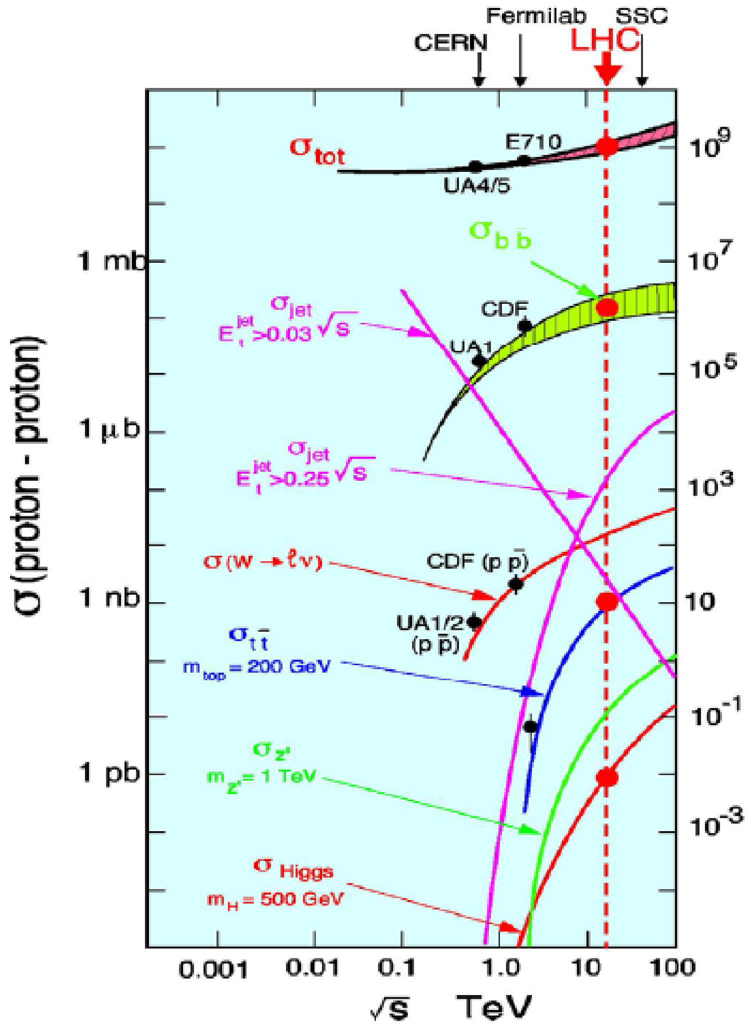
Reminder: Jets



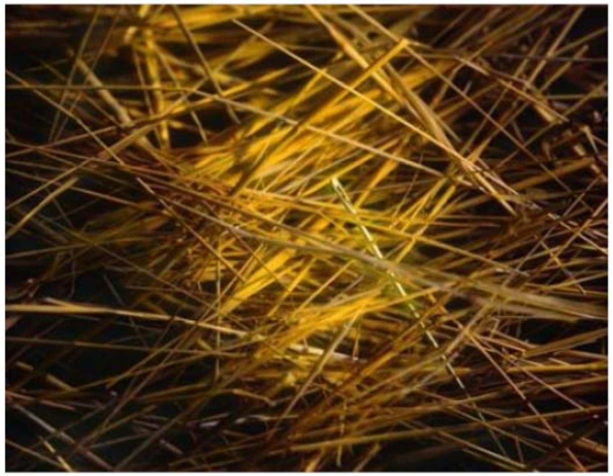
Why do we need Event Selection?

- Rates for L=10^{34} cm^{-2}-s^{-1} (LHC design):

Inelastic pp reactions	10^9 /s
bb pairs tt pairs	$5 \cdot 10^6$ /s 8 /s
W→eν Z →ee	150 /s 15 /s
Higgs (150 GeV) Gluino, Squarks (1TeV)	0.2 /s 0.03 /s



Big challenge
to find the rare
exciting events!!



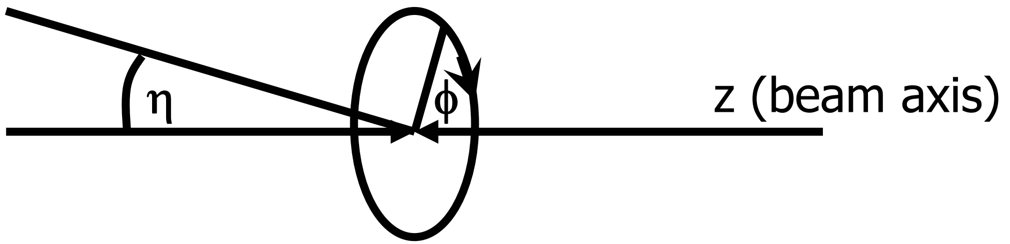
Important Simple Variables

- Number (N) of
  - Jets
  - Leptons

  } Model dependence, e.g. mean N_{jet} can vary from 0 to 4 for 1-lepton events in mSUGRA (CMS LM points)
- Transverse momentum (p_T) of
  - Jets
  - Leptons

  } Model dependence (softer or harder spectra possible)
- Angle ϕ : no (large) ϕ dependence expected – good crosscheck!
- Pseudorapidity η (see next page)
- Relative isolation of leptons within a cone ΔR defined as:

  $\Delta R = \mathrm{sqrt}\,(\Delta\eta^2 + \Delta\Phi^2)$ Isolation similar for all mSUGRA models!



Pseudorapidity

- **Rapidity** of a particle of momentum $p=(E,0,0,p_z)$ is defined to be

  $y = ½ \log((E+p_z)/(E-p_z))$

  Advantage: the rapidity difference is invariant under the longitudinal boost

- For massless particles, $p_z = E \cos\theta$, (θ : polar angle)

→ $y = ½ \log((1+\cos\theta)/(1-\cos\theta))$
$= \log(\cot(\theta/2))$
$= \eta$: pseudo-rapidity

Which channels?

To discover SUSY we need to select events with SUSY specific signature!

Which one?

- Channels with only hadrons in the final state? – Expect highest cross section, but difficult backgrounds!
- Or channels with leptons? – Cleaner but smaller signals!

We usually distinguish our analyses by the number of leptons in the final state:

different number of leptons → different (irreducible) backgrounds:

- 0 leptons (all-hadronic): ttbar, W and Z + jets, QCD multi-jet events

Adding at least one lepton reduces the background:

- mainly ttbar, W and Z with jets, less QCD multi-jet events

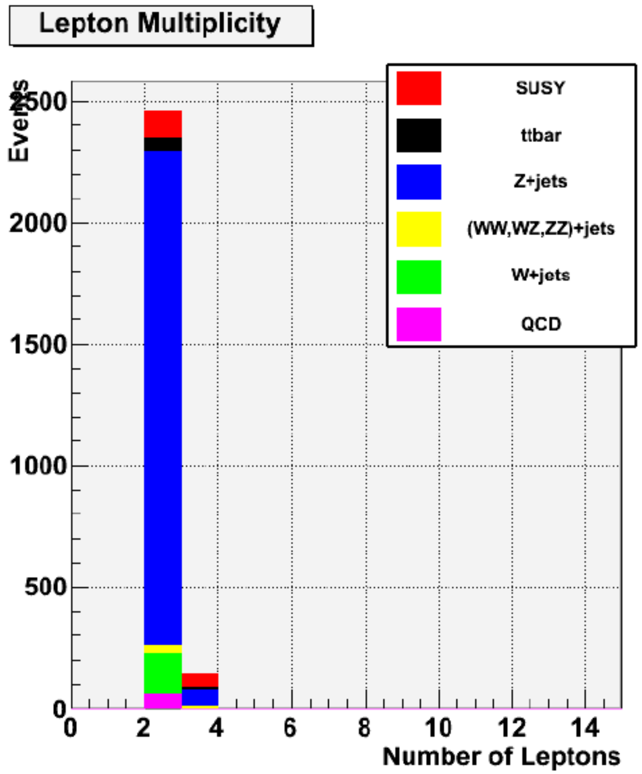
Typical Event Selection

Example for a typical event selection of a leoptonic analysis
Slides from talk of D. Sprenger, same sign di-lepton analysis:

Step 1: Demand 2 same-sign Leptons

- **At least 2 same-sign leptons (e or μ, $p_T > 10$ GeV)**
- 100 GeV of MET
- 3 jets ($p_T > 50$ GeV)

Events	$\geq$ 2 SSL	MET	Jets
LM0 dataset	2260	1349	830
$L = 100\ \mathrm{pb}^{-1}$	168.72	100.71	61.96
BG datasets	9229	331	48
$L = 100\ \mathrm{pb}^{-1}$	2436.57	22.11	2.30



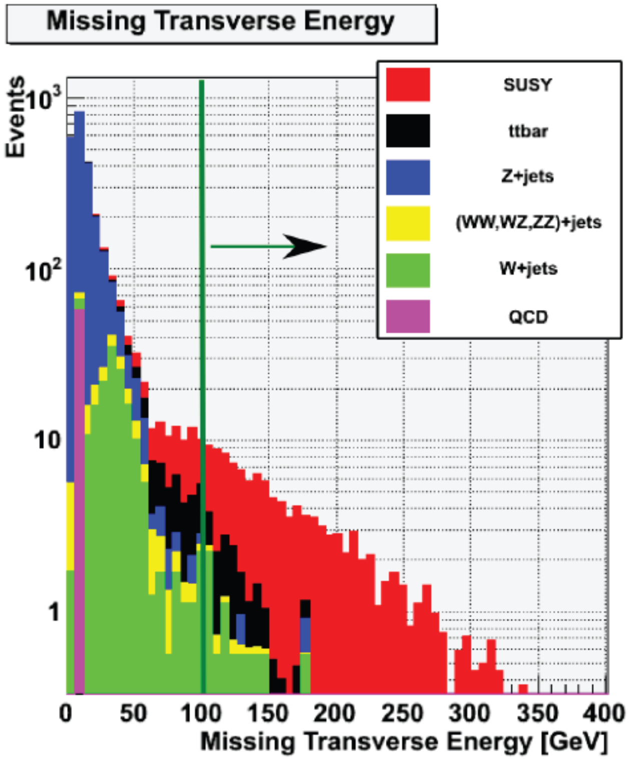
Typical Event Selection (2)

Slides from talk of D. Sprenger,
same sign di-lepton analysis

Step 2: MET Cut

- At least 2 same-sign leptons (e or μ, $p_T > 10$ GeV)
- **100 GeV of MET**
- 3 jets ($p_T > 50$ GeV)

Events	$\geq$ 2 SSL	MET	Jets
LM0 dataset	2260	1349	830
$L = 100$ pb $^{-1}$	168.72	100.71	61.96
BG datasets	9229	331	48
$L = 100$ pb $^{-1}$	2436.57	22.11	2.30



Typical Event Selection (3)

Slides from talk of D. Sprenger,
same sign di-lepton analysis

Step 3: Jet Cuts

- At least 2 same-sign leptons (e or μ, $p_T > 10$ GeV)
- 100 GeV of MET
- **3 jets ($p_T > 50$ GeV)**

Events	$\geq$ 2 SSL	MET	Jets
LM0 dataset	2260	1349	830
$L = 100$ pb $^{-1}$	168.72	100.71	61.96
BG datasets	9229	331	48
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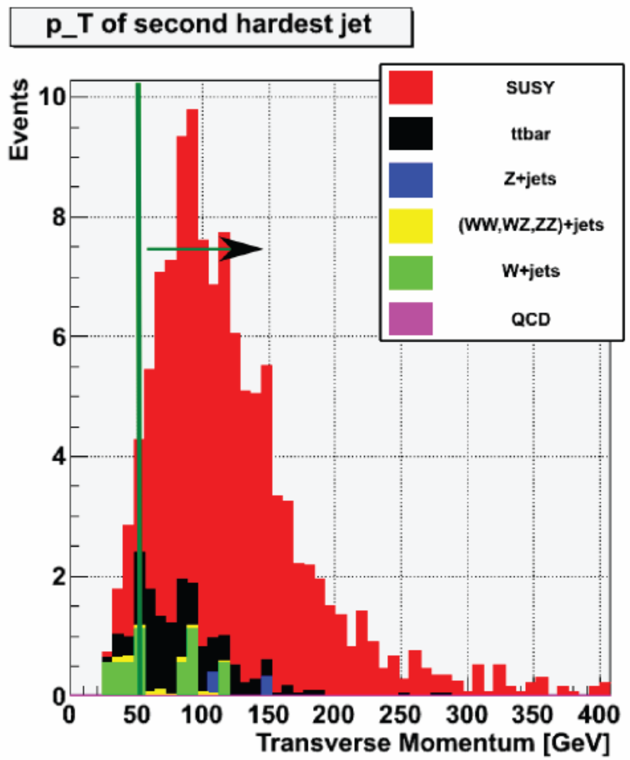


Where we are...

- SUSY models
- Event selection
- **Interesting observables**
  → Observables with strong separation power
- Background determination
- Model independent searches
- Systematic uncertainties

Interesting Observables

Need to find variables that distinguish BSM from SM signatures!

- Missing transverse energy (expected for only weakly interacting neutral particles leaving the detector)
  - Calculated from all energies in calorimeter: E_T^{miss}
  - Calculated from all jets: H_T^{miss}
- α_T
- $\Delta\Phi$
- Transverse mass calculated from lepton p_T and E_T^{miss}: M_T
- Effective mass of all objects: M_{eff}

$$M_{eff} = \sum_{jets} \vec{p}_T^{\,jet} + \vec{p}_T^{\,lepton} + E_T^{miss}$$

- Sum of transverse energies of all jets above certain p_T threshold:

$$H_T = \sum_{jets} \vec{p}_T^{\,jet}$$

Note: use only transverse variables as partonic center of mass energy not known in hadronic collisions

Interesting Observables: E_T^{miss}

- Missing E_T: vector sum of the transverse energy deposited in all calorimeter cells (this combines, ideally, the momenta of all photons, electrons, hadronically decaying taus, and jets) and adding to this the transverse momenta of any muons, whose energy is measured using the muon detection system

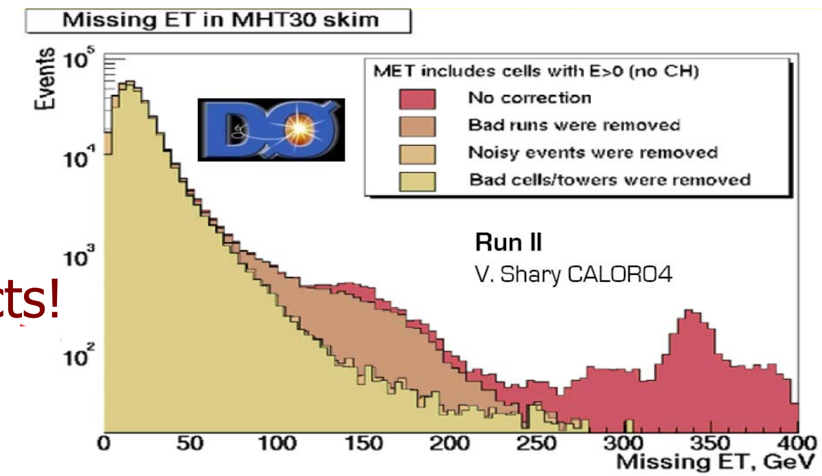
$$\vec{p}_T^{\,\text{miss}} = -\left(\sum_{\text{calo towers}} \vec{p}_T - \sum_{\text{muons}} \vec{p}_T^{\,\text{deposited in calo towers}} + \sum_{\text{muons}} \vec{p}_T^{\,\text{tracker}} \right)$$

- The magnitude of the resultant vector is the missing E_T:

$$E_T^{\text{miss}} = \left| \vec{p}_T^{\,\text{miss}} \right|$$

Attention:

E_T^{miss} might be polluted by detector effects!



Interesting Observables: H_T^{miss}

- Analog to E_T^{miss}, but using jets above a certain jet threshold only:

$$H_T^{\mathrm{miss}} = \left| - \sum_i \vec{p}_T^{\,\mathrm{j_i}} \right|$$

Attention:

- You might have a cut on jet momentum of e.g. $p_T>50$ GeV
- But there might be several jets below that threshold which could still lead to a considerable amount of ignored momentum in the event!
- One idea to control this: add cut on ratio R with

$$R\left(H_T^{miss}\right) = \frac{H_T^{miss}\left(\text{selected jets with } p_T > 50\,\text{GeV}\right)}{H_T^{miss}\left(\text{all jets with } p_T > 30\,\text{GeV}\right)}$$

(numbers are just examples)

Interesting Observables: α_T

- α is a variable developed for 2-jet events:

$$\alpha = \frac{E_T^{j2}}{M_{inv}^{j1,j2}}$$

L. Randall and D. Tucker-Smith, arXiv:0806.1049.

  → Exactly 0.5 for perfectly measured QCD event

  → In addition, as the E_T of the second energetic jet enters in the numerator, uncertainties introduced through energy mis-measurements partly cancel out in α (if one of the two jet energies is measured wrong by a large amount the order of the two jets will be swapped)

- You can also use the transverse mass:

$$\alpha_T = \frac{E_T^{j2}}{M_{inv\ T}^{j1,j2}}$$

- For massless particles (with $\Delta\Phi$ = difference in azimuthal angle of the jets):

$$\alpha_T = \frac{E_T^{j2}}{\sqrt{2E_T^{j1}E_T^{j2}(1-\cos\Delta\phi)}} = \frac{\sqrt{E_T^{j2}/E_T^{j1}}}{\sqrt{2(1-\cos\Delta\phi)}}$$

Interesting Observables: α_T (2)

Now extend α_T to n-jet events:

- Two pseudo jets are formed which balance each other as good as possible in the "pseudo-jets" $H_{T1} = \Sigma E_{Ti}$ and $H_{T2} = \Sigma E_{Tj}$ (E_{Ti} and E_{Tj}: transverse energies of the jets within a pseudo jet)
- Assuming massless jets, one can write:

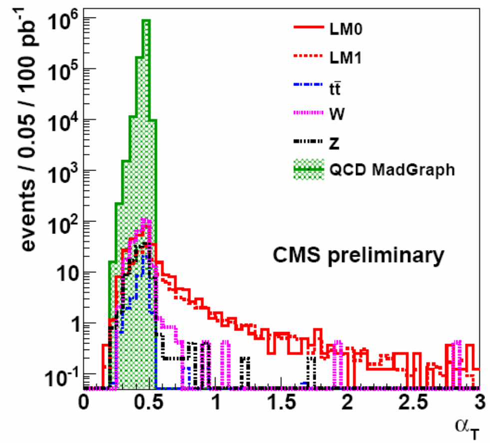
$$\alpha_T = 0.5 \frac{H_T - \Delta H_T}{\sqrt{H_T^2 - {H_T^{miss}}^2}}, \quad \text{with } \Delta H_T = H_{T1} - H_{T2}$$

$$\alpha_T = 0.5 \frac{1 - \Delta H_T / H_T}{\sqrt{1 - {H_T^{miss}}^2 / H_T^2}}$$

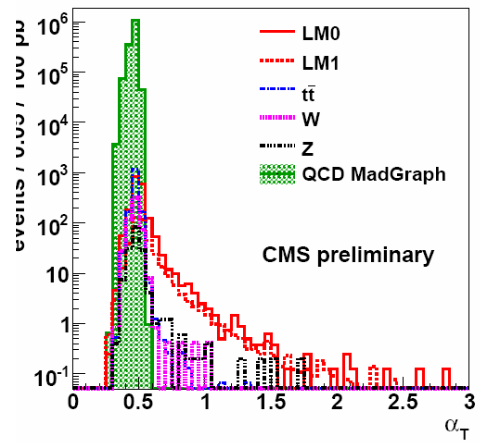
Interesting Observables: α_T (3)

- α_T has a good separation power, especially for QCD background:

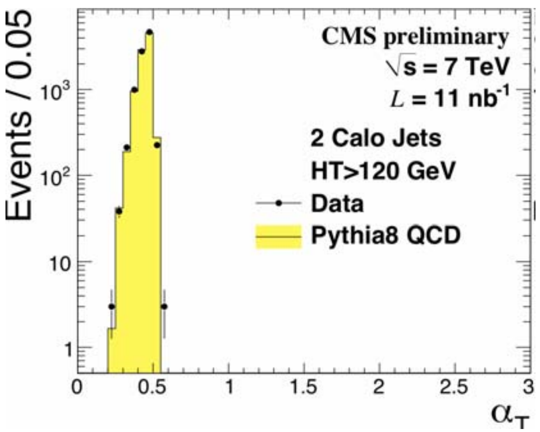
2-jet events

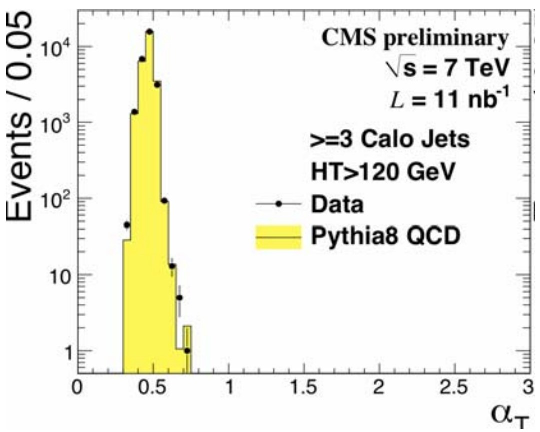


n-jet events



CMS MC study on 10 TeV 2009





CMS first data

α_T for Events containing a Lepton

- "Leptonic version" of α_T extends the definitions of the kinematic variables, including the lepton object in addition to the jets
- Intention: suppression of the QCD background that survives the one-lepton selection due to fake leptons or leptons from heavy-flavor decays

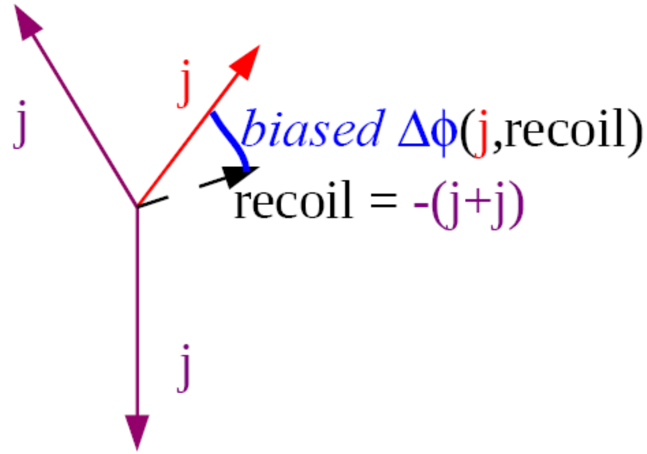
- Great advantage: α_T quite insensitive to energy scale uncertainties
  - Test it yourself by varying the energy scale by e.g. 10%
  - Then compare the change in α_T to other discriminative variables like H_T^{miss}

Conclusion: cutting on α_T is powerful to suppress QCD background in hadronic and single-leptonic analyses
(but there are other backgrounds left)

Interesting Observables: ΔΦ*

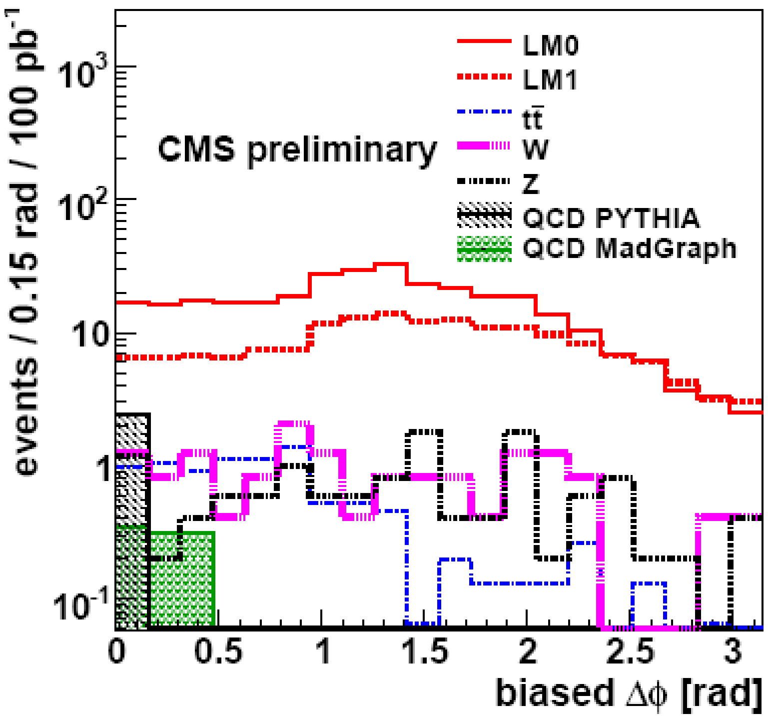
- ΔΦ*: minimum angle between opposite direction of sum of all jets except one and the omitted jet

$$\Delta\phi^* = \min_k \left(\Delta\phi \left(\left(\sum_i -\vec{p}_i \right) + \vec{p}_k ; \vec{p}_k \right) \right)$$



- Basic idea: test each jet to see if a mismeasurement of that jet could be responsible for the H_T^{miss} in the event
- Expect peak at zero for QCD when there is mismeasurement of a single jet and it is more uniform for real E_T^{miss}

Interesting Observables: ΔΦ (2)*

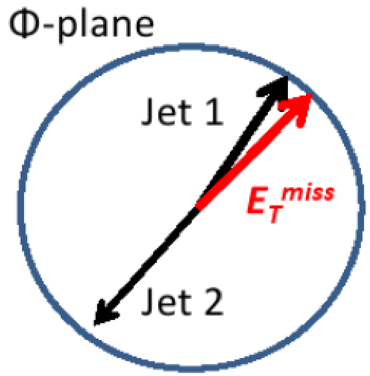


CMS MC study on 10 TeV 2009

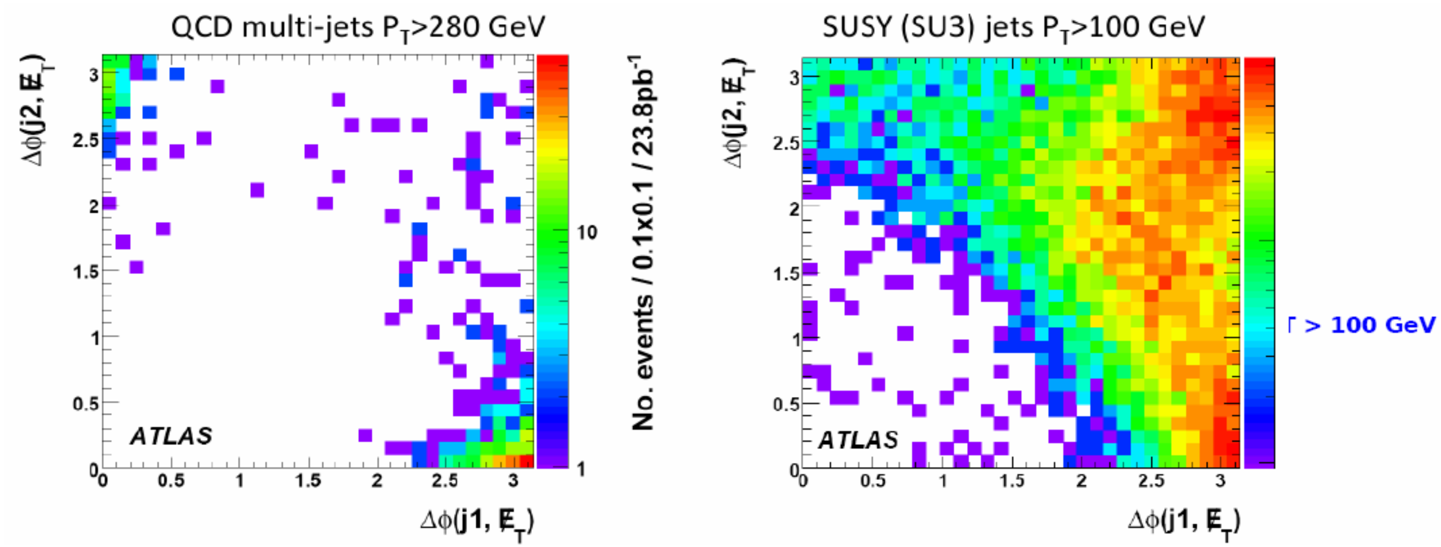
Conclusion: cutting on Δφ* is powerful to suppress <u>QCD</u> background in hadronic analyses
(but there are other backgrounds left)

Interesting Observables: min($\Delta\Phi(j^i, E_T^{miss})$)

- Similar to $\Delta\Phi$*:
- Reject events in which MET is closely associated with one of the leading jets in Φ (standard at TeVatron)

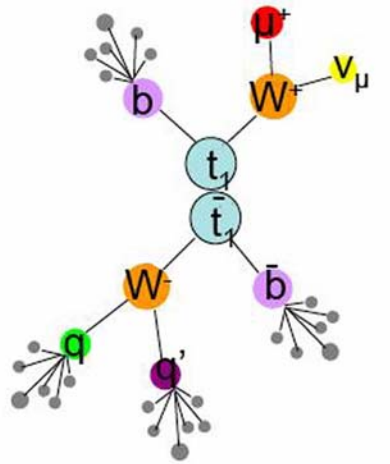


- Example from ATLAS:



Interesting Observables: χ^2(ttbar)

- Construct a variable with the four highest p_T jets, using the hypothesis of **semi-leptonic ttbar** for each event to reconstruct hadronic W mass, hadronic top mass, and leptonic top mass:



$$\chi^2(t\bar{t}) = \frac{(M_{j_1 j_2} - M_W)^2}{\sigma^2_{jj}} + \frac{(M_{j_1 j_2 j_3} - M_t)^2}{\sigma^2_{jjj}} + \frac{(M_{W_{l\nu} j_4} - M_t)^2}{\sigma^2_{l\nu j}}$$

- χ^2(ttbar) has maximum at 0 with exponential drop, while for the different mSUGRA points the maximum is shifted to higher values

- Caution: Of course it doesn't always work perfectly, the best χ^2 is not always the right combination, in these cases the χ^2 falls more like signal events

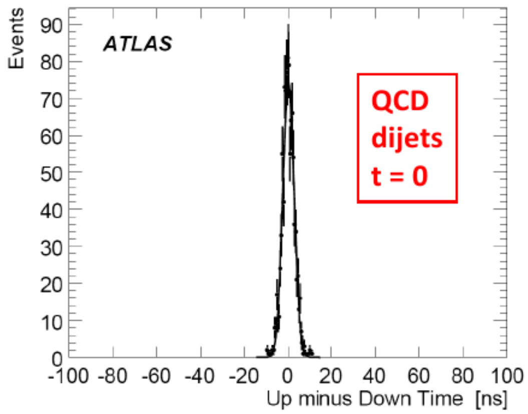
Interesting Observables: Calorimeter Timing

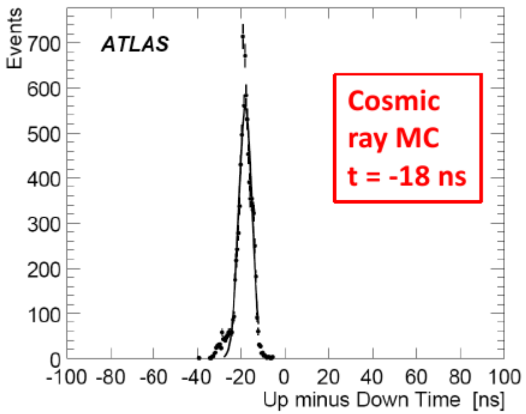
- Cosmic rays can generate fake E_T^{miss}
- Measure (mean) time-of-flight difference in Calorimeter

$$t_{\text{up (down)}} = \sum_i \left(E_t^{\text{up (down)}} \cdot t_i \right) \Big/ \sum_i E_t^{\text{up (down)}}$$

$$t_{\text{TOF}} = t_{\text{up}} - t_{\text{down}}$$

- Example (ATLAS):





$t_{TOF} = 0$
for particles
from collisions

$t_{TOF} = -18$ ns
for cosmics

Where we are...

- SUSY models
- Event selection
- Interesting observables
- **Background determination**
  - Overview over different methods
  - Examples for estimation of the different backgrounds
- Model independent searches
- Systematic uncertainties

Reminder

- Main backgrounds come from the following physics processes:
  - QCD
  - ttbar
  - Vector bosons + jets
- We have to predict everything that we cannot suppress by cuts…

Predicting the remaining Background…

- SUSY signal is expected to be found in tails of SM distributions:
  - Monte Carlo describes well peak regions, but not necessarily tails
  - Standard Model events appear with similar signature
- Mis-measurements of physics objects (e.g. E_T^{miss}) can be caused by different effects:
  - Dead or un-instrumented regions of detector
  - Punchthrough (from hadronic calorimeter to muon chambers)
  - Overlaps of events with:
    - Cosmics
    - Machine-induced backgrounds
  - Mis-calibration leading to mis-measured jets

Best solution:

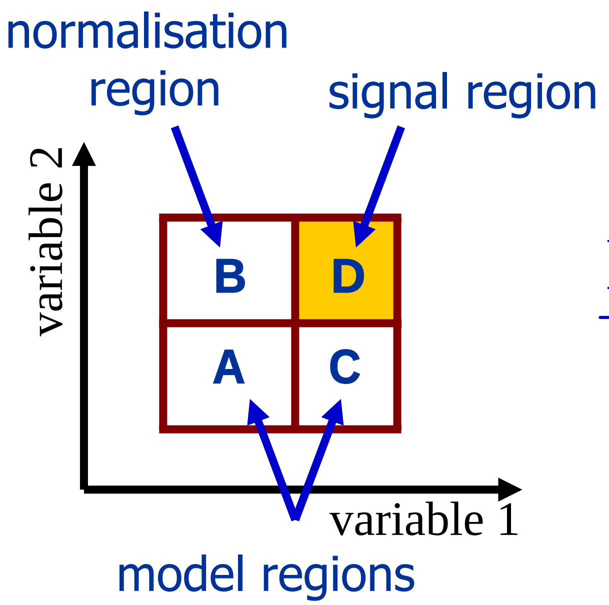
Use (mainly) data-driven methods to determine the background

Data-driven Methods

- Factorisation (ABCD and tiles) methods
  - Use two (independent) variables to extrapolate background behavior from signal depleted into signal region
- Template methods
  - Select well understood and measured background processes and use it to predict background shapes in signal regions
- Replacement methods
  - Select well understood and measured background processes and replace a part of the measured observables

Factorisation (ABCD) Method

- Straightforward method, if two variables are uncorrelated:



$$\frac{D}{C} = \frac{B}{A}$$

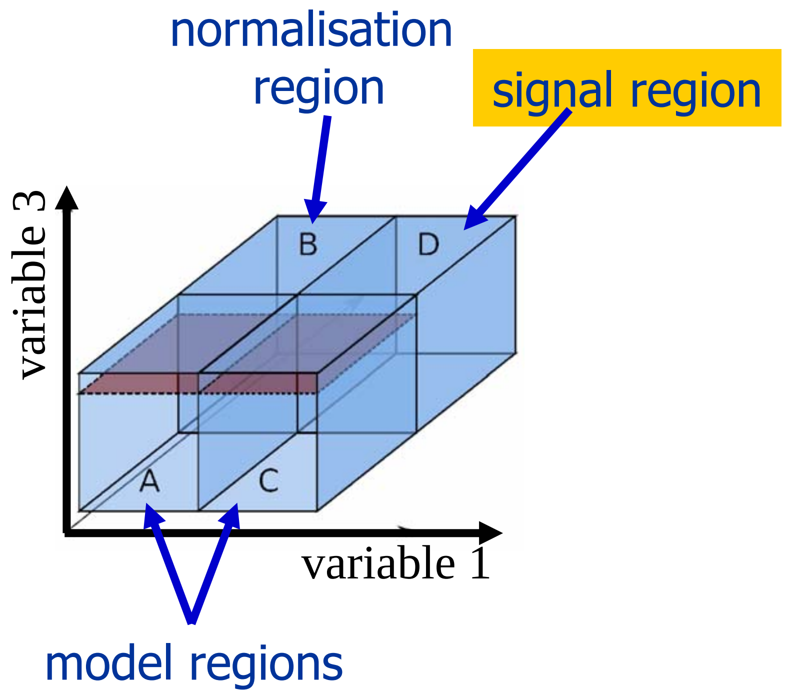
- Estimate number of background events in signal region: D=C·B/A

- Attention:
  - most variables are correlated
  - signal can be spilled into the normalisation region

ABCD-Method with Signal Spilling

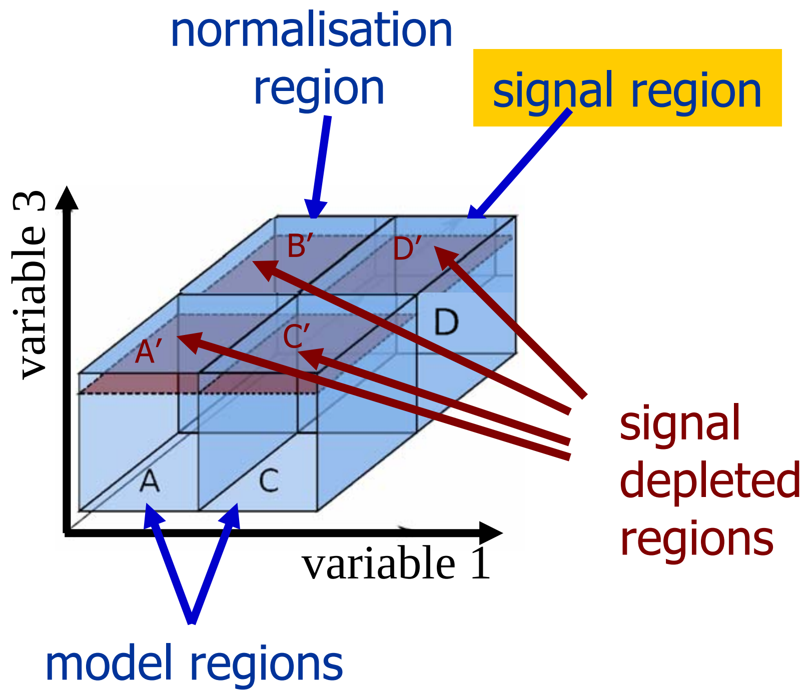
- What if model regions are spilled with signal?

→ Introduce additional cut on a signal suppressing variable in model regions!



ABCD-Method with Correlation of the Variables

- Estimate the correlation using 8 fields:
- Take signal-depleted sub-regions A′B′C′D′ of ABCD and measure:
  k=(A′/B′)/(C′/D′)
- Then correct the estimation for the signal in region D with k



Tiles-Method

Idea: Use the Monte Carlo prediction for the shapes of SM backgrounds

- Relative inclusive fractions of SM background events in each region ("tile" – definition similar to ABCD method) predicted by MC
- Discriminating variables are independent for signal events (not necessarily for BG events)
- Signal and BG must not have the same shape (otherwise no discriminative power)
- Express N_{event} in each region in terms of SM and SUSY contribution:

$$N_A = f_A \cdot N_{SM} + SUSY_A$$

$$N_B = f_B \cdot N_{SM} + SUSY_B$$

$$N_C = f_C \cdot N_{SM} + SUSY_C$$

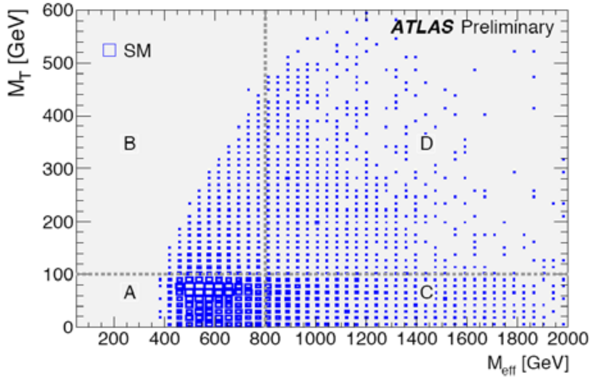
$$N_D = f_D \cdot N_{SM} + SUSY_D$$

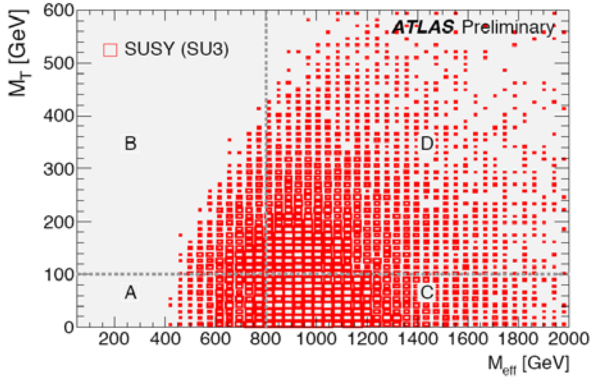
$$SUSY_A \cdot SUSY_D = SUSY_B \cdot SUSY_C$$

f_A, f_B, f_C, f_D: from Monte Carlo
N_A, N_B, N_C, N_D: from data

Tiles-Method (2)

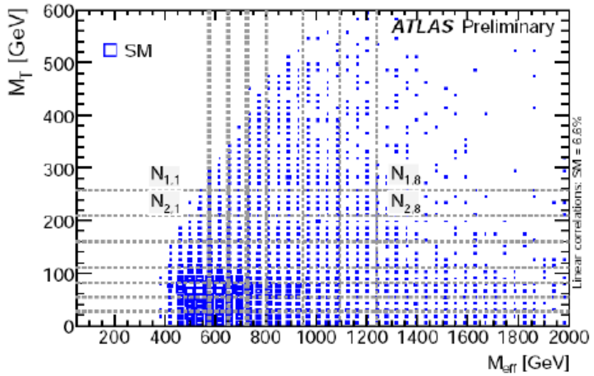
Method can be used for 2x2 tiles…

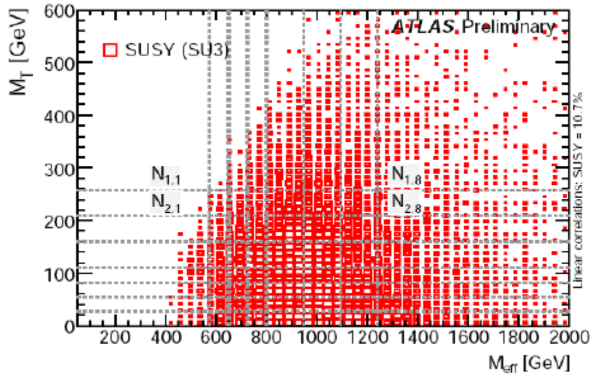




- ☹ few degrees of freedom
- ☺ less sensitive to signal correlation

- But also for more tiles





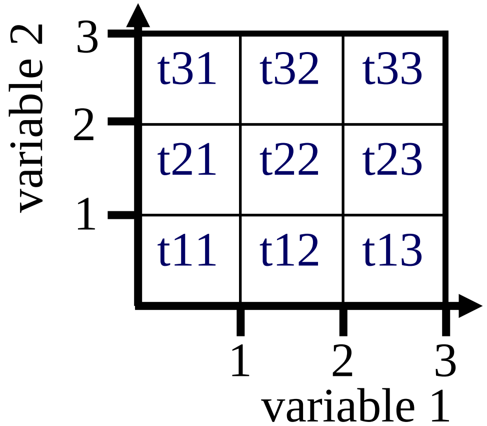
ATL-PHYS-PUB-2009-077
& V.Zhuravlov SUSY09

- ☹ large statistical fluctuation
- ☺ goodness of fit
- ☺ sensitivity to signal shape
- ☺ new parameters:
  - linear correlation factor
  - separate background contributions

- Solve over-constrained system of equations
- Minimize extended log-likelihood estimator

Prediction from Templates

- → Collect QCD events with topologies similar to signal events
- → Fill variable to investigate of QCD event in 2-dim matrix



- → Then measure the corresponding variables for your signal candidate event, and extract the predicted value for the background from template for this bin

Example for Prediction from Templates: Artificial E_T^{miss}

Missing transverse energy can have several artificial sources:

- Instrumental effects
- Software
- Collision or non-collision backgrounds
- Some effect you haven't yet thought of…

Predict these effects from data with templates!

→ Fill measured E_T^{miss} of collected QCD events in 2-dim matrix (e.g. with variable1=N_{jet}, variable2=H_T, which is expected to be less polluted by artificial effects)

→ Then measure these variables for your signal candidate event, and extract the E_T^{miss} template for this bin

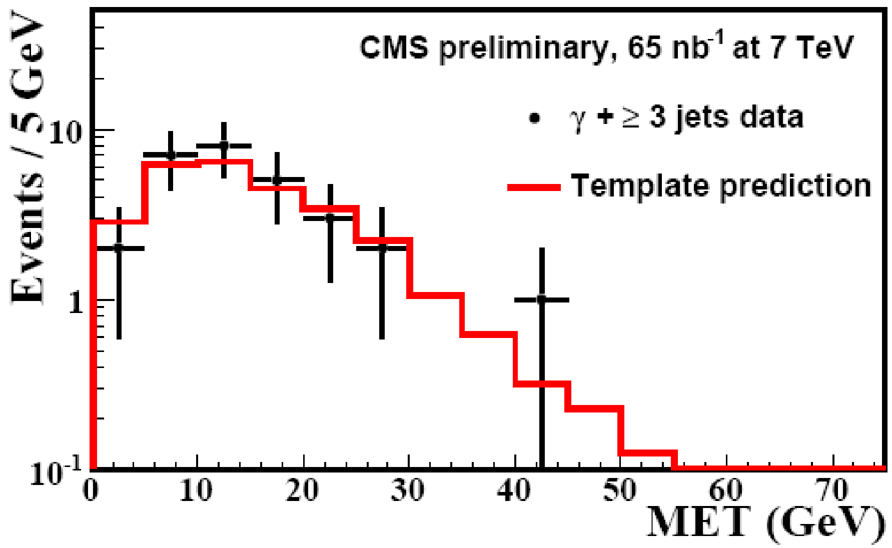
Sounds straight forward, but attention:

- H_T of QCD events lower than expected for SUSY → need extrapolation
- QCD and signal events might be triggered by different (and differently efficient) triggers

Example for Prediction from Templates: Artificial E_T^{miss}(2)

How can we check that it works with early data?
Predict the E_T^{miss} for γ+jets events using QCD jets:
→ Prediction quite good, given that:

- Photon sample expected to be polluted by neutral pions
- Jet energy scale for jets less well measured than the photon
- Different triggers used for the two data samples

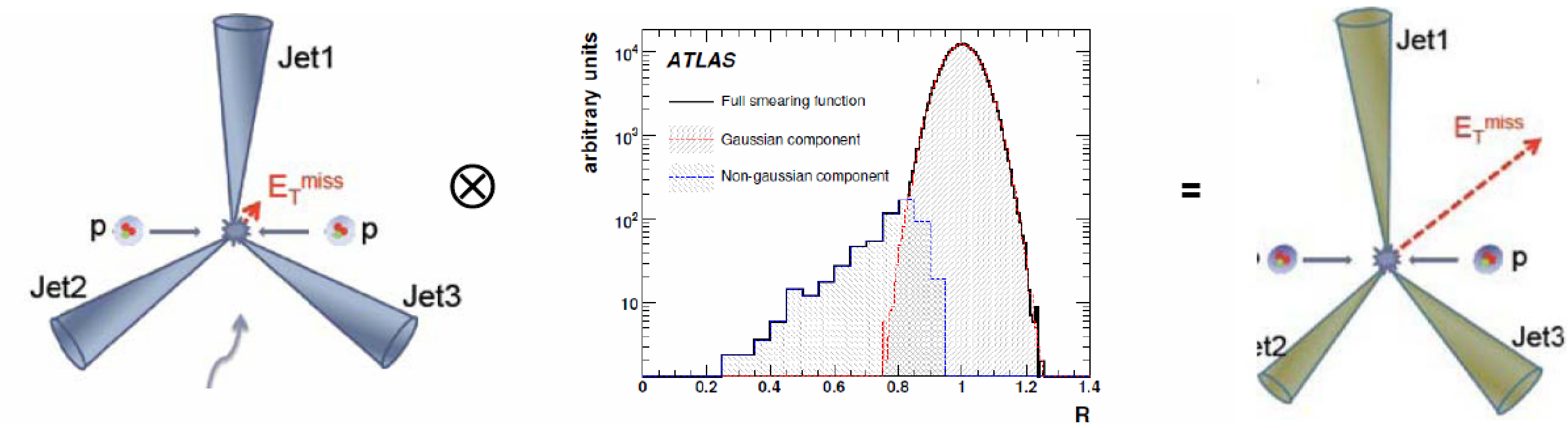


Examples: Methods to Determine QCD Background

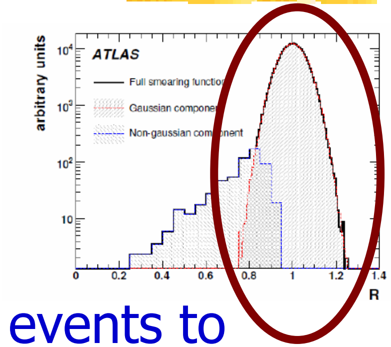
- Jet smearing
- Lepton isolation

Jet Smearing Method

- Parameterise a response function from well measured events (see next pages…)
- Smearing of the jets will result in artificially created E_T^{miss} used to estimate the real E_T^{miss} distribution
- Obtain the normalisation from the multijet data events with low E_T^{miss}



Jet Smearing – Gaussian Part



Idea: Generate the **Gaussian** response function either with well measured dijet or with γ+jet events:

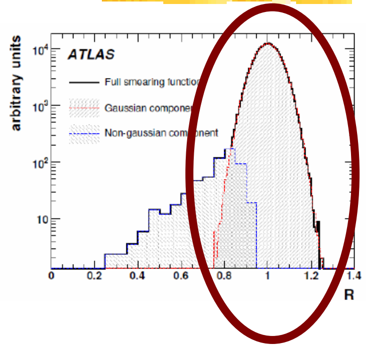
- In case of γ+jet events (photon well measured):
  - Use transverse momentum conservation in γ+jet events to calculate Gaussian response of calorimeters to jets from the distribution of the photon-jet p_T balance (with events containing exactly 1 jet):

$$R_1 = 1 + \frac{p_T^{miss} \cdot p_T^{\gamma}}{\left| p_T^{\gamma} \right|^2}$$

  - Measure this distribution in bins of p_T^{γ}

Jet Smearing – Gaussian Part (2)

- In case of dijet events:
  - Apply jet smearing with the Gaussian jet response on low E_T^{miss}, well measured, dijet seed events
  - This produces a set of smeared events
  - Compare the E_T^{miss} distribution of the smeared events with the E_T^{miss} distribution of all jet data in the low E_T^{miss} region
  - Vary the Gaussian parametrisation and repeat the above two steps to find the closest match and therefore the optimal Gaussian fit

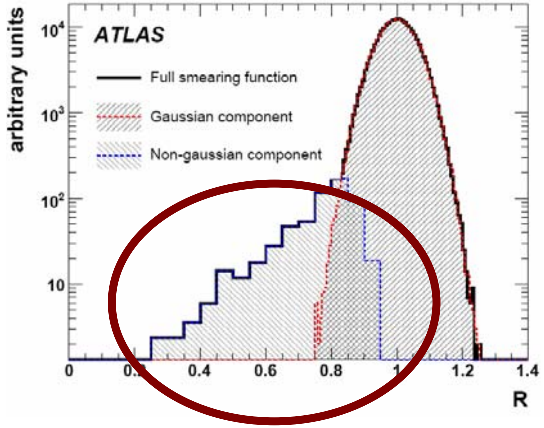


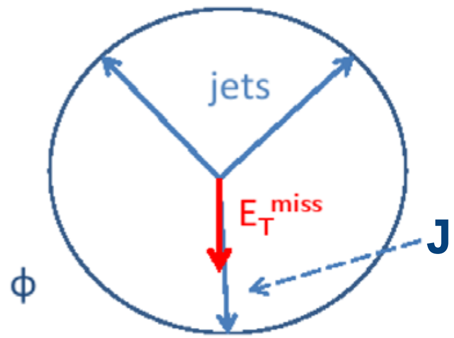
  - Still need to measure the non-Gaussian part… (see next page)

Jet Smearing – Non-Gaussian Part

- Generate the **non-Gaussian** response function with multi-jet events (preferably Mercedes-like events) where exactly one jet 'J' is parallel to the E_T^{miss}
  - Response of the calorimeter to jet J, if its p_T lies in the non-Gaussian tail, can be obtained from:

$$R_2 = \frac{p_T^{\mathrm{J}} \cdot p_T^{\mathrm{J,true}}}{\left| p_T^{\mathrm{J,true}} \right|^2} \quad \text{with} \quad p_T^{\mathrm{J,true}} \approx p_T^{\mathrm{J}} + p_T^{miss}$$

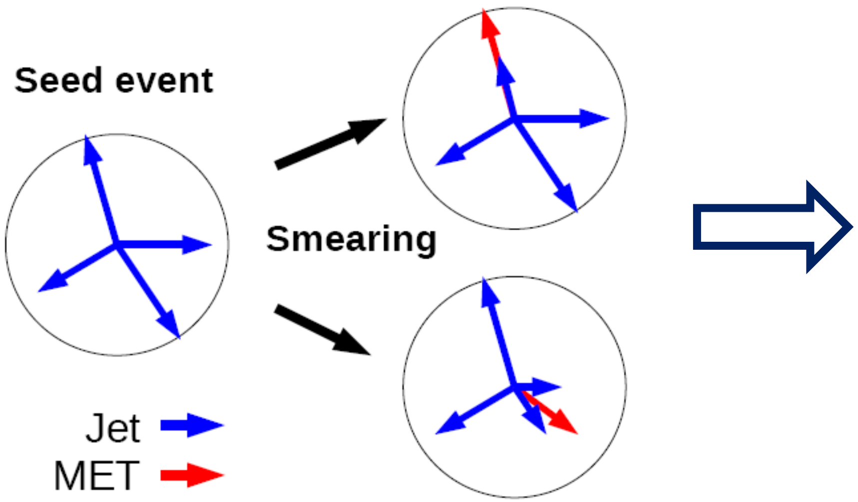


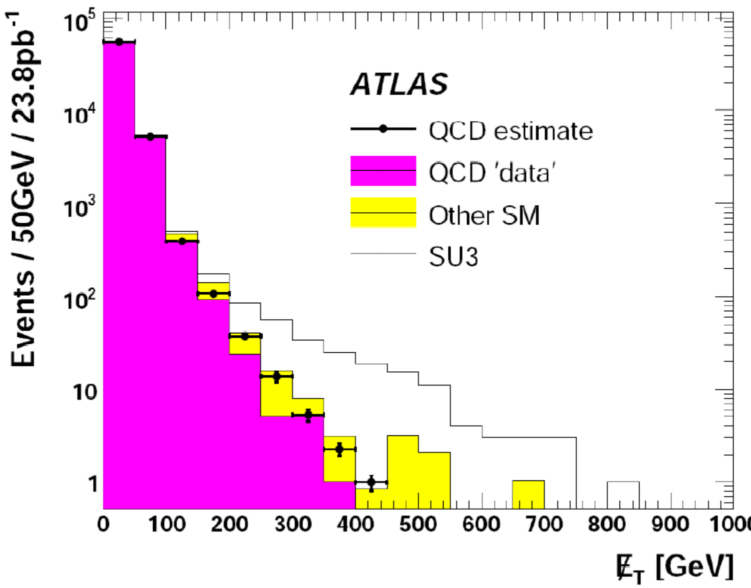


Jet Smearing – Full Jet Response

- Construct full jet response by approximately normalising the Gaussian and the non-Gaussian components
- Derive the normalisation by comparing the measured non-Gaussian response with the tail of the dijet balance distribution
- Use the full response function to 'smear' the four-momenta of jets in events with low E_T^{miss}

→ The smeared jets can now have sufficient E_T^{miss} to enter the SUSY signal region and hence provide an estimation of the multijet background in this region





Background for prompt Leptons

If SUSY events contain leptons they are prompt!

- Different sources of background leptons possible:
  - Non-prompt leptons from semileptonic heavy quark decays
- For Muons:
  - Decay of long living kaons and pions
  - Calorimeter punchthrough (to muon chambers)
- For Electrons:
  - Jets mimicking electrons
  - Photon conversions in tracker

Lepton Isolation Predictions

- SUSY (and EW) leptons are prompt → should be isolated
- Check e.g. the combined relative isolation (with $\Delta R = \sqrt{\Delta\eta^2+\Delta\phi^2}$)

$$\text{Isolation} = \sum_{\Delta R<0.3} E_T^{\text{ECAL}} \Big/ E_T^{\text{lepton}} + \sum_{\Delta R<0.3} E_T^{\text{HCAL}} \Big/ E_T^{\text{lepton}} + \sum_{\Delta R<0.3} p_T^{\text{track}} \Big/ p_T^{\text{lepton}}$$

Attention: Sums in Isolation exclude the energy and momentum of the investigated lepton

→ Expect value close to 0 (essentially <0.1) for isolated leptons

→ Background mainly >0.3

Try it yourself! These numbers are just examples, and you could also use single isolation for each detector component

But Attention:

EW background (W→lν) is located in SUSY signal region!

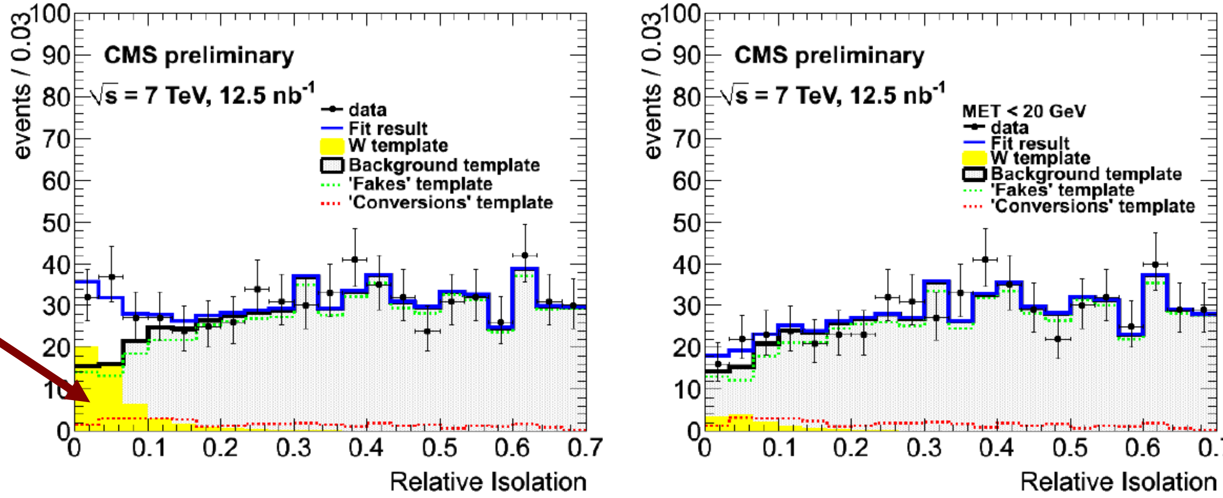
Lepton Background Predictions using Fit and Extrapolation for Isolation

- Using the combined relative isolation described before:
  - SUSY signal and EW decays are mainly in Isolation<0.15
  - Background more or less in region Isolation>0.3
- Idea: produce background enhanced sample and fit this in the background region
  - Test different fits/fit regions etc. on this sample (e.g. for small E_T^{miss})
  - Then apply the best fit to data which could contain a signal (e.g. for large E_T^{miss})
  - From this fit predict the number of background events in signal region
- Or use templates:
  - Instead of fit use directly a template data sample (extracted by anti-selection)

Lepton Background Predictions using Templates for Isolation

- Predict QCD background contributions from Isolation distributions of control samples for background:
- Example from CMS: Electron background – two template samples:
  - one for conversion backgrounds
    → select these events by inverting conversion rejection
  - one for jet backgrounds (mainly mis-reconstructed leptons, but also including heavy flavor decays)
    → select these events by anti-selecting electrons (all selection criteria applied, but no $\Delta\phi$ and $\Delta\eta$ matching

Test on early data:
W is the signal!

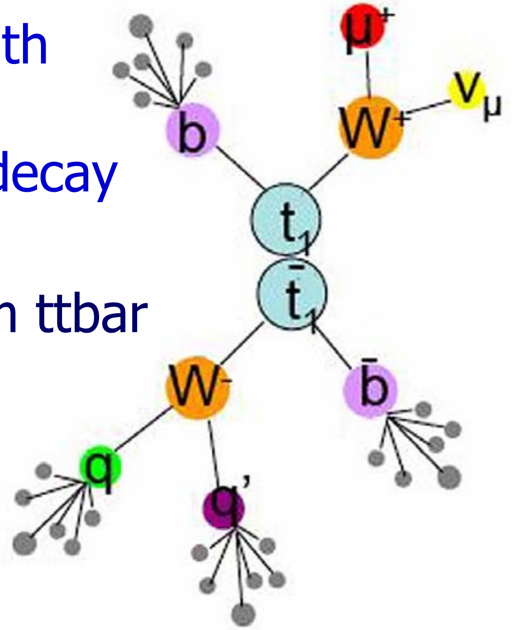


Examples: Methods to estimate ttbar Background

- ttbar background estimation with ttbar enriched samples
- Top redecay
- ttbar with lepton replacement

ttbar Background Estimation using b-Tagging or χ^2(ttbar)

- ttbar is a significant background for:
  - Hadronic analyses (e.g. semi-leptonic decay with mis-identified lepton)
  - Single-leptonic analyses (e.g. double-leptonic decay with one mis-identified lepton)
- Idea: Measure the ttbar background for SUSY from ttbar enhanced data sample:
  - by b-tagging
  - by cutting on χ^2(ttbar)
  - ...



- Extrapolate from background region to signal region (e.g. from small E_T^{miss} to large E_T^{miss}
- Important:
  - Check how the prediction changes in case of signal in control region (usually overestimation, but signal still visible)!

Top Redecay

- Use the Monte Carlo purely for modelling of relatively well-understood decay and hadronisation processes
- Obtain the initially poorly understood aspects of process generation, such as parton distributions and the underlying event model, from data:
  - Isolate a pure di-leptonic ttbar events:
    → select clean low E_T^{miss} (to reduce SUSY signal) opposite sign di-lepton events
  - Then reconstruct the kinematics of the top quarks, remove their decay products from the reconstructed event
  - Redecay the reconstructed top quarks using an event generator (e.g. PYTHIA) and merge the simulated re-decay products back into the parent (`seed') event

ttbar with Lepton Replacement

Estimation of mis-reconstructed (di-)leptonic top decays due to:

  - One un-identified tau
  - One lost electron or muon
  - One lepton lost inside a jet
  - One lepton is not in the p_T or η acceptance
  - Two tau leptons
- Idea in case of one-lepton SUSY search:
  - Collect good reconstructed di-leptonic events
  - Take these events and artificially change them to events discussed above, e.g.
    - Use each of the leptons as seed for simulation of tau decays
    - Replace electrons by jets and muons by standalone muons
  - Estimate the identification efficiency of these events (from simulation)
  - Reweight these events accordingly
- Similar approach for no-lepton SUSY search…

Methods to estimate VectorBoson Background

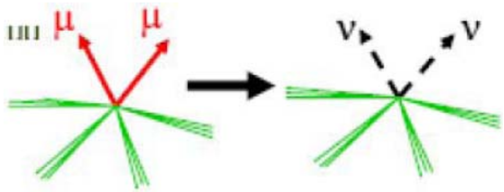
- Main problem: decays including neutrinos

→ Replacement methods to model these decays

Modeling the ν Background

Invisible Z decay ($Z \rightarrow \nu\nu$+jets) is a significant background!

- Model it by looking at 'visible' decays, preferably $Z \rightarrow \mu\mu$+jets:
- Ansatz:
  - Declare di-muon tracks invisible to emulate neutrinos
  - Then re-calculate E_T^{miss} for this event
  - Correct for the muon reconstruction efficiency and neutrino branching ratio
  - Since the production mechanisms are the same in both processes, the missing transverse energy is correctly estimated without having to rely on Monte Carlo simulations

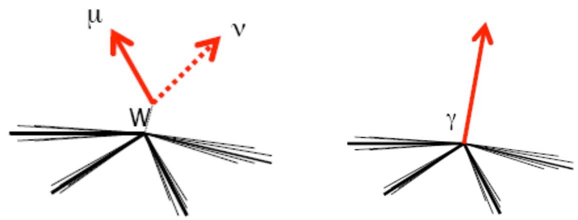


Problem: small cross-section, need to collect about 1 fb^{-1} for reasonable statistics

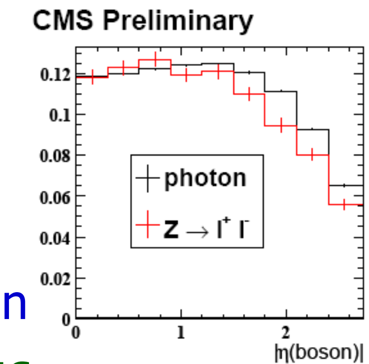
→ Alternatives for the first data analysis needed:
  - → release cuts to get larger number of events or
  - → use different processes (see next page)

Modeling the ν Background (2)

- Alternatives to Z→$\mu\mu$+jets:
  - W→$\mu\nu$+jets: expect about 6 times more events, but no 'candle'
  - γ+jets: expect about 30 times more events than for Z→$\mu\mu$+jets
- Ansatz:
  - Declare muon track or photon invisible to emulate neutrinos



  - Then re-calculate E_T^{miss} for this event
  - Correct for the muon or photon reconstruction efficiency and neutrino branching ratio
  - η distribution for γ and Z differs (due to different phase space factors for massive Z bosons versus massless on-shell photons, and due to the different vector and axial couplings); better at higher p_T, where bosons are more likely in the central region

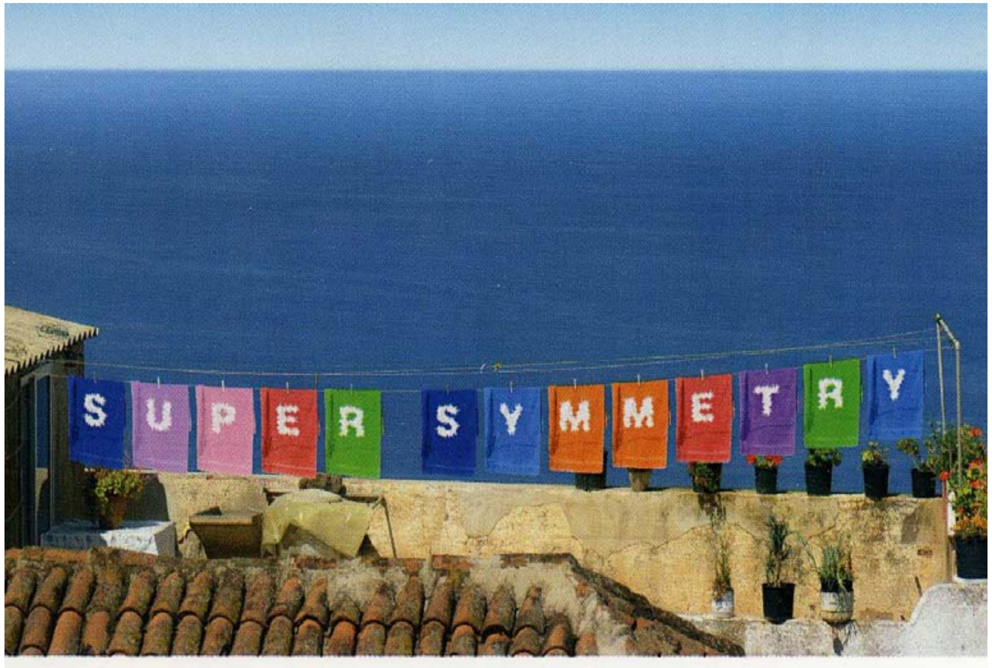


SUSY signals could bias the prediction (depending on the SUSY scenario, more for leptons (mSUGRA) or photons (GMSB)

→ Useful to have background estimations from different processes

Where we are...

- SUSY models
- Event selection
- Interesting observables
- Background determination
- ⇨ **Model independent searches** ⇦
- Systematic uncertainties



Model Independent Searches

- Combined model independent searches look for deviations from the Standard Model by looping over **many** different channels
- Goal: don't focus on channels sensitive to particular models, but examine data in as many channels as possible!

- Detector has to be well understood…

- Algorithms used by CDF (all high p_T data) and D0 (lepton final states):
  - Vista
  - Sleuth
  - Bump hunter

Vista

- Experiment-independent program developed by CDF to compare event counts and 1-D histogram shapes between data and the standard model expectation
- Account for 'trials factor' k (number of different final states) by calculating p with:

  $p = 1 - (1 - p_{fs})^k$ with p_{fs}: Poisson probability that the number of predicted events would fluctuate

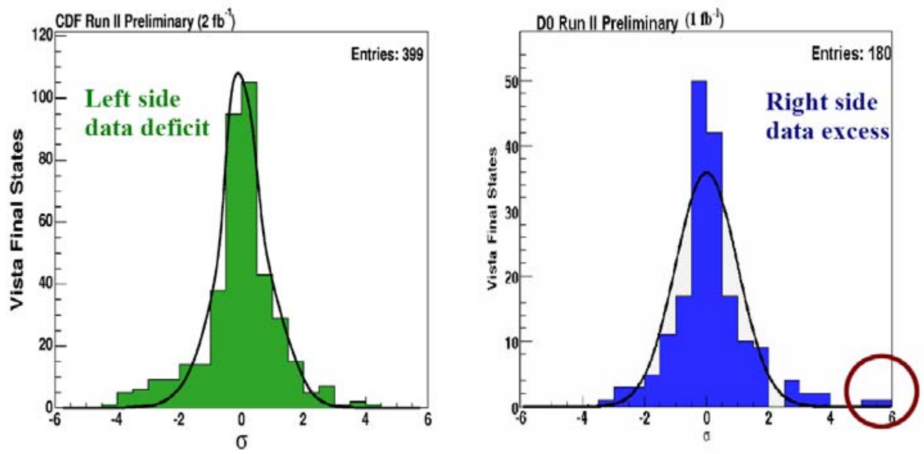
- Checks overall event counts and Kolmogorov-Smirnov probabilities
  → most sensitive to differences in the central parts (not tails) of distributions

- Sensitivity to new physics with large cross-sections or modelling issues affecting variables across different final states

Phys. Rev. D 78:012002, 2008
Phys. Rev. D 79:011101, 2009

Vista Results

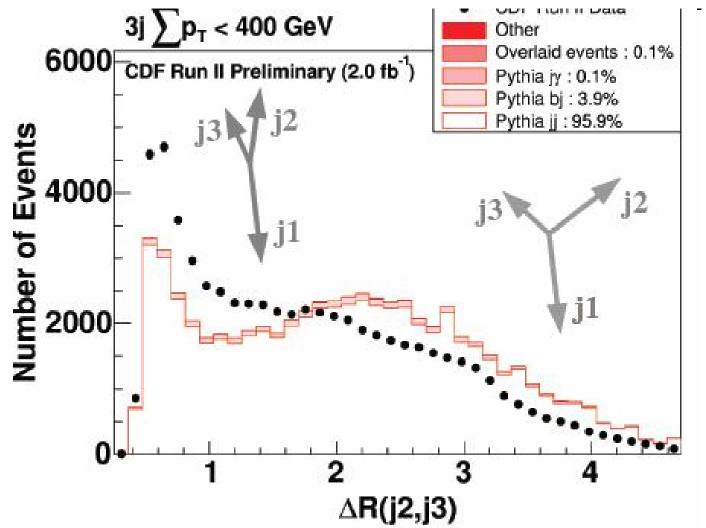
- Overall event counts: histograms contain one entry per each final state checked
  - CDF sees no access
  - D0 sees one entry above 5σ



CDF Curve: pseudoexperiments DØ Curve: Gaussian

- Shape test:

  More discrepancies seen, **but**
  - most discrepancies come from QCD
  - bad modelling of **soft gluon emission**



Sleuth

- Originally developed by D0 and then improved by H1
- Relies on the following assumptions:
  - Data can be categorized into exclusive final states such that any signature of new physics appears predominantly in one of these final states
  - New physics will appear with objects at high p_T relative to the Standard Model and instrumental background
  - New physics will appear as an excess of data over Standard Model and instrumental background

- Checks the high-p_T tails of final states by comparing:

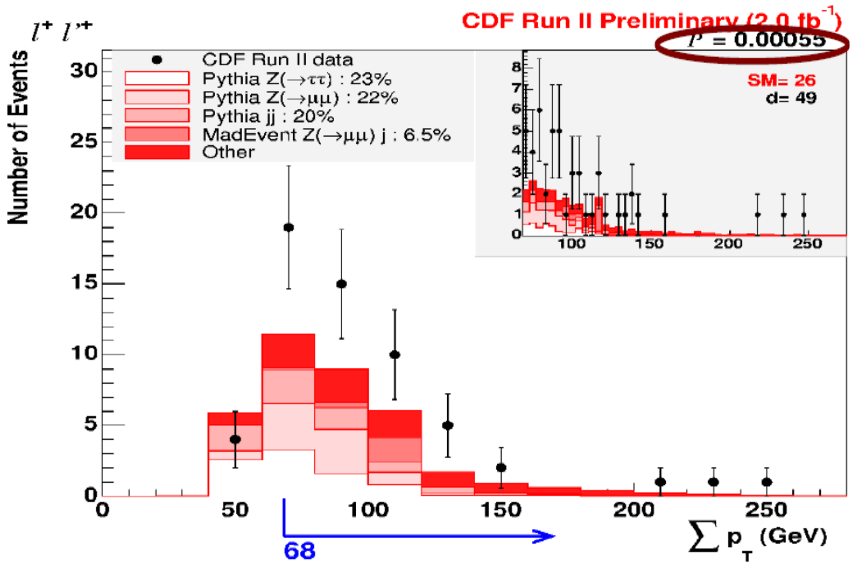
$$\sum p_T = \sum_i \left|\vec{p}_i^{\,\text{jets}}\right| + \left|\vec{p}^{\,\text{unclustered}}\right| + \left|\vec{p}^{\,\text{miss}}\right|$$

where $\sum_i \vec{p}_i^{\,\text{jets}} + \vec{p}^{\,\text{unclustered}} + \vec{p}^{\,\text{miss}} = \vec{0}$

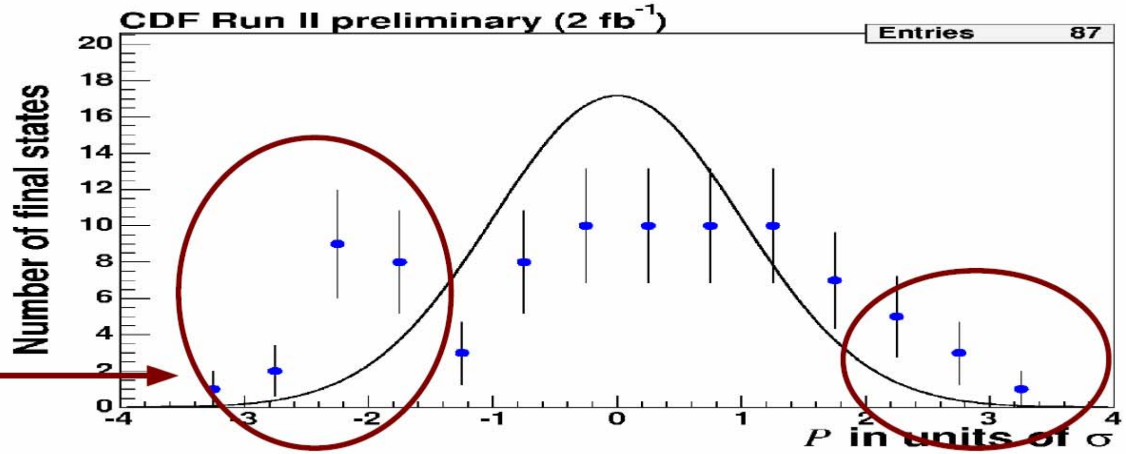
Phys. Rev. D 62:092004, 2000
Phys. Rev. D 64: 012004, 2001
Phys. Rev. Lett. 86 3712, 2001
Phys. Lett. B 602 14, 2004

Sleuth Results

- Few discrepant states found, e.g. same-sign dileptons:
  - Small probability (0.00055) before final state trials factor
  - After trials only 2σ effect
- Otherwise no large deviation found…



High probability- overestimate of SM background?



Low probability- modeling issues, new physics?

Bump Hunter

Idea: scan the spectrum of most mass variables with a sliding window:

- Define a search window of varying width (e.g. 2 x expected detector mass resolution)
- Compare data to SM background
- Define a possible bump at least 5 data events
- Verify that side-bands agree better than central region
- Estimate significance of bumps by pseudo-experiments

Where we are...

- SUSY models
- Event selection
- Interesting observables
- Background determination
- Model independent searches
- **Systematic uncertainties**

Systematic Uncertainties

Finally you finished your analysis:

- Data are taken, selection is optimized, Monte Carlo is produced, background is estimated, fit is implemented and working!

→ **Result** = $x \pm \sigma_{stat}$

- The thesis/paper is of course overdue, but still the systematics have to be evaluated. . .
- And worse: No clear concept how to do it!
- Common solution in this situation:

  "Let's vary a few cuts, that's quickly done, and see if and how the result changes. We then call the variations of the result the systematic uncertainty!"

Worst Method!

What are Systematic Uncertainties?

- Badly known **detector acceptance** or **trigger efficiency**
- Wrong **detector calibrations**
- Badly known **detector resolutions**
- **Time variations** of the experimental conditions
- Badly known **background**
- Uncertainties in the **simulation/theoretical model**
- Uncertainties on **input parameters** (branching ratios, lifetimes, luminosity,…)
- **Computational errors / program bugs / fit routines**
- **Biased experimentalist** (wants to measure "expected" result)
- All other usually **unknown effects** on the measurement

How to find systematic Uncertainties?

First: Think about any possible effect!

- Is every single **input number/parameter** well-known and understood? (efficiencies, calibrations, theory, external parameters, PDG, . . .)
- Every possible **detector effect** considered? (geometrical acceptance, trigger efficiency, resolutions, detector inefficiencies, calibrations [energy scales!], . . .)
- **Backgrounds** complete and well understood?
- **Fit routine** working correctly?
- **Theoretical inputs** correct? (e.g. fragmentation function)

In case of any doubt:

Think of the cause of a possible effect!

→ Look at corresponding distributions

Example for Background Estimation

Is my background estimation correct?

Example: DELPHI search for SUSY particles

Eur.Phys.J., C31, 421 (2004)

E.g.: stop-quark search in e^+e^- annihilation:

- stop-quark should be pair-produced and decay like $\tilde{t} \rightarrow c\tilde{\chi}^0_1$
- Signature: Missing energy and two acoplanar jets
- Main analysis problem (as usual for searches):
  Background suppression and estimation
- Main backgrounds:
  - SM 2-jet,
  - SM 4-jet,
  - two-photon events ($ee \rightarrow ee\gamma\gamma$)
- How can we make sure that backgrounds are understood?

→ Look for regions with large background contributions – are they well-described?

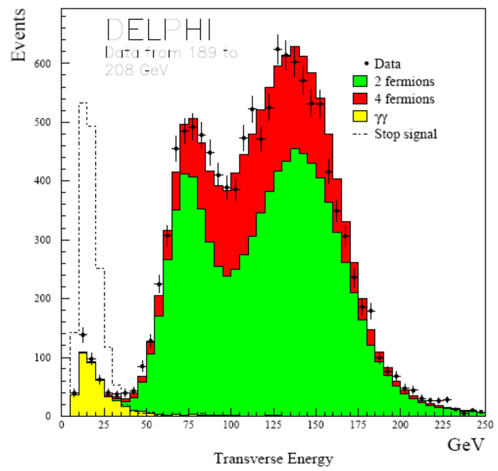
- How can we enlarge backgrounds?

→ Release corresponding cuts!

Example for Background Estimation (2)

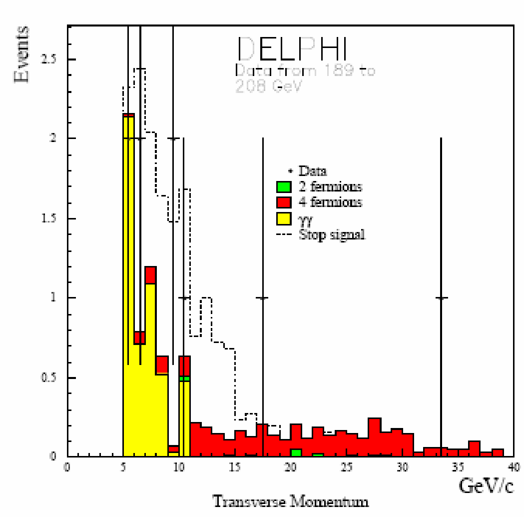
- Look at transverse energy with loosened cuts:

→ about 15% discrepancy found



- With final (tight) selection, vary background by the 15% obtained above

→ limit changes

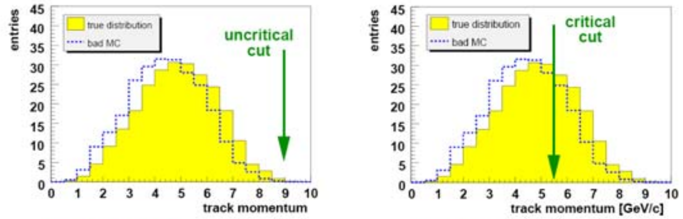


Attention:

Be careful when extrapolating from very many to very few events! Tails might not be well described and events in the tails may behave differently compared to "normal" events!

Other Systematics

- Acceptance description
  - Poor MC description (e.g. inefficiencies)
  - Critical if selection cuts hard into acceptance



Acceptance:
true: $\epsilon_{true} = 99.8\%$
bad MC: $\epsilon_{wrong} = 99.9\%$

Acceptance:
true: $\epsilon_{true} = 64.5\%$
bad MC: $\epsilon_{wrong} = 75.3\%$

- Result as function of parameters
  - Usually the data sample consists of several sub-samples of more or less similar size with similar experimental conditions (detector status, trigger conditions, magnet polarities, collider performance, etc.)
  - Important check: Determine separate results for each sub-sample!
  - Do they agree? If not:
    1. Why not?
    2. Possibly discard sub-sample from analysis!

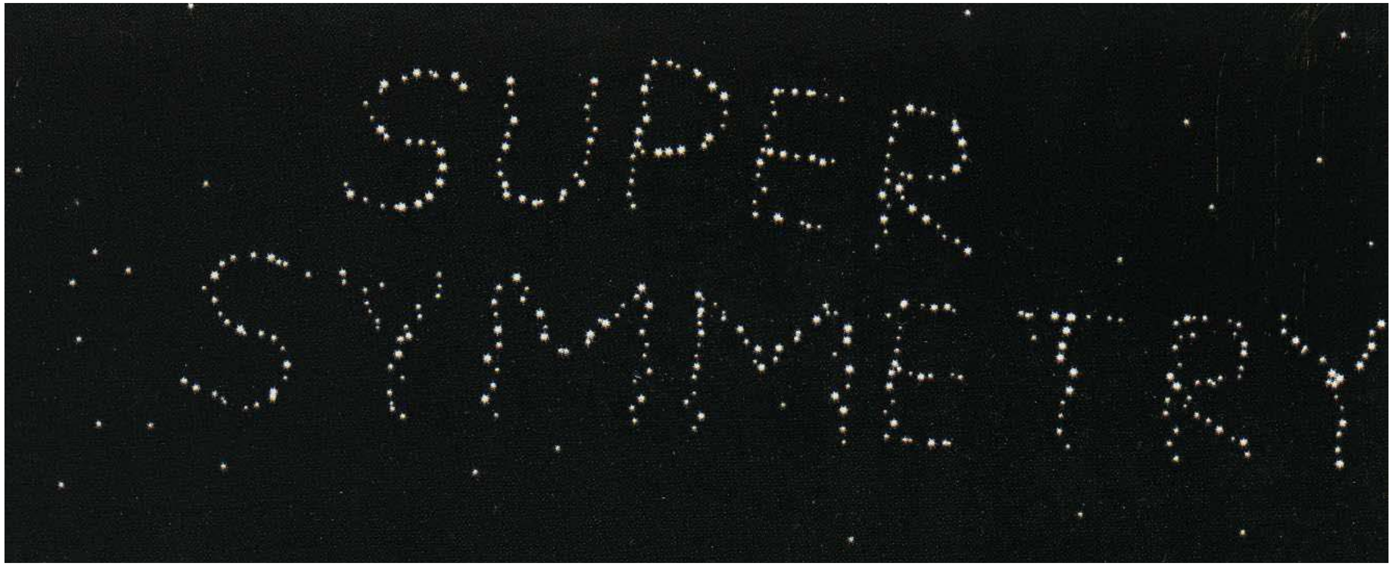
Other Systematics (2)

- Fit routines
  - Trivial test: Run full MC sample (as large as possible) with known input parameters instead of data – result as expected?
  - Check for biases: Repeat the above MC analysis (or possibly toy-MC) 20–100 times with MC sample size equal to data sample size:
    - Do results follow a (Gaussian) distribution around the input value with variance as expected?
  - Repeat analysis with different binning (but distinguish statistical from systematic fluctuations!)

- Cut tuning – never tune on data (always tune on Monte Carlo)!

Summary: Program for LHC measurements

- With first data up to now: start with QCD background determination
- Next step: validate W and Z measurements
- Then finally check top backgrounds with enough luminosity
- Find SUSY signal?!?
- Evaluate your systematics…
- What then? – Need to measure SUSY parameters (→ see lecture by Ben Allanach)



Thank you for listening

Backup slides follow…

CMSSM

Simplest ansatz: CMSSM – assume universality at high energy scale

- Universal scalar masses: $\tilde{m}^2 = m_0^2$
- Universal gaugino masses: $M_i = m_{1/2}$ ("GUT relation")
- Universality of soft-breaking trilinear terms:

  $$\mathcal{L}_{\rm tri} = A_0(H_U Q y_u \bar{u} + H_D Q y_d \bar{d} + H_D L y_l \bar{e})$$
- Results in **five** parameters, if possible phases are ignored:

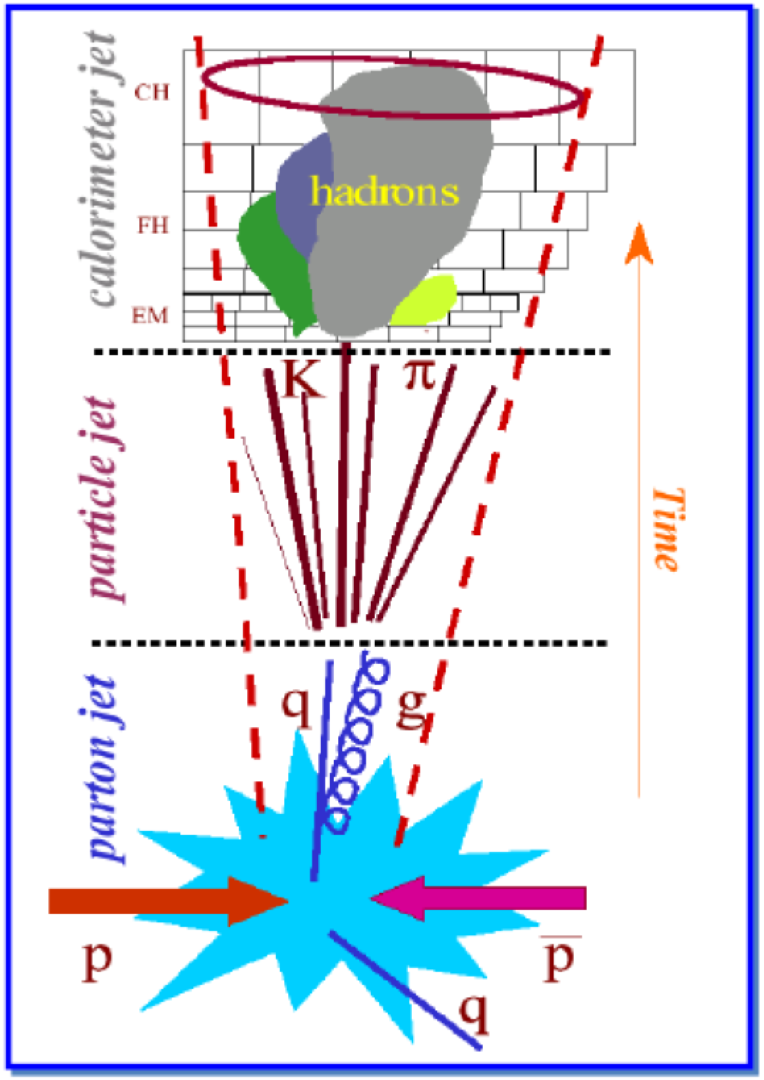
  $m_0^2, m_{1/2}, A_0, b, \mu$
- Require correct value of M_z,

  → $|\mu|$, b given in terms of tan $\beta = v_u/v_d$ and sign μ

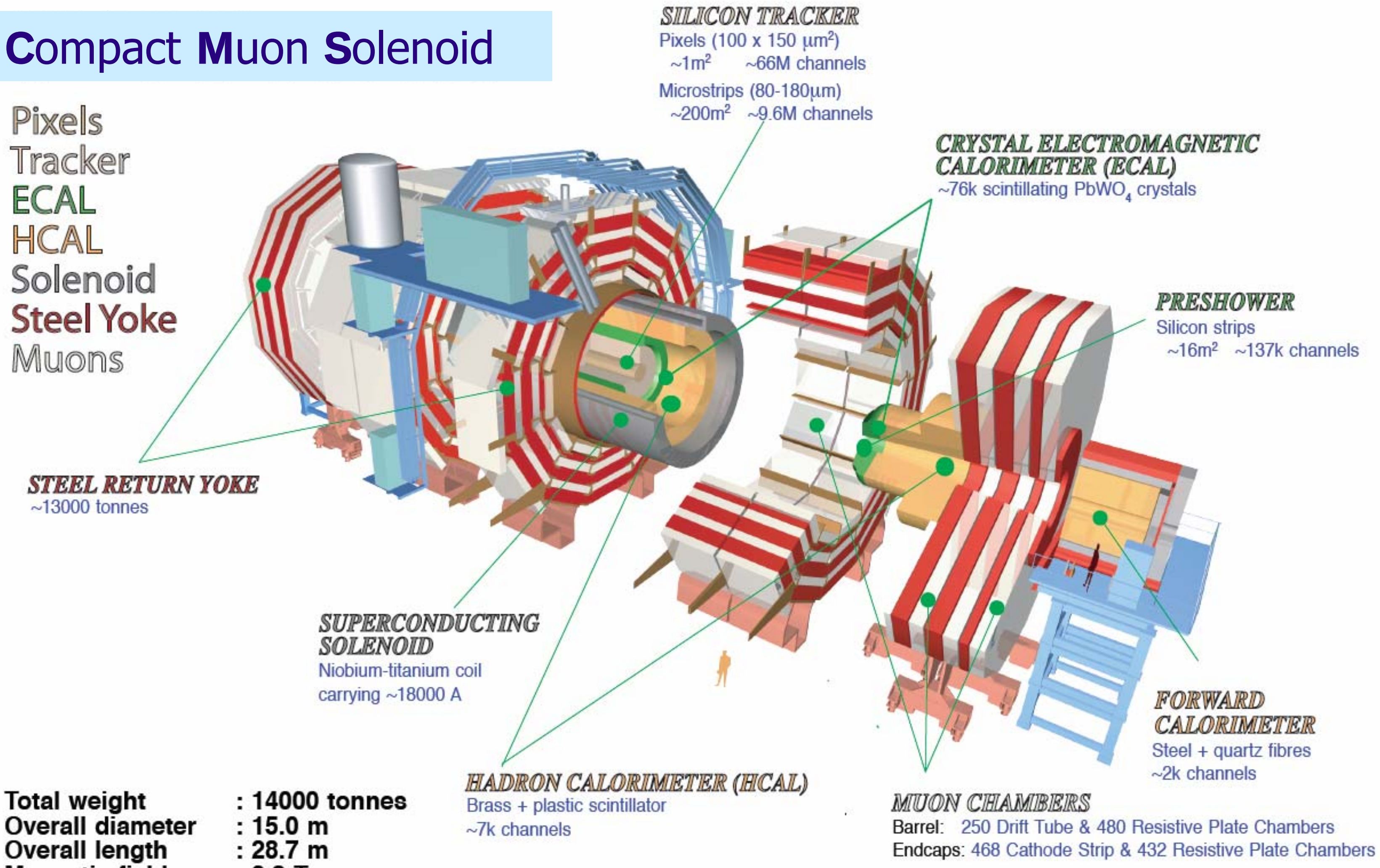
➔ CMSSM parameters:

$m_0^2, m_{1/2}, A_0$, tan β, sign μ

Jets

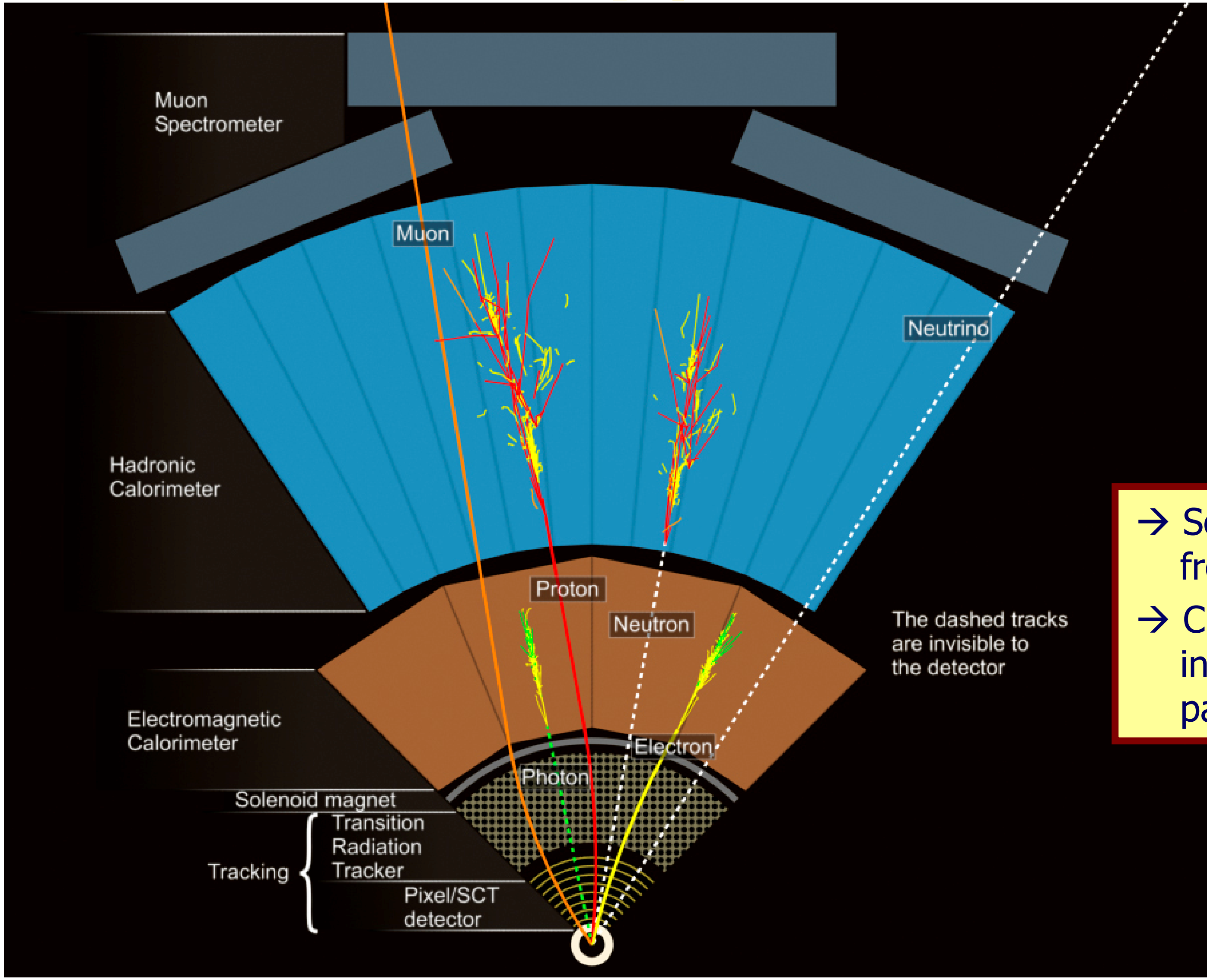

calorimeter jet
CH
FH
EM
hadrons
particle jet
K
π
parton jet
q
g
Time
p
$\bar{p}$
q

Compact Muon Solenoid



Total weight	**: 14000 tonnes**
Overall diameter	**: 15.0 m**
Overall length	**: 28.7 m**
Magnetic field	**: 3.8 T**

ATLAS (2)



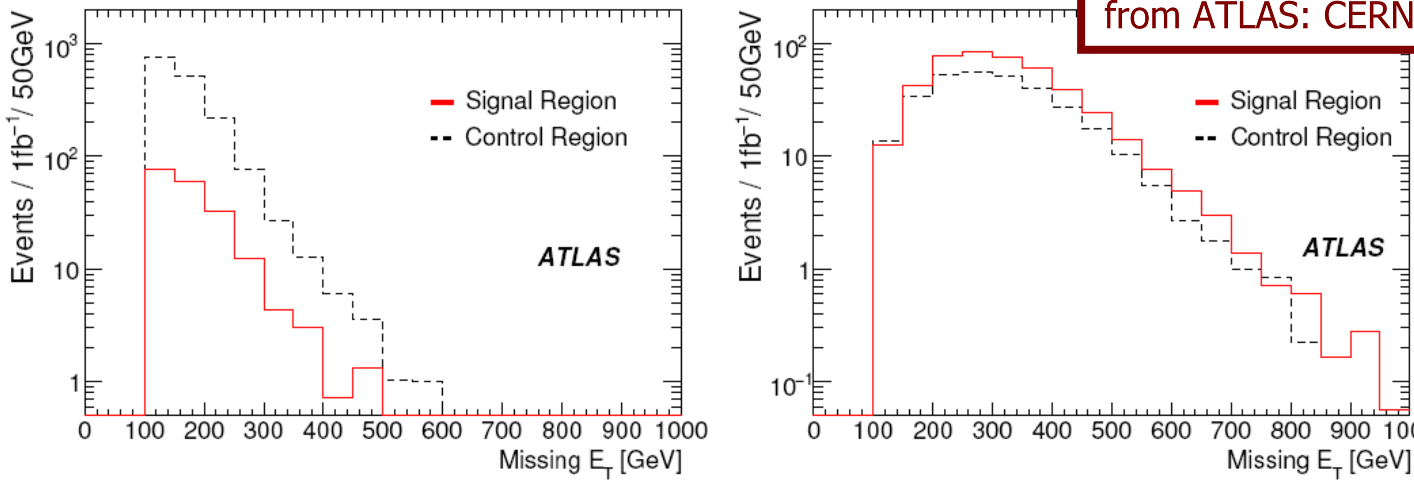
→ Solenoid magnet in front of calorimeters

→ Curvature of tracks in muon system: into paper plane!

ttbar Estimation with ABCD Method: M_T vs E_T^{miss}

- Reminder: M_T= transverse invariant mass of lepton and E_T^{miss}
- Select events with small M_T (<100GeV) as control sample, which contain mainly ttbar and about 15% W events
- Check that variable to check (e.g. E_T^{miss}) look similar in control and signal sample

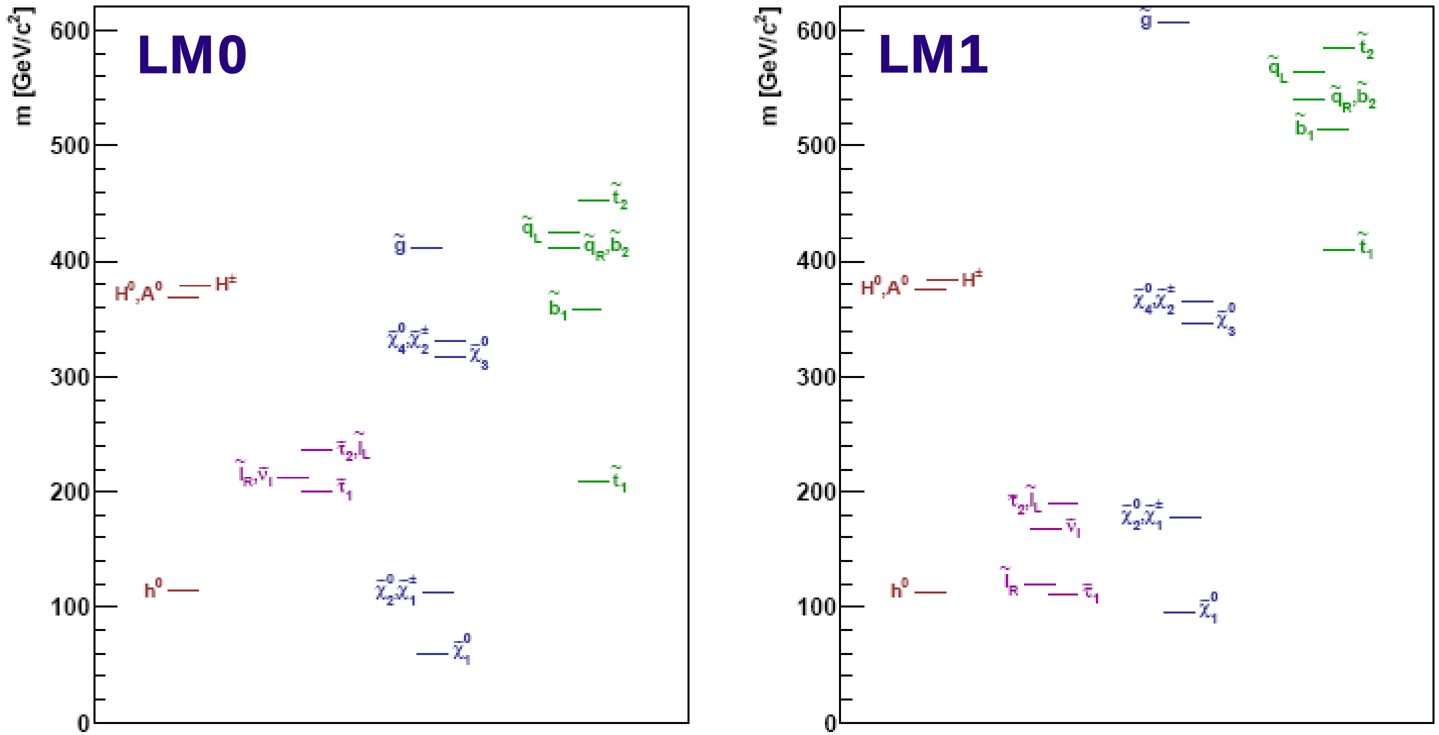
from ATLAS: CERN-OPEN-2008-020



- Get normalisation from region which is expected to be only mildly populated with signal (e.g. 100 GeV < E_T^{miss} < 200 GeV)
- Extrapolate ttbar contamination in signal region
- If signal found, re-insert signal in normalisation region and redo extrapolation

Sparticle Masses

- $\tilde{g}\tilde{q}$ production favored, but also $\tilde{q}\tilde{q}$ and $\tilde{q}\bar{\tilde{q}}$



Model	$m(\tilde{g})$	$m(\tilde{\chi}_1^0)$	$m(\tilde{\chi}_2^0)$	$m(\tilde{\chi}_1^+)$	$m(\tilde{\chi}_2^+)$	$m(\tilde{t}_1)$	$m(\tilde{b}_1)$	$m(\tilde{u}_L)$	$m(\tilde{e}_L)$	$m(\tilde{\nu}_{eL})$
LM0	409	60	113	114	327	207	356	415	231	217
LM1	603	96	178	179	360	407	510	552	186	167

Sparticle Decay

- Gluino decay: if (as in LM0 and LM1) $m(\tilde{g}) > m(\tilde{q})+m(q)$:
  $\tilde{g} \to \tilde{q}\bar{q}$ or $\tilde{g} \to \bar{\tilde{q}}q$
  [BTW: Other models with $m(\tilde{g}) < m(\tilde{q})+m(q)$: weak decay via virtual intermediate-state squark → long gluon lifetime]
- Squark decay: $\tilde{t}_1$ and $\tilde{b}_1$ decay similar to $t \to bW^-$:
  - $\tilde{t}_1 \to \tilde{\chi}_1^+ b$ (100%)
  - $\tilde{b}_1 \to \tilde{\chi}_2^0 b$ (29%)
  - $\tilde{b}_1 \to \tilde{\chi}_1^- t$ (24%)
  - $\tilde{b}_1 \to \tilde{t}_1 W^-$(24%)
- Chargino decay:

  Natural 2-body decays (forbidden in LM0 – masses too high):
  - $\tilde{\chi}_1^- \to \tilde{\mu}^- \nu$
  - $\tilde{\chi}_1^- \to \tilde{\nu} \mu^-$
  - $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-$
  - $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$

  } Decay via off-shell bosons (3-body decays)

Sparticle Decay

- Gluino decay: if (as in LM0 and LM1) $m(\tilde{g}) > m(\tilde{q})+m(q)$:
  $g \to \tilde{q}\bar{q}$ or $g \to \bar{\tilde{q}}q$
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  - $\tilde{b}_1 \to \tilde{\chi}_1^- t$ (24%)
  - $\tilde{b}_1 \to \tilde{t}_1 W^-$ (24%)
- Chargino and neutralino decay:

  Natural 2-body decays (forbidden in LM0 due to masses):
  - $\tilde{\chi}_1^- \to \tilde{\mu}^- \nu$
  - $\tilde{\chi}_1^- \to \tilde{\nu} \mu^-$
  - $\tilde{\chi}_1^- \to \tilde{\chi}_1^0 W^-$
  - $\tilde{\chi}_2^0 \to \tilde{\chi}_1^0 Z$

  } Decay via off-shell bosons (3-body decays)

Sources of jets

Sources of prompt leptons!

Sparticle Decay (2)

- Additional chargino and neutralino decays

  Similar to chargino decay from previous page (3-body), e.g.:
  - $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z^* \rightarrow \chi_1^0 \mu^+ \mu^-$ (3.3%)

  Additional 2-body decays:
  - $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 Z$
  - $\tilde{\chi}_2^+ \rightarrow \tilde{\chi}_1^0 W^+$
  - $\tilde{\chi}_2^+ \rightarrow \tilde{\chi}_1^+ Z$

All are sources of prompt leptons!

→ **Need to look for (many) jets and (optionally) leptons and missing energy in the final state**

Interesting Variables: M_T

M_T is used for single-leptonic analyses:

- Measure of the transverse invariant mass of the lepton and the missing momentum (with $\Delta\Phi$: angle between lepton and E_T^{miss})

$$M_T^2 = 2 p_T^{\text{lepton}} E_T^{miss} (1 - \cos \Delta\Phi)$$

- For an event containing a single $W \rightarrow \mu\nu$ decay,
  $M_T^2 = (p(\mu) + p(\nu))^2 = M_W^2$

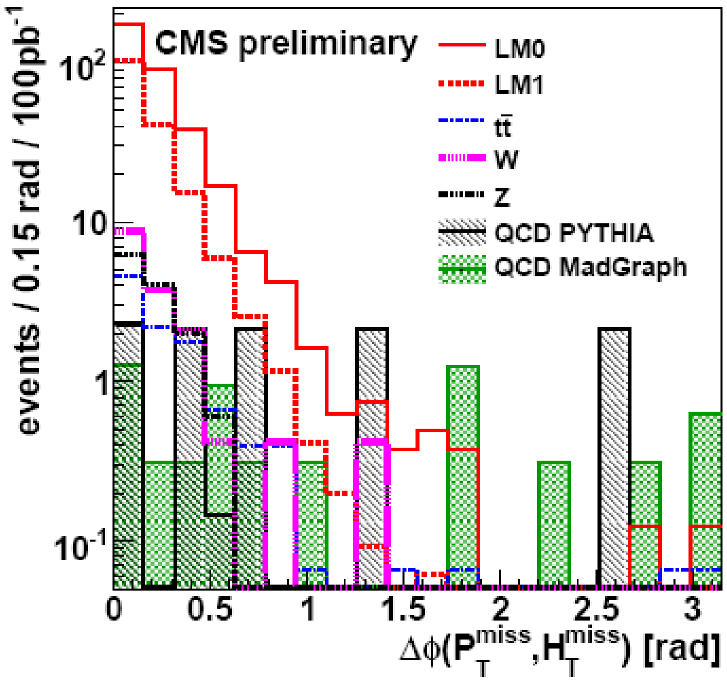
  Single $W \rightarrow \mu\nu$ decays appear as peak with sharp falling edge close to the W mass

→ If a W decay is the source of both the lepton and the E_T^{miss}, the requirement $M_T > M_W$ would remove most of the SM events

- But: this cut also removes a significant fraction of the SUSY events!
- Need to combine with another cut…

Interesting Observables: $\Delta\Phi(p_T^{miss}, H_T^{miss})$

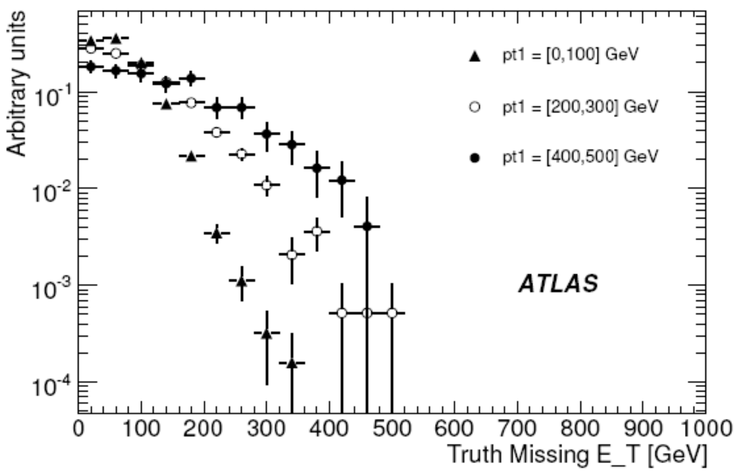
- Missing p_T from tracks and missing energy from jets should point into the same direction when track and jet kinematics agree!
- H_T^{miss} can be mismeasured because of neglected jets or because of other disturbing sources
- Tracking-based p_T^{miss} has completely different sources of systematic uncertainties as calorimeter based H_T^{miss}



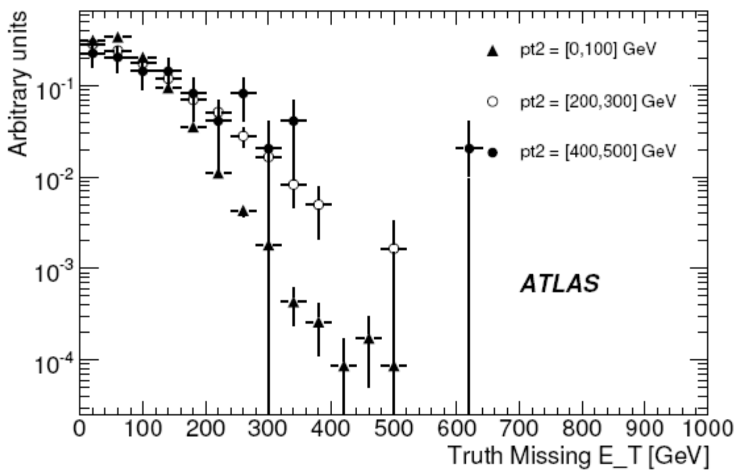
Interesting Variables: H_{T2}

- For many background estimation methods a variable not correlated to E_T^{miss} is wanted
- One idea: take the sum of 2nd to 4th leading jet (and lepton) p_T:

$$H_{T2} = \sum_{i=2}^{4} p_T^{\text{jet } i} + p_T^{\text{lepton}}$$



p_T(1st jet) vs E_T^{miss}



p_T(2nd jet) vs E_T^{miss}

- To further reduce dependence compare to $E_T^{miss}/\Sigma E_T$

Background determination for α_T: H_T vs $|\eta|$ of leading Jet

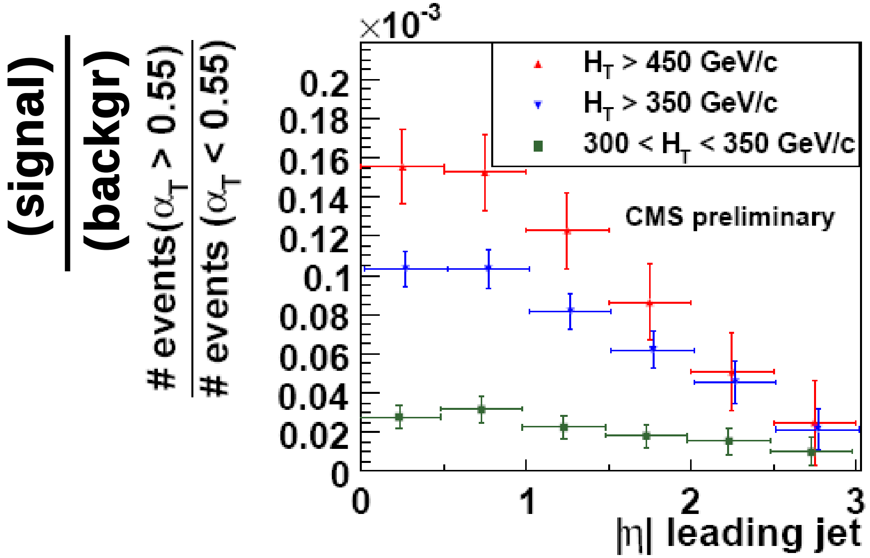
Try to understand the background for α_T:

- SUSY signal is expected to be more central and in higher H_T region ($H_T = \Sigma E_T^{jets}$)
- Background relatively flat in $|\eta|$ and H_T

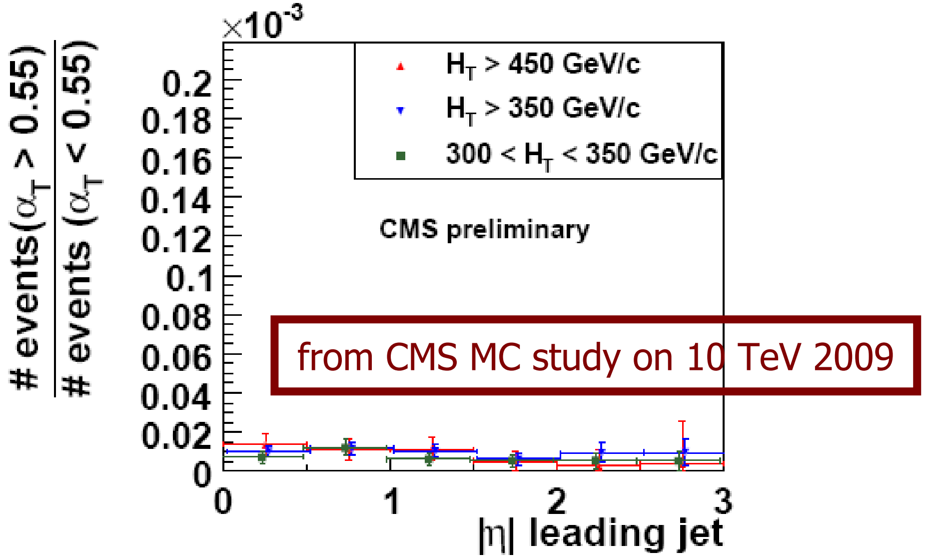
→ Can lower H_T region be used to extrapolate background expectation to higher H_T values?

→ Check behavior for both α_T regions (signal and bg region):

SM+SUSY (LM0)



SM only



CMS Benchmark Point Characteristics

- **Point LM1 :**
  - Same as post-WMAP benchmark point B' and near DAQ TDR point 4.
  - M(gluino) > M(squark), hence gluino -> squark+quark is dominant
  - B(X02 -> slep_R lept) = 11.2%, B(X02 -> stau_1 tau) = 46%, B(X+1 -> sneut_L lept) = 36%
- **Point LM2 :**
  - Same as post-WMAP benchmark point I'.
  - M(gluino) > M(squark), hence gluino -> squark+quark is dominant (sbot1+b is 25%)
  - B(X02 -> stau_1 tau) = 96%, B(X+1 -> stau_1 nu) = 95%
- **Point LM3 :**
  - Same as NUHM point gamma and near DAQ TDR point 6.
  - M(gluino) < M(squark), hence gluino -> squark+quark is forbidden except B(gluino -> sbot1,2 bot) = 85%
  - decays: B(X02 -> lept lept X01) = 3.3%, B(X02 -> tau tau X01) = 2.2%, B(X+1 -> W+ X01) = 100%
- **Point LM4 :**
  - Near NUHM point alpha in on-shell Z0 decay region.
  - M(gluino) > M(squark), hence gluino -> squark+quark is dominant with B(gluino -> sbot1 bot) = 24%
  - decays: B(X02 -> Z0 X01) = 97%, B(X+1 -> W+ X01) = 100%
- **Point LM5 :**
  - In h0 decay region, same as NUHM point beta.
  - M(gluino) > M(squark), hence gluino -> squark+quark is dominant with B(gluino -> sbot1 bot) = 19.7% and B(gluino -> stop1 top) = 23.4%
  - decays: B(X02 -> h0 X01) = 85%, B(X02 -> Z0 X01) = 11.5%, B(X+1 -> W+ X01) = 97%

CMS Benchmark Point Characteristics (2)

- **Point LM6 :**
  - Same as post-WMAP benchmark point C'.
  - M(gluino) > M(squark), hence gluino -> squark+quark is dominant
  - B(X02 -> slepL lept) = 10.8%, B(X02 -> slepR lept) = 1.9%, B(X02 -> stau1 tau) = 14%, B(X+1 -> sneut lept) = 44%
- **Point LM7 :**
  - Very heavy squarks, outside reach, but light gluino.
  - M(gluino) = 678 GeV, hence gluino -> 3-body is dominant
  - B(X02 -> lept lept X01) = 10%, B(X+1 -> lept nu X01) = 33%
  - EW chargino-neutralino production cross-section is about 73% of total.
- **Point LM8 :**
  - Gluino lighter than squarks, except sbot1 and stop1.
  - M(gluino) = 745 GeV, M(stop1) = 548 GeV (A0 = -300), gluino -> stop1+t is dominant
  - B(gluino -> stop1+t) = 81%, B(gluino -> sbot1+b) = 14%, B(squarkL -> q+X02) = 26-27%,
  - B(X02 -> Z0 X01) = 100%, B(X+1 -> W+ X01) = 100%
- **Point LM9 :**
  - Heavy squarks, light gluino. Consistent with EGRET data on diffuse gamma ray spectrum, WMAP results on CDM and MSUGRA (see W. de Boer et al., astro-ph/0408272 v2). Similar to LM7.
  - M(gluino) = 507 GeV, hence gluino -> 3-body is dominant
  - B(X02 -> lept lept X01) = 6.5%, B(X+1 -> lept nu X01) = 22%
- **Point LM10 :**
  - Similar to LM7, but heavier gauginos.
  - Very heavy squarks, outside reach, but lighter gluino.
  - M(gluino) = 1295 GeV, hence gluino -> 3-body is dominant
  - B(gluino> -> t tbar X04) = 11%, B(gluino -> t b X+2) = 27%