Cornell University
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Model Discrimination with the CMS Detector: a Case Study

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Particle Physics Seminar

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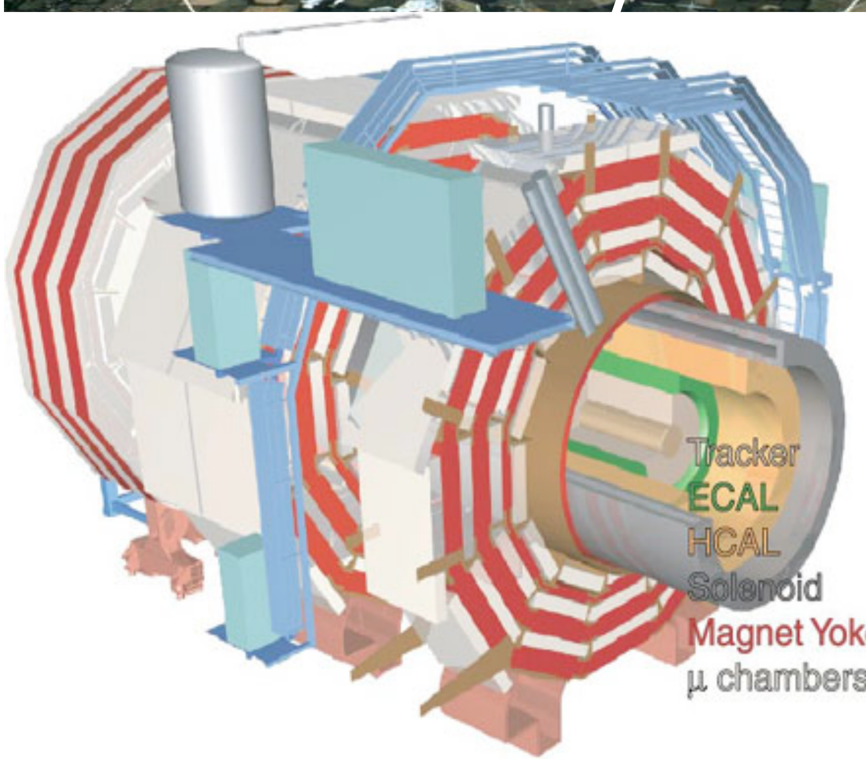
5/8/2009

Perelstein, Spethmann, JT, Vaughan, Hallenbek
arXiv:0812.3135 [hep-ph], to appear in PRD

The Large Hadron Collider (LHC) at CERN



14 TeV
pp collisions

First years of LHC data

- Begin running with a large number of possible New Physics extensions to the SM

- Strong limitations on our understanding of first data sample
  - Small statistics
  - Poorly understood detector, immature simulation
  - Primitive triggers, jets, flavor tagging,..

- If we see excess over SM predictions, what do we do next to identify the correct New Physics model
  - What are the most powerful model discriminators?
  - How do we deal with the large parameter space of the many NP models?

This study

- pick a simple signature with good prospects for clear excess over SM prediction
  - Many New Physics models make a compelling case for pair production of exotic particles decaying to jets + Missing energy (+ X) at the TeV scale
  - Same experimental signature predicted for many of them ("Look-alikes")
  - Difference in *spin* of exotic particles

- Can we exclude classes of NP models based on spin information, assuming realistic conditions? How sensitive are we to exp. effects?

Perelstein, Spethmann, JT et al arXiv:0812.3135 [hep-ph], to appear in PRD,

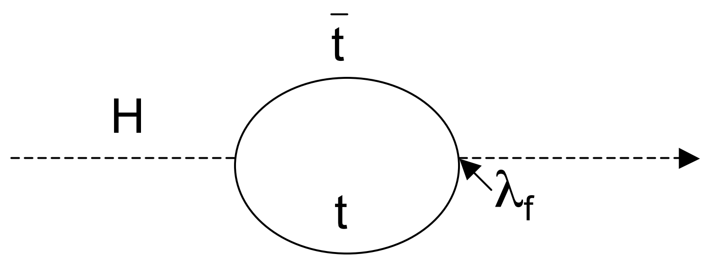
See also: Lykken, Spiropulu, Hubisz, et al Phys.Rev.D78:075008 .

Jets + Missing Energy (+X) at LHC:

- Why do we think we will see signs of New Physics at the LHC?
- Plausible extensions to the SM that result in this signature:
  - MSSM
  - Little Higgs with T-parity
  - UED,…

“Hierarchy”-Problem

- As the Higgs propagates, it interacts virtually with all particles it can couple to, e.g. Fermions
- this will contribute to the Higgs mass (“radiative corrections”)



- Higgs mass can receive enormous corrections proportional to the largest scale in the theory (“Planck Mass”, 10^{19} GeV)

$$\Delta m_H{}^2 = \frac{|\lambda_t|^2}{16\pi^2}(-\Lambda_{UV}{}^2 + \ldots)$$

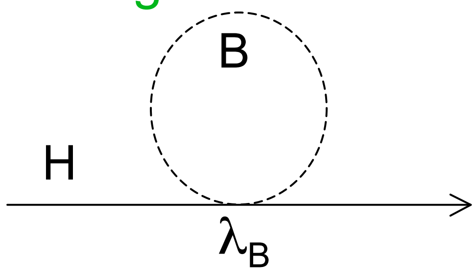
One plausible solution: Supersymmetry

A symmetry which relates bosons to fermions:

$$Q|Boson\rangle = |Fermion\rangle$$

$$Q|Fermion\rangle = |Boson\rangle$$

– We know that a boson loop would contribute to Δm_H with opposite sign



$$\Delta m_H^2 = \frac{\lambda_B}{16\pi^2}(\Lambda_{UV}^2 + ...)$$

– This allows for systematic cancellation between Fermion and Boson loop contributions

$$\lambda_B = |\lambda_f|^2$$

– Supersymmetry implies that Fermions and Bosons come in "super"-multiplets, e.g. (t (spin ½), t (spin 0))

“Minimal” Supersymmetric Standard Model (MSSM)

- Minimal extension of SM that realizes Supersymmetry
- Superpartner for each SM d.o.f., most general SUSY-breaking terms
- Introduces a discrete R-parity (SM particles are even, superpartners are odd.)

Names	Spin	P_R	Gauge Eigenstates	Mass Eigenstates
Higgs bosons	0	+1	$H_u^0\ H_d^0\ H_u^+\ H_d^-$	$h^0\ H^0\ A^0\ H^\pm$
squarks	0	−1	$\widetilde{u}_L\ \widetilde{u}_R\ \widetilde{d}_L\ \widetilde{d}_R$	(same)
			$\widetilde{s}_L\ \widetilde{s}_R\ \widetilde{c}_L\ \widetilde{c}_R$	(same)
			$\widetilde{t}_L\ \widetilde{t}_R\ \widetilde{b}_L\ \widetilde{b}_R$	$\widetilde{t}_1\ \widetilde{t}_2\ \widetilde{b}_1\ \widetilde{b}_2$
sleptons	0	−1	$\widetilde{e}_L\ \widetilde{e}_R\ \widetilde{\nu}_e$	(same)
			$\widetilde{\mu}_L\ \widetilde{\mu}_R\ \widetilde{\nu}_\mu$	(same)
			$\widetilde{\tau}_L\ \widetilde{\tau}_R\ \widetilde{\nu}_\tau$	$\widetilde{\tau}_1\ \widetilde{\tau}_2\ \widetilde{\nu}_\tau$
neutralinos	1/2	−1	$\widetilde{B}^0\ \widetilde{W}^0\ \widetilde{H}_u^0\ \widetilde{H}_d^0$	$\widetilde{N}_1\ \widetilde{N}_2\ \widetilde{N}_3\ \widetilde{N}_4$
charginos	1/2	−1	$\widetilde{W}^\pm\ \widetilde{H}_u^+\ \widetilde{H}_d^-$	$\widetilde{C}_1^\pm\ \widetilde{C}_2^\pm$
gluino	1/2	−1	$\widetilde{g}$	(same)
goldstino (gravitino)	1/2 (3/2)	−1	$\widetilde{G}$	(same)

Table 7.1: The undiscovered particles in the Minimal Supersymmetric Standard Model (with sfermion mixing for the first two families assumed to be negligible).

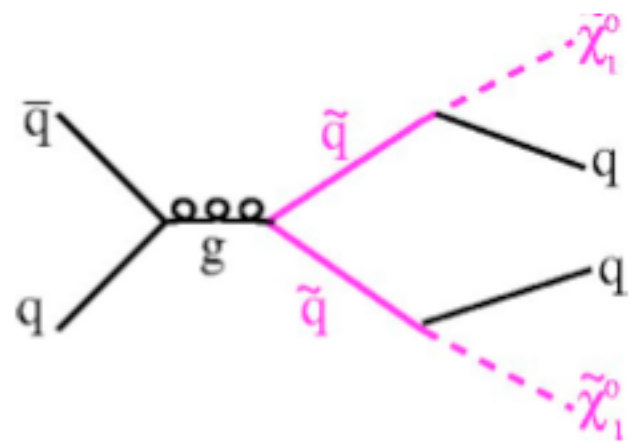
34 new particles

[table: S. Martin, hep-ph/9709356]

Generic MSSM predictions

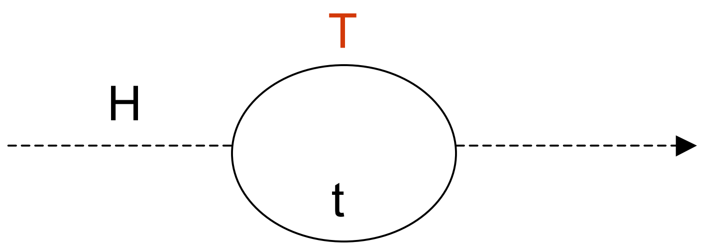
- All SM states are R-even, superpartners R-odd, so superparticles need to be pair produced, and Lightest SuperPartner (LSP) is stable

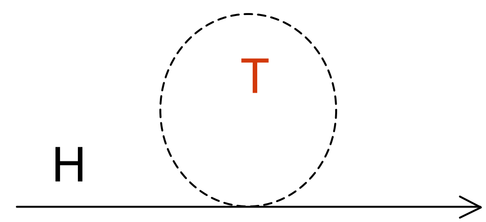
- LSP can be a WIMP dark matter candidate

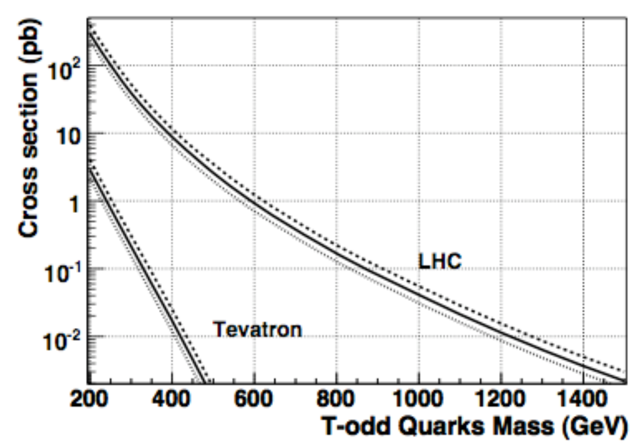


Another plausible Solution: Little Higgs Models with T-parity

Higgs Mass instability cancelled by particles of the same spin, e.g. spin 1/2 “heavy top” T
  – Consequence of symmetry structure
- Have to introduce T-parity to satisfy exp. constraints
  – T-odd partner for each SM particle (T-quarks, T-leptons)
- Lightest T-odd particle is stable, spin-1 “heavy photon”
  – WIMP DM candidate







[Carena, Hubisz, MP, Verdier, hep-ph/0610156, PRD75:091701]

Summary MSSM vs.LHT

Same for UED

MSSM:

– "boson cancels fermion"

– Squarks have spin 0

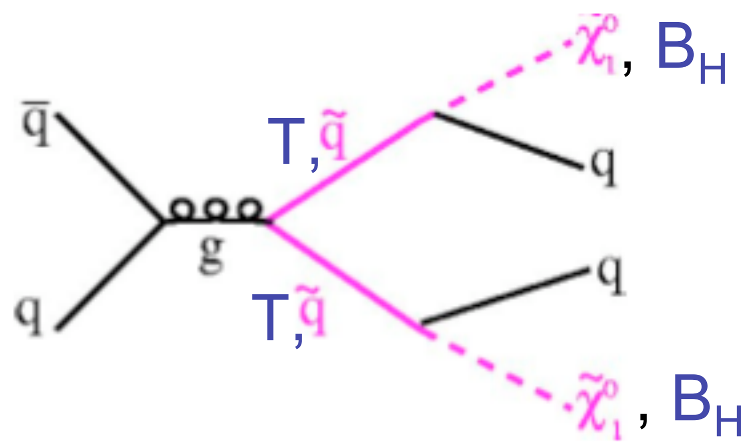
– dark matter candidate χ^0 has spin 1/2

Little Higgs with T-parity:

–"boson cancels boson"

–T-quarks have spin 1/2

–dark matter candidate B_H has spin 1



"Look-alike" models

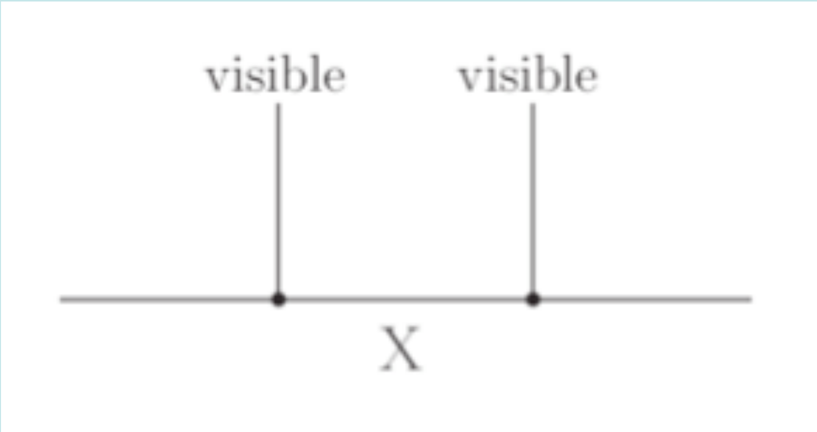
Dominant Production at LHC: jets and missing energy

Similarly, many other extensions of the SM at the EWK scale possible

- Light Higgs and "mirror particles" at TeV scale
- Lightest New Particle (LNP) is stable and weakly interacting
- Same LHC phenomenology: *pair production* of new states which then decay down to LNPs and SM states
  - jets, MET (and leptons) in the detector

What can we do to distinguish between them?

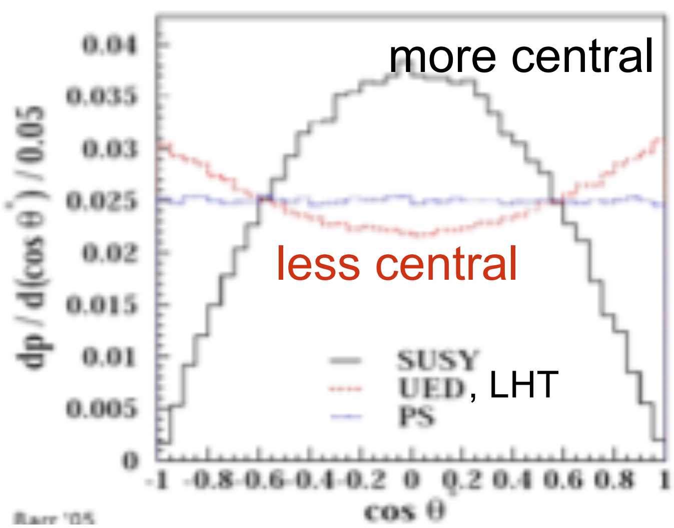
- Complete spectrum and coupling strengths hard to measure (ILC)
- Determine spins of new particles X through angular correlations between decay products, but notoriously difficult



Pair Production of exotic particles

Angular distribution of decay products carries spin information.

– Total event rate provides information too (fermions have "more DOF" than scalars).



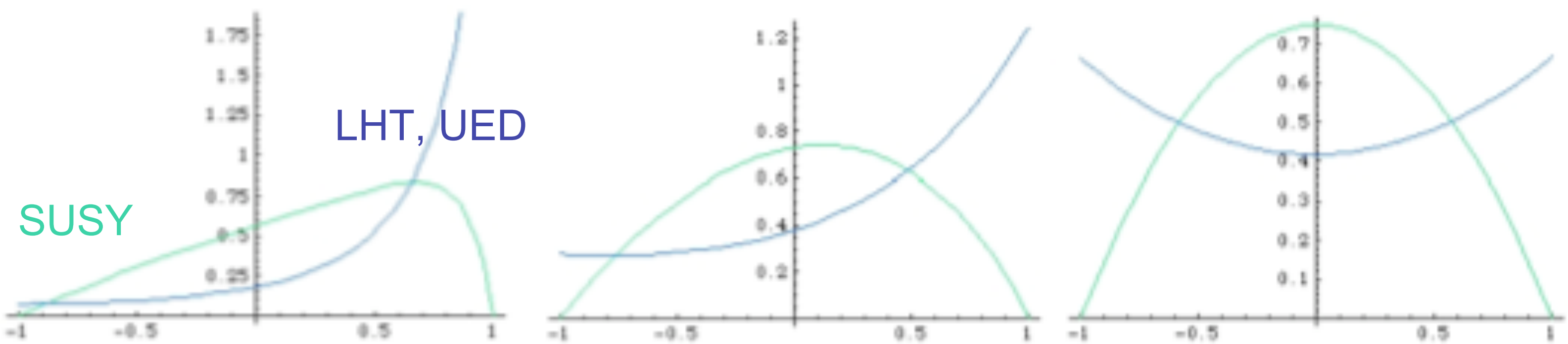
For example: Jets from spin-0 squarks more central (cons.of ang.mom.)

COM frame unknown: need boost invariant variables.

pseudorapidity $\Delta\eta$ or $\cos\theta^* \equiv \cos\left(2\tan^{-1}\exp(\Delta\eta/2)\right) = \tanh(\Delta\eta/2)$

Squark Pair Production

- Strong dependence of angular distributions on gluino mass
- Heavier gluino more favorable



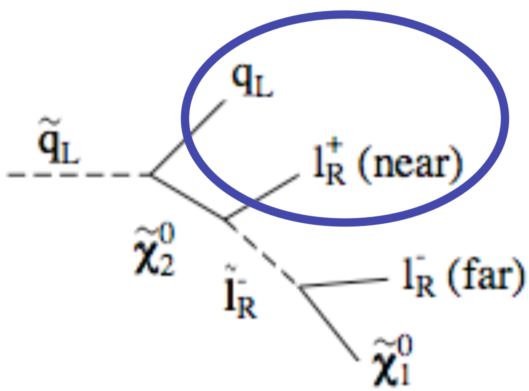
(left to right: $m(\tilde{g})/m(\tilde{q}) = 1.5, 3.5, 30$).

Shown are quark-initiated processes only, in parton COM frame

Side note: spin correlations in cascade decay

Barr hep-ph/0405052, …

- Almost all existing proposals to measure spin rely on cascade decays
  - E.g. use invariant mass of lepton and jet, since it depends on angle between q and l in χ_2^0 rest frame
- Studies so far ignore backgrounds and are done at generator level



problems: low rates and combinatorics

Jets + MET: experimental challenges

- The Signal and its Backgrounds
- Experience from the Tevatron
- Plans for the LHC

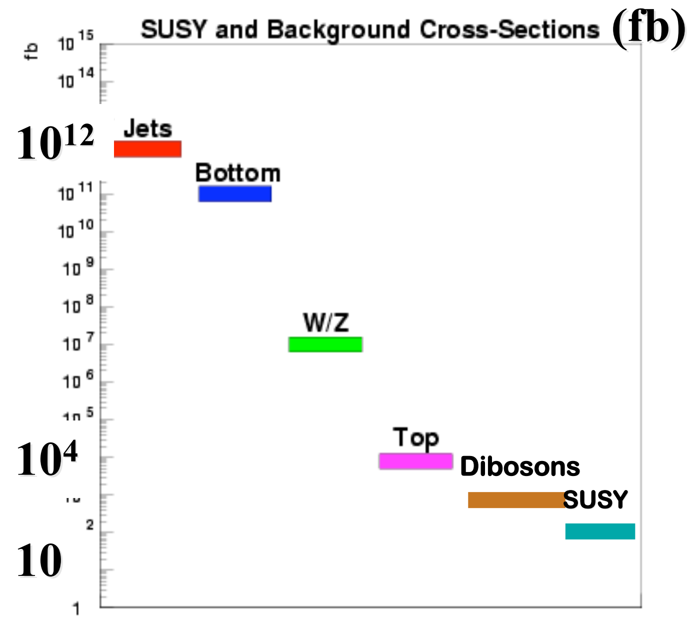
Jets + MET: exp. signature

LNP escapes the detector and results in "missing transverse energy" (MET)

Signature: at least 2 jets, large MET and 0 leptons

Backgrounds:

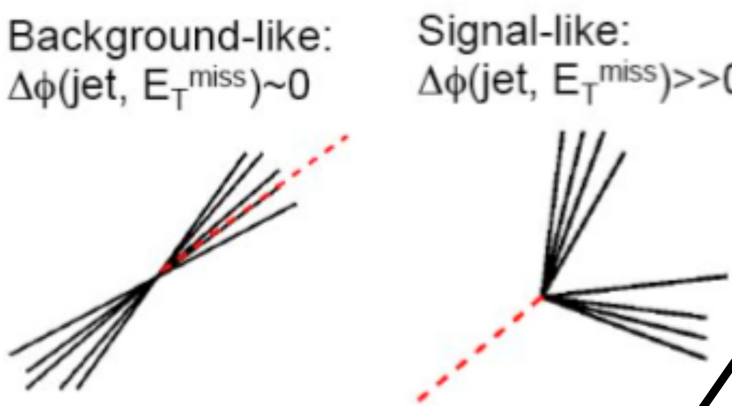
- Z(νν)+jets, W+jets, ttbar
  - Neutrinos give MET
  - Most have associated leptons
- QCD
  - MET from mis-measurement
  - Detector/Instrumental effects

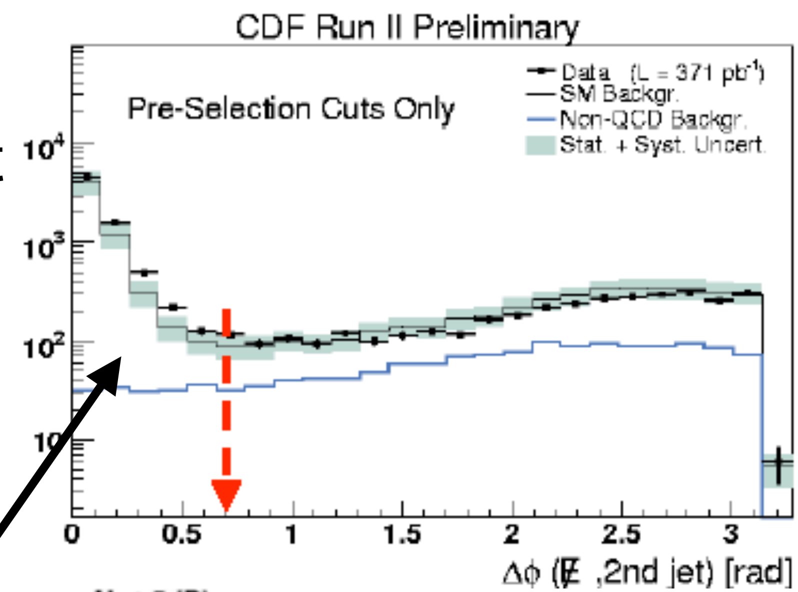


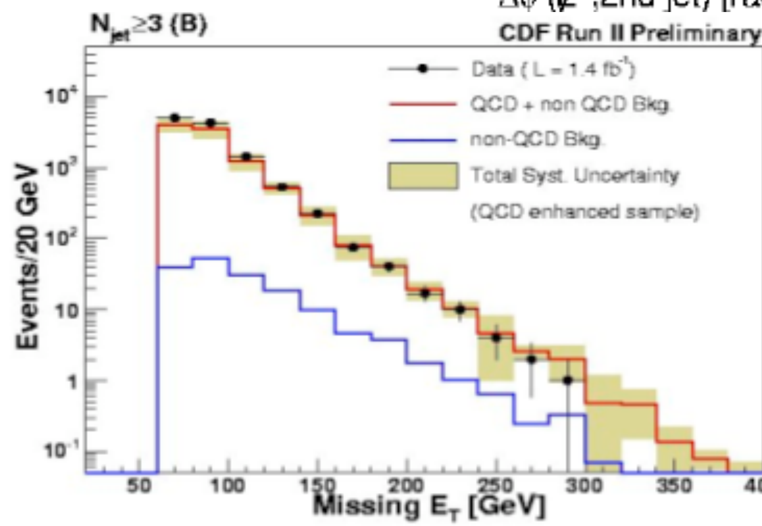
Physics Backgrounds, Tevatron Experience

QCD:

– MET from mis-measurement



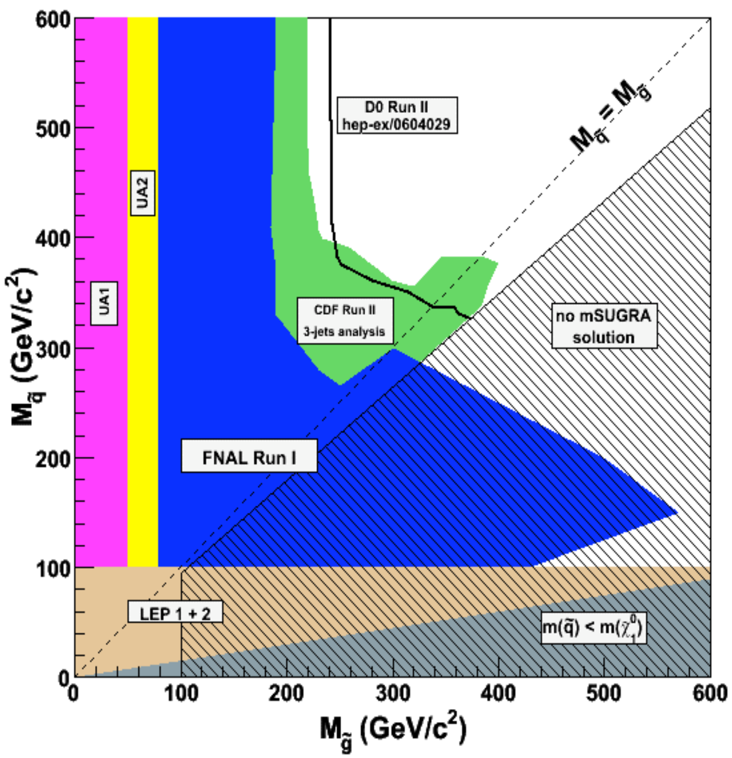


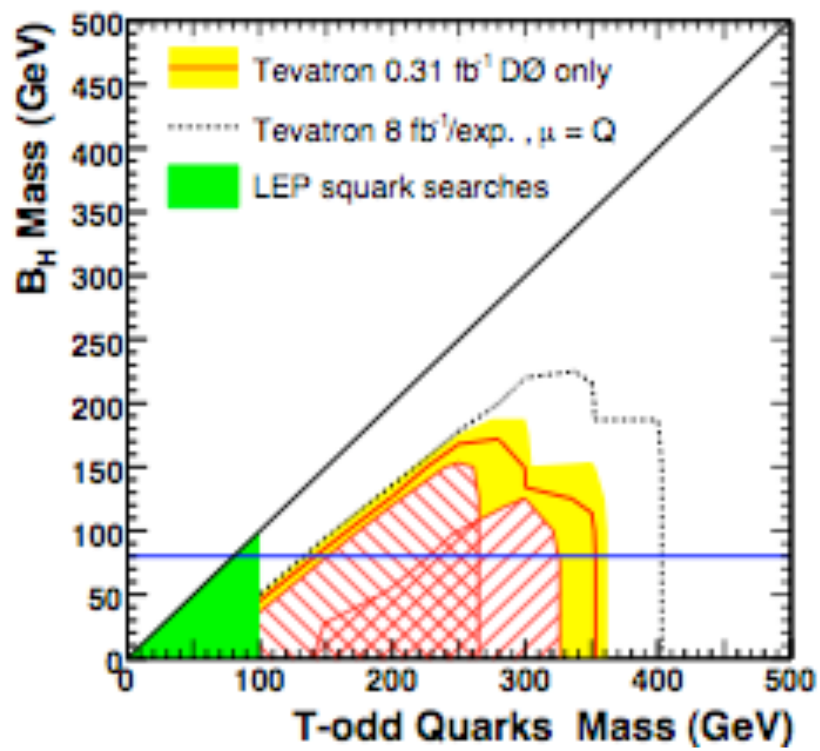


QCD control region used to understand and model jet background correctly, esp. high MET tails

SUSY (and LHT) at Tevatron

Roughly excluding m(squark)<400 GeV,
M(T-quark)<400 GeV in direct searches

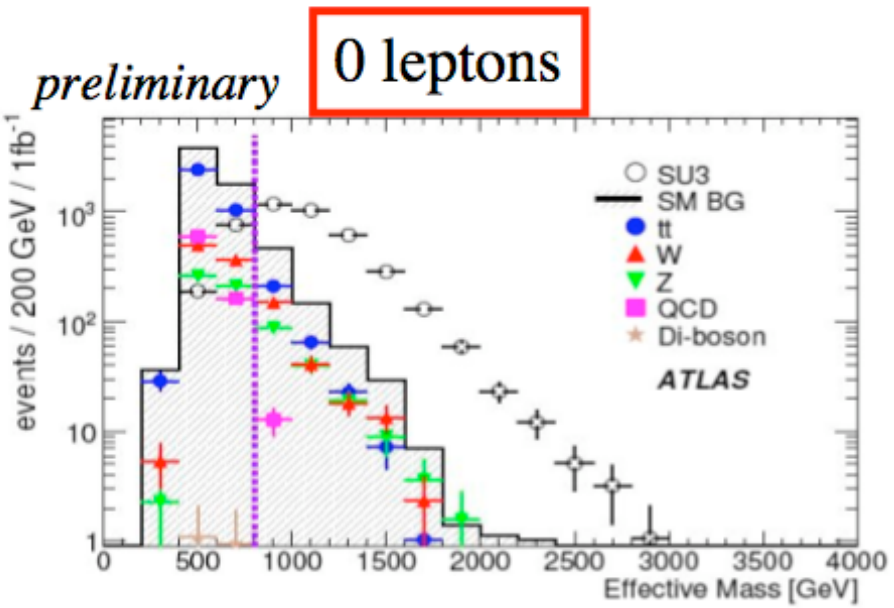




Projections for the LHC

Example: Atlas jet+MET analysis

- m(squark)=600 GeV, m(gluino)=700 GeV
- Require jets, large MET and 0 leptons



Note that "signal" here is optimized benchmark point

This Study

- Given the experimental challenge, can we use measurements of angular jet correlations to tell the spin of the underlying particle (squark or T-quark or ..) and thus exclude certain classes of NP models?

- How to deal with huge parameter space of each model?

This study

- As a case study, we assume MSSM with certain parameter choice is true ("mock-data")
  - Assume that MSSM squark pair-production dominates and that direct 2-body decays causes excess in 2 hard jets + large MET signature

- try to fit with a look-alike "wrong model", and scan over its parameter space
  - Here: "look-alike" is Little Higgs Model
  - Use jet distributions as model discriminators

- How much data would we need to exclude the wrong model? How sensitive are we to experimental effects?

Our “data” point

- the following MSSM parameters create chosen “data” signature

$$
\begin{aligned}
m(\tilde{Q}_L^{1,2}) &= m(\tilde{u}_R^{1,2}) = m(\tilde{d}_R^{1,2}) = 500 \text{ GeV} \;; \\
m(\tilde{Q}_L^{3}) &= m(\tilde{u}_R^{3}) = m(\tilde{d}_R^{3}) = 1 \text{ TeV} \;; \\
m(\tilde{L}_L^{1,2,3}) &= m(\tilde{e}_R^{1,2,3}) = 1 \text{ TeV}\,; \quad A_{Q,L}^{1,2,3} = 0; \\
M_1 &= 100 \text{ GeV}\,; \quad M_2 = 1 \text{ TeV}\,; \quad M_3 = 3 \text{ TeV}\,; \\
M_A &= 1 \text{ TeV}\,; \quad \mu = 1 \text{ TeV}\,; \quad \tan\beta = 10\,.
\end{aligned}
$$

- Parameter choice motivated by creating simple signature (pair production of 1st generation squarks)
- Gluino relatively heavy, different than LM1 (SU3) benchmark point (light Gluino)!
- Cross-section is ~5 pb

Analysis Cuts

- Guided by CMS jets+MET SUSY analysis:
  - At least 2 jets
  - Pt_{jet1}>150 GeV, Pt_{jet2}>100 GeV
  - $|\eta_{jet1}|<1.7$&& $|\eta_{jet2}|<1.7$
  - MET>300GeV (corrected for jets)
  - No identified leptons in the event

SM Backgrounds

- Selected SM background events for $2fb^{-1}$ after cuts

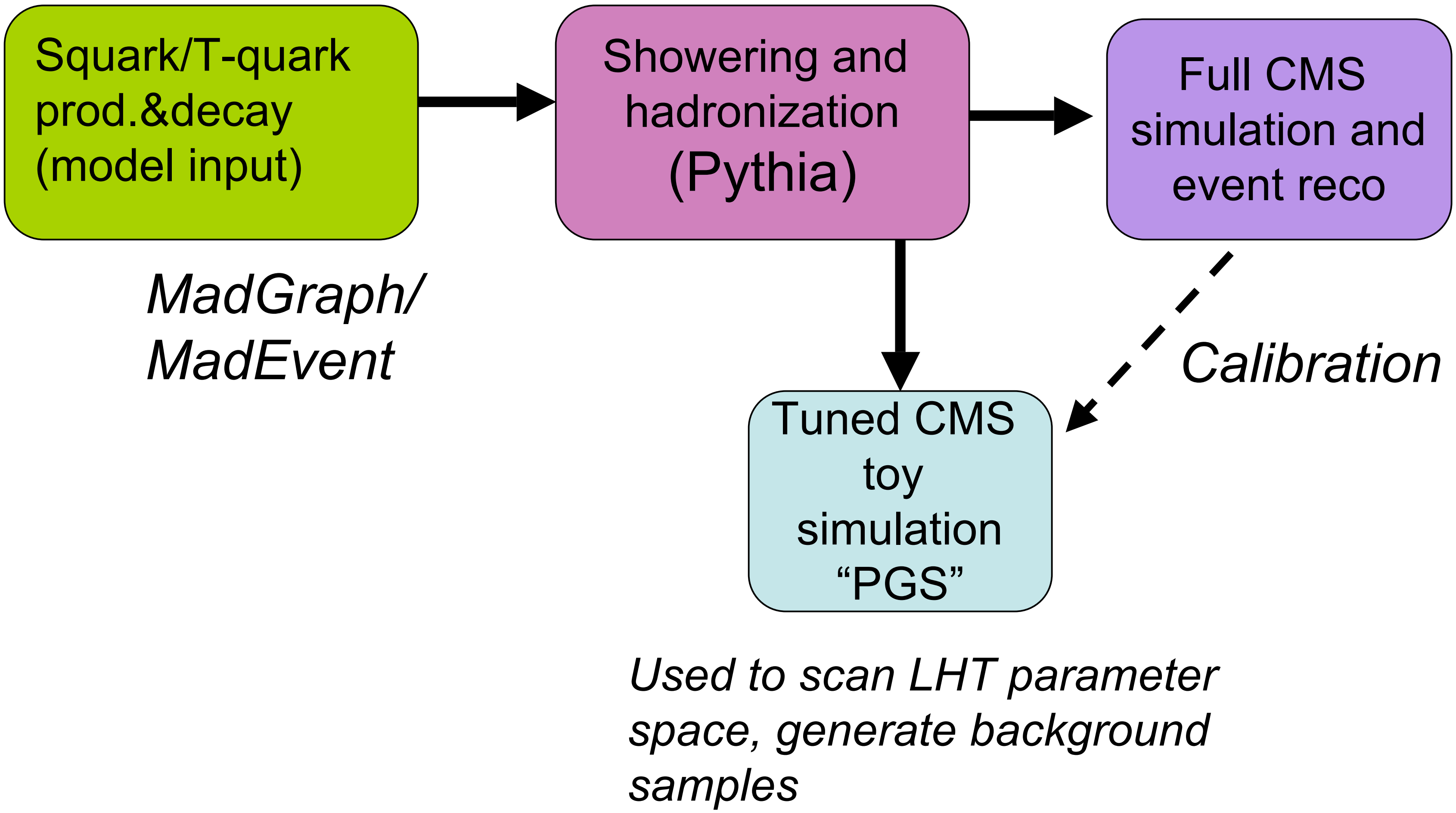
signal	Z(νν)+jets	(W->νl)+2 jets	(W->ντ)+1jet	ttbar	Total bkg
1296	746	396	85	72	1299

- Note: QCD background not considered, since simulation will not get this right at all
- Even though: S/N only ~ 1-2
  - heavy gluino results in low signal cross-section
  - We kept this "non-optimal" MSSM point as a generic (and realistic) case

Fitting with the “wrong spin” model

- Pick 10 Observables that are sensitive to angular correlations
- Scan LHT parameter space to find the best fit point. LHT ruled out only if that point is ruled out.
- Each point in the scan requires MC simulation, efficient and realistic simulation is the key
  - using parametrized toy MC PGS (“pretty good simulation”) tuned for CMS detector

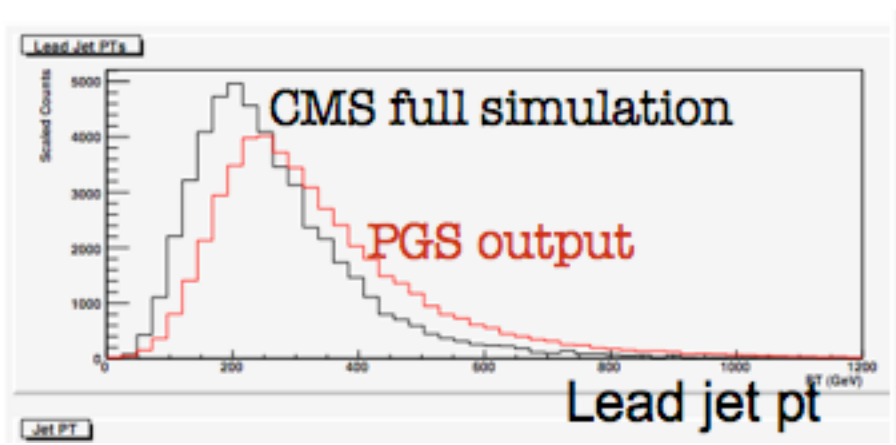
Simulation Setup



Tuned CMS toy simulation

For jet+MET signature the main issue are jet energies

- PGS jet distributions tuned by comparing to Full CMS simulation for MSSM data point and one LHT sample (100k events)
- Straightforward for high-pt jets (>100 GeV)



corrections applied to PGS generated jet energy:

From CMS note 2006/036

"Measurement of Jets with the CMS Detector"

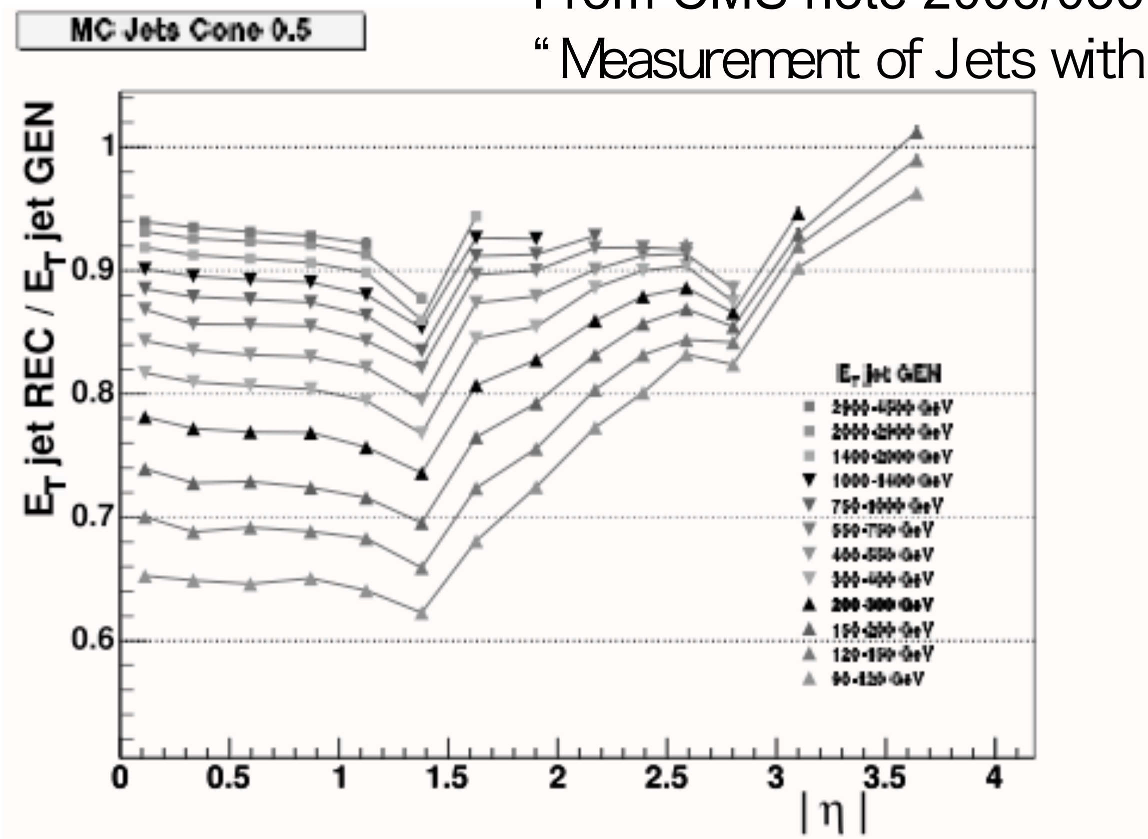
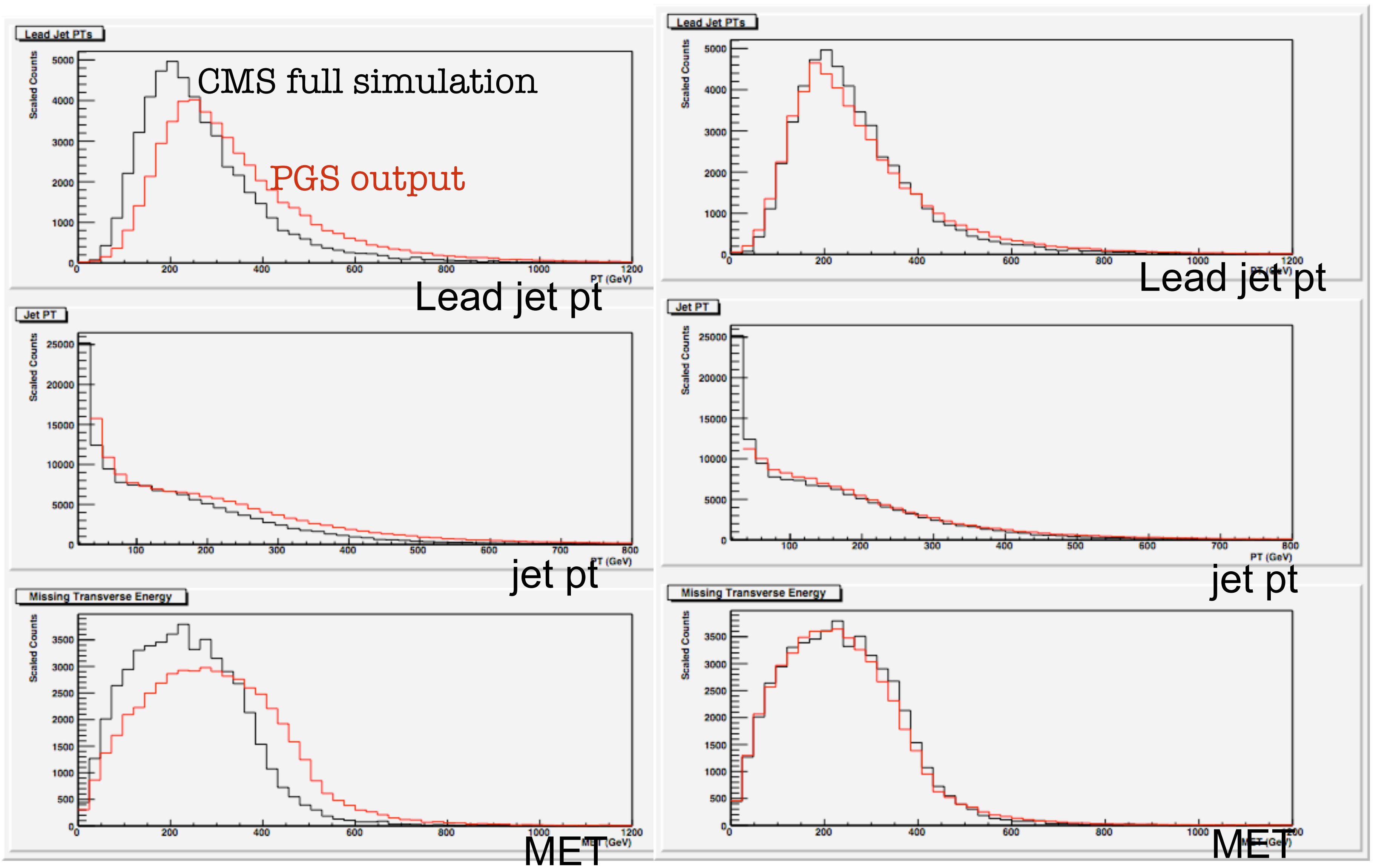


Figure 2: The ratio of the reconstructed jet transverse energy E_T^{Rec} to the generated transverse energy E_T^{MC} as a function of pseudorapidity of generated jet $|\eta|$ for jets with different E_T^{MC} reconstructed by the interative cone $R = 0.5$ algorithm before MC jet calibration.

Jet energy (MSSM)

before PGS jet energy scaling | after PGS jet energy scaling



Summary PGS toy simulation

- Validated using MSSM "data" sample and 1 LHT sample
  - 100k events each
  - Find very good agreement after tuning

- Vary T-quark mass and heavy photon mass (125 points in parameter space)
  - number of events in each sample correspond to 10 fb^{-1}

- PGS used to generate the background samples
  - again cross-checked with Full Simulation results

Observables

- Pick variables sensitive to angular correlations
- Found set of 10 (correlated) quantities

10 Observables

- 5 Asymmetries and ratios based on angular correlations
  - Use large bins of distributions for robustness
  - Use ratios of counts in different bins
- Additionally: $\langle H_T \rangle$, $\langle MET \rangle$, $\langle p_t \rangle$, $\langle \eta \rangle$
- Cross section
  - Calculated from total number of signal and background events after cuts

Asymmetries, Ratios

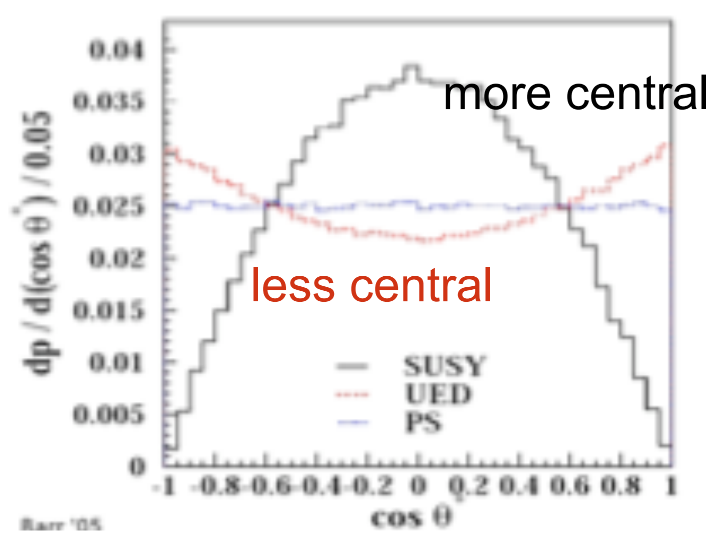
- Beamline asymmetry (alignment of 2 leading jets with the beam pipe)

$$BA = \frac{N_+ - N_-}{N_+ + N_-}$$

  - N_+ (N_-) is number of events with 2 lead jet $\eta_1\eta_2>0$ ($\eta_1\eta_2<0$)
- Directional asymmetry (alignment of jets with each other)
  - let θ be the angle between the two leading jets. N_+ (N_-) is number of events with cos θ positive (negative)
- Transverse Momentum Asymmetry
  - The ratio N_+/N_- of the number of jets with pt larger than the average and the number of jets with pt smaller than the average
- Transverse Momentum Bin Ratios
  - Distribute jets into 3 pt bins and define bin count ratios $R_1 = N_2/N_1$ and $R_2 = N_3/N_1$

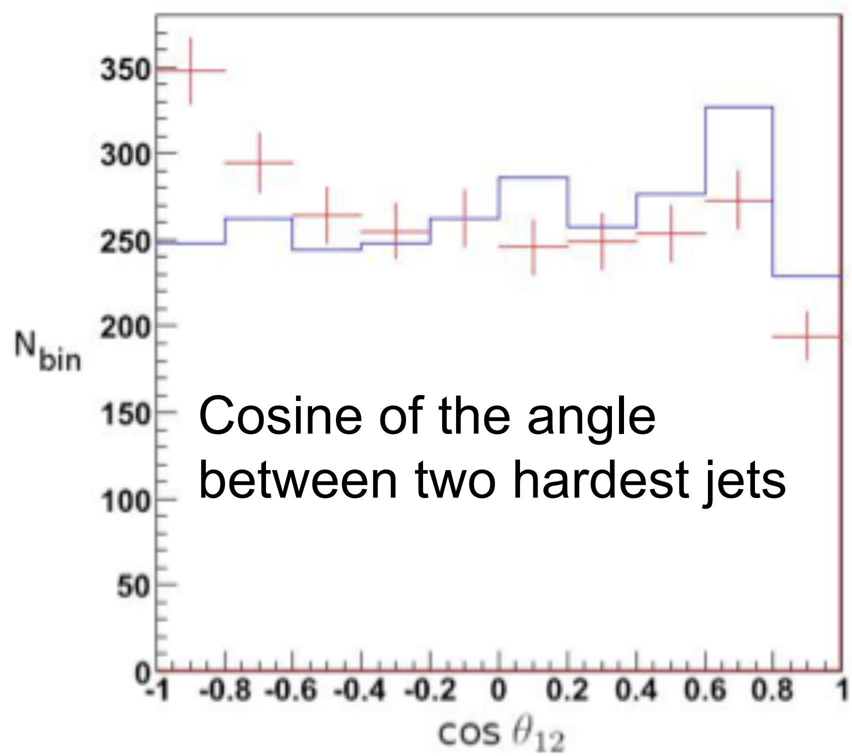
Asymmetries

- $\Delta\eta_{jj}$ smaller for MSSM, $\eta_1\eta_2>0$ more often
  - Beam Line (and Directional) asymmetry "more positive" for MSSM



$$\cos\theta^* \equiv \cos\left(2\tan^{-1}\exp(\Delta\eta/2)\right) = \tanh(\Delta\eta/2)$$

example distributions at one LH point (M_Q= 500, M_B=100 GeV)



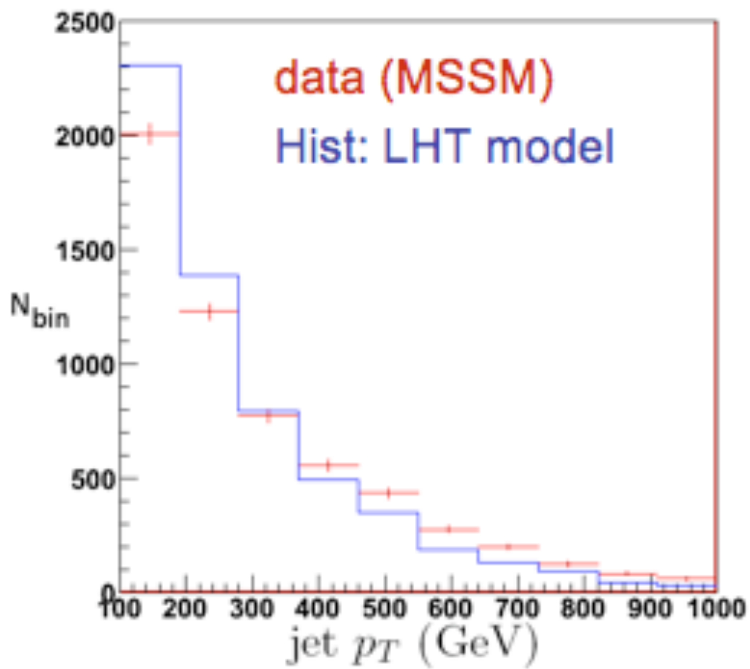
data (MSSM) $2fb^{-1}$

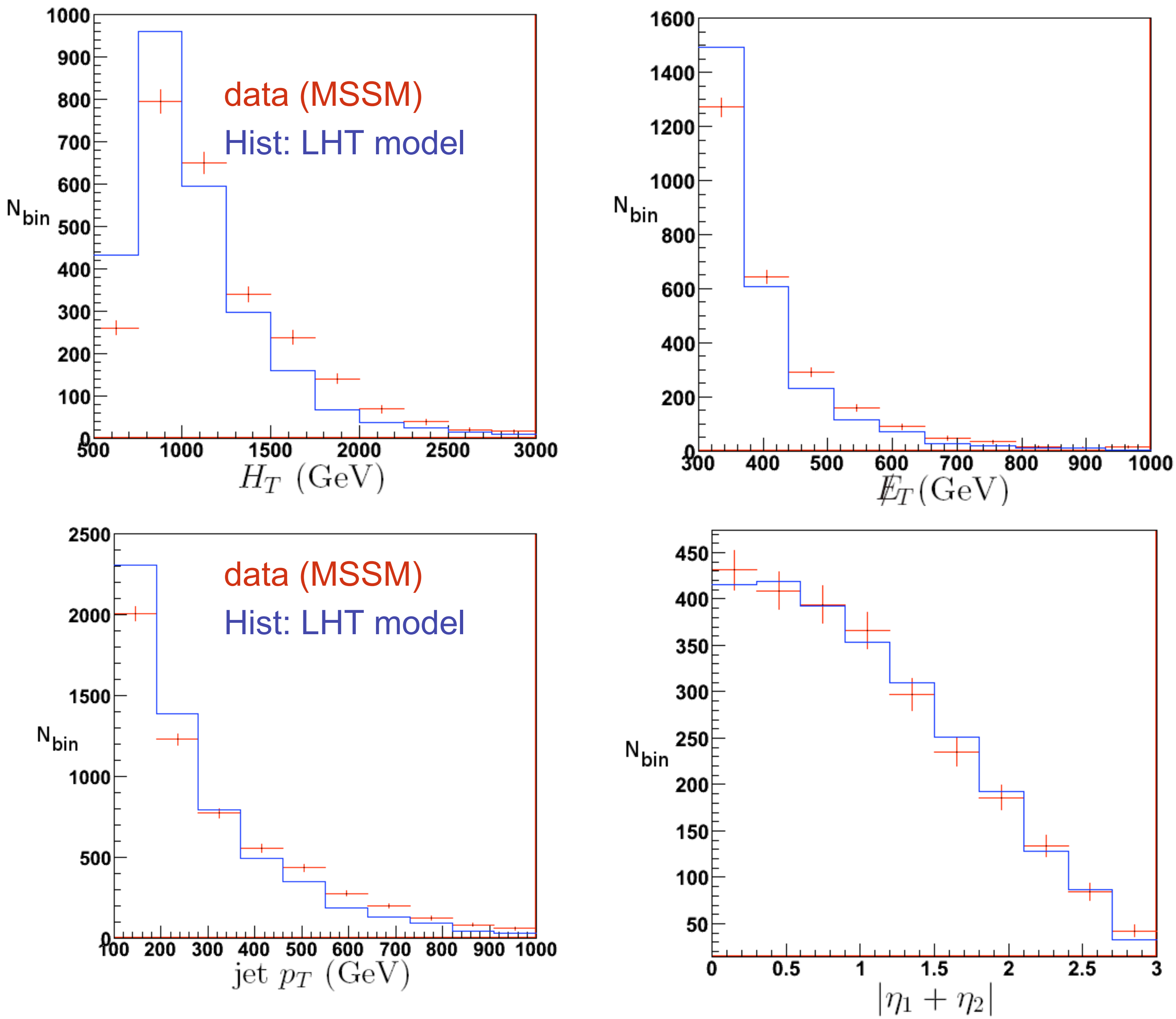
Hist: LHT model

Includes the background contributions

Observables: p_t

- Different p_T spectra of jets depending on squark/T-quark masses and angular distributions
  - e.g. for same jet energy, central jets have higher p_T




data (MSSM)
Hist: LHT model
N_{bin}
H_T (GeV)
$\not{E}_T$ (GeV)
jet p_T (GeV)
$|\eta_1 + \eta_2|$

Syst.Uncertainties

- Jet energy and jet η uncertainty estimated using parameterizations from CMS TDR1

$$\sigma_{p_T} = \left(\frac{5.6}{p_T^{\mathrm{PGS}}} + \frac{1.25}{\sqrt{p_T^{\mathrm{PGS}}}} + 0.033 \right) p_T^{\mathrm{meas}}$$

- Estimated systematic on the cross section measurement using luminosity uncertainty, pythia factorization and renormalization scale, total ~30%

- Note that we don't yet include systematic uncertainties on shapes - potentially large uncertainty

Statistical Analysis

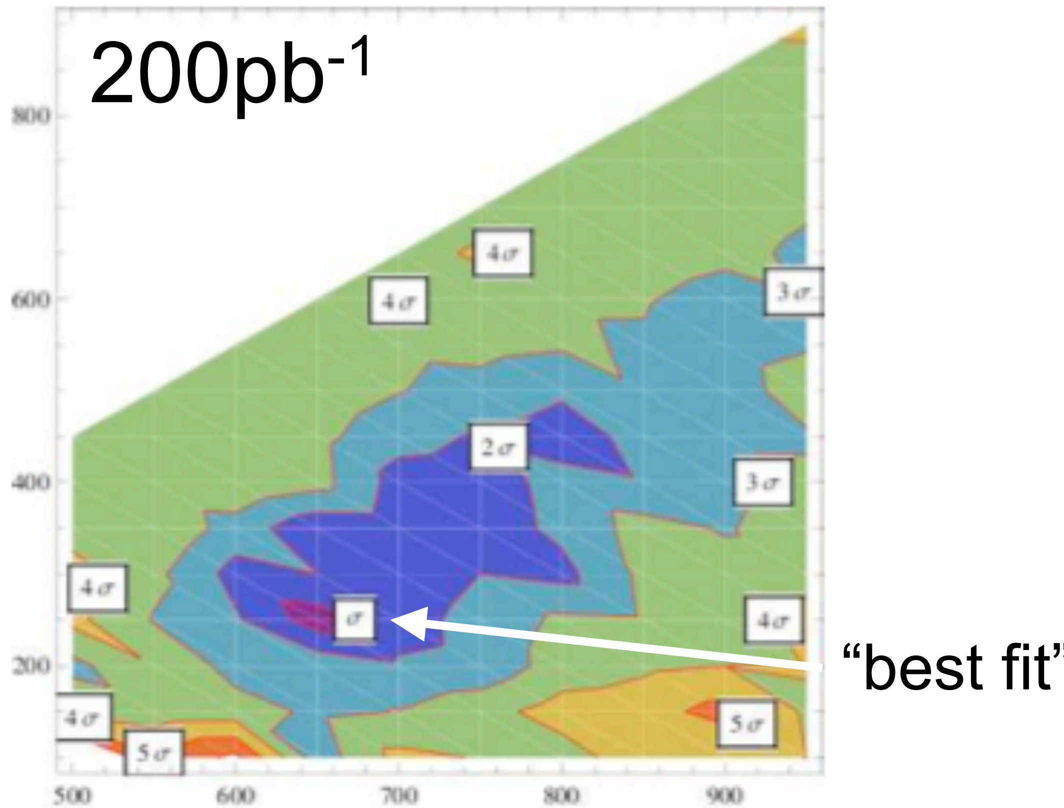
1. Compute “measured” value of observables using “data”
2. For each LHT point in the scan, we compute the expected central values
3. Use standard χ^2 technique to estimate quality of fit between expected and measured values
   - Assume observables to be gaussian distributed with stat. and syst errors
   - Correlation matrix obtained from MC samples
4. Can convert each χ^2 value into probability that disagreement between model and data is the result of fluctuation

Results

- Expressed as “Exclusion Plots”
  - For each of our scan points, at which confidence level can we exclude the look-alike model from our data point?

Exclusion Plots

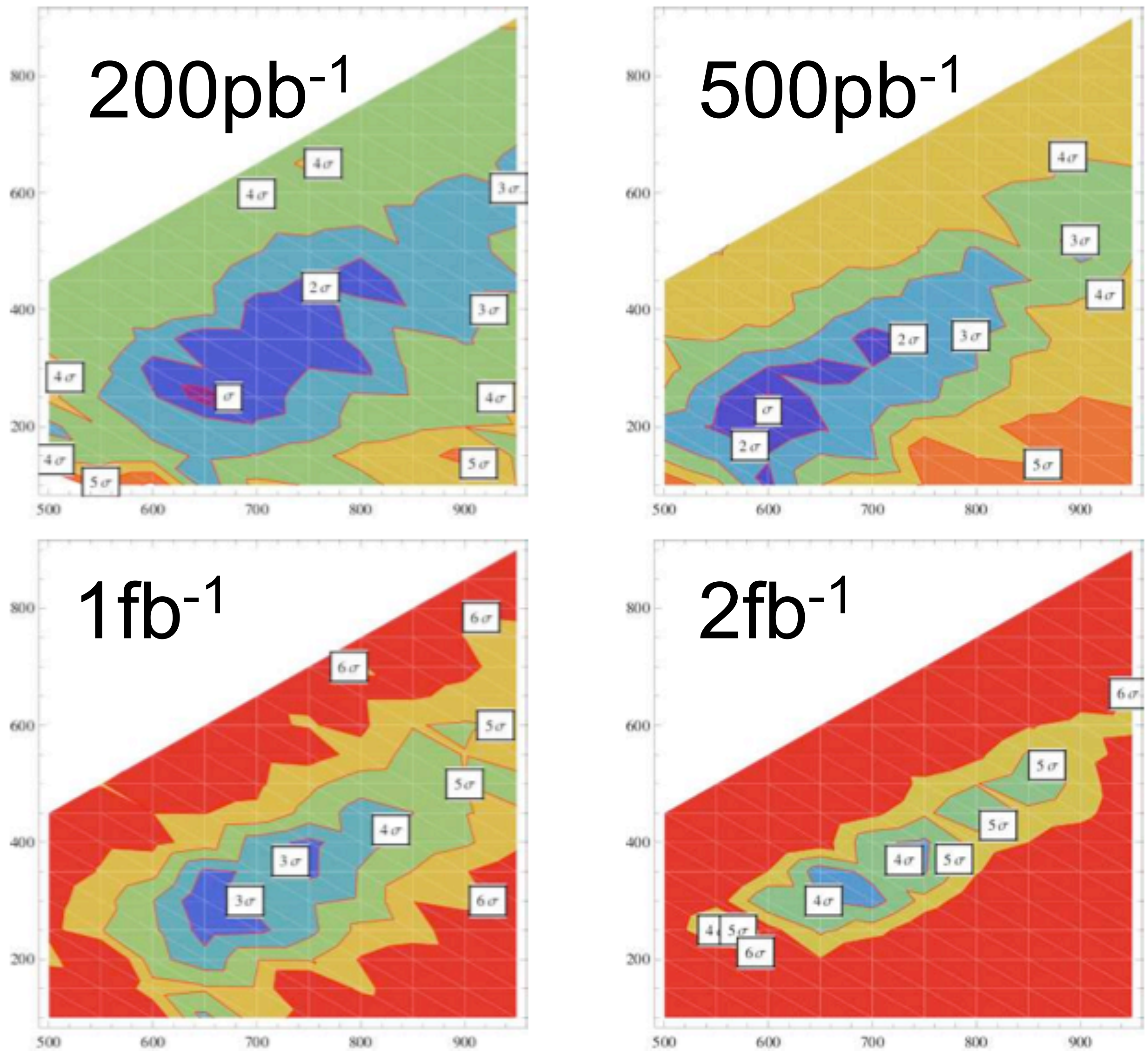
- Combined fit to 10 observables
- Y-axis: heavy photon (B_H) mass
- X-axis: heavy T-quark mass



Green: 4σ deviation between "data" and LHT model
Light blue: 3σ deviation
dark blue: 2σ deviation, etc..

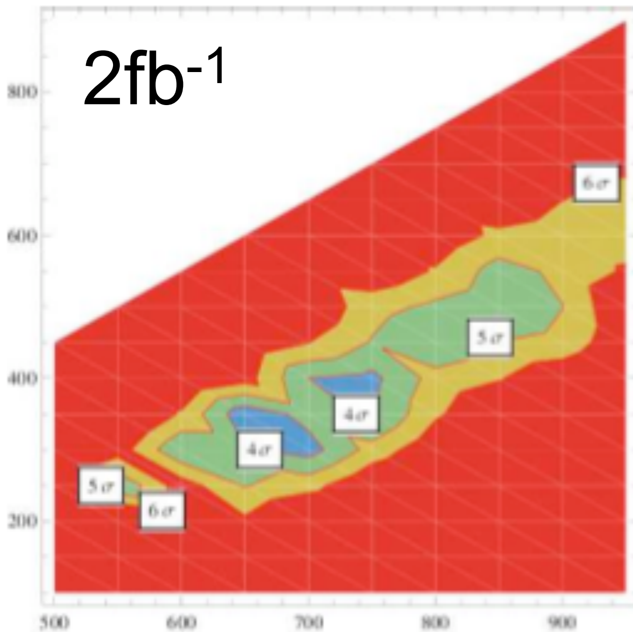
Exclusion Levels

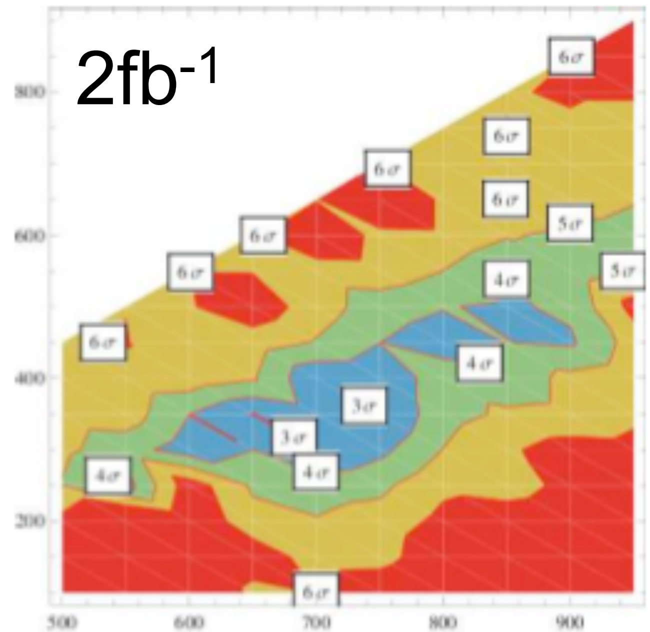
- Combined fit to 10 observables
- Y-axis: heavy photon (B_H) mass
- X-axis: heavy T-quark mass



E.g “best fit” point: less than 1 σ deviation from the “data”

How dependent on individual observables?





Exclusion levels without cross-section info

..without <MET> and <H_T> info

Correlation matrix

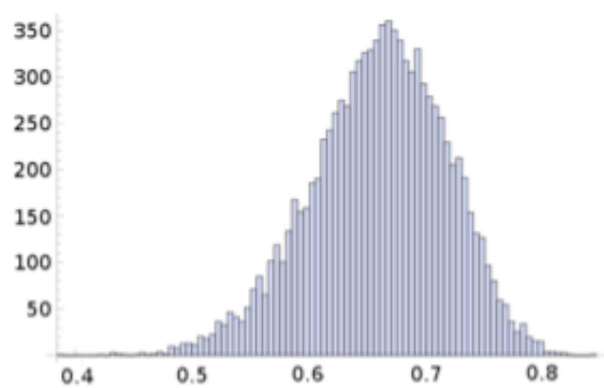
- Correlation between variables change χ^2 values of combined fit considerably
- Estimate correlations from the MC using bootstrapping method

	$\langle p_T \rangle$	$\langle H_T \rangle$	$\langle \not{E}_T \rangle$	$\langle \lvert\Sigma\eta\rvert \rangle$	BLA	DA	PTA	R_1	R_2
$\langle p_T \rangle$	1	0.86	0.42	-0.08	-0.03	-0.37	0.30	0.88	0.00
$\langle H_T \rangle$	0.86	1	0.66	-0.10	-0.05	-0.34	0.22	0.76	-0.06
$\langle \not{E}_T \rangle$	0.42	0.66	1	-0.04	-0.04	-0.06	0.05	0.35	-0.11
$\langle \lvert\Sigma\eta\rvert \rangle$	-0.08	-0.10	-0.04	1	0.64	0.50	-0.01	-0.07	0.02
BLA	-0.03	-0.05	-0.04	0.64	1	0.41	-0.02	-0.02	-0.00
DA	-0.37	-0.34	-0.06	0.50	0.41	1	-0.21	-0.38	-0.16
PTA	0.30	0.22	0.05	-0.01	-0.02	-0.21	1	0.22	0.64
R_1	0.88	0.76	0.35	-0.07	-0.02	-0.38	0.22	1	0.14
R_2	0.00	-0.06	-0.11	0.02	-0.00	-0.16	0.64	0.14	1

- Example: MSSM plus BKGD “data” ($2fb^{-1}$)

Determine correlations

- Ideally generate every point in LH parameter space ~1000x to determine correlation between variables. Takes too long.
- Instead, subdivide each sample into small samples and determine correlation
  - pick 20 sets "with replacement" and repeat 10,000x
  - Get distribution of correlation matrix values plus error



Correlation between H_t and MET
For 2 fb-1 of SUSY plus BKGD events
20 subsamples and 10,000 repeats

Summary

- Have developed the machinery to study exclusion levels of a New Physics model, given a data signal, backgrounds, and systematic uncertainties.
  - Based on angular correlations of decay products
  - Scans over parameter space of the model in question
  - First study of its kind
- Presented case study of a specific MSSM data signal and LHT "look-alike"
  - Uses "generic" (=non-optimal) MSSM point as "truth"
  - made a few simplifications:
    - Jets + MET signature assumed dominant
    - Backgrounds, toy MC, etc

Conclusions

- Difficult task but not impossible: jet angular correlations “washed out” by background and jet reconstruction uncertainty
  - Will for example need considerable amount of data (>2fb^{-1}) to reliably exclude large areas of “wrong-spin model”
  - Even then, need to combine information from many observables

Lessons and Extensions

- Scanning parameters of the candidate model is crucial
- Improvements needed to make this study fully realistic
  - shapes of distributions assumed to be exact
  - Better/complete background estimates
  - Cross-check results with CMS FastSim
- Further studies
  - Sensitivity to masses in the “correct” model?
  - Repeat for signature with leptons
  - Fit to UED and other models

Backup Slides

Backgrounds

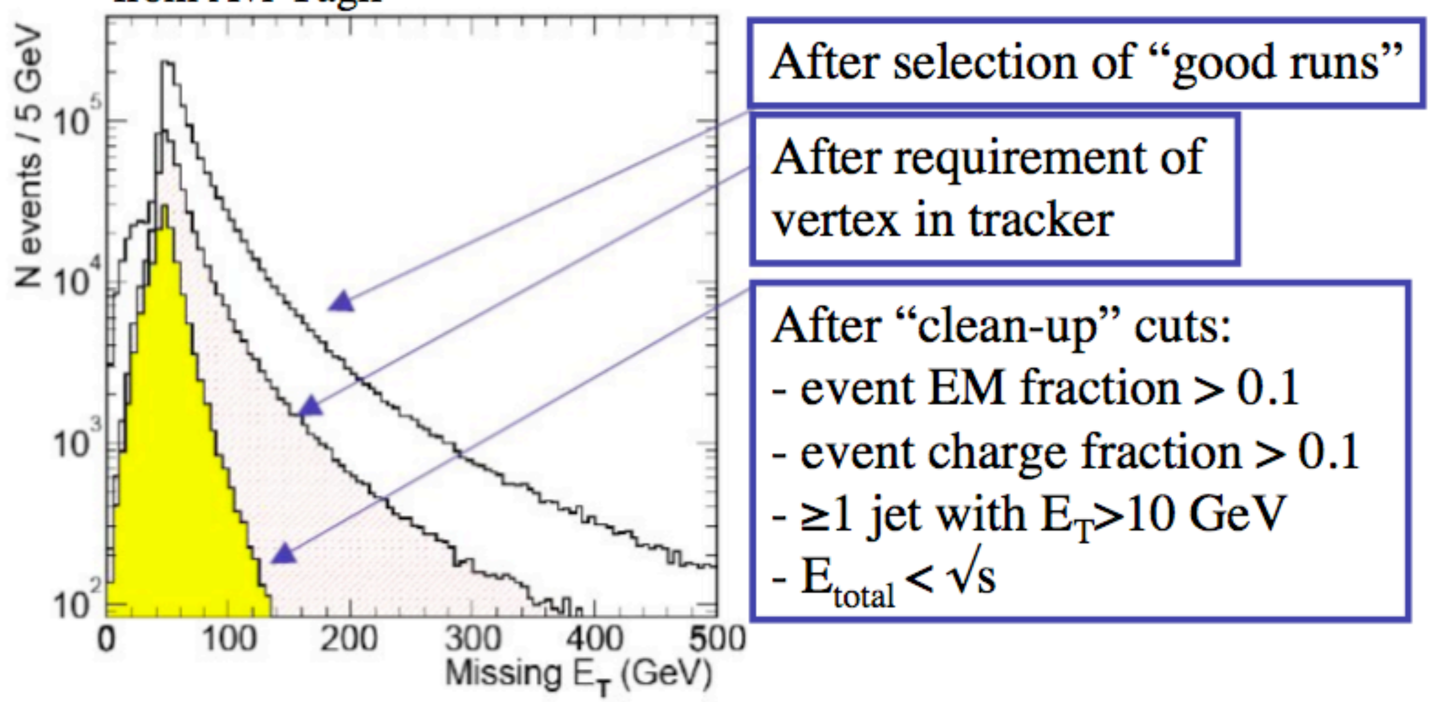
	σ_{tot}	σ_1	σ_2	σ_3	σ_6	σ_7	N_{sim}
Signal (SUSY)	5.00	4.98	4.10	2.91	2.06	0.65	10,037
$(Z \to \nu\nu) + jj$	271.54	259.73	94.05	64.34	10.21	0.20	543,080
$(W \to \nu\ell) + jj$	55.80	52.58	19.30	12.89	6.27	0.37	111,602
$(W \to \nu\tau) + j$	138.27	92.67	12.18	2.49	0.52	0.04	276,540
$t\bar{t}$	398.52	384.14	27.85	13.89	1.62	0.04	797,039
total BG	864.13	789.11	153.37	93.61	18.62	0.65	1,728,261

- Size of each sample corresponds to 2fb^{-1} of LHC data
- Listing dominant backgrounds EXCEPT QCD jet background with mis-measured MET

Instrumental Backgrounds

- Sources: Calorimeter noise, cosmic rays and beam halo muons showering hard in calorimeter
- From CDF experience: lengthy process to understand MET distribution

from Avi Yagil



Comparison to jet+MET TDRII analysis

- For similar cuts TDRII jet+MET analysis quotes S/N=26 (factor 10 higher LM1 SUSY signal x-section because of light gluino)

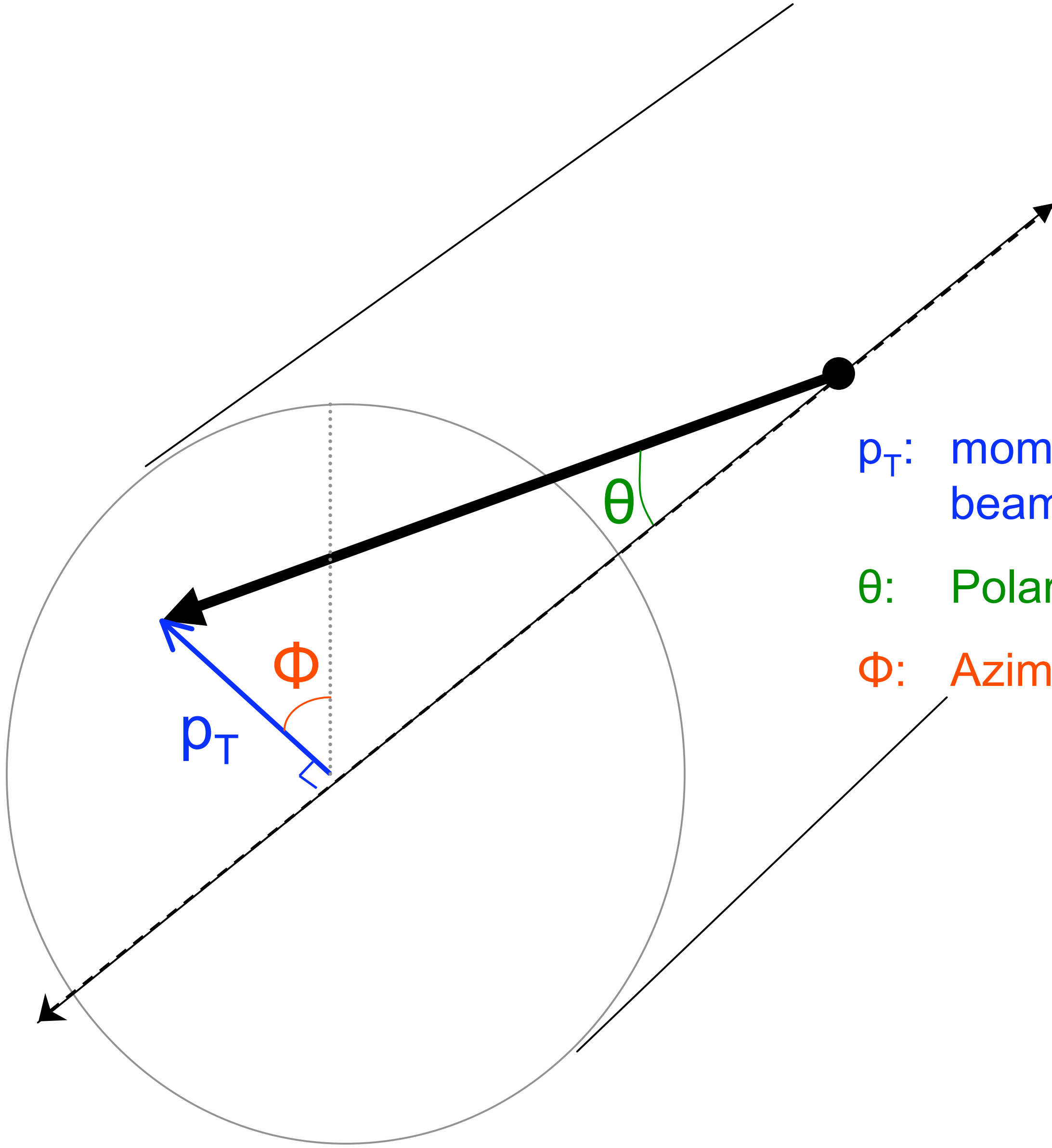
Table 4.3: Selected SUSY and Standard Model background events for 1 fb^{-1}

Signal	$t\bar{t}$	single t	$Z(\rightarrow \nu\bar{\nu})$+ jets	$(W/Z,WW/ZZ/ZW)$ + jets	QCD
6319	53.9	2.6	48	33	107

Main systematic: varying the pythia renormalization and factorization scale

	MSSM	LHT
Down		
BLA	0.149±0.006	0.090±0.006
DA	-0.025±0.009	-0.017±0.009
Mid		
BLA	0.147±0.006	0.106±0.006
DA	-0.051±0.009	-0.002±0.009
Up		
BLA	0.159±0.006	0.103±0.006
DA	-0.029±0.009	-0.021±0.009

This is a systematic effect of the order of ±0.02 (we don't know the "correct" factorization scale)



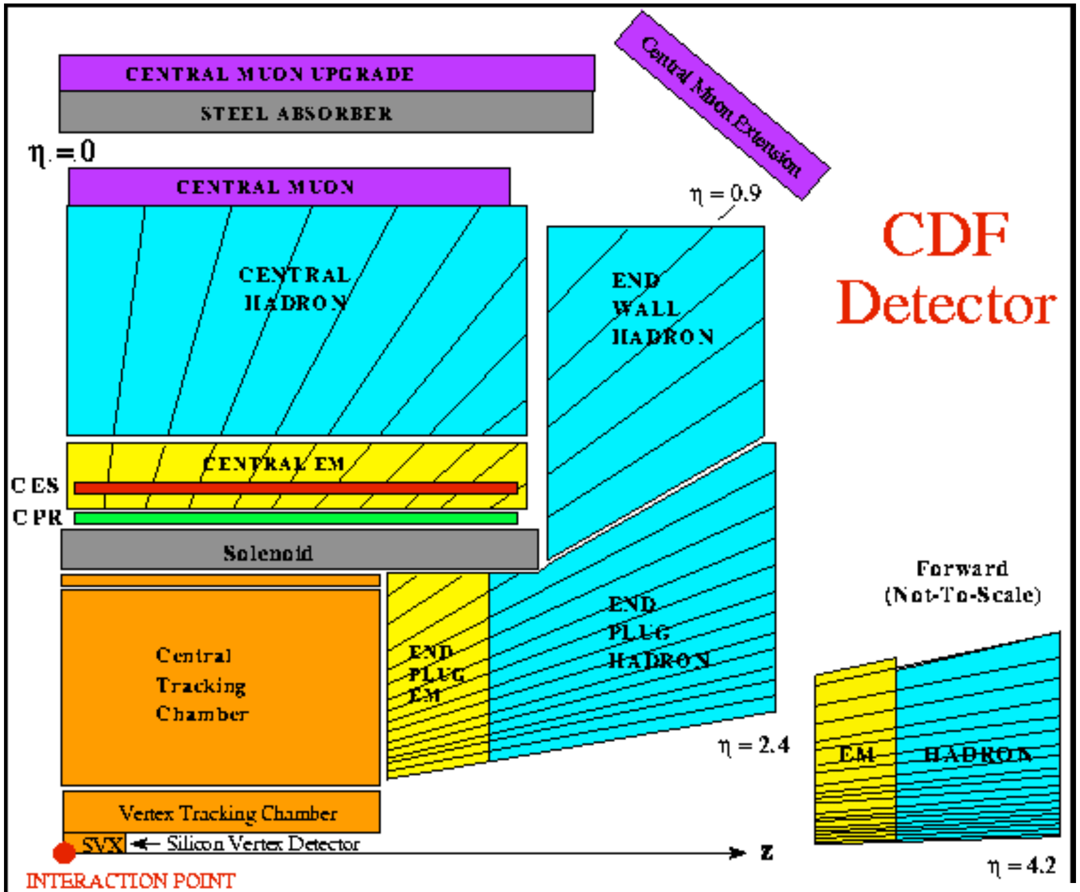
Components

p_T: momentum transverse to the beam axis

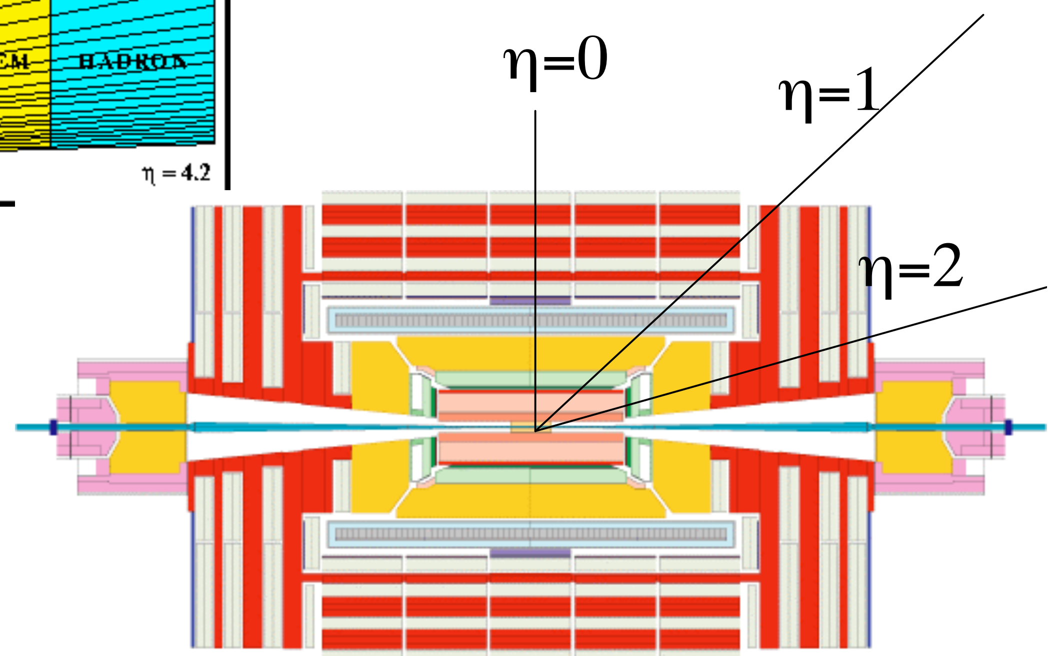
θ: Polar angle

Φ: Azimuthal angle

Pseudorapidity



CMS Detector:



Before cuts

After cuts