Imperial College London

Collider Physics Analysis Procedures

Alex Tapper

Slides available at:

http://www.hep.ph.ic.ac.uk/~tapper/lecture.html

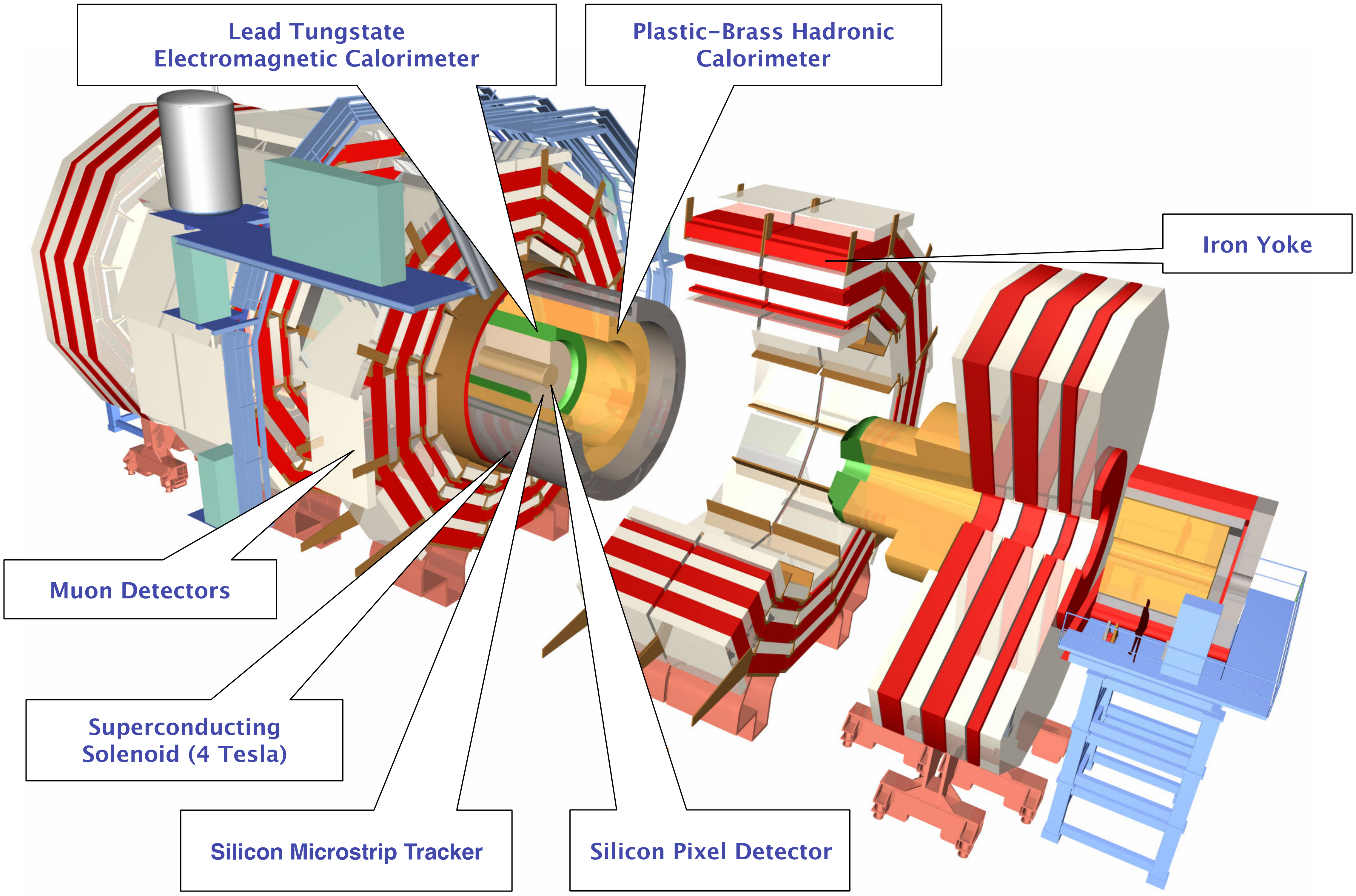
Aim

- Overview of analysis techniques at CMS
- Contrast with Tevatron (see DØ lecture)
  - New energy regime
  - New detector
  - Emphasis on robustness and data-driven techniques
  - Nothing "fancy" (b-tagging, NN, BDT...)

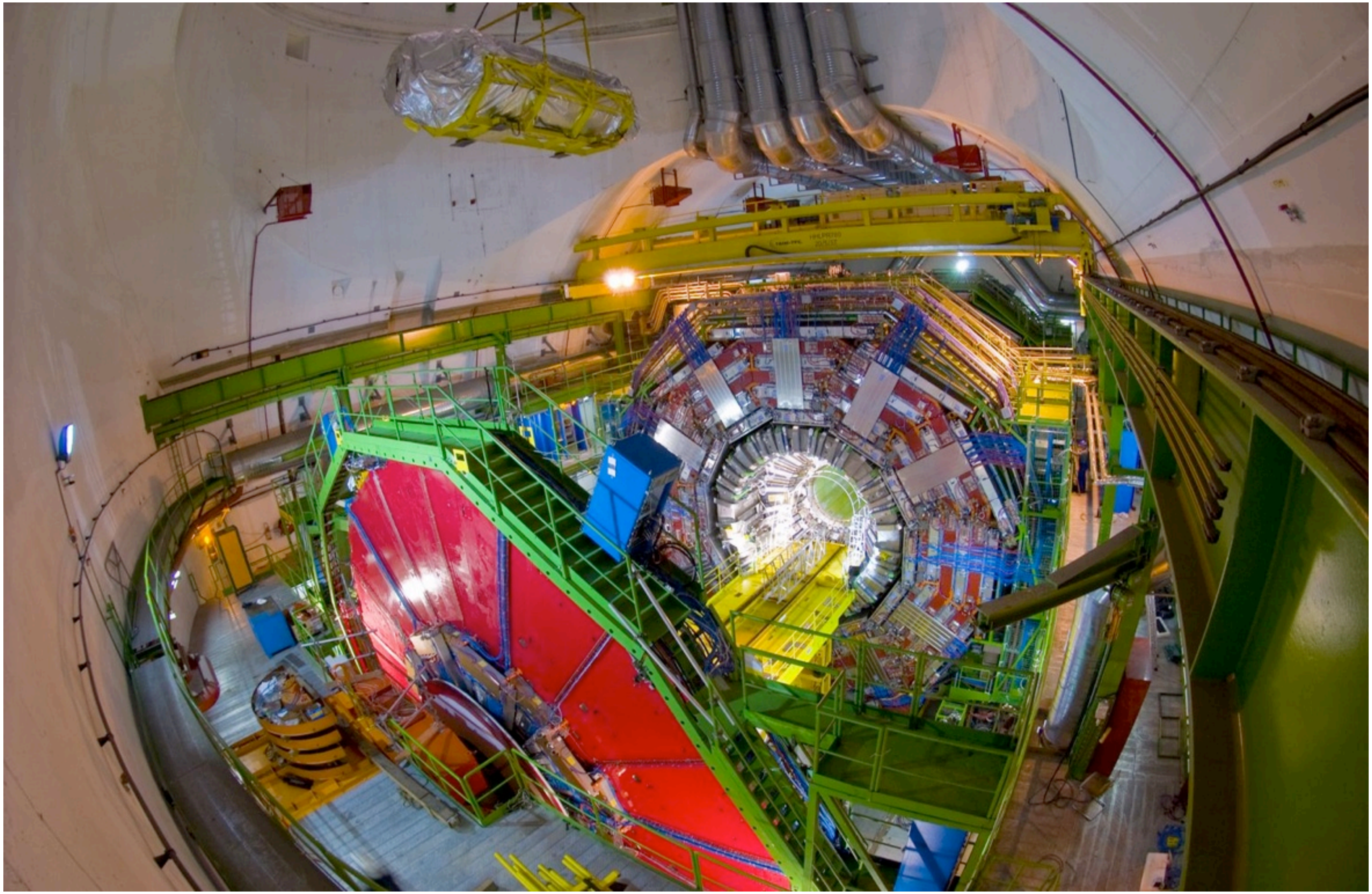
Outline

- Quick reminder of CMS detector
- Basic physics objects
- Analysis - SUSY search
- Summary

The CMS detector



The CMS detector

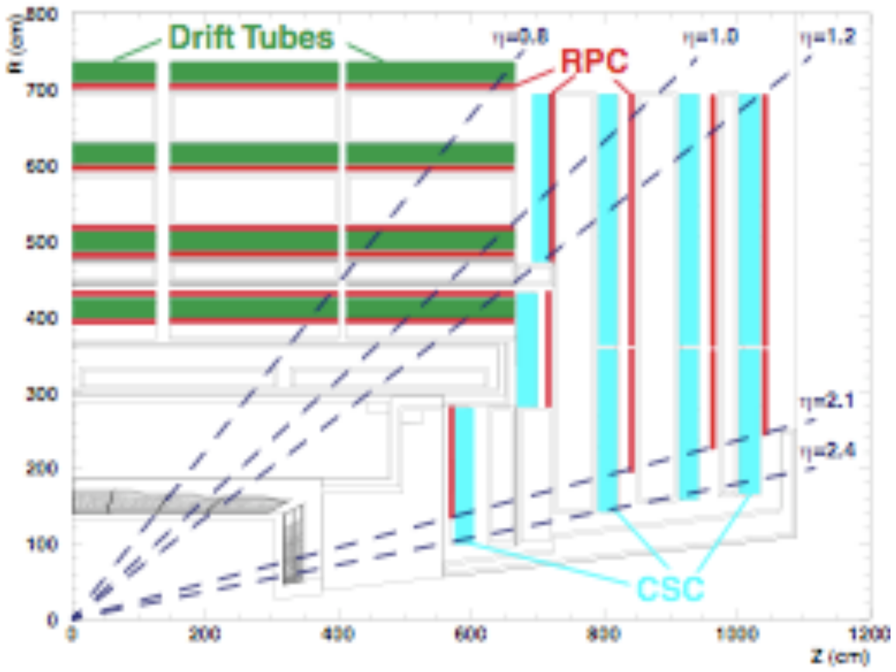


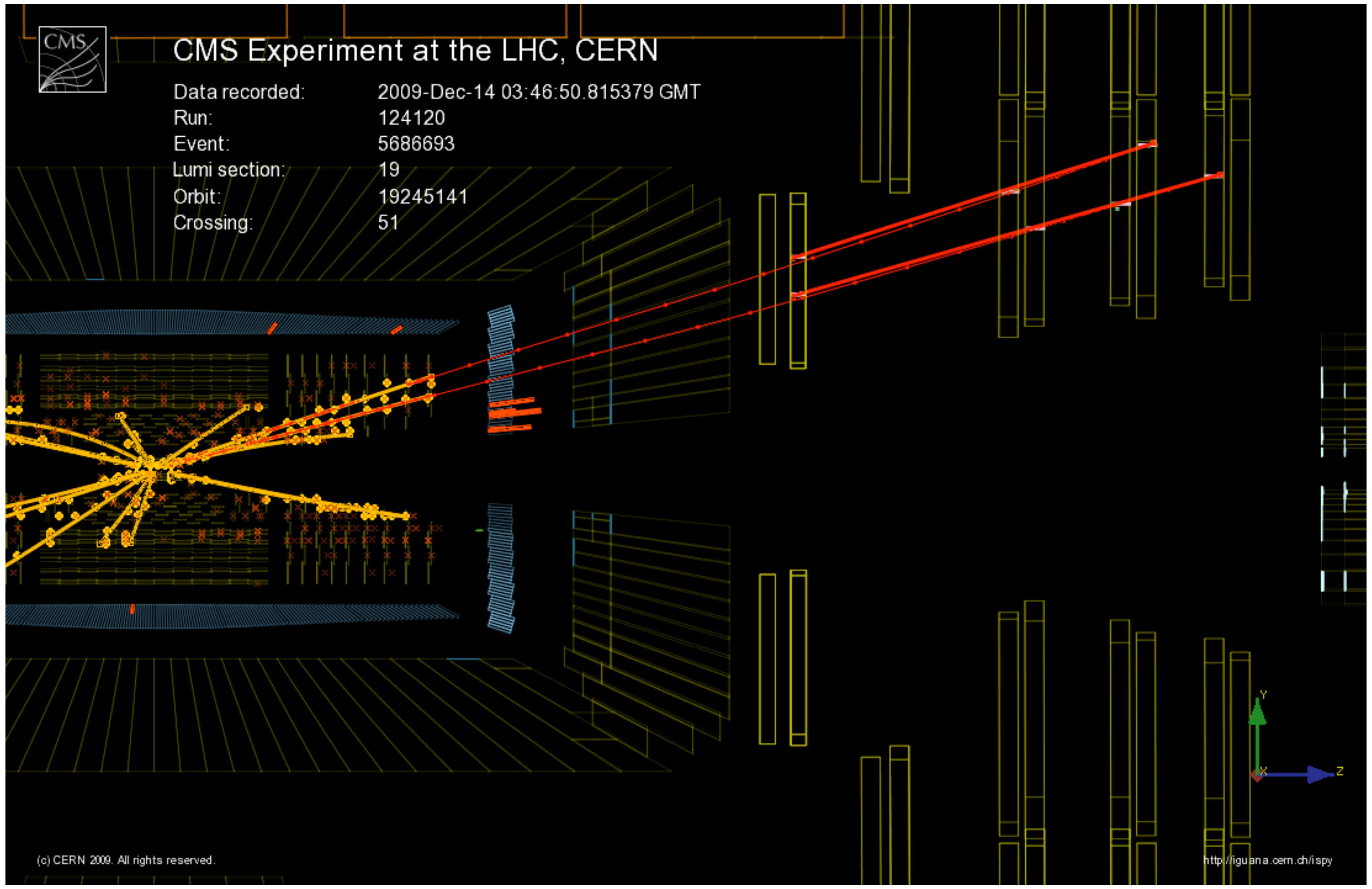
Analysis objects

- Basic list of objects needed for analysis
  - Leptons
    - muons, electrons, taus
  - Hadronic jets
  - Energy sums
    - MET, E_T....

- Typically want the E_T, η and ϕ of each reconstructed object
- Also often quality flags or isolation

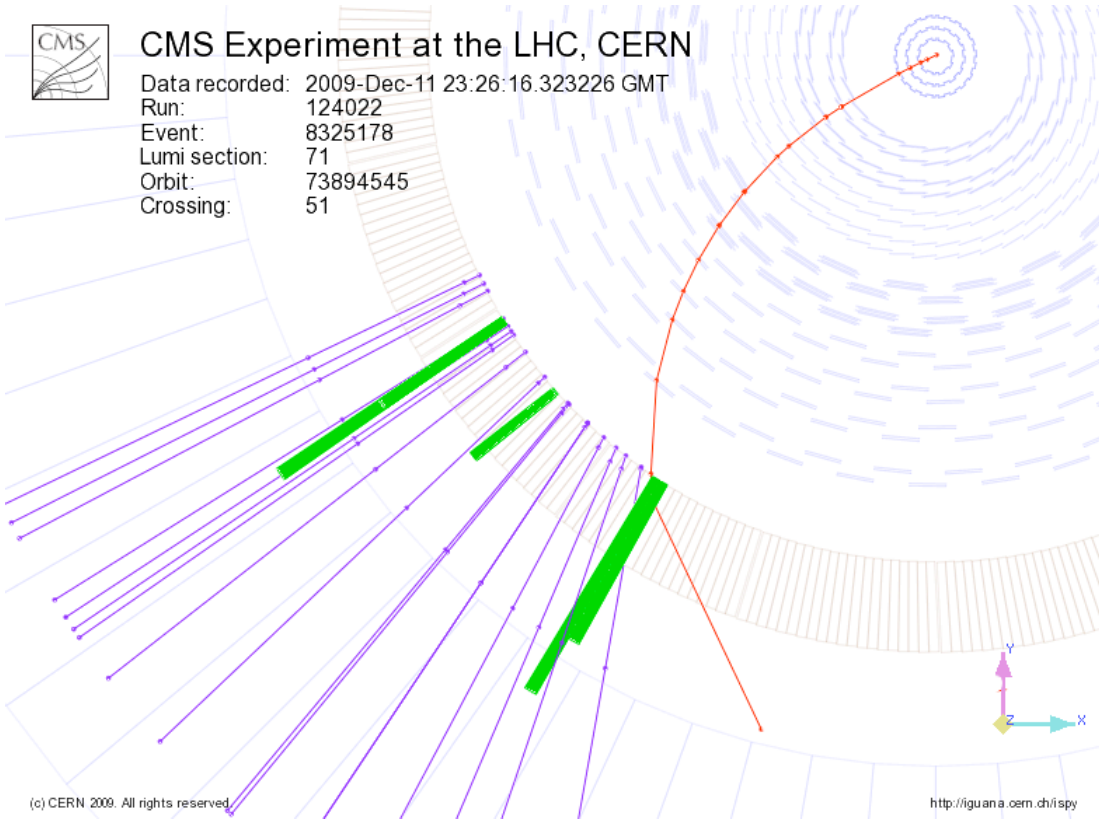
Analysis objects: muons





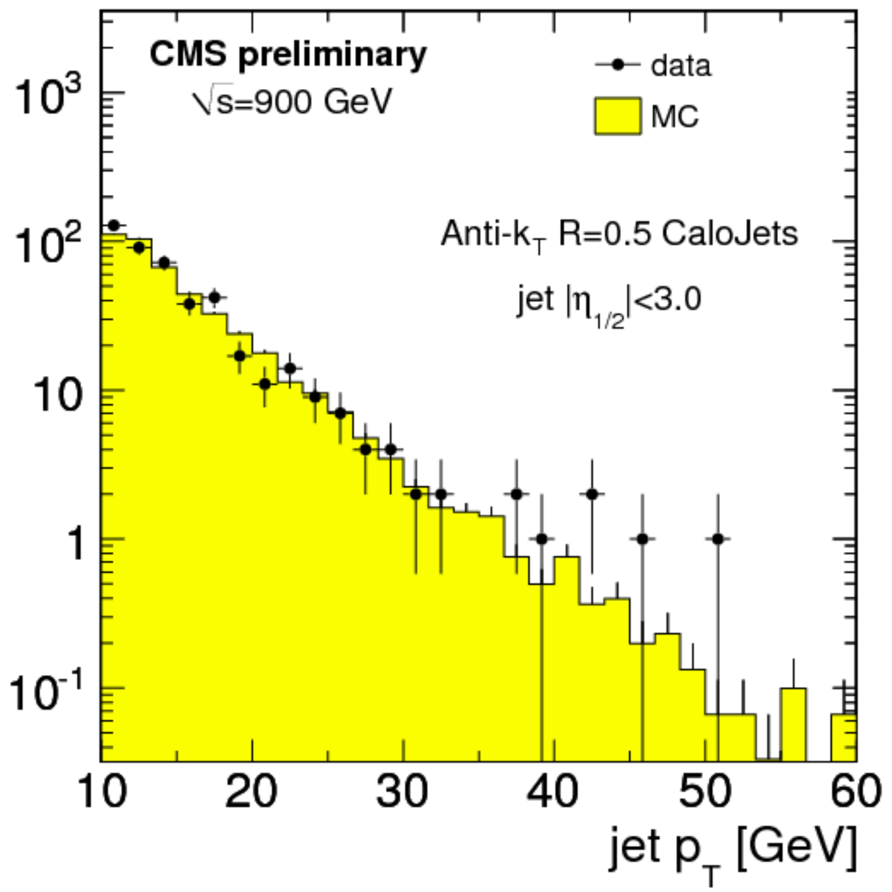
- Muons
  - Easiest to reconstruct
  - Use tracks in silicon and muon chambers

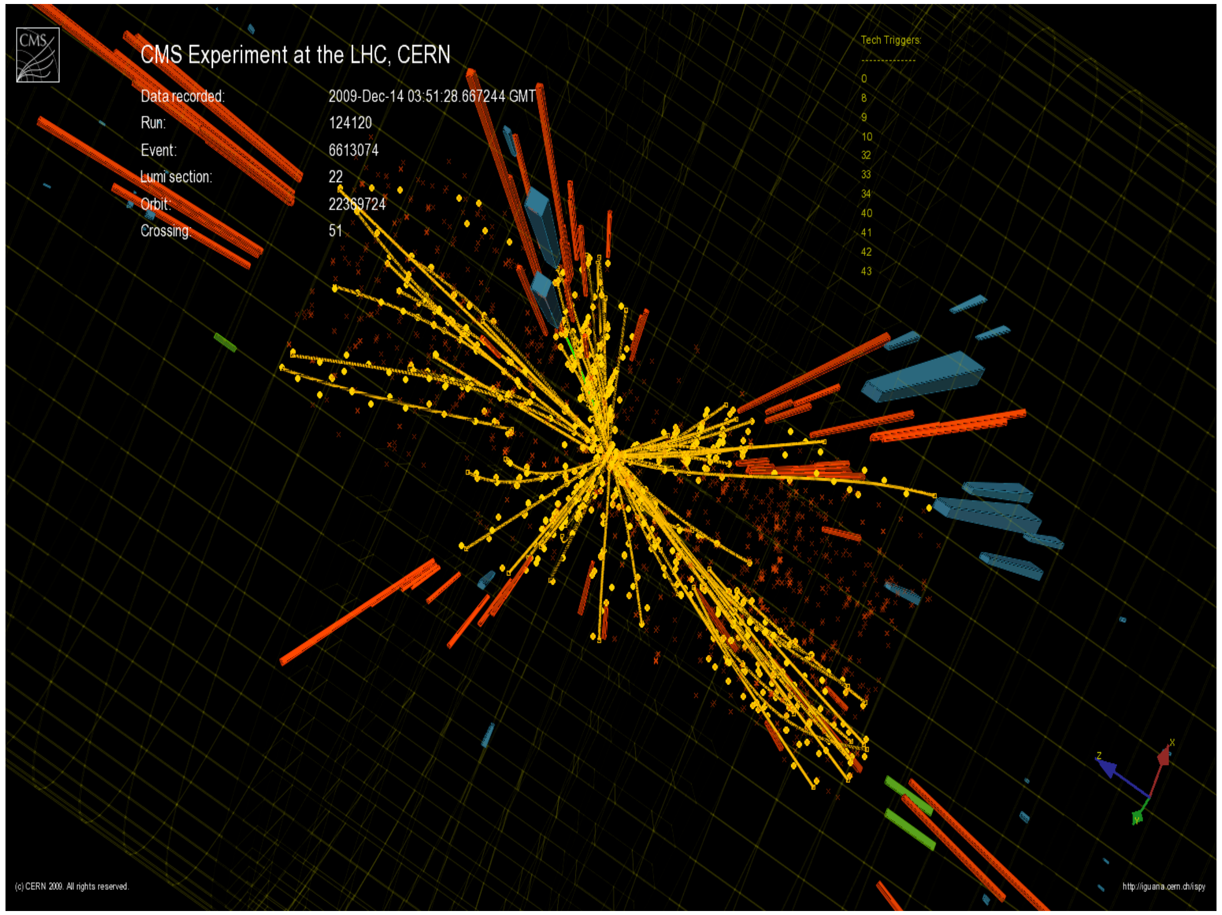
Analysis objects: electrons & photons



- Electrons
  - Search for isolated, compact EM energy
  - Matched track
  - Strikingly in 4T B-field all electrons have Bremsstrahlung photons
  - Algorithms collect photons in electrons

Analysis objects: hadronic jets

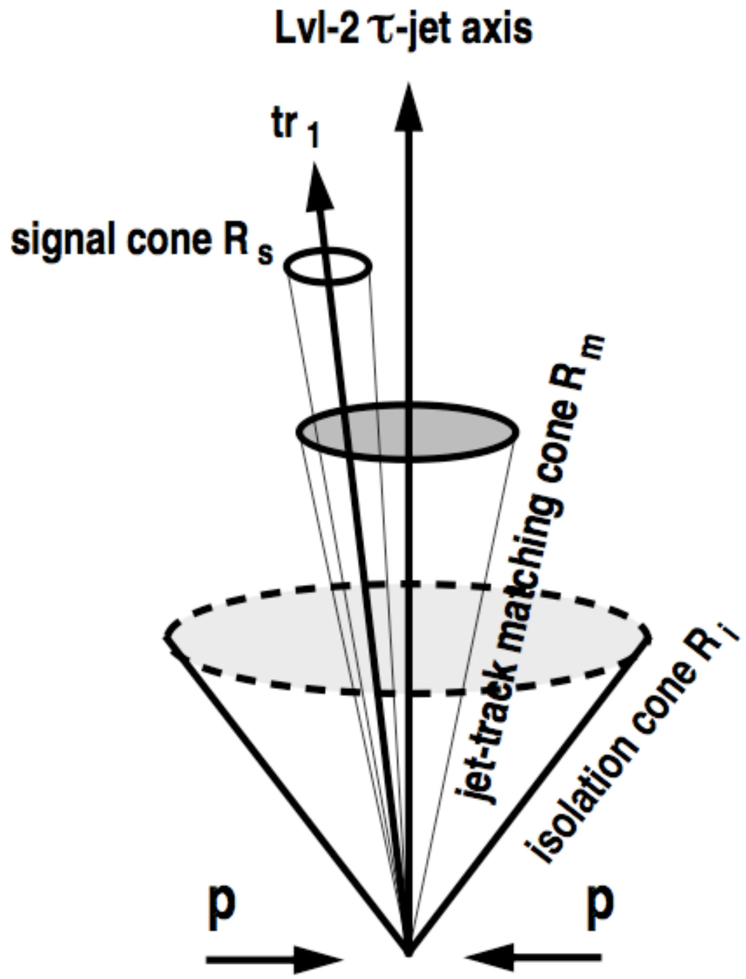




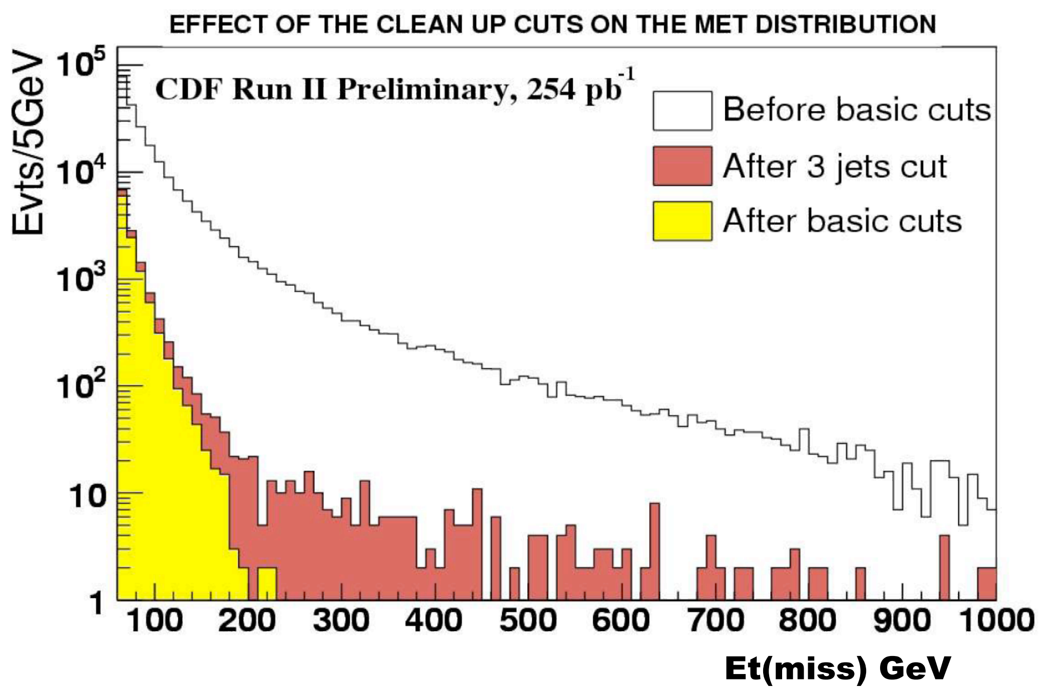
- Jets
  - Attempt to cluster together energies from parton
  - Traditionally jets made from clustering HCAL and ECAL energies according to some algorithm (anti-K_T)

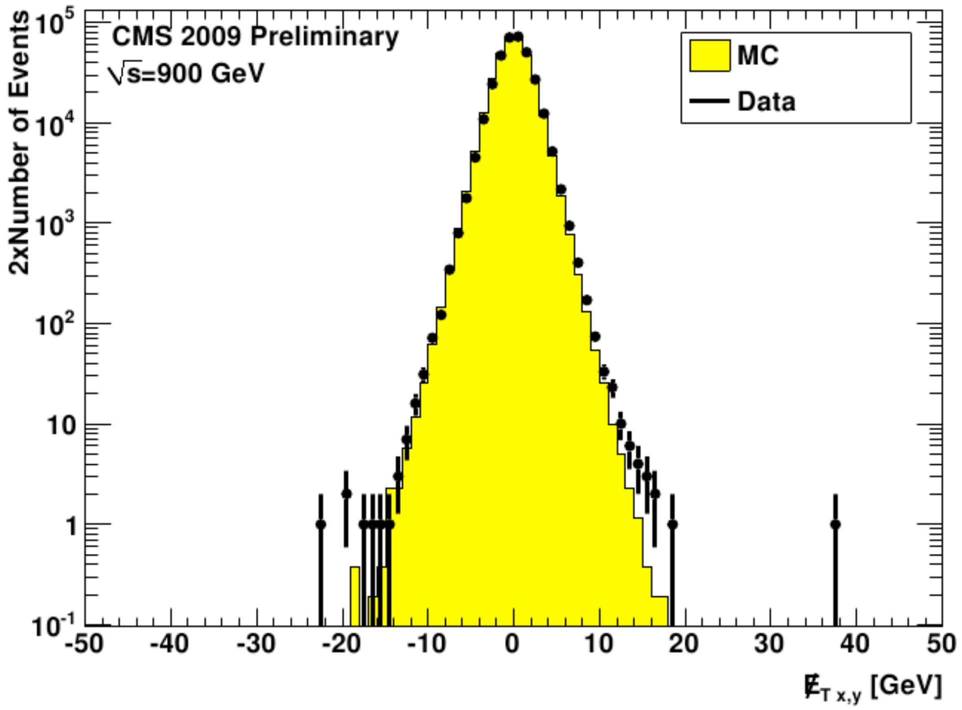
Analysis objects: taus

- Taus
  - Hadronic decays of tau leptons
  - Either one or three pronged decays to pions
  - Thin jets with few constituents
  - Backgrounds from QCD jets
  - No taus in CMS yet....



Analysis objects: MET

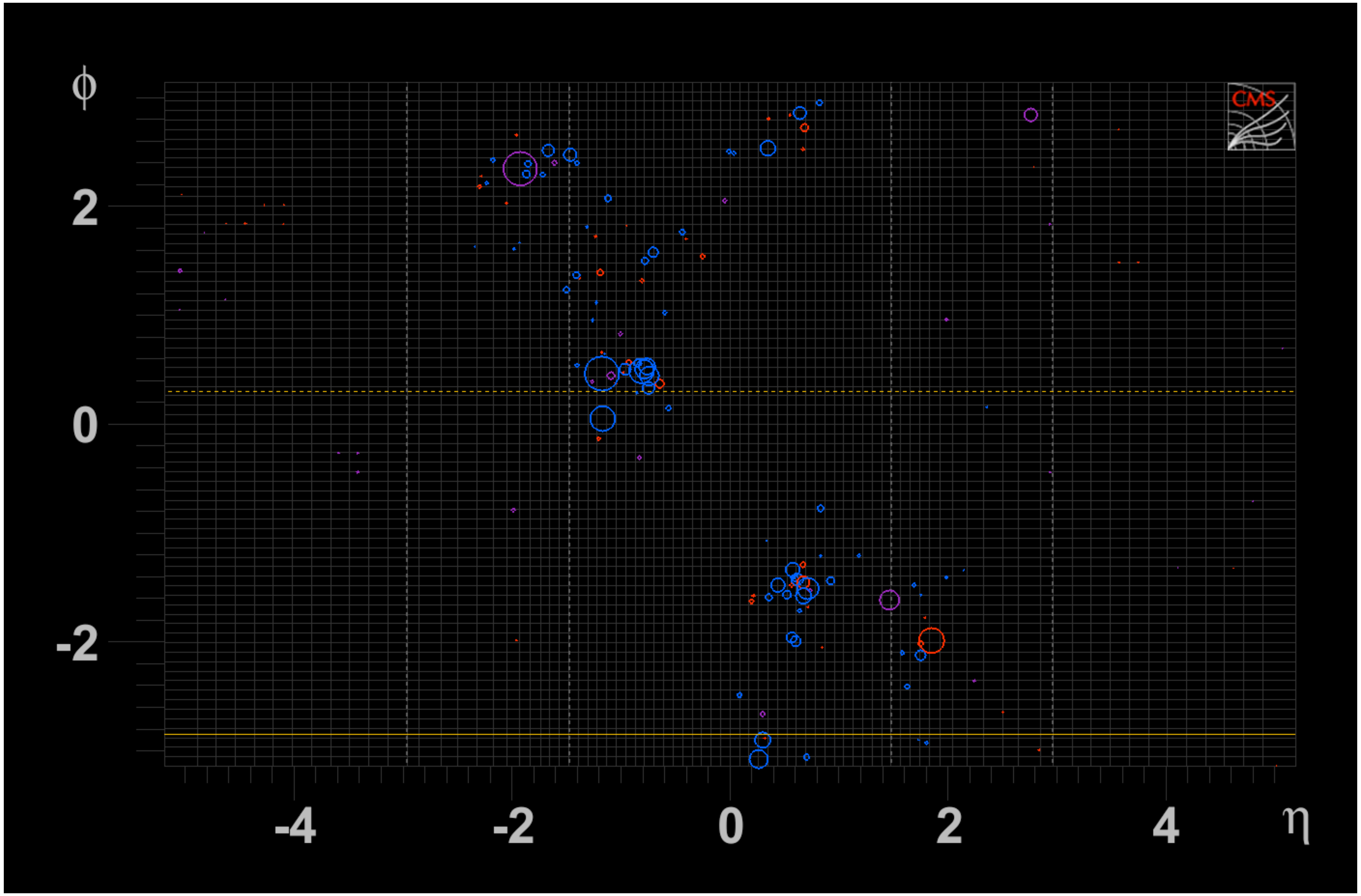




- MET
  - Vector sum of all energy deposits in the event
  - Very sensitive to mis-calibration, non-uniformity, beam backgrounds
  - Tevatron experience scary

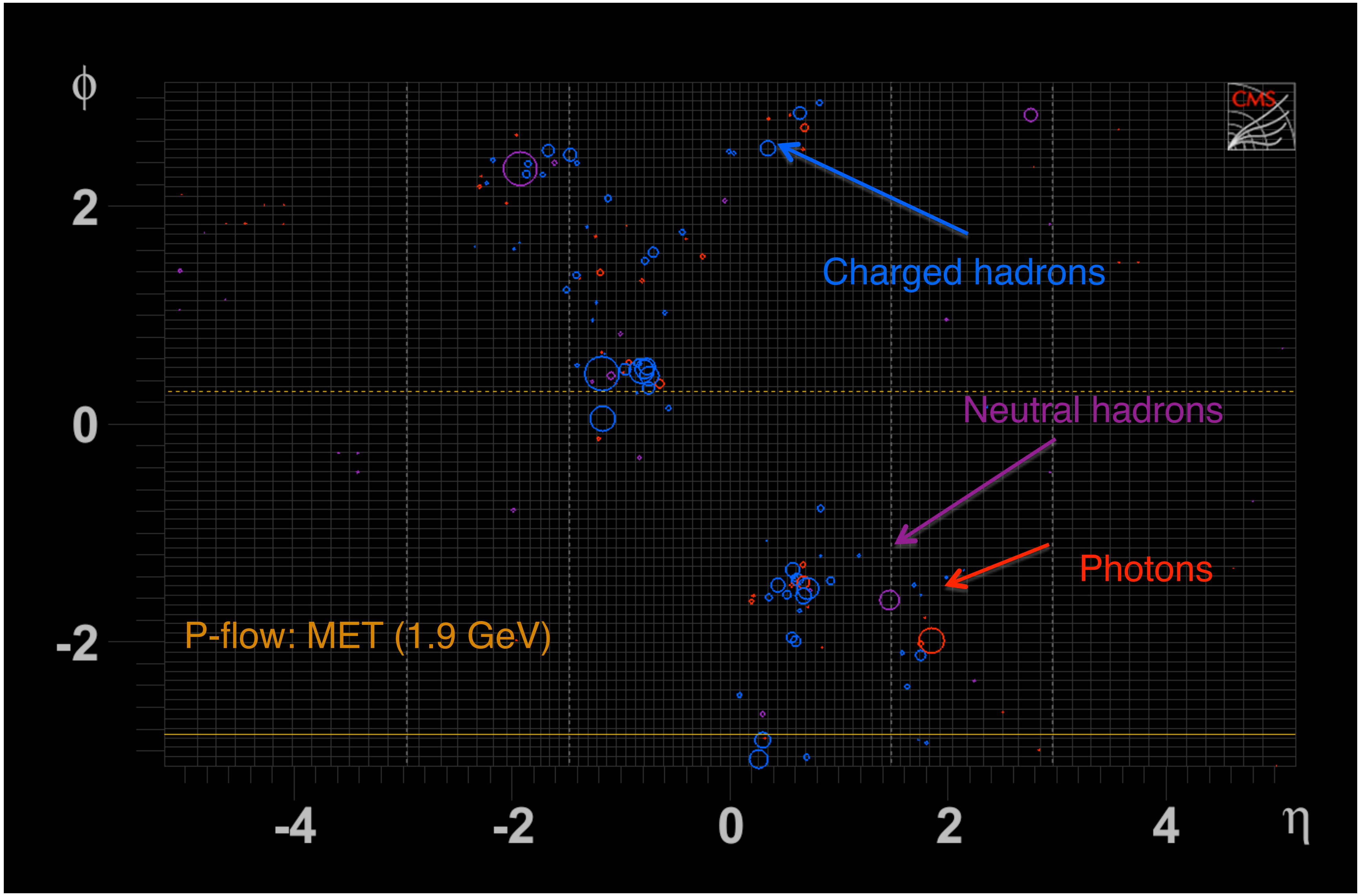
Analysis objects: particle flow

- Particle flow - The Rolls Royce of reconstruction



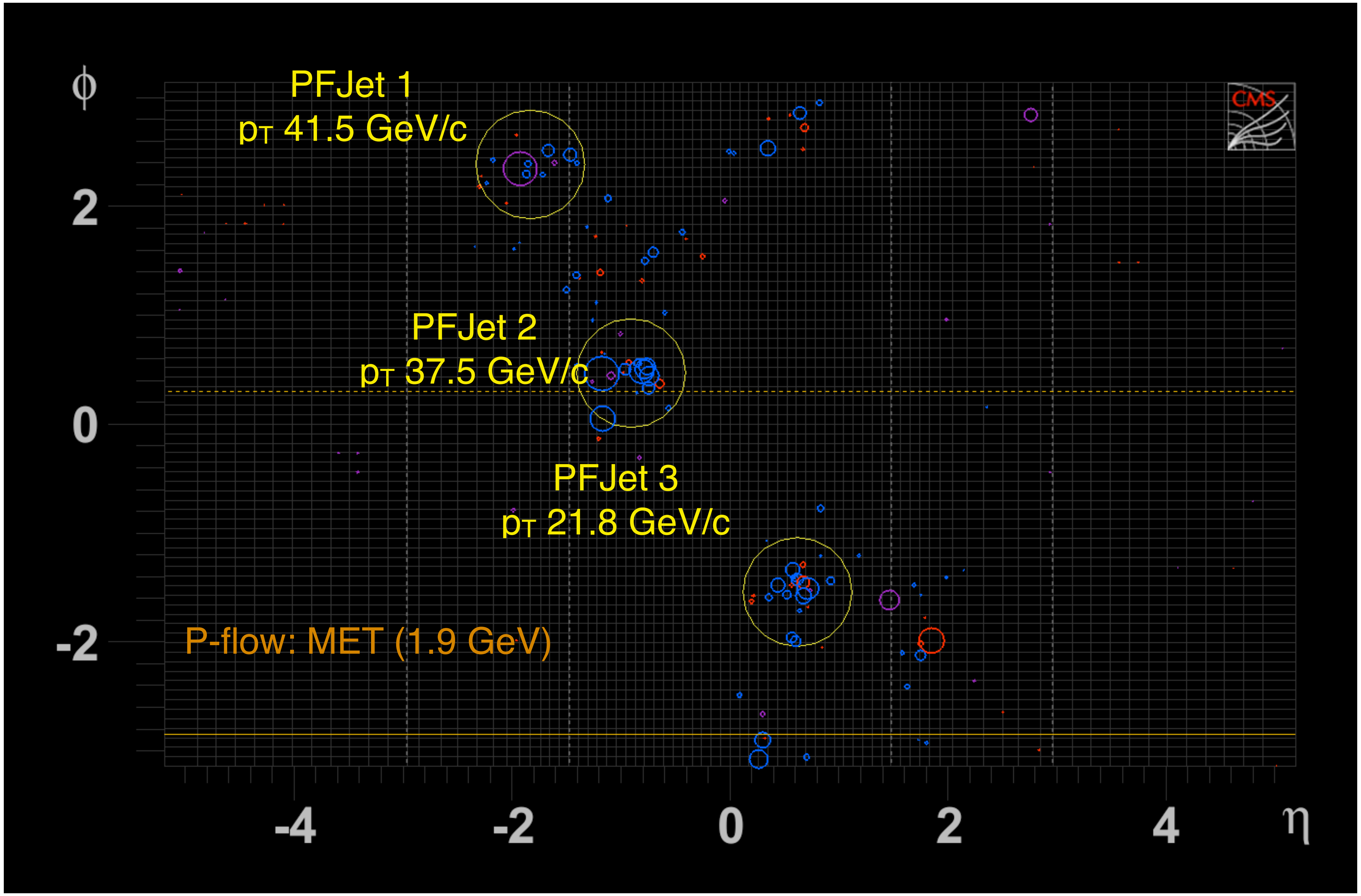
Analysis objects: particle flow

- Particle flow - MET comes naturally

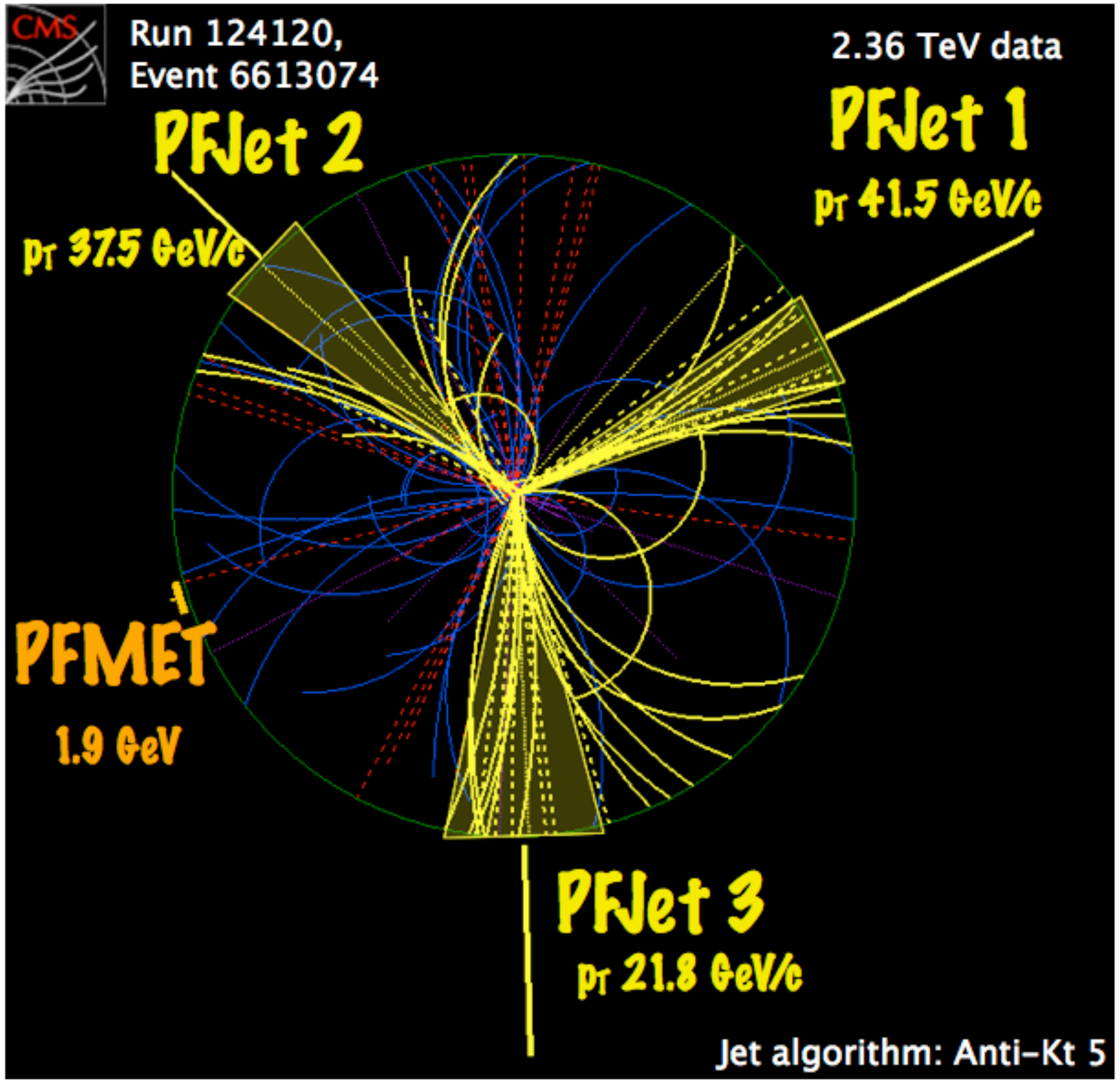


Analysis objects: particle flow

- Particle flow - jets too



Analysis objects: particle flow



PFJets with (uncorrected) p_T > 20 GeV/c

Particle inside the jet:

- Charged hadrons
- Photons
- Neutral hadrons

Particles outside the jet:

- Charged hadrons
- Photons
- Neutral hadrons

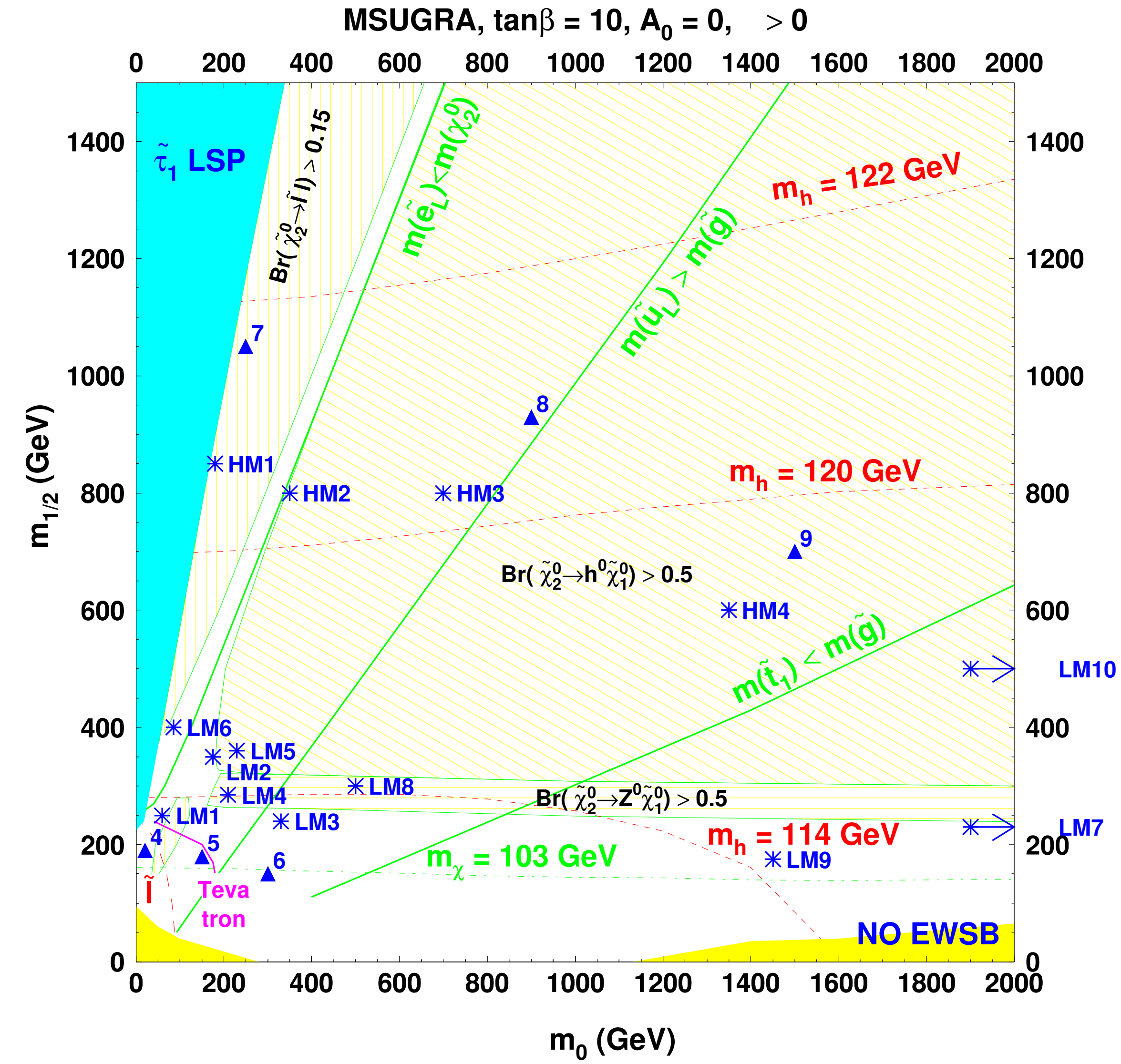
PFMET (1.9 GeV)

Analysis strategy: overview

1. Take data
   - Detector, trigger, DAQ
2. Reconstruct physics objects
   - Muons, electrons, taus, jets, MET....
3. Simulation
   - Generate events, detector simulation
4. All the tools to make a measurement

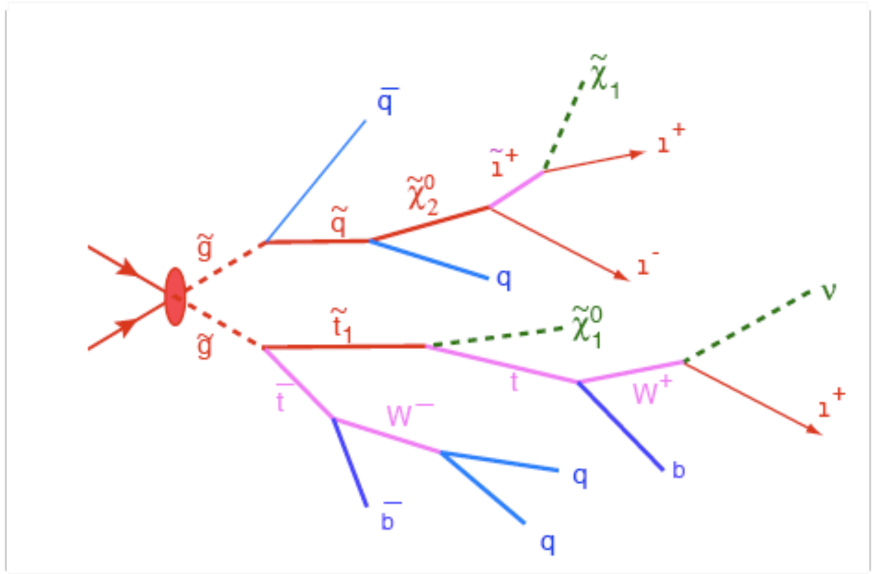
SUSY search strategy

- Be as model independent as possible
  - But the MSSM has > 100 parameters
  - Need more constrained models
  - Choose a set of benchmark points that are representative of a range of topologies and areas of phase space
  - Range of models
    - MSUGRA (high and low masses)
    - GMSB
    - Split SUSY
  - In this talk MSUGRA at low masses, just above the Tevatron (LM0 and LM1)



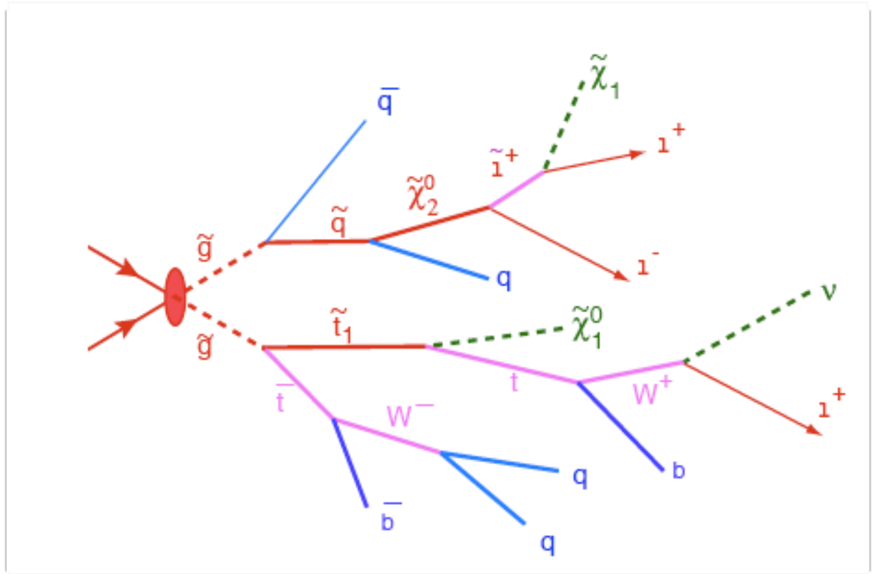
J. Phys. G: Nucl. Part. Phys. 34 (2006)

SUSY search strategy



- Production
  - Squark and gluino expected to dominate
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of SUSY model

SUSY search strategy



- Production
  - Squark and gluino expected to dominate
  - Strong production so high cross section
  - Cross section depends only on masses
  - Approx. independent of SUSY model
- Decay
  - Details of decay chain depend on SUSY model (mass spectra, branching ratios, etc.)
  - Assume RP conserved ➔ decay to lightest SUSY particle (LSP)
  - Assume squarks and gluinos are heavy ➔ long decay chains
- Signatures
  - MET from LSPs, high-ET jets and leptons from long decay chain
  - Focus on robust and simple signatures
  - Common to wide variety of models
- Let Standard Model background and detector performance define searches not models

Backgrounds

- Physics
  - Standard Model processes that give the same signatures as SUSY
  - Cannot rely on Monte Carlo predictions ➔ measure in data
- Detector effects
  - Detector noise, mis-measurements etc. that generate MET or extra jets
  - Commissioning and calibration
- Beam related
  - Beam-halo muons (and cosmic-ray muons), beam-gas events
  - Data and simulation already ➔ measure in situ too

Backgrounds

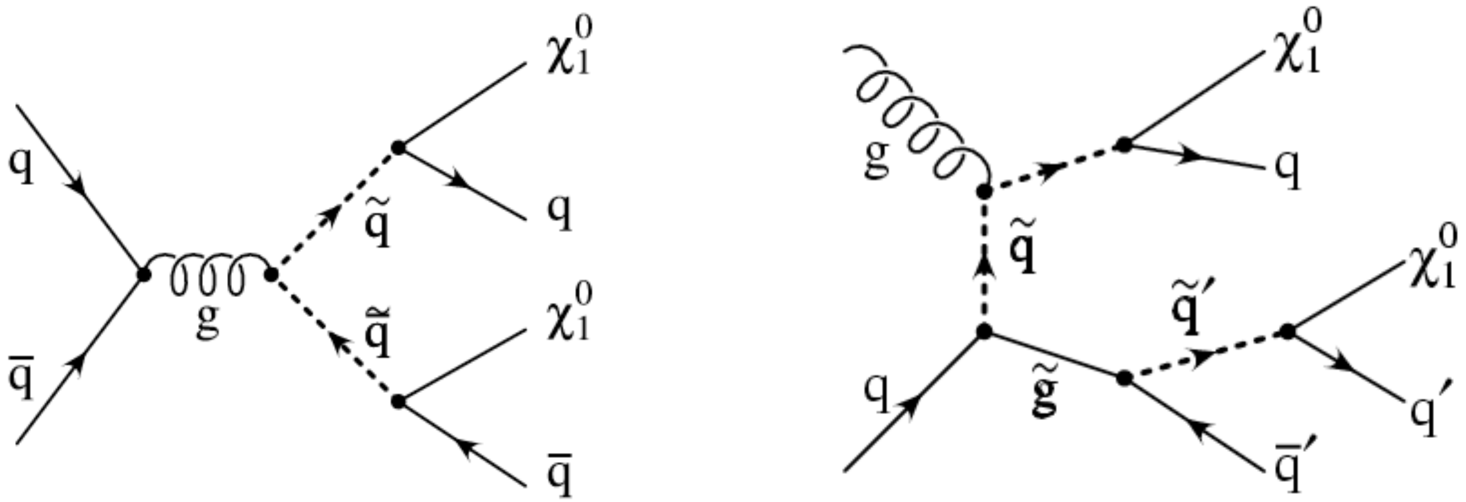
- Data-driven background estimates are the key challenge in early SUSY searches

- General idea is find a control region where SM is dominant and use this to predict SM background in signal region
- Two approaches pursued:
  - Matrix (ABCD) methods ➔ playing variables off against each other
  - Replacement methods ➔ modify SM with same topology as signal to predict signal
- In both cases need to identify clean SM control region
- Difficult to avoid using Monte Carlo in some way

- Will discuss all hadronic (jets + MET) search giving examples of data-driven methods ➔

All-hadronic SUSY search

- SUSY particles produced strongly and decay through long cascade

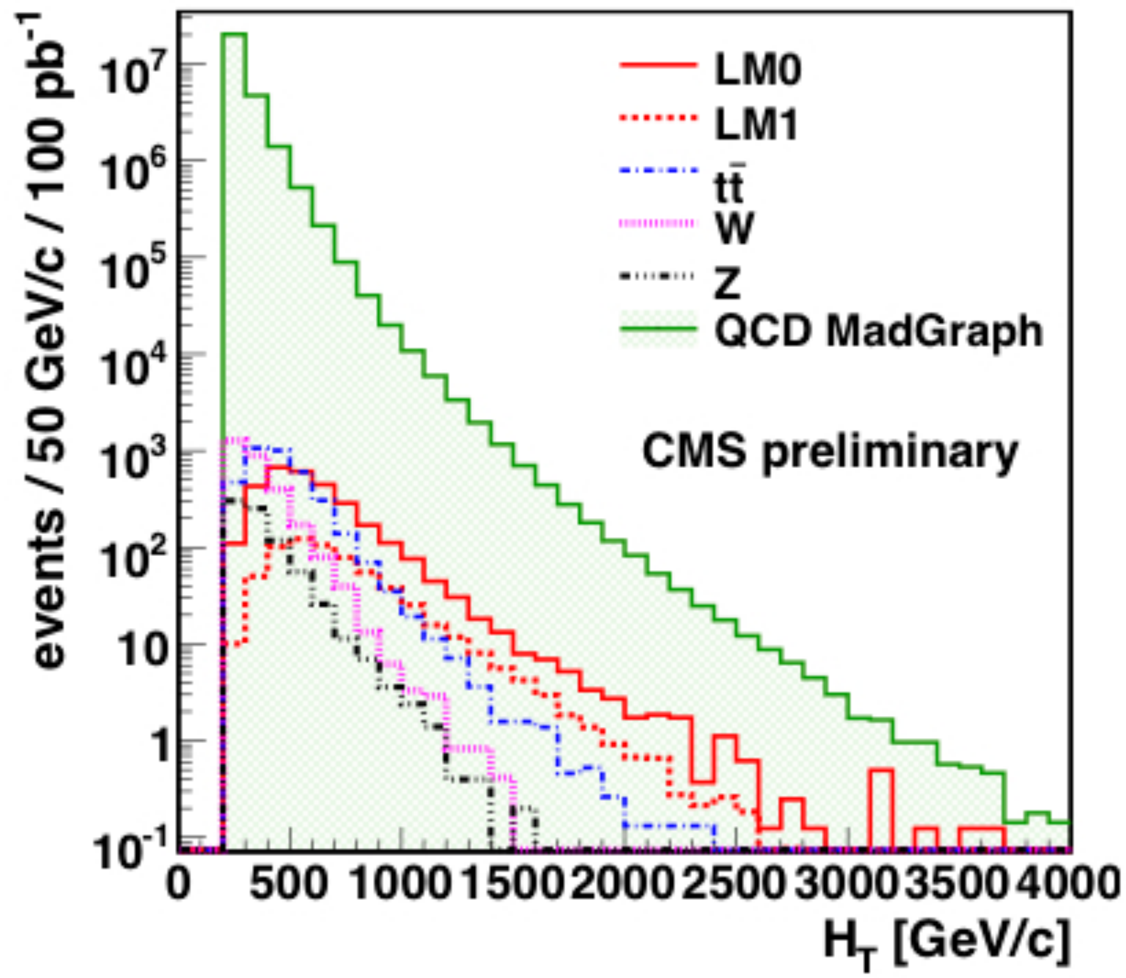


- Search for excess of events with large MET (from LSP) and several hadronic jets
- Veto events with leptons

All-hadronic SUSY search

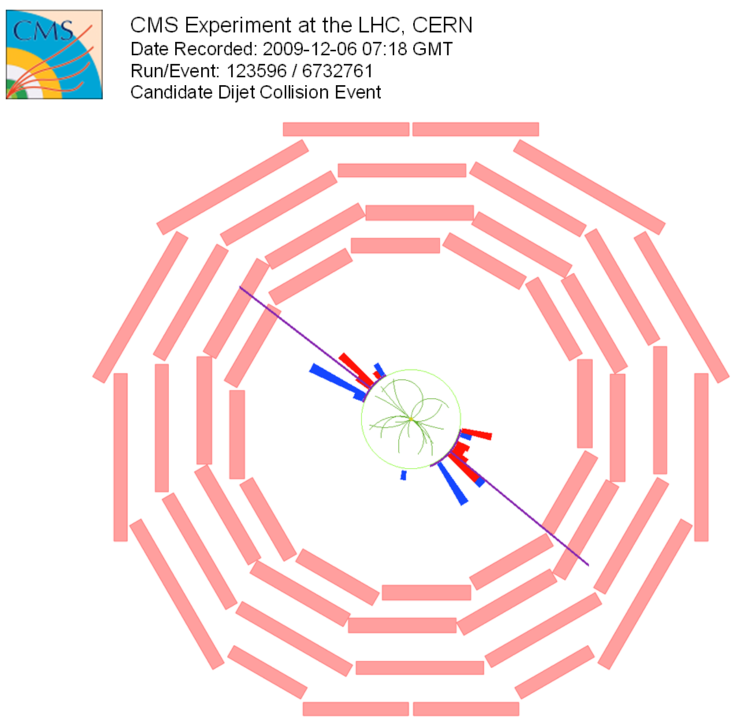
- Simple (pre)selection
  - At least two jets with E_T>50 GeV and $|\eta|<3.0$
  - Veto events with an electron or muon P_T>10 GeV
- Use energy sums based on jets
  - More robust since you can put minimum E_T cut
  - H_T scalar sum of jet E_T
  - MHT vector sum of jet E_T
- Enhance SUSY-like processes
  - E_T of two highest E_T jets > 100 GeV $|\eta_{j1}|<2.0$
- Look at simulation to see what processes form backgrounds to your signal →

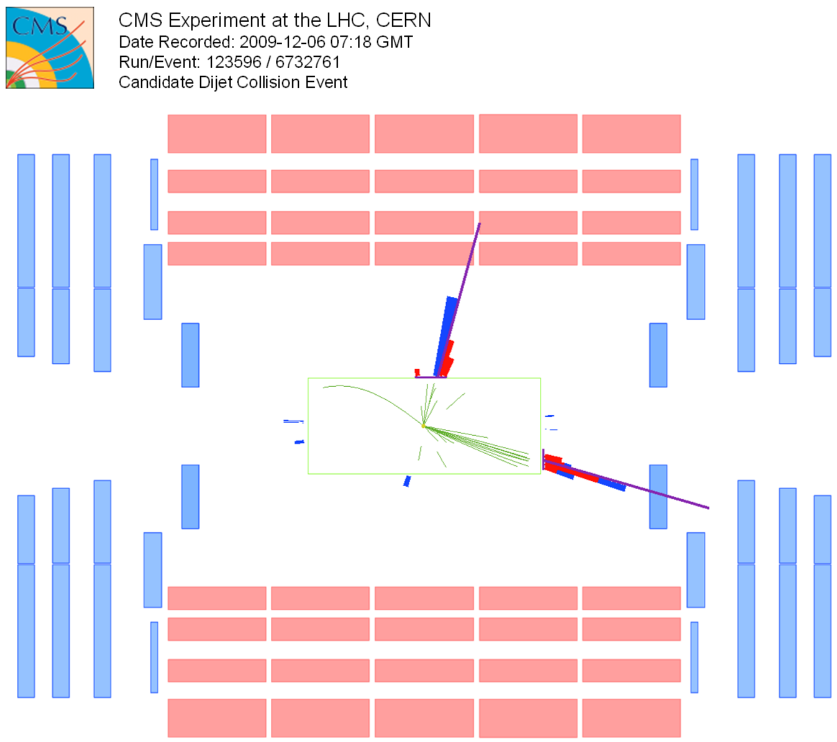
All-hadronic SUSY search



- QCD is by far largest background
- Z-boson decays
- Top-pair production and W-boson decays

Background from QCD

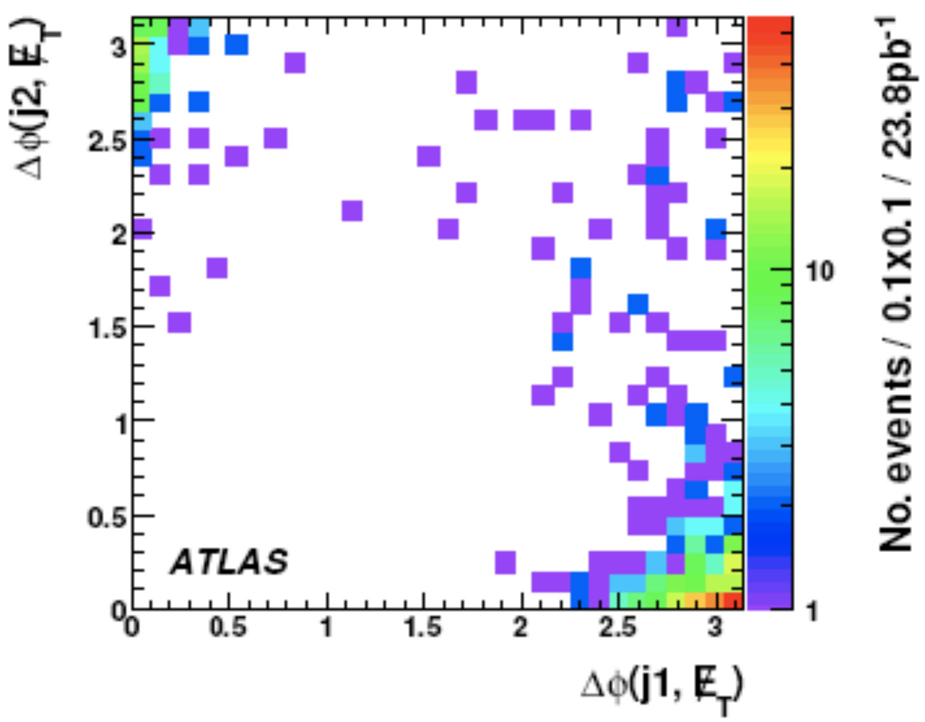


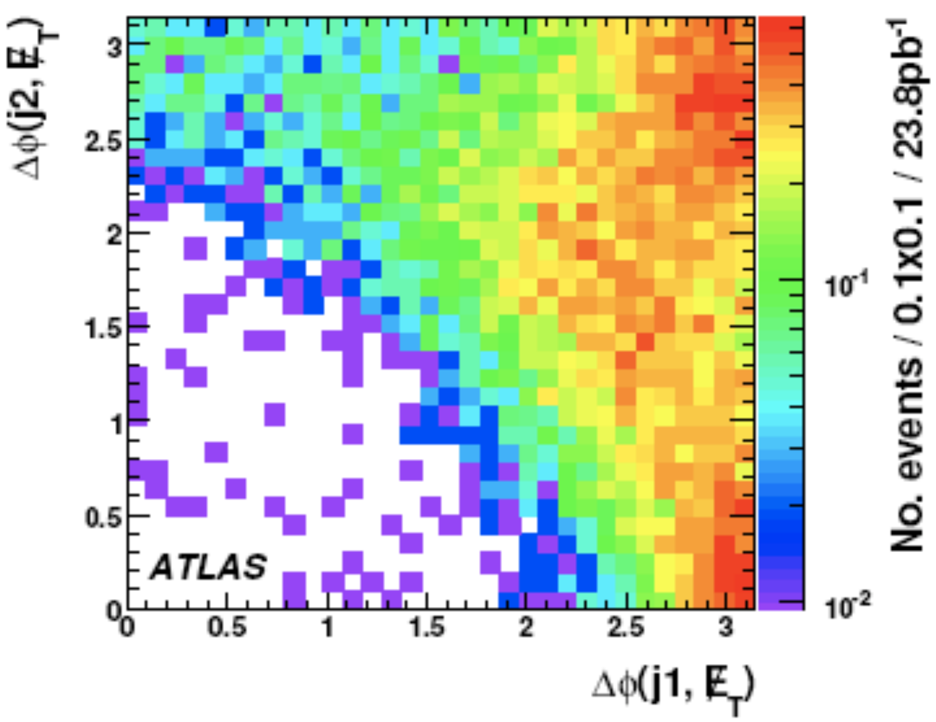


- QCD processes lead to di-jet events
- Gluon radiation gives >2 jets
- When perfectly measured no MET but...
  - Not a perfect detector
  - Semi-leptonic decays in jets (b and c quarks)

Background from QCD

- Mis-measurement of a jet leads to MET along the jet axis
- Remove with $\Delta\Phi(jet_i, MET) > 0.3$ rad

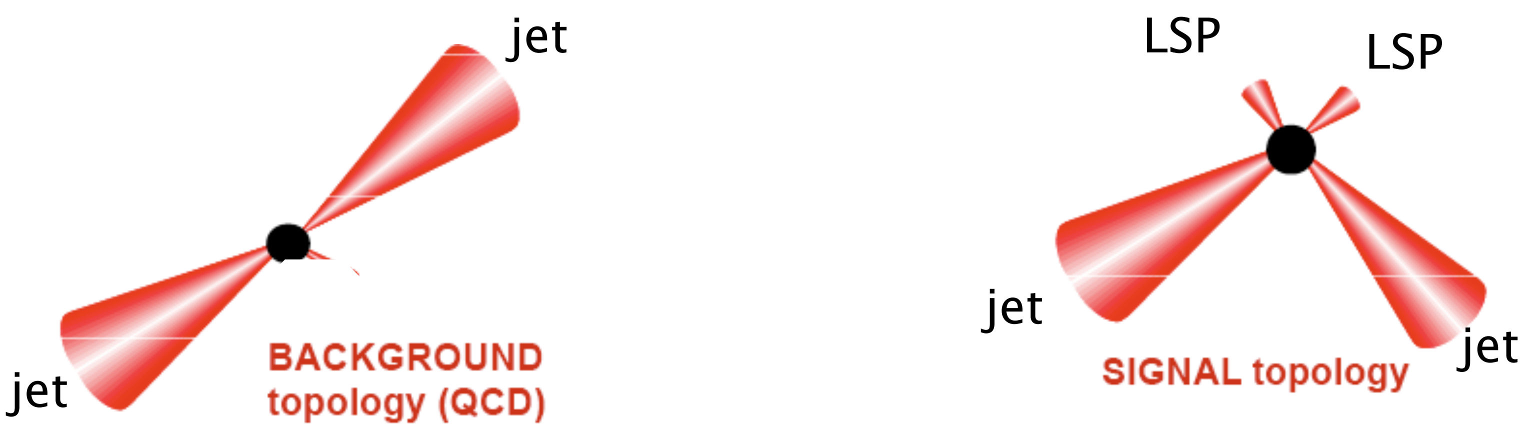




- Also several methods developed to predict MET tail from QCD events

All-hadronic search

PRL101:221803 (2008) & CMS-PAS-SUS-09-001



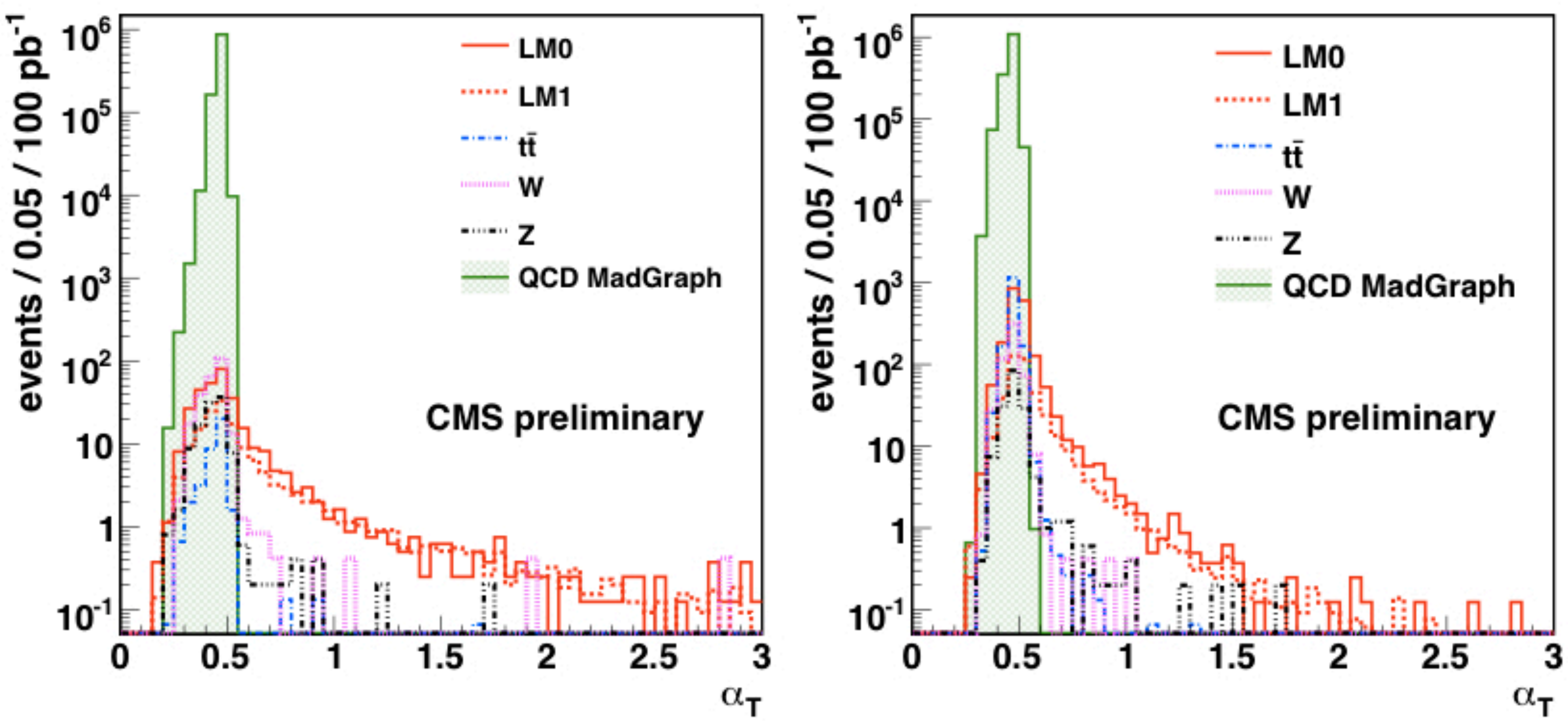
- A novel approach combining angular and energy measurements

$$\alpha_T = \frac{E_{T\ j2}}{M_{T\ j1j2}} = \frac{\sqrt{E_{T\ j2}/E_{T\ j1}}}{\sqrt{2(1-\cos\Delta\varphi)}}$$

- Perfectly balanced events have α_T=0.5
- Mis-measurement of either jet leads to lower values

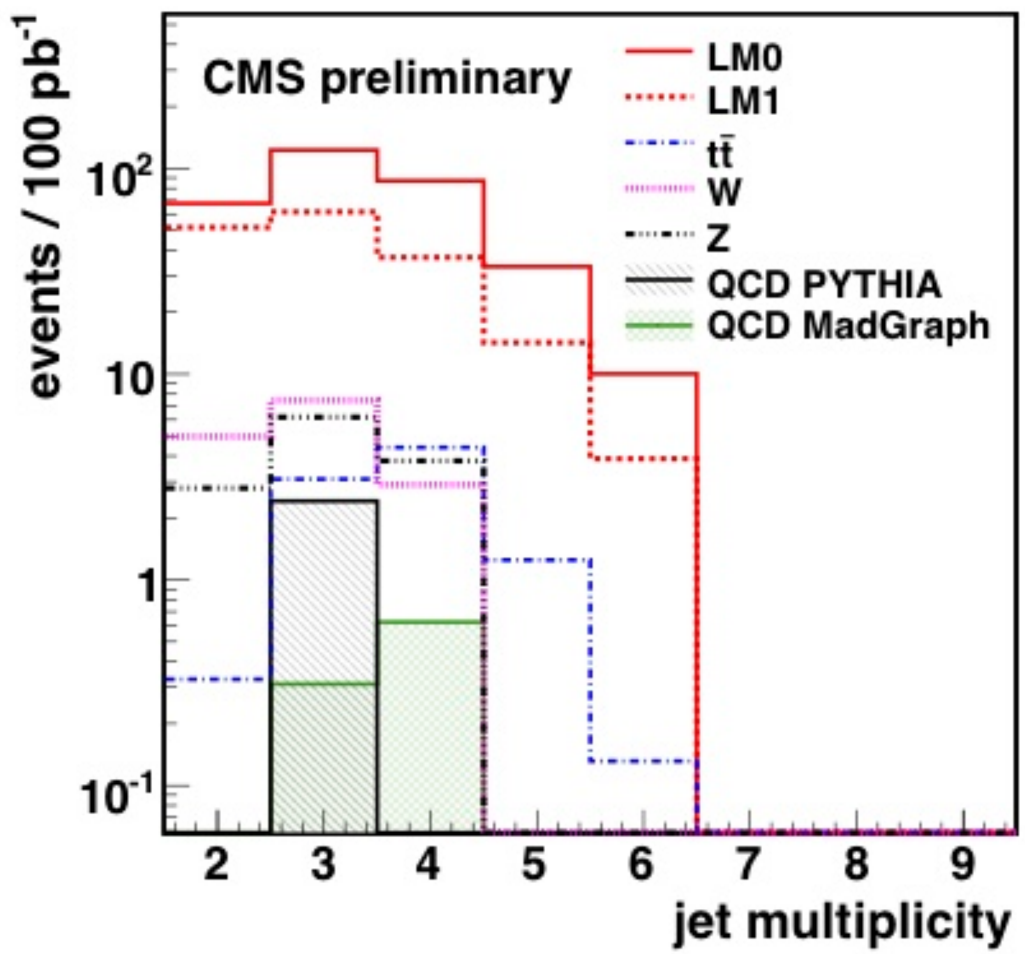
All-hadronic search

PRL101:221803 (2008) & CMS-PAS-SUS-09-001



- Originally proposed for di-jet events ➔ generalised up to six jets
- Perfectly balanced events have α_T=0.5 (cut at α_T>0.55)
- Mis-measurement of either jet leads to lower values

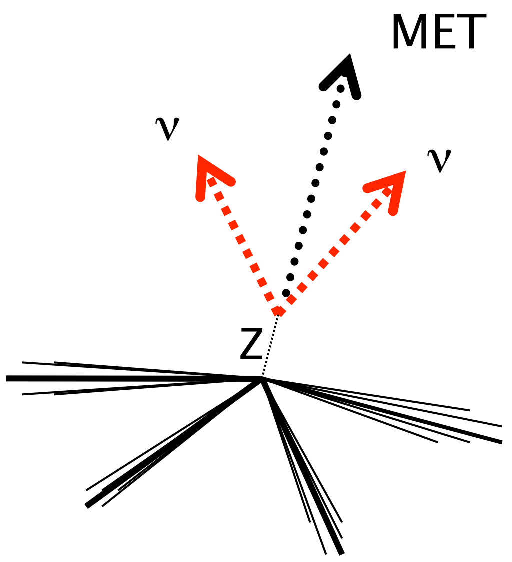
All-hadronic SUSY search

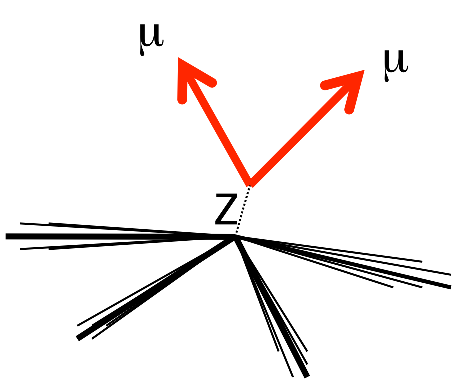


- After cut on α_T>0.55 QCD under control
- Look at other backgrounds →

Z-boson background

- Data-driven background estimate
  - Find a **control region** in phase space where SM background dominates
  - Use measurements in this region to infer SM background in signal region
  - Example Z → νν + jets ➔ irreducible background
  - **Replacement technique**

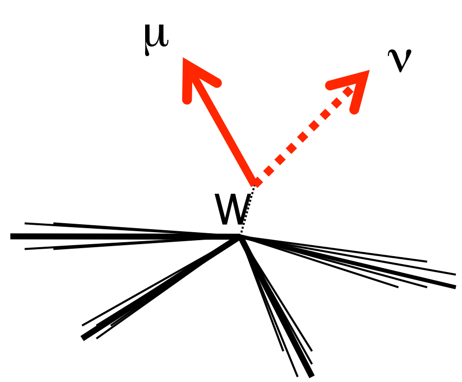




Z → ll + jets

Strength: very clean

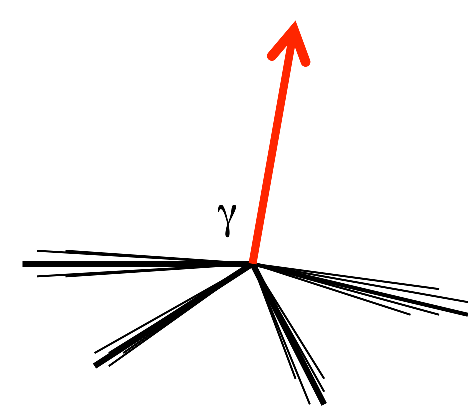
Weakness: low statistics



W → lν + jets

Strength: larger statistics

Weakness: background from SM and SUSY



γ + jets

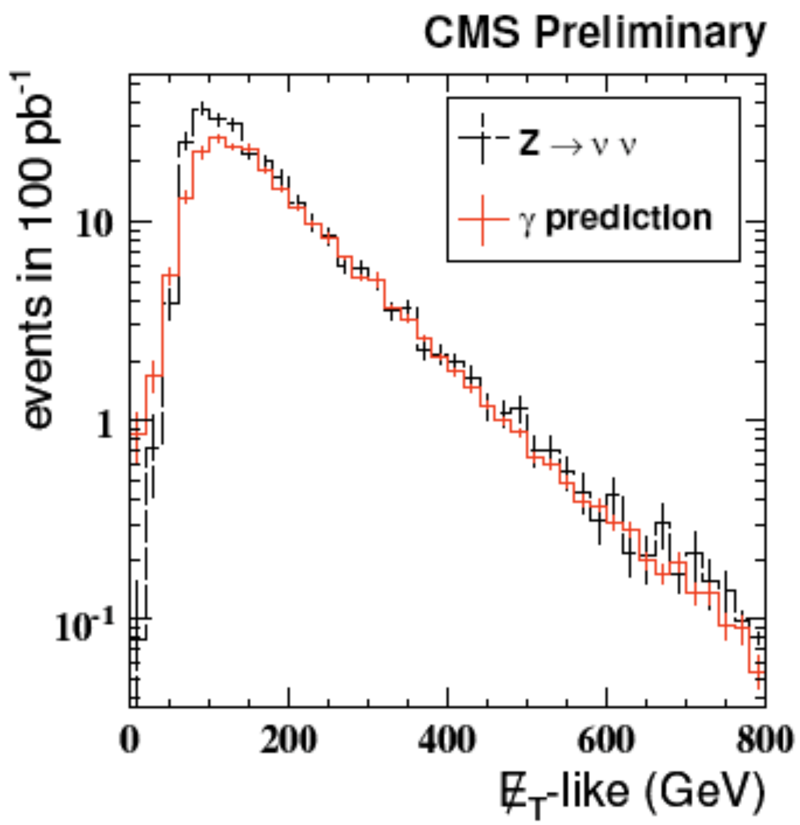
Strength: large statistics and clean at high E_T

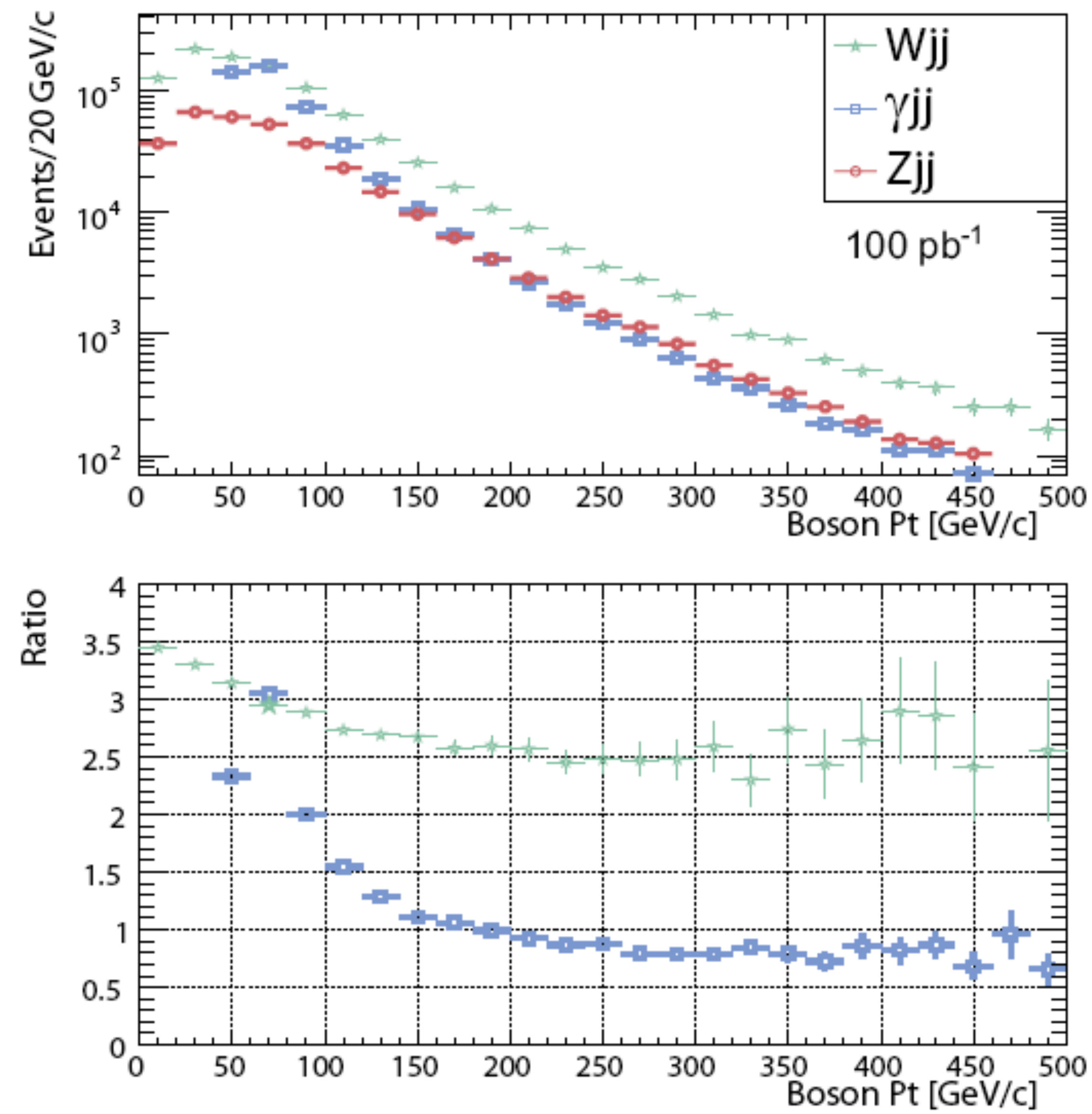
Weakness: background at low E_T, theoretical errors

Z-boson background

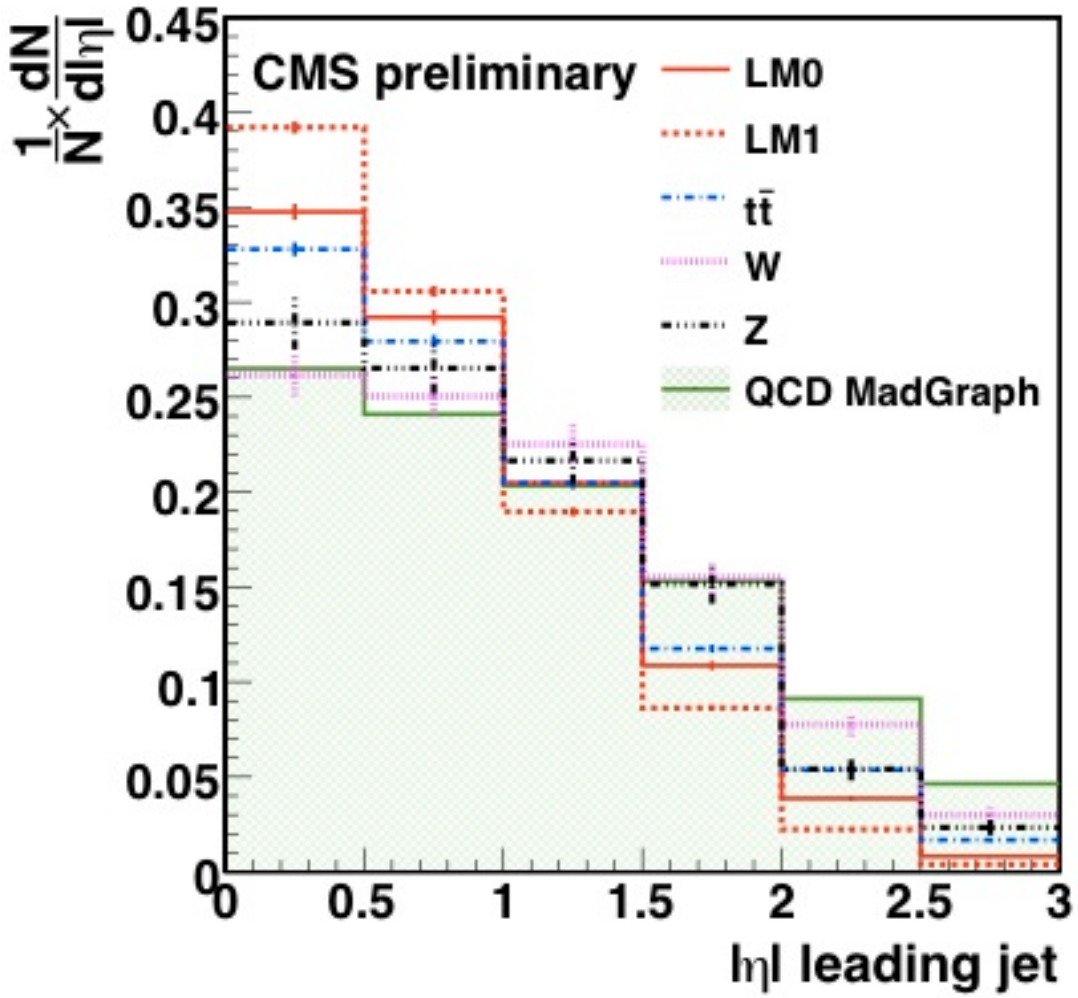
- Select γ + ≥3 jets with Eγ>150 GeV
  - Clean sample S/B>20
  - Remove photon from the event
  - Recalculate MET
  - Normalise with σ(Z+jets)/σ(γ+jets) from MC or measurements

CMS-PAS-SUS-08-002



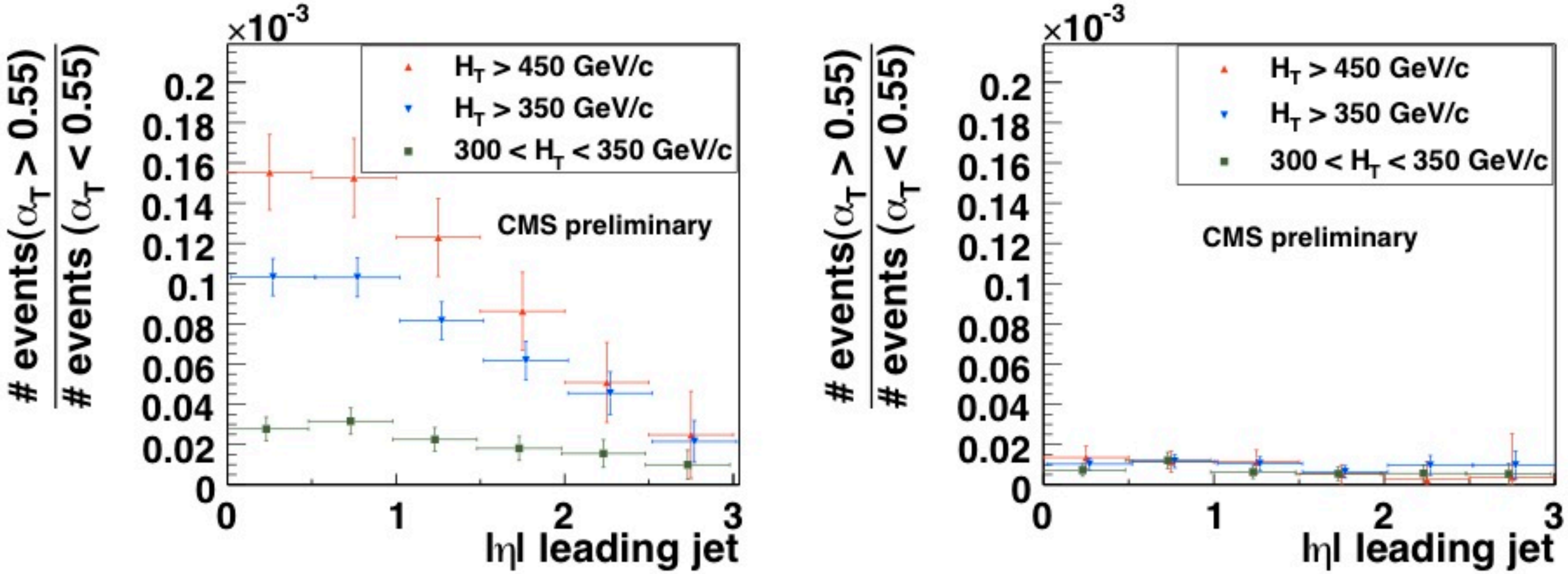


Background estimation



- SUSY signal more central than W, Z and QCD
- Consequence of s-channel pair-production of heavy particles
- Try and use this property →

Background estimation



- Use high |η| as a signal free control region
- Use this to extrapolate background prediction into central signal region
- Check behaviour at low H_T which is signal free
- Scan H_T and see excess to discover SUSY!

All-hadronic SUSY search

Selection cut	$QCD_{MadGraph}$	$Z \rightarrow \nu\bar{\nu}$	$W \rightarrow \nu\ell$	$t\bar{t}$	$Z \rightarrow \ell\ell$	LM1	LM0
Trigger	2.5×10^7	821	6618	17054	1157	926	7080
Preselection	2×10^6	243	927	3154	109	448	2508
$H_T > 350\,\mathrm{GeV/c}$	2×10^6	185	667	2603	76	442	2408
$\alpha_T > 0.55$	5.3	10	10	10	0.3	117	266
$R(H_T^{miss}) < 1.25$	$0.9^{+1.0}_{-0.9}$	10.0 ± 1.4	10.4 ± 1.7	8.8 ± 0.8	$0.3^{+0.4}_{-0.3}$	116 ± 1	253 ± 6

- Hundreds of SUSY events with Standard Model backgrounds of 10s of events
- Robust early search with possibility to discover SUSY in 2010
- Data-driven methods to control and check background estimates

Summary

- Overview of collider physics techniques
- Emphasis on early searches
- Incomplete! Much more to learn....

Backup: Benchmark points

Low mass (LM) mSUGRA benchmarks

Benchmark	m0	m1/2	A0	tanb	sgn(mu)	Notes
LM0	200	160	–400	10	1	
LM1	60	250	0	10	+	
LM2	185	350	0	35	+	
LM2mhf360	185	360	0	35	+	
LM3	330	240	0	20	+	
LM4	210	285	0	10	+	
LM5	230	360	0	10	+	
LM6	85	400	0	10	+	
LM7	3000	230	0	10	+	
LM8	500	300	–300	10	+	
LM9	1450	175	0	50	+	
LM9p	1450	230	0	10	+	
LM9t175	1450	175	0	50	+	mtop = 175
LM10	3000	500	0	10	+	
LM11	250	325	0	35	+	
LM12						TBD
LM13						focus point, TBD

High mass (HM) mSUGRA benchmarks

Benchmark	m0	m1/2	A0	tanb	sgn(mu)	Notes
HM1	180	850	0	10	+	
HM2	350	800	0	35	+	
HM3	700	800	0	10	+	
HM4	1350	600	0	10	+	

GMSB (GM) benchmarks

Benchmark	Lambda	M_mess	N5	C_Grav	tanb	sgn(mu)	Notes
GM1b	80	160	1	1	15	+	
GM1c	100	200	1	1	15	+	
GM1d	120	240	1	1	15	+	
GM1e	140	280	1	1	15	+	
GM1f	160	320	1	1	15	+	
GM1g	180	360	1	1	15	+	