Signature for New Physics from Jets and Missing Energy

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On behalf of the CDF and D∅ Collaborations

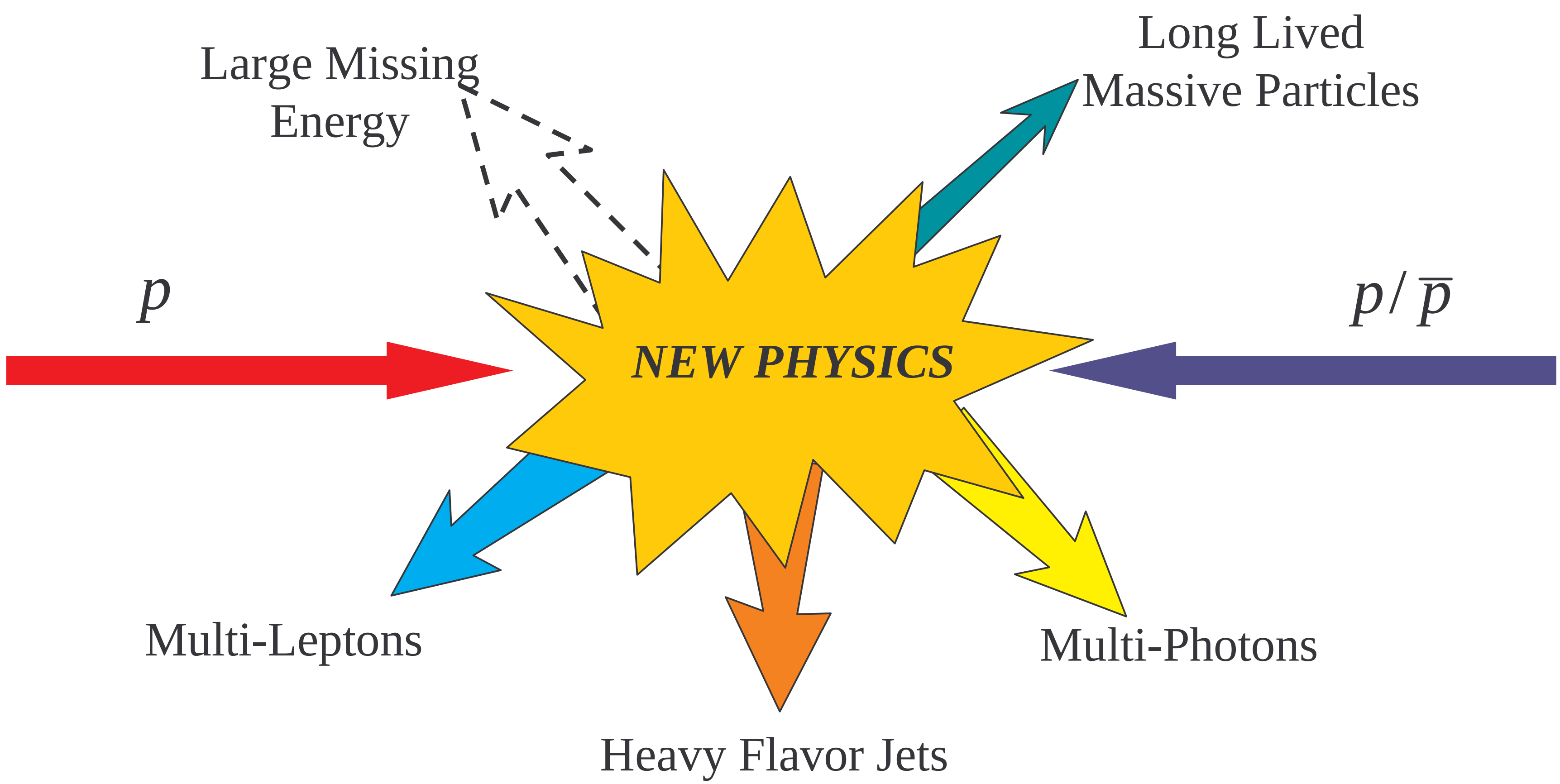
TeV4LHC Workshop

Fermilab 16-18 September 2004

- Introduction
- Recent results from Tevatron
- Experience from Tevatron

Signatures of New Physics

- New physics can manifest itself in several rare final state signatures of p-p and p-pbar collisions



Signatures of New Physics

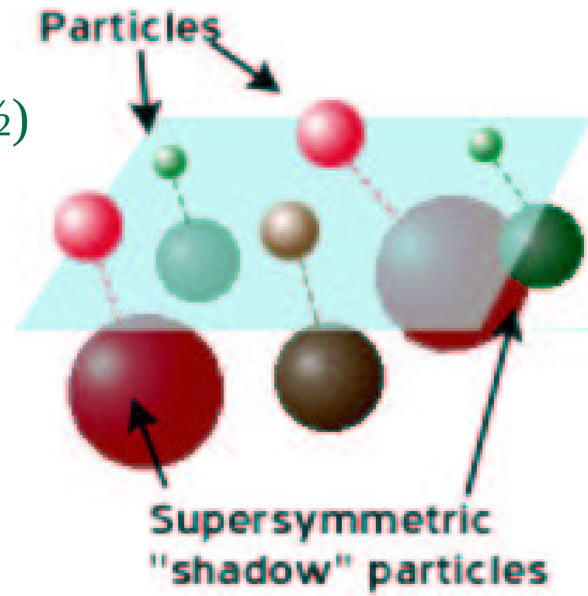
- One of the final state signatures that one may find new physics in is
  - Missing Energy + Jets
    - Missing energy due to :
      - Neutrinos
      - Massive charged particles : behave like min. ionizing particle in the calorimeter
      - Exotic neutral massive particles
    - Jets from generic QCD or Heavy Flavor
- New Physics :
  - SUSY
  - Leptoquarks
  - Extra Dimension
  - ……

SUperSYmmetry

- Postulates symmetry between bosons and fermions
  - Every SM particle has a SUSY partner (spin differ by ½)

$$e, \nu, u, d, \ldots \text{(spin ½)} \Rightarrow \tilde{e}, \tilde{\nu}, \tilde{u}, \tilde{d}, \ldots \textbf{(spin 0)}$$

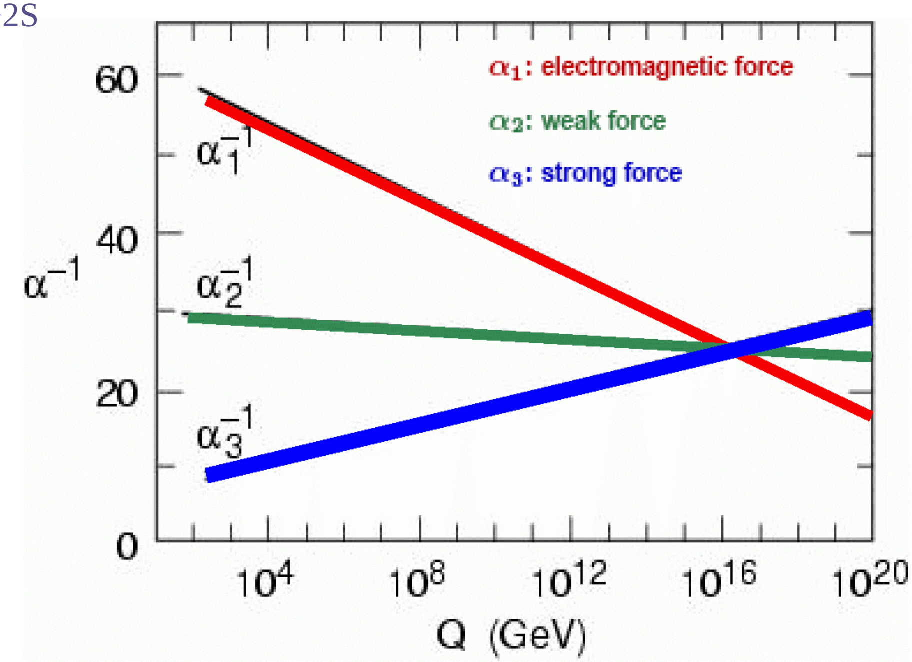
$$\gamma, W^{\pm}, Z^{0}, g, \ldots \text{(spin 1)} \Rightarrow \tilde{\chi}^{0}_{1,2,3,4}, \tilde{\chi}^{\pm}_{1,2}, \tilde{g} \ldots \text{(spin ½)}$$



  - Breaks down the rigid classification :

matter ↔ fermions	forces ↔ bosons

- New quantum number : R-parity = $(-1)^{3B+L+2S}$
  - Particles: R=1, SParticles: R=-1
- Can unify gauge couplings
- Can incorporate gravity (SUperGRAvity)
- May have a candidate for dark matter
- SUSY is not an exact symmetry
  - The SM particles and its SUSY partners have same quantum #, except that their masses are different



Phenomenology of SUSY (R-parity)

R-parity is conserved :

- SUSY particles are pair produced
- Lightest SUSY Particle (LSP) stable
  - If neutral ⇒ dark matter candidate
  - Escape detection ⇒ missing transverse energy ($\not{E}t$, MET)

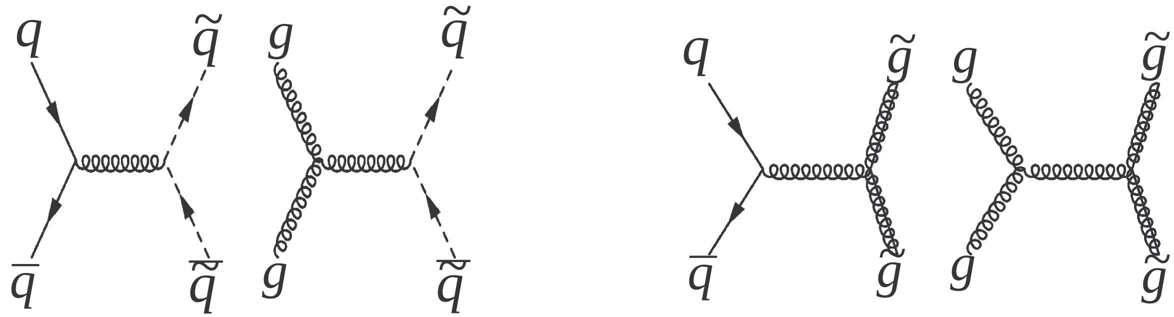
R-parity not conserved :

- SUSY particle can be singly produced

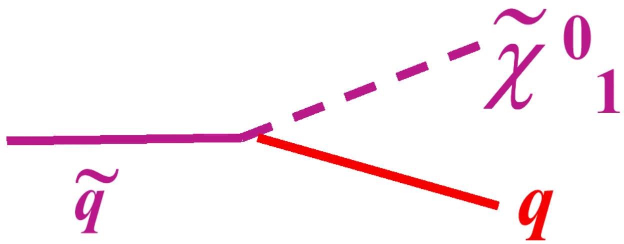
  ⇒ Larger production rate
- LSP decays to SM particles, no dark matter candidate
- Final states :
  - Not always have large missing energy
  - More jets/leptons

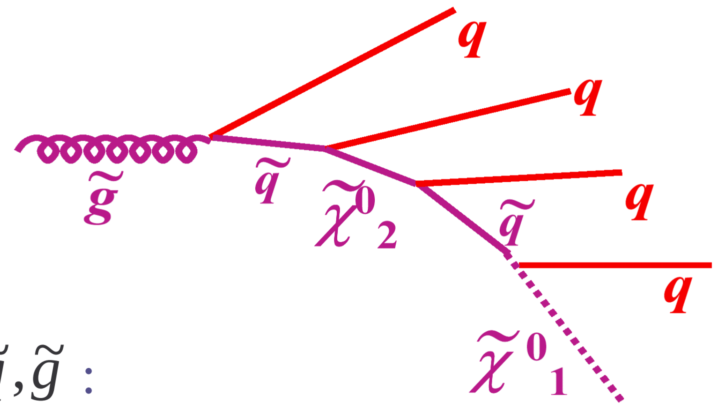
Searches for Squarks and Gluinos in MET + Jets

- Light colored sparticles($\tilde{q},\tilde{g}$) can be copiously pair produced at Tevatron



- Decays of $\tilde{q}$, $\tilde{g}$ may produce multiple jets and large $\not{E}$t (R-parity conserved)





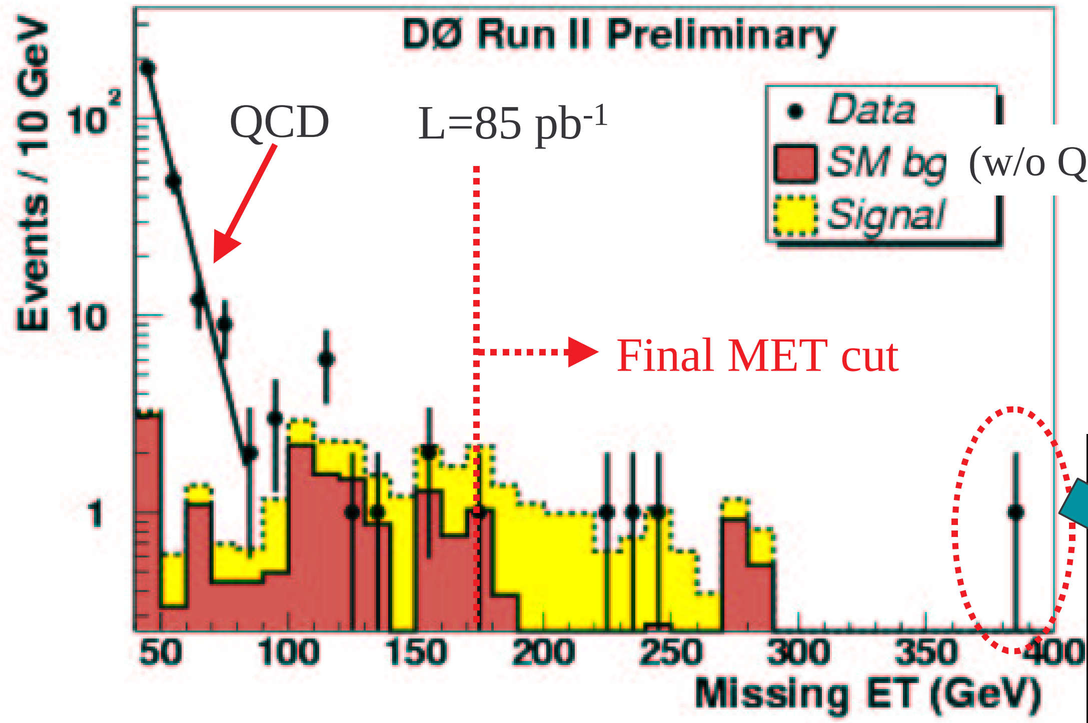
$\tilde{\chi}^0_1$: LSP

- D∅ has performed direct search for $\tilde{q},\tilde{g}$:
  - Using Jets+$\not{E}$t data sample (~85 pb^{-1})
  - Require ≥2 jets (Et_1>60 GeV, Et_2>50 GeV)
  - Jets to be acoplanar , not pointing in same direction as $\not{E}$t (reduce QCD multi-jets)

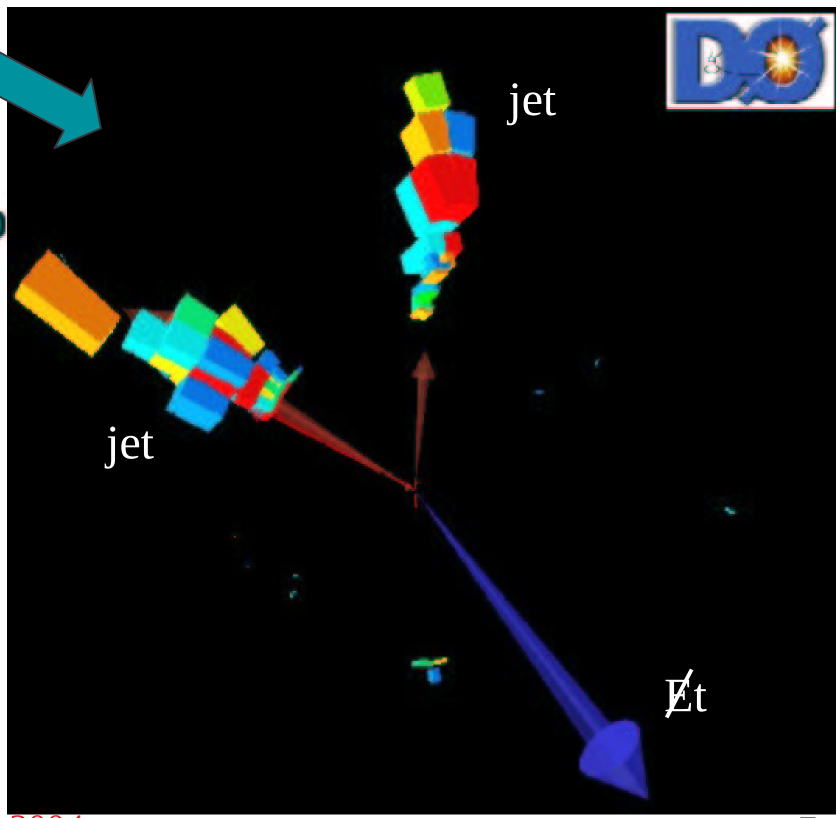
- No isolated leptons (e,μ)
- $\not{E}$t > 175 GeV
- $H_T = \sum_i Et^i_{jet} > 275$ GeV

} Reduce W/Z+jets

Searches for Squarks and Gluinos in MET + Jets



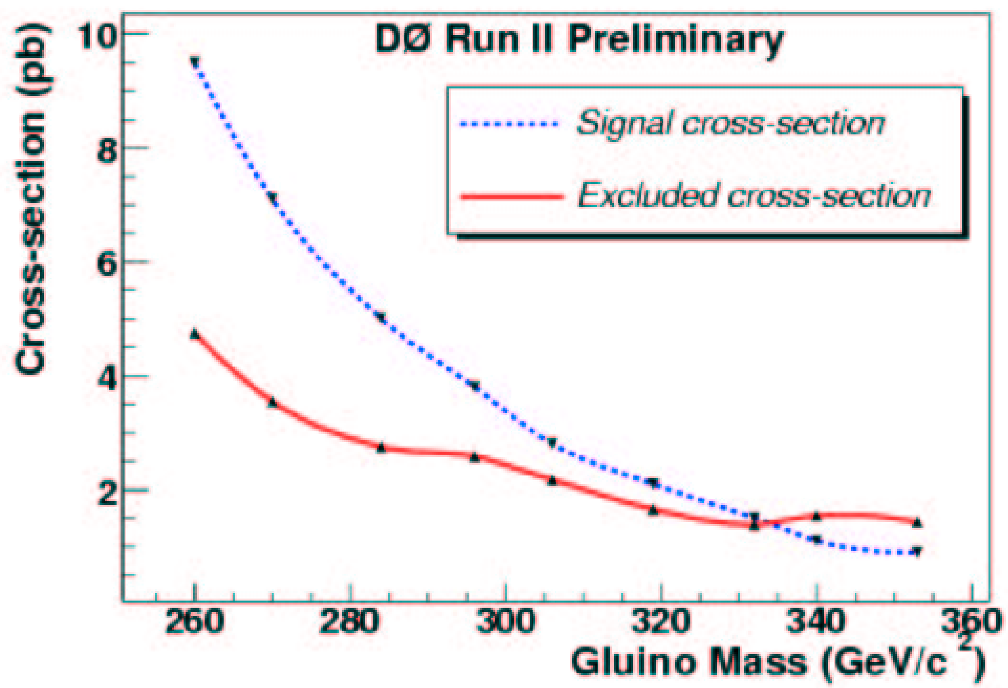
- A large $\not{E}t$ event (w/ 2 large Et jets)
  - $\not{E}t$ = 381 GeV
  - Et_1=289 GeV, Et_2=117 GeV

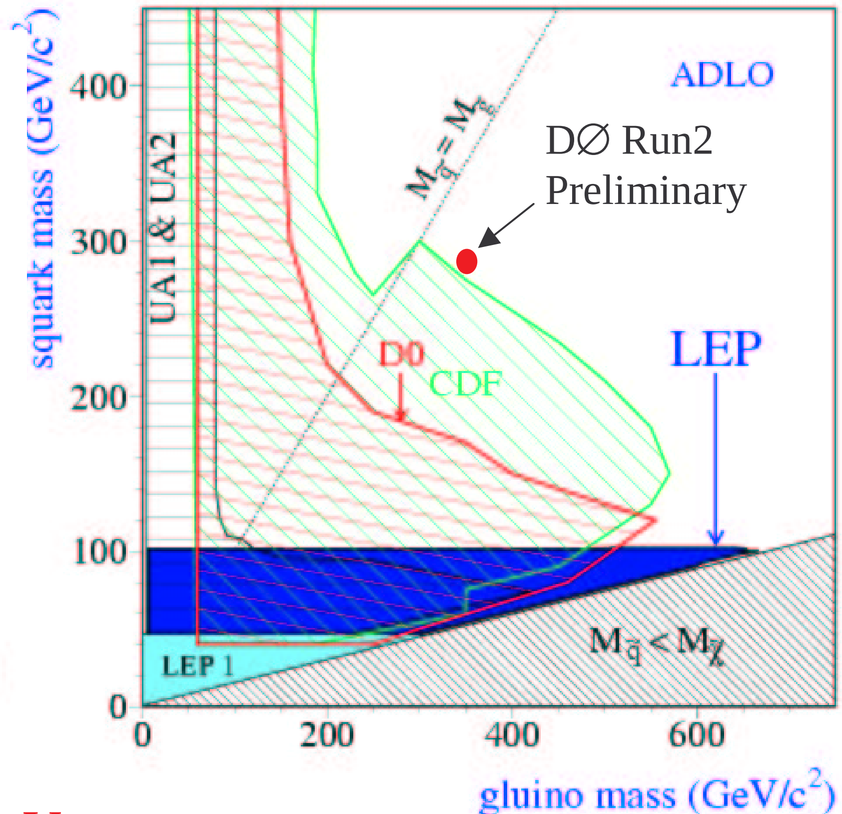


- Observed 4 events, expect 2.7±1.0 (stat)
- SM background mostly from :
  - Z(→νν)+jets
  - W(→τν)+jets

Searches for Squarks and Gluinos in MET + Jets

- Interpret results in mSUGRA scenario :
    - m_0=25 GeV, tanβ=3, A_0=0, μ<0
- Signal efficiency : ~2 - 7 % ($m_{1/2}$ = 100-140 GeV)





- Set gluino (squark) mass limit at 333 (292) GeV

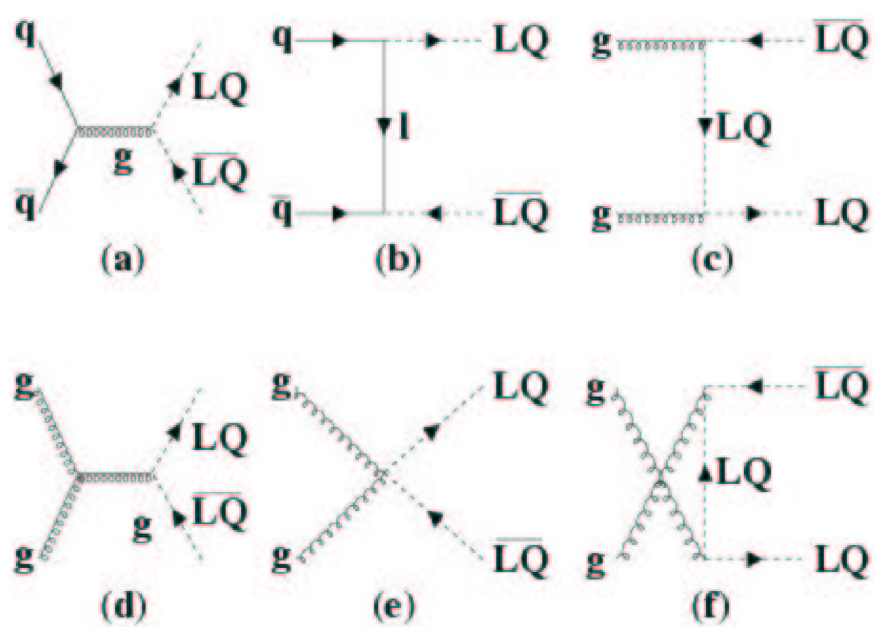
- **Have extended Run1 limit !**

Leptoquarks

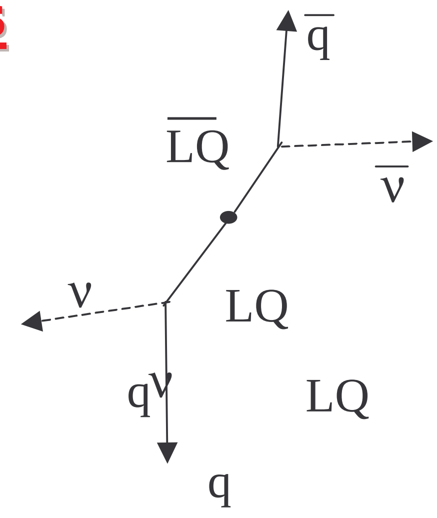
- In SM, symmetry between leptons and quarks
  - Representation of fermion fields under SM gauge groups
  - Replication over 3 family generation
- Could indicate new symmetry between lepton and quarks => new particles
- Leptoquark
  - Appears in several extension of SM : GUTS, Technicolor, Compositeness, SUSY (RPV)
  - Scalar or vector, color triplet bosons
  - Carry L and B, fractional EM charge
  - Assume LQ couples to lepton and quark of same generation to avoid FCNC constraint => 3 generation LQ

- LQ decays :
  - $LQ \rightarrow lq \ \ (l = e,\mu,\tau) \ \ \beta = 1$
  - $LQ \rightarrow \nu q \qquad \beta = 0$

  β:branching ratio to charged lepton
- LQ production at Tevatron:
  - Predominantly pair produced through gluon splitting
  - σ(M=200 GeV) ~ 0.3 pb



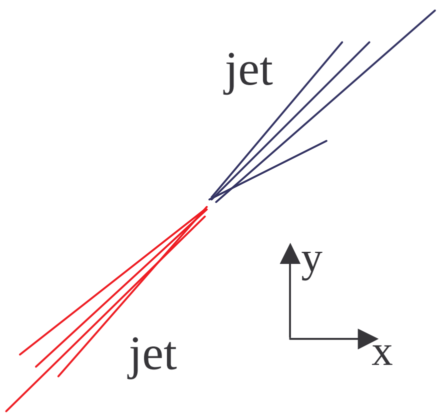
Search for Scalar Leptoquarks



- CDF and D∅ searched for $LQLQ \rightarrow \nu\nu qq$ (β=0)
  - ⇒ 2 jets and large MET

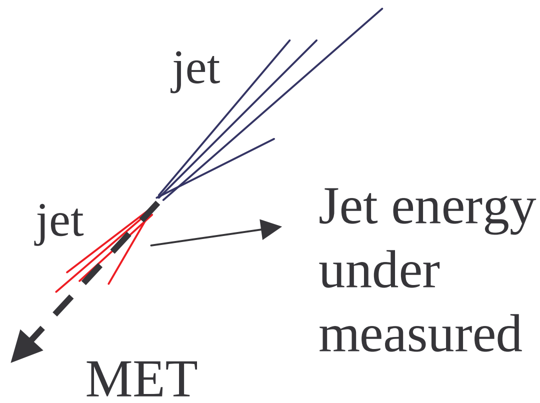
SM processes that have the same signature 2jets+MET in the final states

QCD multi-jets: $p\bar{p} \longrightarrow q\bar{q}$



- 2 jets are back-to-back
- jets balance each other in transverse energy

⇒ small MET



Fake MET due to mis-measured jet energy. MET in the same direction as the jet

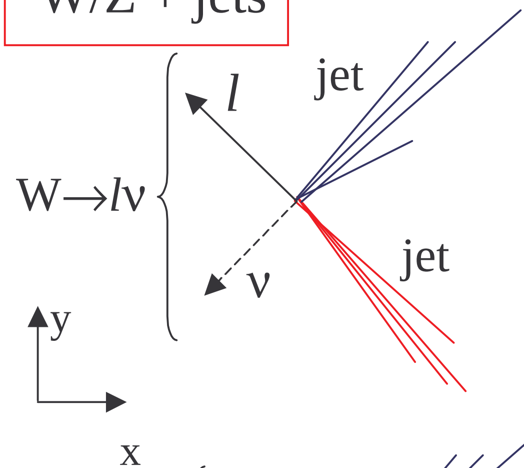
Event selection :

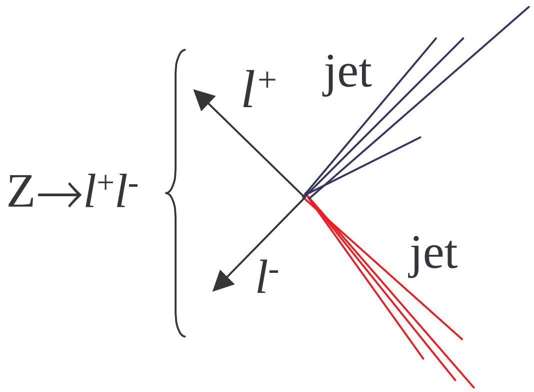
- 2 or 3 jets
- Large MET (> ~60 GeV)
- MET is not in the same direction as any of the jets
- Jets are not back-to-back

Search for Scalar Leptoquarks

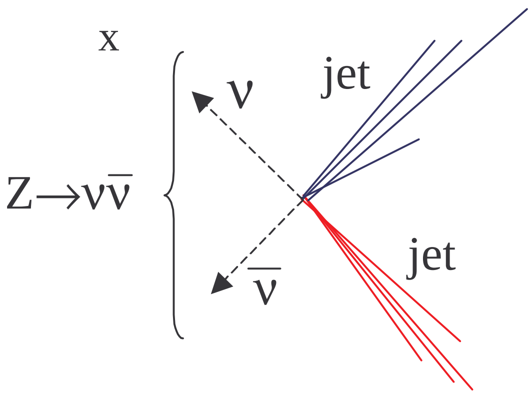
SM processes that have the same signature 2jets+MET in the final states

W/Z + jets





- Reject these contributions by requiring that there is no isolated charged lepton (*e*,μ), or no isolated track in the event



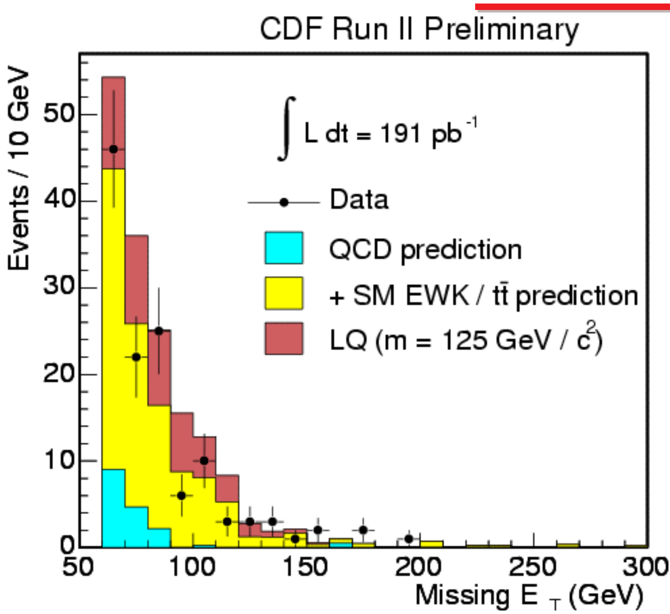
- Has exactly the same signature as the LQ signal
- Can only reduce its contribution based on kinematic cuts (jet Et, MET, …)

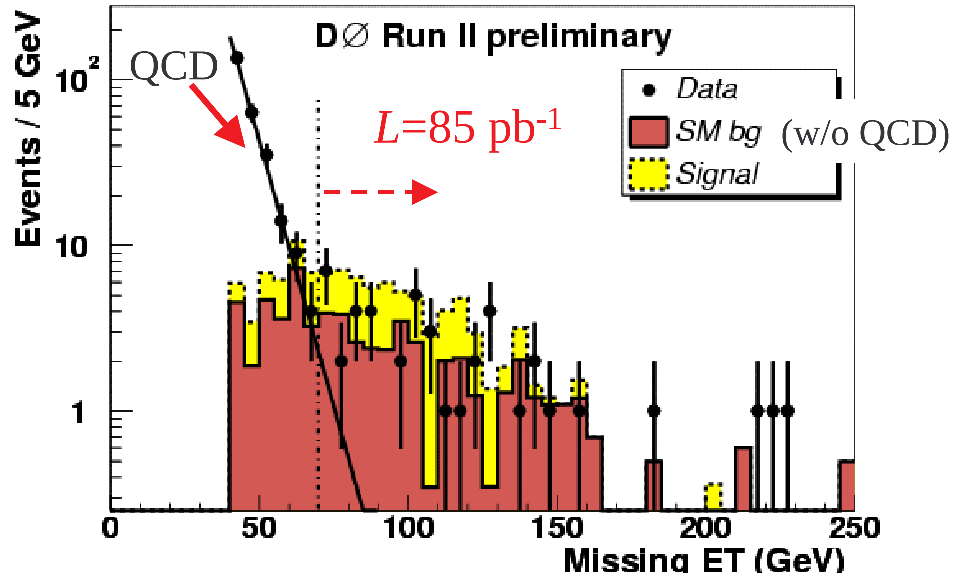
After apply all selection cuts :

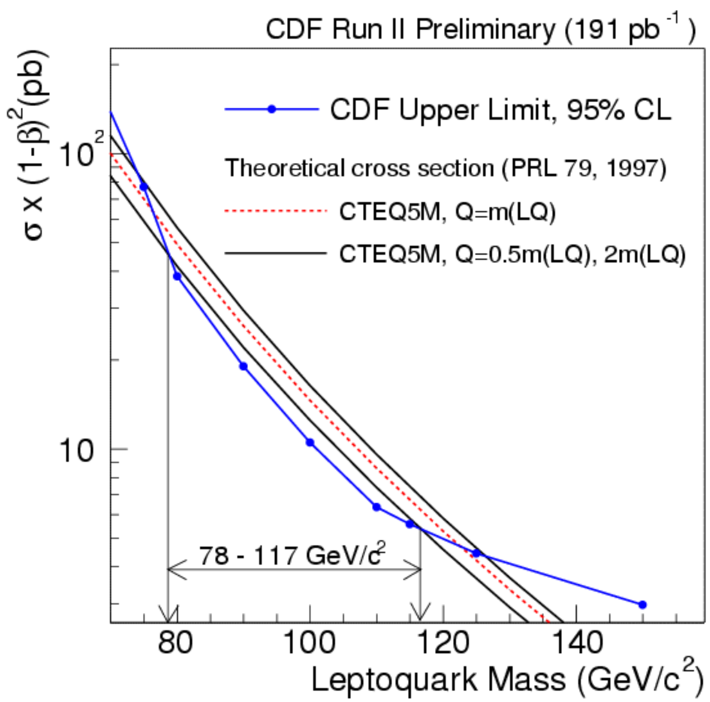
- CDF : Nobs=124, Nexpect=118±14 (L=191 pb^{-1})
- D∅ : Nobs=44, Nexpect=41.5±7.3 (L=85 pb^{-1})

Dominant background from Z(νν)+jets

Search for Scalar Leptoquarks

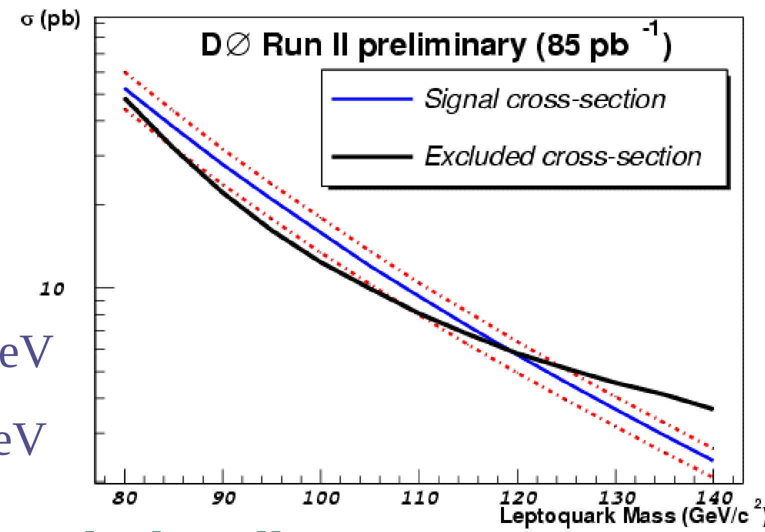






Exclusion :

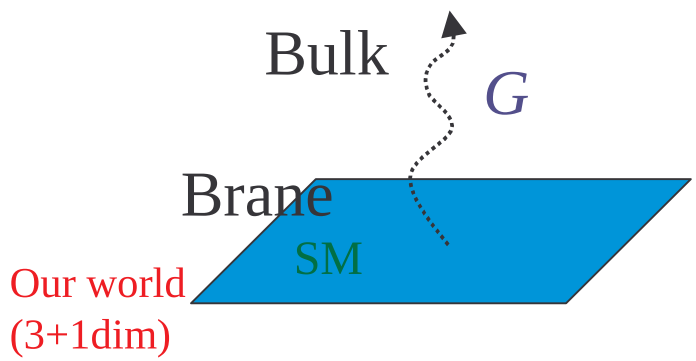
- CDF: 78-117 GeV
- DØ : 85-109 GeV



Results can be applied to all 3 generations since no flavor identification

Searches for Extra Dimensions

- The large gap between EW and Planck scales is assumed to be due to the geometry of the extra dimensions
- The actual gap between EW and the effective fundamental scale is ~ 1 TeV
  - Thus solve the hierarchy problem



- SM particles confined to the brane (our 3 spatial dimension world)
- Gravity propagates in the whole D-dim space
- Gravity is weak on brane since it acts in a more extended space than the brane

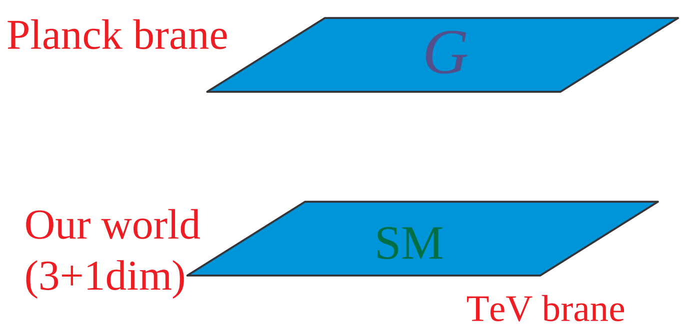
Large Extra Dimensions (ADD) Model

("ADD" => N. Arkani-Hamed, S. Dimopoulos, and G.Dvali)

- $M_{Pl}^2 \sim R_c^n M_D^{2+n}$
  - M_{Pl}: Planck scale
  - R_c : radius of ED
  - M_D: new effective fundamental scale
  - n : # extra dimensions

- Large extra dimension : R~1mm for n=2, $M_D \sim$ 1TeV
- Kaluza-Klein states of Graviton is dense and evenly spaced
  - Mass spectrum appear continuous
  - Interfere with SM scattering amplitude

Randall-Sundrum (RS) Model



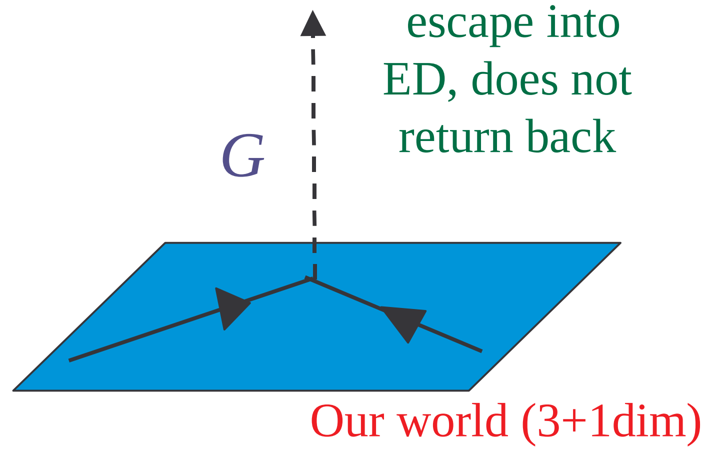
- Two branes
  - SM confined in one brane, Gravity localized in the other brane
- Kaluza-Klein states of Graviton are widely and unevenly spaced
  - Can resolve resonances

Searches for Extra Dimensions at Tevatron in Direct *G* Emission

• **Direct G emission :**

$$q\,\bar{q} \rightarrow \gamma G$$ Photon +MET

$$q\,\bar{q} \rightarrow Gg$$
$$qg \rightarrow Gq$$
$$gg \rightarrow Gg$$
jet+ MET



• DØ performed search for ED in the MET+jets final state

  • Data sample : 85 pb^{-1}

Event Selection :

• Large MET (MET > 150 GeV)

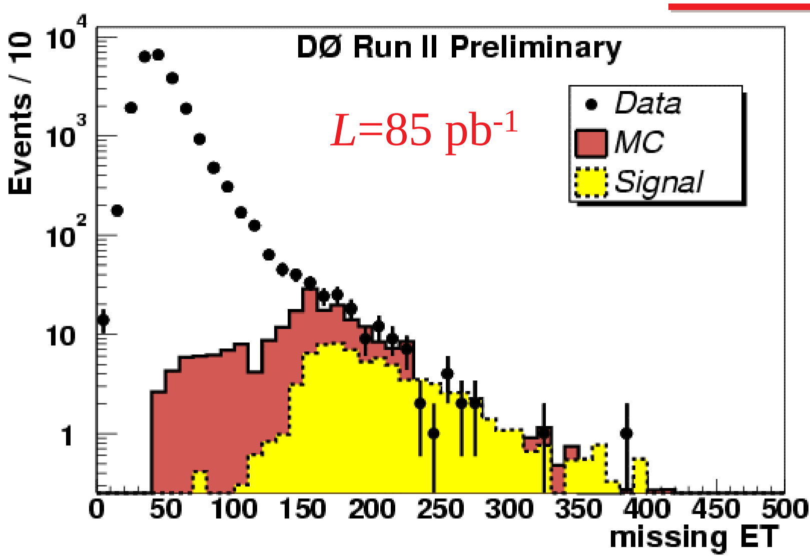
• A energetic central jet (Et>150 GeV)

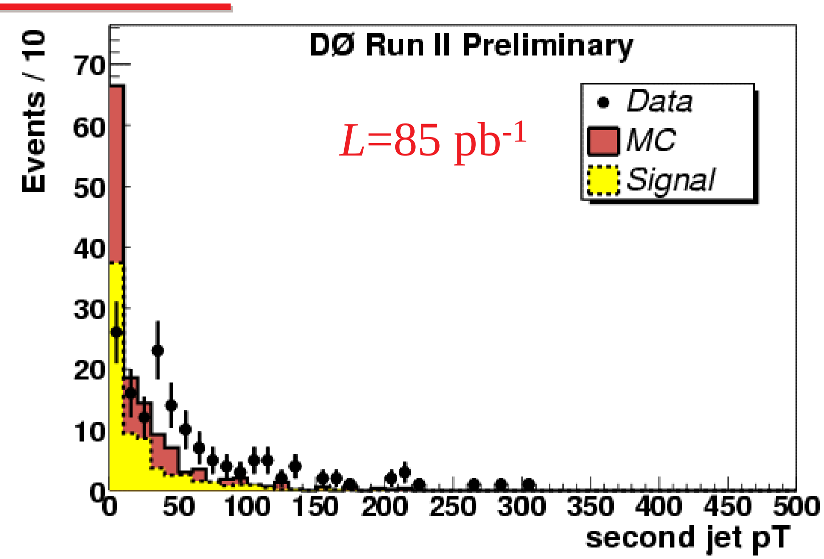
• Veto events with isolated leptons (e,μ)

• 2^{nd} leading jet Et<50 GeV

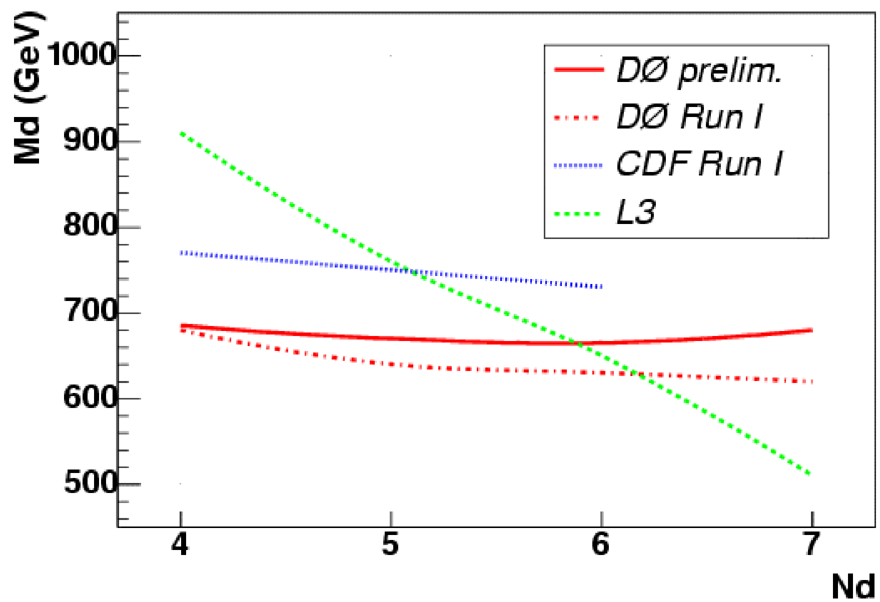
• MET should not point in direction of jets (min. $\Delta\phi$(jet,MET) > 30 deg)

Searches for Extra Dimensions at Tevatron in Direct *G* Emission





- Analysis sensitive to the understanding of calorimetry
  - Largest uncertainty is in the jet energy scale (signal ~20%, bg ~ +50%, -30%)
- Nobs=63
- Nexpect=100.2±6.2(stat)±7.5(syst from cross section)
- Obtain lower limit on the effective fundamental scale M_D



Other Searches in MET+Jets

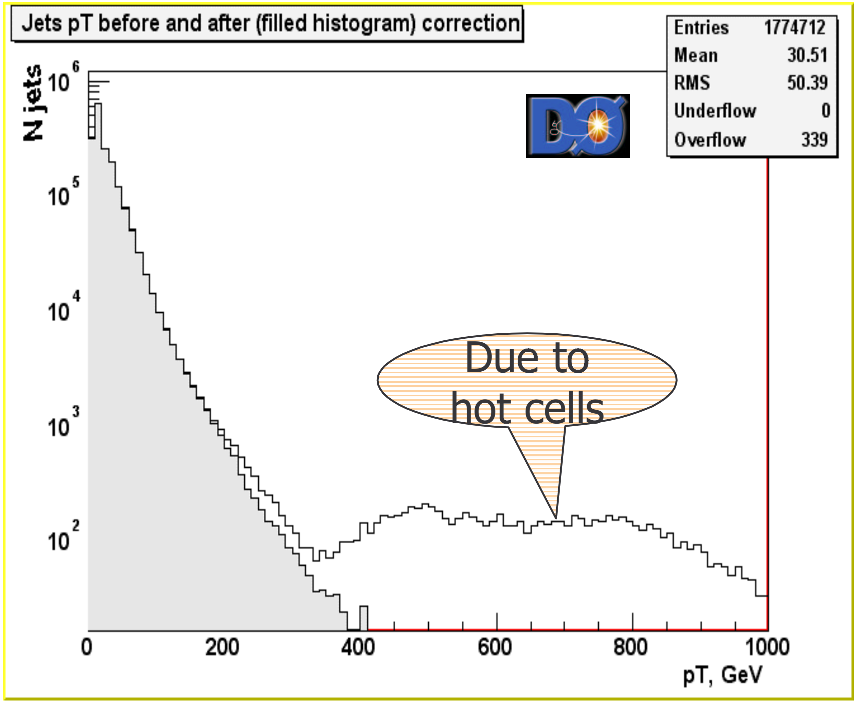
- For results on searches for sbottom in gluino decays in MET+Jets signature (CDF) : please refer to Daniella Bortoletto's talk on Friday

Experience from Tevatron

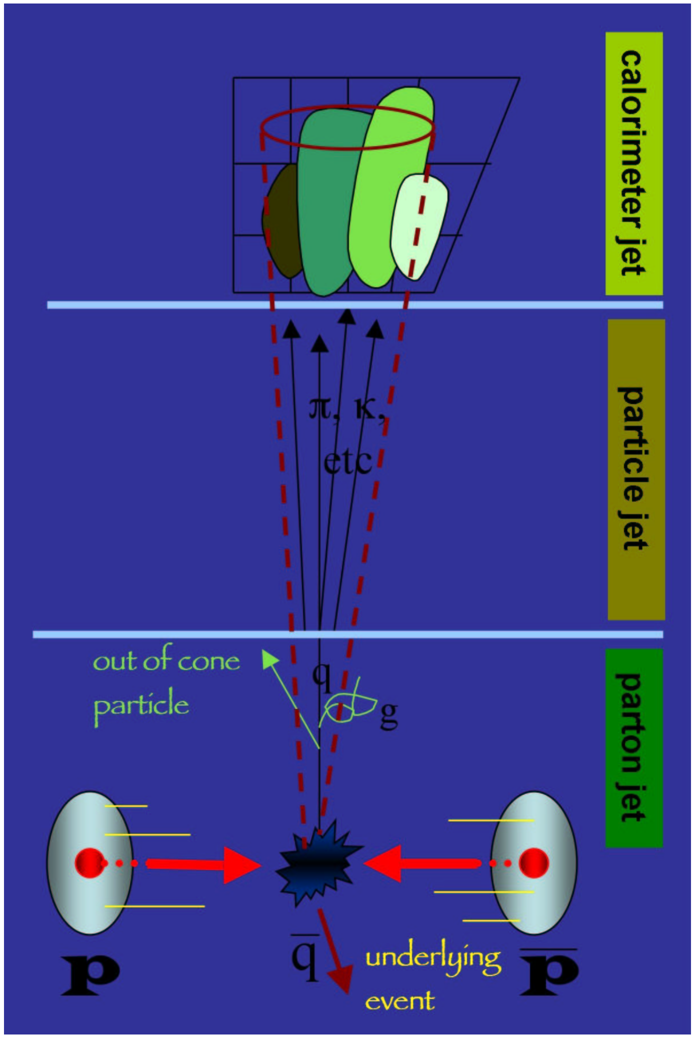
- To perform searches for new physics in MET+jets:
  - Excellent understanding of the EW processes (W/Z+jets)
    - Good source of large MET and jets, main SM background to new physics searches in MET+jets
  - One needs to have good measurement of quantities related to jets and MET
    - Largest uncertainty in current Run2 searches in MET+jets is the uncertainty on the signal and background estimate due to jet energy scale uncertainty (~10% - 50%)

Factors affecting Jets and MET measurement :

- Calorimeter performance
  - Large geometric coverage
  - Uniform response
    - Monitor channels' gain variation !
  - Low "noise"
    - Hot channels can fake jets and high MET
    - Low noise allow lower energy threshold on the calorimeter channels for jet and MET measurement
  - Few "dead" region (e.g. gap between detectors)
    - Jet energy mis-measured, events may appear as high MET if jet enters this region
    - May veto event if jet enters this region
    - Need to fix "holes" (due to broken channels) quickly



Need Good Data Quality Monitoring !!!



+ Right Simulation of Calorimeter Response !!!

Jet Calibration (Jet Energy Scale) :

- Correction from calorimeter-jet to parton-jet
  - Non-uniformity in calorimeter response (cracks, gains,…)
  - Underlying events
  - Multiple interactions
  - Energy outside jet cone
- Apply jet correction to correct jet energy and also MET

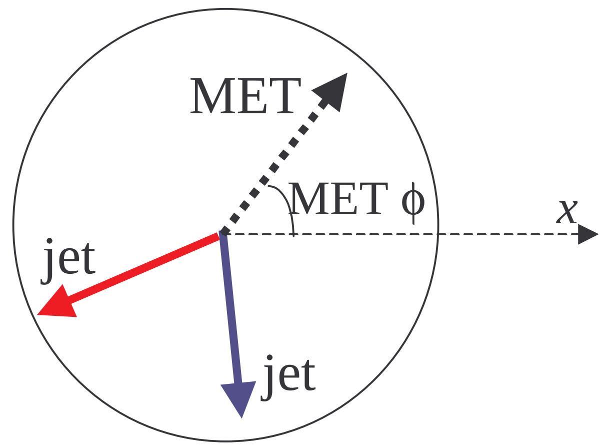
Proper Operation of Other Sub-detectors

- Muon systems
  - Muon deposits little energy in calorimeter ⇒ need to correct MET due to muon
  - Need to reconstruct and Id muons
- Tracking systems
  - Determine primary interaction position, for proper jet Et and MET measurement
  - Determine # of multiple interactions

Other Factors affecting Jet and MET Measurements :

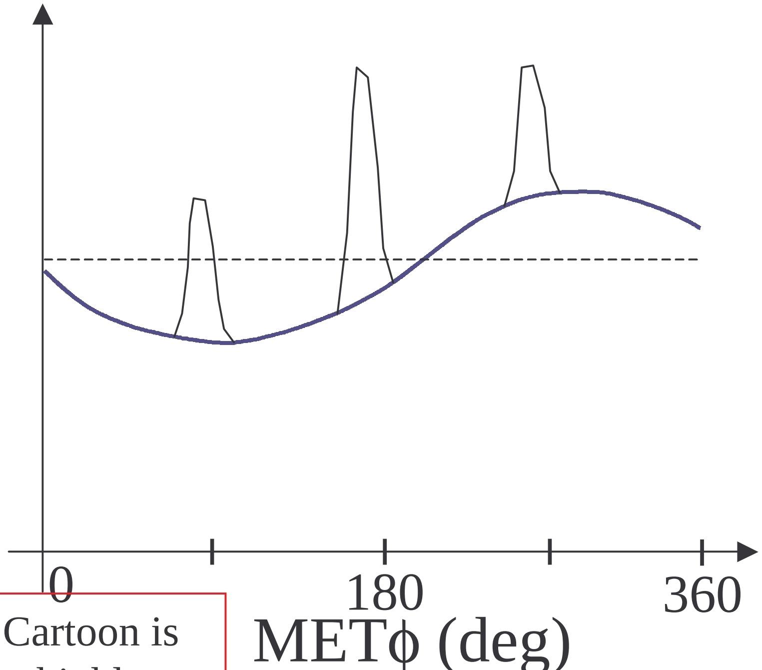
- Beam halo
- Beam losses
- Cosmic

Can fake as jets and events with large MET



Experience from CDF at Beginning of Run 2 :

- First look at MET data

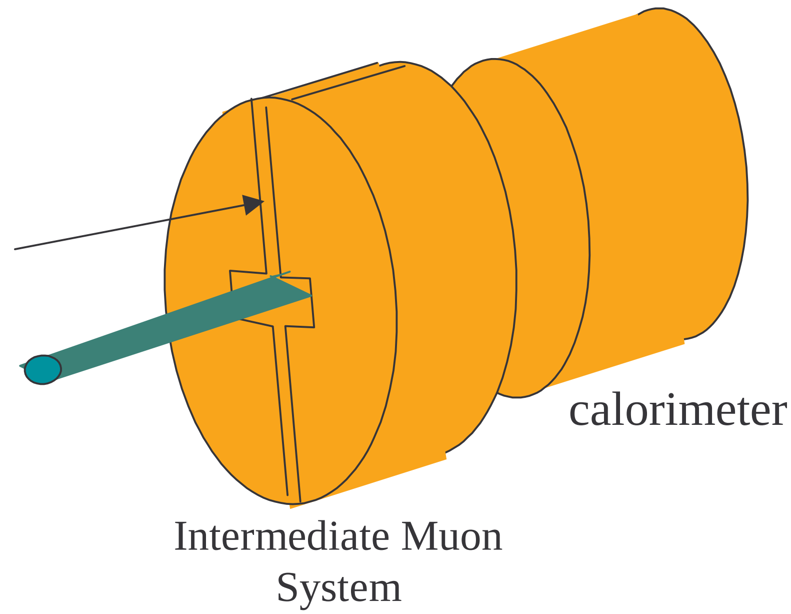


Cartoon is highly exaggerated

- "Sine" modulation is found due to beam offset in X-Y
  - Before Sept 2003: (Vx,Vy) ~ (-1mm, +4mm) at Vz=0
  - Reconstruct MET using (Vx,Vy)=(0,0)
  - Almost no modulation for hard interaction events (e.g. high Et jet in central region)
  - Now the collision point is closer to (Vx,Vy)=(0,0) ⇒ smaller modulation

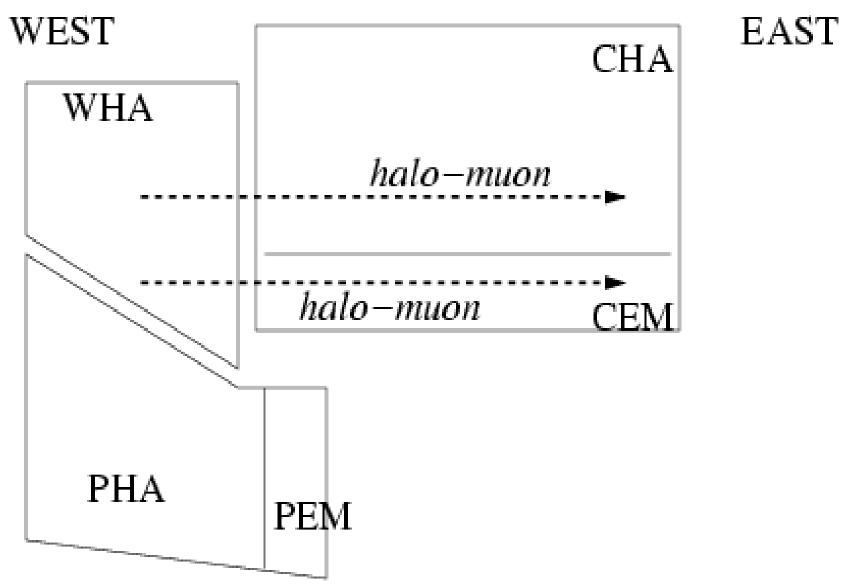
Peaks at MET ϕ = 90 and 270 deg

- Due to beam losses
- ~4 cm gap in the Intermediate Muon System (act as a shielding wall)
- More shieldings had been added to reduce this effect



Peaks at MET ϕ = 180 deg

- Due to halo muons produced by beam halo hitting the CDF roman pots
  - Observed relative height of peak increases when roman pots move closer to beam
  - halo muon traverses horizontally through the calorimeter, depositing energy in either EM or HAD only
  - Overlapping of halo muons in bunch crossings with hard interactions is low ($\leq 10^{-6}$) (CDF note 5926)

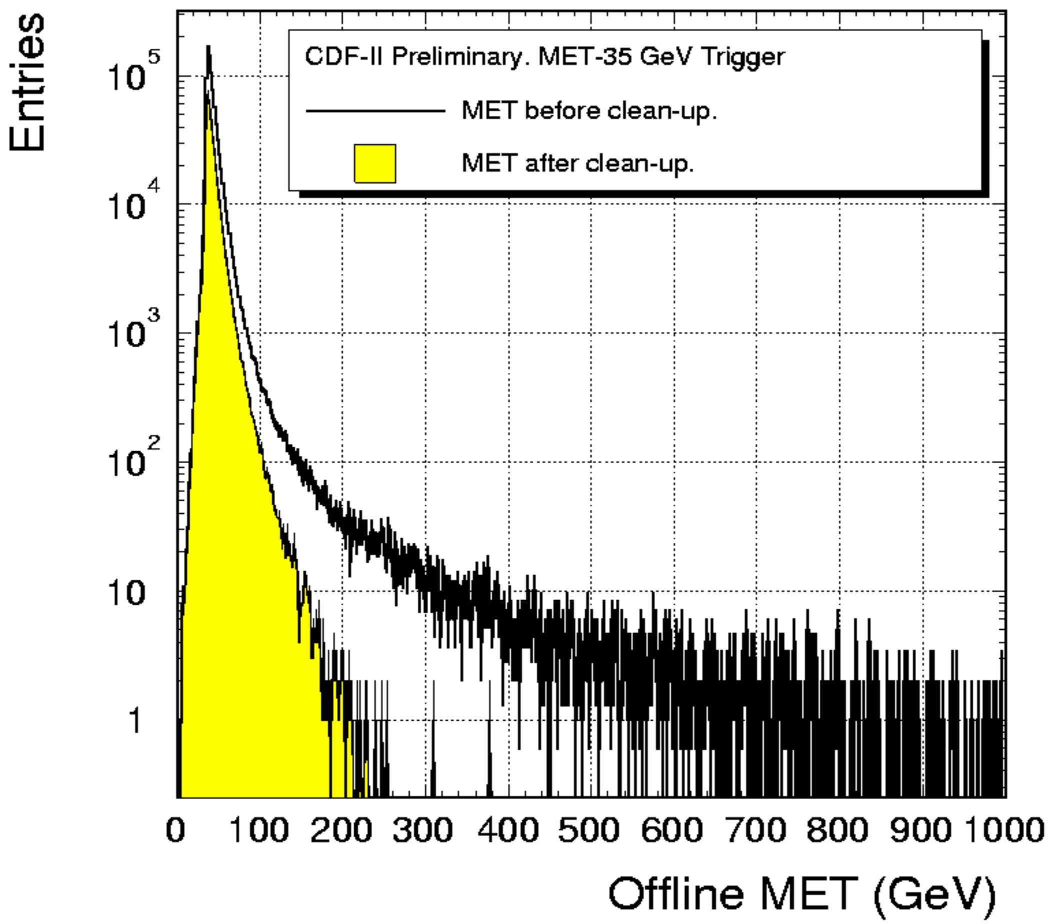


Develop Offline Algorithms to Clean Up Non-Collision Background Events

- $\geq$ 1 central jet
- Require reconstructed primary vertex
- Apply event quantity cuts :

  - $$\frac{\text{Total Cal EM energy}}{\text{Total Cal energy}} > 0.1$$

  - $$\frac{\sum_i Pt_i(track)}{\text{Total Cal energy}} > 0.1$$



Monitoring Beam Background

- High beam background could also create other problems to the experiment:
    - Damaging power supplies
    - High current in the chambers
- CDF installs several scintillator counters to monitor beam background, and provide real-time feed back to the accelerator division

Summary :

- Since the starting of Run2 CDF and D∅ have worked to understand their high MET data, and have now control over the conditions for good jets and MET measurements
- Using ~200 pb^{-1} of Run2 data both experiments have not yet observed hints of new physics
  - However we will have ~20X more data to come – STAY TUNED !
- LHC should have a good chance of discovering new physics in the MET+Jets channel
  - The experiments should prepare the tools to allow them have a quick understanding of their detectors, and quality of data
  - Understand Standard Model backgrounds
  - Pay attention to beam related backgrounds, and have a quick channel of communication with the accelerator people