Jets and Missing ET in New Physics Searches

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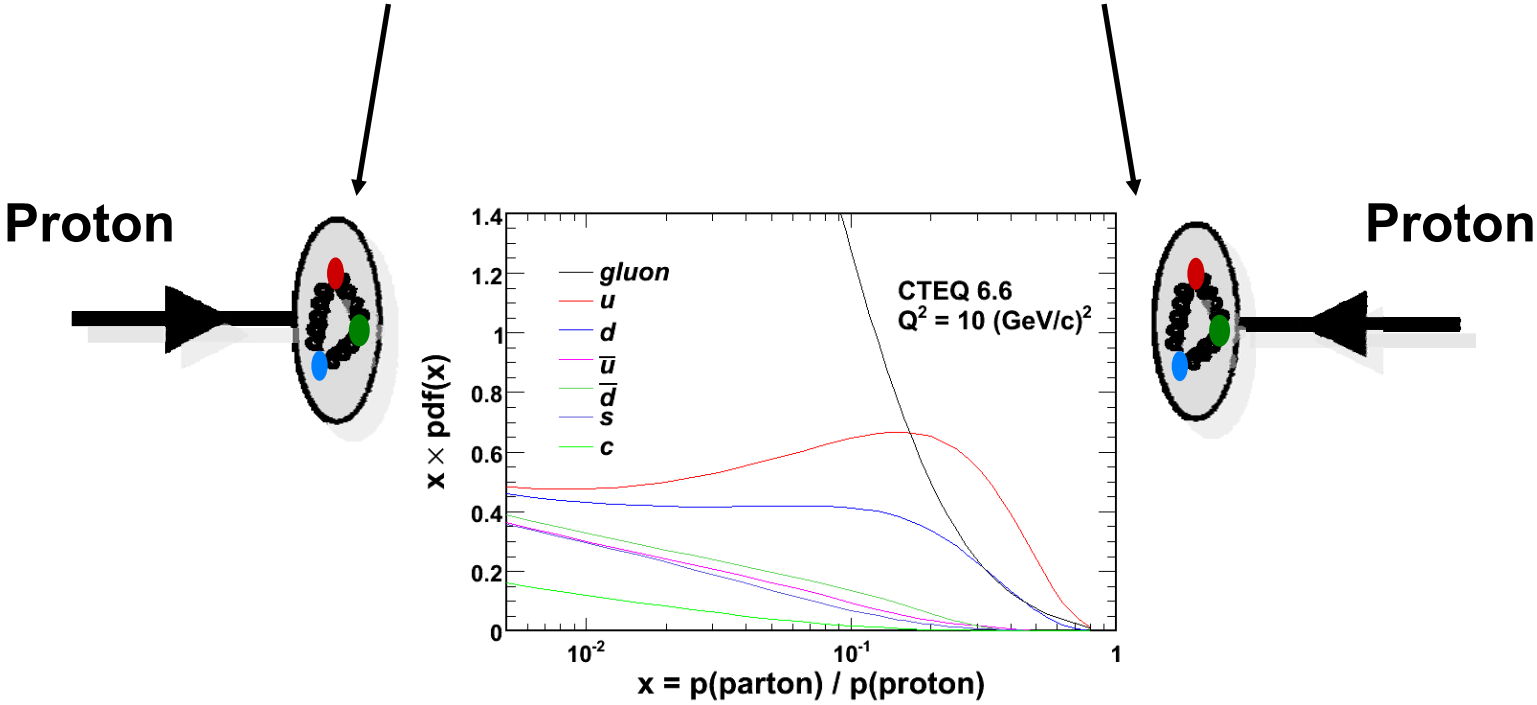
Jets

- Jets are the clusters of particles originating from the fragmentation of hard-scattered partons.
- So, jets are the experimental signatures of the quarks and gluons.
- Jets are copiously produced from the Standard Model processes

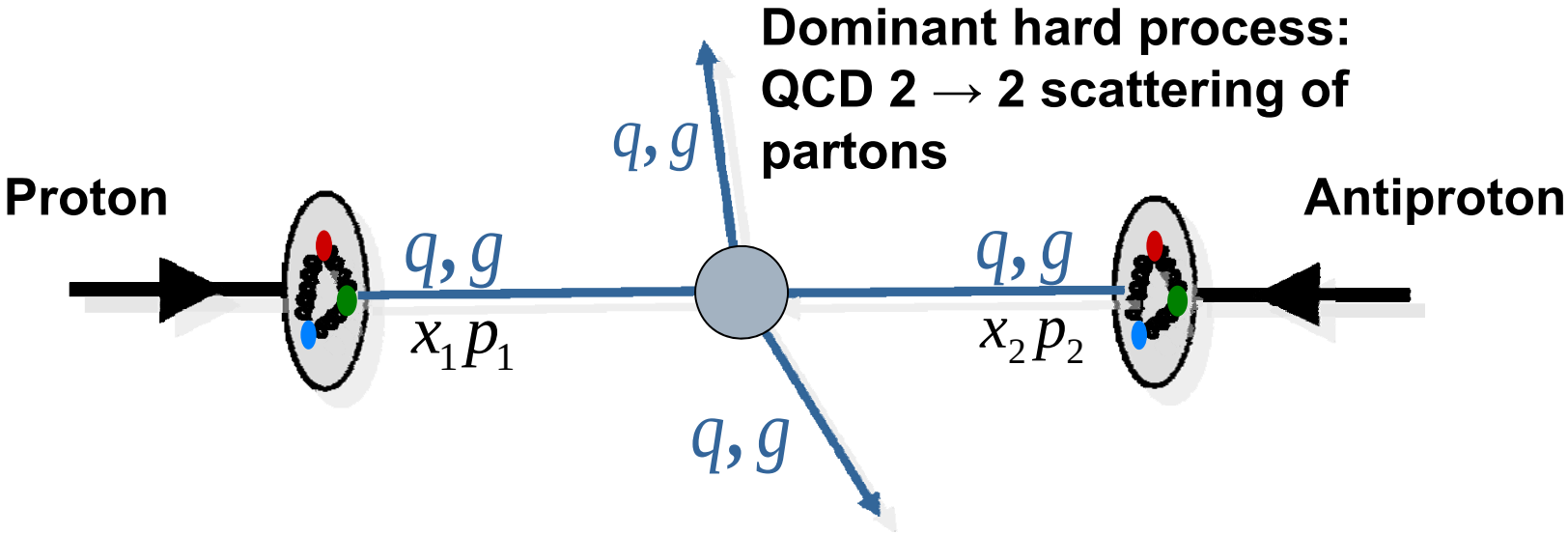
Proton-Proton Collision

Proton-Proton Collision

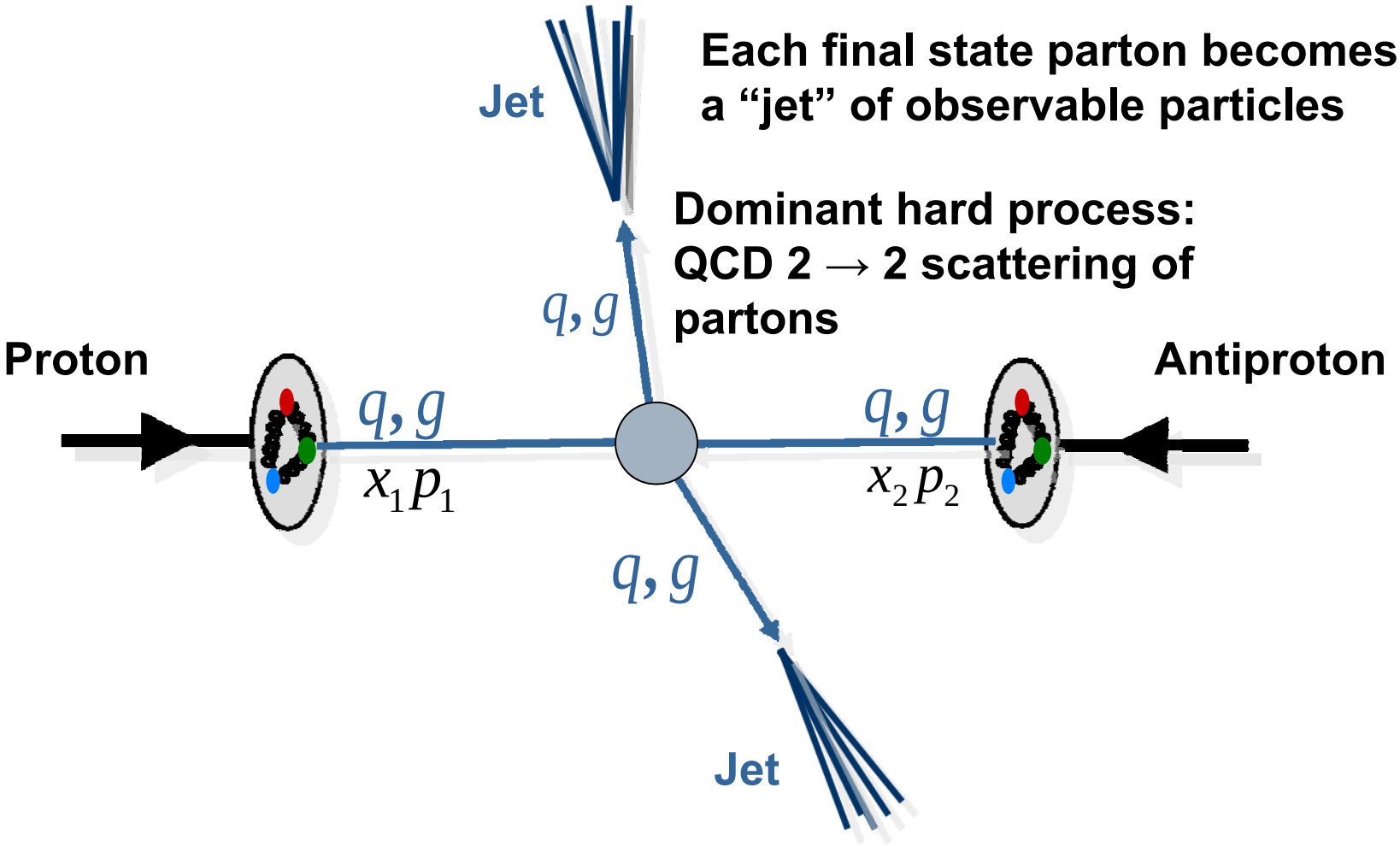
Partons inside proton:
Parton Distribution Functions (PDF's)



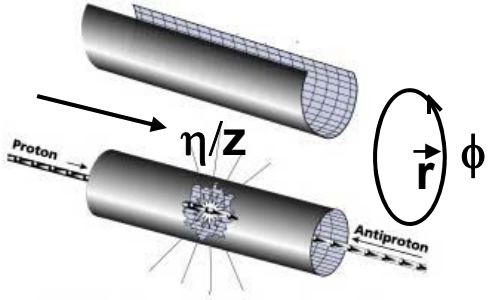
Proton-Proton Collision



Proton-Proton Collision

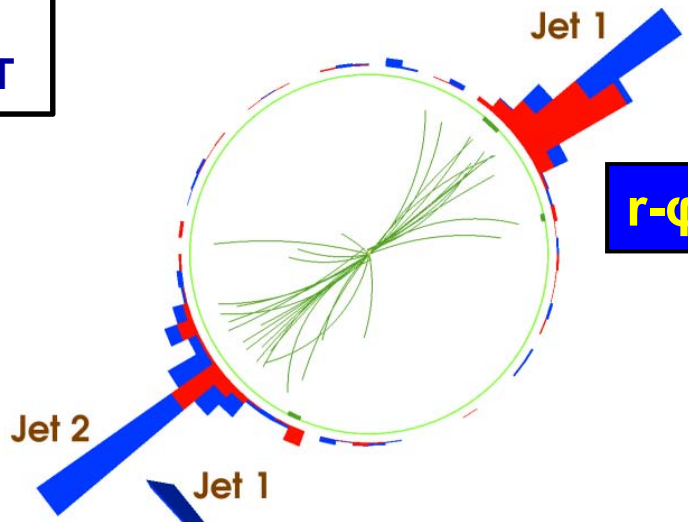


Jets

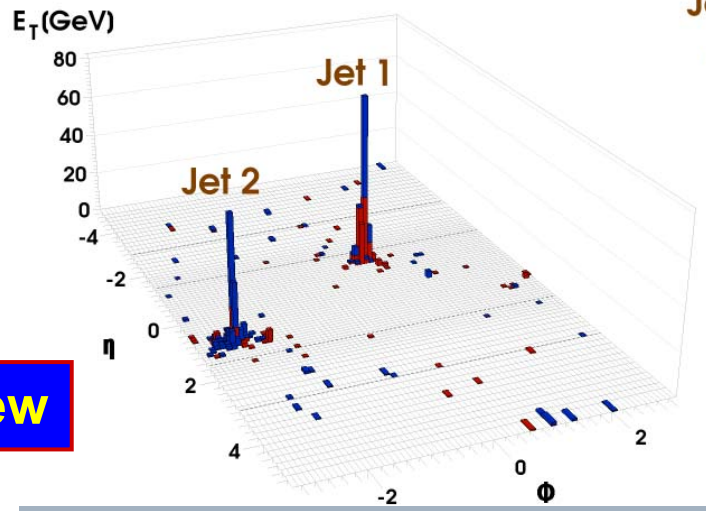


CMS Experiment at LHC, CERN
Run 133450 Event 16358963
Lumi section: 285
Sat Apr 17 2010, 12:25:05 CEST

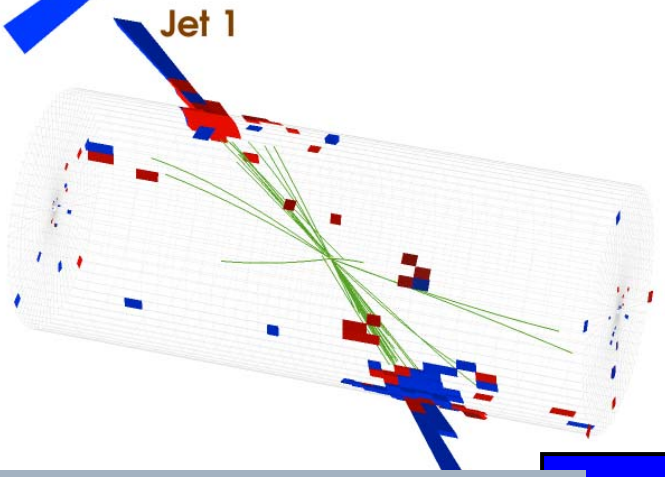
Jet1 p_T : 253 GeV
Jet2 p_T : 244 GeV
Dijet Mass : 764 GeV



r-φ view



η-φ view

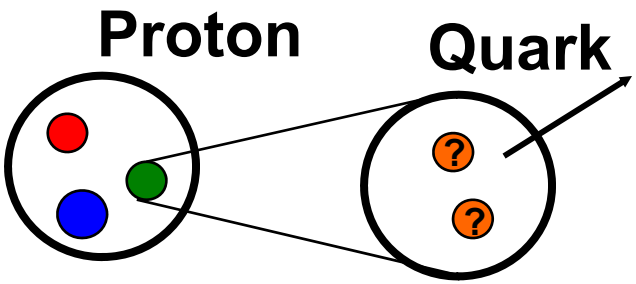


-z view

Jets are rec

We already see energetic jets at the LHC

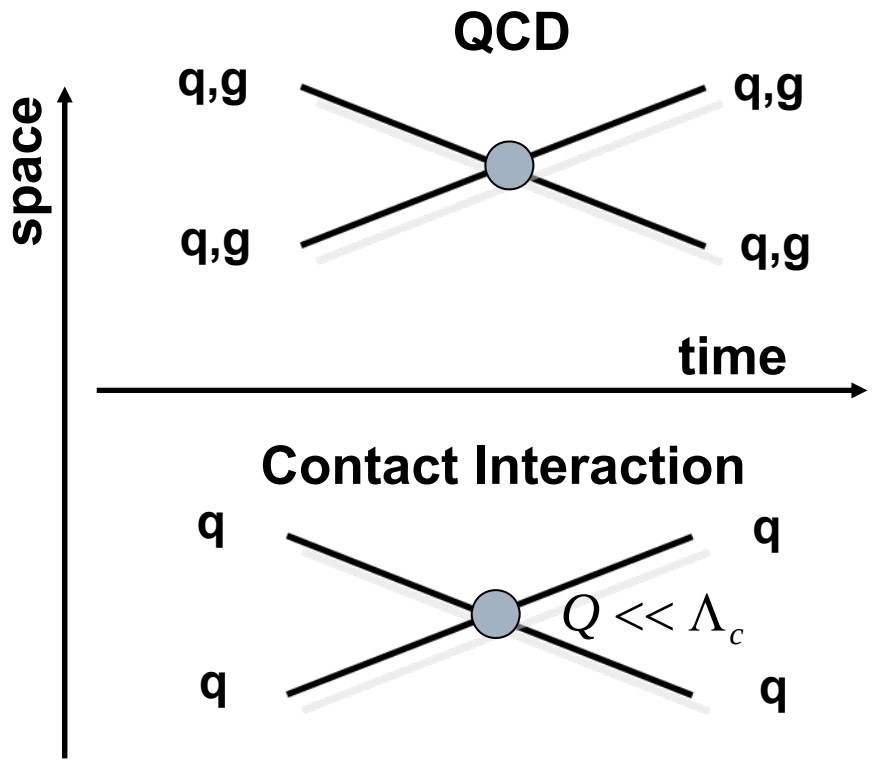
New Physics Searches with Jets (1)

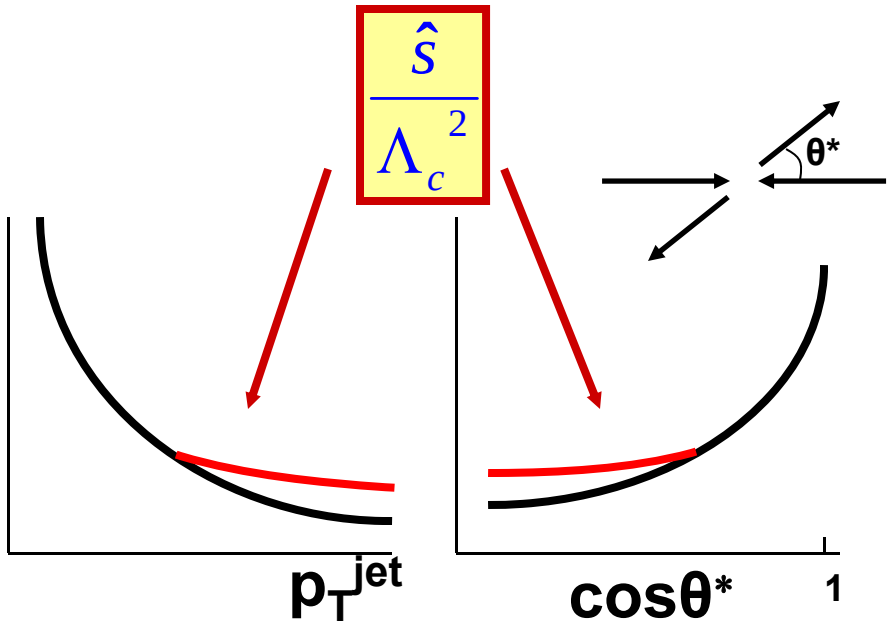


Preons?

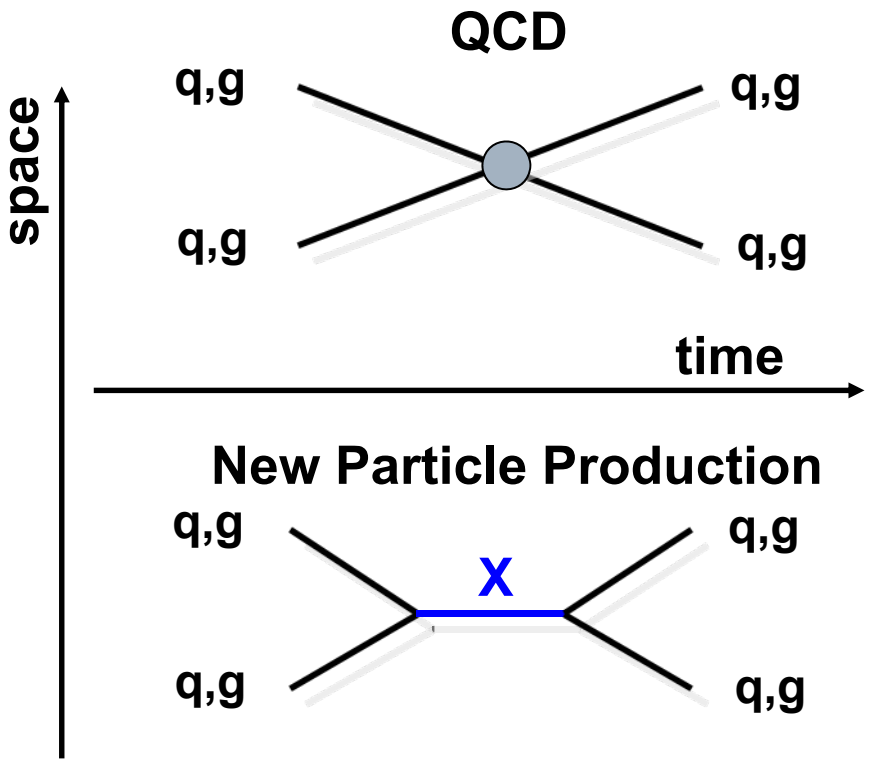
$r_{preon} \sim \hbar c / \Lambda_c$ **(Λ_c=4 TeV, r ~ 5 ·10^{-20} m)**

Existence of substructure below Λ_c appears as contact interactions

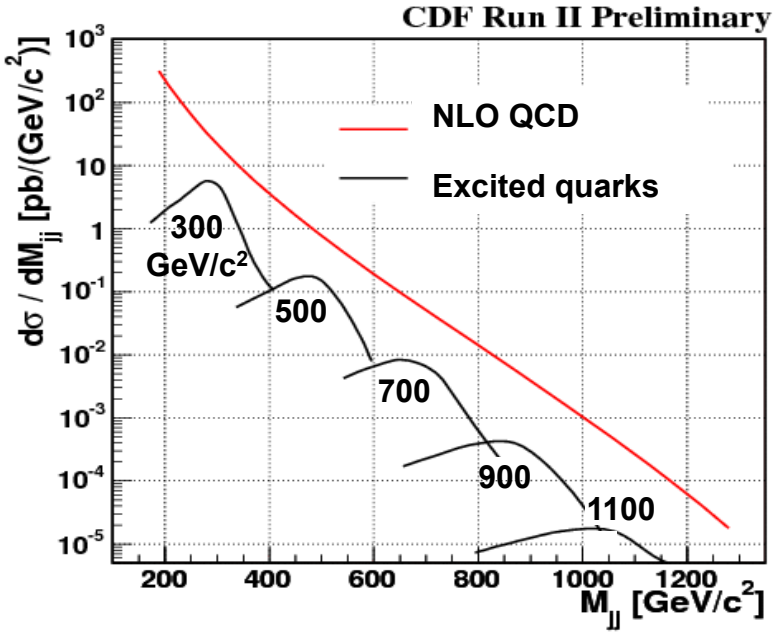


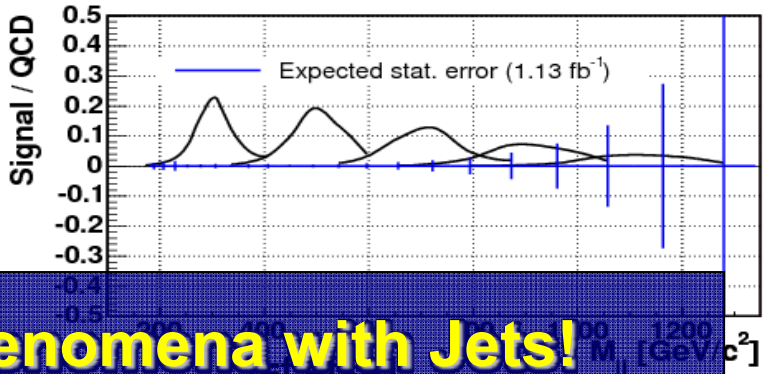


New Physics Searches with Jets (2)



→ dijet mass resonances





Many new physics models predict new particles decaying into dijets!

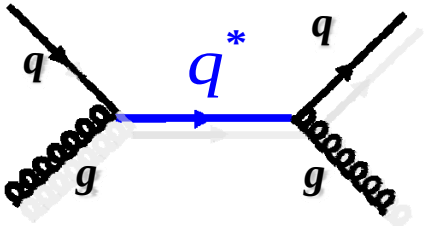
Search for new physics phenomena with Jets!

Dijet Resonance Models

- Dijet Resonances are predicted in many new physics models.

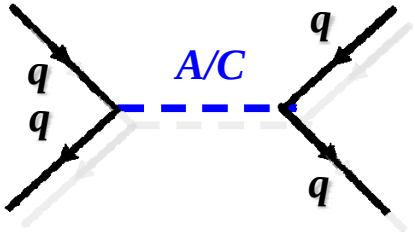
Compositeness?

Excited quark



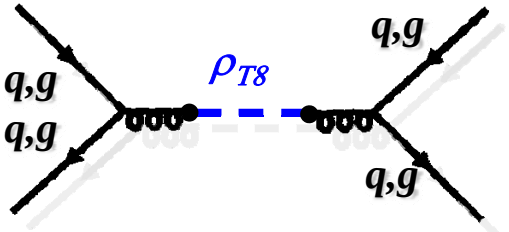
Extra Color Force?

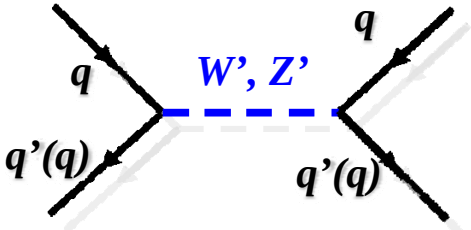
Axigluon/Coloron



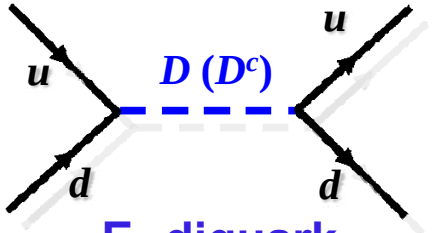
Technicolor?

Techni-ρ

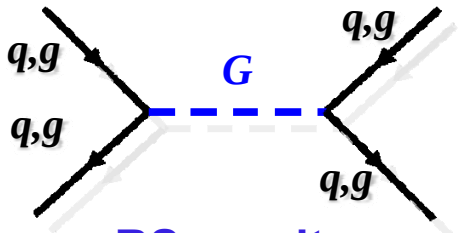




W' & Z'



E_6 diquark



RS graviton

Grand Unified Theory?

Superstrings & GUT ?

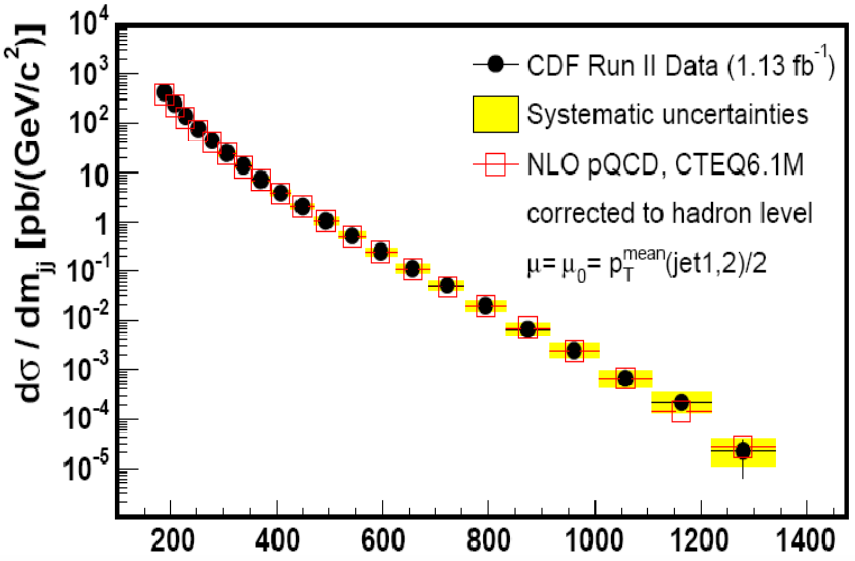
Extra dimensions?

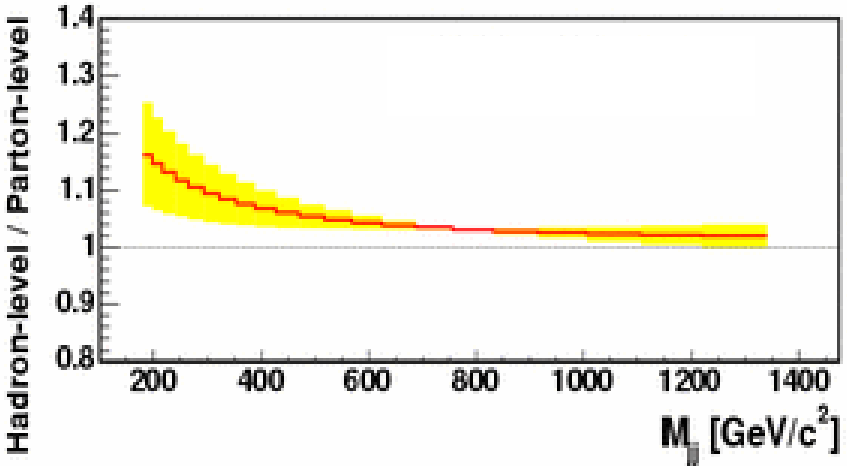
Searches at the Tevatron

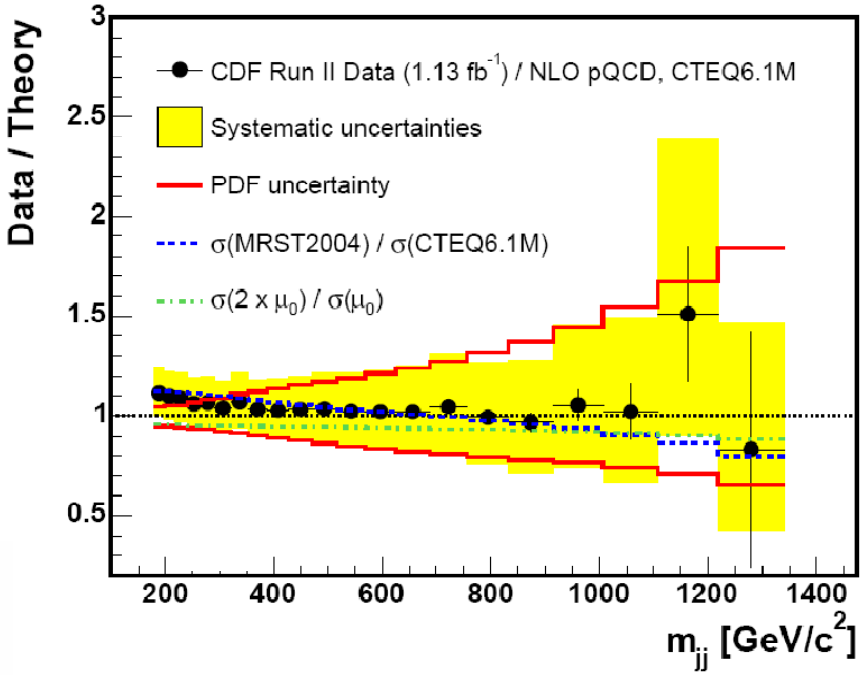
- Forming dijet mass spectrum
  - Correct individual jet 4-momenta by the jet energy corrections
  - Form the dijet mass from the leading 2 jets and form the spectrum
  - Make a "unfolding" correction to correct for the smearing of the dijet mass measurement – consistent with the QCD prediction?
- Search for resonant structure over a smooth function fit
  - BG is dominated by QCD dijets
  - Model QCD dijet mass spectrum by a smooth functional form fitted to data
    - Theoretical predictions on QCD dijets have large uncertainties
  - Use a function which fits the predictions from Pythia, Herwig event generators, & (N)LO perturbative QCD calculations .

$$\frac{d\sigma}{dm} = p_0(1-x)^{p1} / x^{p2+p3\log(x)}, \quad x = m/\sqrt{s}$$

Dijet Mass Differential Cross Section



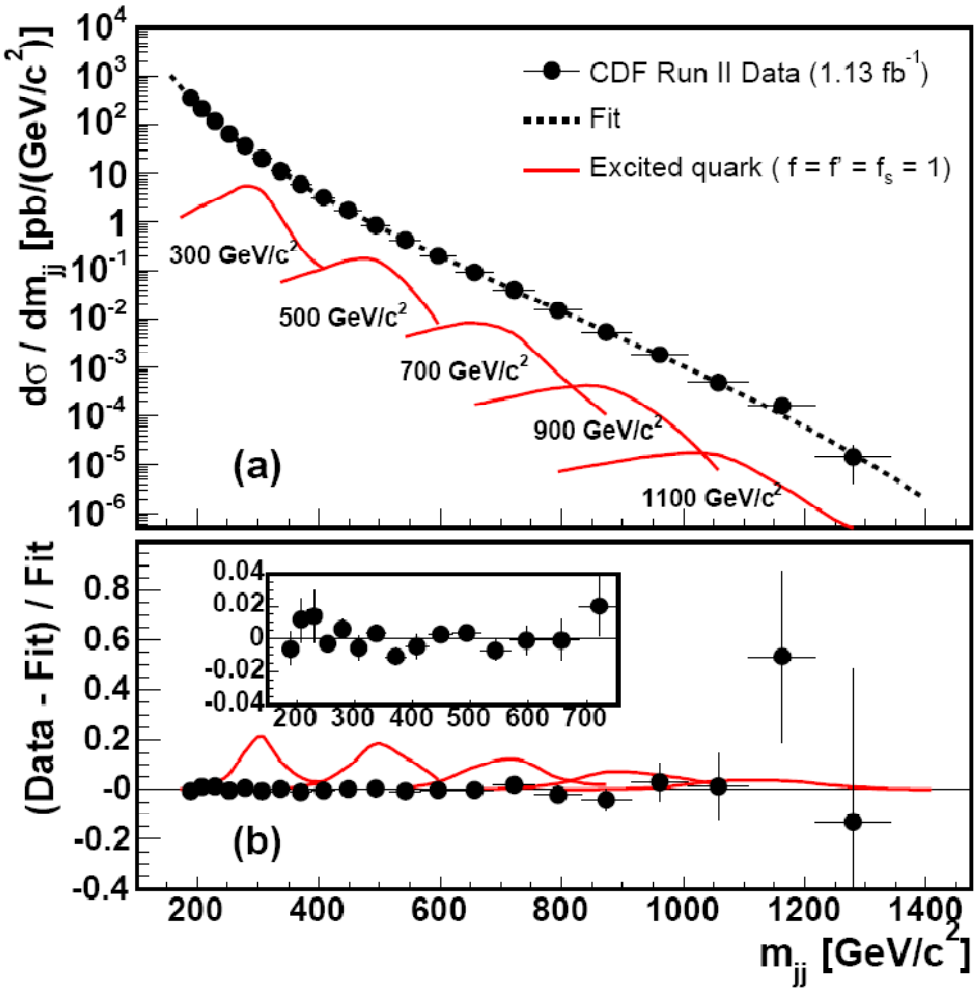




Consistent with NLO QCD predictions (χ^2/n.d.f.=21/21)

Phys. Rev. D, 79. 112002

Search for Resonances



No convincing resonance found in the measured dijet mass spectrum (x^2/n.d.f.=16/17).

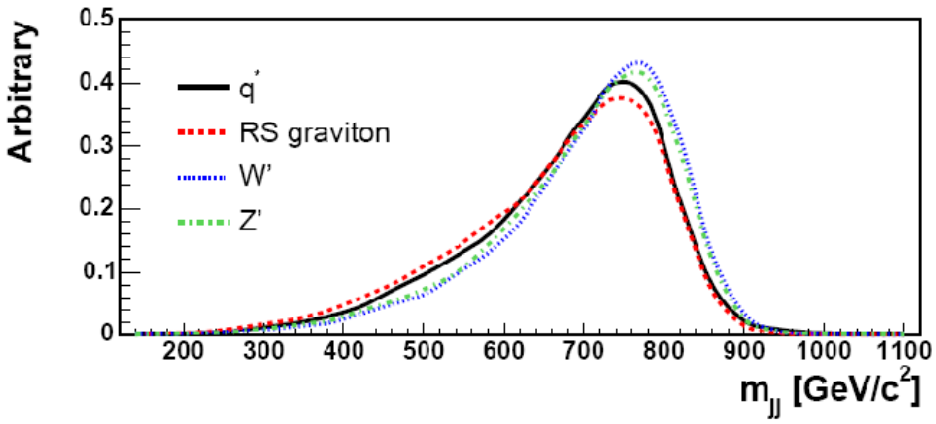
- Set 95% C.L. upper limits on new particle production

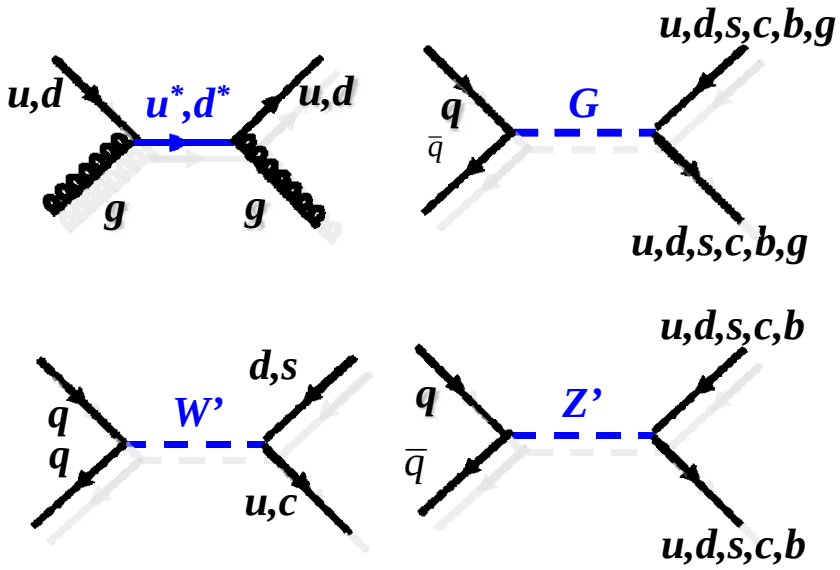
Dijet Resonance Models

- Dijet mass distributions for
  - Excited quark (q*)
  - RS graviton (G)
  - W'
  - Z'

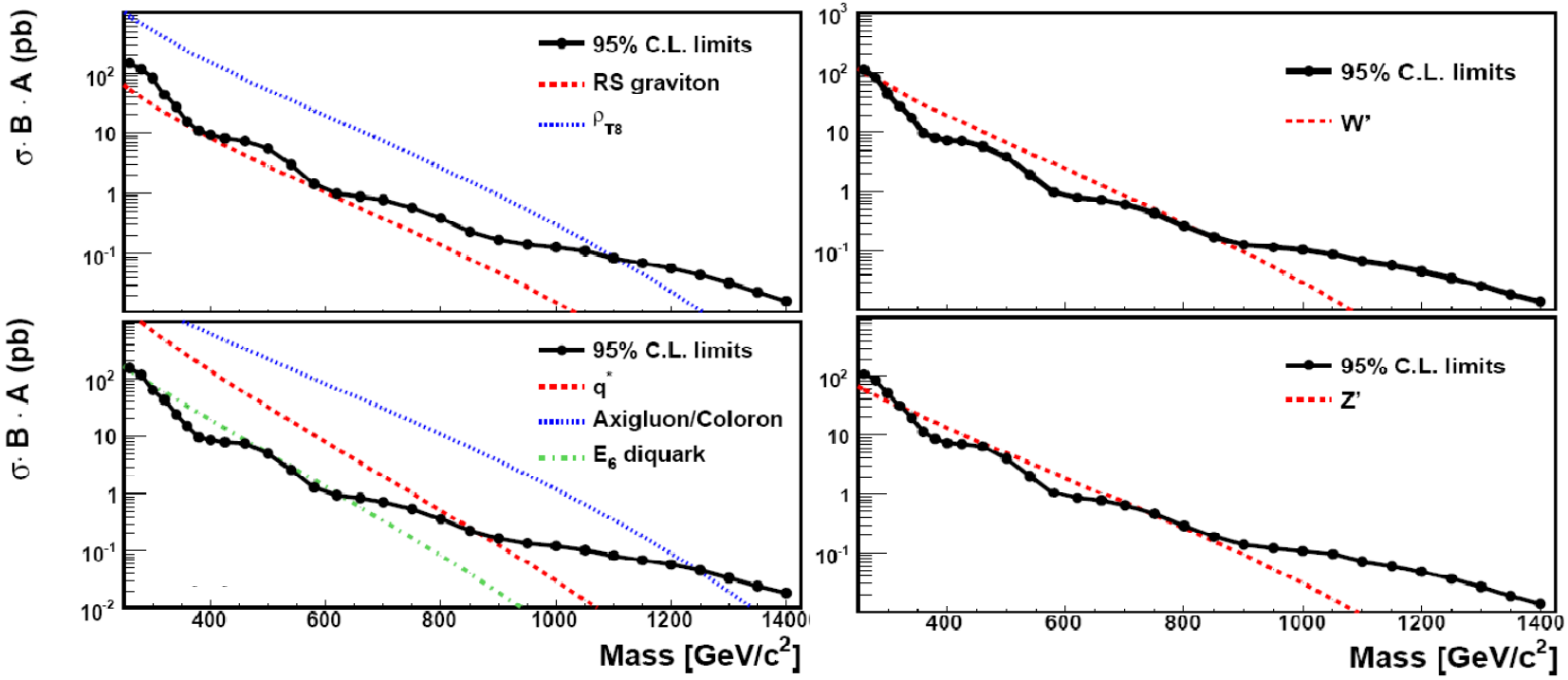
  modeled by Pythia MC.
- Gluons make the dijet mass resonance shape wider.

  (~20% effect on resonance cross section sensitivities)
- Determine 95% CL limits using signal shapes from these four models separately
- For other models, compare predictions with one of these limits that are applicable to each model





Upper Limits @ 95% CL

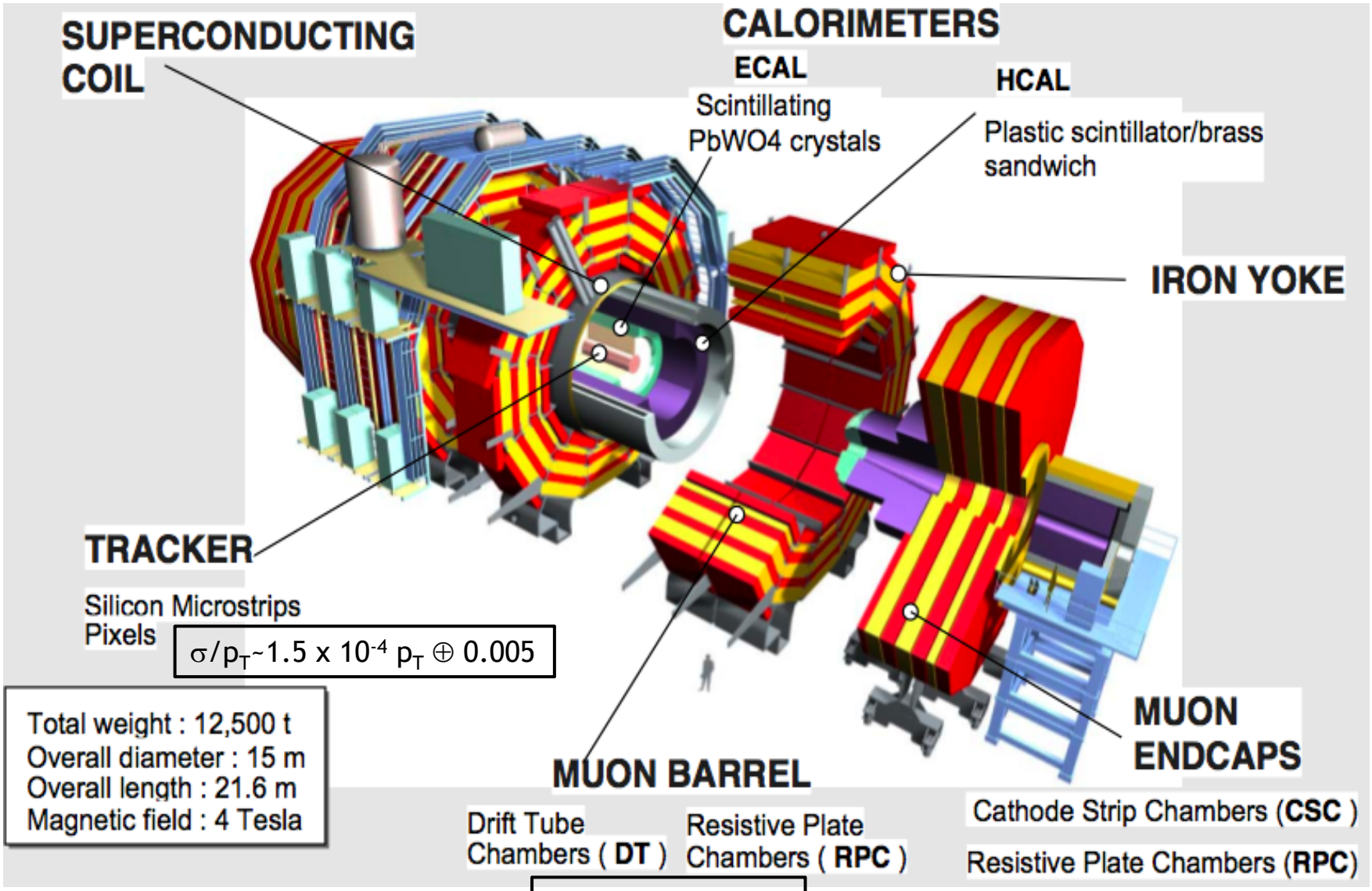


Dijet resonance models are excluded at the 95% C.L. above the black curves.

- For the excited quark, axigluon/coloron, color-octet technirho, E6 diquark, most stringent mass limit to date
- For W', Z', RS graviton, most stringent mass limit in the jj channel to date

The Large Hadron Collider

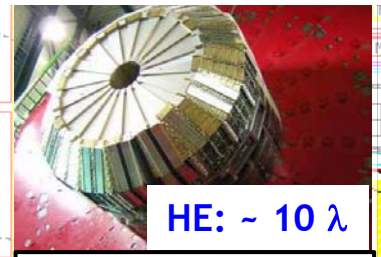
CMS Detector



CMS Calorimeter

- HCAL calibration
  - Test Beam measurements with 50 GeV pions.
  - Further "in-situ" calibration
    - φ inter-calibration with Zero Bias and Min Bias events
    - Absolute energy scale with E/p of isolated tracks
- ECAL calibration
  - Test Beam measurements with electrons
  - Further "in-situ" calibration
    - $\pi^0 \rightarrow \gamma\gamma$ and $Z \rightarrow e^+e^-$ events.

Brass & Scintillating tiles
$\Delta\phi$ x $\Delta\eta$ = 0.087x0.087
for $|\eta| < 1.7$



HE: ~ 10 λ

$\sigma/E \sim 100\%/\sqrt{E} \oplus 5\%$

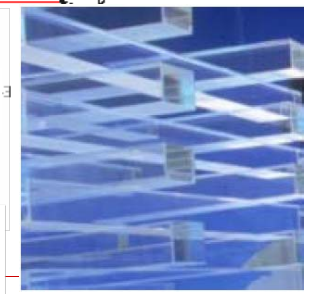
HB: ~ 6-10 λ

HF: Iron and Quartz fibers , ~ 10 λ

EB: 2.4x2.4x23 cm³, ~ 25 λ

EE: 3x3x22 cm³ ~ 24 λ

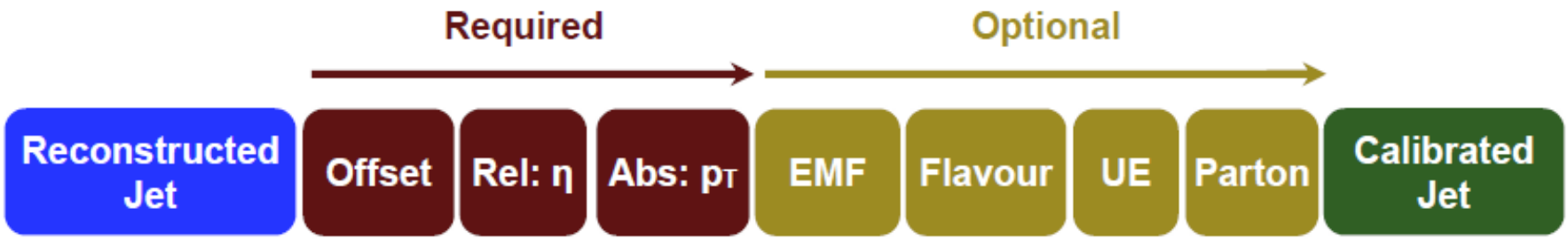
$PbWO_4$ crystals



S = 2.8%, N = 120 MeV, C = 0.30%

$$\left(\frac{\sigma}{E}\right)^2 = \left(\frac{S}{\sqrt{E}}\right)^2 + \left(\frac{N}{E}\right)^2 + C^2$$

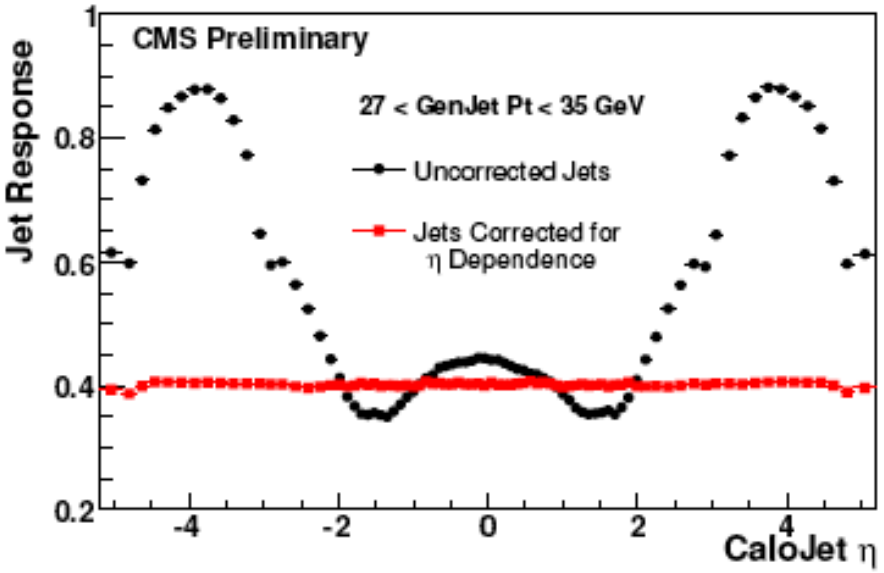
Jet Energy Correction

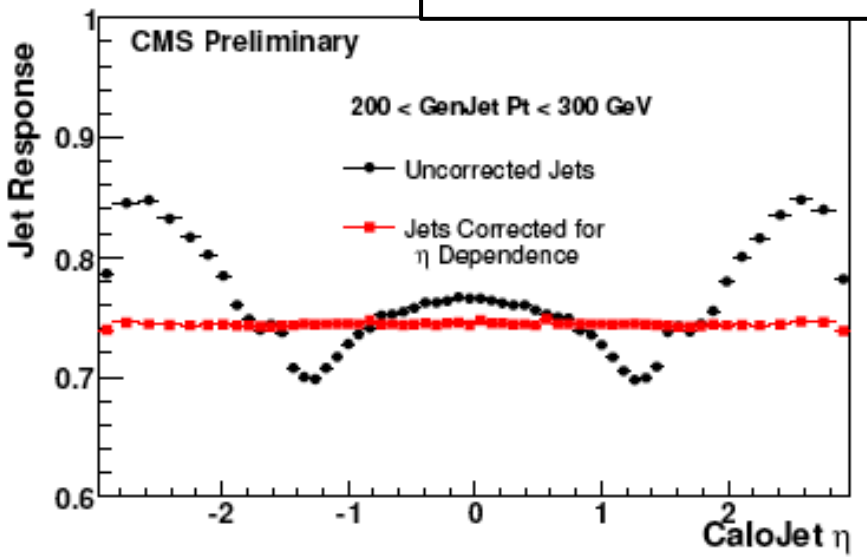


- Energies measured by the calorimeters need to be corrected for the calorimeter non-linearity and non-uniformity
- Multi-step approach a la Tevatron experiments
  (correct for different effects step-by-step)
  - Offset: correct for noise and pileup
  - Relative (η): Equalize jet response to the control region (barrel)
    - Use dijet p_T balance
  - Absolute (p_T): Correct measured p_T to particle level p_T
    - Use photon+jet and Z+jet p_T balance
  - And optional analysis dependent corrections

Relative Jet Energy Correction

CMS PAS JME-07-002
CMS PAS JME-08-003





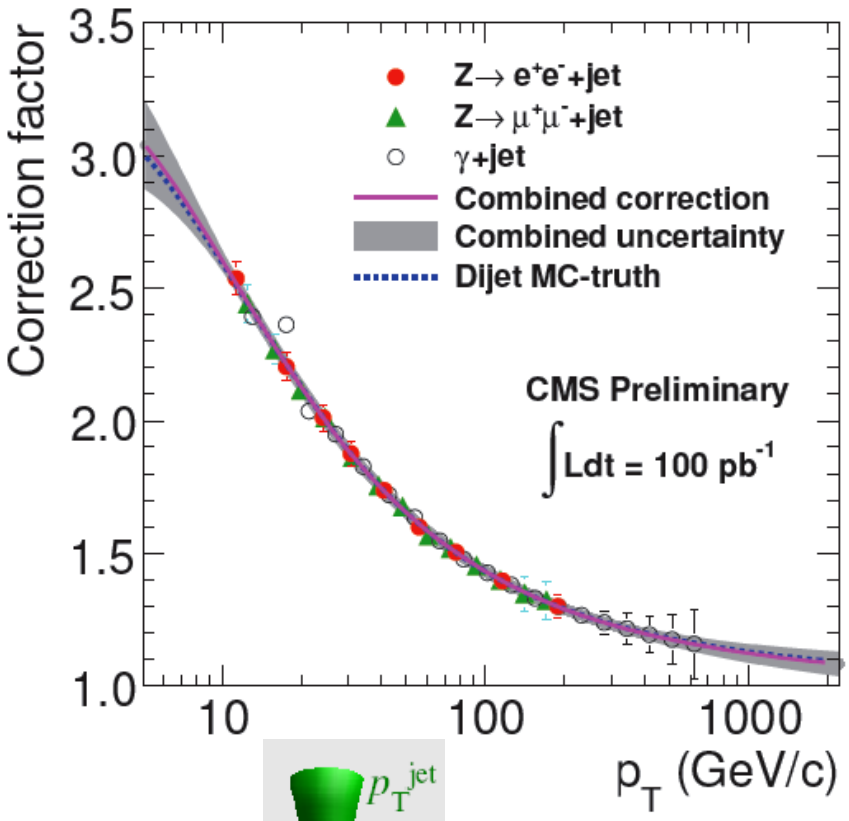
- The relative correction equalize jets outside the "barrel" region to jets in the barrel, where the absolute scale will be determined
- It will be measured from data with the dijet balance method.
- 1 pb^{-1} of data should be enough to derive this correction

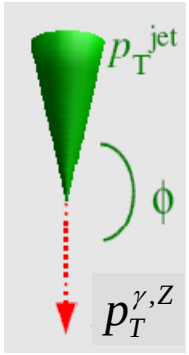
Trigger jet: barrel region
Probe jet: anywhere

$$\Delta p_T f \equiv \frac{\Delta p_T}{p_T^{ave}} = \frac{p_T^{probe} - p_T^{trigger}}{(p_T^{probe} + p_T^{trigger})/2}$$

$$\beta \equiv \frac{p_T^{probe}}{p_T^{trigger}} = \frac{2 + \langle \Delta p_T f \rangle}{2 - \langle \Delta p_T f \rangle}$$

Absolute Jet Energy Correction



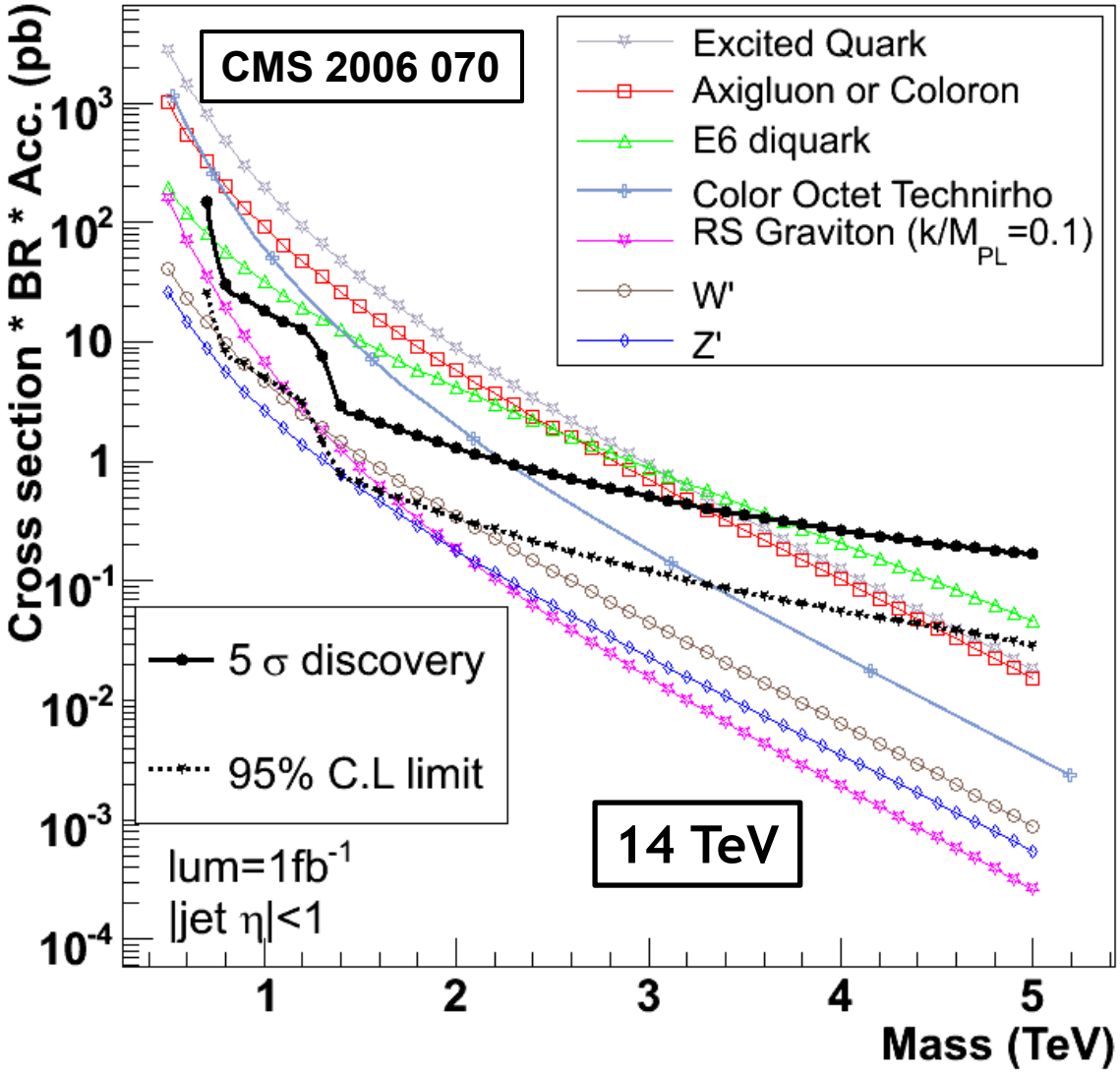


CMS PAS JME-09-004
CMS PAS JME-09-005
CMS PAS JME-09-009

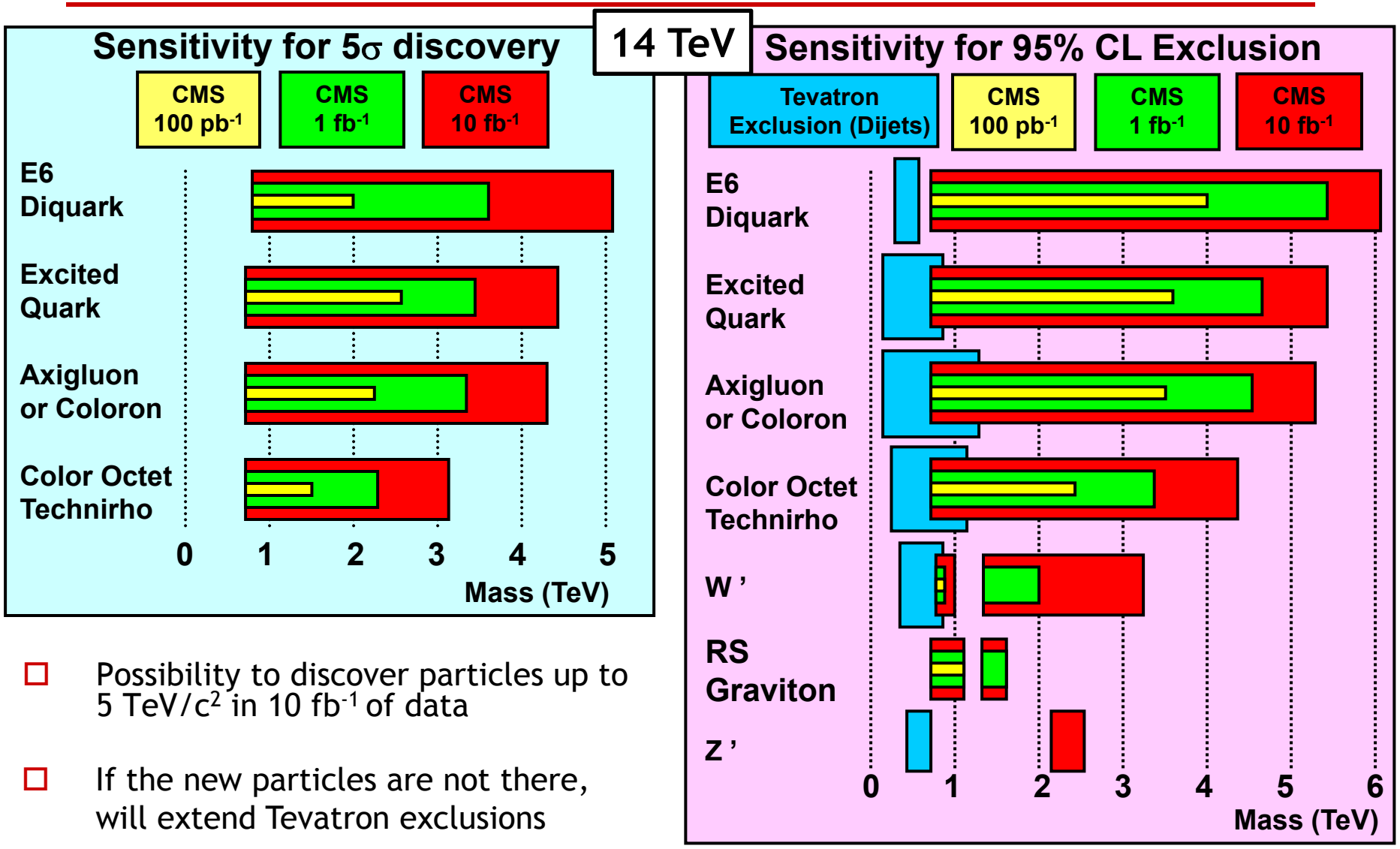
- The absolute correction corrects the measured p_T to the particle-level on average
- It will be determined from data with p_T-balancing in events with γ/Z+jet.
- The results of the three individual measurements (γ+jet, $Z\rightarrow e^+e^-$+jet, $Z\rightarrow \mu^+\mu^-$+jet) will be combined into a single correction.
- The MC will be used to extrapolate in the high p_T region, where the data-driven method cannot reach

CMS Sensitivity to Dijet Resonances

- Analysis strategy essentially the same as the CDF analysis
- Cross section for discovery or exclusion for 1 fb^{-1} shown (studied also done for 100 pb^{-1} and 10 fb^{-1})
- Compared to cross section for 8 models
- Many models are within the reach with the early data



LHC Sensitivity to Dijet Resonances

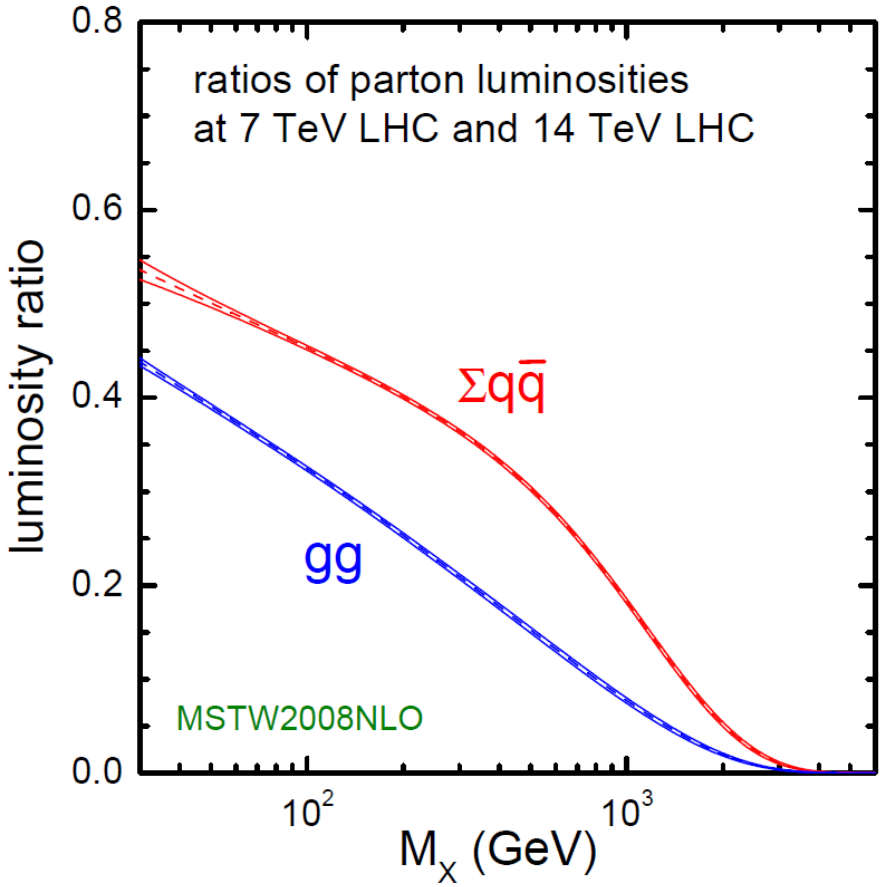


- Possibility to discover particles up to 5 TeV/c^2 in 10 fb^{-1} of data
- If the new particles are not there, will extend Tevatron exclusions

From the CMS experiment, Courtesy of Robert Harris

Sensitivity @ 7 TeV

- What is the sensitivity at 7 TeV?



The sensitivity at 14 TeV will go down roughly according to this parton luminosity ratio

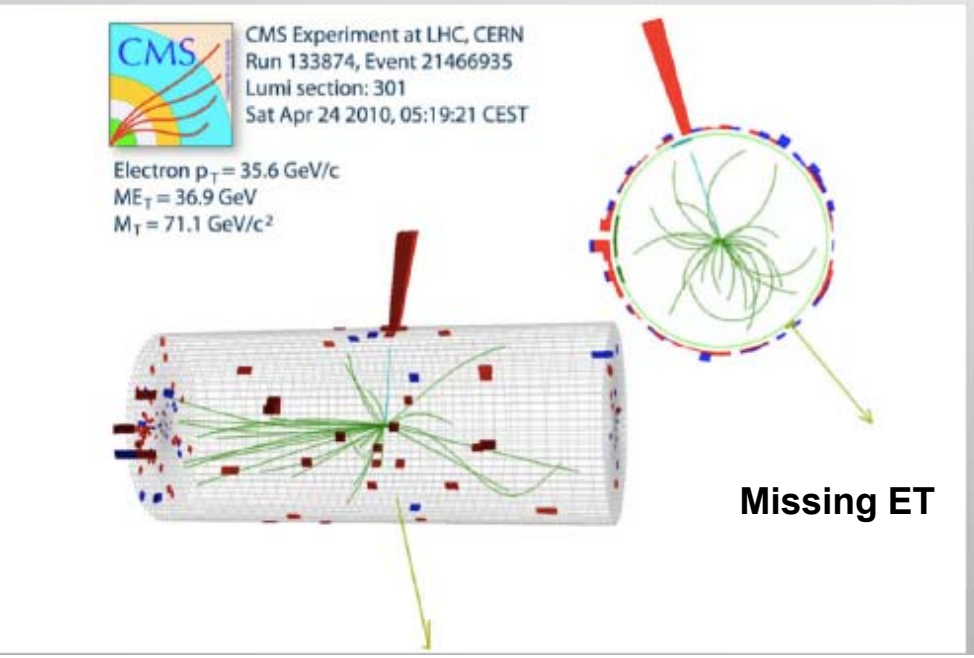
Courtesy of J. Stirling

Missing ET (MET)

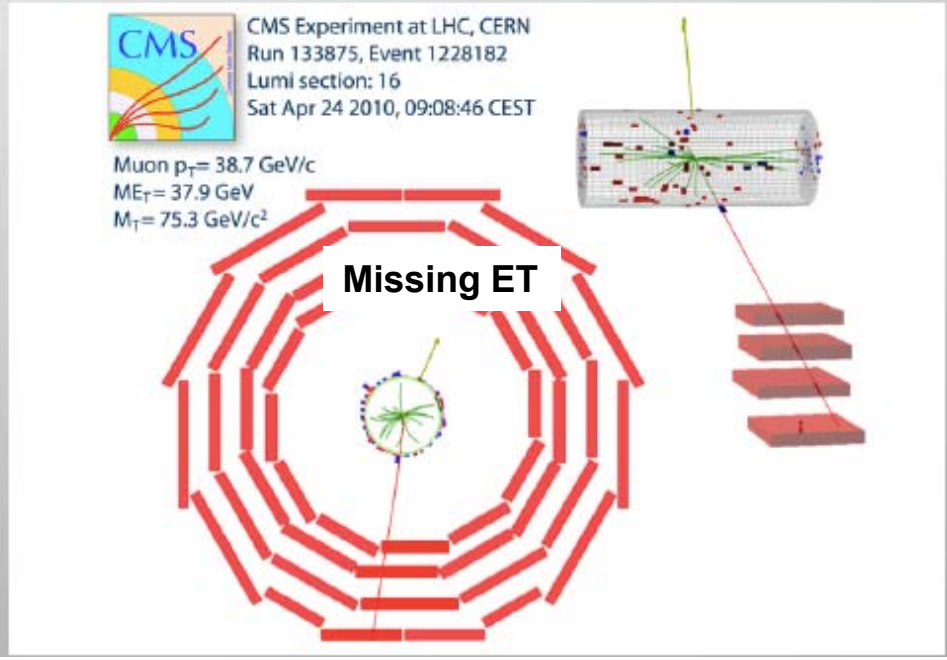
- The general-purpose high energy collider experiments' detectors detect most species of particles produced in particle collisions.
  - Good coverage in the transverse region with respect to the beam-axis
- Exceptions are neutrinos and hypothetical weakly interacting particles, which escape from the detector without a trace.
- Their presence can be inferred from the Missing Transverse Momentum. Its magnitude is missing ET.

Missing ET

W→ev: three candidates found



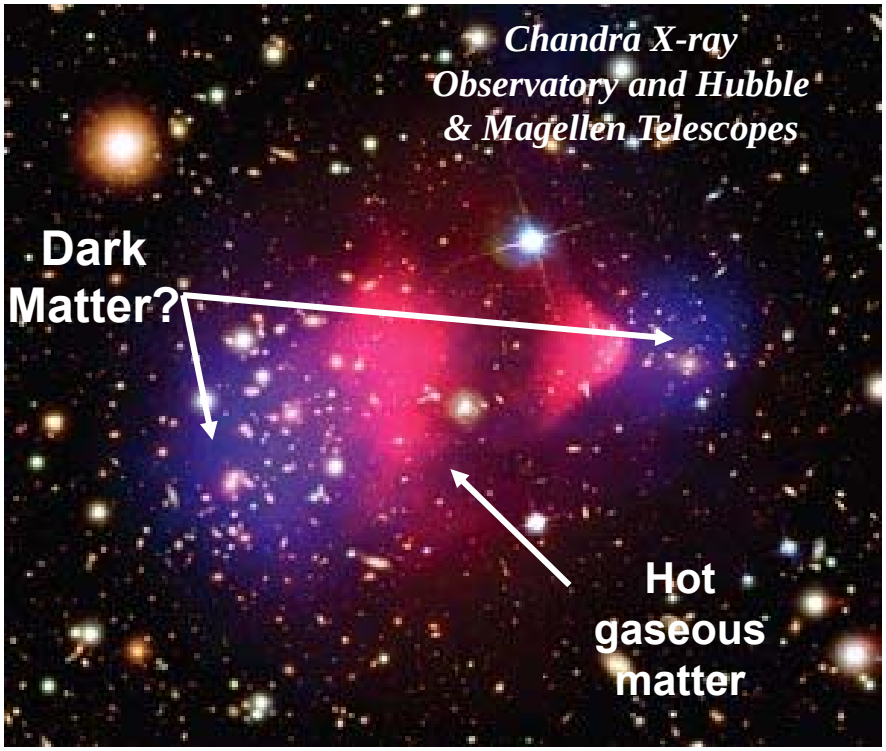
W→μν: three candidates found

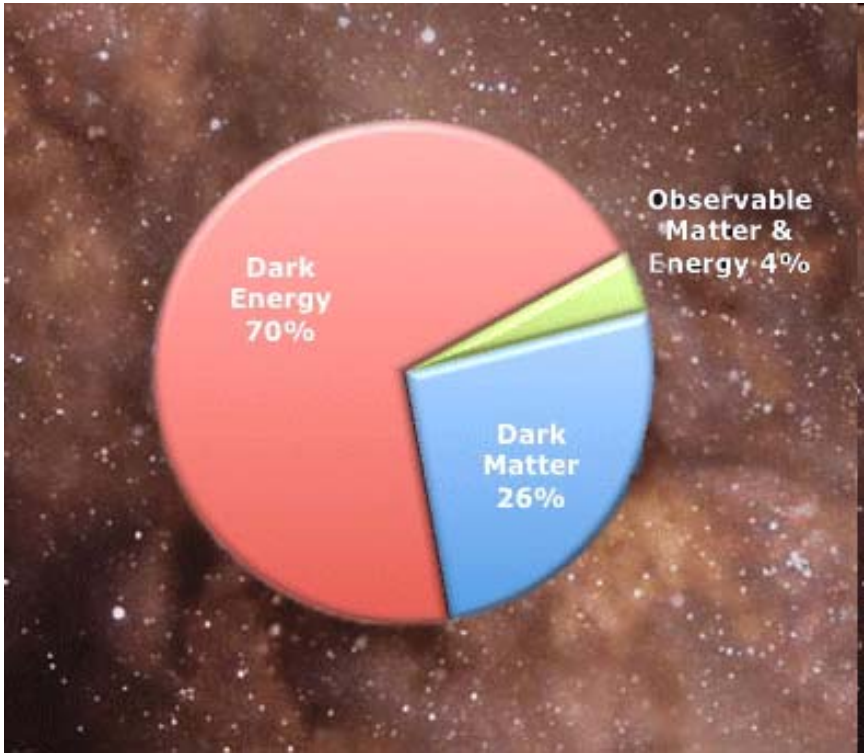


We already see events with missing ET from W→lν at the LHC

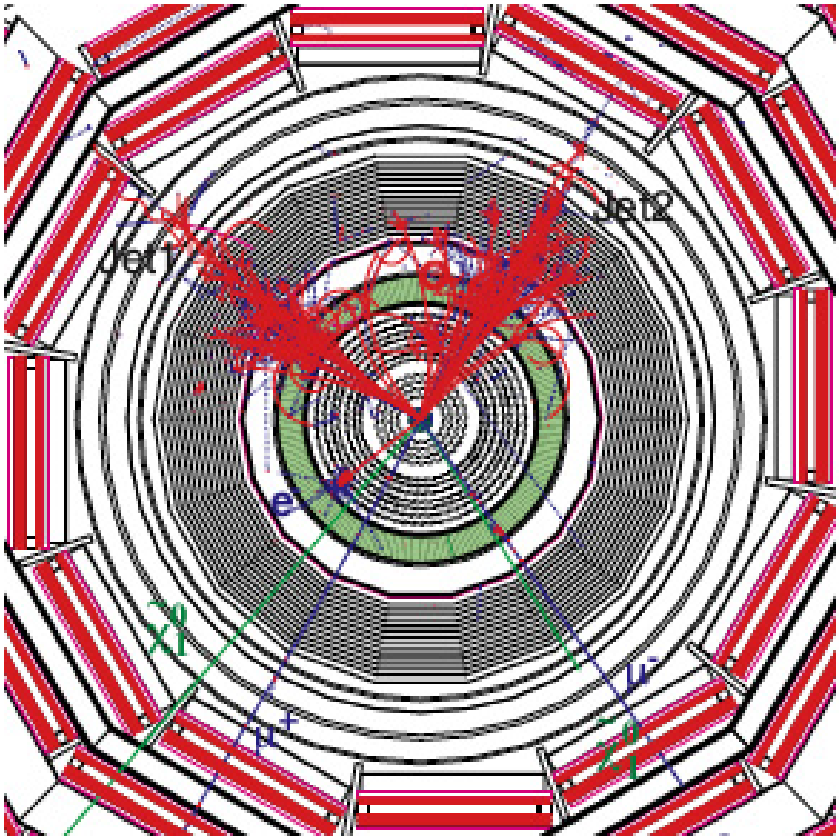
Dark Matter

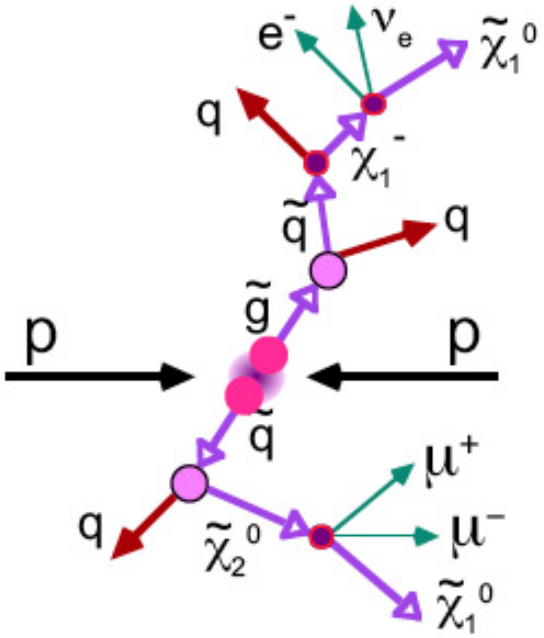
- Missing ET is the very important variable in search for physics beyond the Standard Model
- We know the dark matter exists. If we can create the dark matter particles at the LHC, the events will have high missing ET.





Supersymmetry and Missing ET

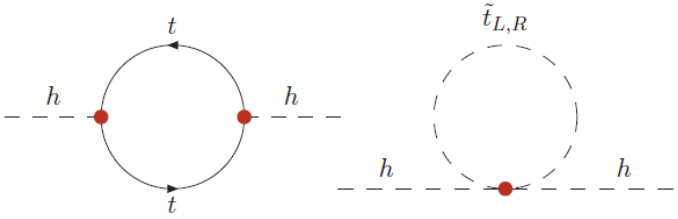




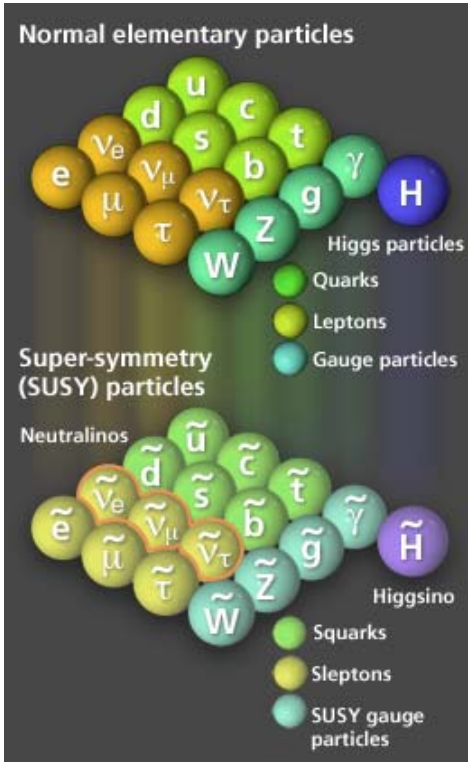
Supersymmetry is one of the well motivated theories which offers a candidate for dark matter

Supersymmetry (SUSY)

- SUSY is a fundamental global symmetry between fermions and bosons.
  - Each fermion has a boson superpertner, and vice versa
  - Higgs mass stabilizes against loop correction (fine tuning problem)
  - Modifies running of SM gauge couplings just enough to give “Grand Unification” at single scale
  - SUSY is broken (sparticles are not seen)

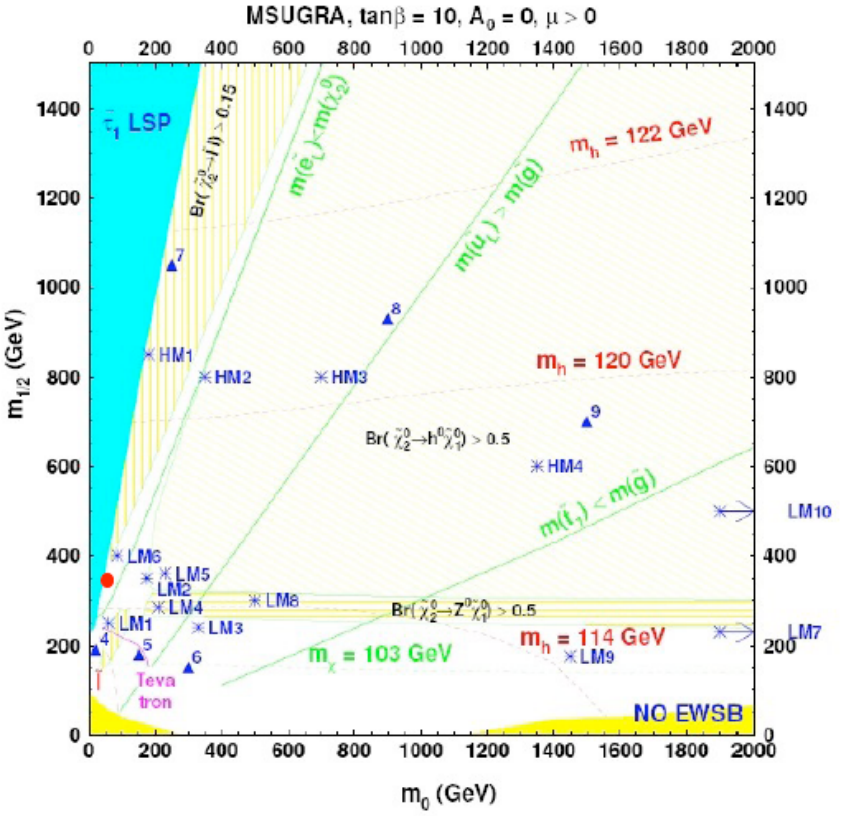


- MSSM: Simple SUSY model consistent w/ SM
  - R-parity conservation
    - $R=(-1)^{2S+3B+L}$
    - Sparticles produced in pairs, decay to an odd number of Lightest Supersymmetry Particle (LSP)
    - LSP is a dark matter candidate
  - SUSY breaking
    - mSUGRA, GMSB, …



SUSY Phenomenology & Approaches

- mSUGRA
  - Gluino/squark production and cascade decay
  - Neutralino χ_1^0 is the LSP
  - Parameters: m_0, $m_{1/2}$, A_0, tanβ, sign(μ)
- Analysis approaches
  - Typically SUSY events have large missing ET, very energetic jets
  - Use a few benchmark points for optimization



	σ(LO)[7/10/14] (pb)	$m_{1/2}$ GeV	m_0 GeV	A_0	tanβ	sign (μ)
LM0	39/110/-	160	200	-400	10	+1
LM1	4.9/16/43	60	250	0	10	+1
LM2	0.6/2.4/43	185	350	0	35	+1
LM3	3.4/12/34	330	240	0	20	+1
LM4	1.9/6.7/19.4	210	285	0	10	+1

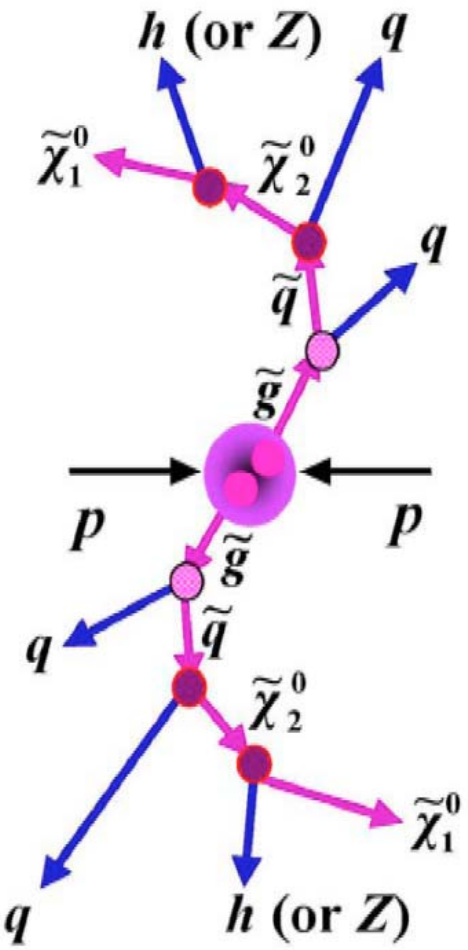
Inclusive Jets+MET Search

Event selection

- Remove electrons/photons
- First jet E_T > 180 GeV
- 2nd jet E_T > 110 GeV
- 3rd jet E_T > 30 GeV
- MET > 200 GeV
- HT = E_{T2} + E_{T3} + E_{T4} + MET > 500 GeV
- $|\eta|<3$, $|\eta^{jet1}|<1.7$
- No isolated tracks
  - Reduce top, EWK events

Background source and estimation

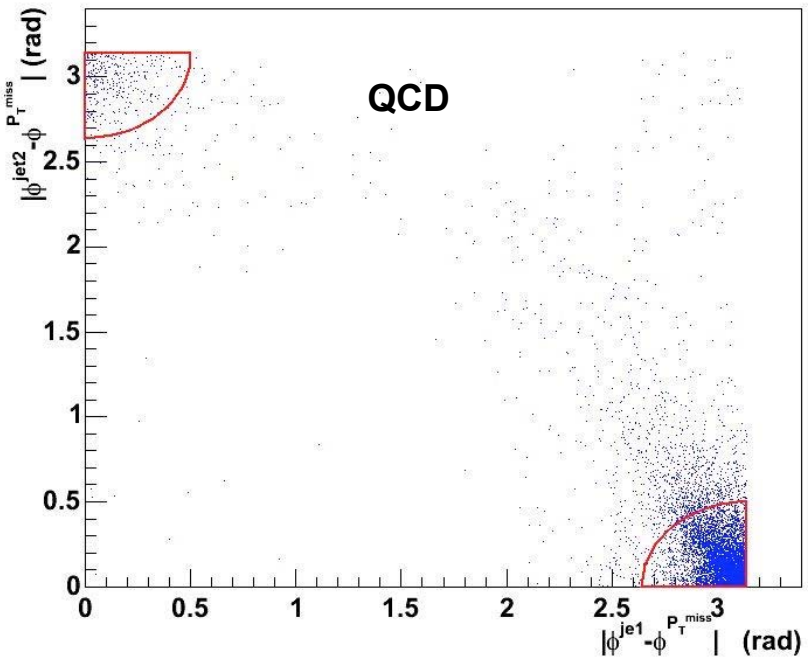
- Background source:
  - QCD, Z ($\rightarrow \nu\nu$)+jets, Top, EWK
- Emphasis on "data-driven" background determinations
  - Rely on control samples in the data, sometimes with assistance from MC

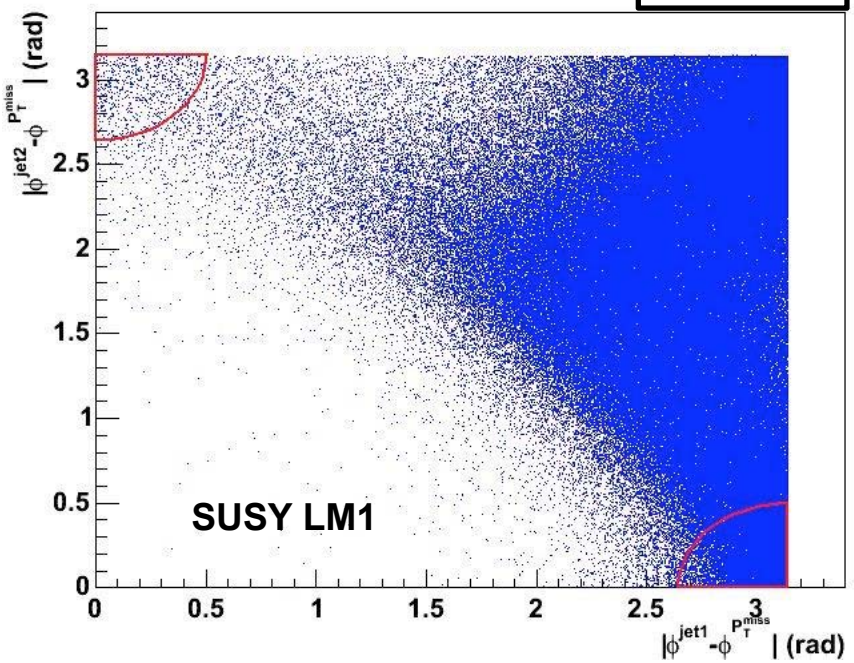


Reducing QCD Background

Δϕ(leading jet,MET) VS Δϕ(sub-leading jet,MET)

14 TeV





- MET in QCD events tends to be along a jet
  - MET arises from jet energy mis-measurement
- "True" MET from LSP not much correlated with jets
- Use φ angles between MET and 2 leading jets
- Remove ~80% QCD, Keeps ~90% SUSY

$$R_{1,2} > 0.5, \quad where$$

$$R_{1,2} = \sqrt{\Delta\varphi_{1,2}^2 + (\pi - \Delta\varphi_{2,1})^2}, \;\&$$

$$\Delta\varphi_{1,2} = |\,\varphi_{jet1,jet2} - \varphi(MET)\,|$$

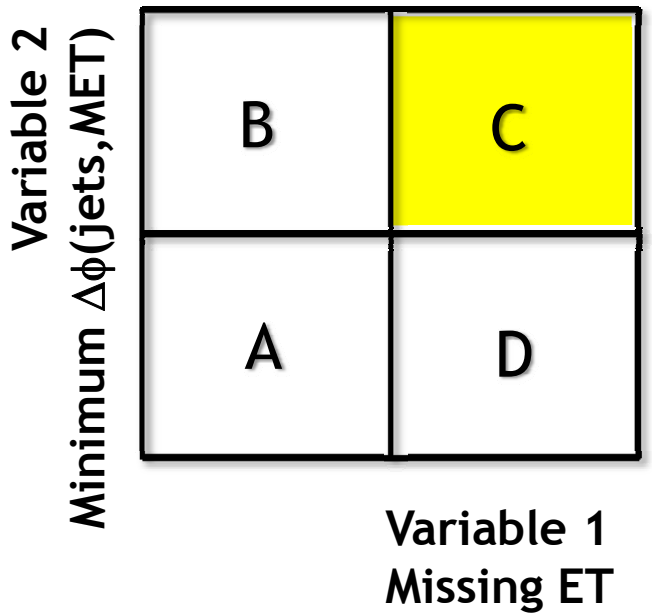
Residual QCD Background

ABCD Method:

- Find two observables uncorrelated for QCD
- Divide the plane in four regions A, B, C, D:

  C is the signal region
- The numbers of QCD events in C:

  $C = D \times B/A$
- Caveats: critical to have little signal content in the other 3 regions
  - Otherwise need to remove signal from A, B, D

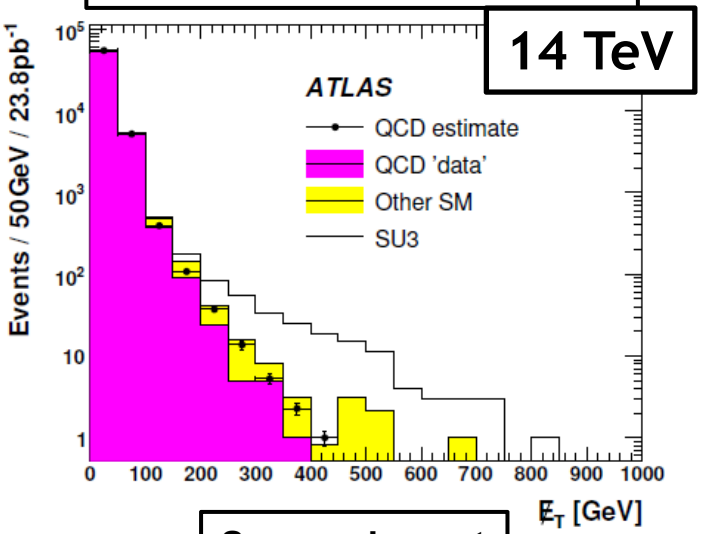


Residual QCD Background Estimate

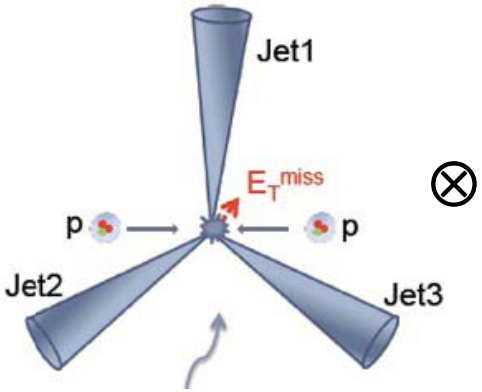
Smearing method:

- Obtain a jet response function R using photon+jets (Gaussian core response) and QCD-multijet (non-Gaussian) events with MET
- Smear jets with R in events in low MET multi-jet events
- Normalize it to size of QCD data with low MET

ATL-PHYS-PUB-2009-065



Low MET Event



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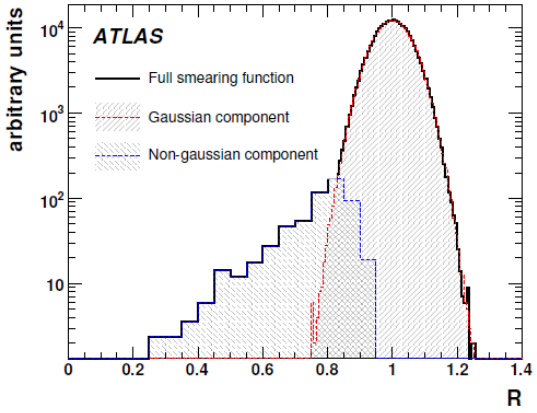
Smear with response function



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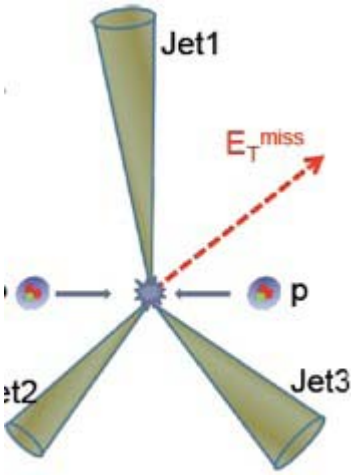
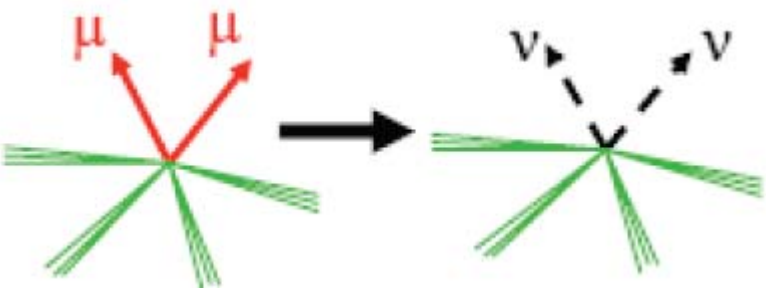
Smeared event

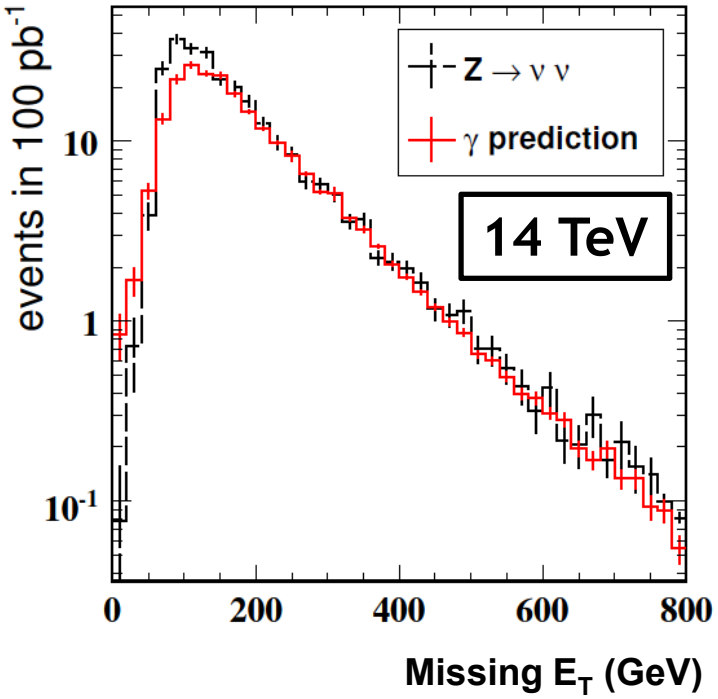


Z(→νν)+Jets Background Estimate

- Use Z(→ee or μμ)+jets events
  - Low background and systematics, but rather small cross sections
  - 5% accuracy with 1.5 fb^{-1}
- Use photon+jets events
  - After removing photon, similar shape for MET>150 GeV
  - Advantage: large cross sections
  - Challenges:
    - Uncertainty on normalization: γ+jets and Z+jets are different processes
    - Photon fake rate
  - 10% accuracy with 100pb^{-1}

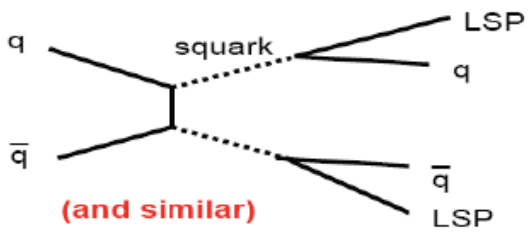


CMS PAS SUS-08-002

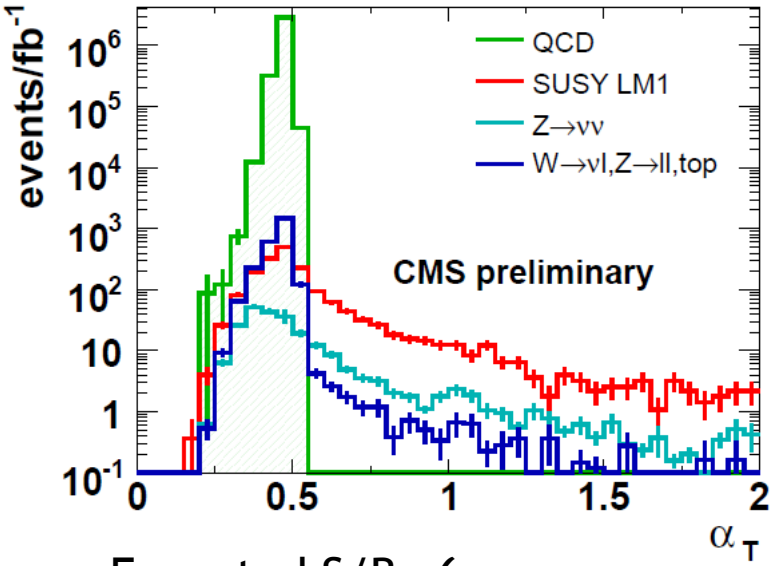


Search in Exclusive Dijet Channel

- Event topology
  - Consider case in which two squarks decay to 2 quarks & 2 neutralinos
    - $m_{squark} < m_{gluino}$
- Analysis strategy
  - Suggested by L. Randall et al
  - Use $\alpha_T = E_T^{jet2}/M_T(j1,j2)$
  - QCD expected to have $\alpha_T < 0.5$
- Event selection
  - $Pt^{jet1,2} > 50$ GeV, $Pt^{jet3} < 50$ GeV
  - Lepton Pt < 10 GeV
  - HT > 500 GeV
- Background estimate
  - Use the ABCD method
  - α_T and $|\eta_{jet1}|$ not correlated
  - Signal region: $|\eta_{jet1}| < 2.5$, $\alpha_T > 0.55$



14 TeV

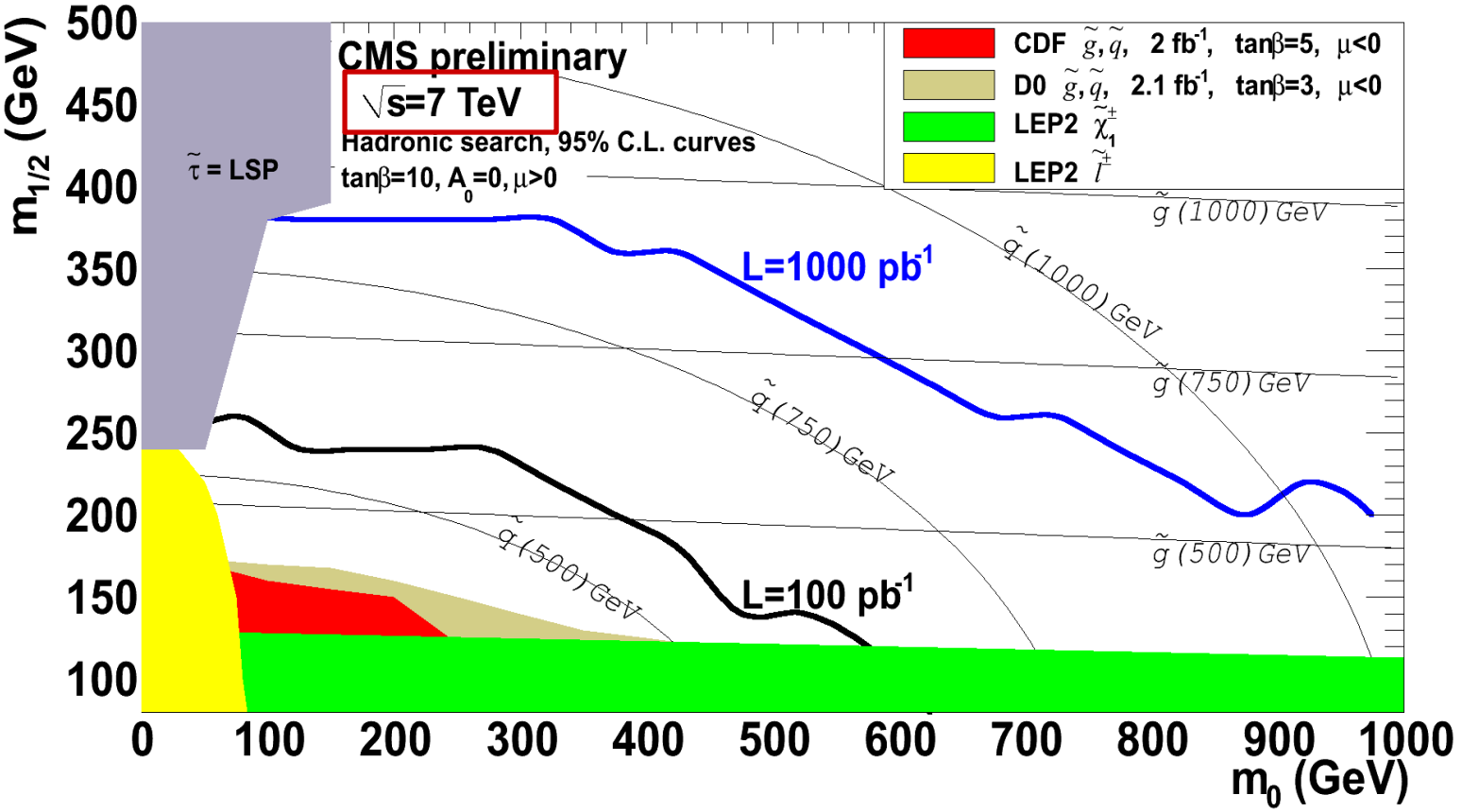


Expected S/B ~6
LM1@100pb^{-1}: ~44 events
Background: ~8 events

CMS PAS SUS-08-005, -09-001

Also extended to exclusive N-jets (N>2)

Inclusive Jets+MET Search

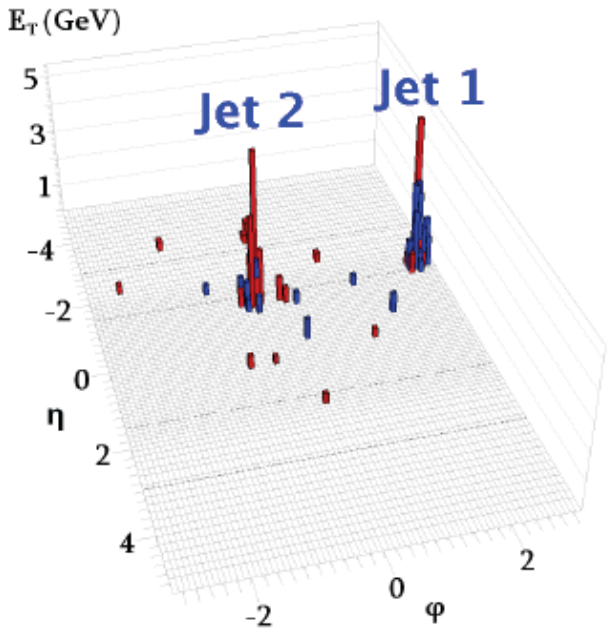


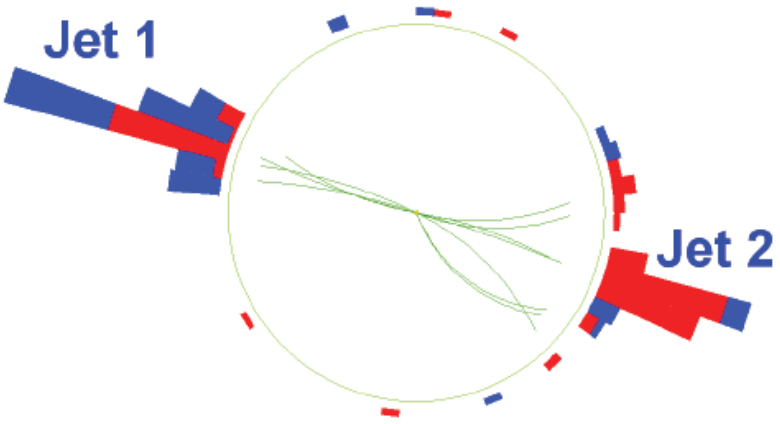
Systematic uncertainty assumed to be 50% overall.
Separate selections for 100 pb^{-1} and 1 fb^{-1}.

Sensitivity will go into the unexplored region very quickly

Commissioning with Collisions

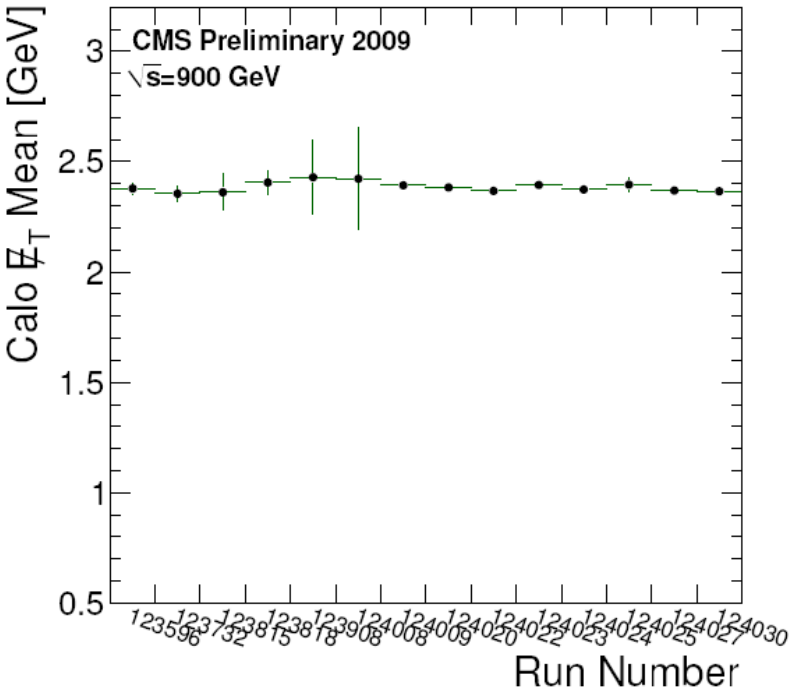
- LHC finally started to deliver pp collisions since November, 2009.
- Commissioning of jets and missing ET with collision data has started

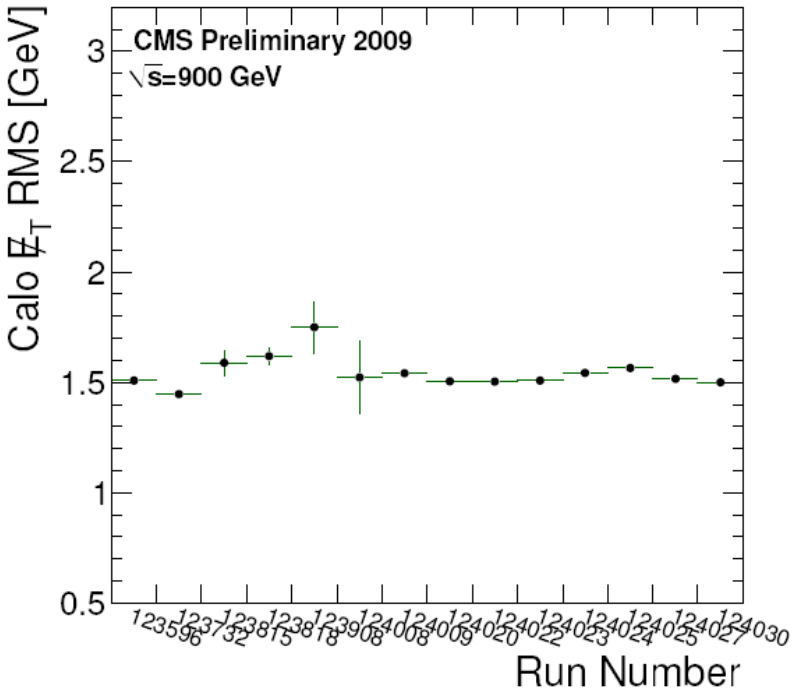




Missing ET vs Time @ 900 GeV

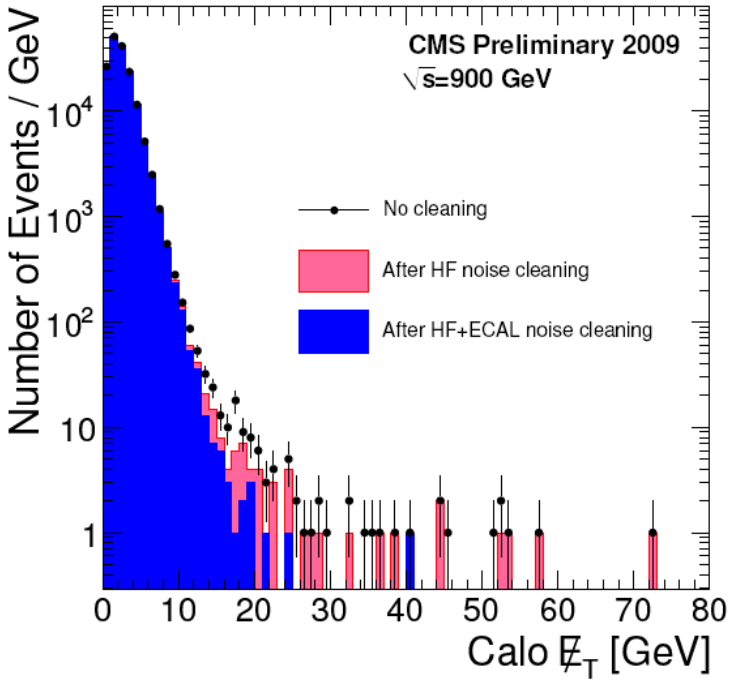
CMS PAS JME-10-002





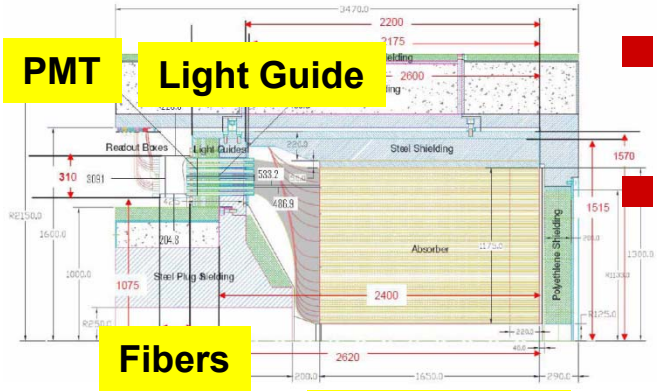
- Very stable missing ET vs time from the first month!
- Data Quality Monitoring (DQM) system successfully operated including the monitoring of jets and MET

Missing ET Tail

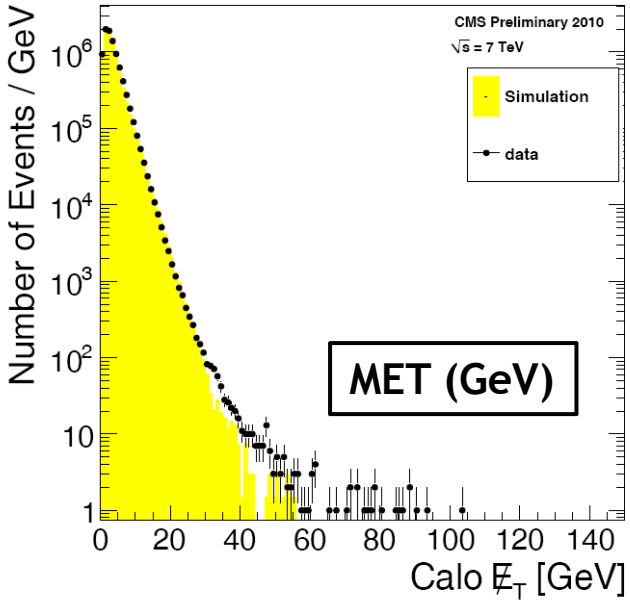


- Anomalous signals were observed in calorimeters (especially in ECAL and HF)
- Particles hitting the electronics directly or random discharge
- "Cleaning" procedure developed
  - Signal isolation (e.g. anomalous signal in ECAL narrower than Moliere radius)
  - Asymmetry in short fiber and long fiber in HF
  - Timing / pulse shape information will provide further cleaning

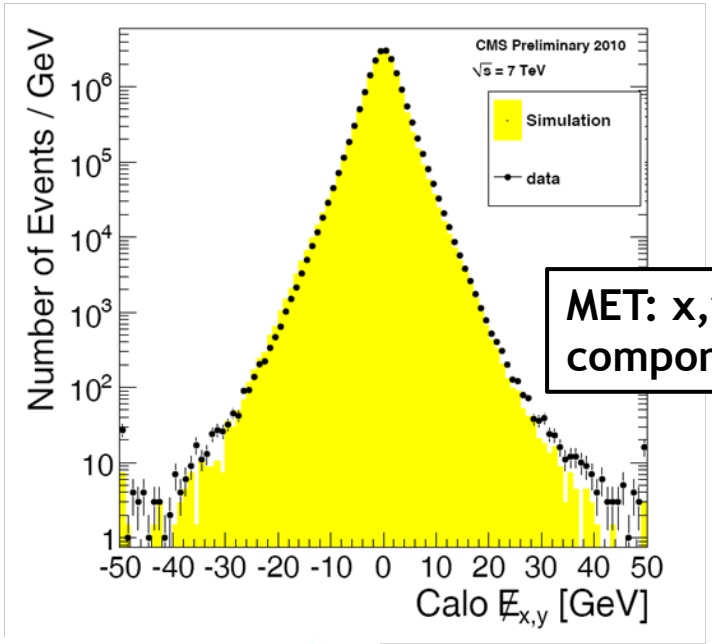
ECAl PbWO4 crystal & readout



Missing ET @ 7 TeV

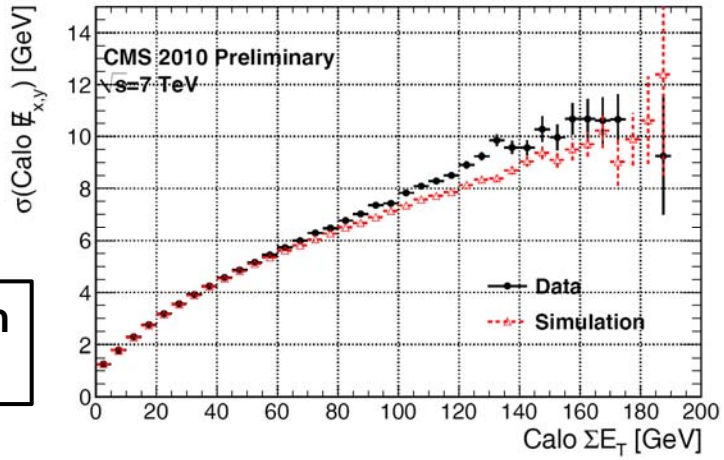


MET (GeV)



MET: x,y components

CMS DP-2010/014



Resolution vs SumET

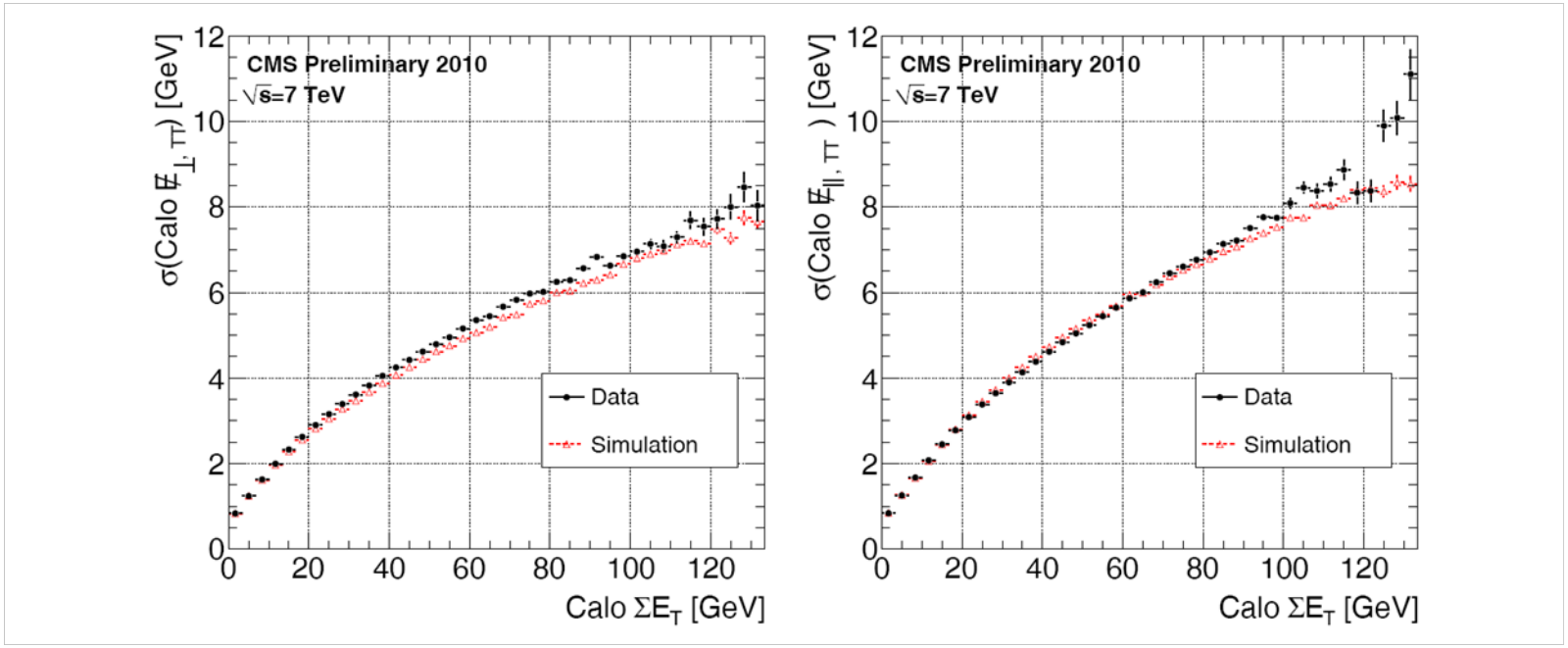
Calorimeter missing ET after application of clean-up procedure removing anomalous noise.

Missing ET Decomposition

- Transverse thrust defines the "event axis" maximizing track momenta

$$TT = \max_{\phi_{TT}} \frac{\sum_i^{tr} |p_T^i \cos(\phi_i - \phi_{TT})|}{\sum_i^{tr} p_T^i}$$ (independent of calorimeter measurement)

  - MET perp. to TT: more sensitive to noise contributions
  - MET para. to TT: more sensitive to particle energy mis-measurement



Low SumET: more sensitive to noise: well described. High SumET: calo response needs better calibration

Track-Corrected MET

- Muon corrections
  - Identify muons
  - Subtract expected deposit for a MIP (~2GeV)
  - Add Muon p_T
- Track corrected MET (TcMET)
  - At low p_T remove calo-response making use of the a calorimetry response-function $\langle E_T \rangle$ determined from simulation
  - Add transverse part of energy measured in the tracker

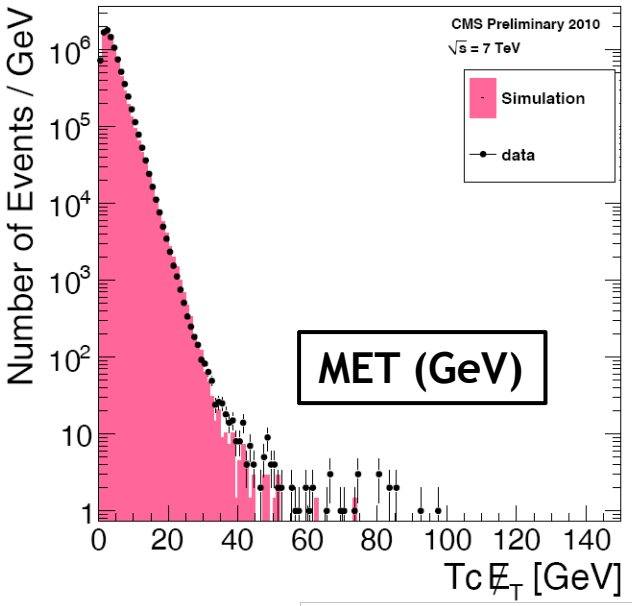
$$\begin{aligned} \not\!\!E_T^{\mu} &= \not\!\!E_T^{\text{calo}} + \delta\not\!\!E_T^{\mu}, \\ &= -\sum_{\text{towers}} \vec{E}_T - \sum_{\substack{\text{good} \\ \text{muons}}} \vec{p}_T + \sum_{\substack{\text{good} \\ \text{muons}}} \vec{E}_T^{\text{MIP}} \end{aligned}$$

Muon corrections

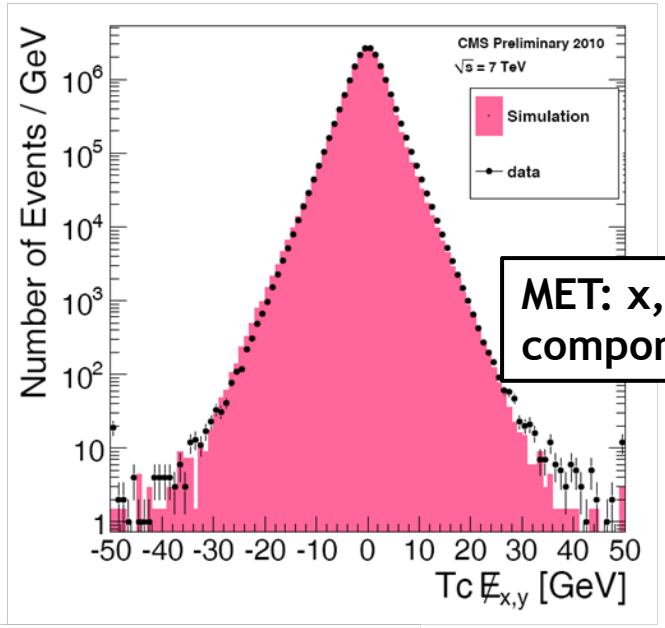
$$\begin{aligned} \not\!\!E_T^{\text{tc}} &= \not\!\!E_T^{\mu} + \delta\not\!\!E_T^{\text{tc}}, \\ &= \not\!\!E_T^{\mu} + \sum_{\substack{\text{good} \\ \text{tracks}}} \langle \vec{E}_T \rangle - \sum_{\substack{\text{good} \\ \text{tracks}}} \vec{p}_T \end{aligned}$$

Track corrected MET (tcMET)

TcMET @ 7 TeV

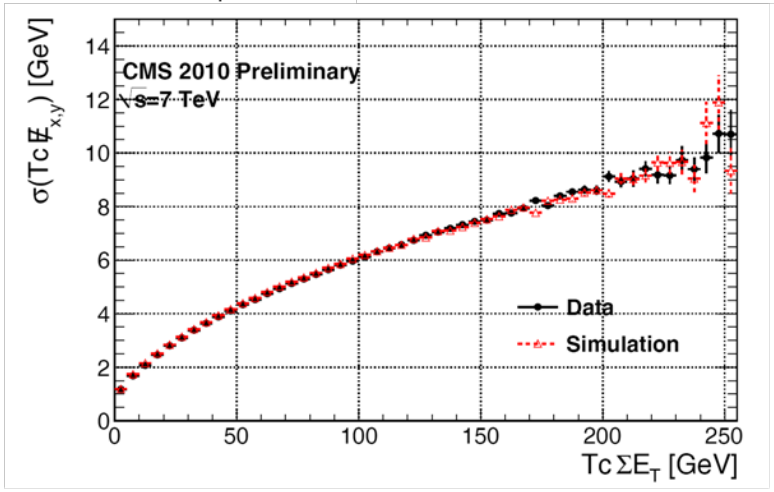


MET (GeV)



MET: x,y components

CMS DP-2010/014



Resolution vs SumET

TcMET after application of clean-up procedure removing anomalous noise.

Particle Flow Missing ET

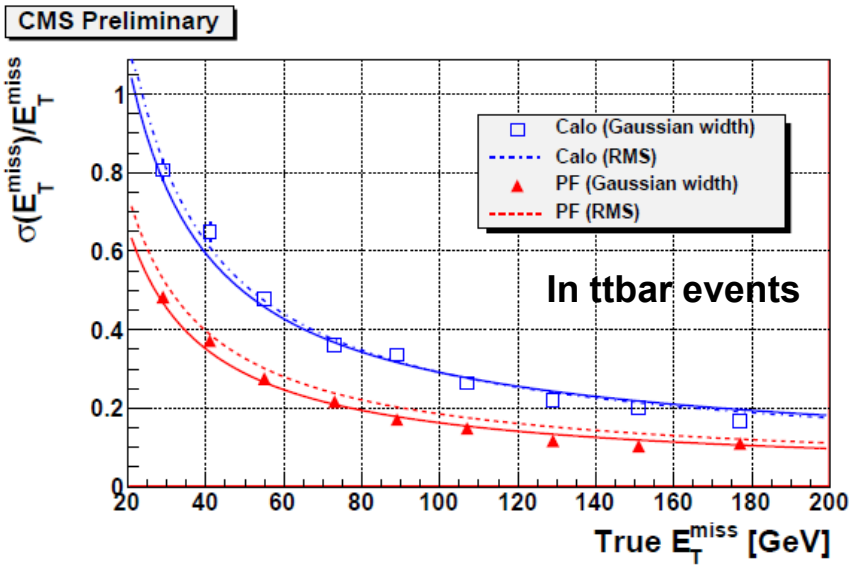
- The particle flow algorithm attempts to reconstruct all stable particles in the event by combining the information from many sub-detectors
  - Charged hadrons
  - Neutral hadrons
  - Electrons
  - Photons
  - Muons

  Strong magnetic filed helps to separate charged and neutral hadrons pointing the same direction.

  CMS provides a good environment for particle flow technique

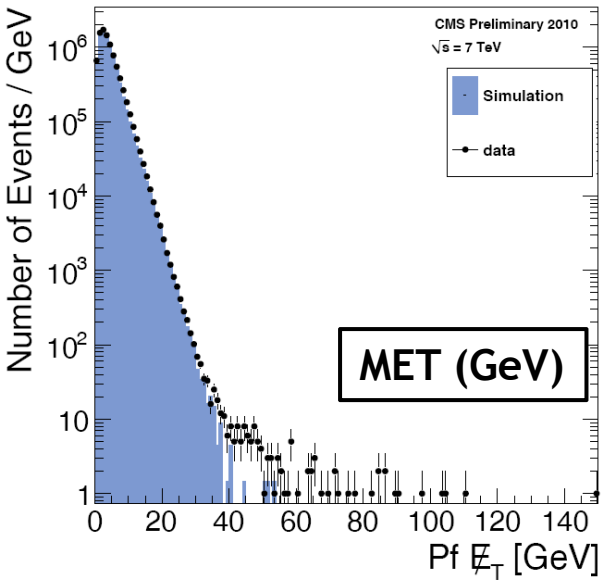
- The particle flow missing ET (PfMET) is the outcome of the vector sum of reconstructed particles

CMS PFT-09-001

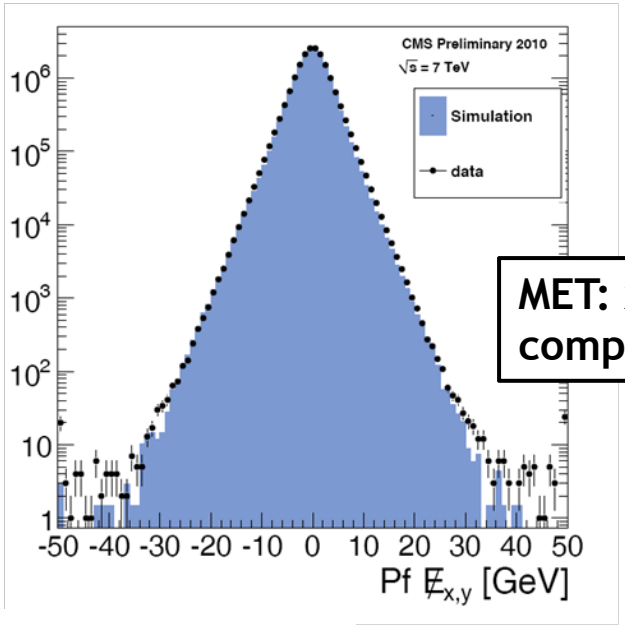


Significant improvement in missing ET resolution

PfMET @ 7 TeV

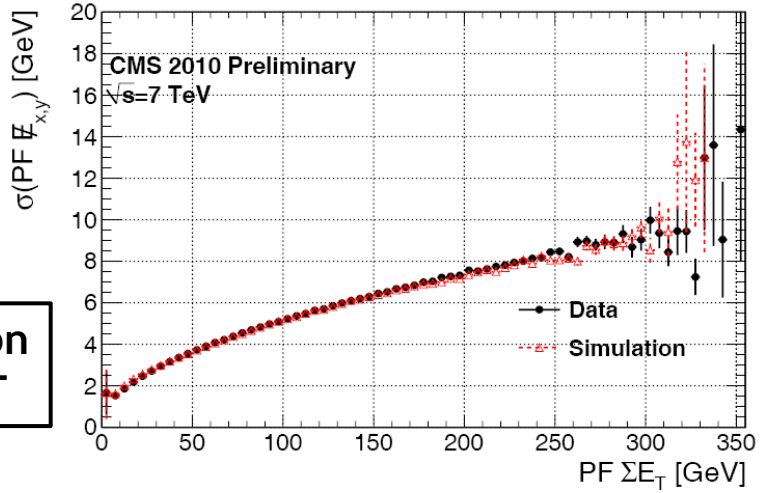


MET (GeV)



MET: x,y components

CMS DP-2010/014

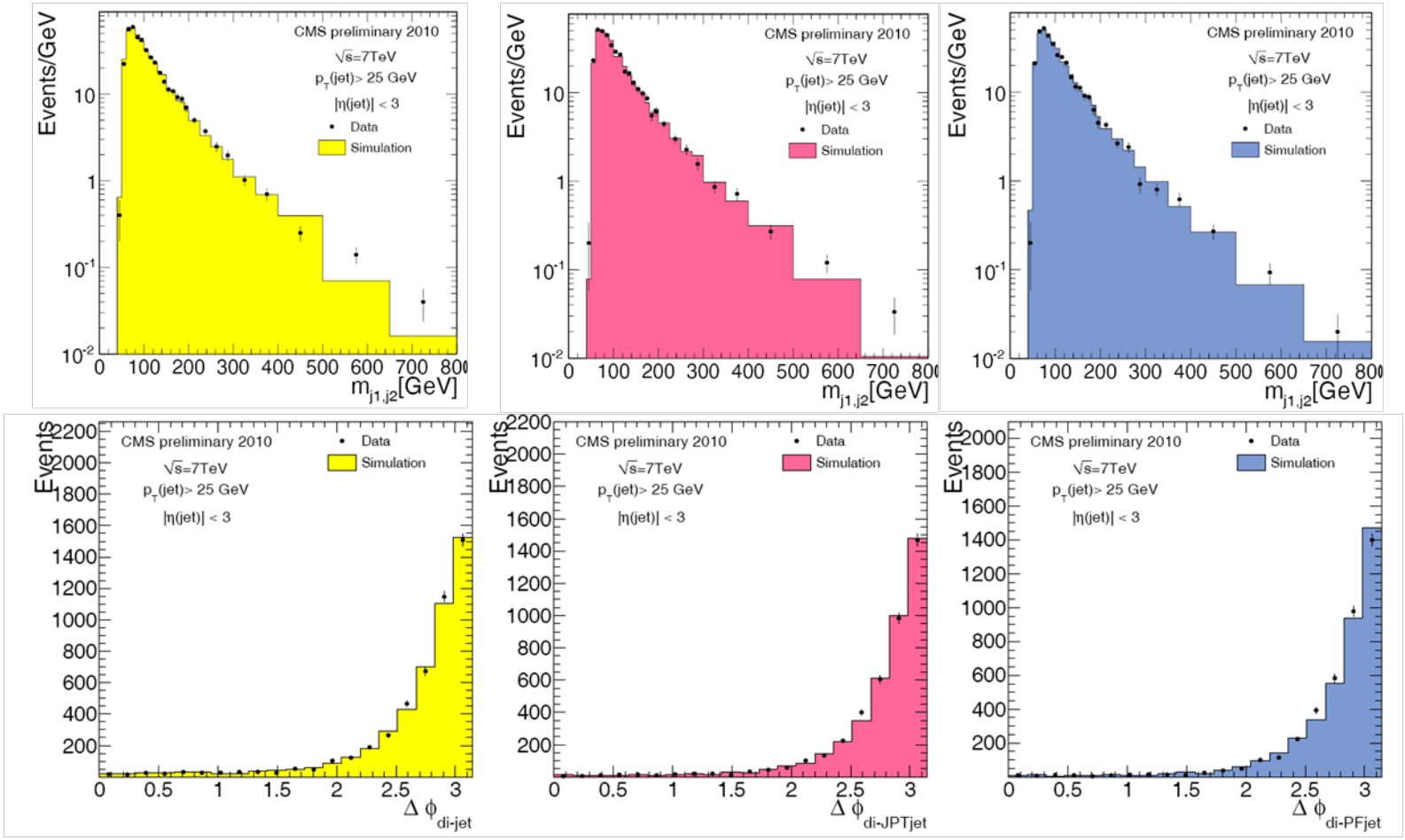


Resolution vs SumET

PfMET after application of clean-up procedure removing anomalous noise.

Jets @ 7 TeV

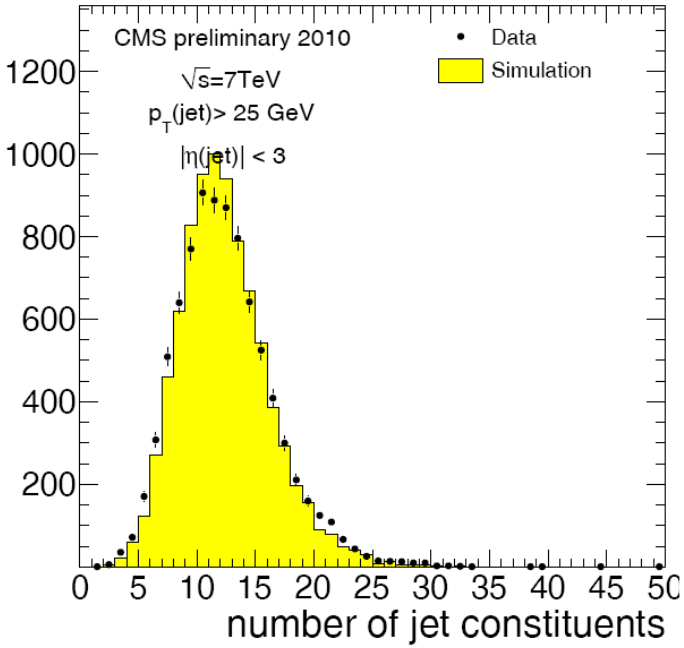
Calorimeter jets | **Jet-Plus-Track jets** | **Particle Flow jets**



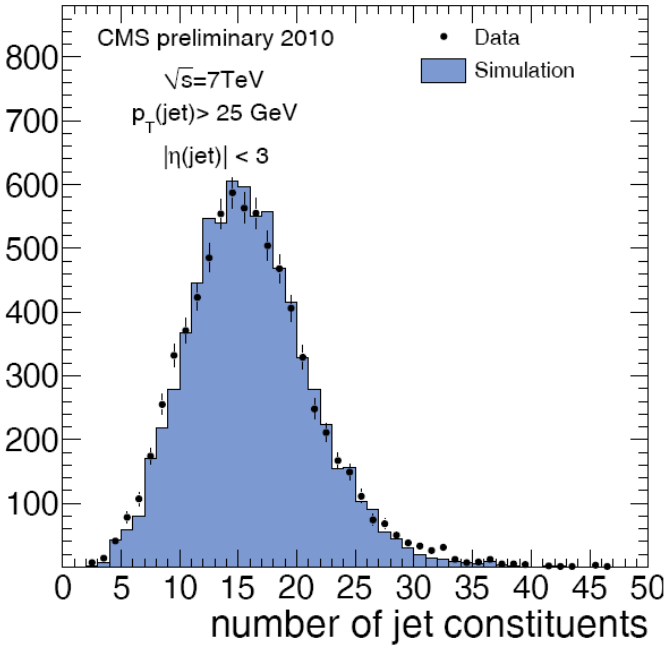
Three different approaches: pure calorimetric, track corrected calo and particle flow.

Jets @ 7 TeV

Calorimeter jets



Particle Flow jets



Summary

- Jets and missing ET play important roles in searches for physics beyond the Standard Model
  - A large variety of models predict final states containing jets and/or missing ET
  - Searches for dijet resonances, Supersymmetry, Extradimensions, Compositeness, Leptoquark, …
  - Jets and missing ET are key ingredients in LHC physics
- CMS established numbers of complementary ways to reconstruct jets and missing ET, and the robust in-situ calibration schemes are in place
- With the arrival of the collision data, commissioning of jets and missing ET is advancing quickly
  - We will see outcome of commissioning work in coming weeks
- Discovery is well within the reach in the 2010-2011 data
  - Let's hope to have an exciting discovery in coming years!