Search for Same-Sign Dilepton SUSY Signatures using Top Decay Events with CMS at the LHC

M. Weinberg

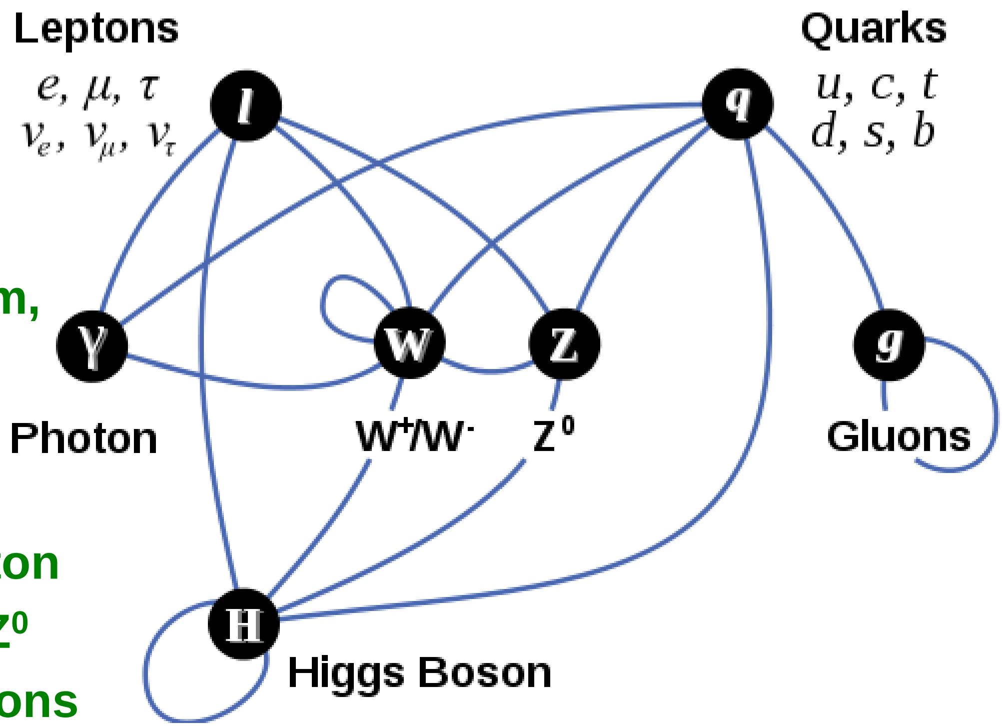
University of Wisconsin

Outline

- **Theory overview**
  - **Standard Model**
  - **Motivation for SUSY/top physics**
- **Experimental setup**
  - **Large Hadron Collider**
  - **Compact Muon Solenoid**
- **Monte Carlo simulation**
- **Object reconstruction**
- **Analysis workflow**
  - **Samples: data and Monte Carlo**
  - **Event selection: lepton and trigger requirements**
  - **Trigger and selection efficiencies**
  - **Top cross section extraction strategy**
    - **Fitting details**
    - **Statistical and systematic uncertainty**
  - **Background estimation for same-sign dileptons**
- **Results**
- **Conclusions**
  - **Top production cross section in muon + jets channel**
  - **Limit on new physics in same-sign dilepton channels**

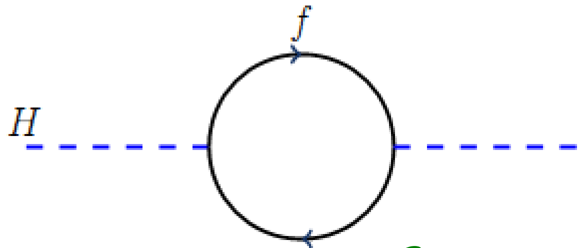
The Standard Model

- **Fundamental particles:**
  - Constituents of matter
    - All *fermions* (spin–½)
    - Leptons: electron, muon, tau, corresponding neutrinos
    - Quarks: up, down, charm, strange, top, bottom
  - Force carriers
    - All *bosons* (spin–1)
    - Electromagnetism: photon
    - Weak interactions: $W^{\pm}$, Z^0
    - Strong interactions: gluons
  - Higgs boson?
    - Generates mass of elementary particles



Problems with the Standard Model

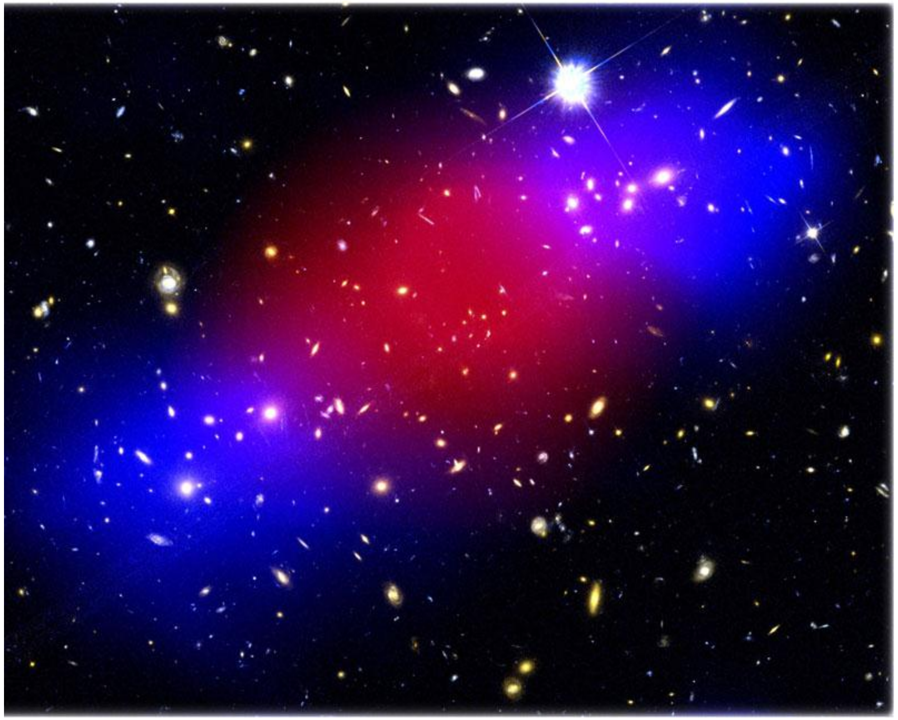
- **Hierarchy problem**
  - **Planck/electroweak scale: $M_P/M_W \sim 10^{16}$**
    - **From weak force: m_H ~ EWK scale**
    - **From fermion loop corrections:**



$$\Delta m_H^{\ 2} = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{UV}^{\ 2} + \cdots$$

  - **Quadratically divergent correction**

- **Dark matter**



Red: baryonic matter (from X-rays)
Blue: total mass (from grav lensing)

  - **All SM particles excluded as DM candidates**

Supersymmetry (SUSY)

- **Each fermion paired with scalar boson, each vector boson paired with fermion**
  - **Every SM particle has “superpartner” not yet discovered**
  - **New particles not discovered: SUSY must be broken symmetry**

Names		spin 0	spin 1/2
squarks, quarks (× 3 families)	Q	$(\tilde{u}_L\ \tilde{d}_L)$	$(u_L\ d_L)$
	$\overline{u}$	$\tilde{u}_R^*$	$u_R^\dagger$
	$\overline{d}$	$\tilde{d}_R^*$	$d_R^\dagger$
sleptons, leptons (× 3 families)	L	$(\tilde{\nu}\ \tilde{e}_L)$	$(\nu\ e_L)$
	$\overline{e}$	$\tilde{e}_R^*$	$e_R^\dagger$
Higgs, higgsinos	H_u	$(H_u^+\ H_u^0)$	$(\tilde{H}_u^+\ \tilde{H}_u^0)$
	H_d	$(H_d^0\ H_d^-)$	$(\tilde{H}_d^0\ \tilde{H}_d^-)$

Names	spin 1/2	spin 1
gluino, gluon	$\tilde{g}$	g
winos, W bosons	$\widetilde{W}^\pm\ \widetilde{W}^0$	$W^\pm\ W^0$
bino, B boson	$\widetilde{B}^0$	B^0

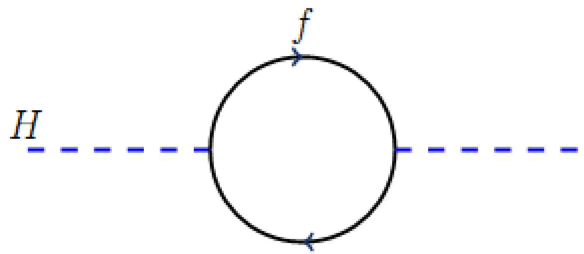
Mixing can occur between gauginos and higgsinos

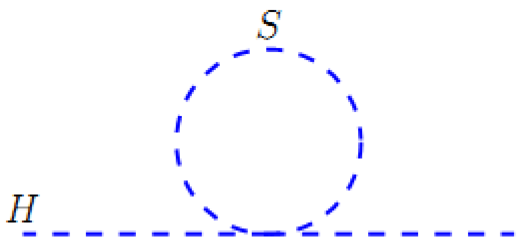
- Gluino exempt due to color
- 4 neutralinos: $\tilde{\chi}_i^{\pm}\ \ (i = 1, 2, 3, 4)$
- 2 charginos: $\tilde{\chi}_i^{0}\ \ (i = 1, 2)$

- **New B/L number violating couplings**
  - **Problem given proton stability**
  - **Define conserved number “R-parity”:** $(-1)^{3(B-L)+2s}$
    - **Lightest SUSY particle (LSP) completely stable**
    - **SUSY particles always decay into odd number of LSPs**
    - **Sparticles produced in pairs**

Consequences of SUSY

- **Predicts scalar boson at EWK scale corresponding to each SM fermion**



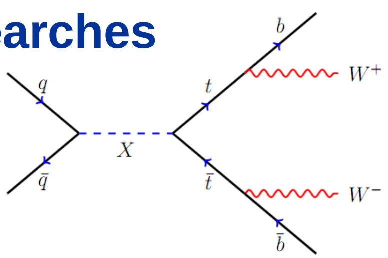


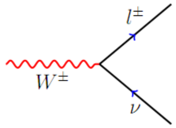
$$\Delta m_H{}^2 = -\frac{|\lambda_f|^2}{8\pi^2}\Lambda_{\mathrm{UV}}{}^2 + \cdots \qquad m_H{}^2 = \frac{\lambda_S}{16\pi^2}\Lambda_{\mathrm{UV}}{}^2 + \cdots$$

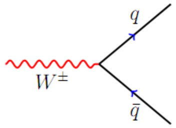
  - **Relative minus sign solves hierarchy problem**
    - **Each SM fermion accompanied by complex scalar with $\lambda_S = |\lambda_f|^2$ so contributions cancel**
- **R-parity conservation**
  - **Stable LSP: Massive, neutral, weakly-interacting**
  - **Ideal dark matter candidate**

Motivation

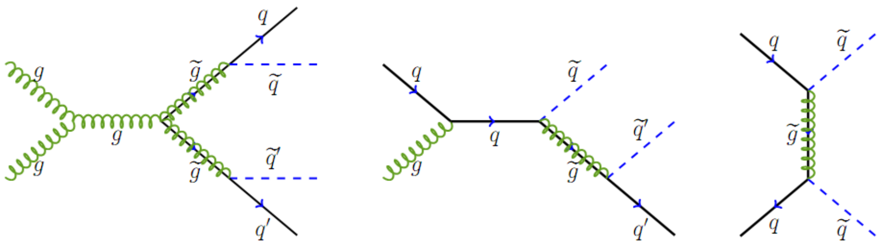
- **Top quark observation major milestone**
- **Understanding top quark signal *vital* for new physics searches**
  - **Top signatures similar to many new physics models**
    - **Semileptonic channel is major background for same-sign dilepton analysis**
  - **Powerful tool for new searches**

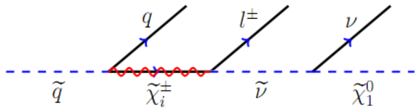






- **Isolated same-sign dileptons very clean signature for new physics**
  - **SM sources vanishingly small**
    - **Primary contribution from 1 isolated lepton plus "fake" (i.e. from semileptonic top events)**
  - **Same-sign leptons occur naturally in many new physics models**





Perturbative QCD

- **Strong interactions described by quantum chromodynamics (QCD)**
  - **Calculable at small distances and high momentum transfer (large Q^2)**
    - **Coupling constant α_s increases with distance**

$$\alpha_s(Q^2) \propto 1/\ln(Q^2/\Lambda_{QCD}{}^2)$$

  - **Approximate solutions obtained by perturbative expansion in α_s terms**

$$d\sigma = A_0 + A_1\alpha_s + A_2\alpha_s{}^2 + A_3\alpha_s{}^3 \cdots$$

Leading order (LO) → $A_1\alpha_s$

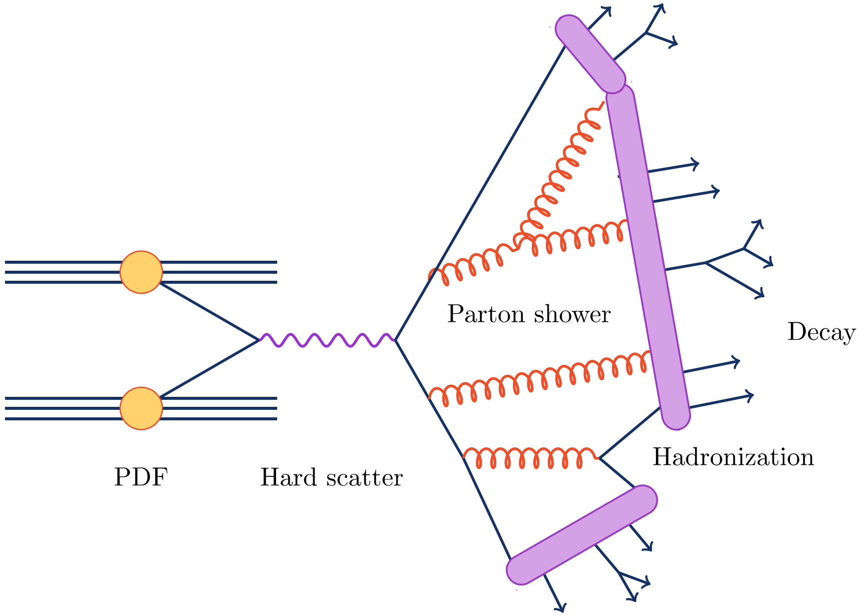
Next-to-leading order (NLO) → $A_2\alpha_s{}^2$

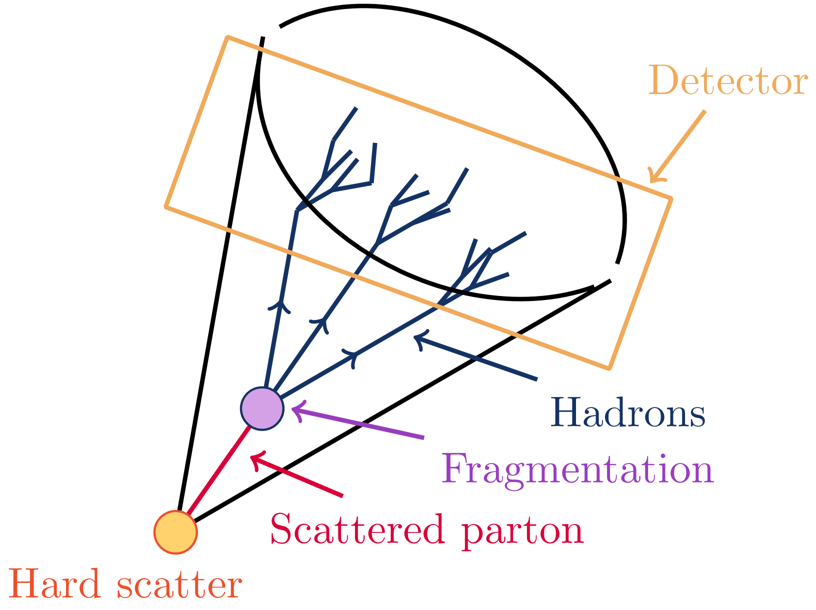
Next-to-next-to leading order (NNLO) → $A_3\alpha_s{}^3$

  - **$\alpha_s(Q \approx M_W = 80$ GeV$)$ ~ 0.1: possible to expand perturbatively**
    - ***Asymptotic freedom***
  - **$\alpha_s(Q \approx 1$ GeV$)$ ~ 0.62: perturbative expansion less accurate**
  - **$\alpha s(Q \approx \Lambda_{QCD}) \rightarrow \infty$: *color confinement*, perturbative QCD invalid**

Parton showers and hadronization

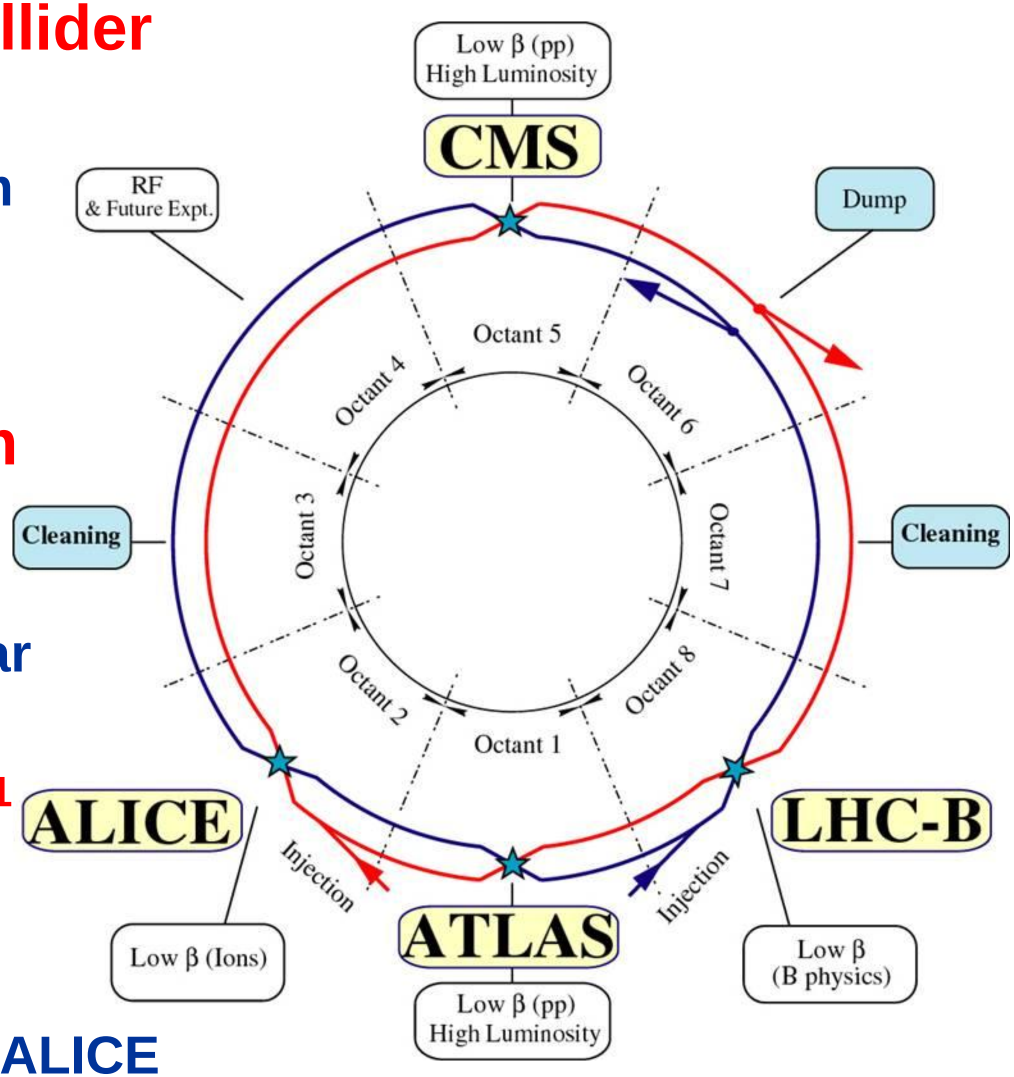
- **Structure of colliding protons modeled with parton distributions functions (PDFs)**
  - **Define probability density for finding parton (quark or gluon) with momentum fraction x at momentum transfer Q^2 of collision**
- **Parton shower: Colored remnants from hard interaction shower due to color confinement**
  - **Eventually hadronize into collimated jets of colorless hadrons**
    - **Modeled from previous experiments with non-perturbative QCD**



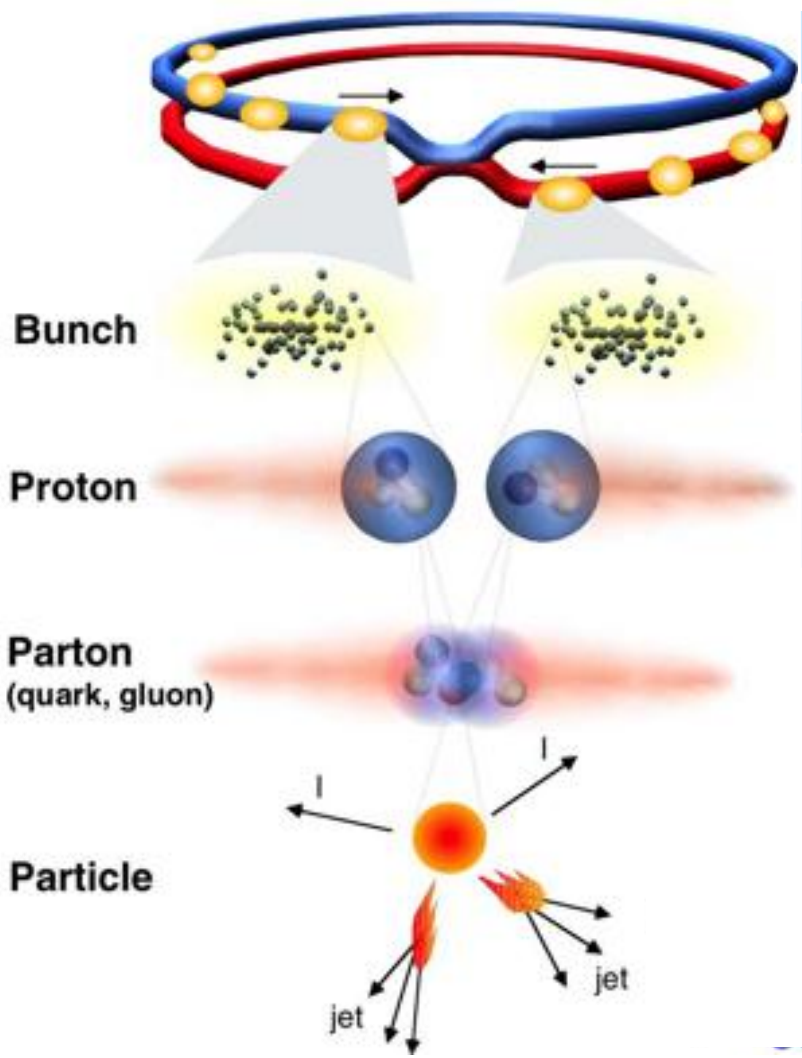


The Large Hadron Collider

- **7 TeV proton-proton collider**
  - 3.5 TeV per beam
  - Nominal: 7 TeV per beam
- **Magnets with 4T field**
  - Nominal: 8T field
- **Circumference of 27 km**
  - In tunnel 100m underground across Swiss/French border near Geneva
- **Luminosity: 10^{32} cm^{-2}s^{-1}**
  - Nominal: 10^{34} cm^{-2}s^{-1}
- **4 collision points**
  - CMS, ATLAS, LHCb and ALICE



Proton-proton collisions at the LHC



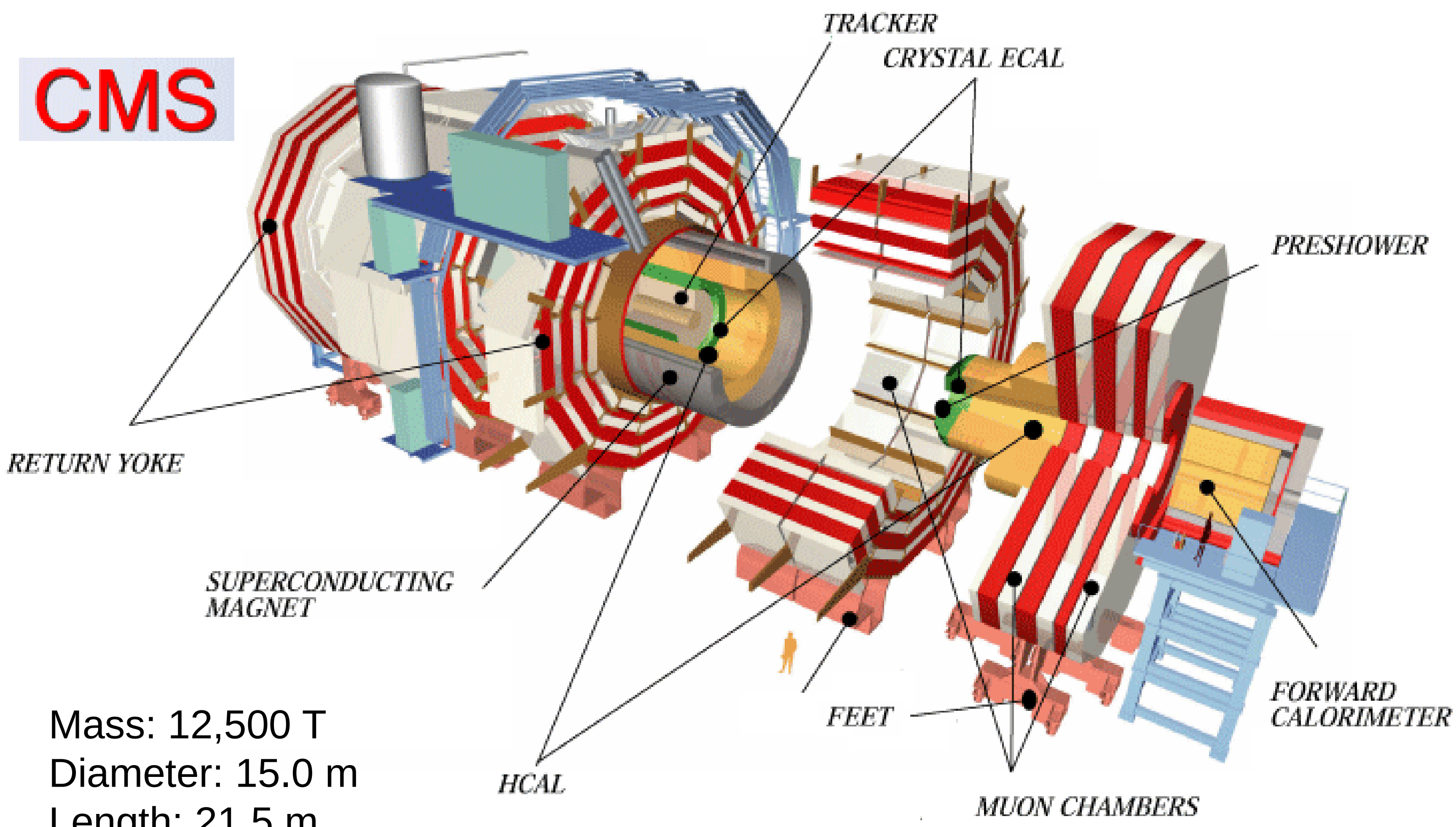
	Design	Achieved
Beam energy	7 TeV	3.5 TeV
Proton-proton Bunches/beam	2835	368 (2010) 1380 (2011)
Protons/bunch	1.15×10^{11}	1.3×10^{11} (2010) 2.7×10^{11} (2011)
Luminosity	10^{34} cm^{-2}s^{-1}	2×10^{32} cm^{-2}s^{-1} 1×10^{33} cm^{-2}s^{-1}

Luminosity L = particle flux/time

Interaction rate: $\frac{dN}{dt} = L\sigma$

Cross section: σ = "effective" area of interacting particles

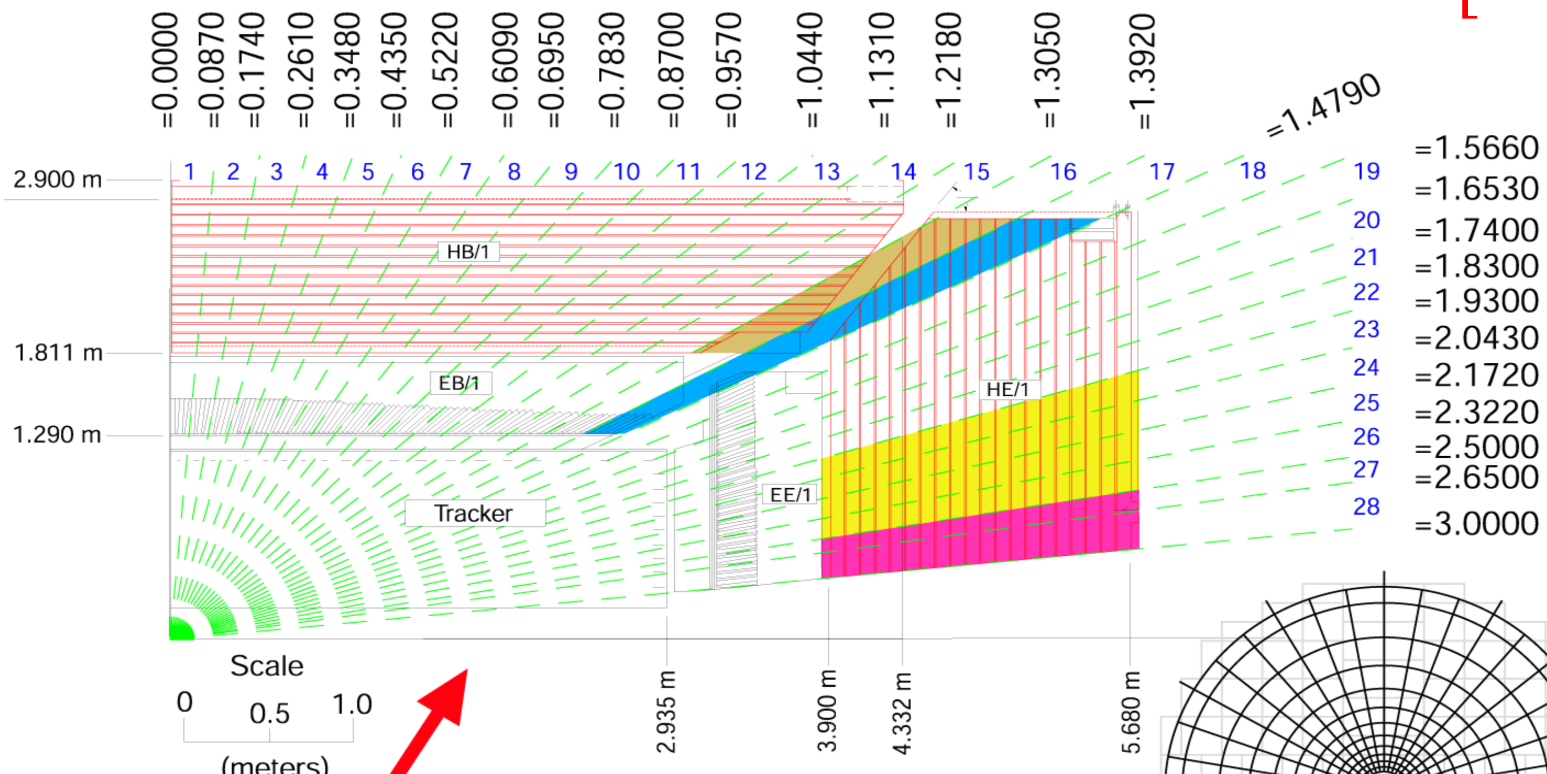
Compact Muon Solenoid (CMS)



Mass: 12,500 T
Diameter: 15.0 m
Length: 21.5 m
Magnetic field: 3.8 T

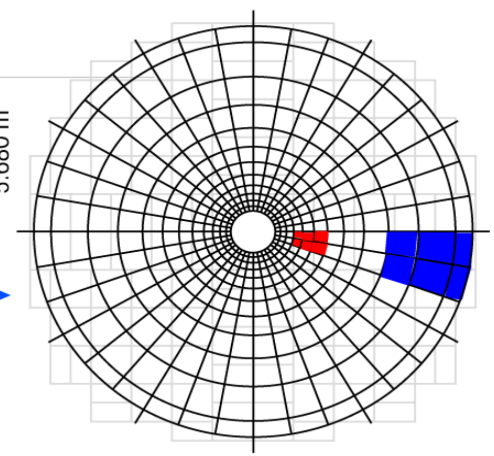
- **Phi and eta (pseudorapidity)**

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$



Barrel & Endcap:
E & H: 72 φ x 56 η
(|η| < 3.0)

Forward:
H only: 18 x 4
(3.0 < |η| < 5.0)

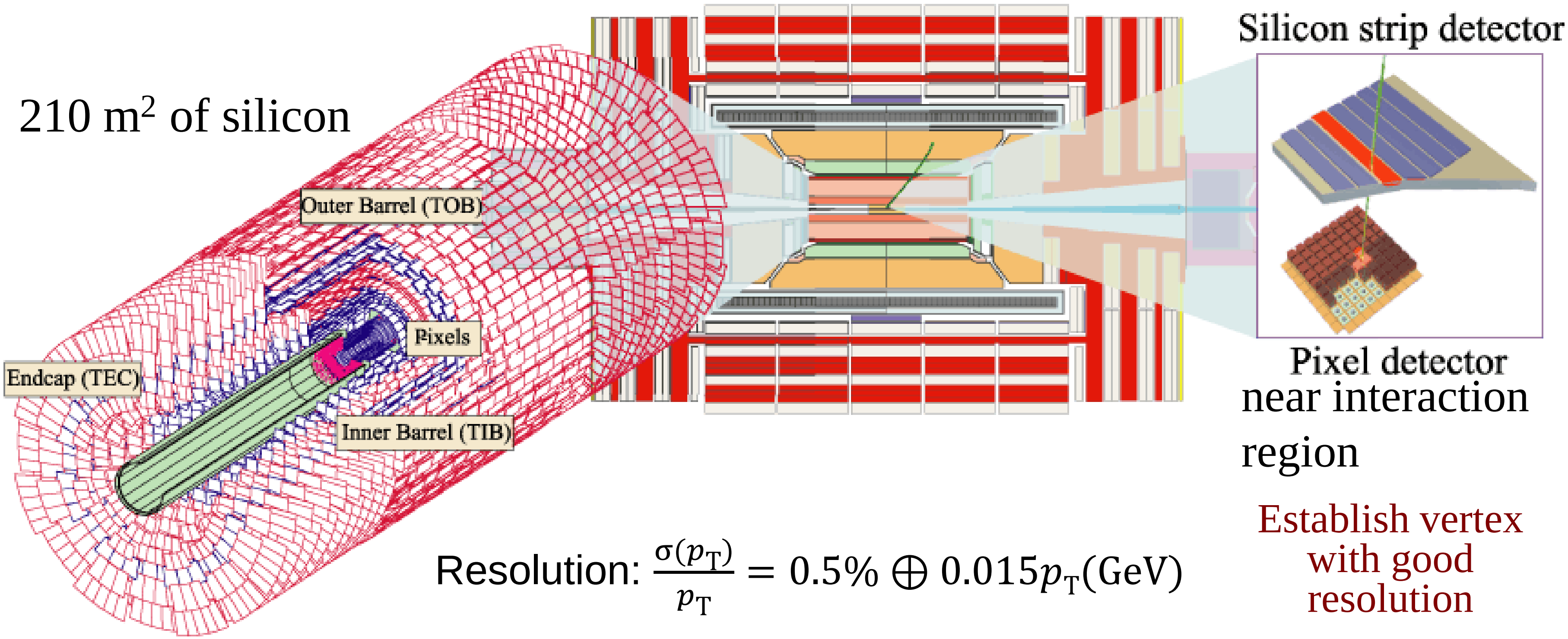


Tracker

- **Measures path and transverse momentum (p_T) of charged particles**
  - **Helps identify electrons from top quark / SUSY particle decays**
  - **Distinguishes electrons from photons**

210 m² of silicon

Barrel and endcaps have



near interaction region

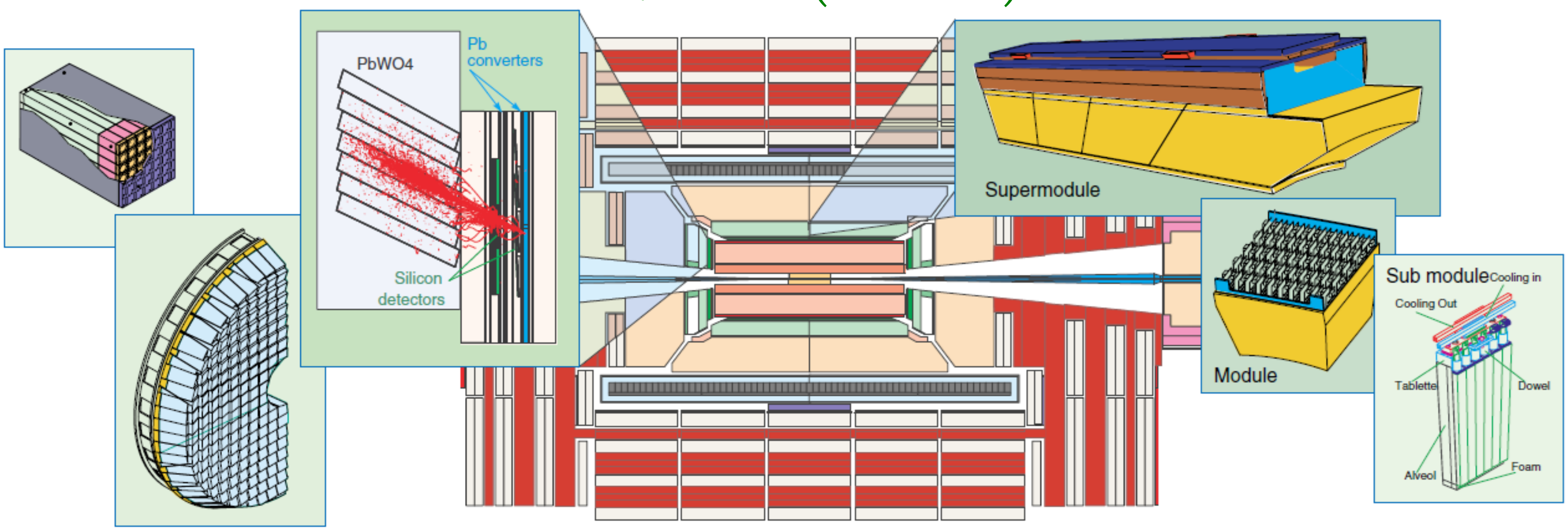
Establish vertex with good resolution

Resolution: $\frac{\sigma(p_T)}{p_T} = 0.5\% \oplus 0.015 p_T(\text{GeV})$

Electromagnetic calorimeter (ECAL)

- **Measures electron/photon energy and position in |η| < 3**
  - **~76,000 lead tungstate crystals**
    - **Density: 8.3 g/cm^3**
    - **Short radiation length: 0.89 cm (25.8 X_0 in length)**
    - **Small Moliere radius: 2.2 cm**

Resolution: $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{2.8\%}{\sqrt{E}}\right)^2 + \left(\frac{41.5\ \mathrm{MeV}}{E}\right)^2 + (0.3\%)^2$



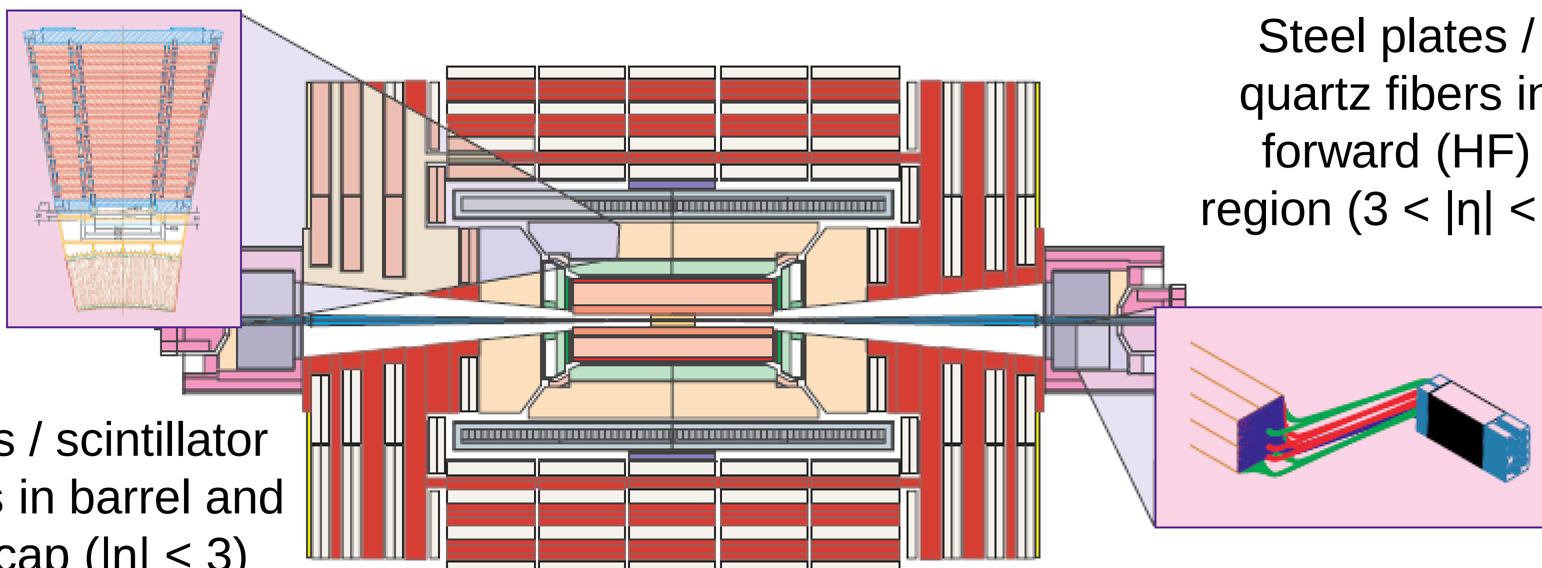
Hadron calorimeter (HCAL)

- **Measures energy and position of showers**
  - **Sampling calorimeter**
  - **Used in measurement of energy of jets in event**

Resolution (barrel): $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{90\%}{\sqrt{E}}\right)^2 + (4.5\%)^2$

Resolution (endcap): $\left(\frac{\sigma}{E}\right)^2 = \left(\frac{198\%}{\sqrt{E}}\right)^2 + (9.0\%)^2$

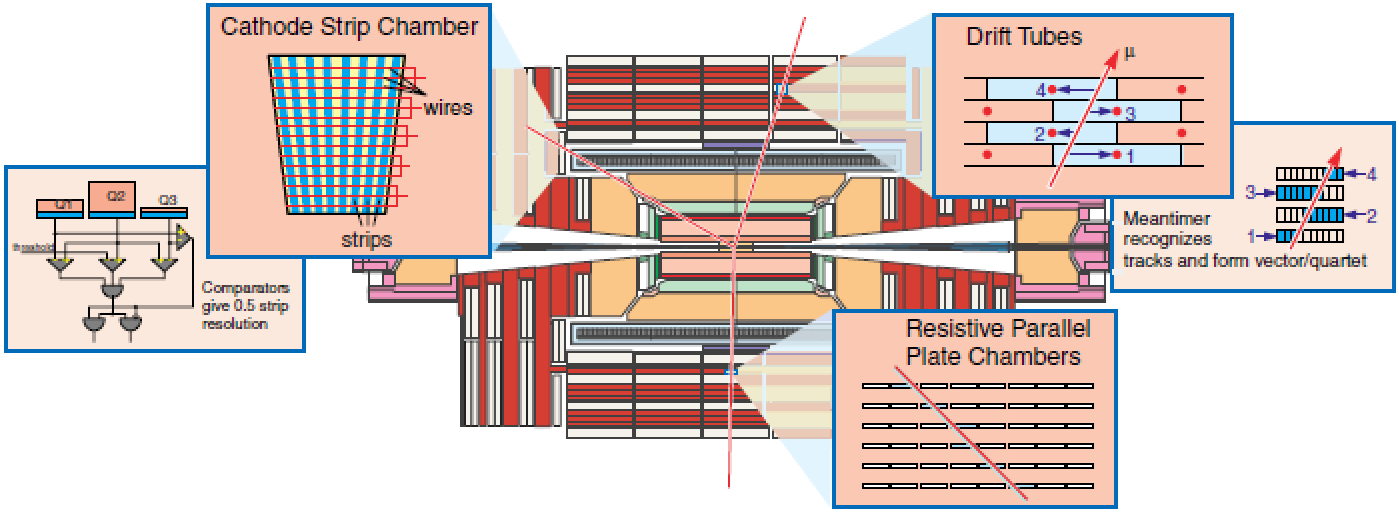
Steel plates / quartz fibers in forward (HF) region ($3 < |\eta| < 5$)



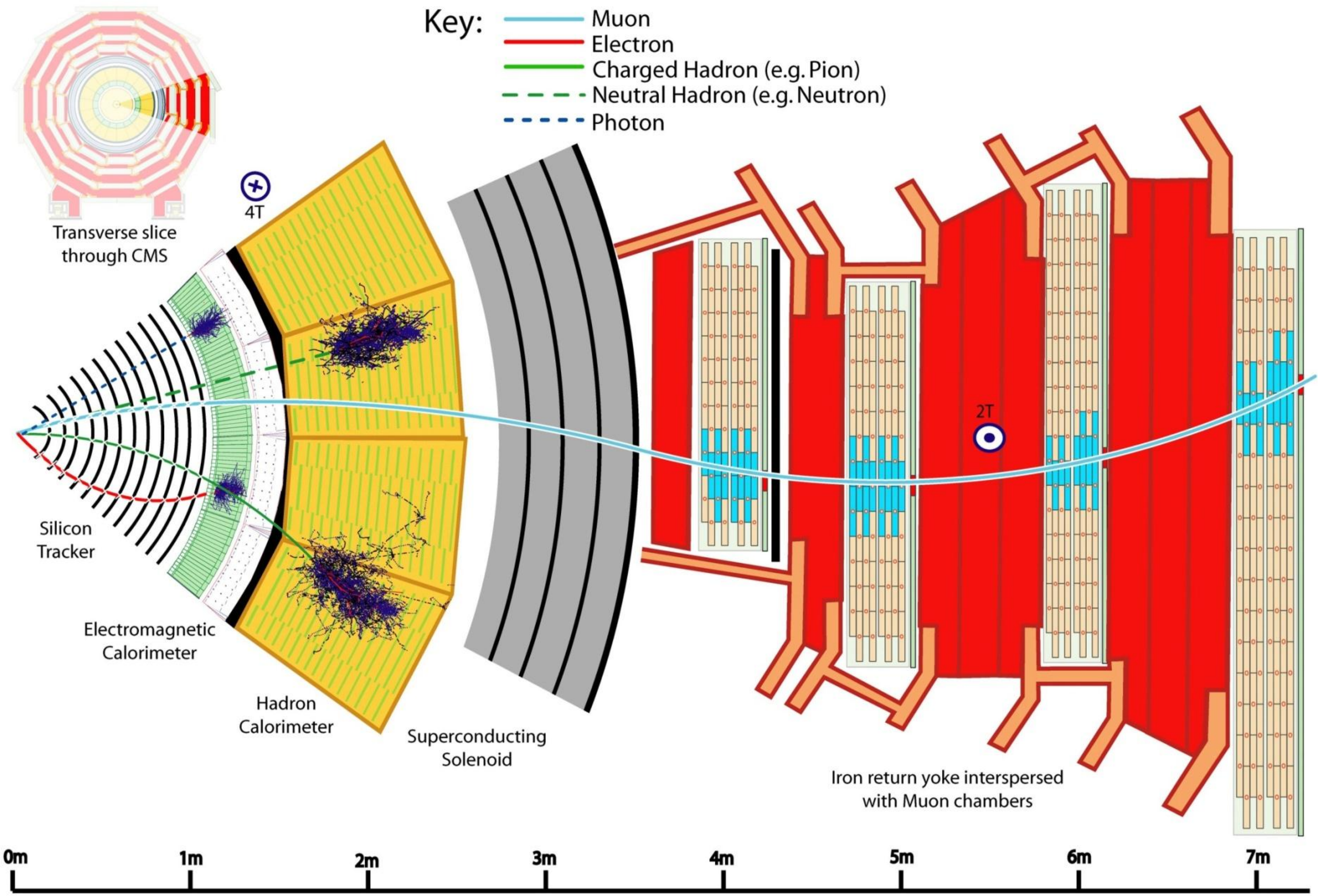
Brass / scintillator layers in barrel and endcap ($|\eta| < 3$)

Muon system

- **Three separate detector systems**
  - **Drift tubes (DT) in central region (|η| < 1.2)**
    - **Precise trajectory measurements**
  - **Cathode strip chambers (CSC) in endcaps (0.9 < |η| < 2.4)**
  - **Resistive plate chambers (RPC) in barrel (|η| < 1.6)**
    - **Precise timing of muons in detector**

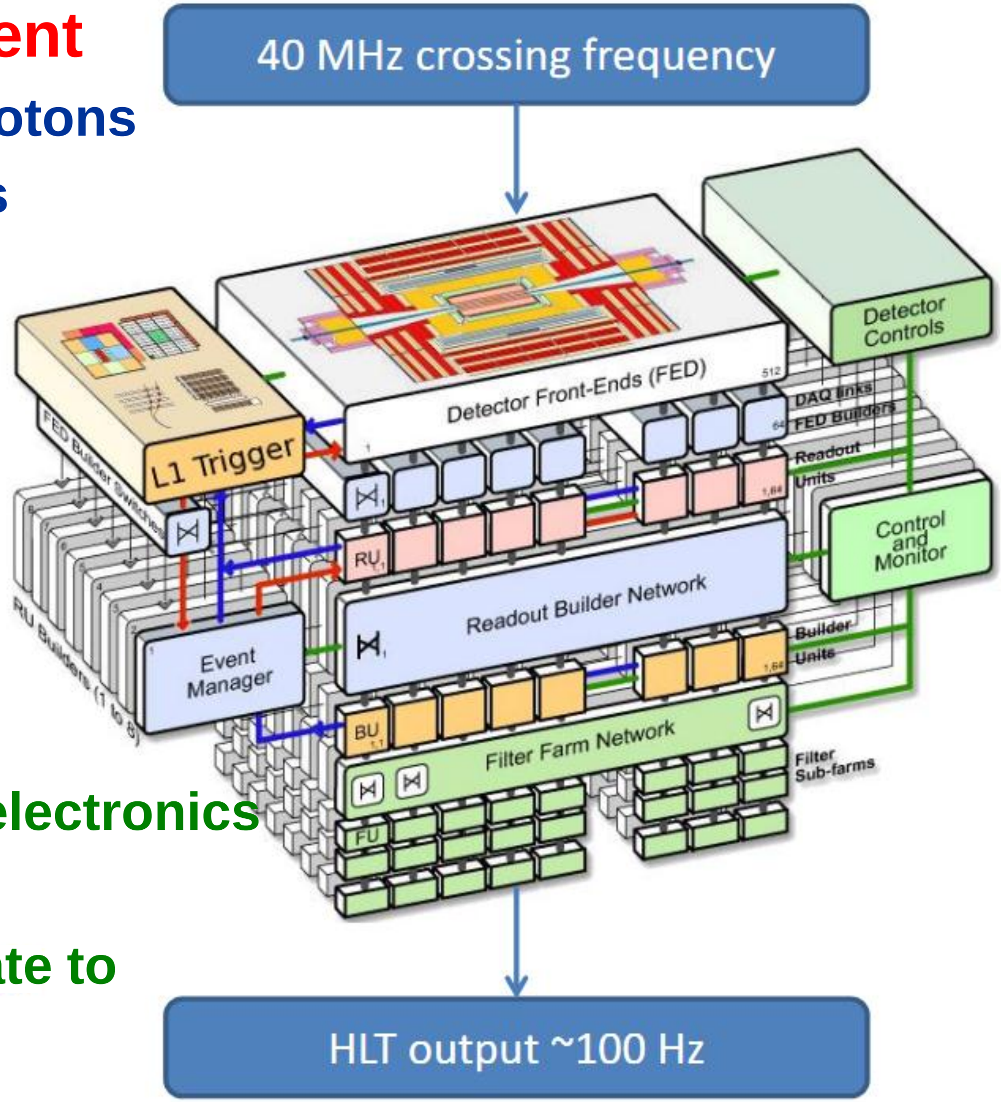


Detecting particles



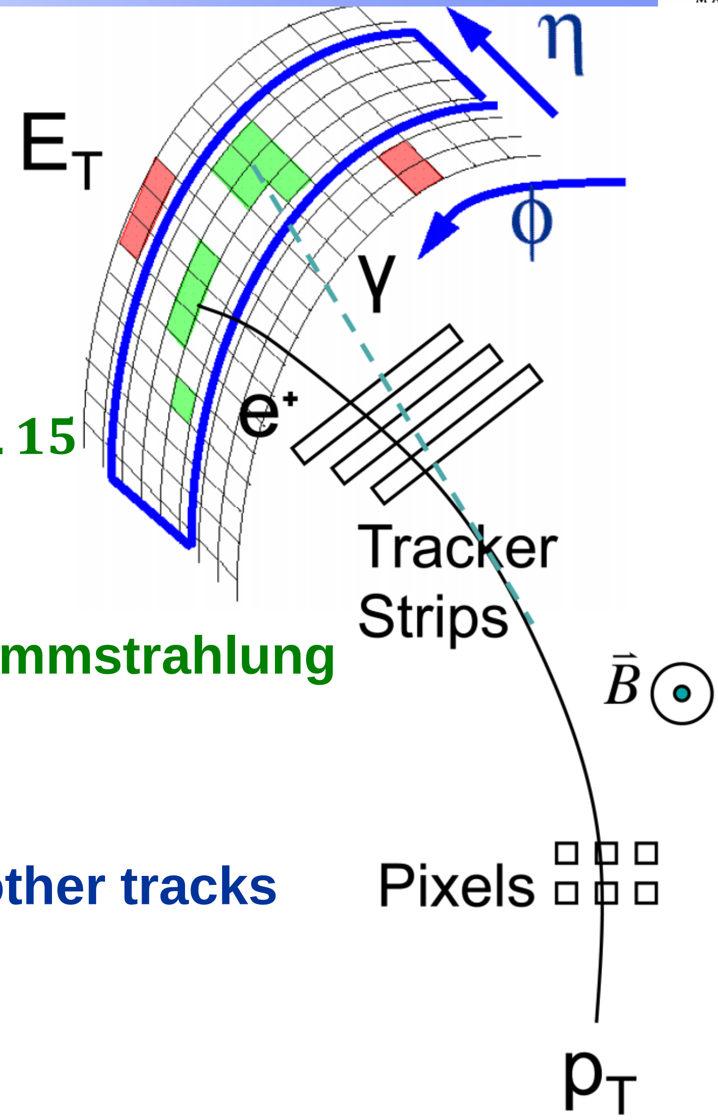
Trigger

- **Cannot retain every event**
  - **Beam contains ~ 10^{11} protons**
  - **~ 25 ns bunch crossings**
  - **2.2 pp interactions per crossing**
- **Trigger designed to select "interesting" events for offline processing**
  - **Level 1 (L1) trigger**
    - **High-speed custom electronics**
  - **High level trigger (HLT)**
    - **Reduce final event rate to ~ 300 Hz**



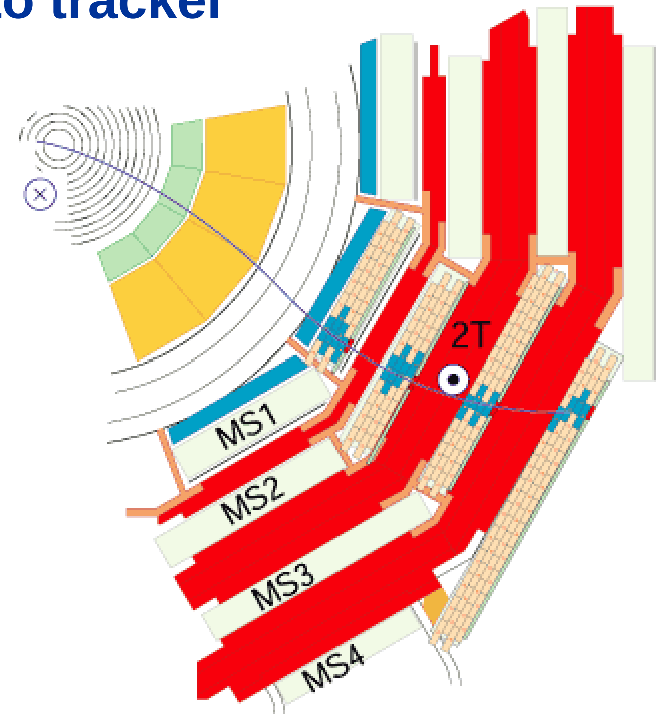
Reconstructing electrons

- **Electron candidates**
  - **Tracks reconstructed from hits in silicon tracker**
  - **Cluster in ECAL matched to tracker hits**
    - **Require $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} < 0.15$**
  - **ID based on shower shape and track-cluster matching**
    - **Wider spread in ϕ due to bremmstrahlung**
  - **Small energy deposit in HCAL**
    - **$E_{Had}/E_{EM} < 0.15$**
  - **Isolation: No nearby energy or other tracks**



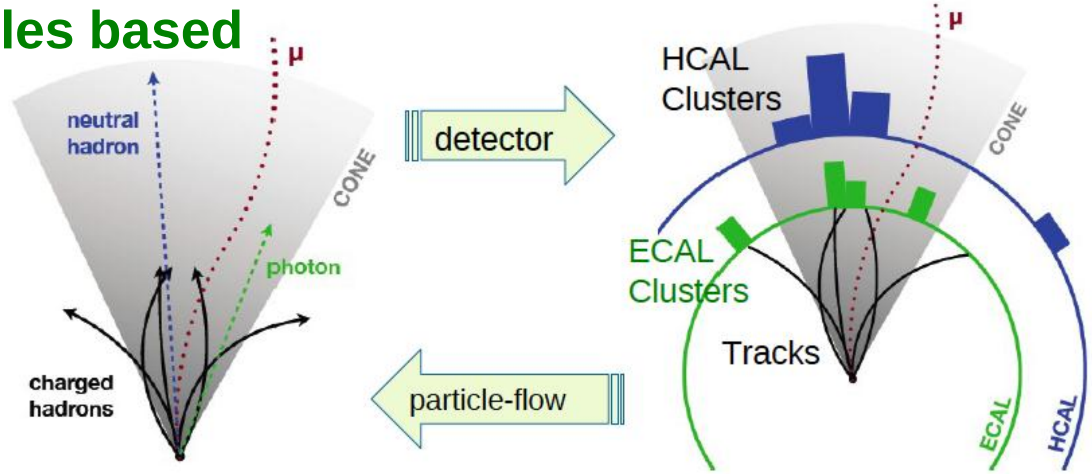
Reconstructing muons

- **Reconstructed via 2 algorithms**
  - **Tracker muon: Seeded from tracks, matched to signals in calo and muon systems**
    - **More efficient for low-p_T muons, require only single segment in muon chambers**
  - **Global muon: Global simultaneous fit to tracker and muon hits**
    - **Useful for high-pT muons (> 200 GeV) due to improved momentum resolution**
  - **Require muons to be reconstructed by both algorithms**



Reconstructing jets

- **Particle Flow (PF) algorithm used to construct jets**
  - Combines information from all CMS subdetectors
  - Creates list of PF objects
    - PF list includes electrons, muons, charged hadrons and neutral hadrons
  - Particle list clustered according to anti-k_T jet clustering algorithm
    - Sequential recombination algorithm
    - Combine particles based on distance measurement starting from closest jet



Missing transverse energy (MET)

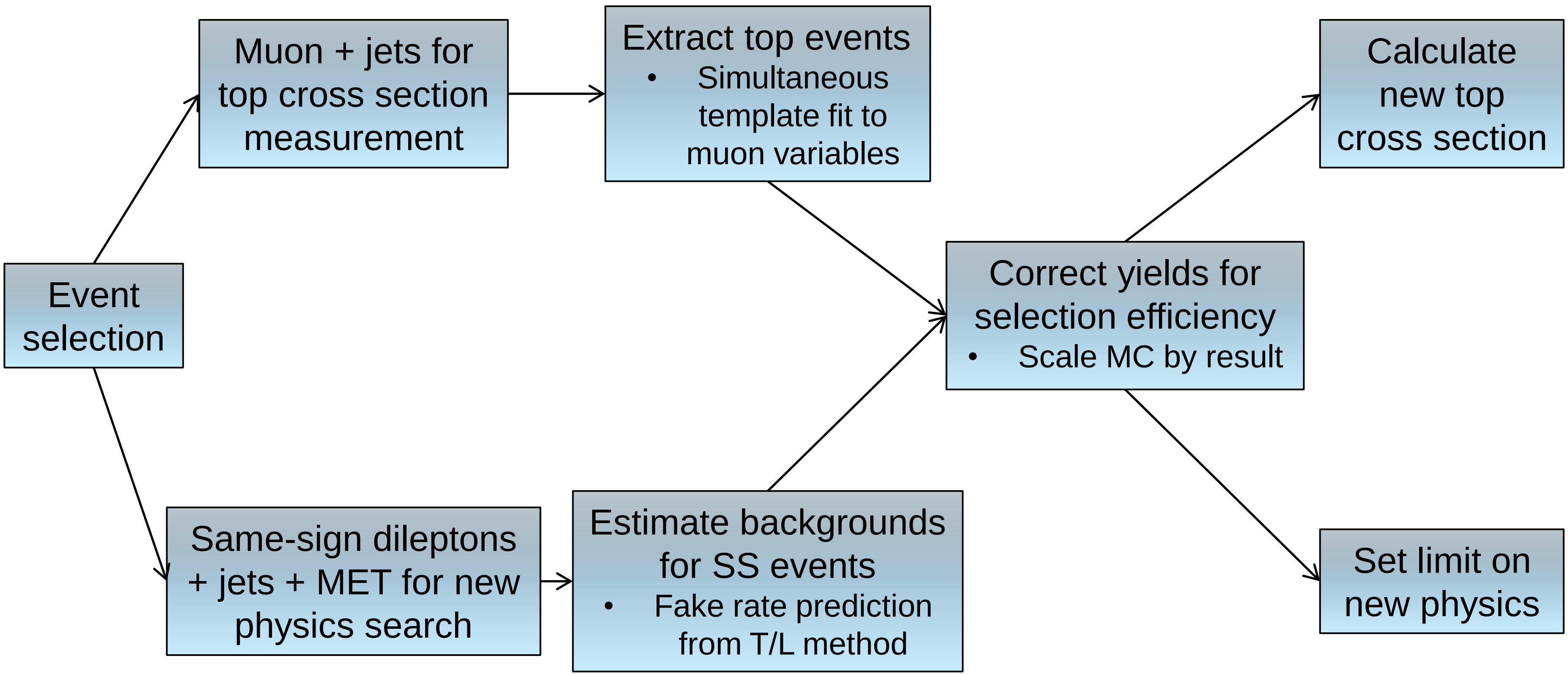
- **Several particles in analysis only detectable from missing energy**
  - **Neutrinos, neutral LSPs interacts weakly with matter**
  - **Rely on momentum conservation in transverse plane**
    - **Define missing transverse energy (MET):**

$$E_T^{\text{miss}} = \left| -\sum_{i}^{n} \overrightarrow{p_{Ti}} \right|$$

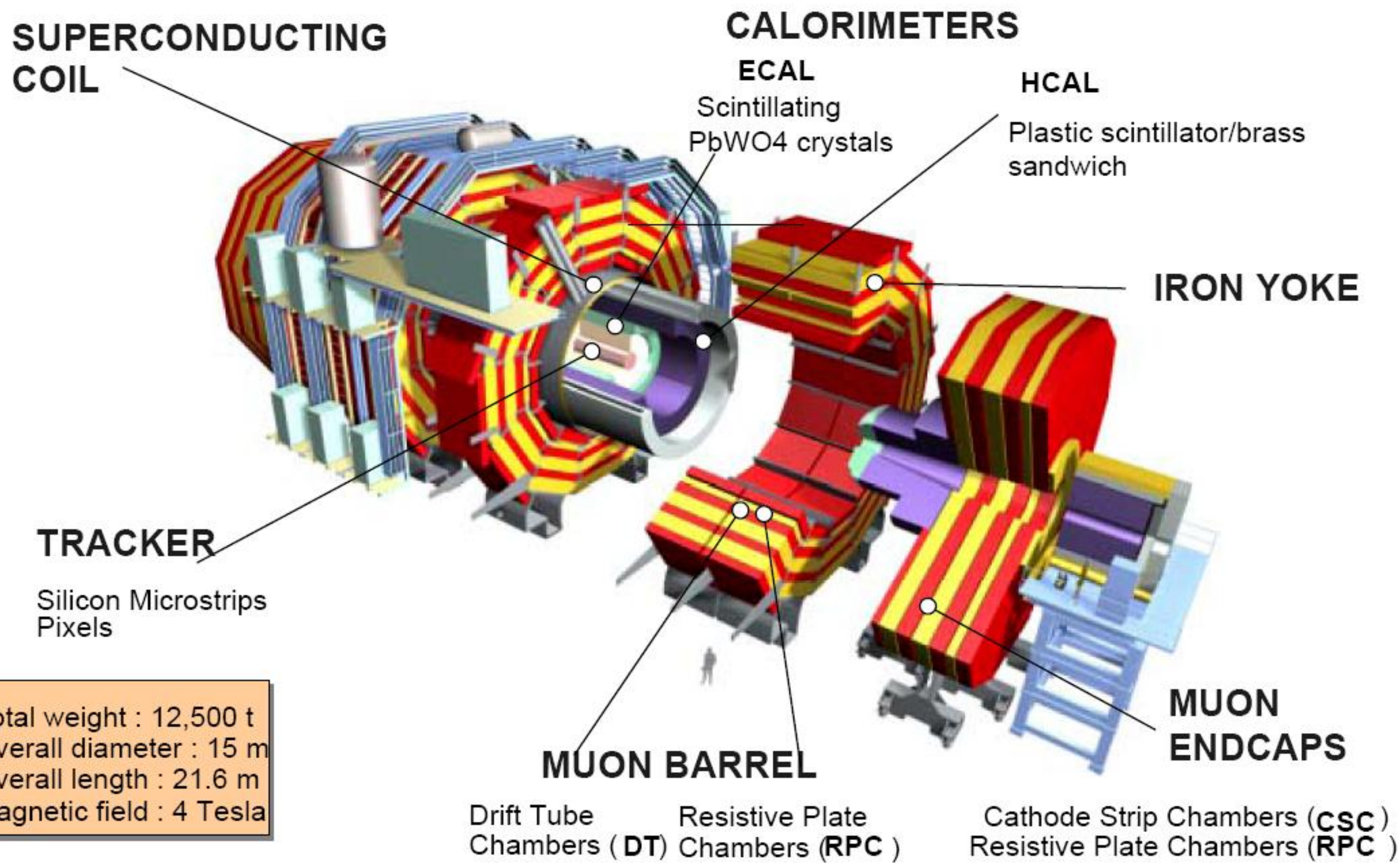
where *i* is index of PF object

  - **MET calculation involves every particle in event**
    - **Sensitive to mismeasurements in p_T of any reconstructed object**

Analysis workflow



Compact Muon Solenoid



Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

Object definitions

- **Electrons (same-sign dileptons)**
  - **High-p_T electron selection**
    - $p_T > 20/10$ GeV, $|\eta| < 2.4$
    - VBTF_ID 80
    - $|d_{0,\,corr}| < 0.02$
    - No muons within $\Delta R < 0.1$
    - No missing hits in inner layers
    - Conversion rejection (dcot > 0.02 OR dist > 0.02)
    - Relative isolation < 0.1
  - **Differences for low-p_T electron selection**
    - $p_T > 10$ GeV, $|\eta| < 2.4$
    - Relative isolation < 0.15

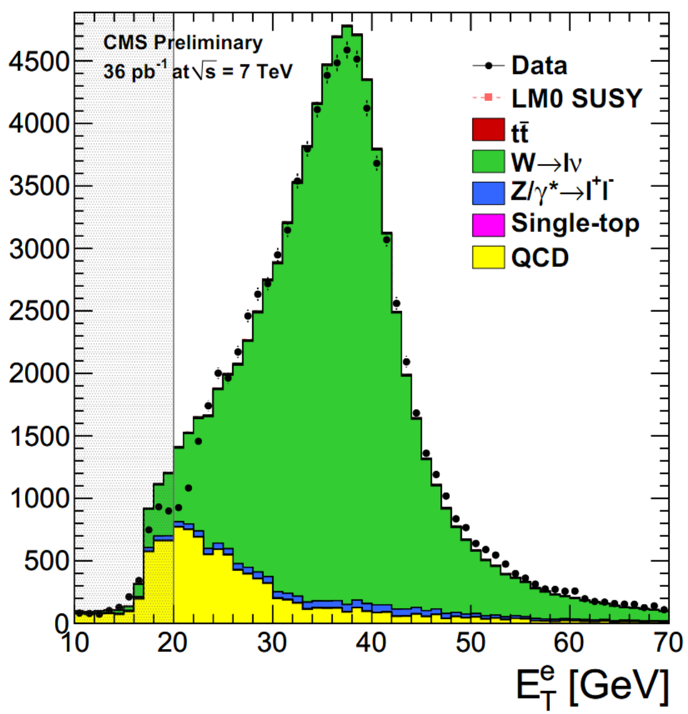
- **Muons**

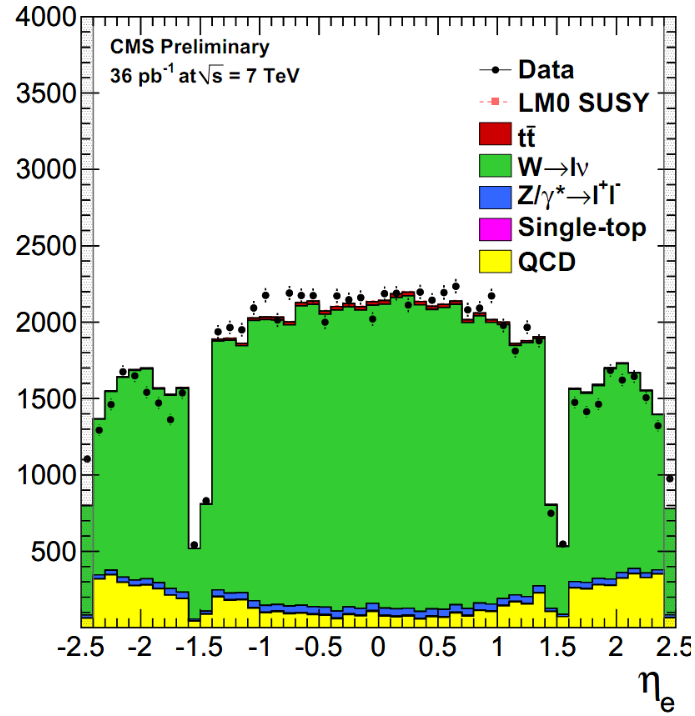
	Top selection	SUSY selection
Kinematic cuts	$p_T > 20$ GeV $\|\eta\| < 2.1$	pT > 20/10 GeV $\|\eta\| < 2.1/2.4$
Rel isolation	< 0.05	< 0.1
X^2/n_{dof}	< 10	< 10
$\|d_{0,\,corr}\|$	< 0.02 cm	< 0.02 cm
ΔZ_{vtx}	< 1 cm	< 1 cm
Silicon hits	≥ 11	≥ 11
Additional cuts	ΔR(μ, jet) > 0.3	---

- **Jets, MET**
  - PF MET
  - L2L3 corrected PF jets with pT > 30 GeV, $|\eta| < 2.5$
  - No jets within $\Delta R < 0.4$ of lepton
  - Loose PF jet ID

Electron selection: E_T and η

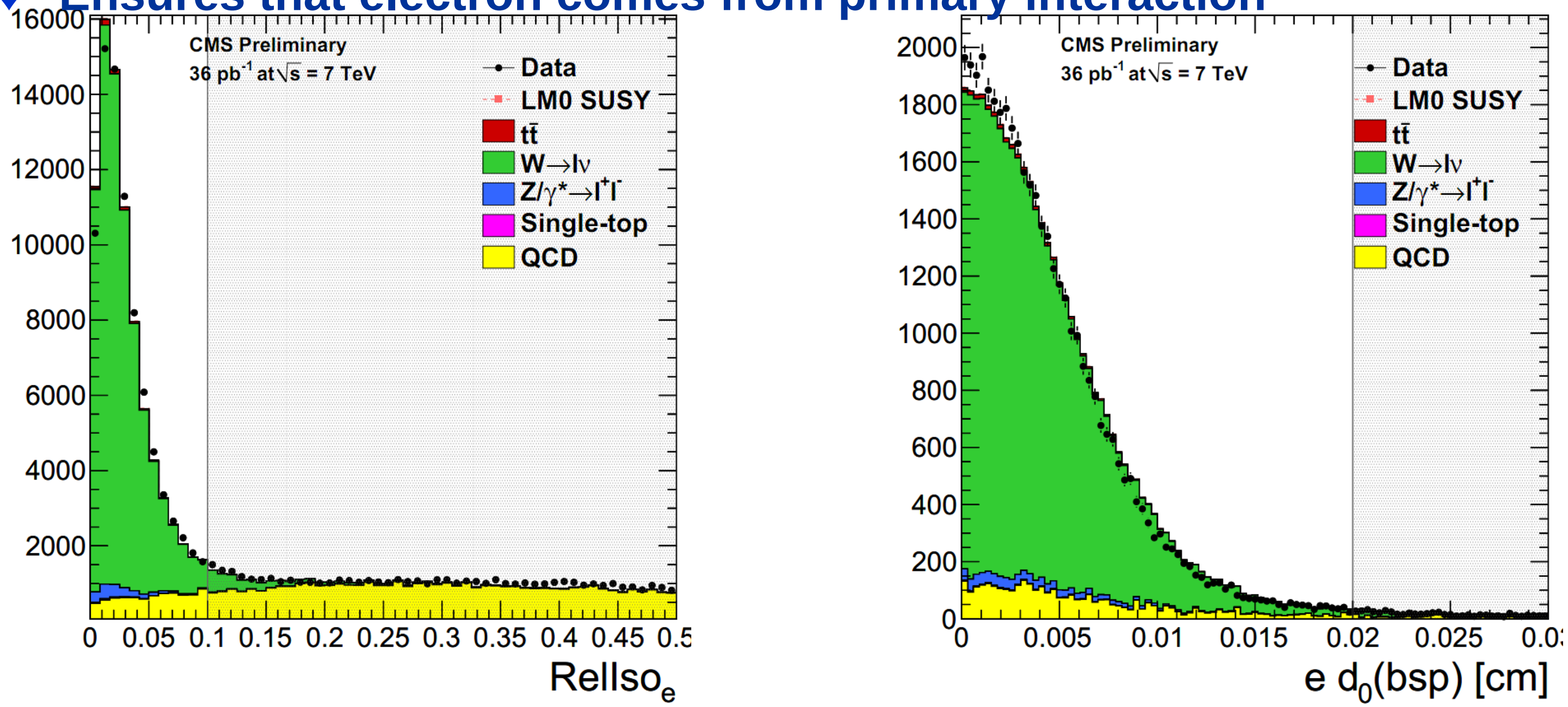
- **Initial cuts: single lepton trigger, MET > 30 GeV**
  - **QCD dominates unless some initial selection applied**
- **All plots shown with previous cuts applied ("progressive" plots)**
- **All MC "out of the box"**
  - **Scaled by σL (NLO σ from MC, L = 36 pb^{-1})**
- **Shaded area represents rejected region for SUSY search**





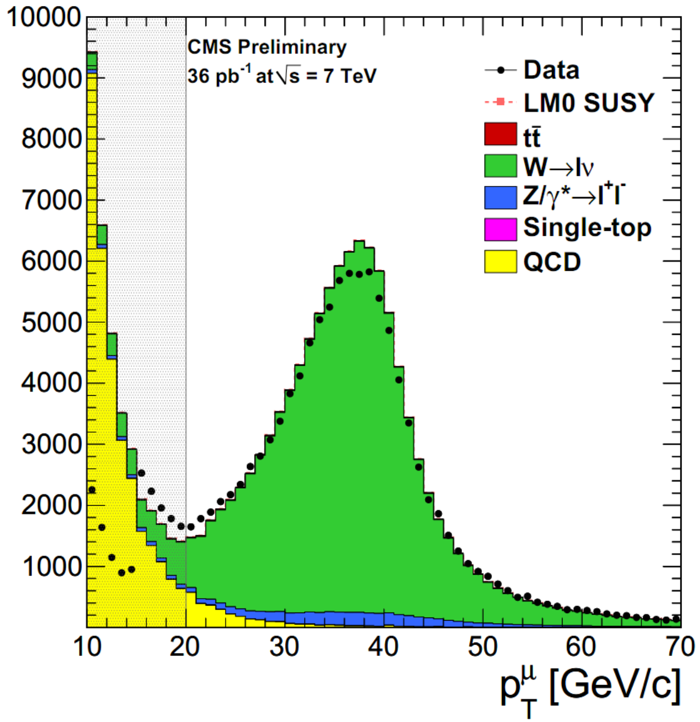
Electron quality selection: RelIso and d_0(bsp)

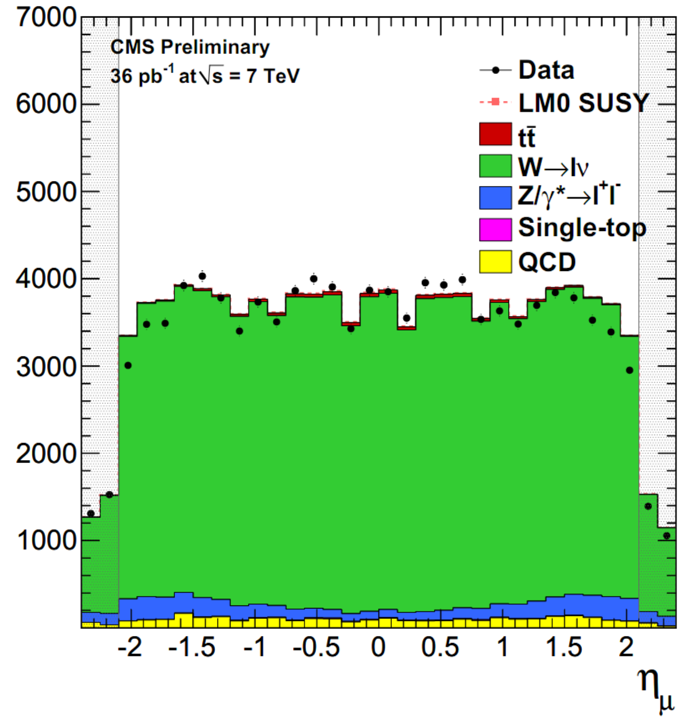
- **Relative isolation < 0.1**
  - RelIso = $(Iso_{trk} + Iso_{ECAL} + Iso_{HCAL}) / E_T$
  - High-RelIso region dominated by QCD
- **d_0(bsp) < 0.02 cm**
  - Transverse impact parameter (w.r.t. beamspot)
  - Ensures that electron comes from primary interaction



Muon selection: p_T and η

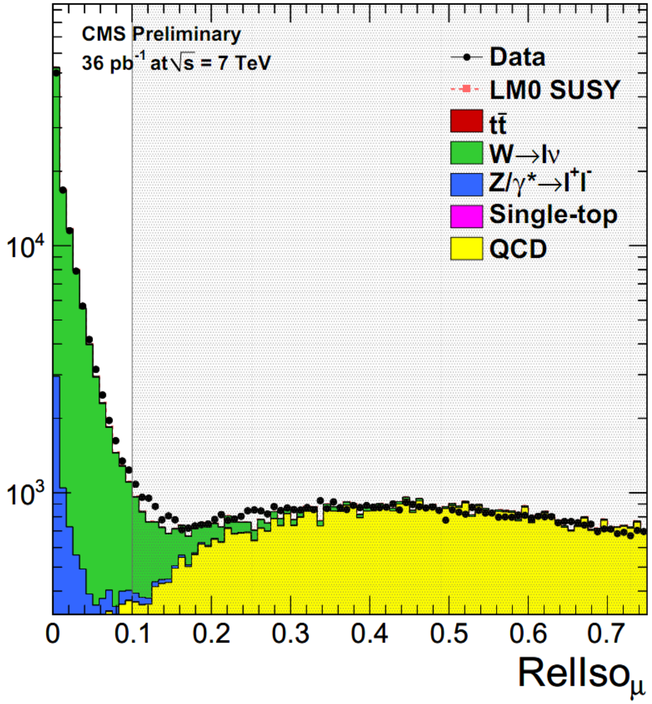
- **Require triggered muon p_T > 20 GeV**
  - Second muon in event must have p_T > 10 GeV
  - Ensures event has high efficiency to pass single lepton trigger
- **Triggered muon must have $|\eta|$ < 2.1**
  - Corresponds to η acceptance of muon trigger

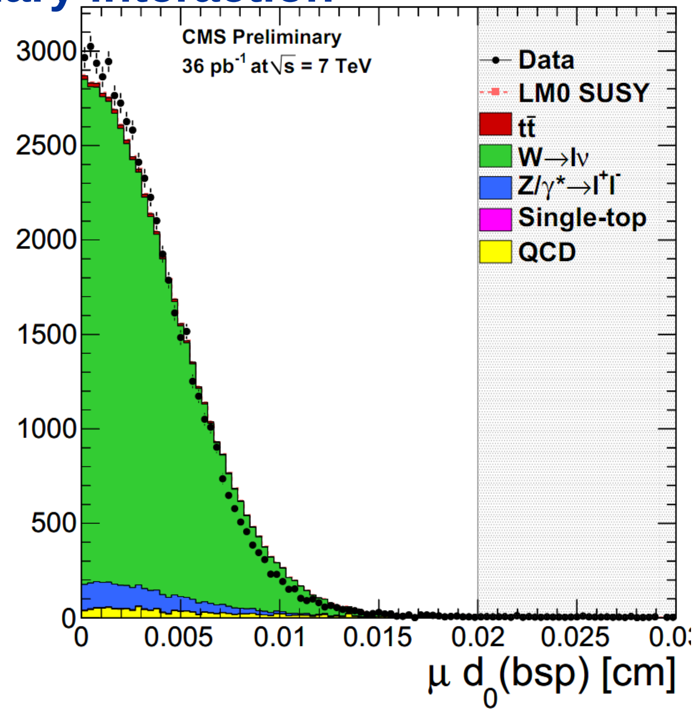




Muon quality selection: RelIso and d_0(bsp)

- **Relative isolation < 0.1**
  - Defined as for electrons
  - High-RelIso region dominated by QCD
- **d_0(bsp) < 0.02 cm**
  - Transverse impact parameter (w.r.t. beamspot)
  - Ensures that muon comes from primary interaction

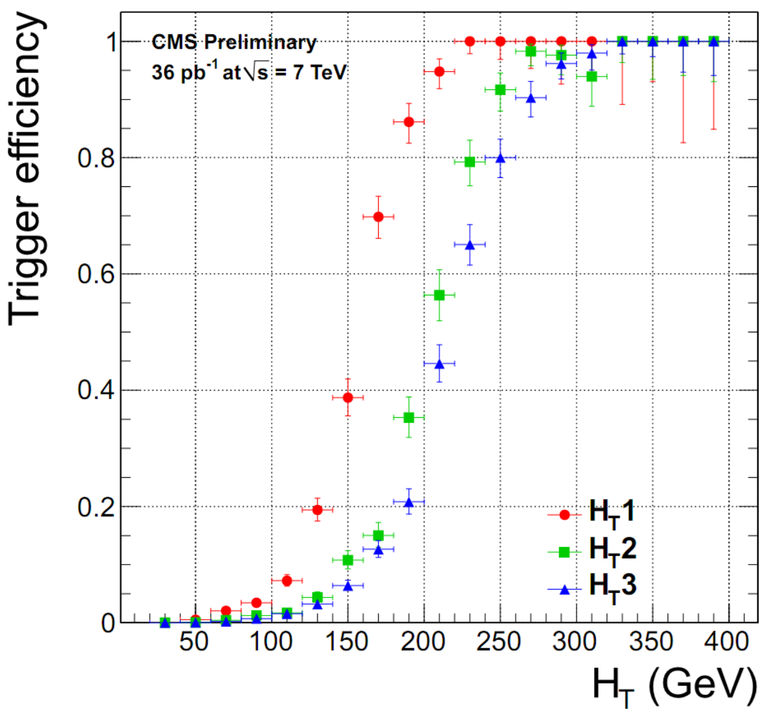




Same-sign dilepton trigger selection

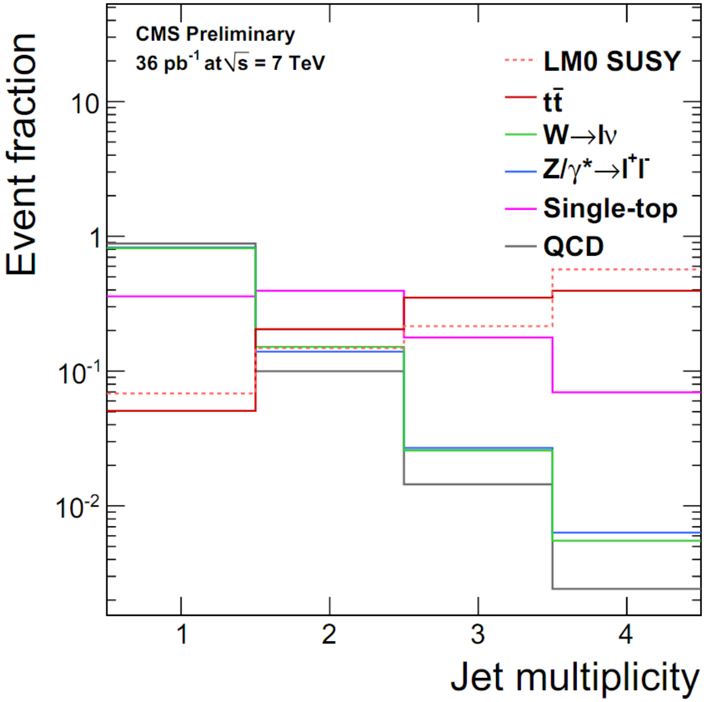
- **Necessary to use multiple single-lepton, H_T triggers**
  - **Move to higher thresholds with increasing luminosity so triggers remain unprescaled**
- **Divide analyses based on trigger:**
  - **Single-muon triggers for top cross section measurement (μ + jets channel)**
  - **Lepton (electron OR muon) triggers for high-p_T same-sign dilepton search**
  - **H_T triggers for low-p_T same-sign dilepton search**

- **H_T trigger efficiency vs reconstructed H_T**
  - **Measured from data via muon triggers**
  - **Efficiency reaches (94 ± 5)% at H_T = 300 GeV**
- **Lepton trigger efficiency**
  - **For μ + jets channel (from T&P): Scale factor = 0.97 ± 0.002**
  - **For same-sign dileptons (from T&P in MC): 0.99 ± 0.01 for all three final states**



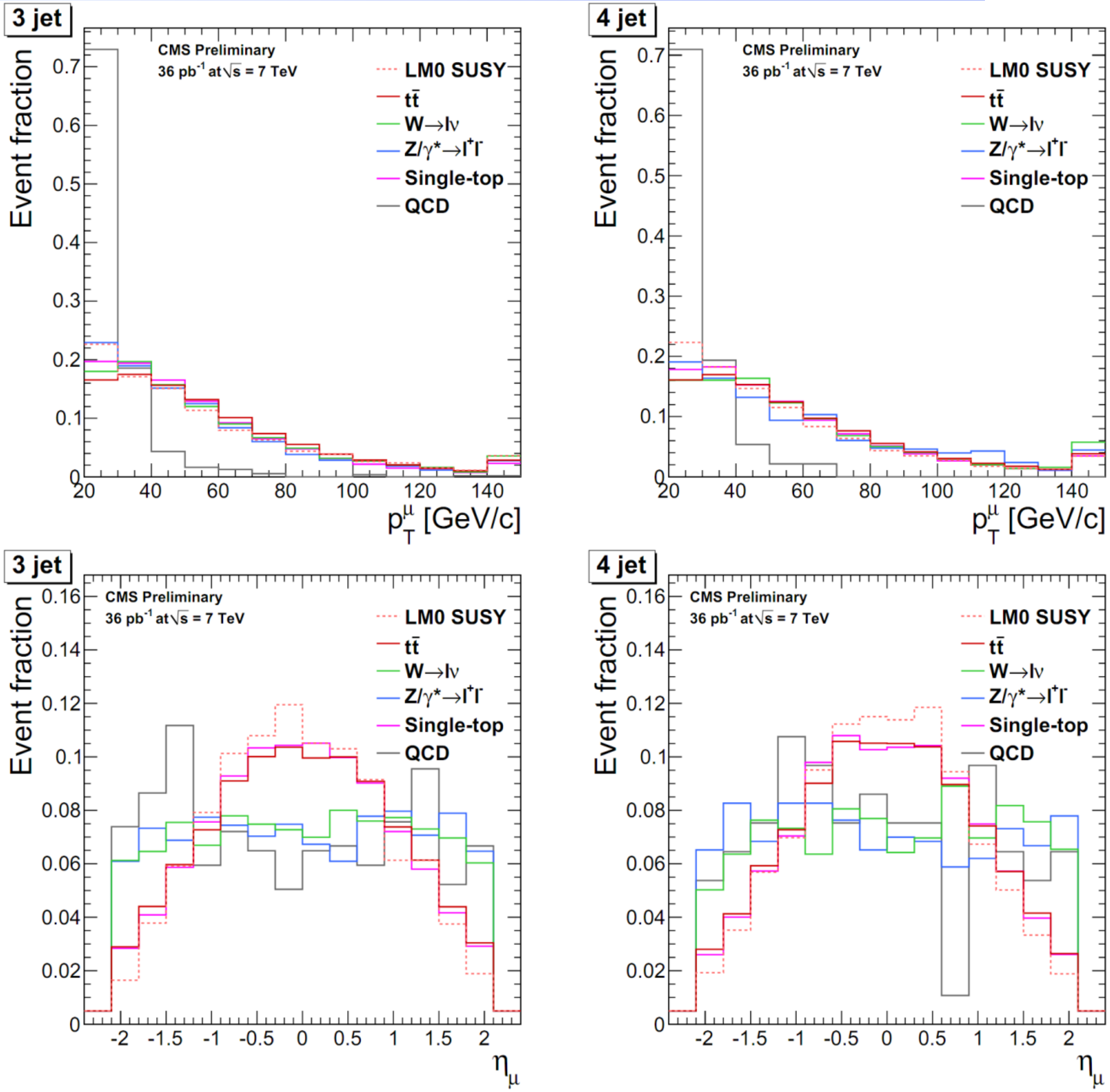
Top cross section extraction

- To estimate backgrounds, we first extract top cross section in top-enriched single muon region
  - Lose all statistics once we impose second same-sign lepton requirement
  - Determine MC scale factors for use in SUSY search
- Extract top cross section using binned maximum likelihood fit
  - Use fit templates taken from MC samples to model each process
  - Simultaneous fit to discriminating variables across multiple jet bins
    - Normalization template implicitly fixed by shape of jet multiplicity spectrum



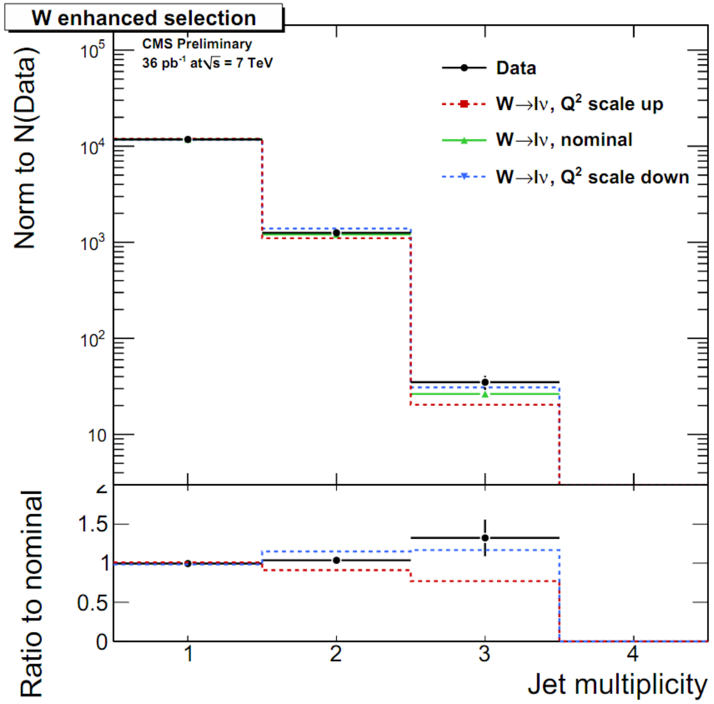
Shape comparisons

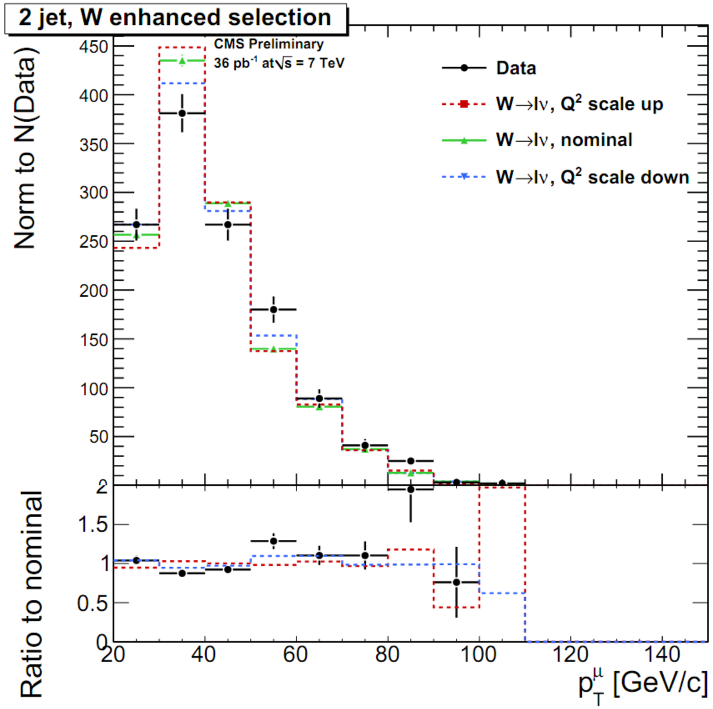
- **Fit performed with muon variables**
  - Appropriate due to insensitivity to systematics like JES
  - Tried multiple variables, jet bin variables, jet bin combinations
- **Additional constraints**
  - W/Z cross section ratio within 30% of theory value
  - Single top cross section within 30% of theory value



W + jets modeling

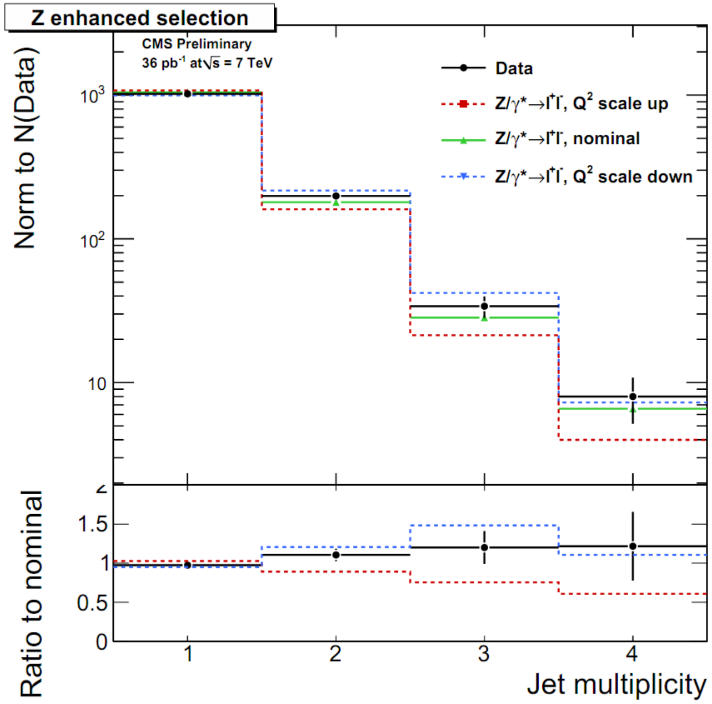
- **Fit relies on MC prediction for W + jets shape**
  - **Necessary to verify shape matches data**
- **Use W-enhanced selection**
  - **M_T > 55 GeV (reduces QCD), H_T < 200 (reduces ttbar)**
- **Sample dominated by W + jets**

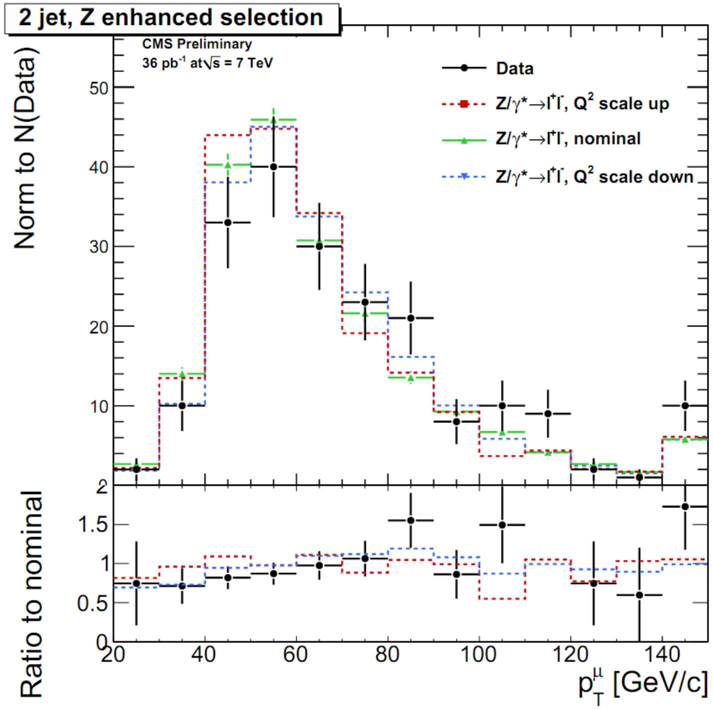




Z + jets modeling

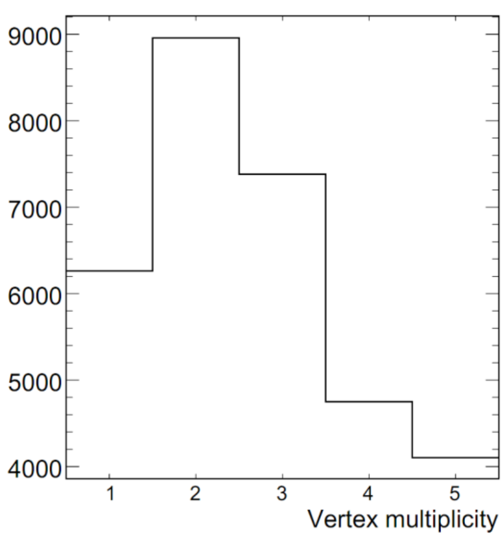
- **Fit relies on MC prediction for W + jets shape**
  - **Necessary to verify shape matches data**
- **Use Z-enhanced selection**
  - **Standard selection, 76 GeV < M_{ll} < 106 GeV**
- **Sample dominated by Z + jets**

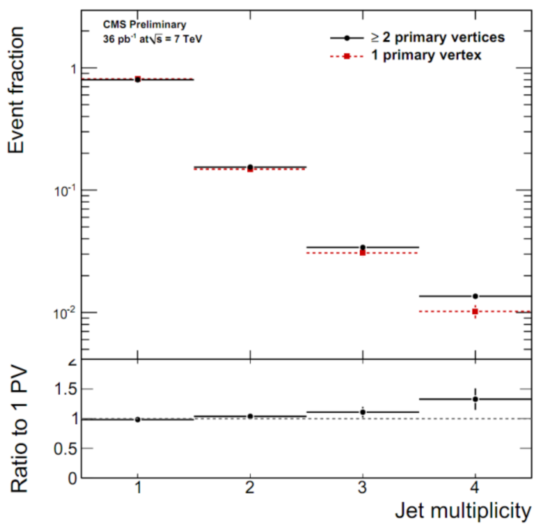


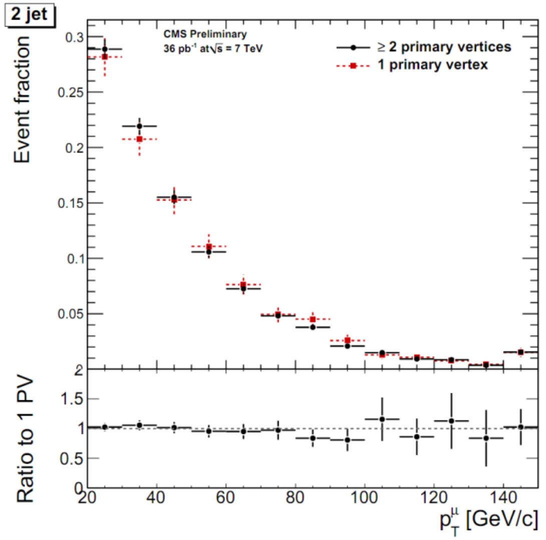


Pile-up

- Comparison of data with exactly on PV to data with 2 or more PVs
  - Consider only good quality vertices
  - Shapes are in reasonable agreement
    - Do not expect pile-up to have large impact on analysis
    - Use MC with pileup and L1Offset corrections in data/MC

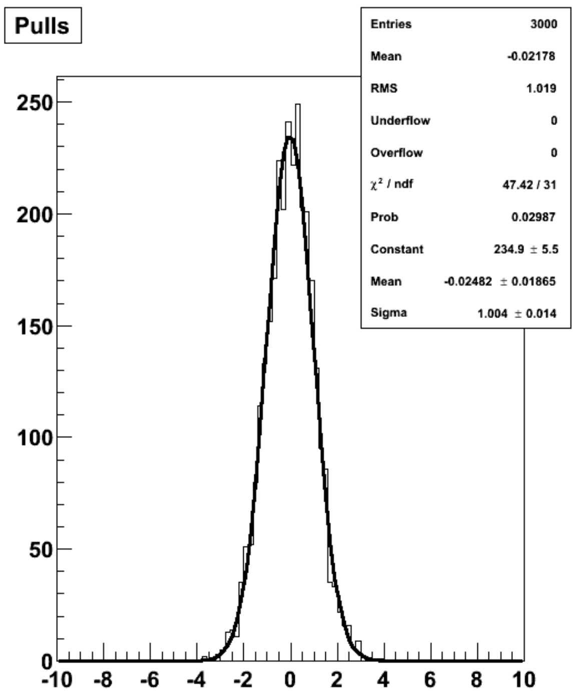


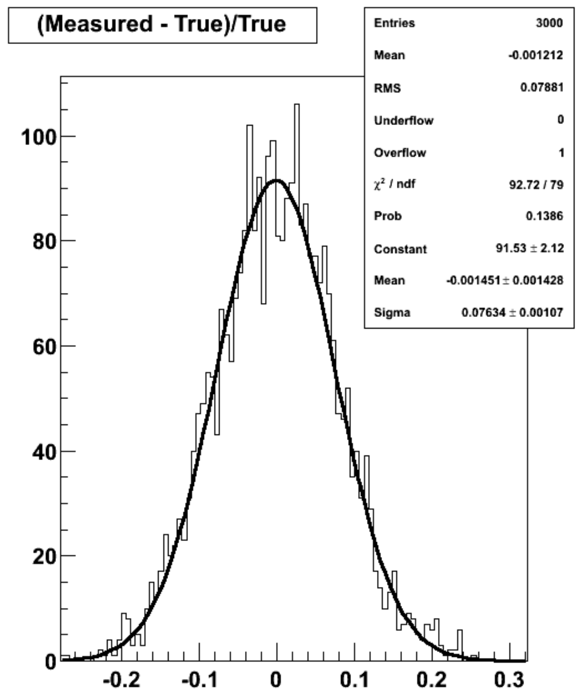




Statistical uncertainty

- **Perform 3000 pseudo-experiments**
  - **From nominal MC templates**
  - **Represents expected distribution of data**
- **Fit to bin-by-bin Poisson fluctuated MC templates**

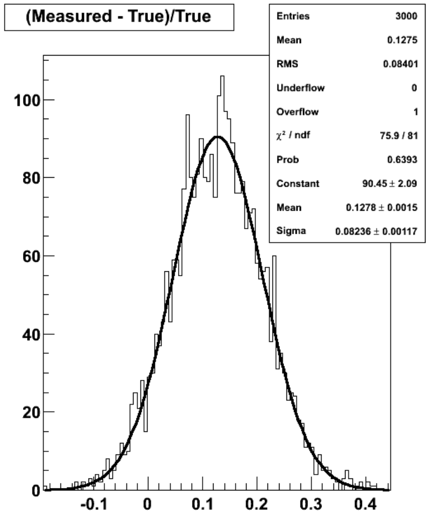




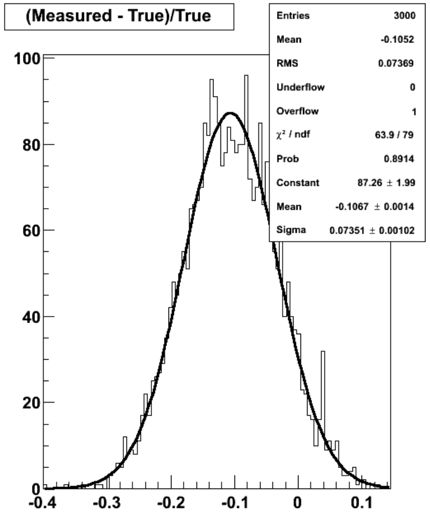
- **Pulls show distribution of $(\sigma_{fit} - \sigma_{exp})$/(fit error)**
  - **Mean of 0, width of 1 indicate fit is well behaved**
- **Sigma of fit represents statistical uncertainty**
  - **7.6% statistical uncertainty**

Jet energy scale uncertainty

- **Vary JES by 1 sigma (using JetMET prescription)**
  - **Table shows percentage change in MC event yields**
  - **Templates from per-jet uncertainty for W/Z + jets, QCD and ttbar**
- **Uncertainty determined from pseudo-experiments fit to nominal MC**
  - **Mean indicates systematic uncert**

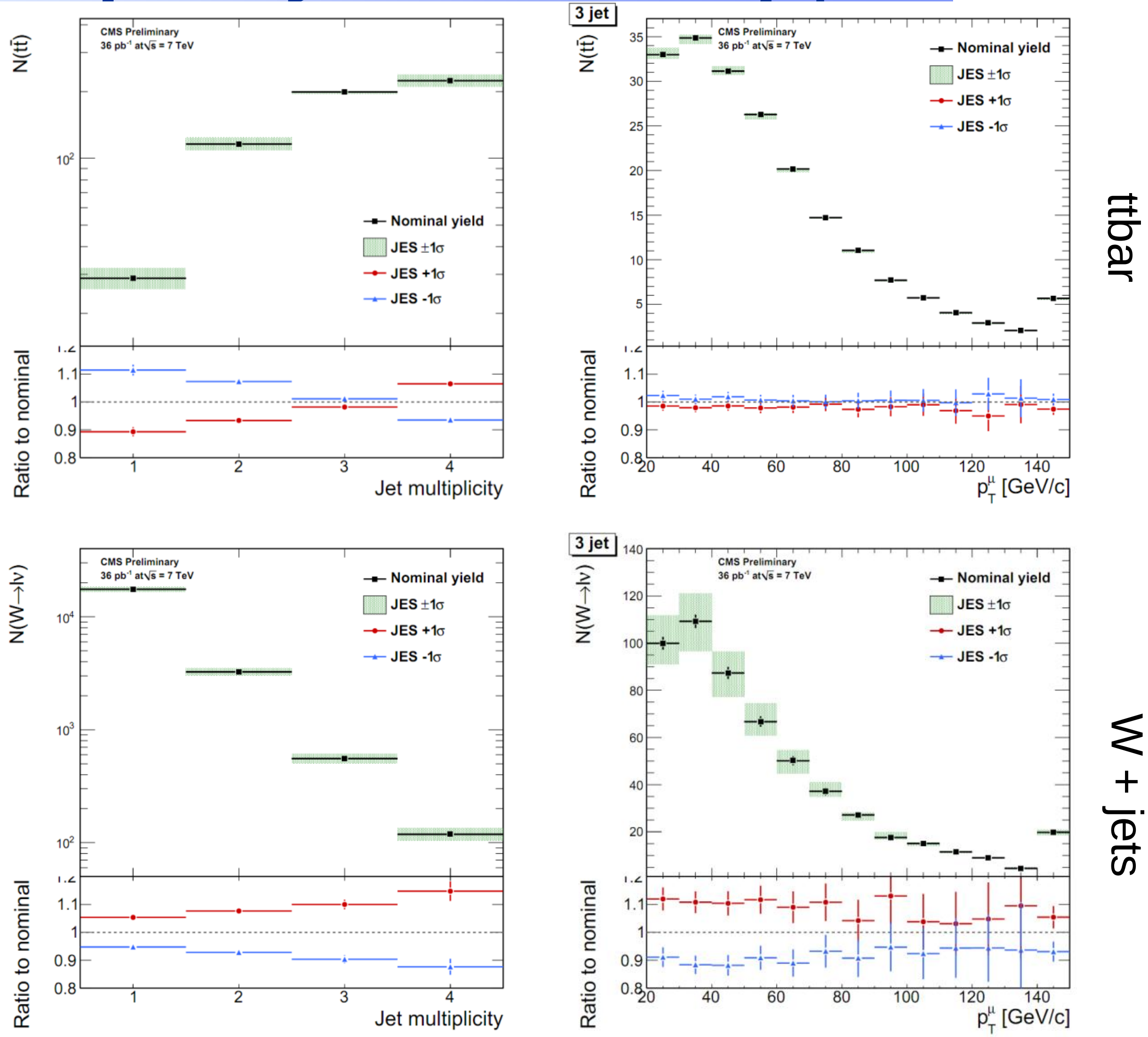


JES systematic yield change							
Cut	Sys	$t\bar{t}$	Single-top (s)	Single-top (t)	Single-top (tW)	$W \to l\nu$	$Z/\gamma^* \to l^+l^-$
2 jets	JES +	-6.6%	+1.4%	+1.5%	-2.6%	+7.7%	+8.1%
	JES -	+7.4%	-1.5%	-1.7%	+3%	-7.2%	-7%
3 jets	JES +	-1.8%	+5.6%	+5%	+2.9%	+10%	+9.1%
	JES -	+1.1%	-6.1%	-5.4%	-3.7%	-9.6%	-11%
$\geq$ 4 jets	JES +	+6.5%	+13%	+9.7%	+11%	+15%	+15%
	JES -	-6.5%	-11%	-8.5%	-10%	-12%	-12%



Jet energy scale uncertainty vs jet multiplicity and muon p_T

- **Effect of shift in JES for ttbar events (top) and W + jets events (bottom)**
  - **1σ shift includes effects due to pileup and p_T- / η-dependent uncertainty**



MC scale factors from fit

- **Result of template fit to muon p_T, η distributions in 3 and ≥ 4 jet bins**
  - Scale factors applied to backgrounds in same-sign dilepton signal region
  - Backgrounds to search well under control
  - Factors adjusted for results of trigger, ID and isolation efficiency measurements
    - Efficiency differences between data and MC obtained via tag and probe method

Sample	Scale factor
$t\bar{t}$	1.01 ± 0.08
$W \to l\nu$	1.11 ± 0.07
$Z/\gamma^* \to l^+l^-$	1.16 ± 0.33
Single-top	1.04 ± 0.30
QCD	2.47 ± 0.43

- **Measured top production cross section:**
  - $\sigma(tt) = 159.1 \pm 12.1(\text{stat})\ ^{+33.8}/_{-28.2}(\text{syst}) \pm 6.4\ (\text{lumi})$ pb
    - In excellent agreement with theoretical expectation based on NLO calculation

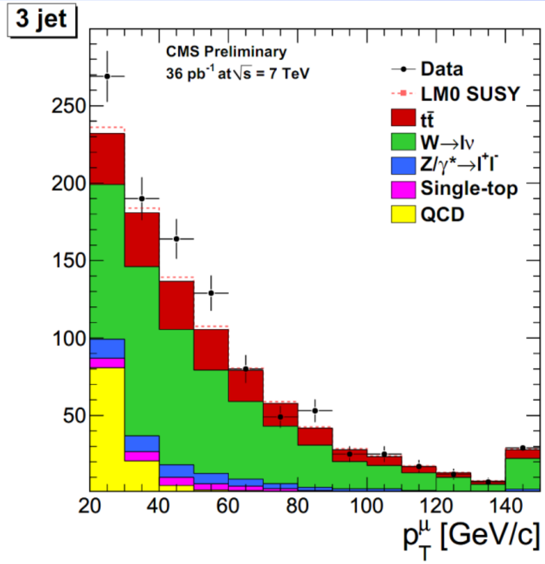
Summary of uncertainties

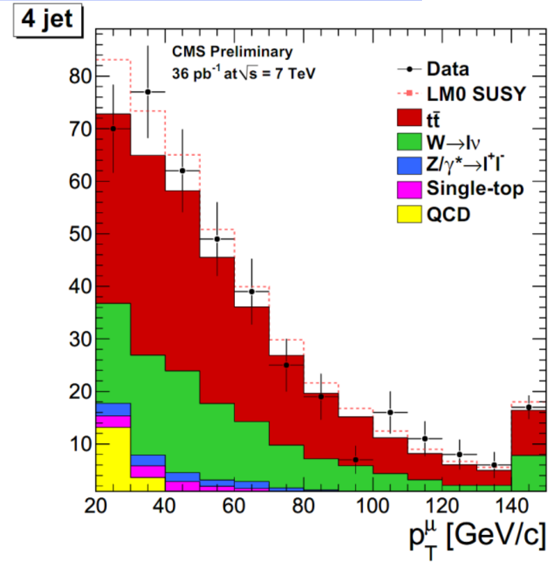
- **Summary of all uncertainties**
  - Uses optimized fit of muon pT and eta to 3 and ≥ 4 jet bins
  - Removing 2 jet bin dramatically decreases contribution from Q^2 scale systematic
  - Dominant contribution to uncertainty now comes from JES

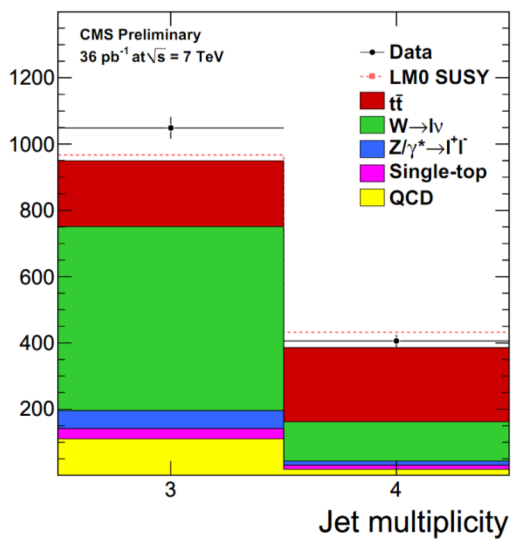
Summary of Uncertainties	
Source	Relative uncertainty
JES	$+12.8/-10.7\%$
Q^2 scale up/down ($t\bar{t}$)	$+11.7/-7.0\%$
Q^2 scale up/down (W/Z)	$\pm 4.8\%$
Matching up/down ($t\bar{t}$)	$+2.1/-2.0\%$
Matching up/down (W/Z)	$\pm 8.2\%$
Pile up	$\pm 4.2\%$
PDF	$\pm 3.0\%$
ISR / FSR	$\pm 4.6\%$
μ-trigger/ID/iso scale	$\pm 3.0\%$
Total systematic	$+21.2/-17.7\%$
Statistical	$\pm 7.6\%$
Total uncertainty (stat + syst)	$+22.6/-19.3\%$
Lumi	$\pm 4.0\%$

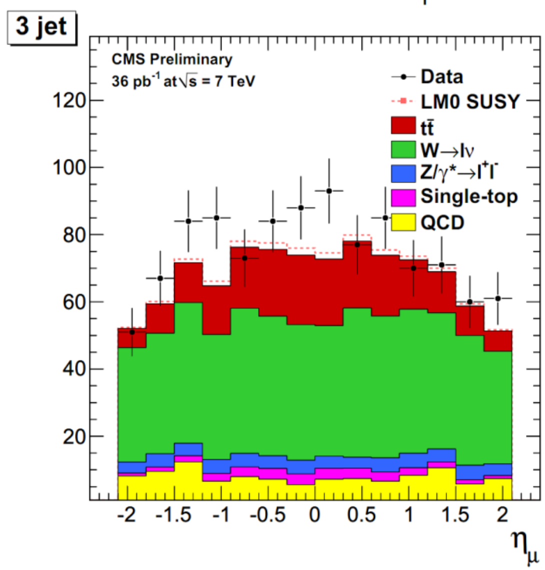
Distributions before fit

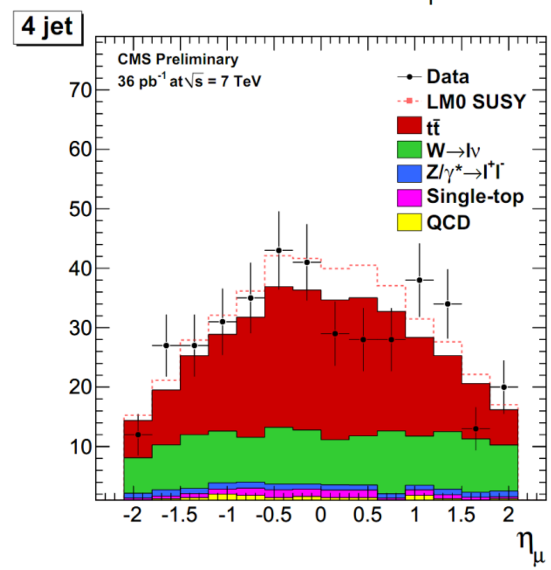
- MC normalized to results of NLO cross section calculation





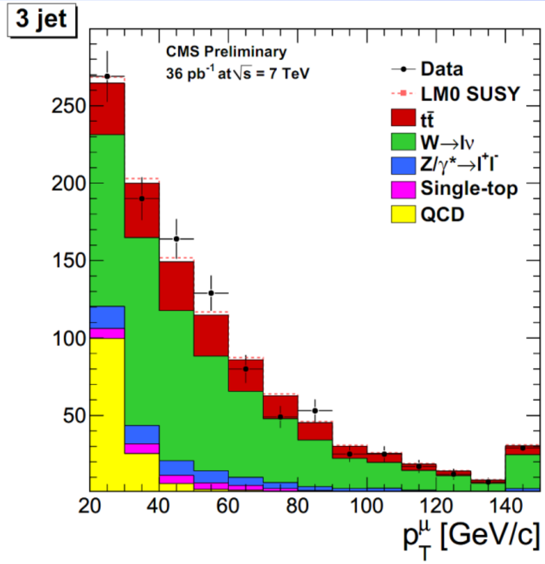


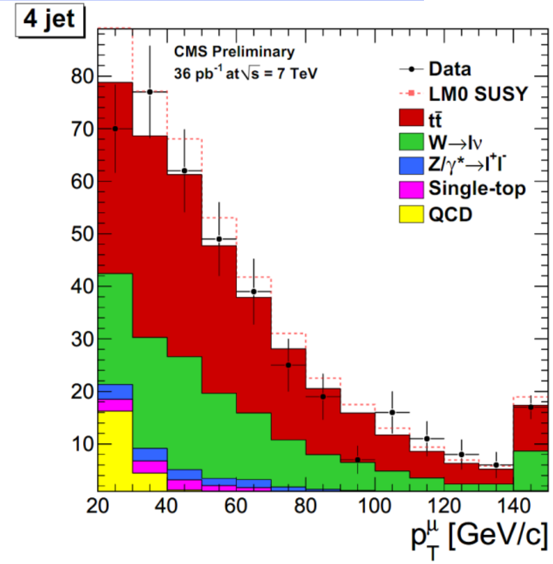


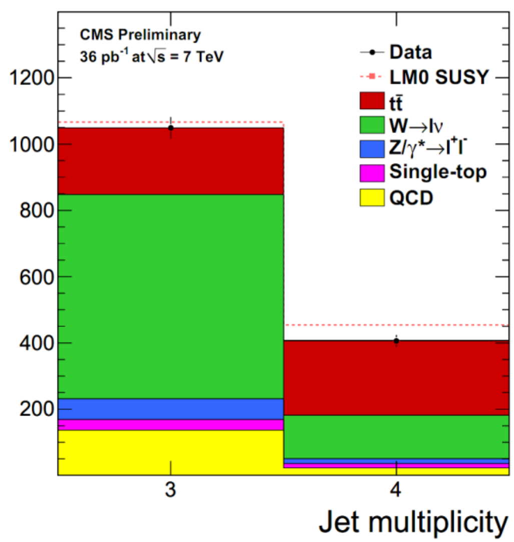


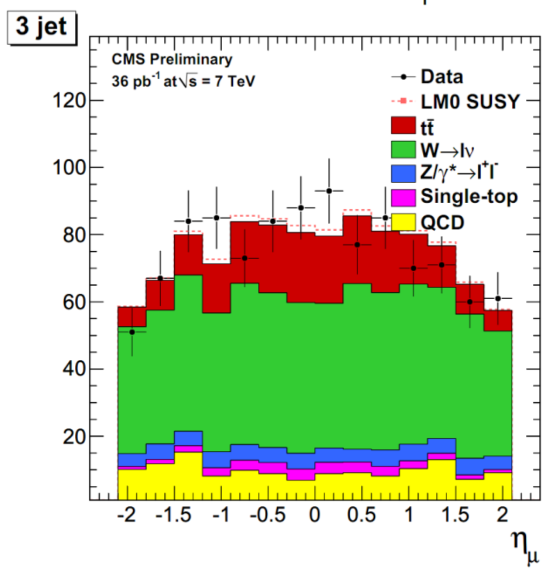
Distributions after fit

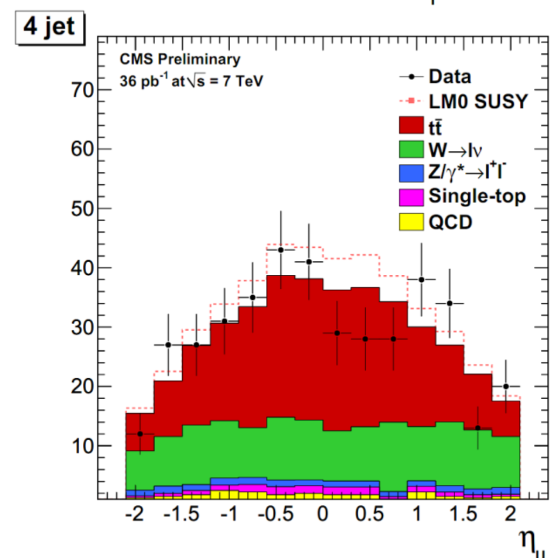
- **MC scaled by result of simultaneous template fit**





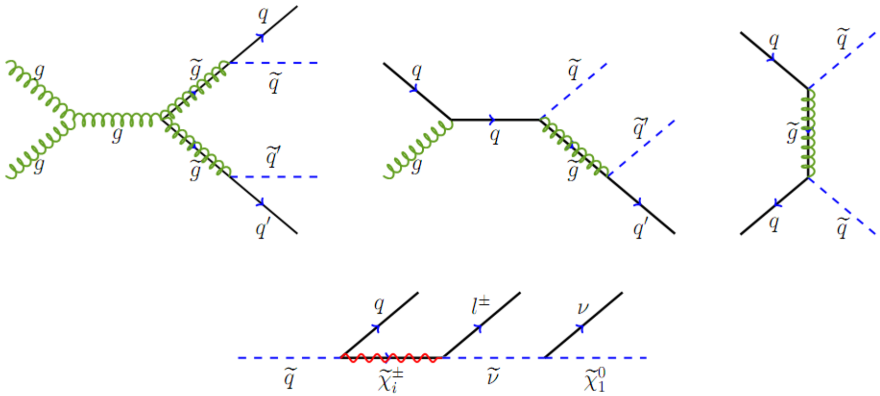






Same-sign dileptons from SUSY

- Same-sign dilepton signature strongly suppressed in SM backgrounds
- Multiple possible mass scales
  - Large difference between squark/gluino mass and chargino mass → large hadronic activity in event
  - Large difference between chargino mass and LSP mass → high-p_T leptons in event
- Consider different search regions to cover widest possible phase space:
  - High-p_T leptons, H_T > 60 GeV, MET > 80 GeV
  - High-p_T leptons, H_T > 200 GeV, MET > 30 / 20 GeV for same / opposite flavor leptons
  - Low-p_T leptons, H_T > 300 GeV, MET > 30 GeV



Signal regions

- **High-p_T lepton region similar to previous selection**
- **Require additional (same-sign) lepton**
  - **Move to region with significantly smaller statistics**

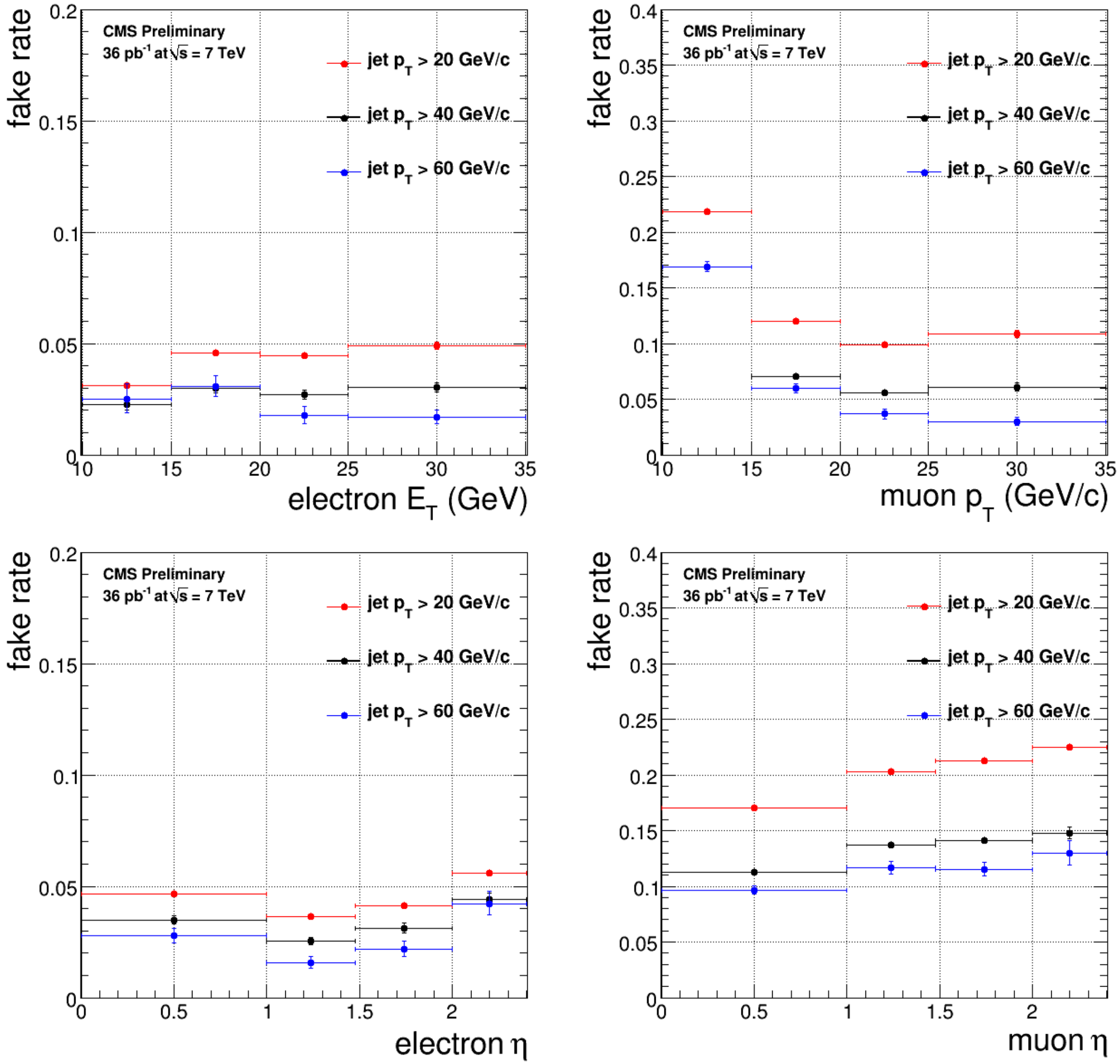
	High-p_T leptons	Low-p_T leptons, high H_T
Triggers	Lepton triggers, allow lower H_T	H_T triggers, allow lower lepton p_T
Preselection: 2 same-sign leptons	$p_{T1} > 20$ GeV $p_{T2} > 10$ GeV	$p_T > 10$ GeV
Isolation	Iso < 0.1, Iso = Iso_{COMB} / max[20 GeV, p_T]	Iso < 0.15, Iso = Iso_{COMB} / p_T
m_Z veto: Opp-sign, same-flavor leptons	$\lvert m_{ll} - m_Z \rvert < 15$ GeV	$\lvert m_{ll} - m_Z \rvert < 15$ GeV
m_{ll}	Opp-sign, same-flavor leptons, $m_{ll} > 12$ GeV	Same-sign leptons, $m_{ll} > 5$ GeV
Sort	No duplicate events; sort by priority: μμ, eμ, ee	No duplicate events; sort by priority: μμ, eμ, ee
Jets	At least 2 PF jets, $E_T > 30$ GeV	At least 2 PF jets, $E_T > 30$ GeV
H_T	$H_T > 60$ GeV / $H_T > 200$ GeV	$H_T > 300$ GeV
MET	MET > 80 GeV / MET > 20 GeV	MET > 30 GeV

Background estimation from data

- **Backgrounds from fake leptons**
  - Background with one fake lepton
    - Prompt lepton + b-jet (ttbar): Dominant background
    - Prompt lepton + light quark/gluon jet (W/Z + jets)
  - Background with two fake leptons
    - Dijets (QCD): Most uncertain background
- **Measured via fake rate method**
  - Define “loose” and “tight” (full selection) leptons
    - Determine probability that lepton passing loose selection also passes tight selection (fake rate)
  - Take events after all cuts (minus lepton selection)
    - Single-fake events: Require one tight lepton and one loose (but not tight) lepton; events weighted by FR / (1 – FR)
    - Double-fake events: Require both leptons to be loose (but not tight); events weighted by $FR_1 / (1 - FR_1) * FR_2 / (1 - FR_2)$

Fake rates

- **Lepton-triggered data**
  - Require reco jet instead of jet trigger
  - Remove real leptons from W/Z decays:
    - MET < 20 GeV and M_T(lep, MET) < 25 GeV
    - $|M_{ll} - M_Z| > 20$ GeV
  - Take fake rate as constant above 35 GeV
- **“Looser” lepton definition to increase statistics**
  - Electron: $I_{rel} < 0.5$, remove ID and d_0(bsp) cuts
  - Muon: $I_{rel} < 0.75$, $\chi^2/n_{dof} < 50$, d_0(bsp) < 2 mm



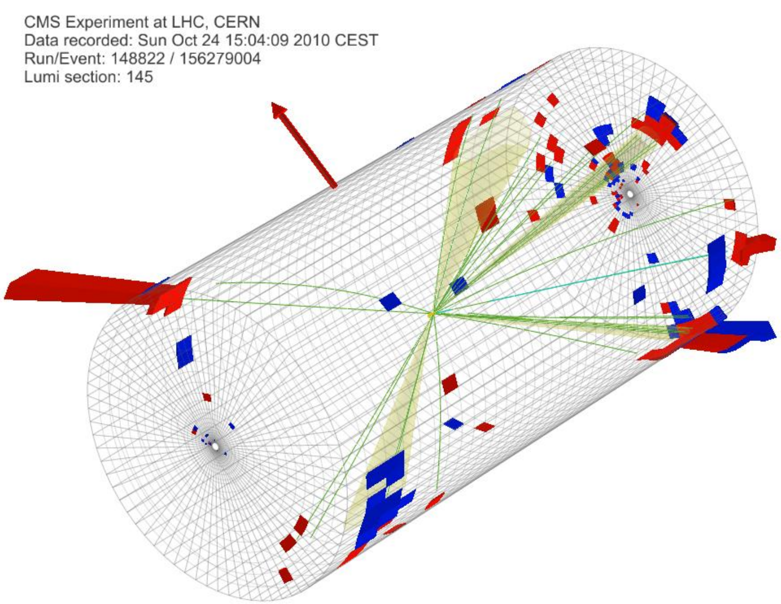
Same-sign dilepton yields for all analyses

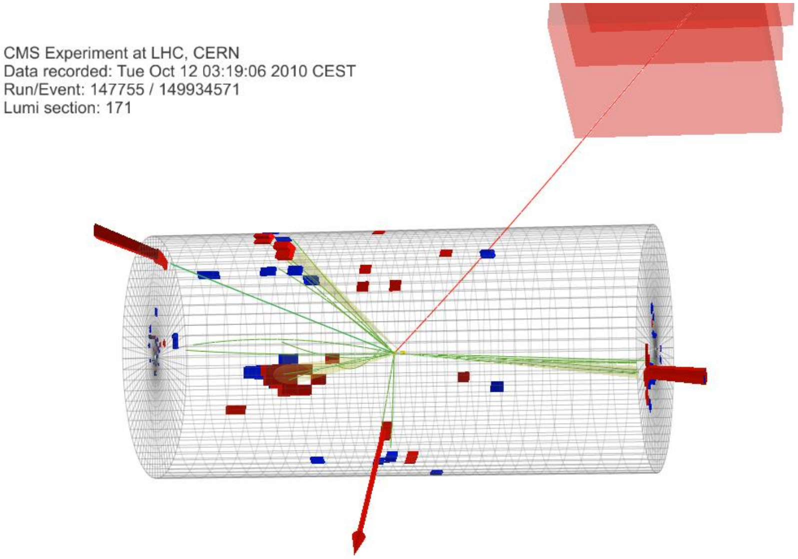
- **Background predicted via fake rate method**
  - Includes looser fake definitions to improve statistical uncertainty
- **MC contribution predicted from fake rate method applied to simulation**
  - Scale factors obtained from fit results included in calculation
  - Includes pileup + L1 offset corrections
  - Results are in better agreement with predicted BG
- **No evidence of excess over background**
  - Set 95% confidence upper limit using Bayesian method with flat prior
  - From LM0 simulation: Expect 5.0 events, 6.0 events, and 5.7 events in each search region

Search Region	ee	$\mu\mu$	$e\mu$	total	95% CL UL Yield
Lepton Trigger					
$E_T^{miss} > 80$ GeV					
MC	0.09	0.20	0.28	0.58	
predicted BG	0.07 ± 0.04	0.43 ± 0.22	0.64 ± 0.17	1.14 ± 0.25	
observed	1	0	0	1	4.2
$H_T > 200$ GeV					
MC	0.26	0.11	0.47	0.84	
predicted BG	0.22 ± 0.08	0.54 ± 0.19	0.79 ± 0.18	1.55 ± 0.26	
observed	1	0	1	2	5.2
H_T Trigger					
Low-p_T					
MC	0.16	0.05	0.18	0.39	
predicted BG	0.15 ± 0.02	0.05 ± 0.03	0.33 ± 0.08	0.52 ± 0.07	
observed	1	0	0	1	4.5

Event displays

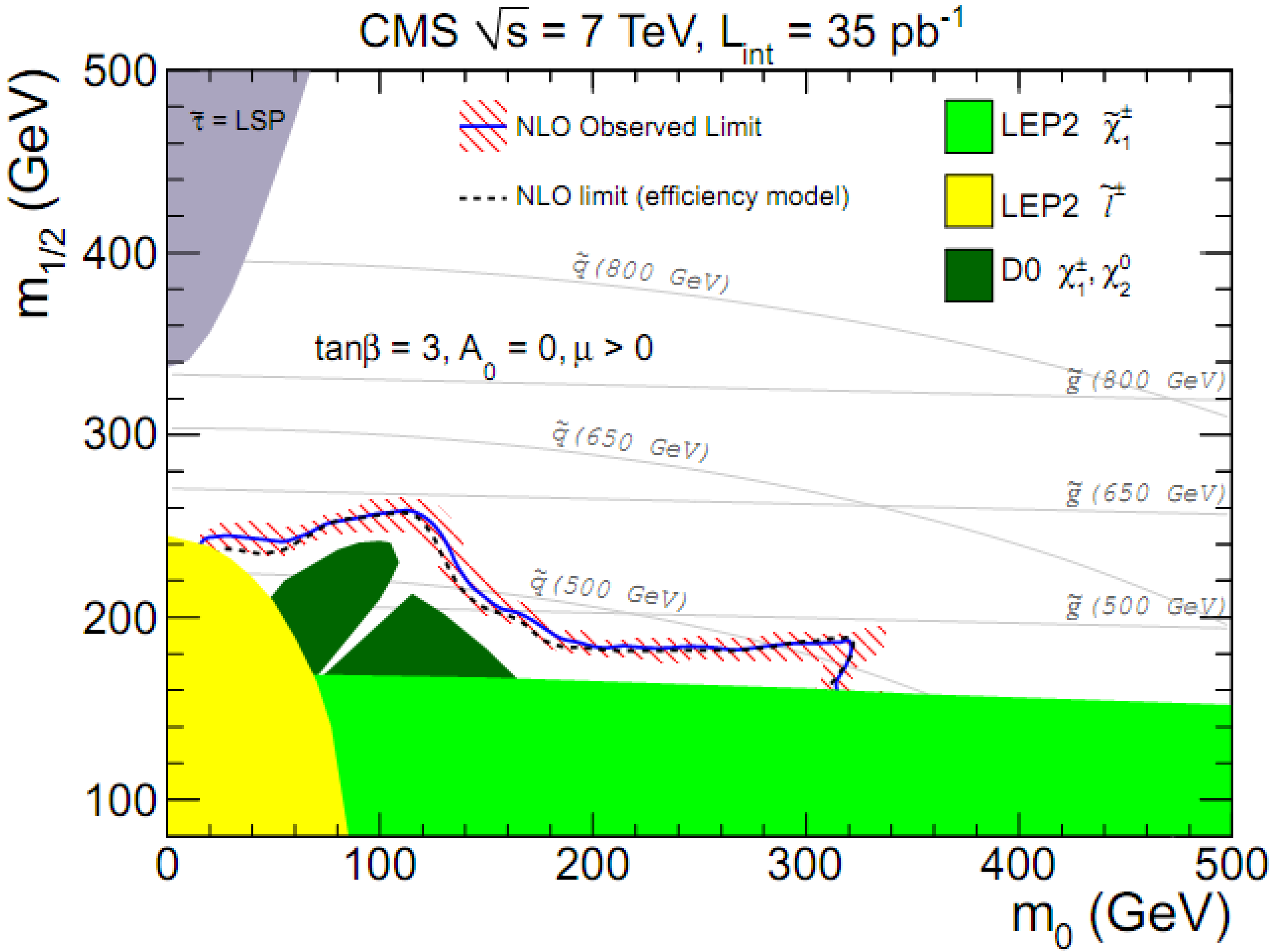
- **Both events in data passing same-sign cuts**
  - **2-electron event (left) passes all three selections**
    - **Electrons: Charge = -1, E_T = 77 GeV, 22 GeV**
    - **H_T = 355 GeV, MET = 109 GeV**
  - **Electron-muon event (right) passes H_T > 200 GeV selection**
    - **Leptons: Charge = +1, electron E_T = 33 GeV, muon p_T = 32 GeV**
    - **H_T = 212 GeV, MET = 49 GeV**





Exclusion contour in CMSSM plane

- **Exclusion contour taken from SUS-10-004 paper**



Conclusions

- **Calculated top production cross section in muon + jets channel**
  - **Results in excellent agreement with theory**
- **Used fit result to scale MC for same-sign dilepton analyses**
  - **See better agreement between MC and predicted BG from fake rate method**
- **Set 95% confidence level upper limit on same-sign dilepton signal yield**

Backup slides

Data samples

- **Data collected from April – November, 2010**
  - **Total integrated luminosity of 36 ± 1 pb^{-1}**
  - **Re-reconstructed using CMSSW_3_9_7 (Dec22 rereco)**
  - **Official JSON file to select good runs, lumi sections:**

    Cert_136033-149442_7TeV_Dec22ReReco_Collisions10_JSON_v4.txt
  - **Use multiple datasets for different analyses:**

Data samples		
Time period	2010A	2010B
Electrons	/EG/Run2010A-Dec22ReReco_v1/AOD	/Electron/Run2010B-Dec22ReReco_v1/AOD
Muons	/Mu/Run2010A-Dec22ReReco_v1/AOD	/Mu/Run2010B-Dec22ReReco_v1/AOD
Jets	/JetMET/Run2010A-Dec22ReReco_v1/AOD	/MultiJet/Run2010B-Dec22ReReco_v1/AOD

  - **Use a variety of single lepton and H_T triggers, based on unprescaled ranges**

Trigger selection			
Run range	e triggers	μ triggers	Jet triggers
132440 – 140040	HLT_Ele10_LW_L1R	HLT_Mu9	HLT_HT100U
140041 – 143962	HLT_Ele15_SW_L1R	HLT_Mu9	HLT_HT100U
143963 – 146427	HLT_Ele15_SW_CaloEleId_L1R	HLT_Mu9	HLT_HT100U
146428 – 147116	HLT_Ele17_SW_CaloEleId_L1R	HLT_Mu9	HLT_HT100U
147117 – 148058	HLT_Ele17_SW_TightEleId_L1R	HLT_Mu15_v1	HLT_HT140U
148058 – 148818	HLT_Ele17_SW_TightEleId_L1R	HLT_Mu15_v1	HLT_HT150U_v3
148819 – 149180	HLT_Ele22_SW_TighterEleId_L1R_v2	HLT_Mu15_v1	HLT_HT150U_v3
149181 – 149442	HLT_Ele22_SW_TighterEleId_L1R_v3	HLT_Mu15_v1	HLT_HT150U_v3

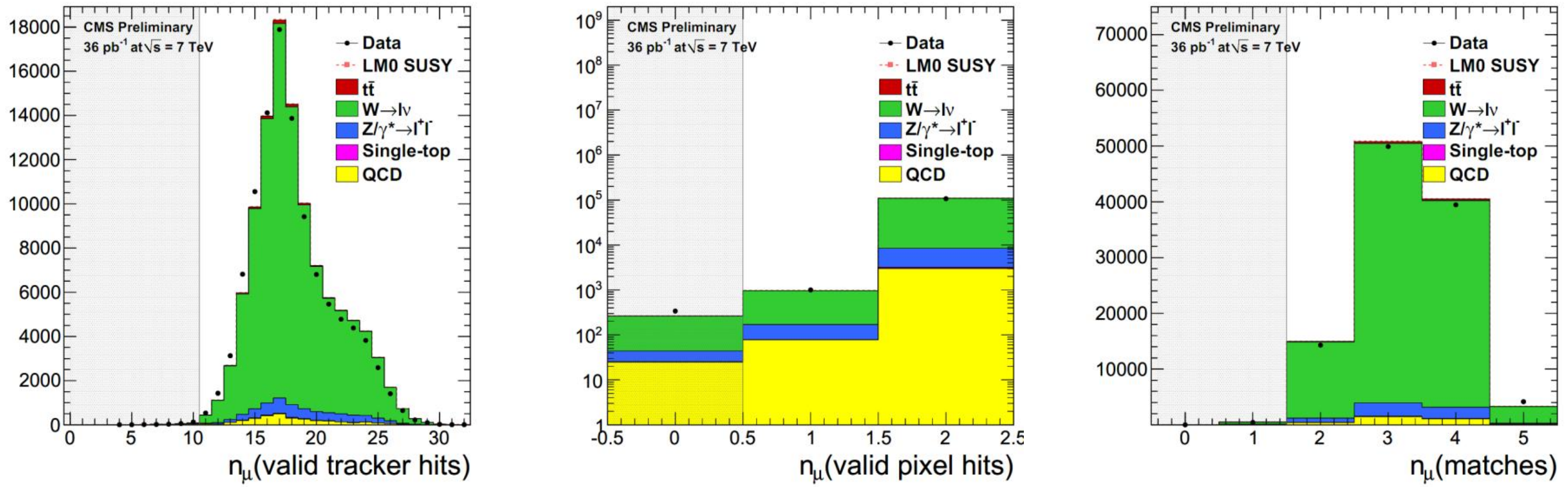
Monte Carlo samples

- **MC samples generated with MADGRAPH and PYTHIA**
  - **Default event tune Z2 used for nominal samples**
  - **Tune D6T used for systematic studies**
  - **All MC samples reconstructed using CMSSW_3_9_7 (Winter10)**
  - **All samples include pileup corresponding to latest data from 2010 run**

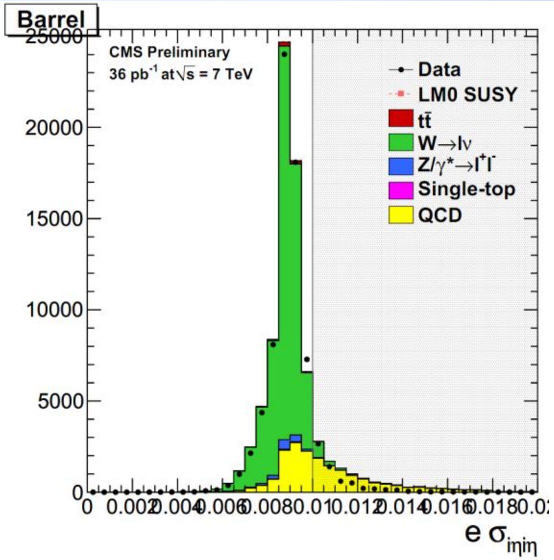
Monte Carlo samples				
Process	Generator	Kinematic cuts	σ (pb)	Generated events
Common samples				
$t\bar{t}$	MADGRAPH	—	157.5	1165716
$W \to l\nu$	MADGRAPH	—	31314.0	15154787
$Z/\gamma^* \to l^+l^-$	MADGRAPH	$m_{ll} > 50$ GeV	3048.0	5257046
t (s-channel)	MADGRAPH	—	1.4	494967
t (t-channel)	MADGRAPH	—	20.93	484060
tW	MADGRAPH	—	10.6	494961
Samples for $t\bar{t}$ production cross section measurement				
QCD (μ-enriched)	PYTHIA	$\hat{p_T} > 20$ GeV, $p_T^\mu > 15$ GeV	84679.3	29504868

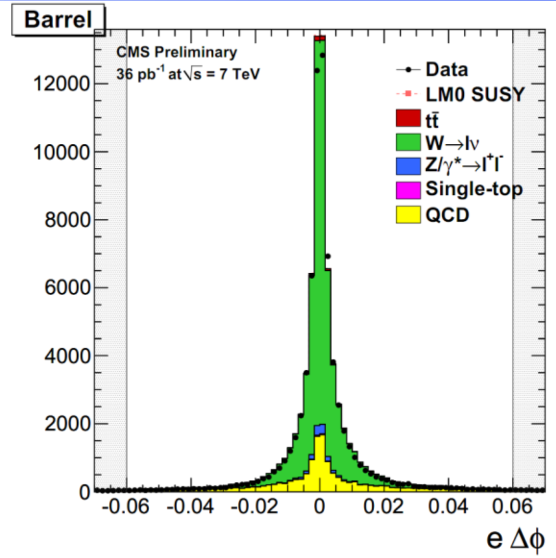
- **Note: For certain studies, a factor of 2 is used to normalize the QCD contribution**

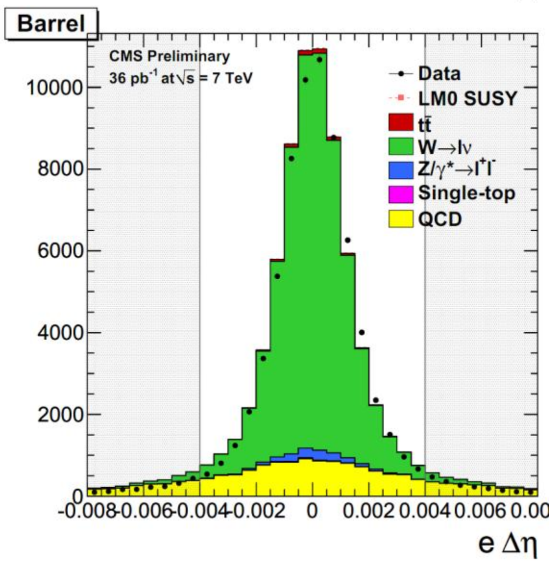
Muon selection: quality cuts

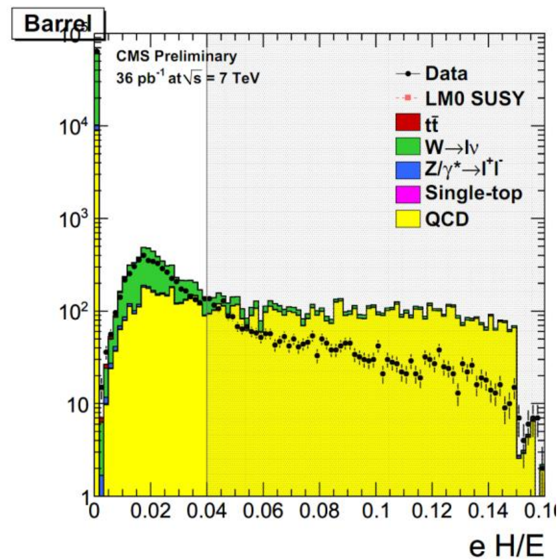


Electron identification: Barrel

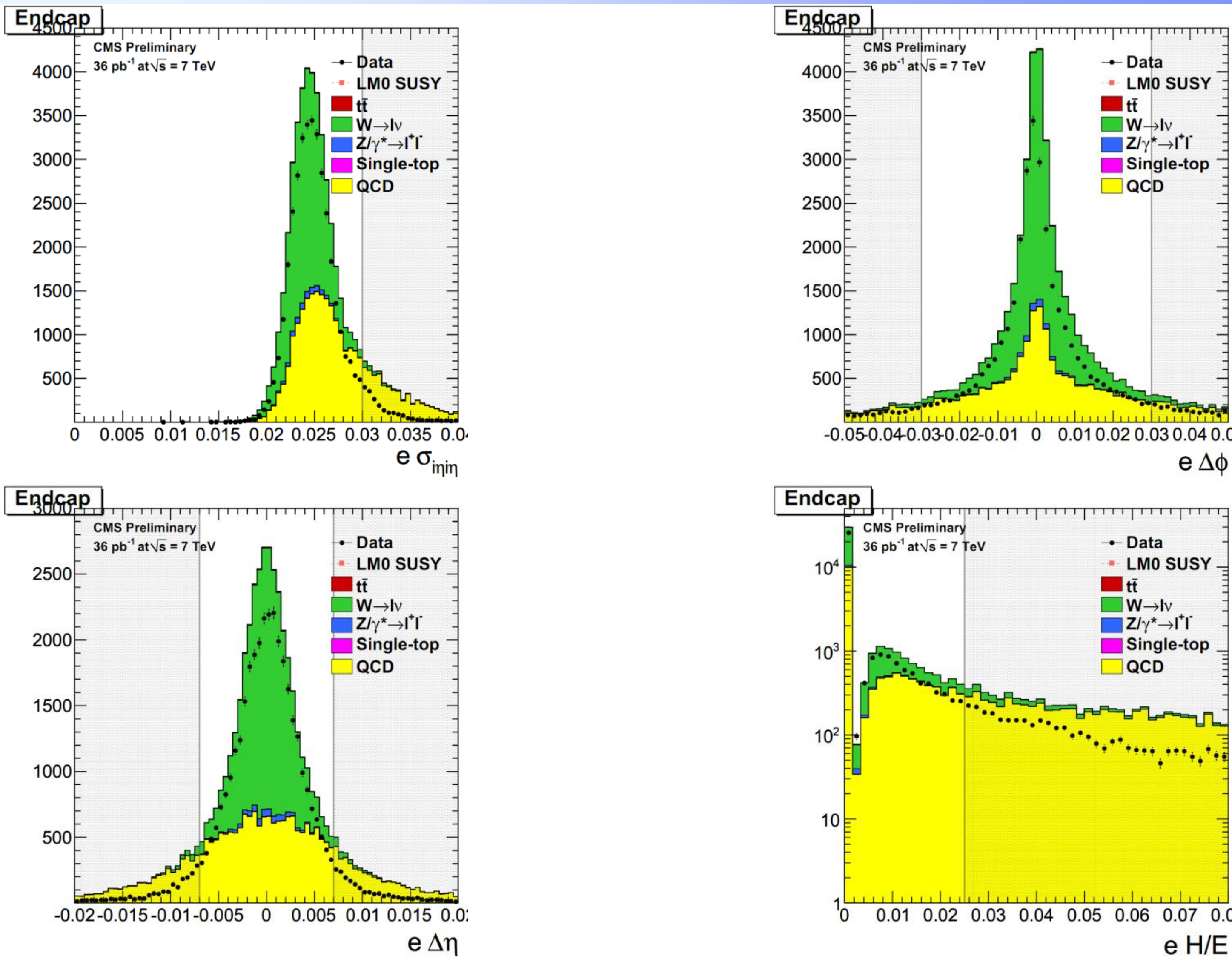




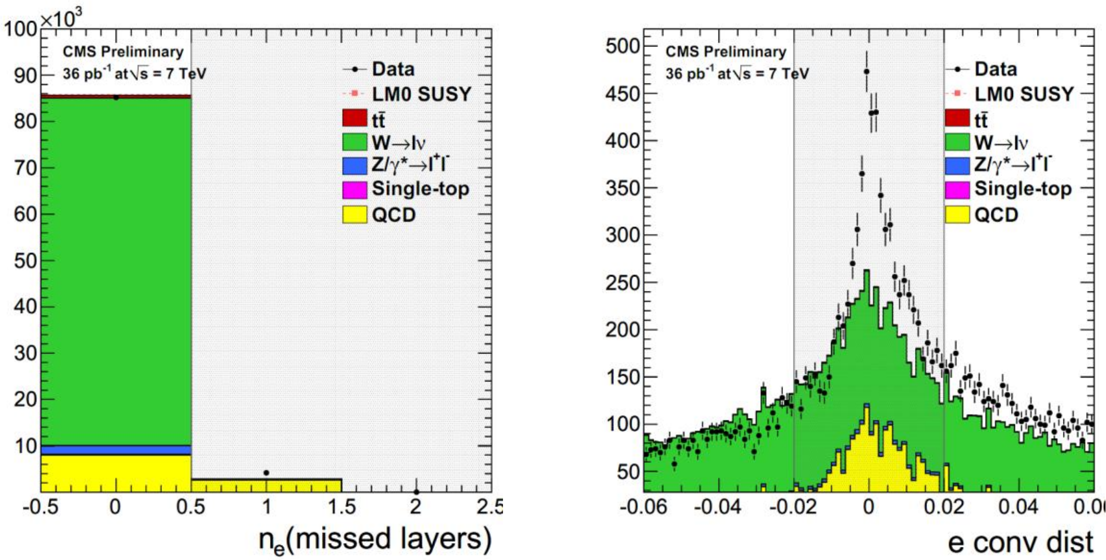


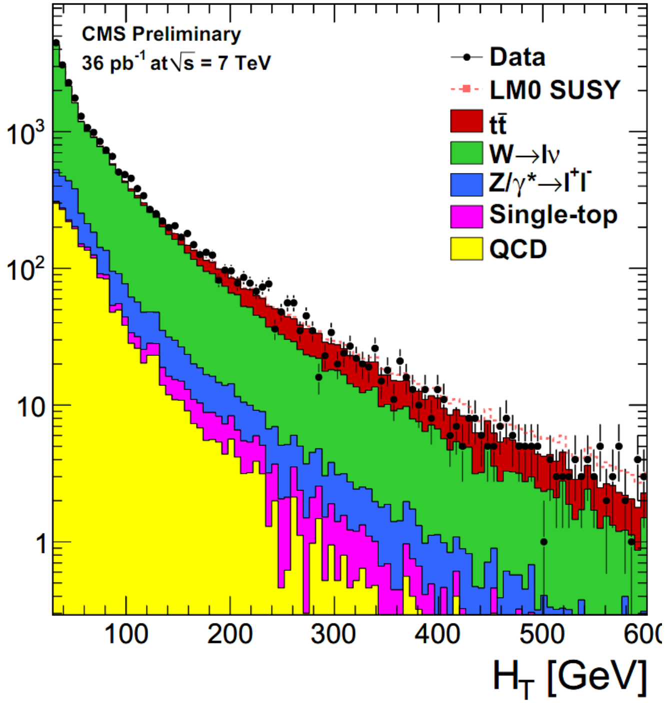


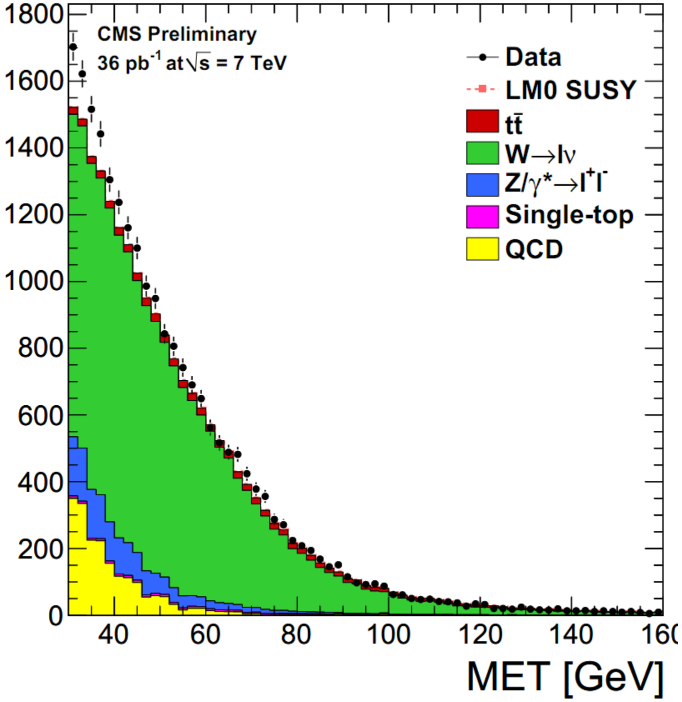
Electron identification: Endcaps



Electron selection: Conversion rejection

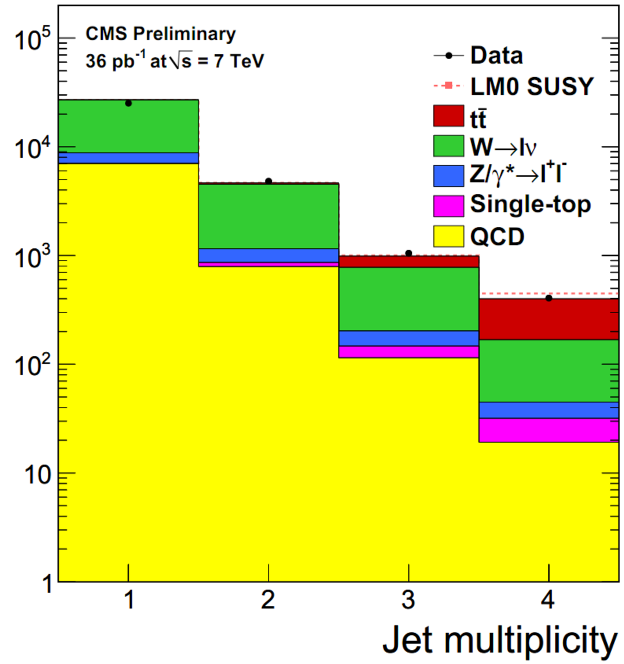



CMS Preliminary
36 pb-1 at √s = 7 TeV
Data
LM0 SUSY
tt̄
W→lν
Z/γ*→l+l-
Single-top
QCD
H_T [GeV]


CMS Preliminary
36 pb-1 at √s = 7 TeV
Data
LM0 SUSY
tt̄
W→lν
Z/γ*→l+l-
Single-top
QCD
MET [GeV]

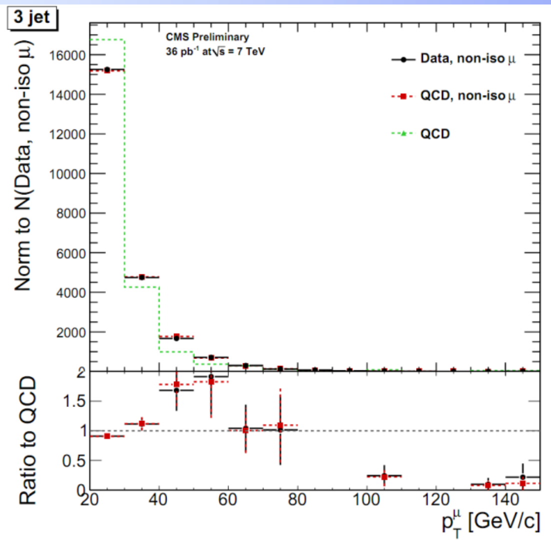
Top analysis: Event yields

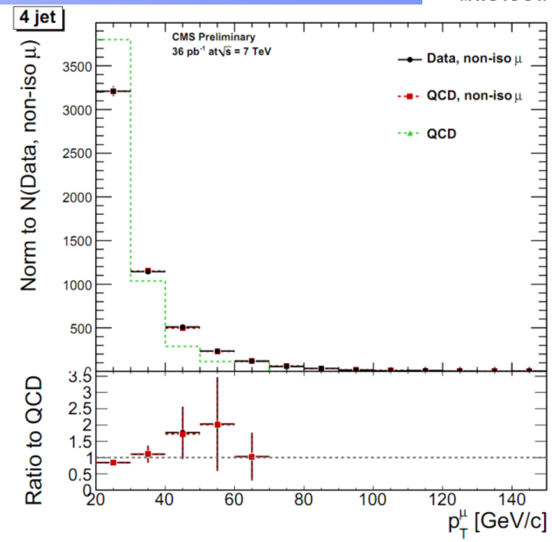
Predicted and observed event yields for 36.0 pb^{-1}							
Cut	$t\bar{t}$	$W \to l\nu$	$Z/\gamma^* \to l^+l^-$	Single-top	QCD	Sum MC	Data
1 jet	29	17565	1655	63	6762	26075	25183
2 jets	116	3253	279	69	764	4480	4816
3 jets	199	555	54	31	111	950	1049
$\geq$ 4 jets	224	118	13	12	19	386	406

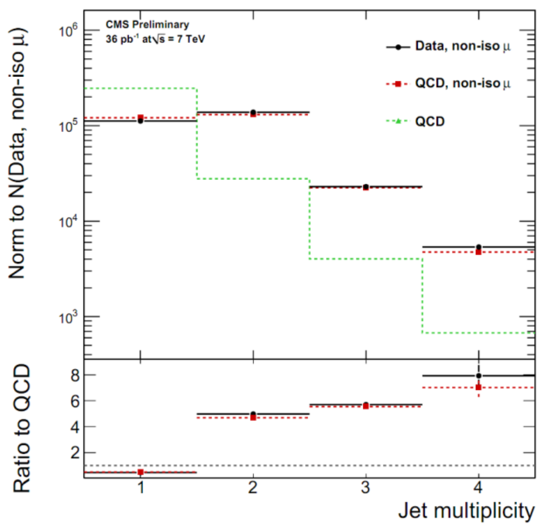


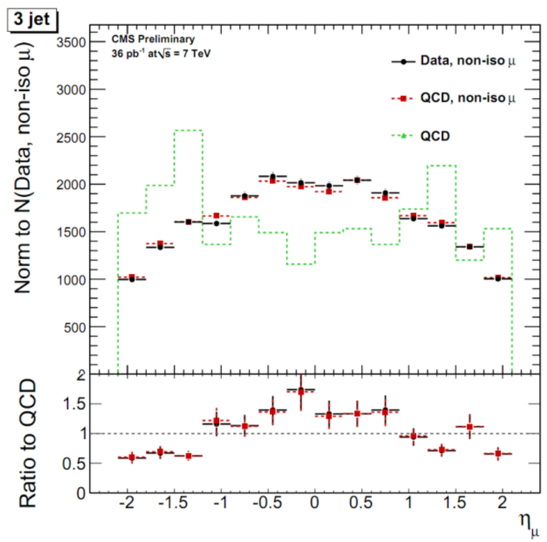
QCD model

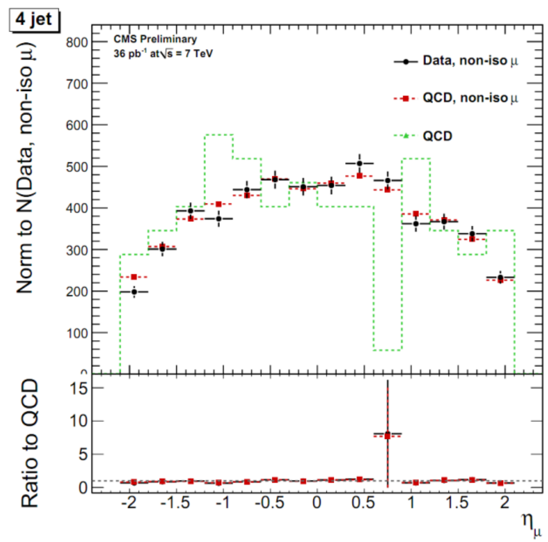
- **Comparison of non-isolated data and QCD MC to nominal QCD MC**
  - **Not suitable model for QCD**
  - **Non-iso data and QCD agree very well; QCD reasonable**







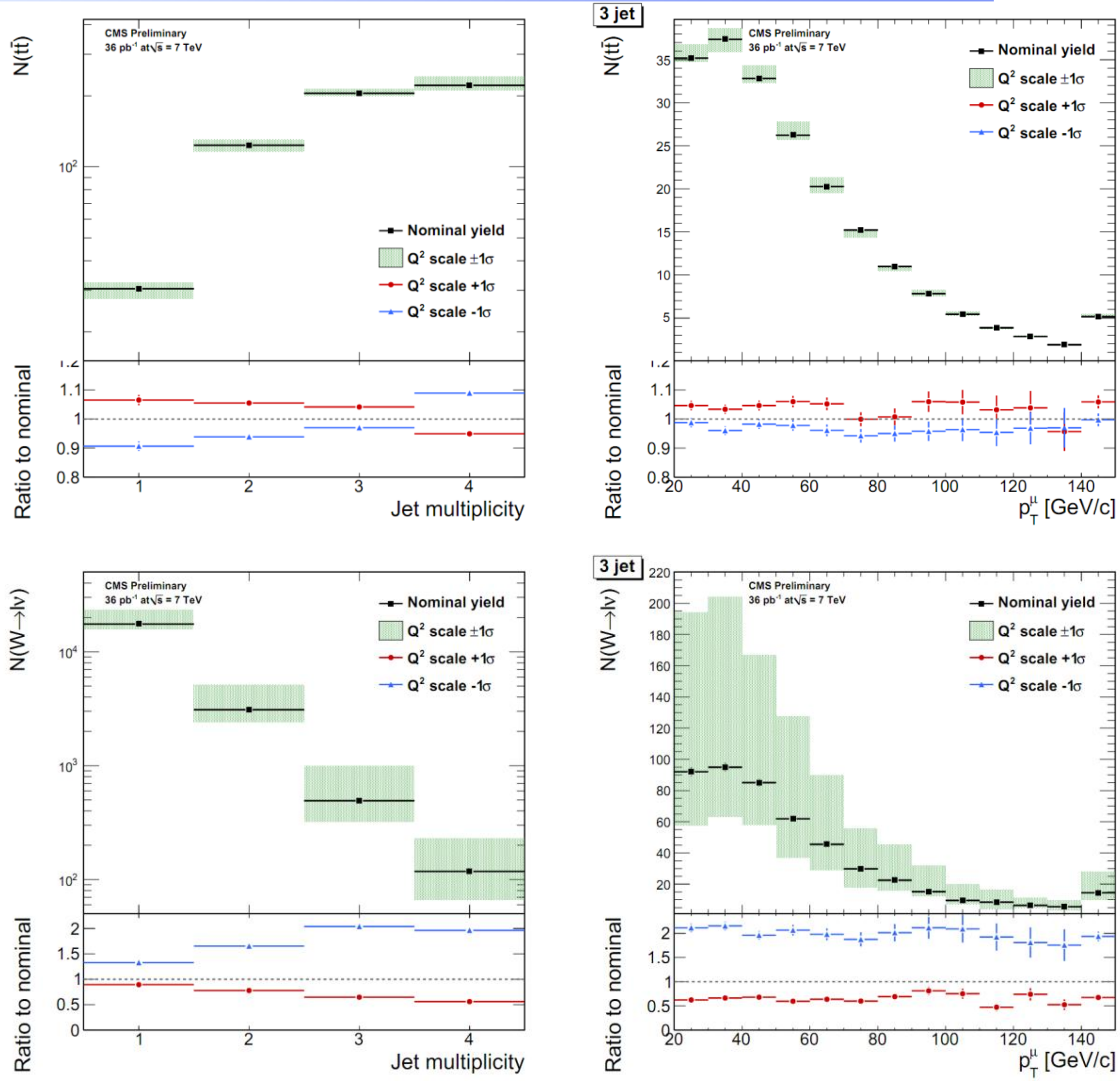




Q^2 scale uncertainty

- **Renormalization / factorization scale uncertainty**
  - **Use specially prepared MC samples**

Q^2 scale systematic yield change				
Cut	Sys	$t\bar{t}$	$W \to l\nu$	$Z/\gamma^* \to l^+l^-$
2 jets	Scale +	+5.5%	-22%	-17%
	Scale -	-6.1%	+66%	+49%
3 jets	Scale +	+4.1%	-35%	-32%
	Scale -	-3%	+100%	+67%
$\geq$ 4 jets	Scale +	-5.1%	-44%	-41%
	Scale -	+9%	+96%	+74%

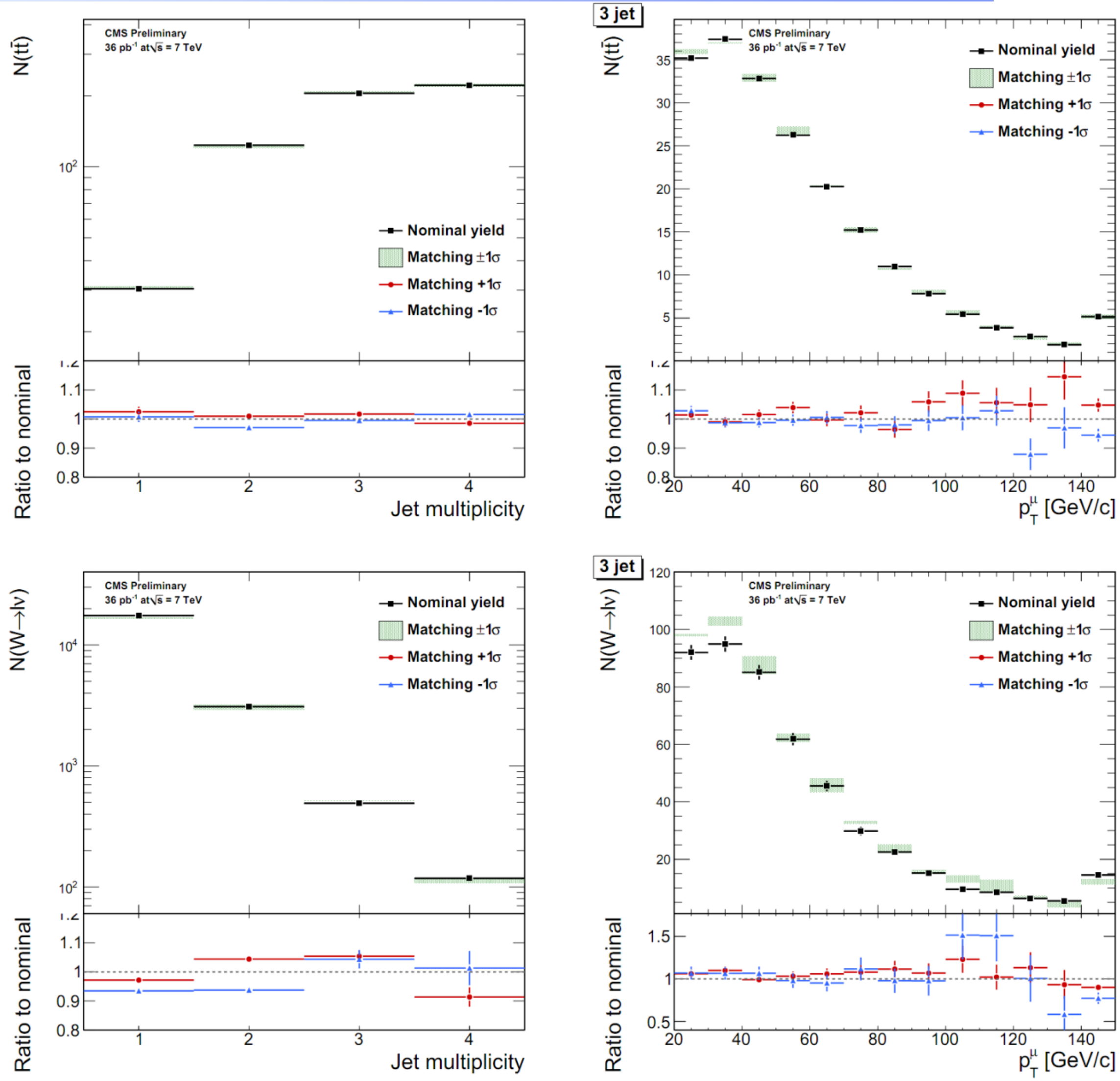


Matching uncertainty

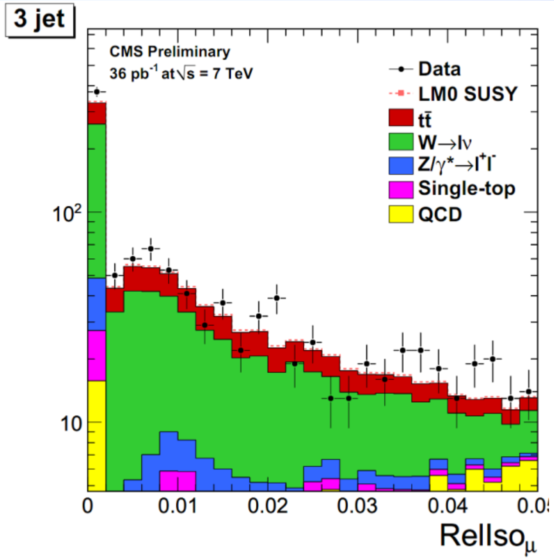
- **Matching of matrix element to parton shower in MC**
  - Use specially prepared MC samples

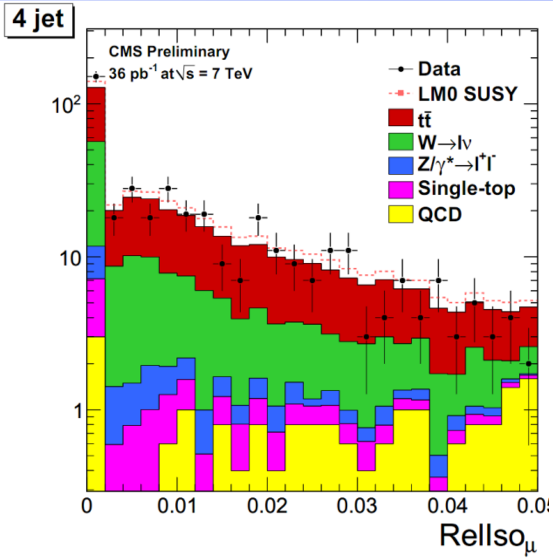
Cut	Sys	$t\bar{t}$	$W \to l\nu$	$Z/\gamma^* \to l^+l^-$
2 jets	Match +	+1%	+4.5%	+0.59%
	Match -	-2.9%	-6.2%	-4.9%
3 jets	Match +	+1.6%	+5.4%	-4.6%
	Match -	-0.49%	+4.4%	-7.7%
$\geq$ 4 jets	Match +	-1.4%	-8.6%	-14%
	Match -	+1.6%	+1.3%	-5.4%

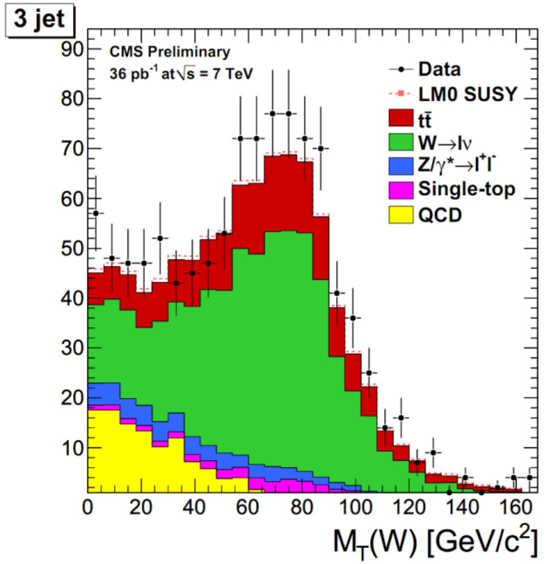
Matching threshold systematic yield change

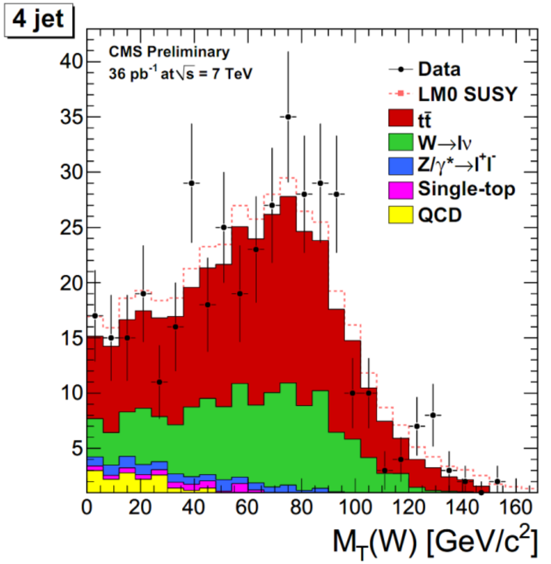


Top analysis: RelIso and $M_T(W)$ NLO cross section

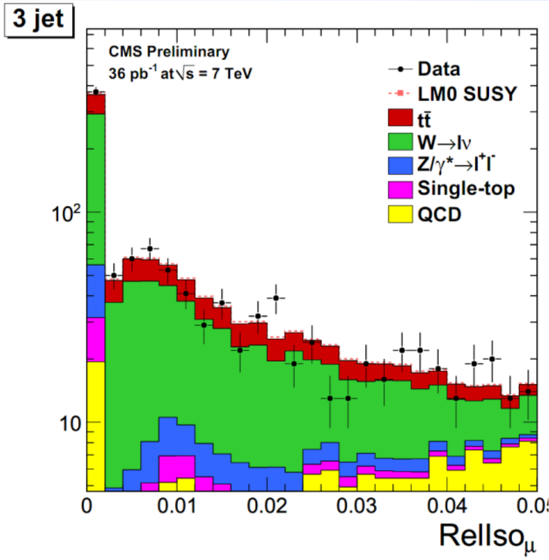


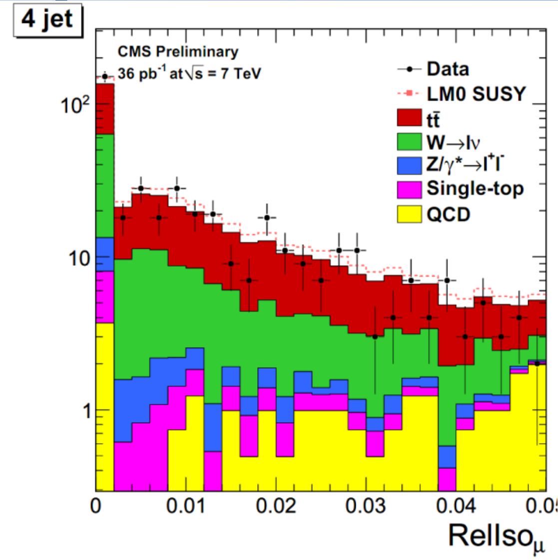


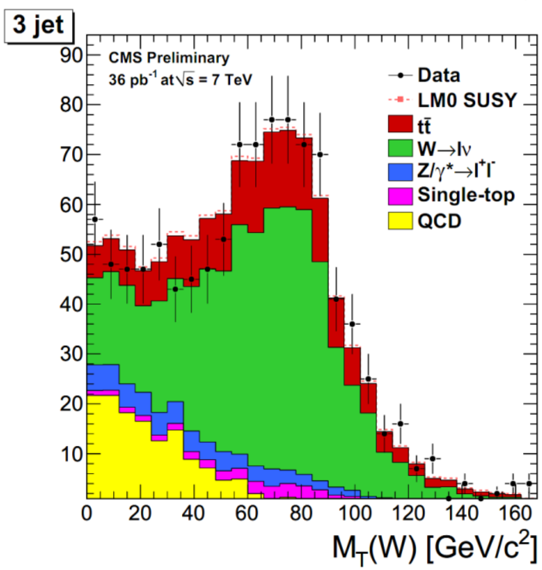


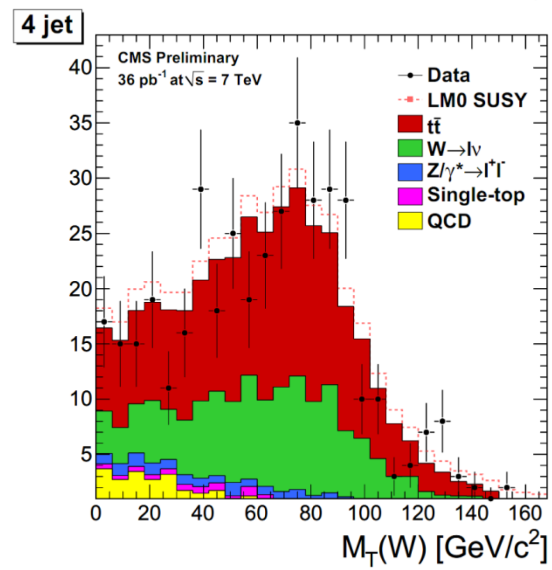


Top analysis: RelIso and M_T(W) Simultaneous template fit

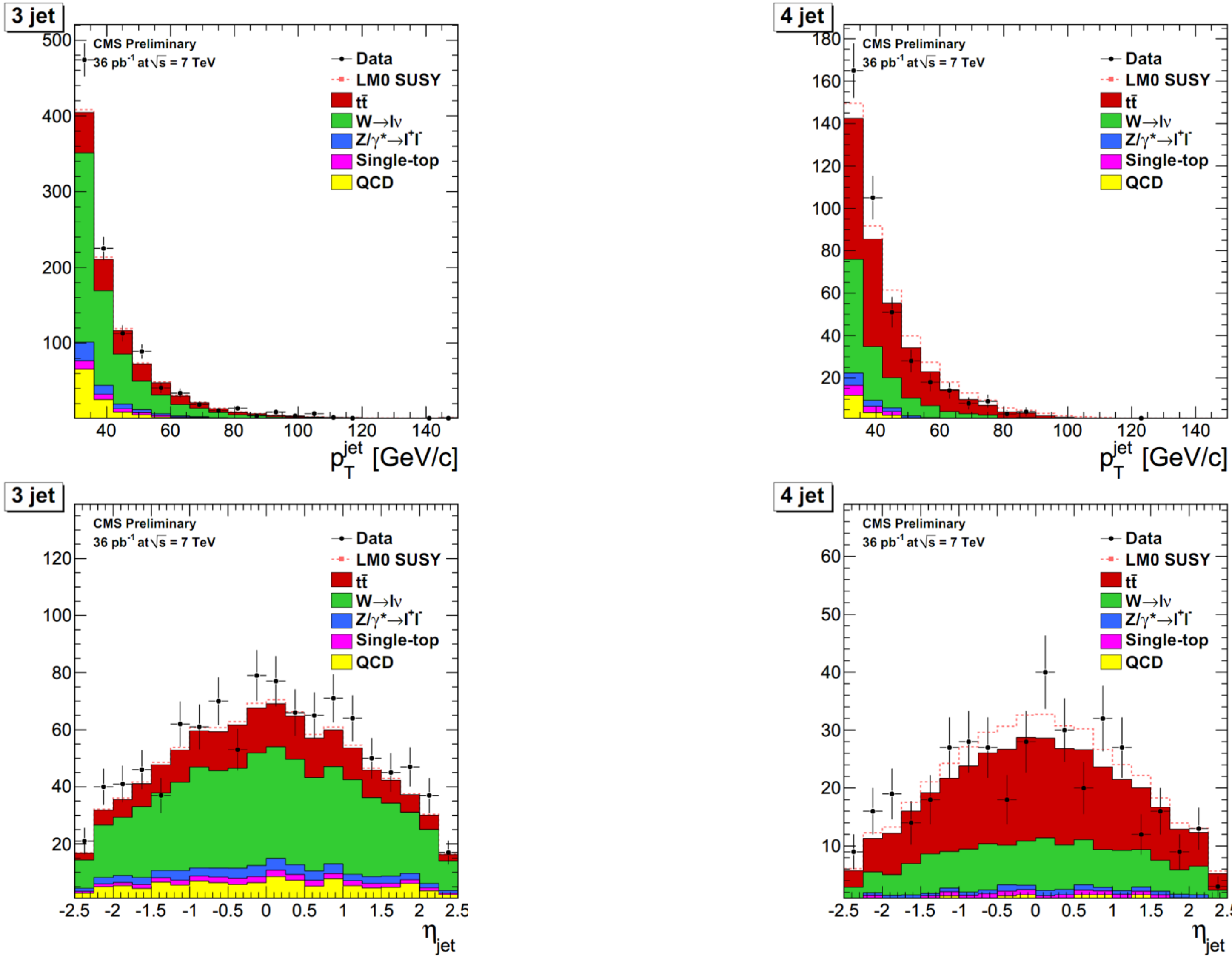




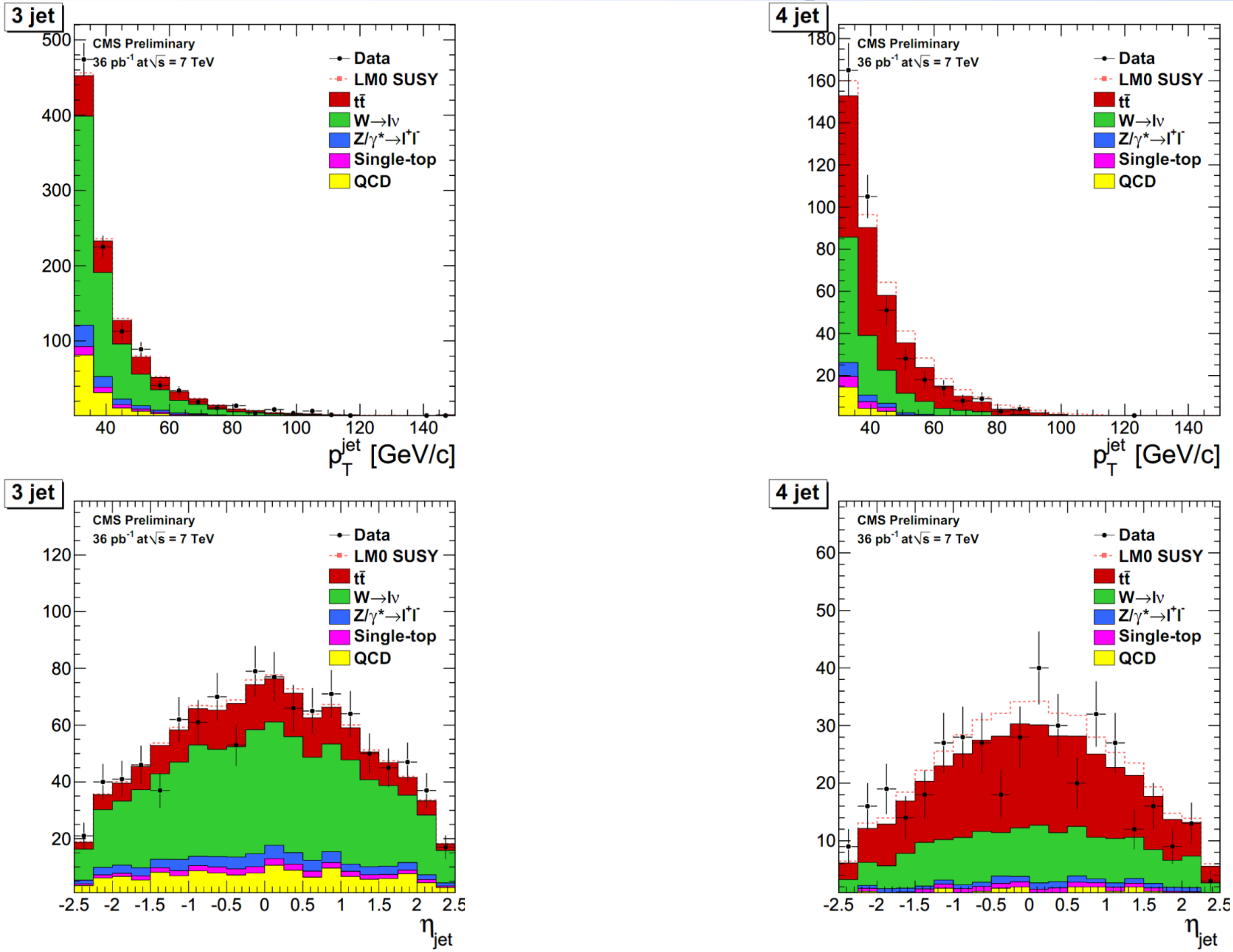




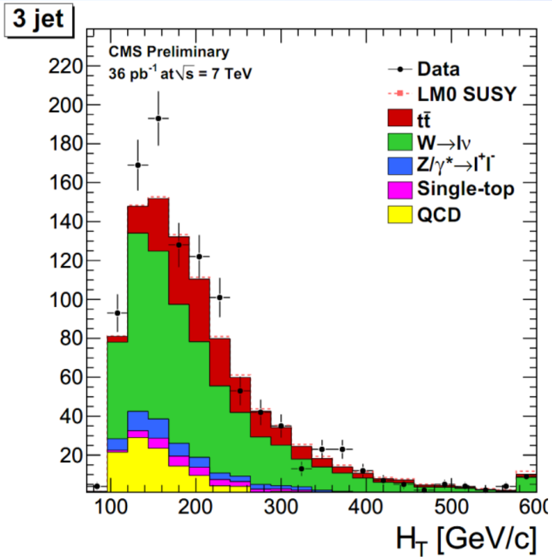
Top analysis: PF jet p_T and η NLO cross section

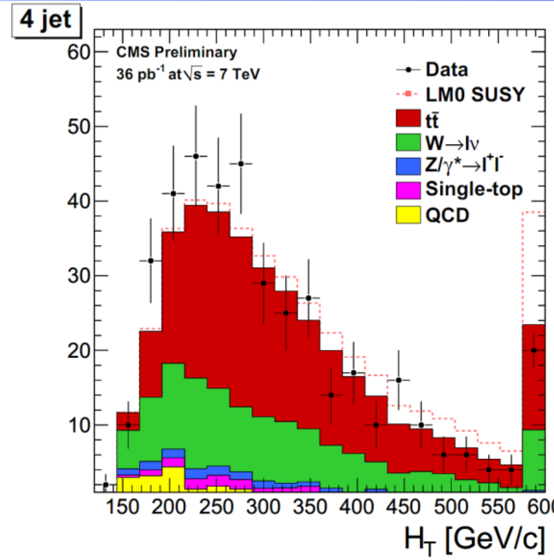


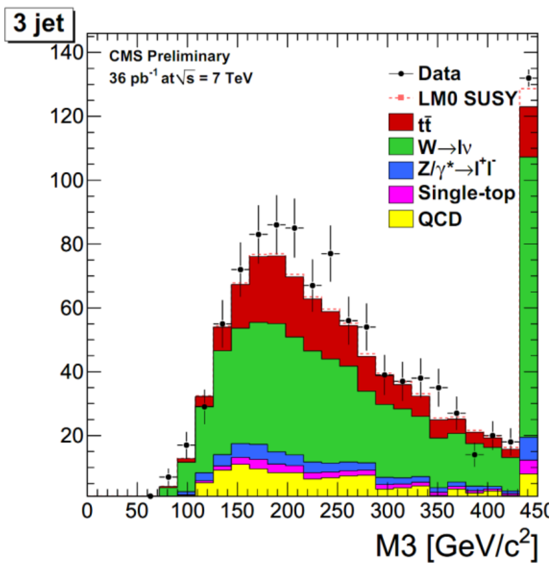
Top analysis: PF jet p_T and η
Simultaneous template fit

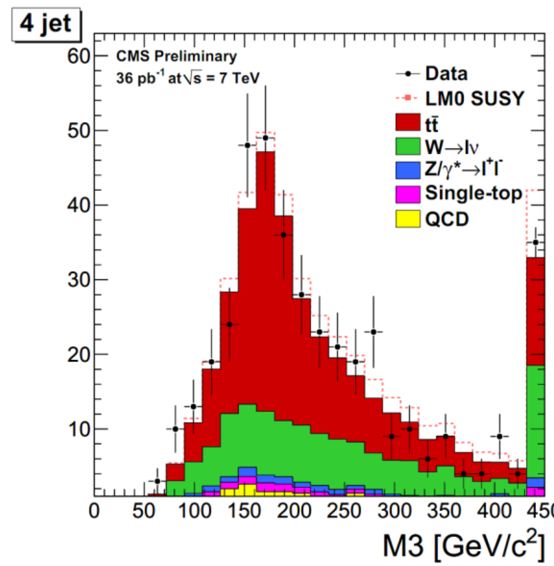


Top analysis: H_T and M3 NLO cross section

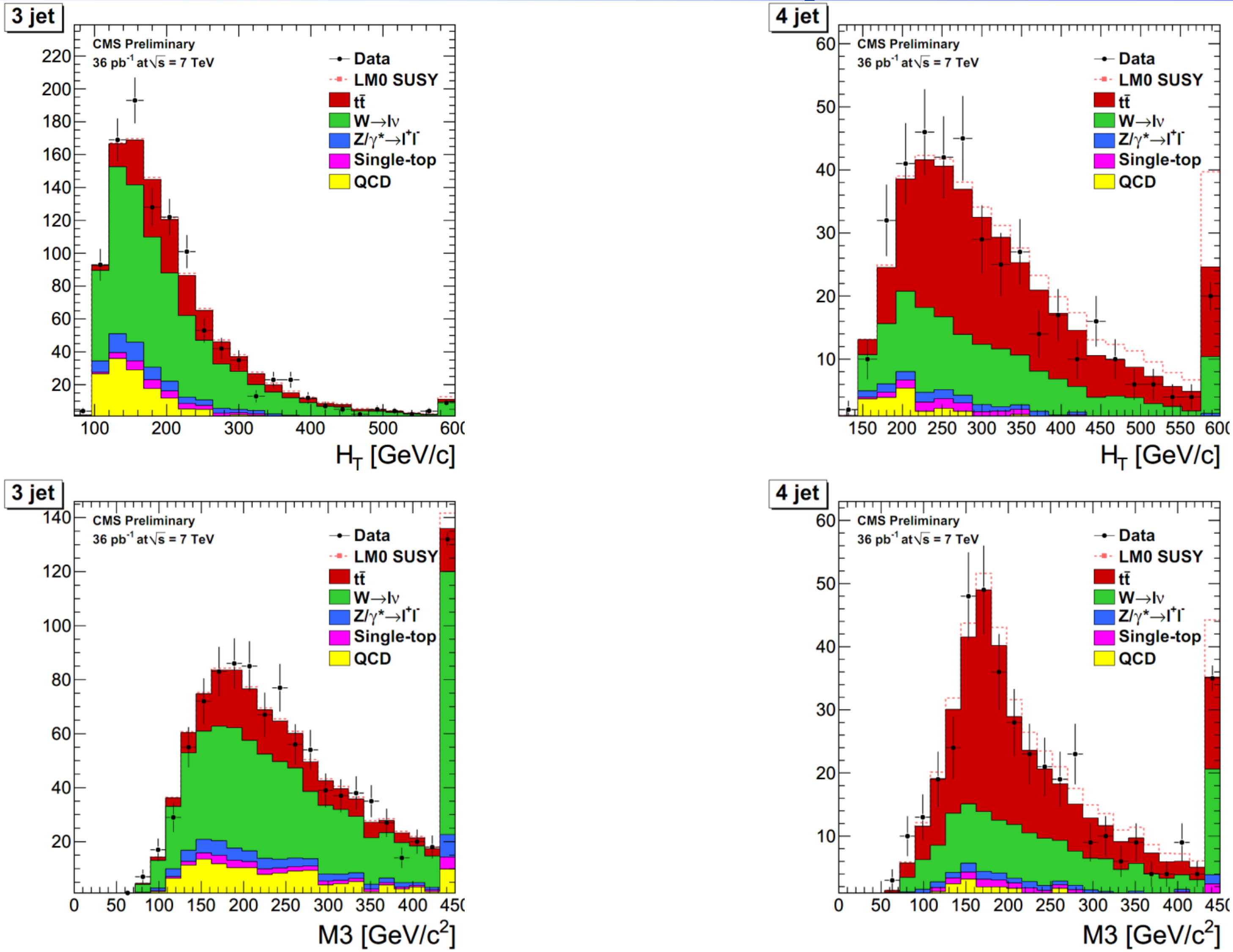








Top analysis: H_T and M3 Simultaneous template fit



Implementation of fake rate method

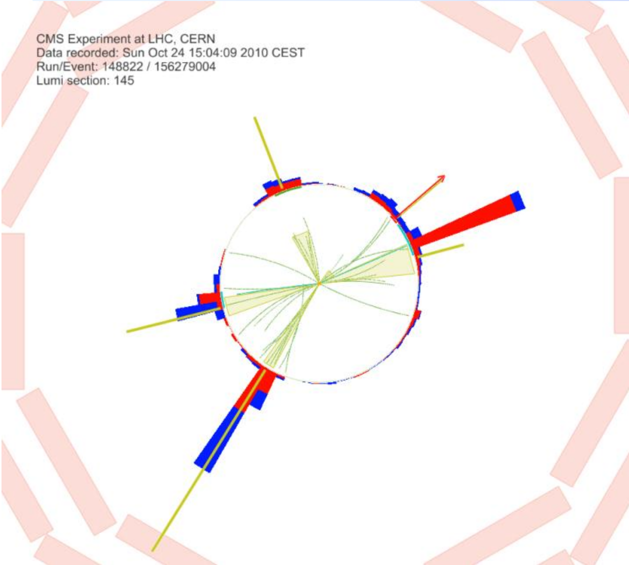
- **Measure fake rate using lepton-triggered data**
  - Require jet of certain energy in place of jet trigger
  - For single jet events, require $\Delta R(\text{lep}, \text{jet}) > 1$
  - Require lepton matched to triggered HLT object
  - Remove real leptons from W/Z decays:
    - MET < 20 GeV and M_T(lep, MET) < 25 GeV (for W + jets)
    - $|M_{ll} - M_Z| > 20$ GeV (for Z + jets)
  - Take fake rate as constant above 35 GeV
- **"Loose" lepton definition loosened further to increase statistics**
  - Electron: $I_{rel} < 0.5$, remove ID and d_0(bsp) cuts
  - Muon: $I_{rel} < 0.75$, $\chi^2/n_{dof} < 50$, d_0(bsp) < 2 mm

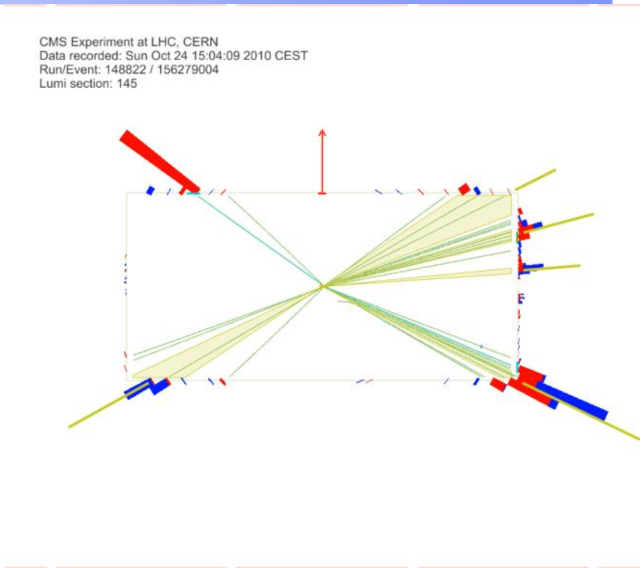
SUSY analysis:
Background composition

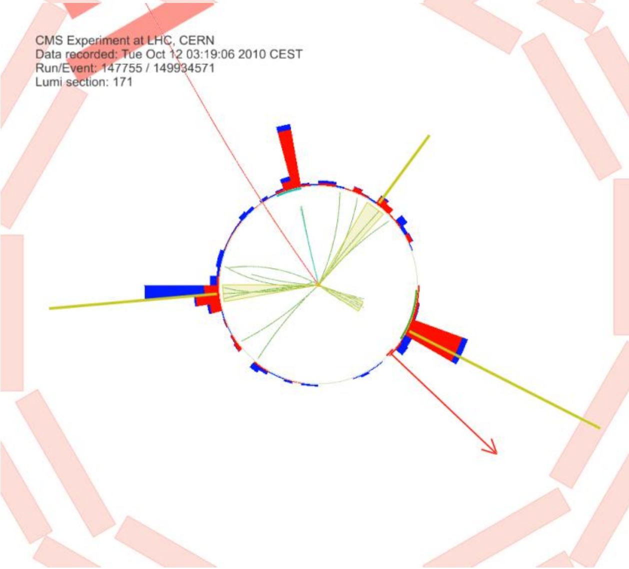
- **Expected number of background events with one or two fake leptons for the three search regions**

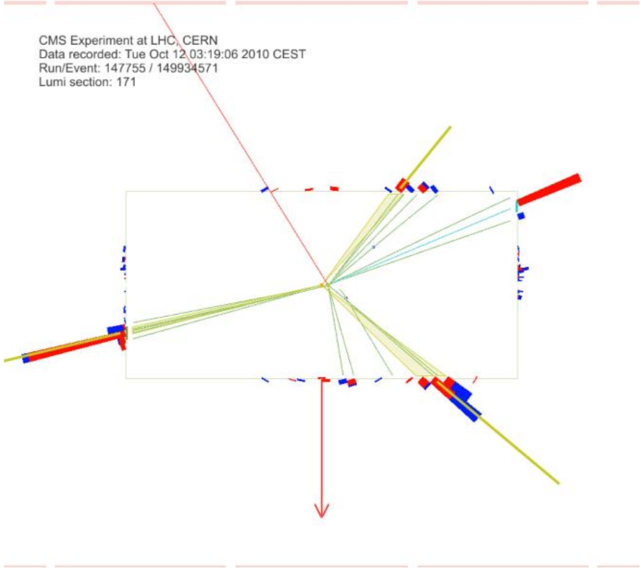
	$MET > 80$ GeV			$H_T > 200$ GeV			Low-p_{T}		
	1 fake l	2 fake l	total BG	1 fake l	2 fake l	total BG	1 fake l	2 fake l	total BG
ee	0.07	0.0	0.07	0.22	0.0	0.22	0.12	0.03	0.15
$e\mu$	0.64	0.0	0.64	0.79	0.0	0.79	0.31	0.02	0.33
$\mu\mu$	0.43	0.0	0.43	0.54	0.0	0.54	0.0	0.05	0.05
total	1.14	0.0	1.14	1.55	0.0	1.55	0.43	0.09	0.52

SUSY analysis: Event displays









Results from SUS-10-004

Search Region	ee	$\mu\mu$	$e\mu$	total	95% CL UL Yield
Lepton Trigger					
$E_T^{miss} > 80$ GeV					
MC	0.05	0.07	0.23	0.35	
predicted BG	$\mathbf{0.23^{+0.35}_{-0.23}}$	$\mathbf{0.23^{+0.26}_{-0.23}}$	$\mathbf{0.74 \pm 0.55}$	$\mathbf{1.2 \pm 0.8}$	
observed	**0**	**0**	**0**	**0**	**3.1**
$H_T > 200$ GeV					
MC	0.04	0.10	0.17	0.32	
predicted BG	$\mathbf{0.71 \pm 0.58}$	$\mathbf{0.01^{+0.24}_{-0.01}}$	$\mathbf{0.25^{+0.27}_{-0.25}}$	$\mathbf{0.97 \pm 0.74}$	
observed	**0**	**0**	**1**	**1**	**4.3**
H_T Trigger					
Low-p_T					
MC	0.05	0.16	0.21	0.41	
predicted BG	$\mathbf{0.10 \pm 0.07}$	$\mathbf{0.30 \pm 0.13}$	$\mathbf{0.40 \pm 0.18}$	$\mathbf{0.80 \pm 0.31}$	
observed	**1**	**0**	**0**	**1**	**4.4**
	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$	total	95% CL UL Yield
τ_h enriched					
MC	0.36	0.47	0.08	0.91	
predicted BG	$\mathbf{0.10 \pm 0.10}$	$\mathbf{0.17 \pm 0.14}$	$\mathbf{0.02 \pm 0.01}$	$\mathbf{0.29 \pm 0.17}$	
observed	**0**	**0**	**0**	**0**	**3.4**