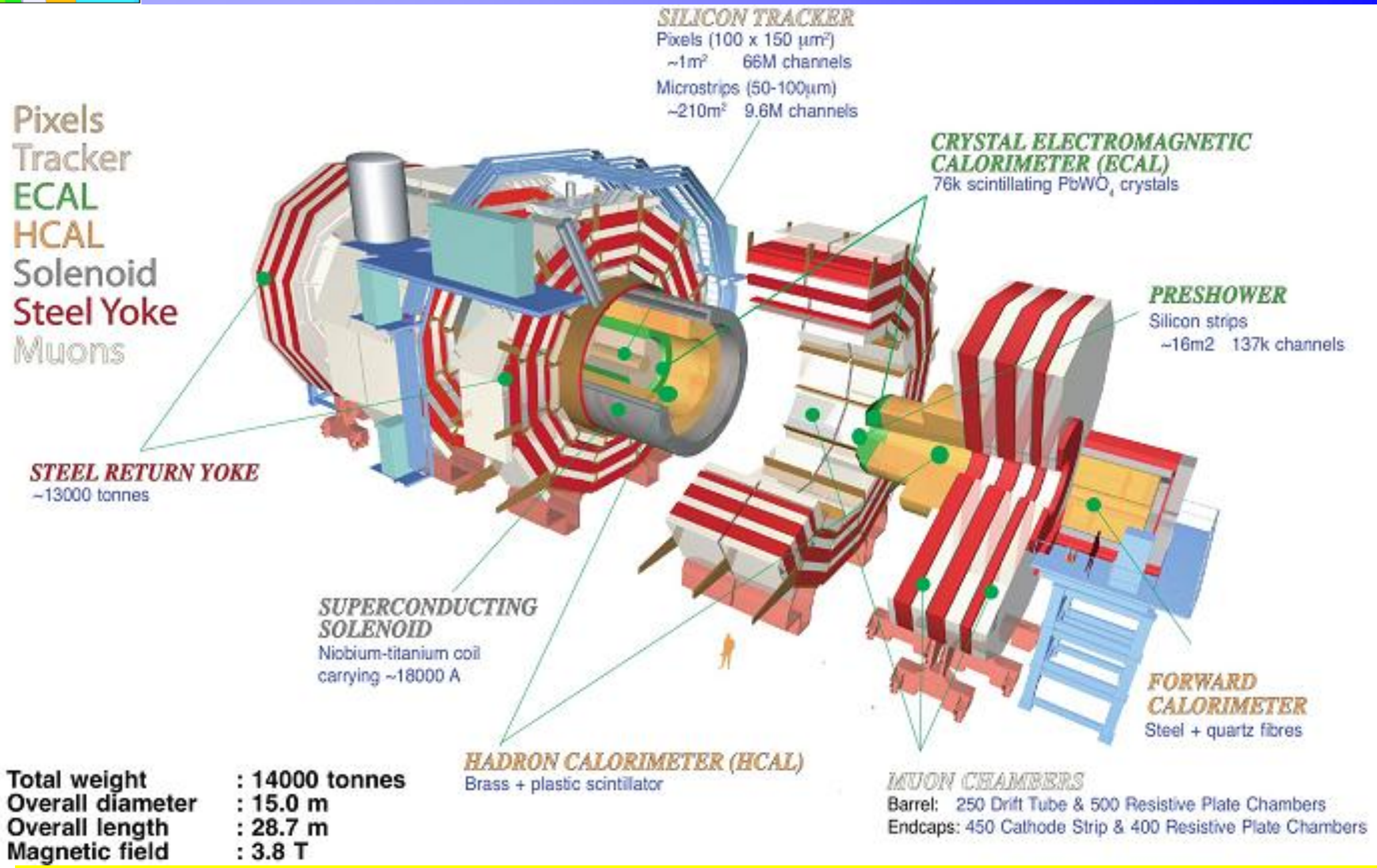
Recent Physics Results From the CMS Experiment

Dan Green

Fermilab

CMS – the Detector



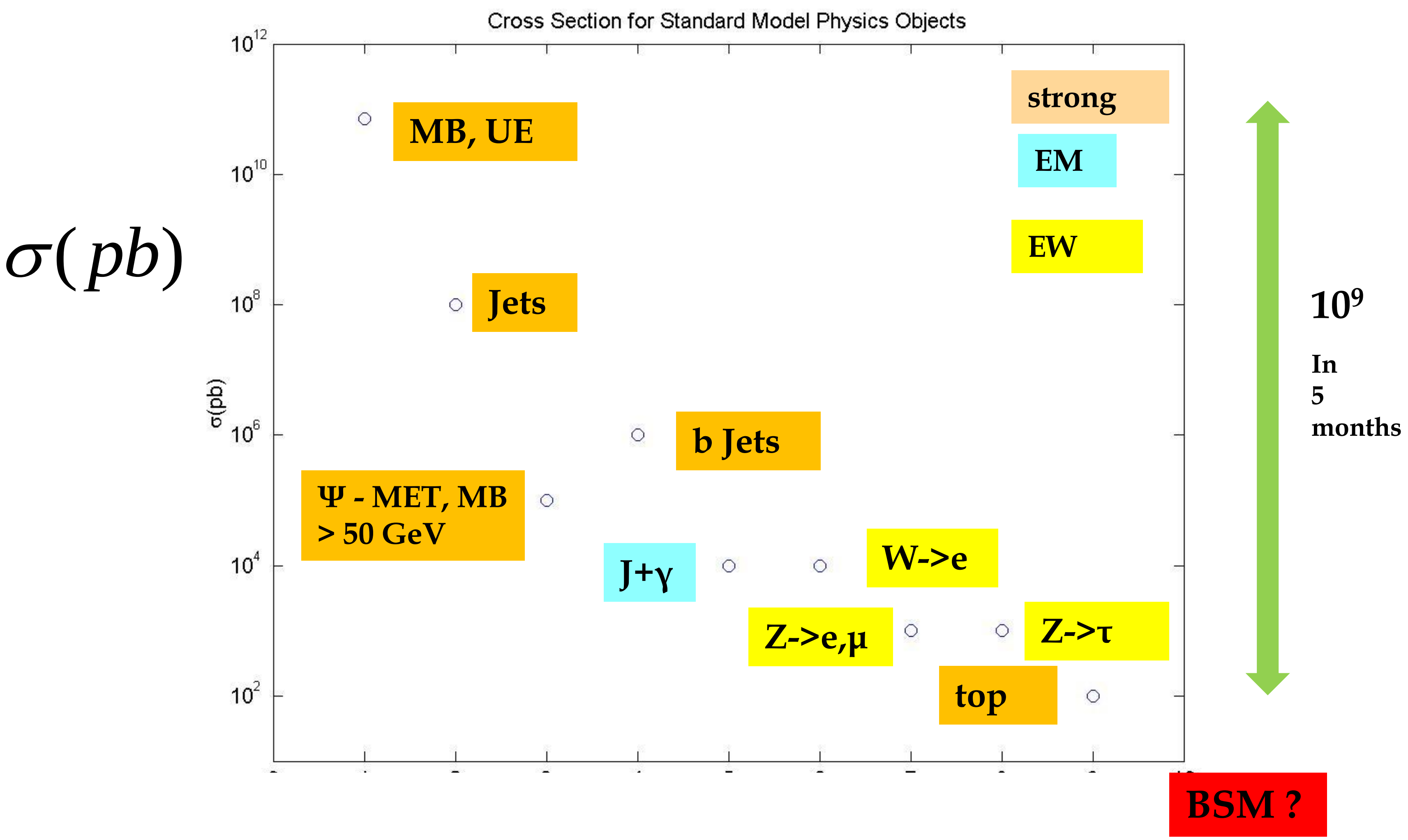
LHC detectors and accelerator are the most complex scientific instruments yet built

The Standard Model

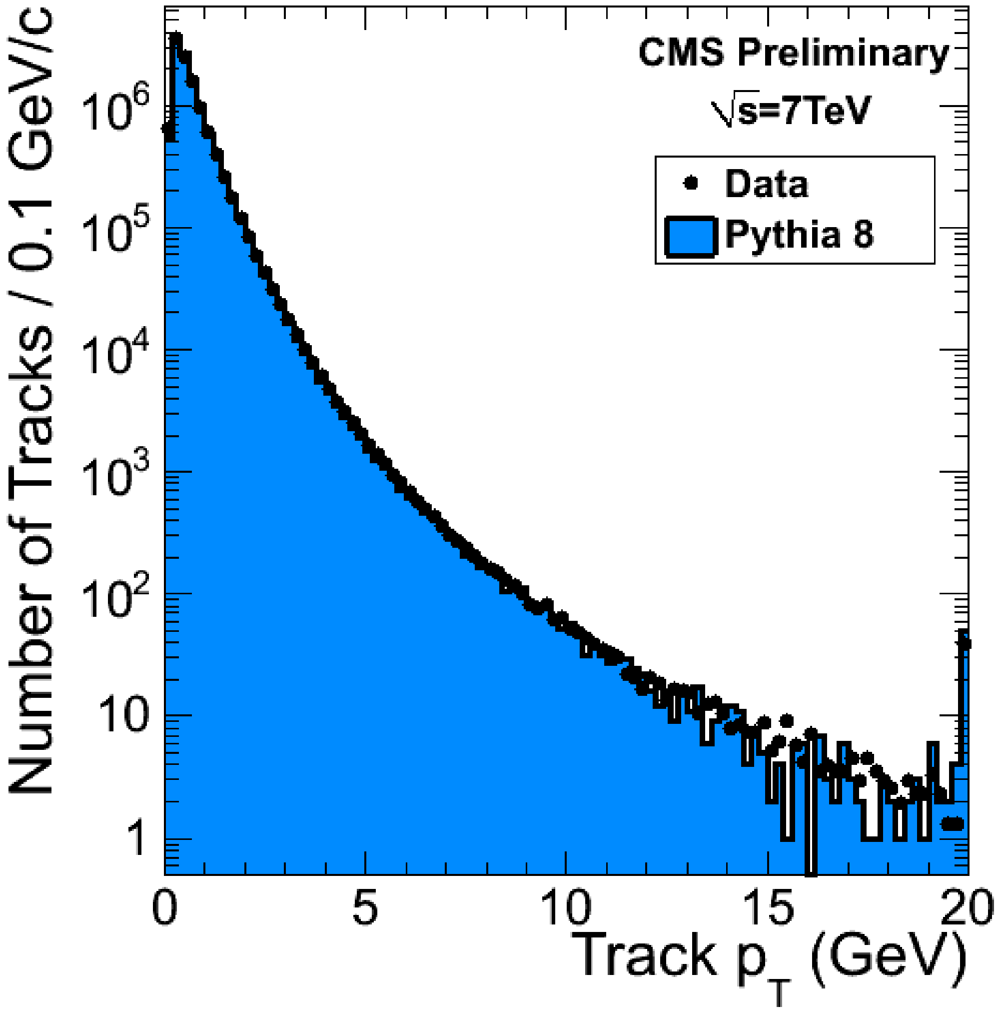
J = 1	g, γ, W^+, Z^o, W^-					Force Carriers
	u d	c s	t b		2/3 -1/3	Quarks
J = 1/2				Q/e=		
	e ν_e	μ ν_μ	τ ν_τ		1 0	Leptons
J= 0		H				

Commissioning a new accelerator in an unexplored energy regime with a new detector -> "rediscover the SM". As of today, CMS has, indeed, observed all the particles of the SM (not the H) !.

Rediscovery of the SM

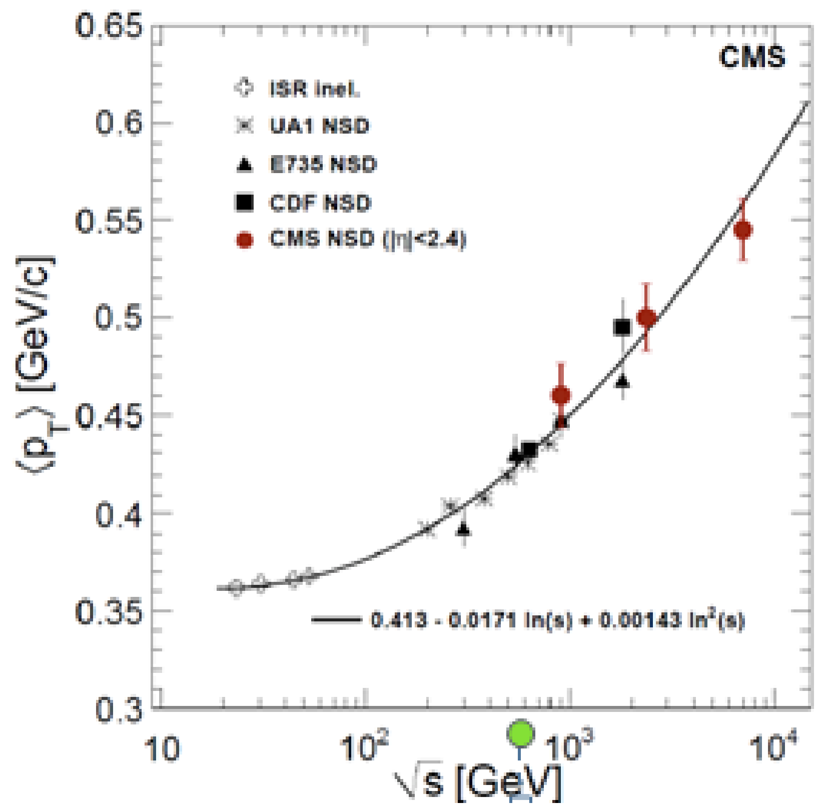


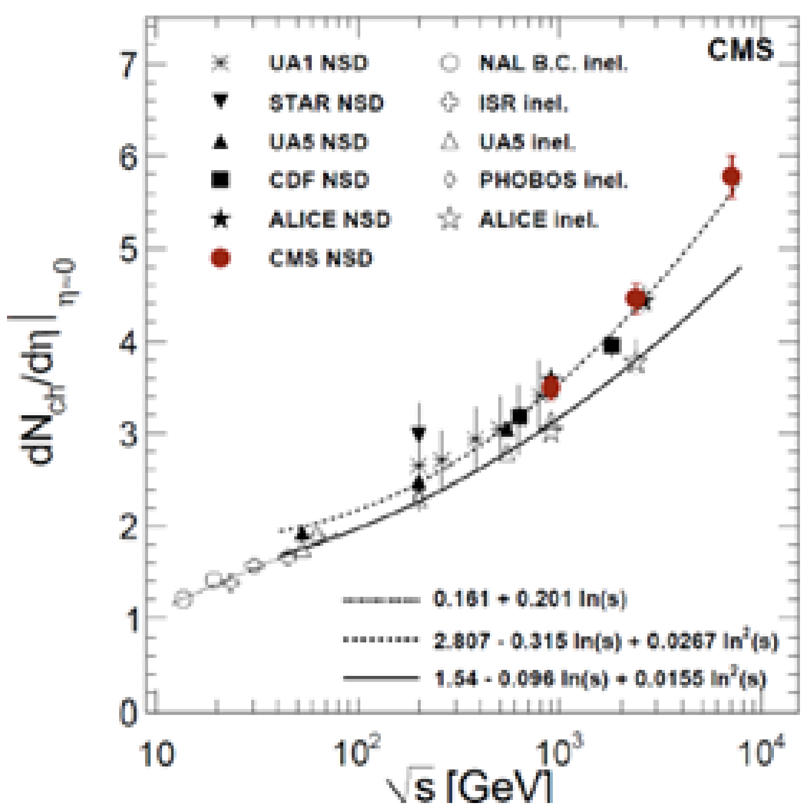
Tracking System



CMS all Si tracker – start by understanding the MB and UE. Tuning of the Monte Carlos needed at the new CM energy of 7 TeV – more soft particles than predicted.

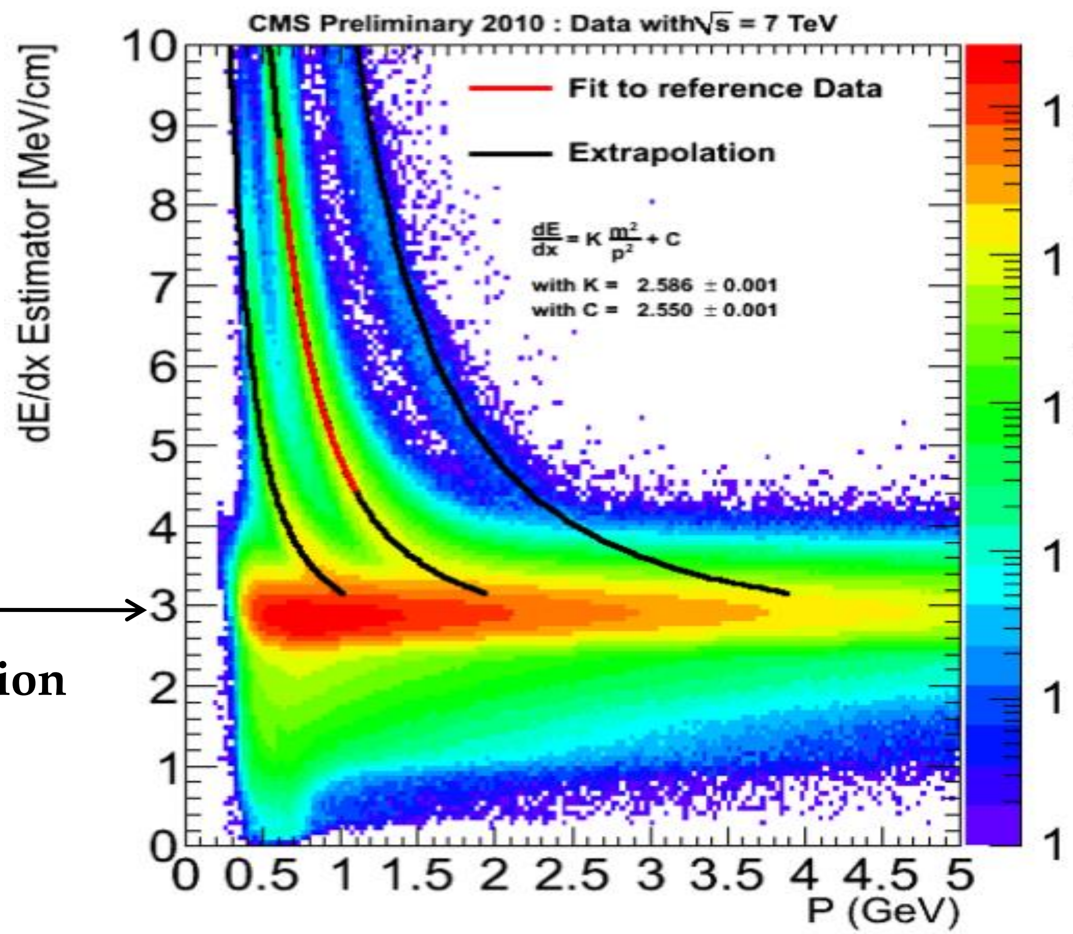
Inclusive Cross Section





CMS data taken and published at 0.9, 2.36 and 7 TeV. Tracking commissioned down to ~ 100 MeV = Pt. Rapidity density of 6 charged particles.

Particle ID – dE/dx in Tracker



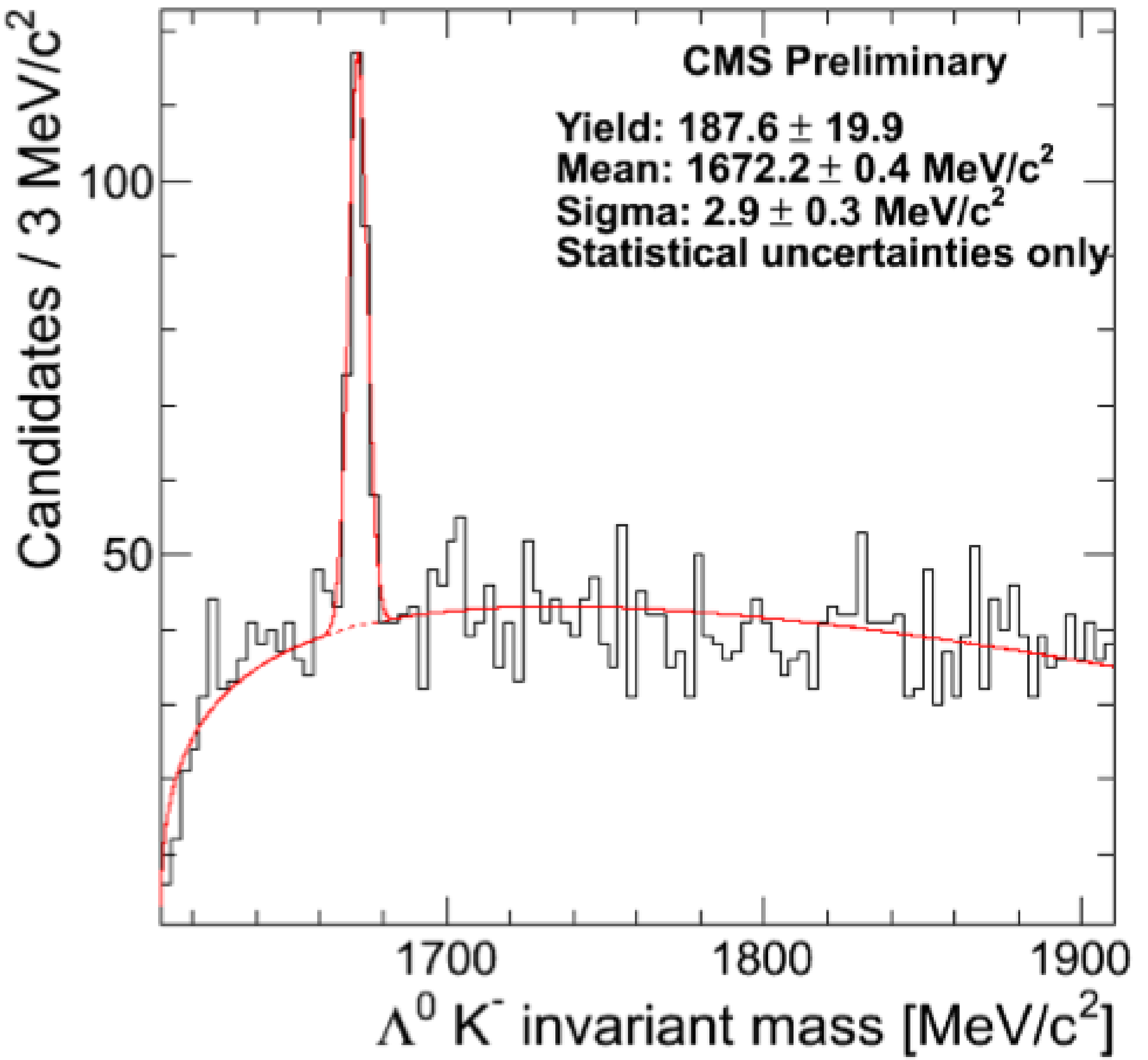
min ion

Use energy deposited in several Si strip layers to measure dE/dx. Useful for particle id. Once commissioned, use in heavy stable particle searches.

$$dE/dx \sim 1/\beta^2 \sim M^2/P^2$$

-mass measurement using P and dE/dx from tracker

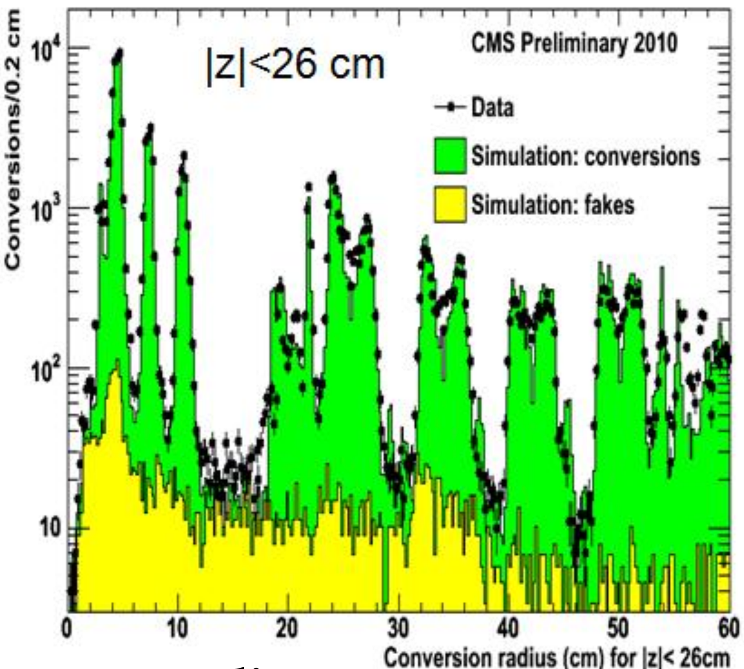
MB Events – s Quarks

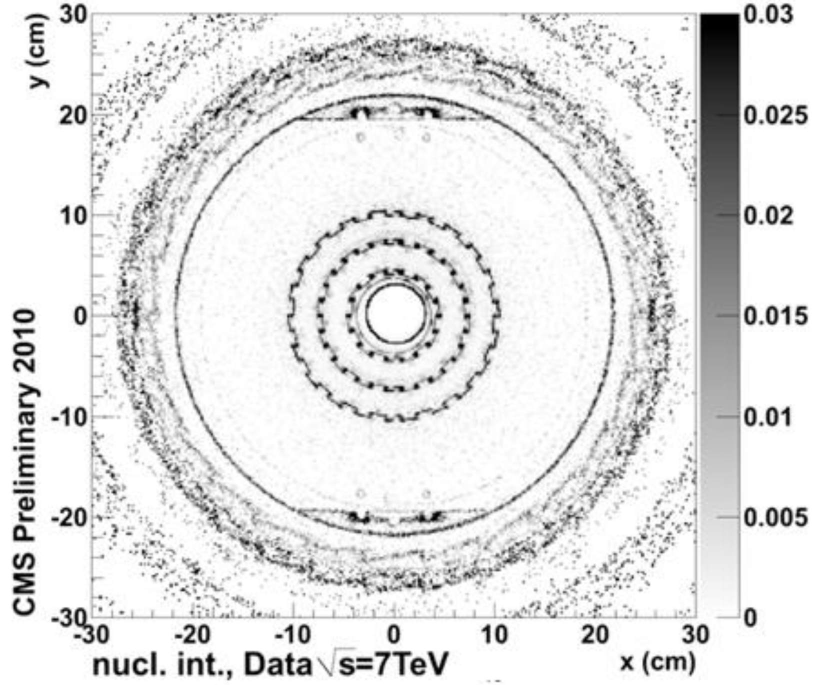


Find s quark decays – secondary vertices for Λ, Ks, Ξ, Ω. Use the dE/dx to find K, p. Checks tracker momentum scale and resolution.

Tracker Material

beam pipe, pixels, strips

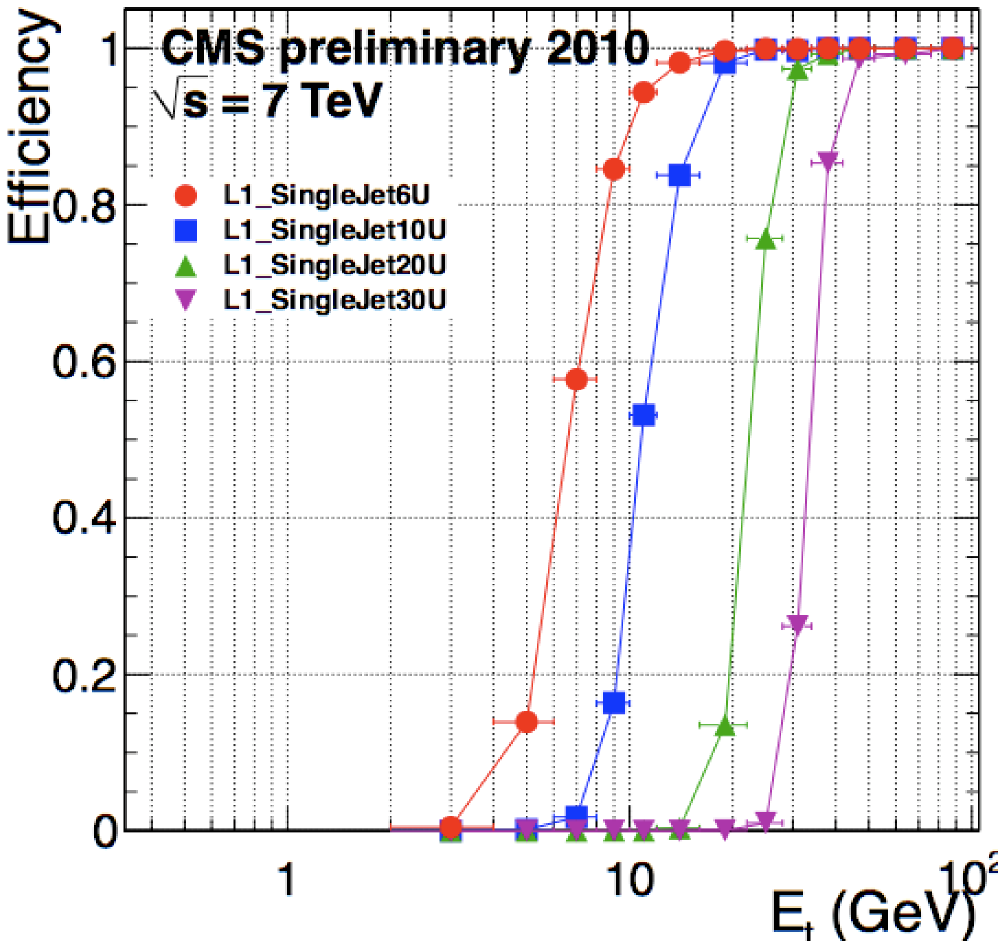




radius

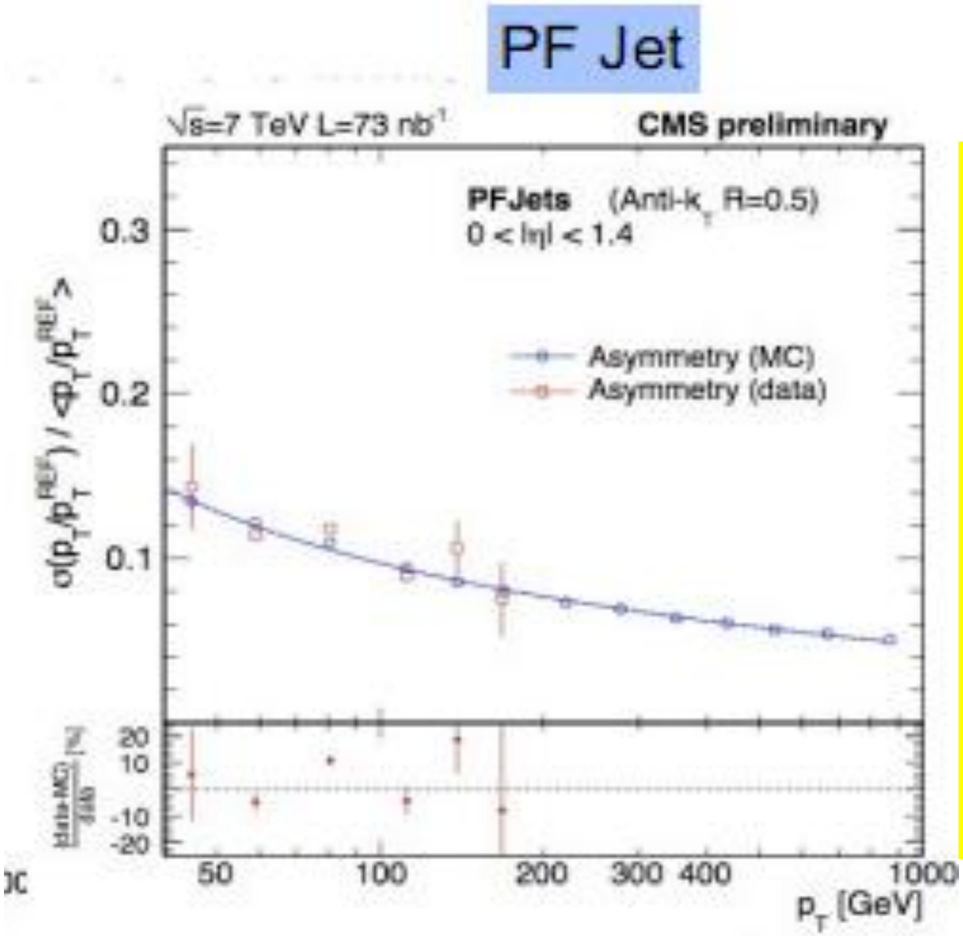
For a complete understanding of the momentum scale and resolution a detailed understanding of the tracker material throughout the system is needed – use photon conversions for high Z and nuclear interactions for low Z material.

Triggers - Commissioning

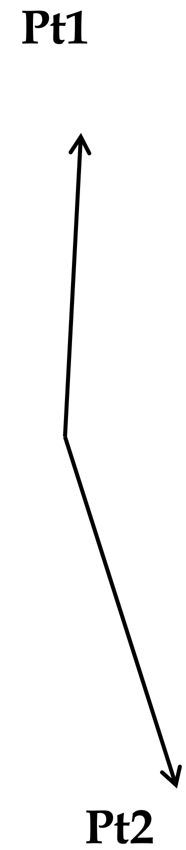


At L = 10^{32}/(cm^{2}sec) MB rate is ~ 10^7 . Triggers need to be sharp in Pt due to steeply falling spectrum. Start with MB and look at "mark and pass" triggers. Establish the turn on curves , behavior in Pt. As luminosity increases, commission higher rejection triggers - bootstrap.

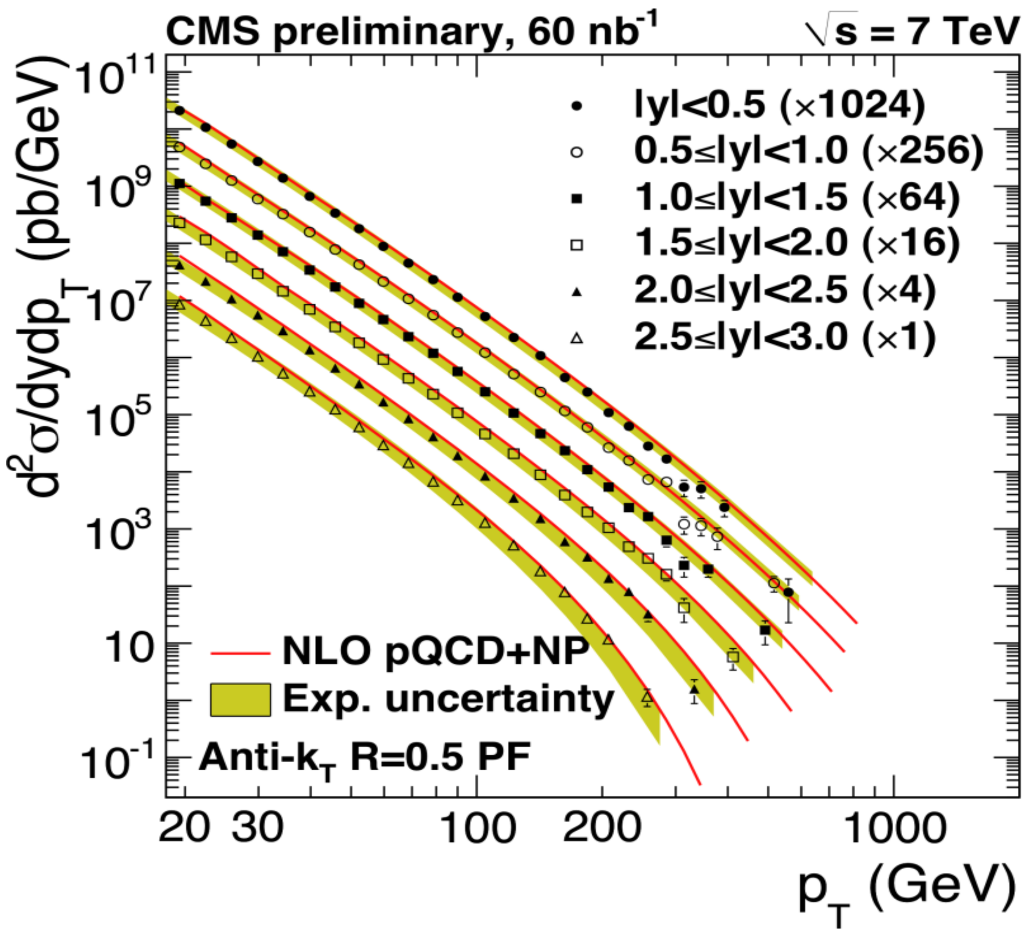
Jets – u, d, s, g Resolution



Jets from q and g – strong production. Use azimuthal symmetry, dijet balance and single particle (isolated) response to calibrate the jet energy scale and measure the jet energy resolution. Resolution ranges from 14 to 5 %.

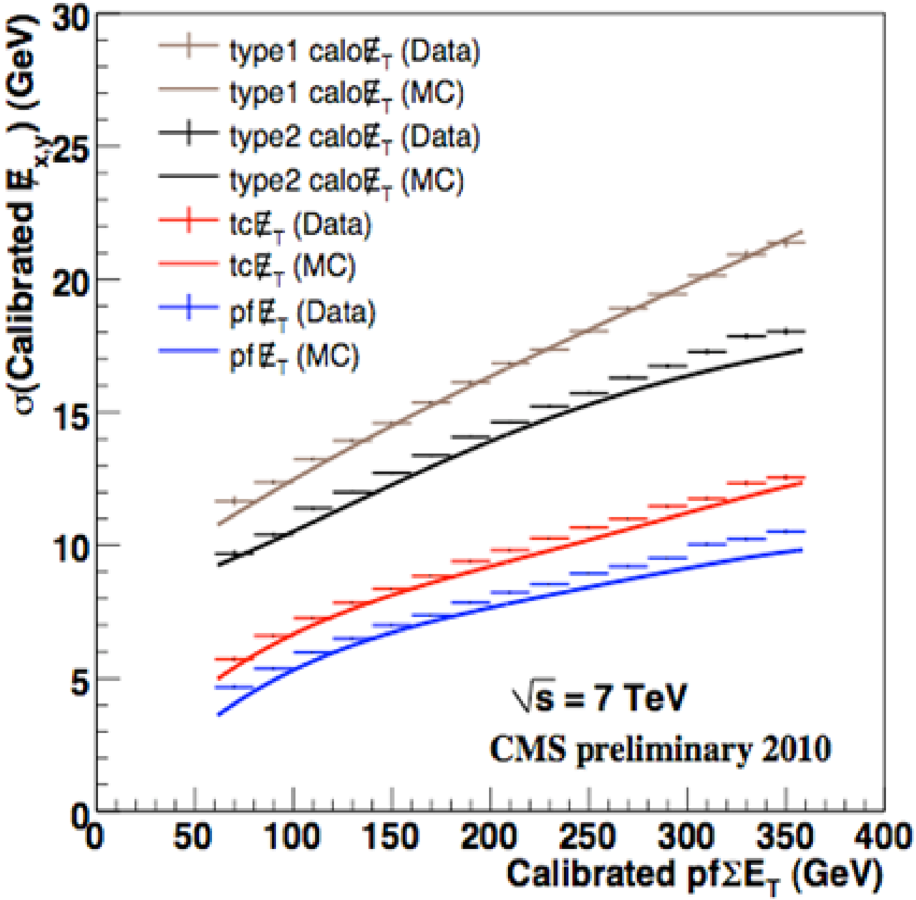


Jet Cross Section



Establish the jet cross section as a function of y and Pt. Monte Carlo agreement is good. Now ready to look at high masses for BSM Physics – more later.

MET "Core" Commissioning

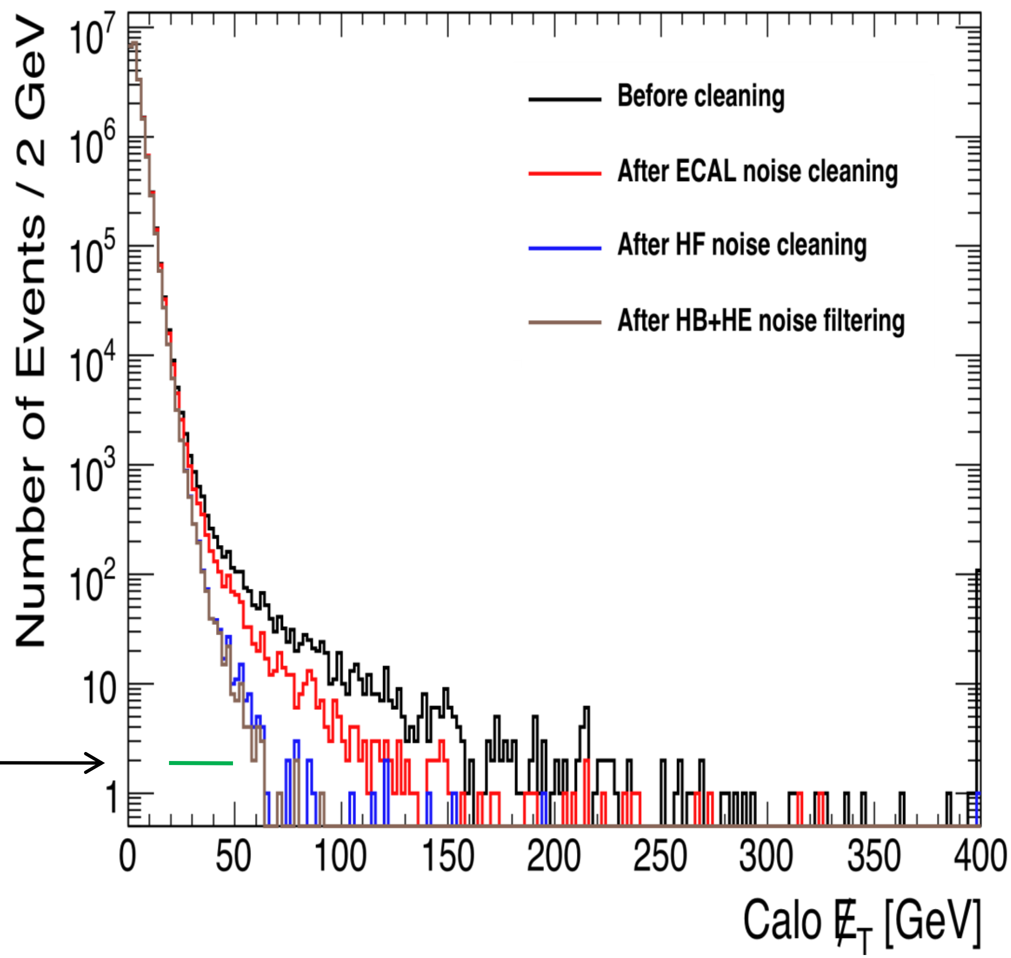


Use calorimetry and tracking to improve the MET resolution. Tracker has better resolution at low E and there are many soft particles in UE and jet fragments. Cleaning of cosmics, beam halo and calorimeter discharges is needed. Gaussian core of MET resolution is

$$\sim 50\% / \sqrt{\sum E_T}$$

MET – "Tail" and Noise Filtering

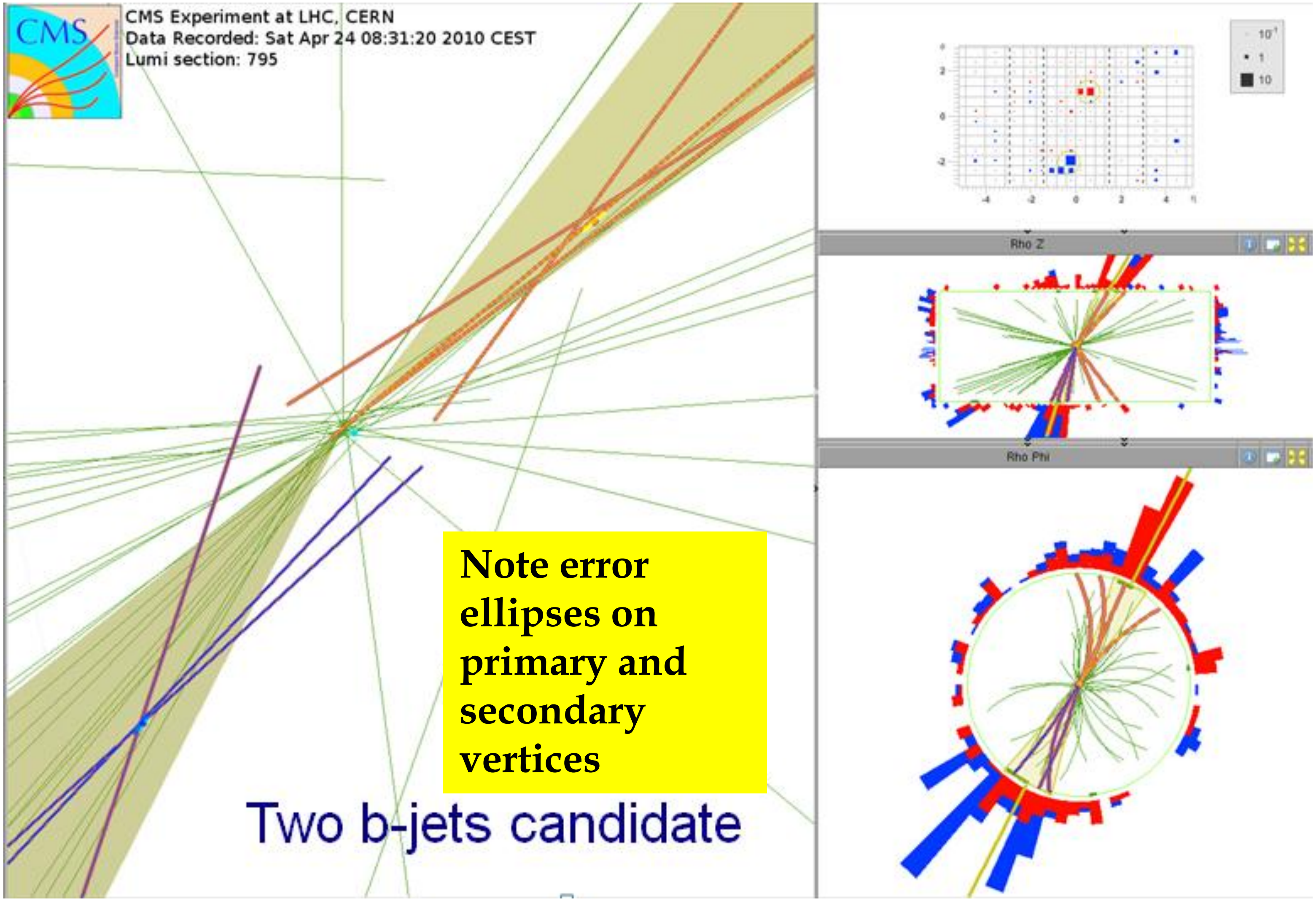
10x
EW



MB events :
The MET noise filtering greatly reduces the tail. An irreducible floor is set by the EW processes, which are ~ 10^7 times smaller in cross section than the inclusive MB events.

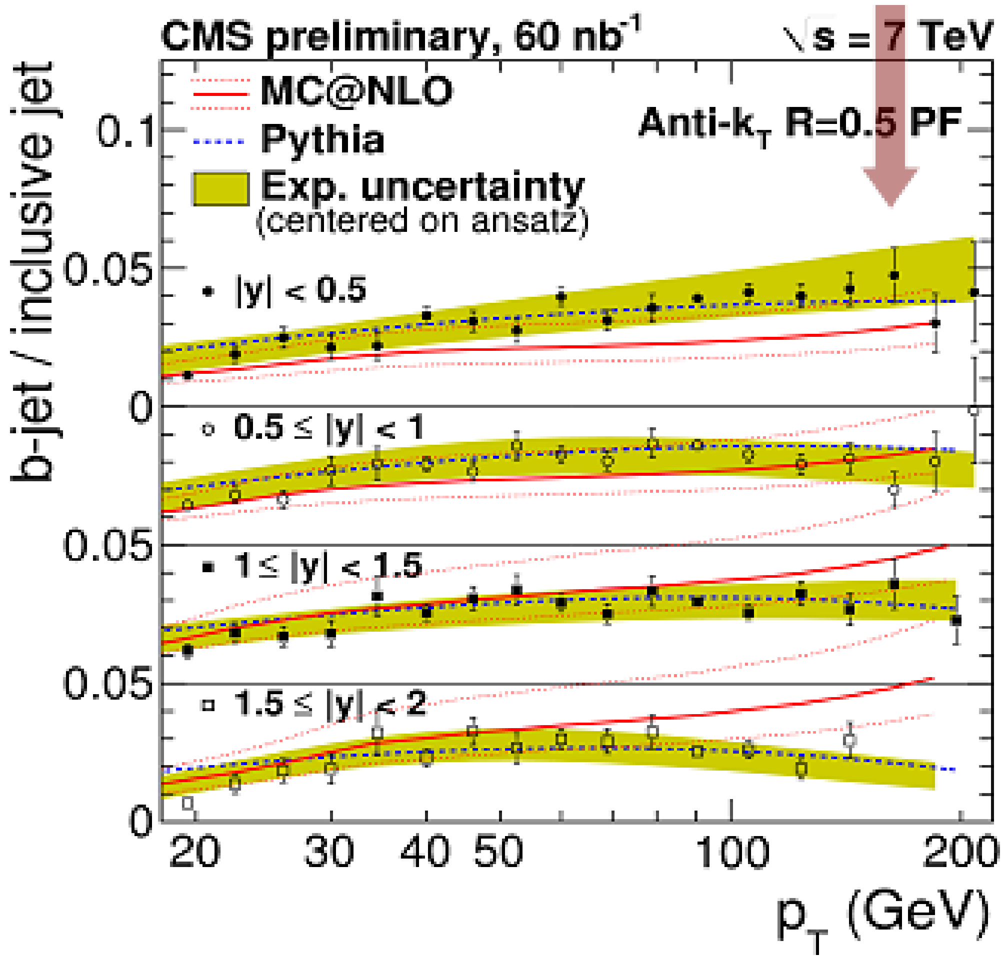
MET commissioned to EW scale – ν_e, ν_μ, ν_τ

Tracker Performance – b Quarks



Note error ellipses on primary and secondary vertices

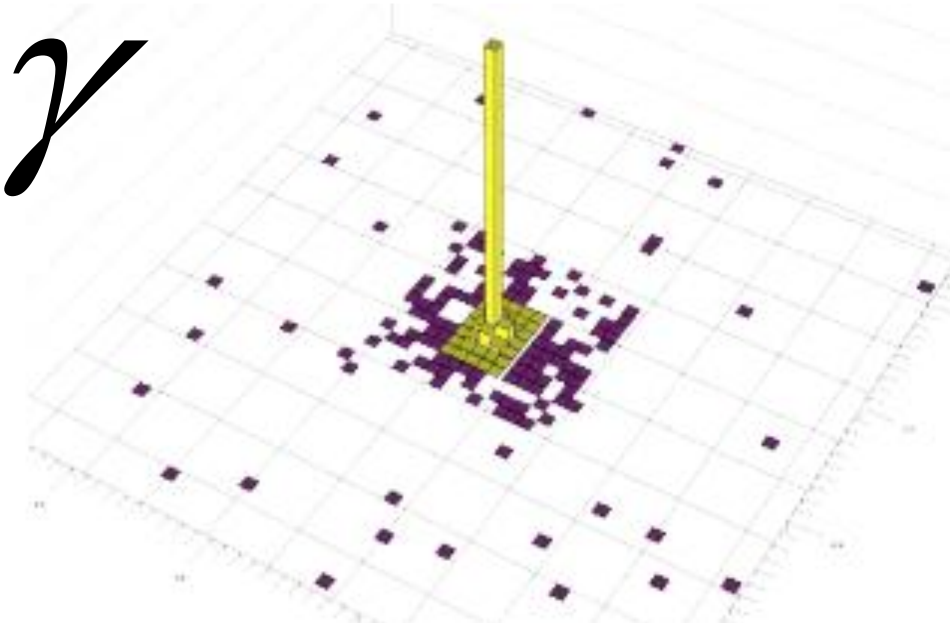
b Cross Section



At the LHC the b cross section is large -> LHCb. The b jet rate is ~ 2 % (Pt dependent) of the inclusive jet rate. Well modeled by PYTHIA Monte Carlo. Use secondary vertex mass, Ptrel templates for u+d+g, c, and b – efficient b tagging with good u+d+g rejection

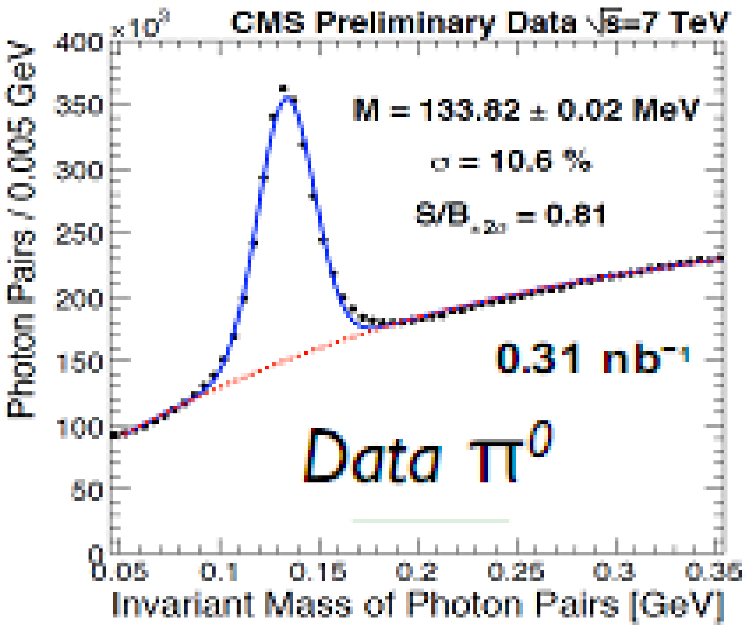
Photons, Electrons and ECAL

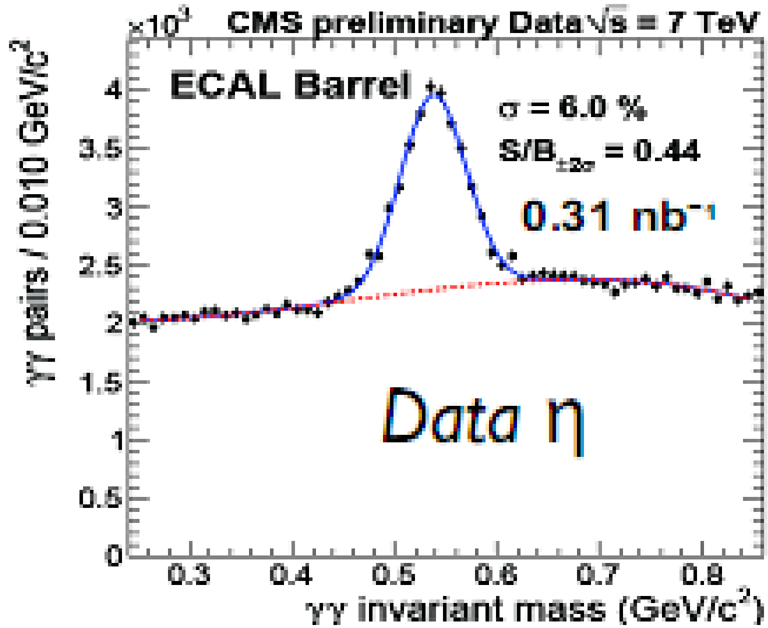
γ



The CMS ECAL has a transverse segmentation ~ 1 Moliere radius. Use that fine granularity for photon ID and for track matching in the case of electrons. ECAL energy resolution is very good for E/p matching of the e track.

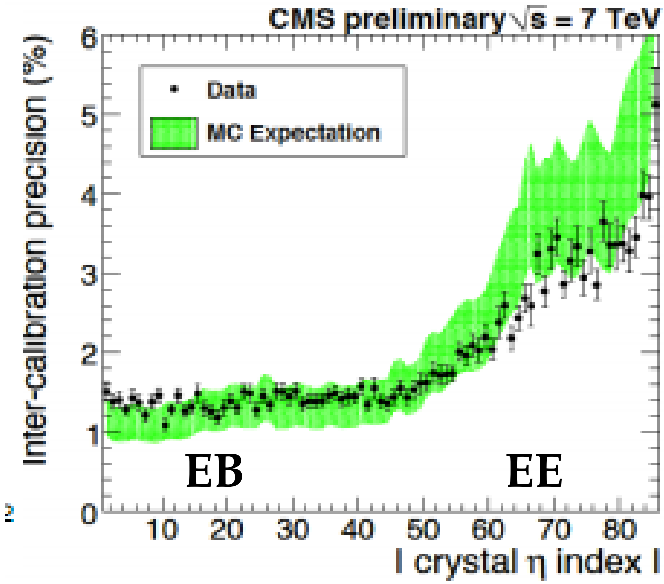
ECAL Calibration



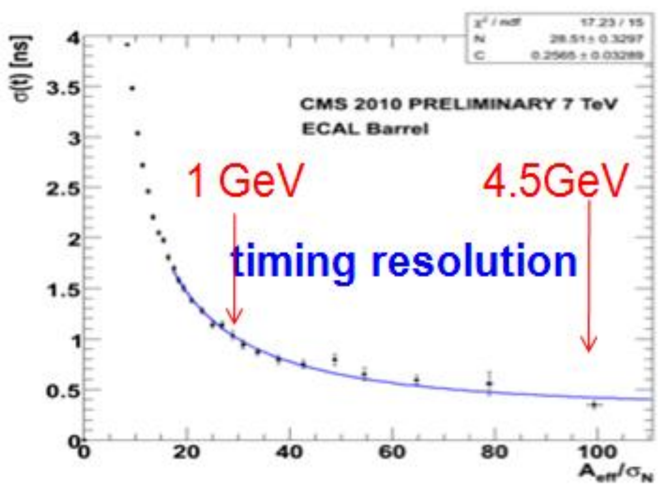


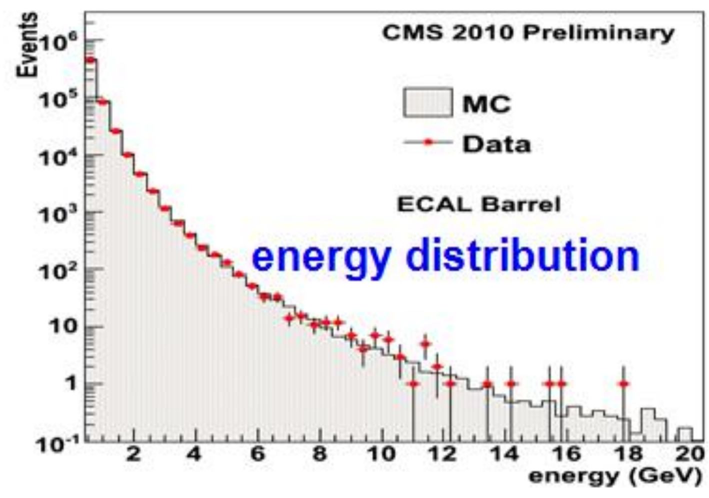
Use low mass resonances to study energy scale calibration and energy resolution. Use azimuthal symmetry to check uniformity of response over the full, |y| < 3, detector coverage. Photon + J (Compton) used to check the JES using the better resolution of the ECAL

ECAL Commissioning

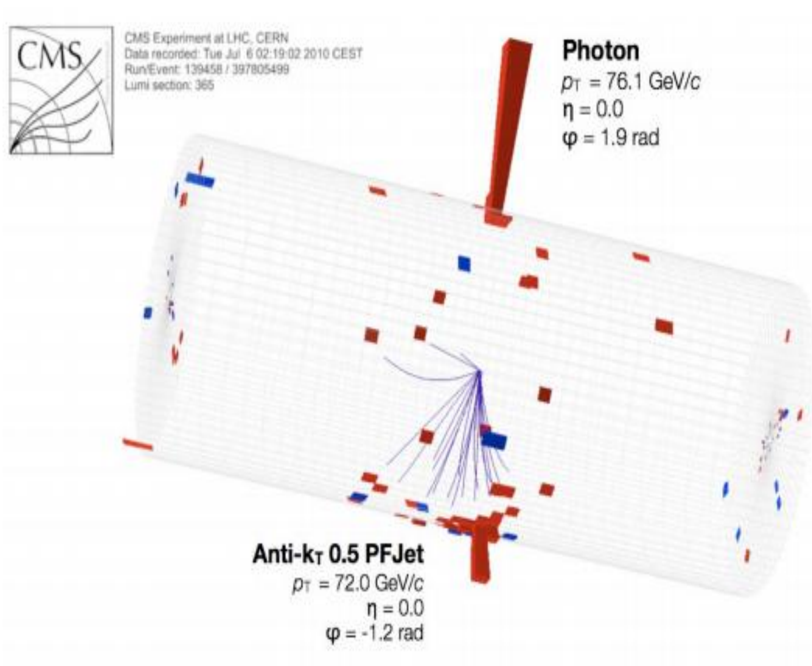


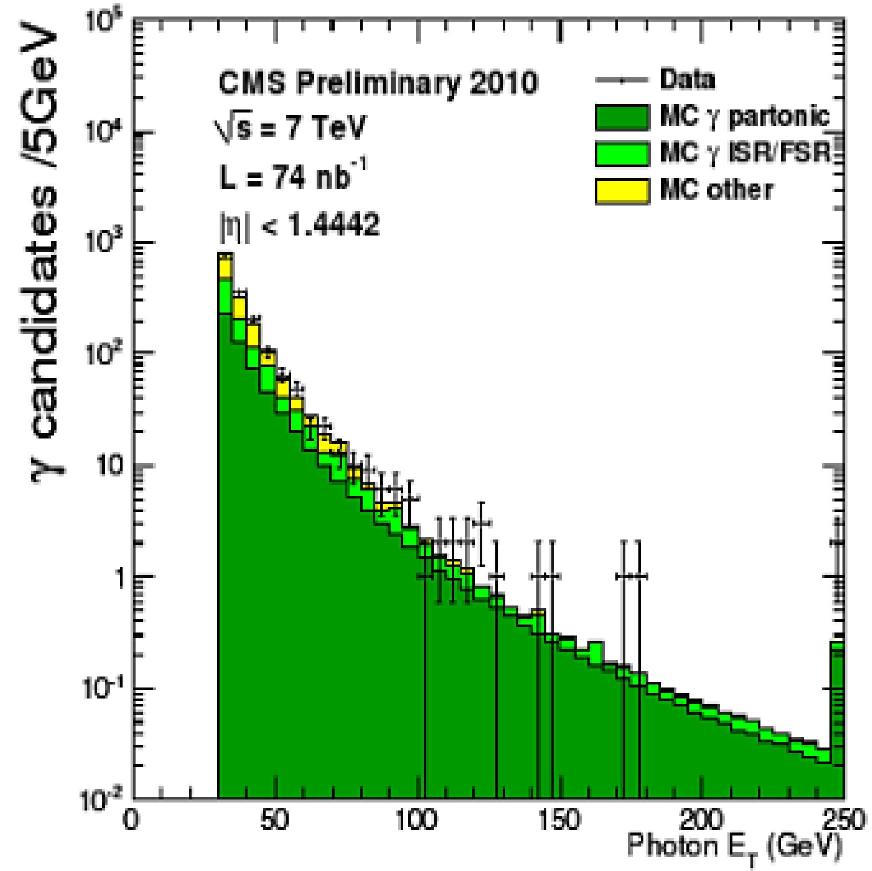
ECAL "clusters". Present calibration to 1 % in the barrel. Timing good to < 0.5 nsec – very useful in "cleaning" and cosmic/halo rejection.





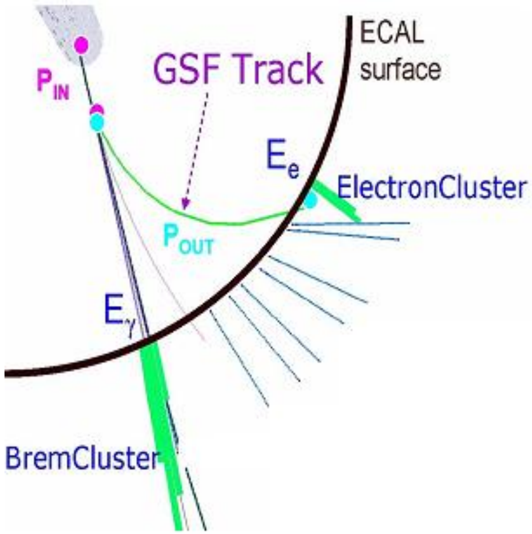
Photon Commissioning



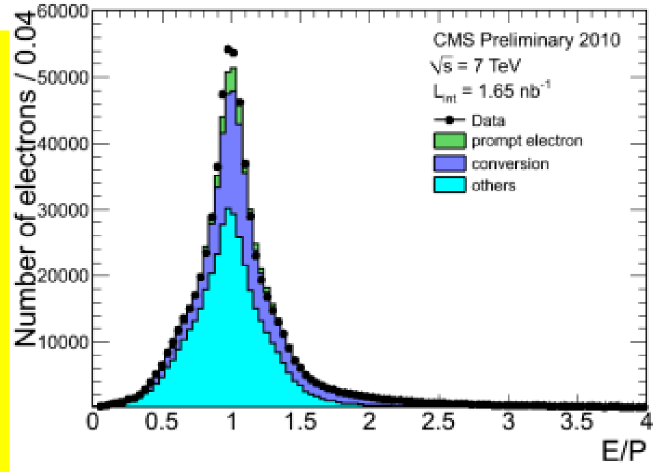


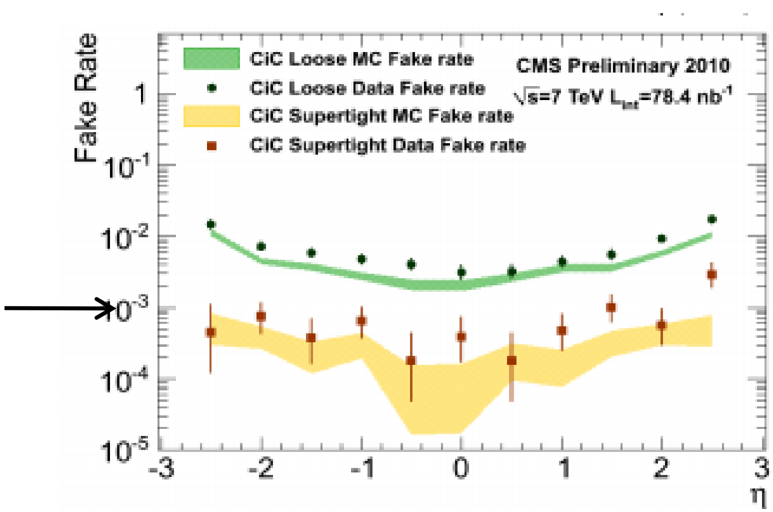
Clean photon + J events. Photon spectrum quite clean for high Pt photons, > 100 GeV. Data /Monte Carlo agreement is good.

Electrons – Track + ECAL

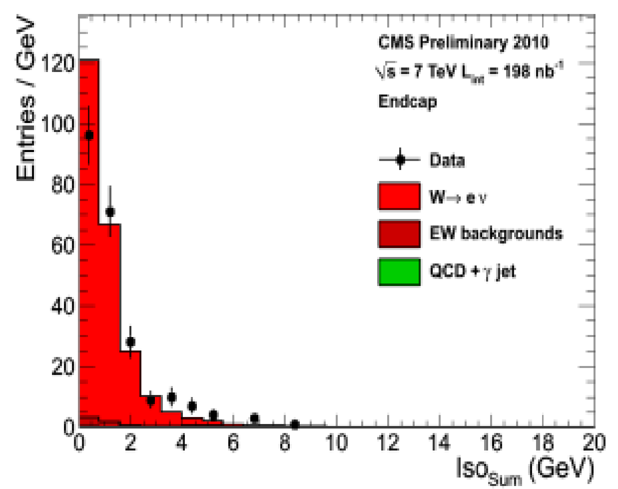


Understanding material of the CMS tracker is crucial. Bremm in pipe and Si -> collect E in φ Use E/p and isolation



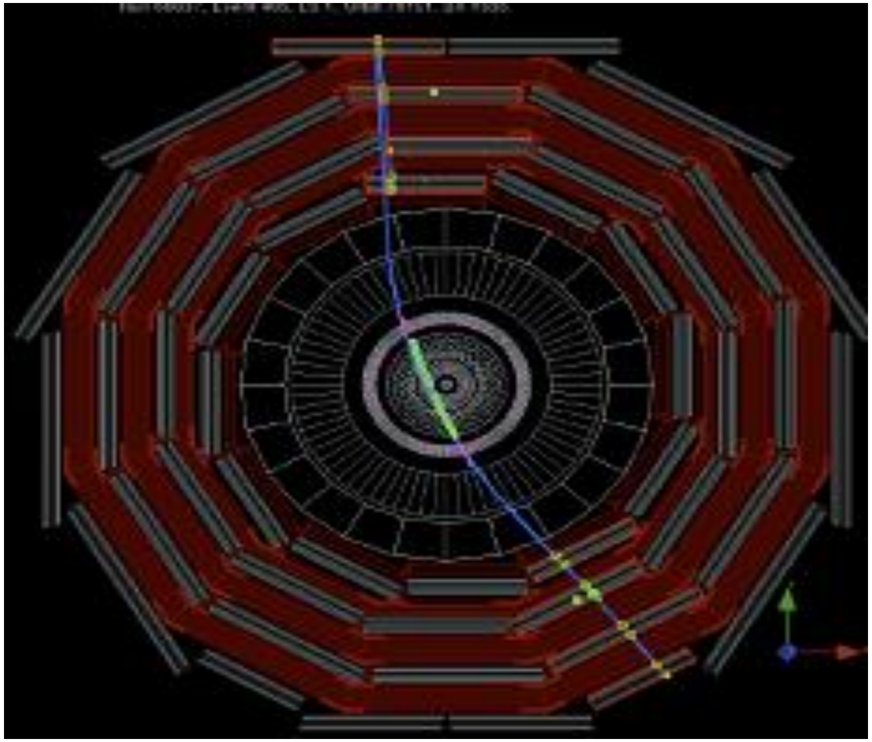


ECAL endcap



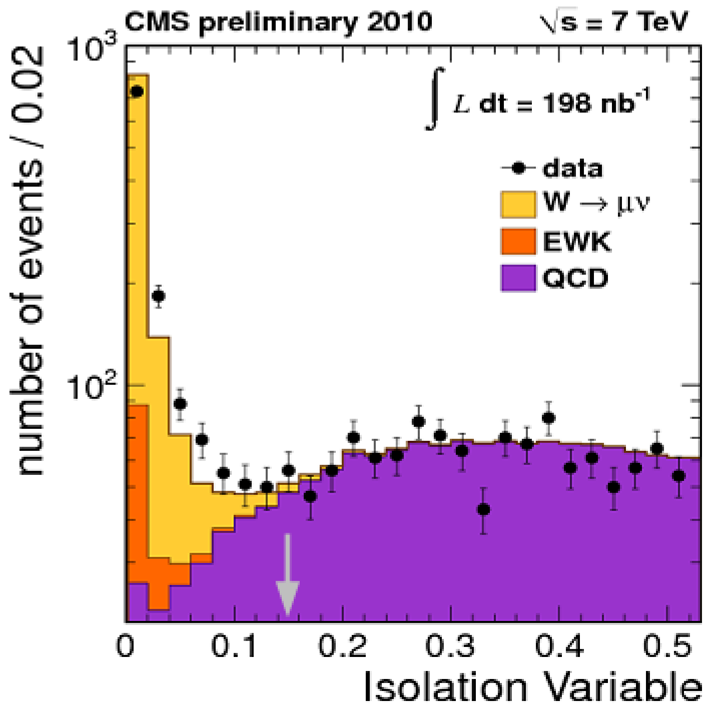
Eiso

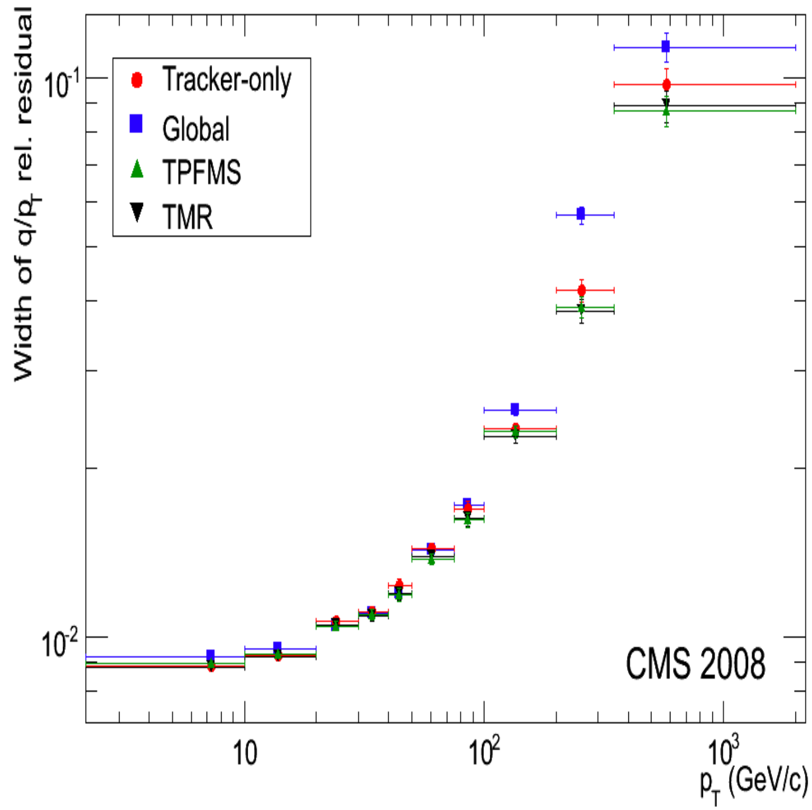
Muons



Experience from ~ 10^9 muons recorded before beam in the LHC. Muons up to 1 TeV in cosmics – gives experience with showering muons (critical energy). LHC "halo" also used for alignment of large |y| muon and tracking detectors - break alignment degeneracies.

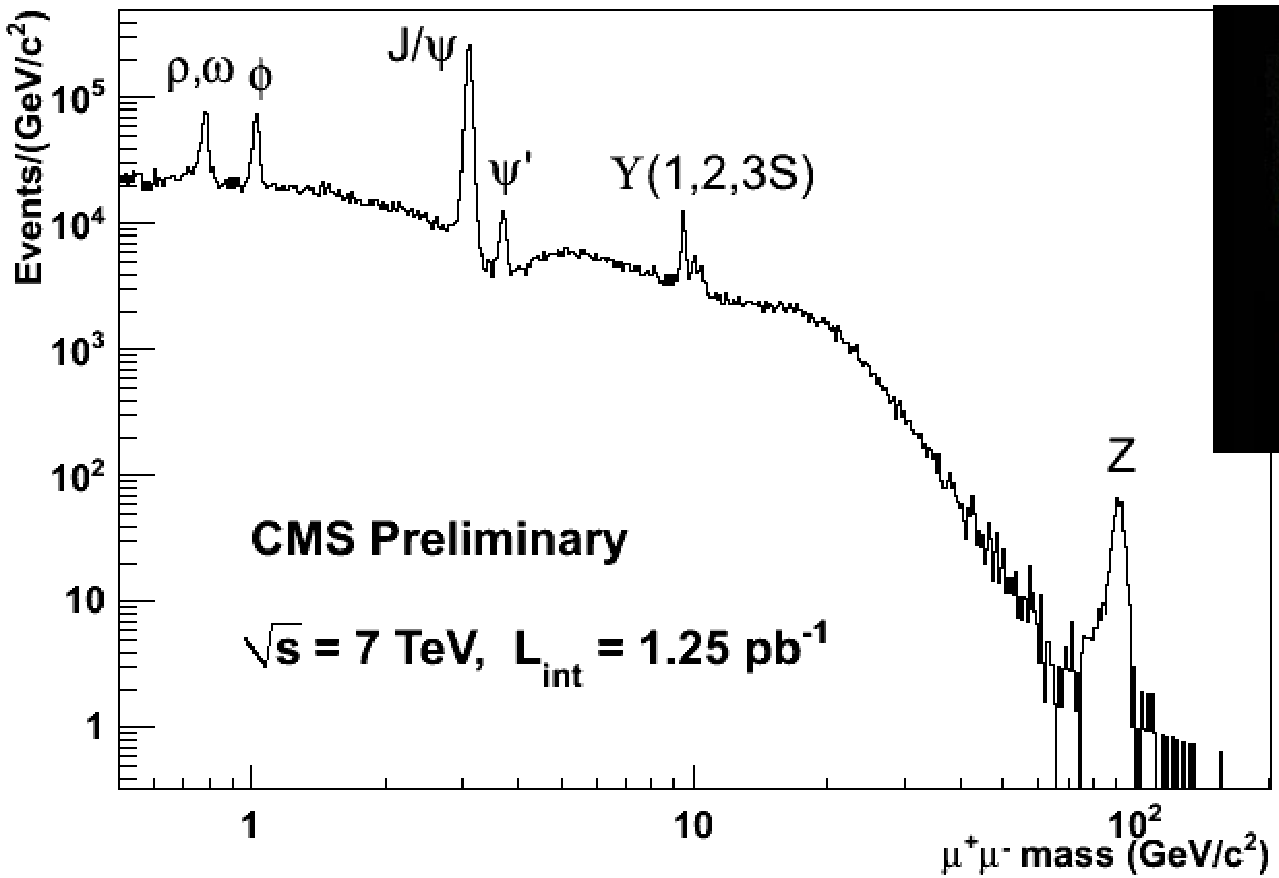
Muon Performance





Isolation uses tracker + ECAL + HCAL. Typical energy cuts, relative to the muon Pt are 0.05 to 0.15 depending on the specific analysis. Muon scale, efficiency and resolution established using tracker/muon system redundancy. Resolution ~ design value of 10% at 1 TeV.

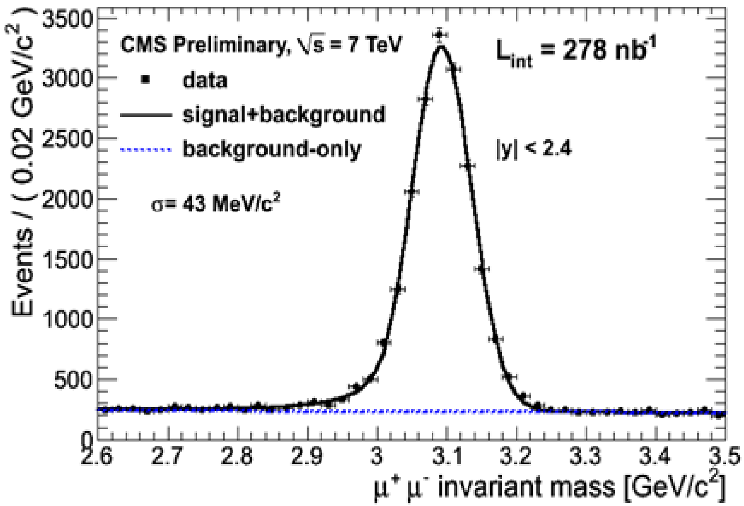
Dilepton "Standard Candles"



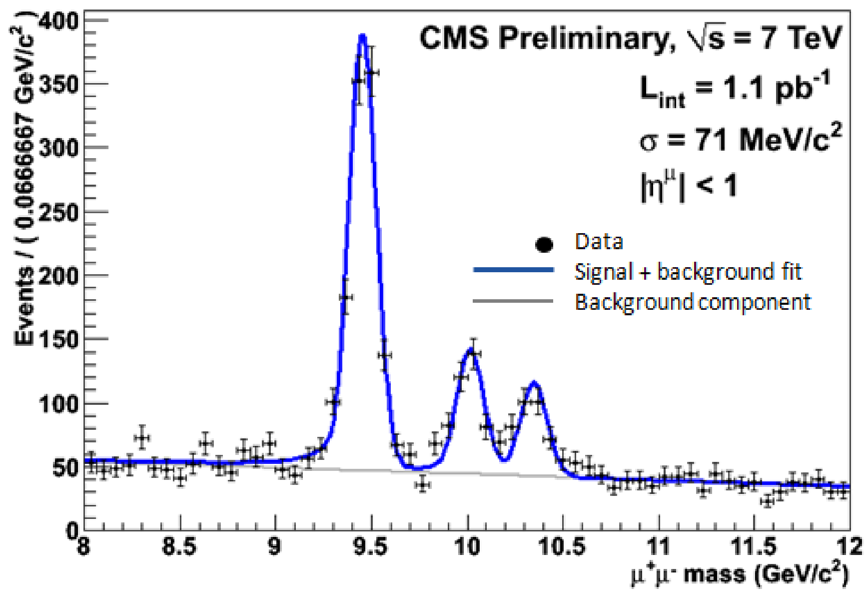
Use known resonances for mass scale, mass resolution and trigger/reco efficiency – "tag and probe"

Mass Scale and Resolution

ψ

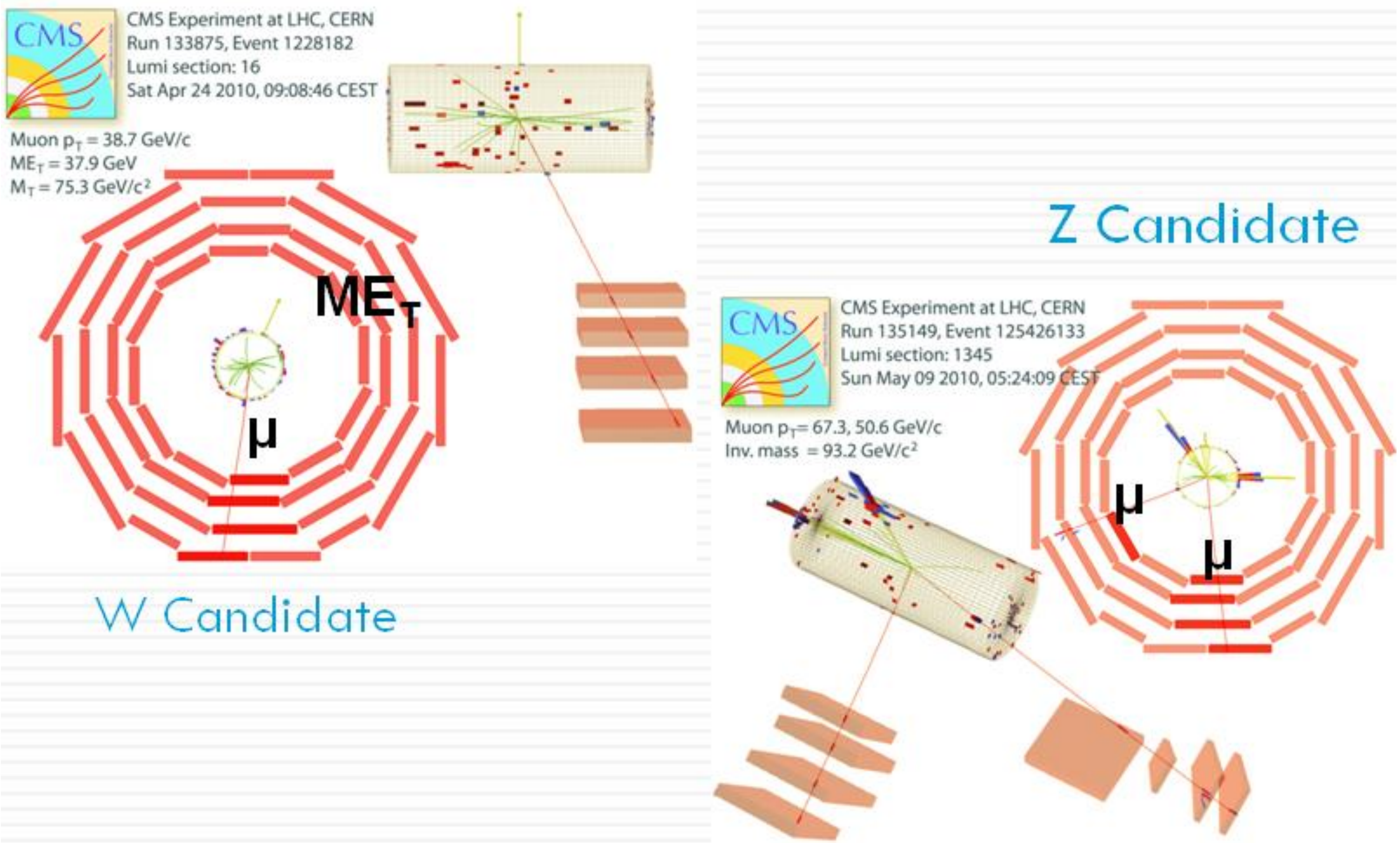


Υ - $\sigma / M \sim 1\%$

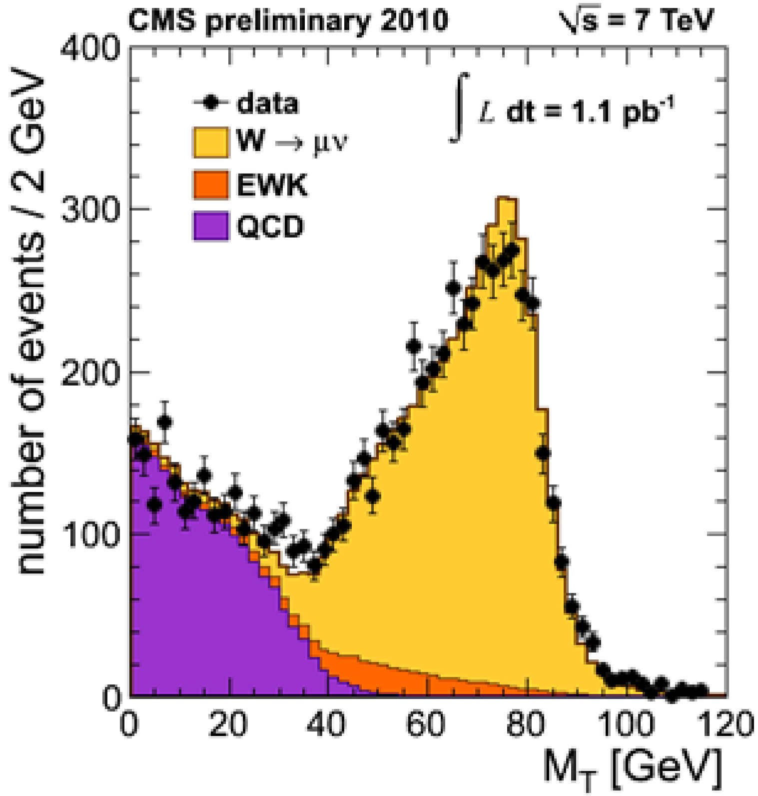


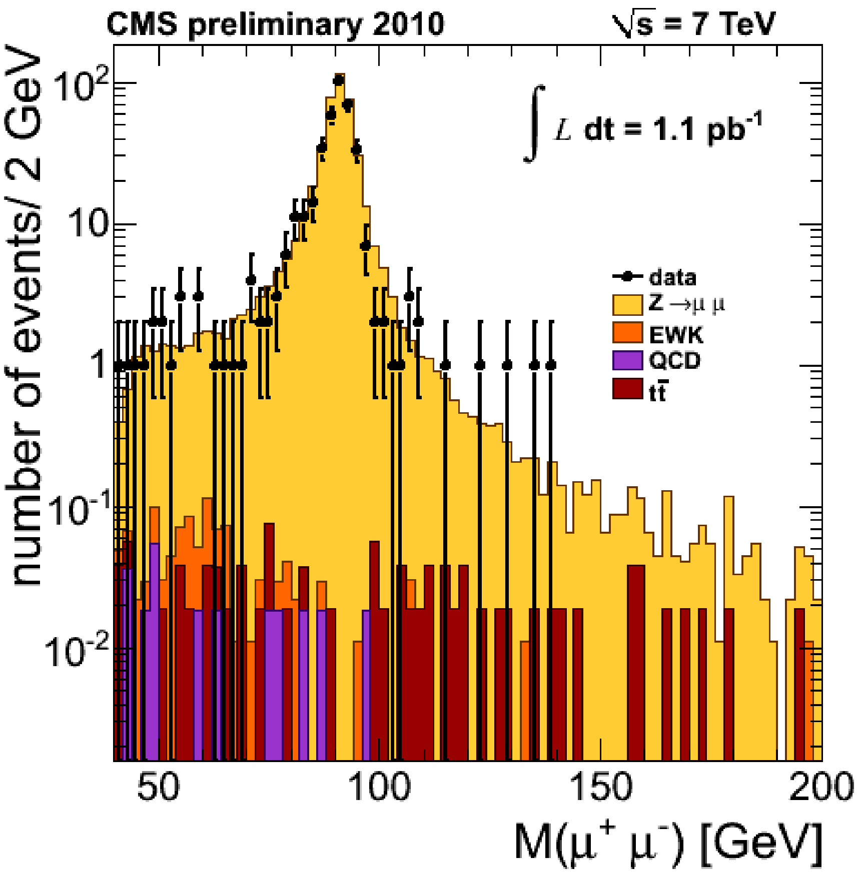
The several "standard candles" will light our way to new discoveries

EW Physics – W and Z, Muons



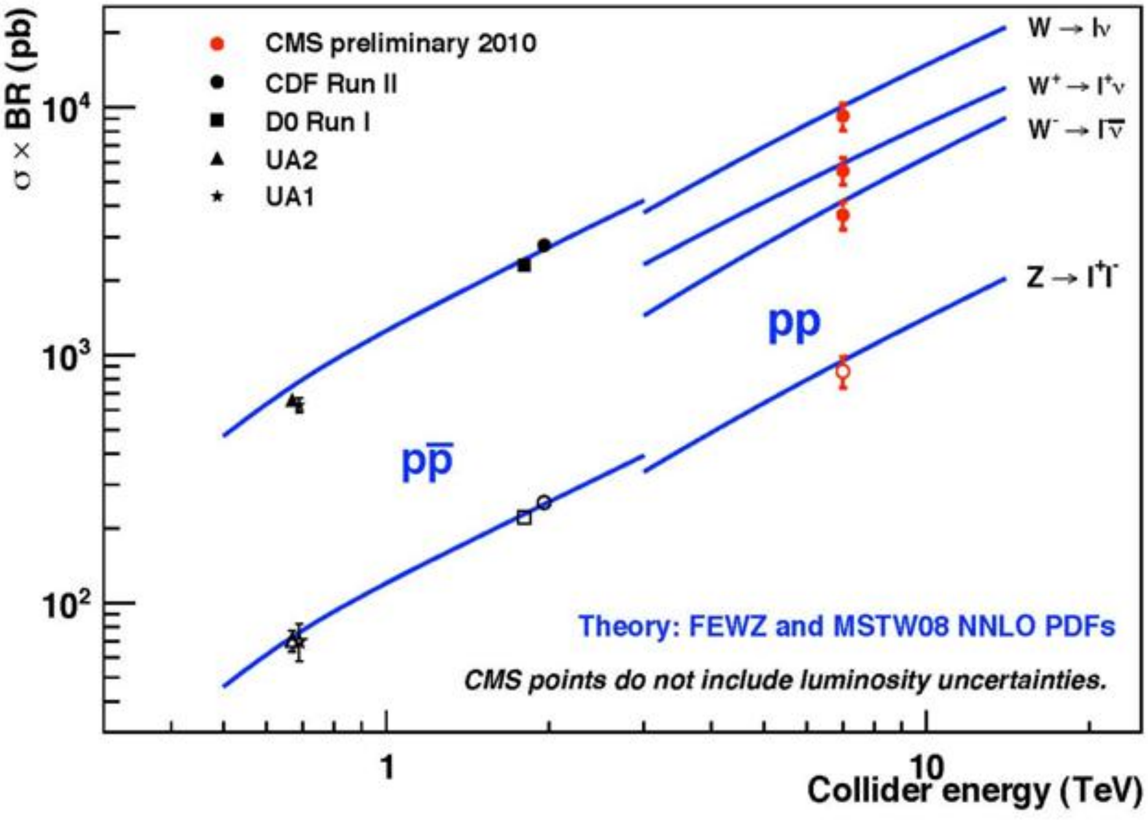
Muon Spectra for M_T and M





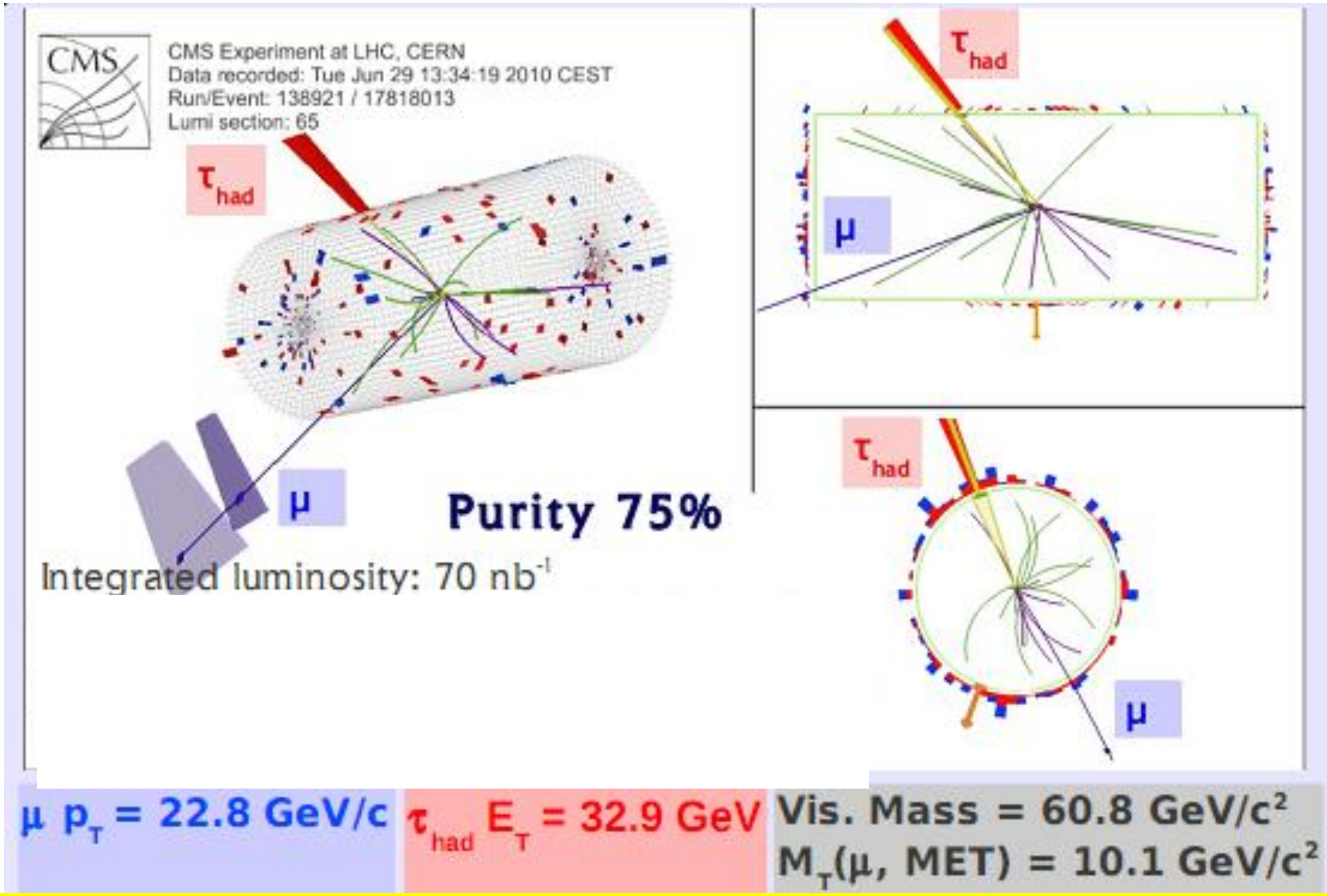
Jacobean peak

EW Cross Sections



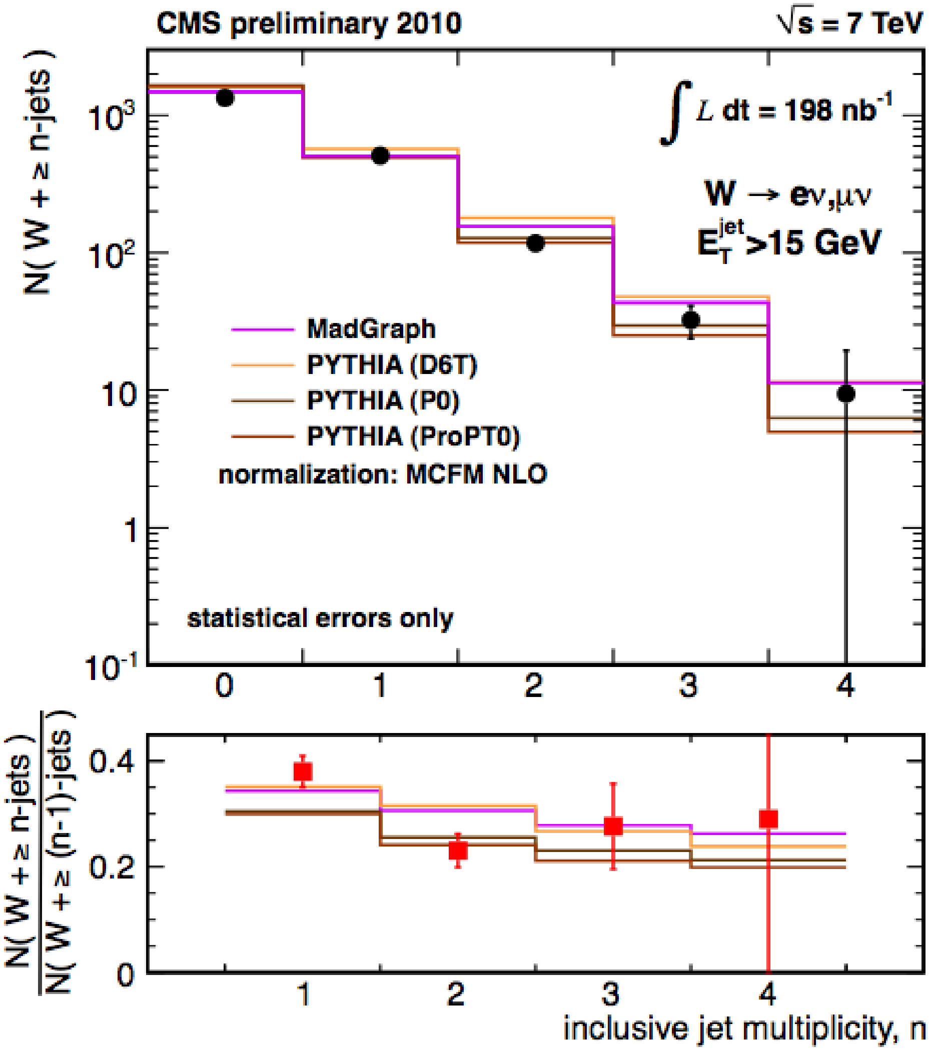
Luminosity error now at 11%. This should drop quickly quite soon – van der Meer methods.

Tau Commissioning in Z Decays



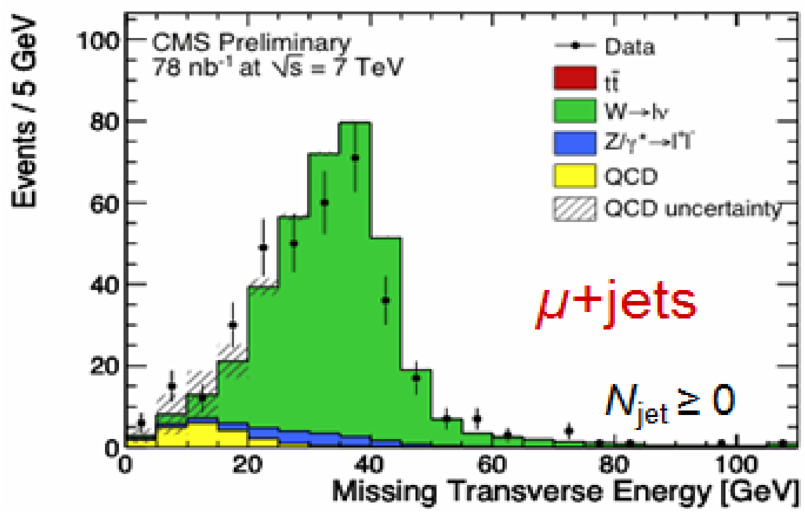
A tau "standard candle" – one tau decays leptonically, one decays hadronically. $\tau^- \rightarrow (\mu^- + \bar{\nu}_\mu) + \nu_\tau, \quad \tau^+ \rightarrow (h^+) + \nu_\tau$
Virtual W decays.

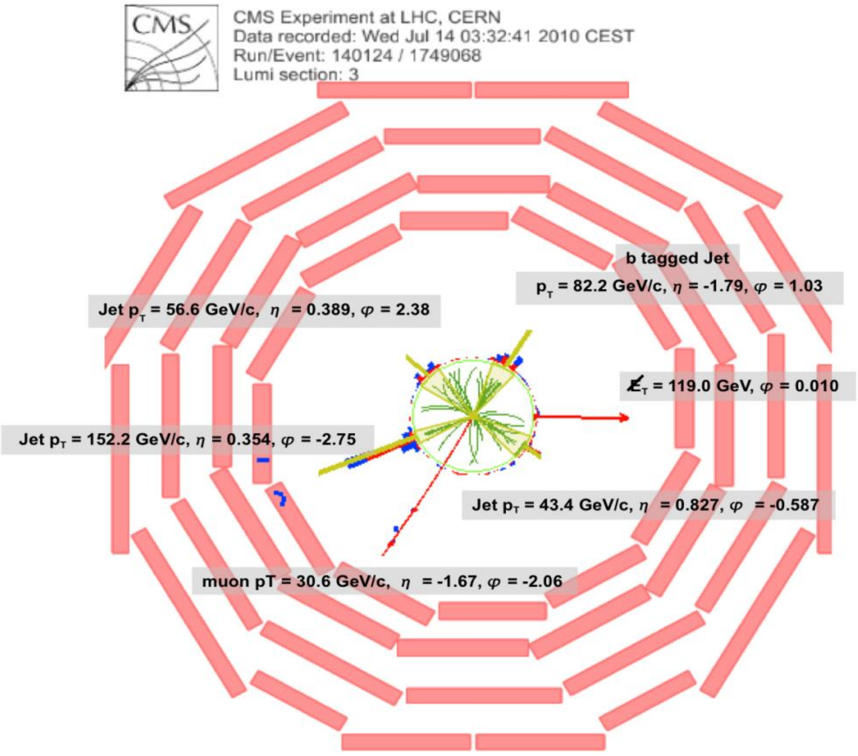
W + J



Processes are backgrounds to top. Need to understand the heavy flavor content of W + nJ. Backgrounds to J + MET SUSY signatures. Is the Monte Carlo reliable? Early days…

Top Candidate – Muon+4J (b tag) +MET





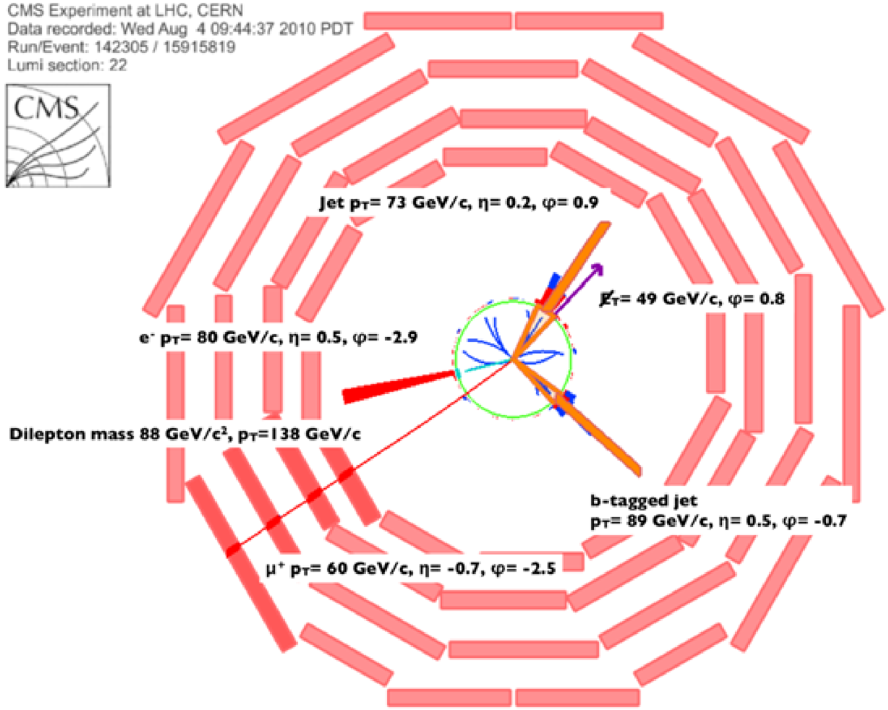
Look at lepton + MET + 4 Jets Candidate events with enhanced number of jets with b tags (all objects commissioned already). Basically no background – clean top signal due to rapid commissioning of b tagging.

$$t \rightarrow W + b \rightarrow (u + \bar{d}) + b$$

$$+$$

$$\bar{t} \rightarrow W + \bar{b} \rightarrow (\mu + \nu_\mu) + \bar{b}$$

Top Candidate - Dilepton



$$t \rightarrow W + b \rightarrow (e + \nu_e) + b$$

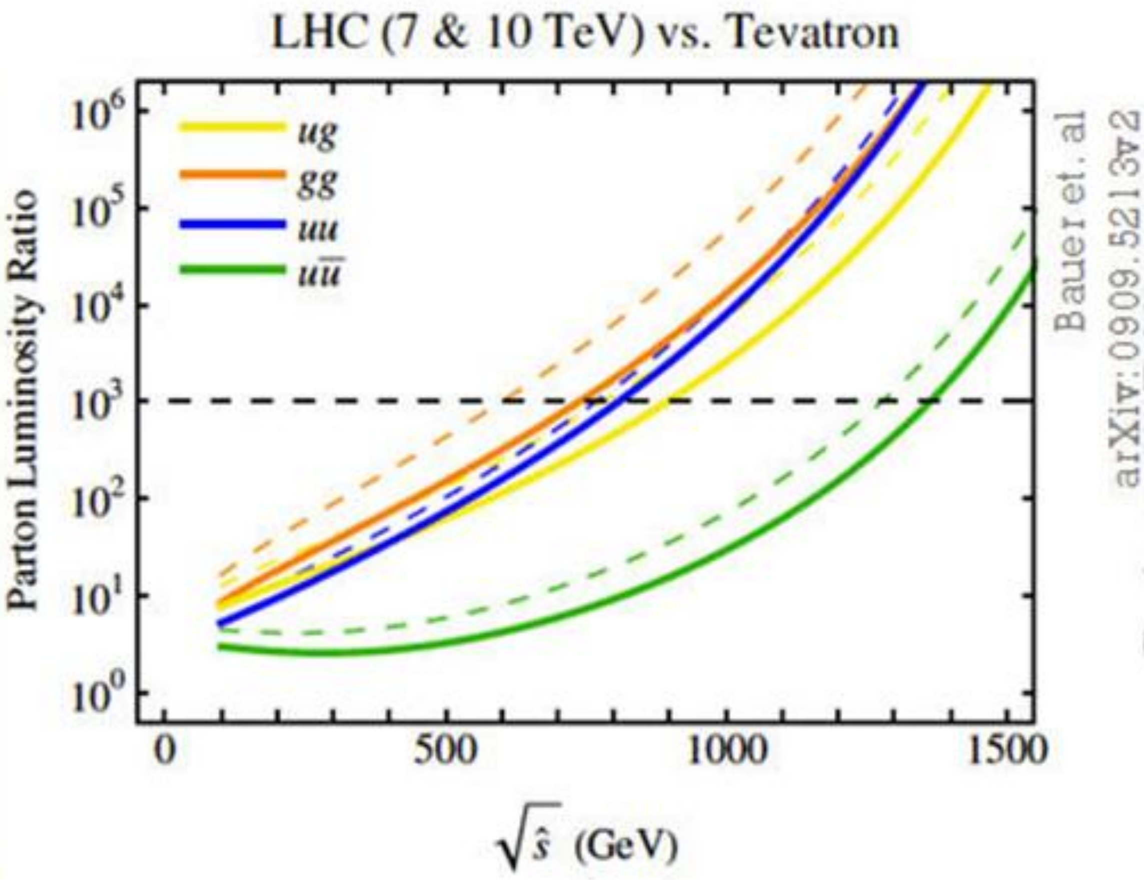
$$+$$

$$\bar{t} \rightarrow W + \bar{b} \rightarrow (\mu + \nu_\mu) + \bar{b}$$

Dilepton with MET and b tagging is a zero background top sample

Start the BSM Searches

At the discovery mass scale of ~ 1 TeV the LHC, operating at 7 TeV has > 1000 times larger cross section than the Fermilab Tevatron. Truly, the LHC is a major advance and a machine for discovery.



Parton Luminosities

How can 10 pb^{-1} == 10 fb^{-1} ? It isn't the hadron luminosity, it's the parton luminosity

$$\sigma(pp) \sim \hat{\sigma}(M) \int f_1(x_1) f_2(x_2)$$

$$\sim \hat{\sigma}(M) f_1(M/\sqrt{s}) f_2(M/\sqrt{s}) \Delta y$$

$$xg(x) \sim (1-x)^6$$

For M = 1 TeV, ratio is ~ 1000 for 2 to 7 TeV. For 1.5 TeV it is ~ 1,000,000.

Data shown is from ICHEP (1 month ago) with ~ 0.2 pb^{-1}. Now hit L = $10^{31}/(cm^2 sec)$ and 10x the ICHEP set. Progress in 2010 has been dizzying.

Generic BSM – Contact Interactions

- At CM energies well below the new physics there is an effective interaction, like G in the Fermi theory.
- On the tail of an S wave BW resonance, the effective coupling is (n.b. interference) , M propagator

$$\sigma_{new} \sim \alpha^2_{new} \hat{s} / M^4_{new}$$

- At higher CM energies one begins to see an s channel propagator or a t channel exchange peak.

- The point-like SM processes go like $\sigma_{SM} \sim \alpha^2_{SM} / \hat{s}$

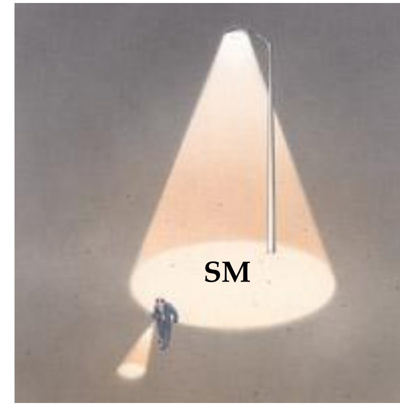
- The interference term would go roughly as

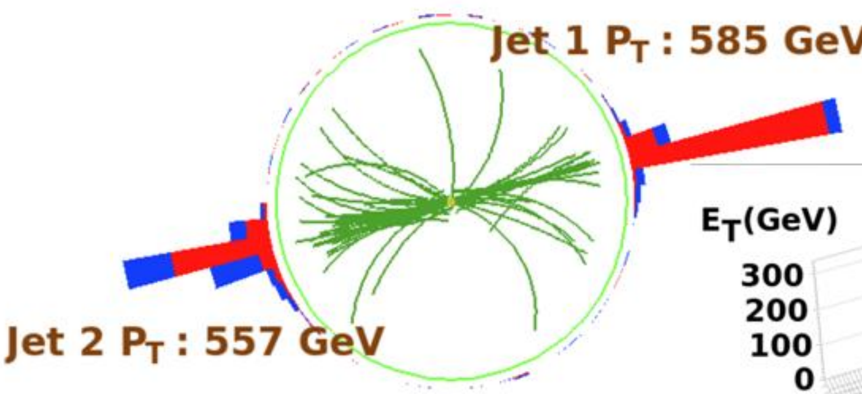
$$\pm \alpha_{SM} \alpha_{new} / M^2_{new}$$

- Ratio grows with partonic CM energy $\hat{s}$, $(\alpha_{new} / \alpha_{SM})(\hat{s} / M^2_{new})$

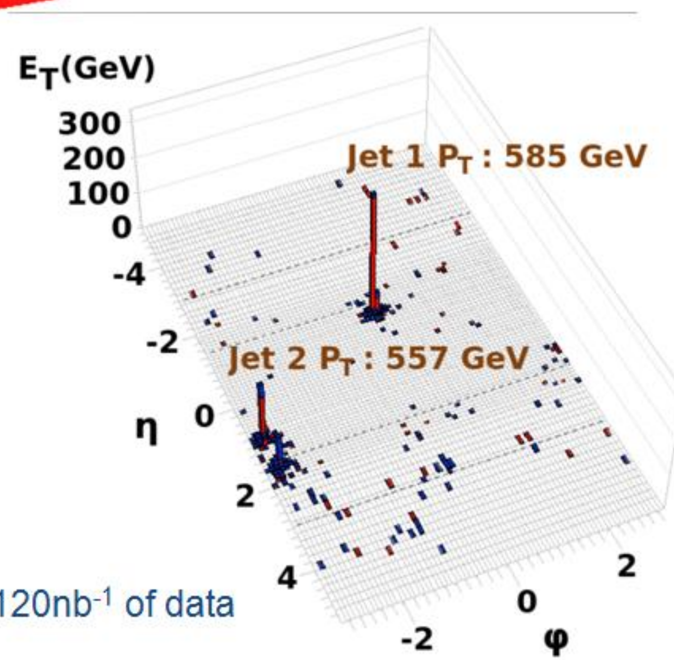
Event Scanning - Dijet

Look for more central, S wave, BSM effects. SM is t channel dominated -> check angular distribution of dijets



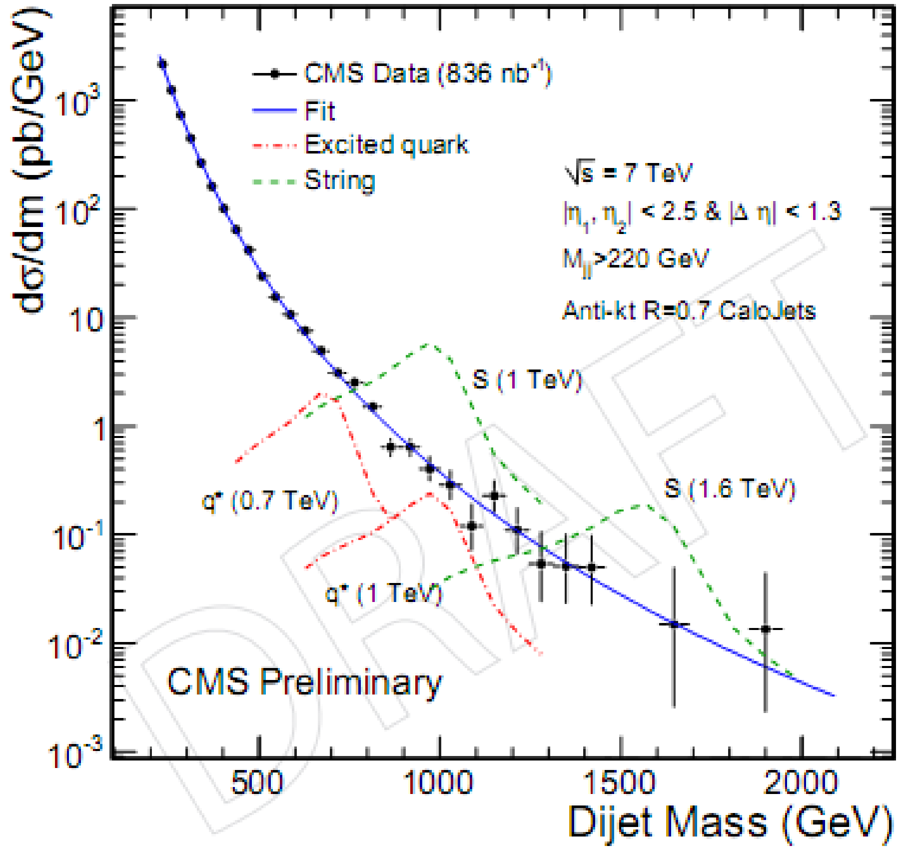


Run : 138919
Event : 32253996
Dijet Mass : 2.130 TeV



The highest mass dijet event in the first $120 nb^{-1}$ of data

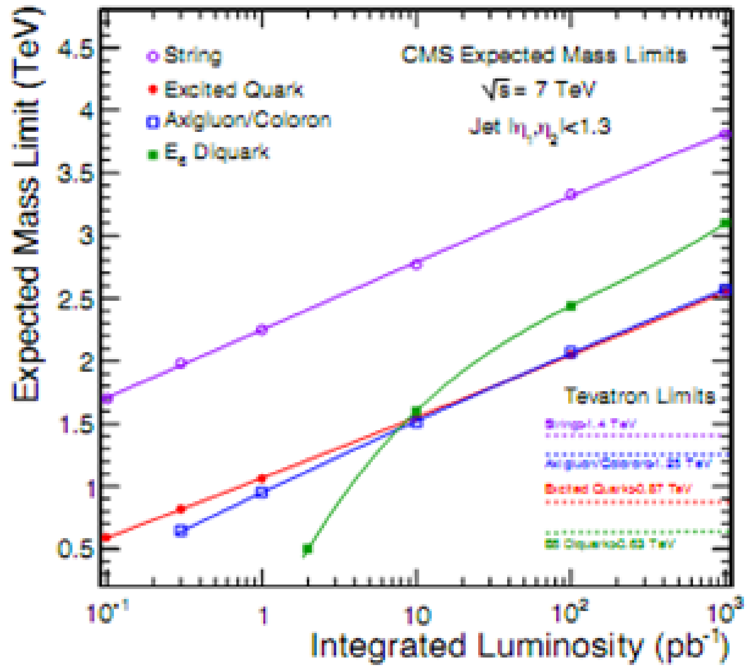
Jet Searches - Present



bump hunting in dijet mass. Limits with 0.8 pb^{-1} are now at or above Tevatron values – e.g. q* mass > 1.14 TeV.

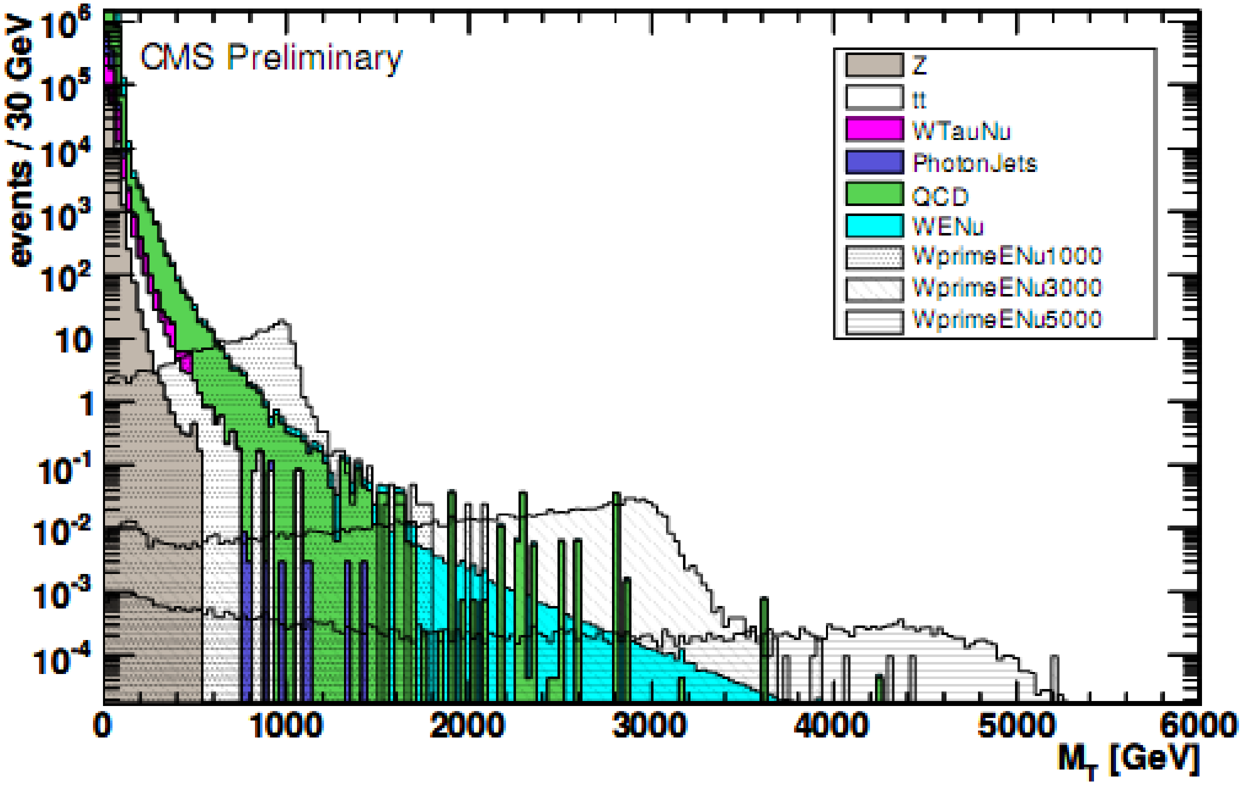
Jet BSM Search Reach with L

Expected resonance mass limits from dijet spectrum



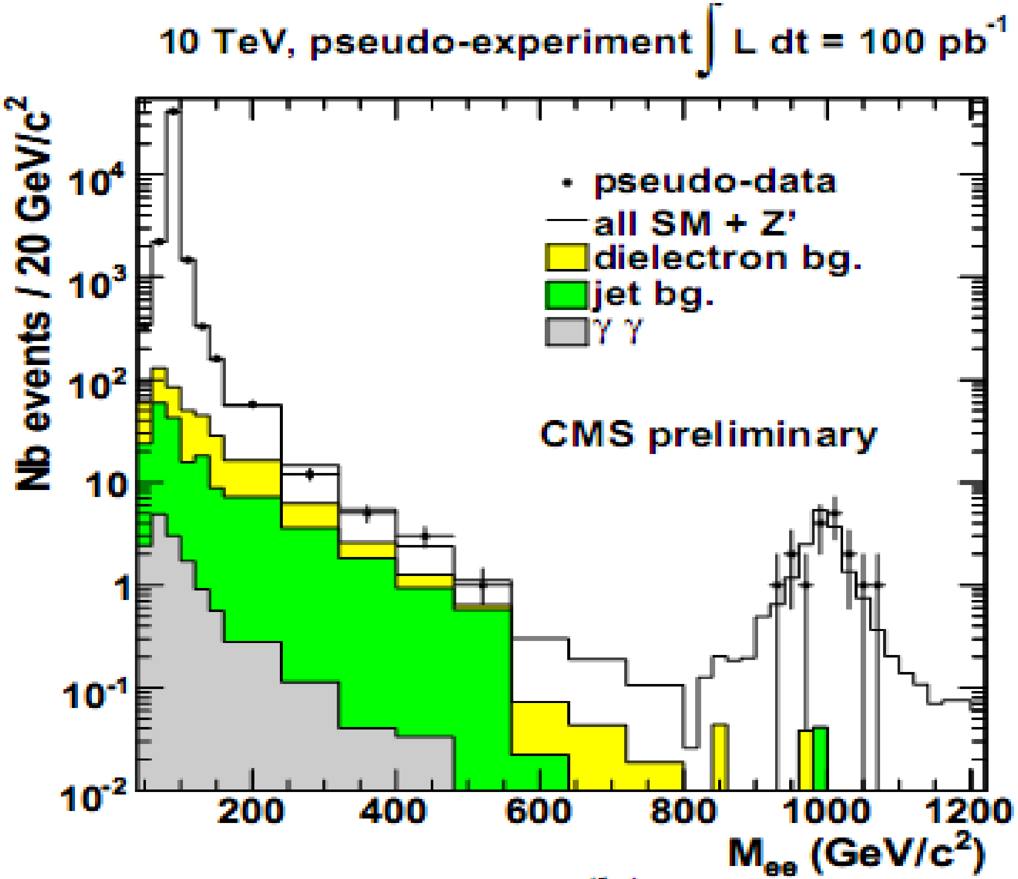
L now ~ 1 x 10^{31}, aim for 10^{32} by end of 2010 -> ~ 10 pb^{-1}/week. Have ~ 100 pb^{-1} by the end of 2010 -> mass limits ~ 2.0 to 3.5 TeV in dijet resonance mass search

Tail of the BW for W



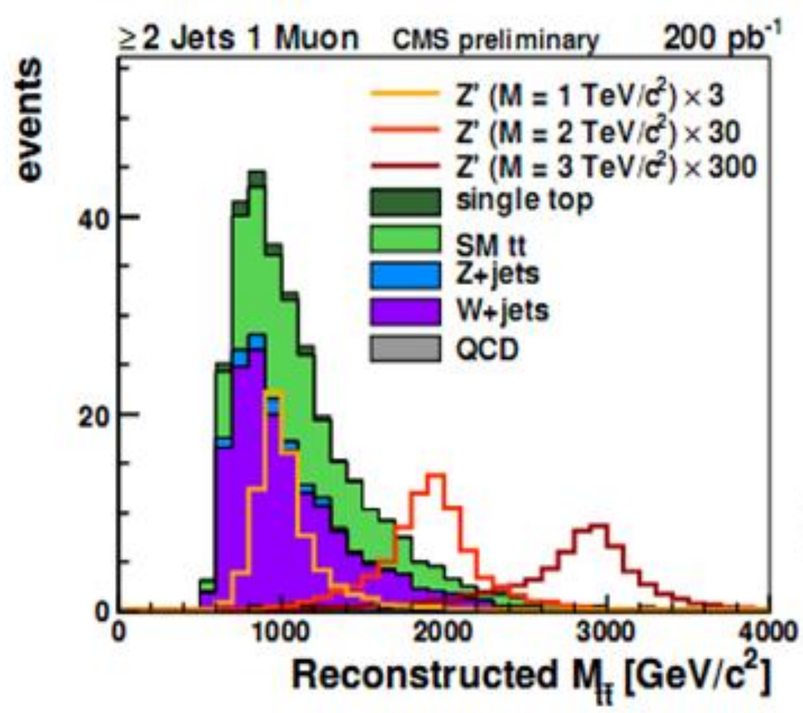
Having established the W, look in the high mass tail for contact interactions (enhanced tail) or new W' resonances (Jacobean peak).

Tail of the BW for Z, DY Continuum



Having established Z look in BW tail for contact interactions or Z′ resonances. Interference effects of a Z′ or Contact Interaction will also show up in Afb decay asymmetry.

Top Tagging



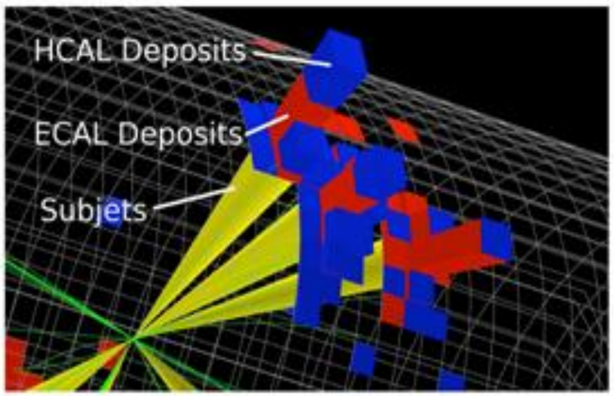
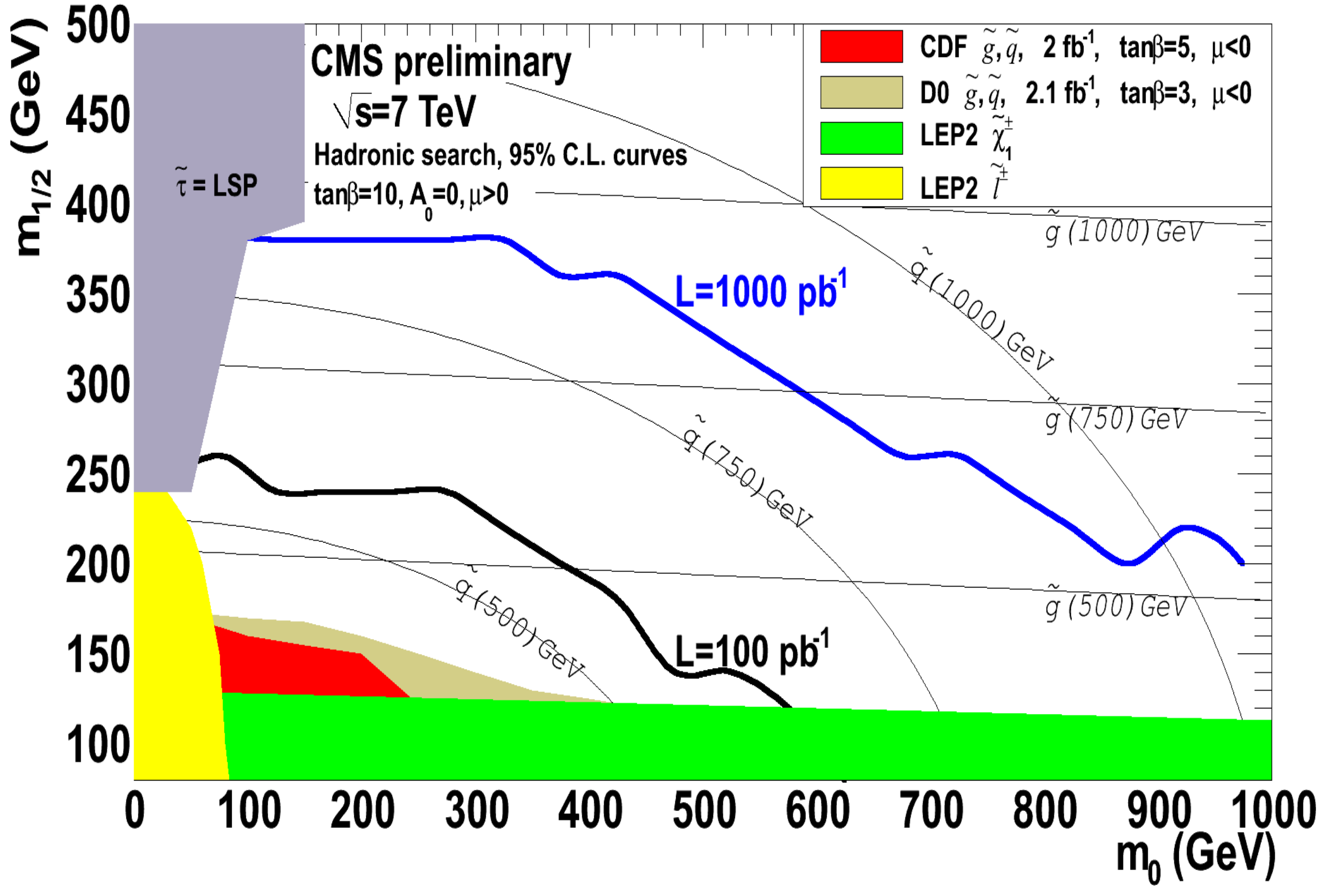


Figure 1: Reconstructed top-quark jet in cylindrical view with $p_T = 800$ GeV/c. The cones represent the subjets. The HCAL and ECAL deposits, and the subjets are indicated on the figure.

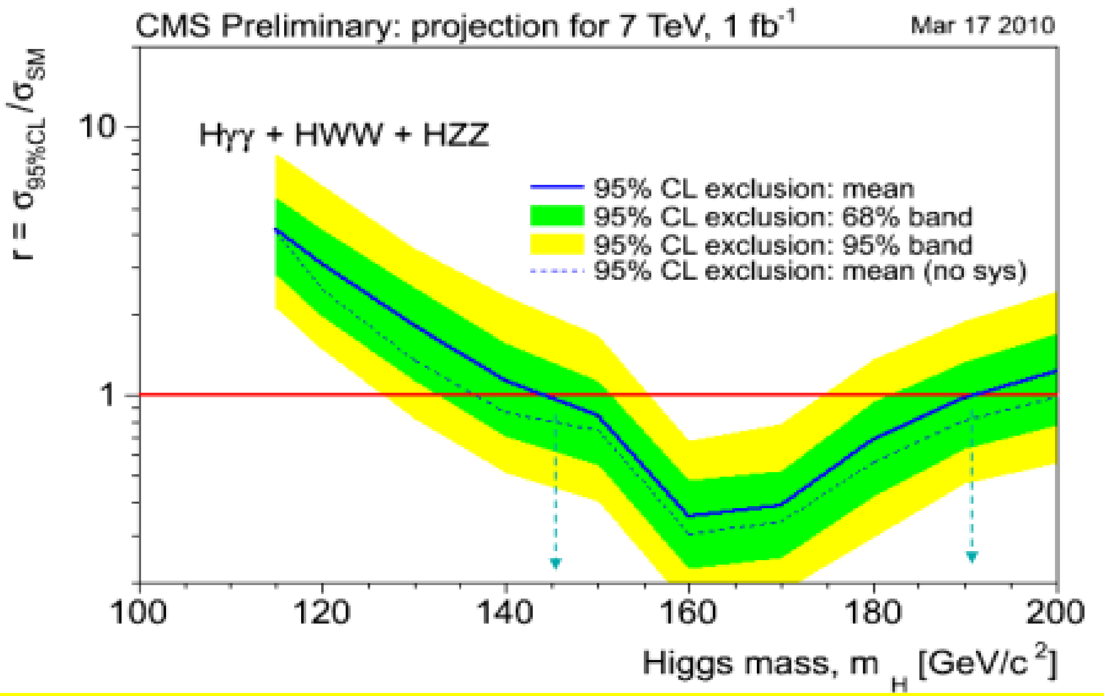
High mass parent decaying into a top pair will cause a "fat jet" with W and b jets merged. Look at jet mass and other variables to distinguish from QCD J backgrounds.

SUSY Searches – J + MET



Energy is very important. By the end of 2010, substantial new parameter space for SUSY will be opened up.

Higgy Searches

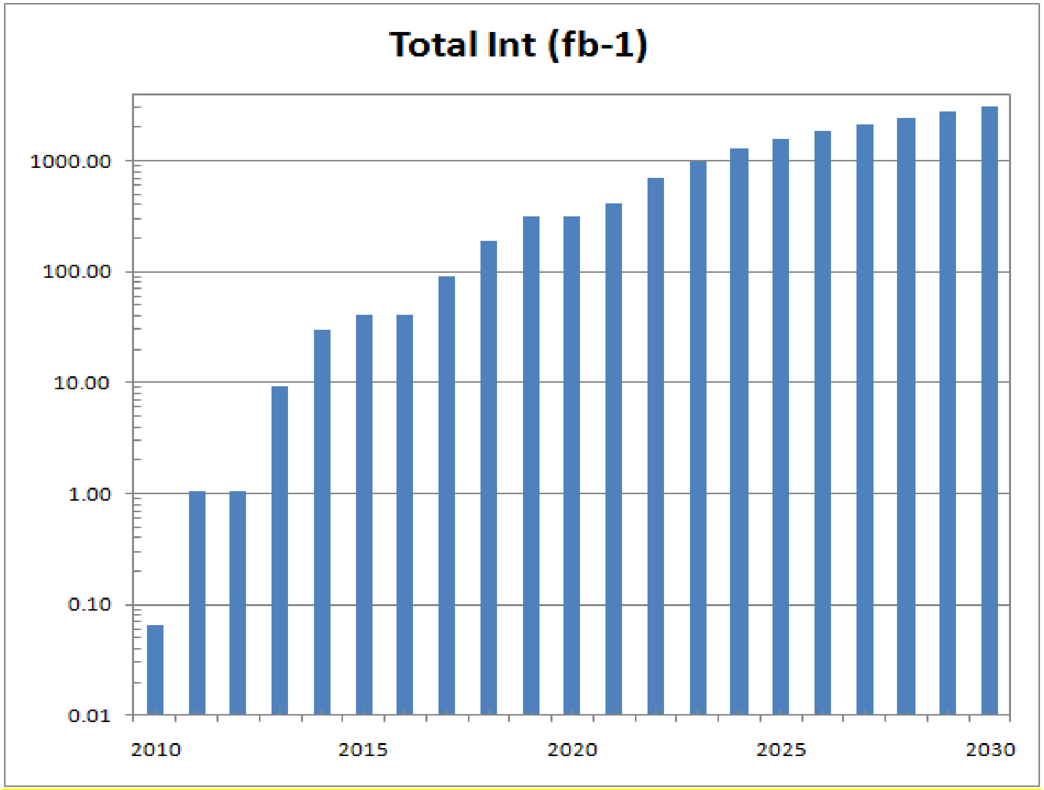


Higgs takes longer. By the end of 2011 (~ 1 fb^{-1}) CMS will exclude a significant mass range for a SM Higgs. Combined CMS + ATLAS excludes ~ (140,200) GeV. This is only for cut based WW+ZZ+γγ. Studying gains due to advanced techniques, e.g. NN and adding other final states, e.g. $b\bar{b} + \tau\tau$ **. May increase exclusion range to LPC limit.**

The 10 year Technical Plan

It's tough to make predictions, especially about the future.

Preliminary Long Term Predictions



To keep pace with the LHC the detectors are starting a long term series of phased Upgrades. Technical proposals this year.

2011 plan:

$$LT \sim n_{1b}^2 \varepsilon N_{bunch} / \beta^*$$

- **Achieved design for n -10^{11} p/bunch**
- **Have gone to 2 m for β^* (design 0.5 m)**
- **More bunches N (but stored energy)**
- **N = 48 (now) -> 384 in 2010 to achieve 10^{32}**
- **Efficiency =0.2**
- **Headroom? β^* -> 2 m, N -> 936 are possible**

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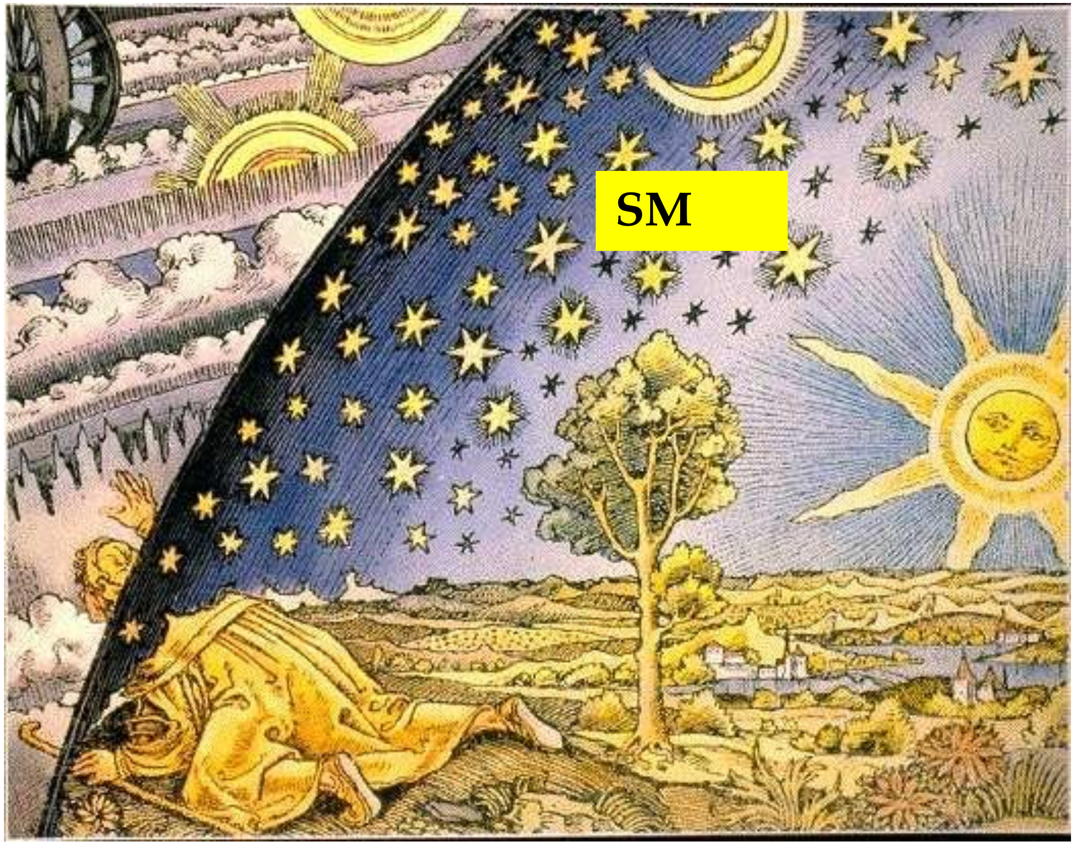
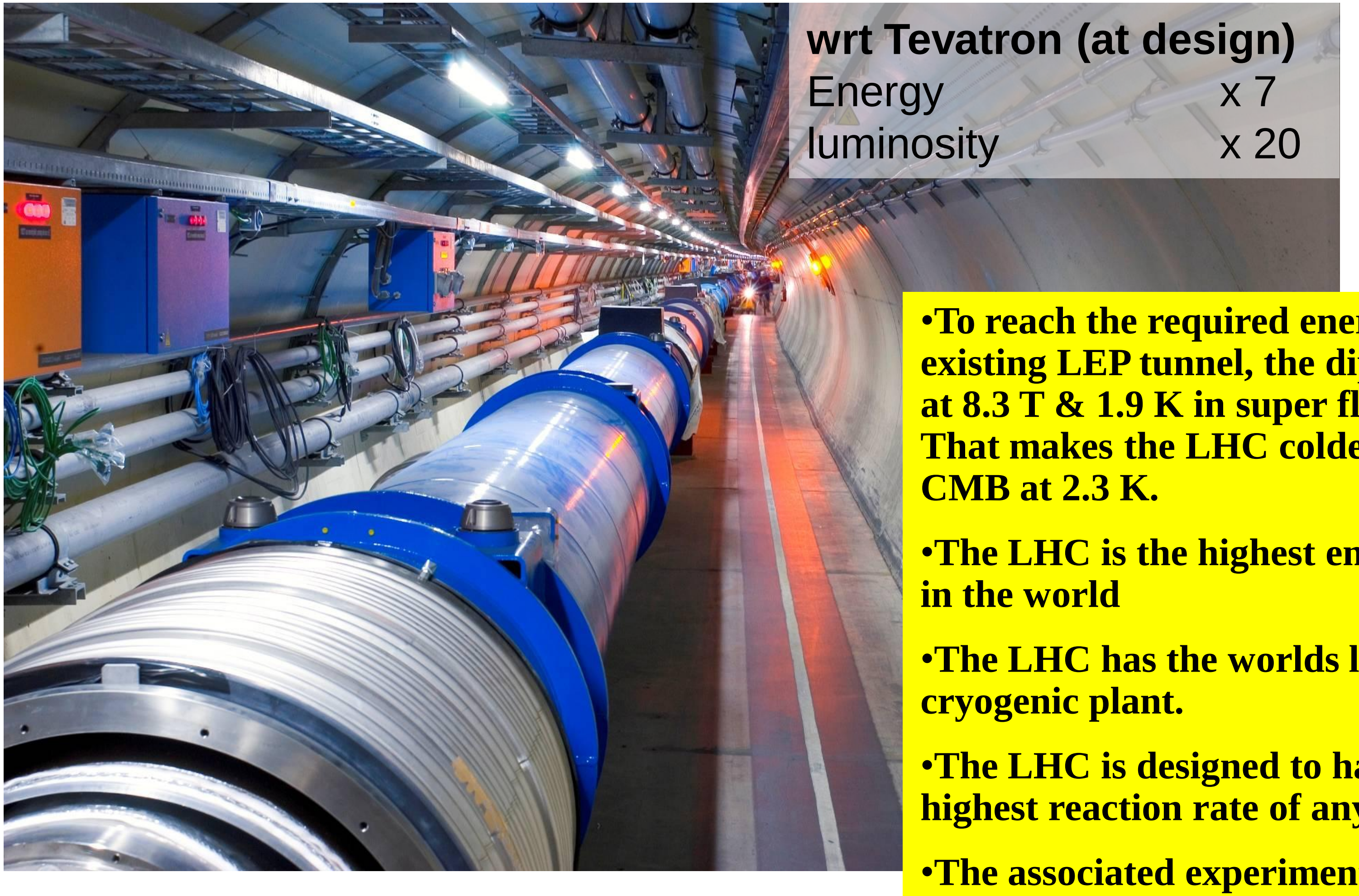
Terascale Incognita



We will soon be arriving in "terascale incognita", please fasten your seat belts. The exploration of the TeV mass scale has begun.

LHC Accelerator - Dipoles



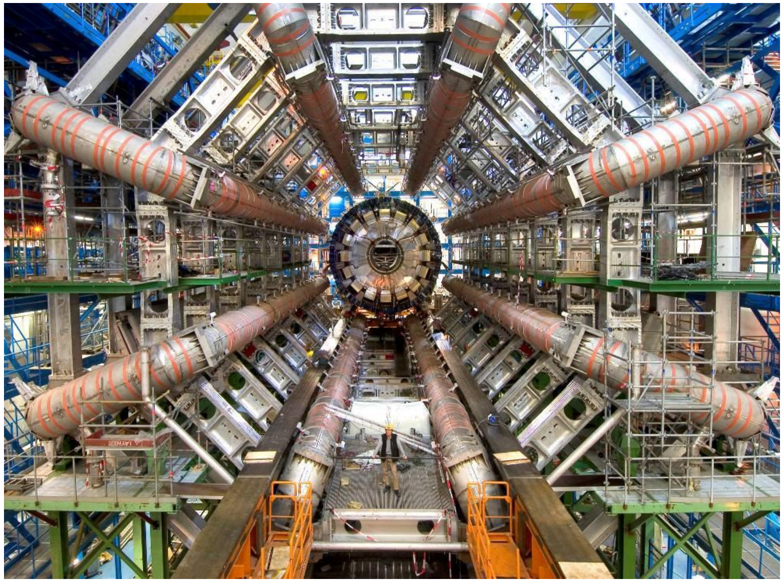
wrt Tevatron (at design)

Energy	x 7
luminosity	x 20

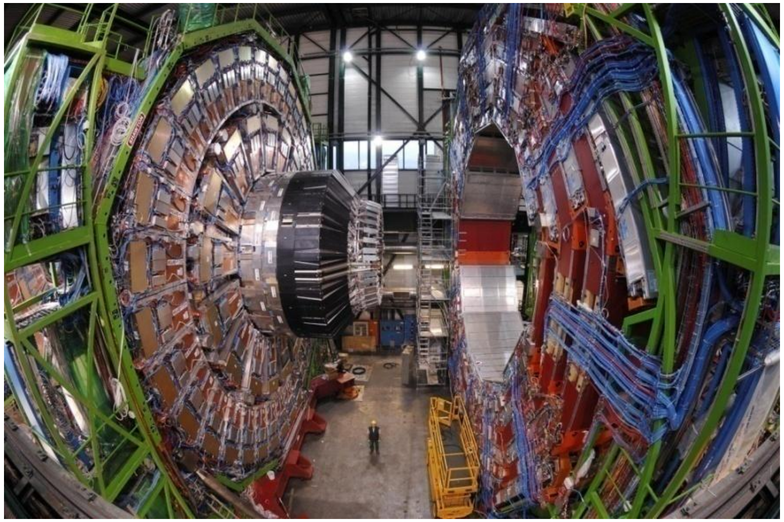
- **To reach the required energy in the existing LEP tunnel, the dipoles operate at 8.3 T & 1.9 K in super fluid helium. That makes the LHC colder than the CMB at 2.3 K.**
- **The LHC is the highest energy collider in the world**
- **The LHC has the worlds largest cryogenic plant.**
- **The LHC is designed to have the highest reaction rate of any collider.**
- **The associated experiments are the largest and most complex scientific instruments ever built.**

The ATLAS and CMS Experiments – at the Leading Edge

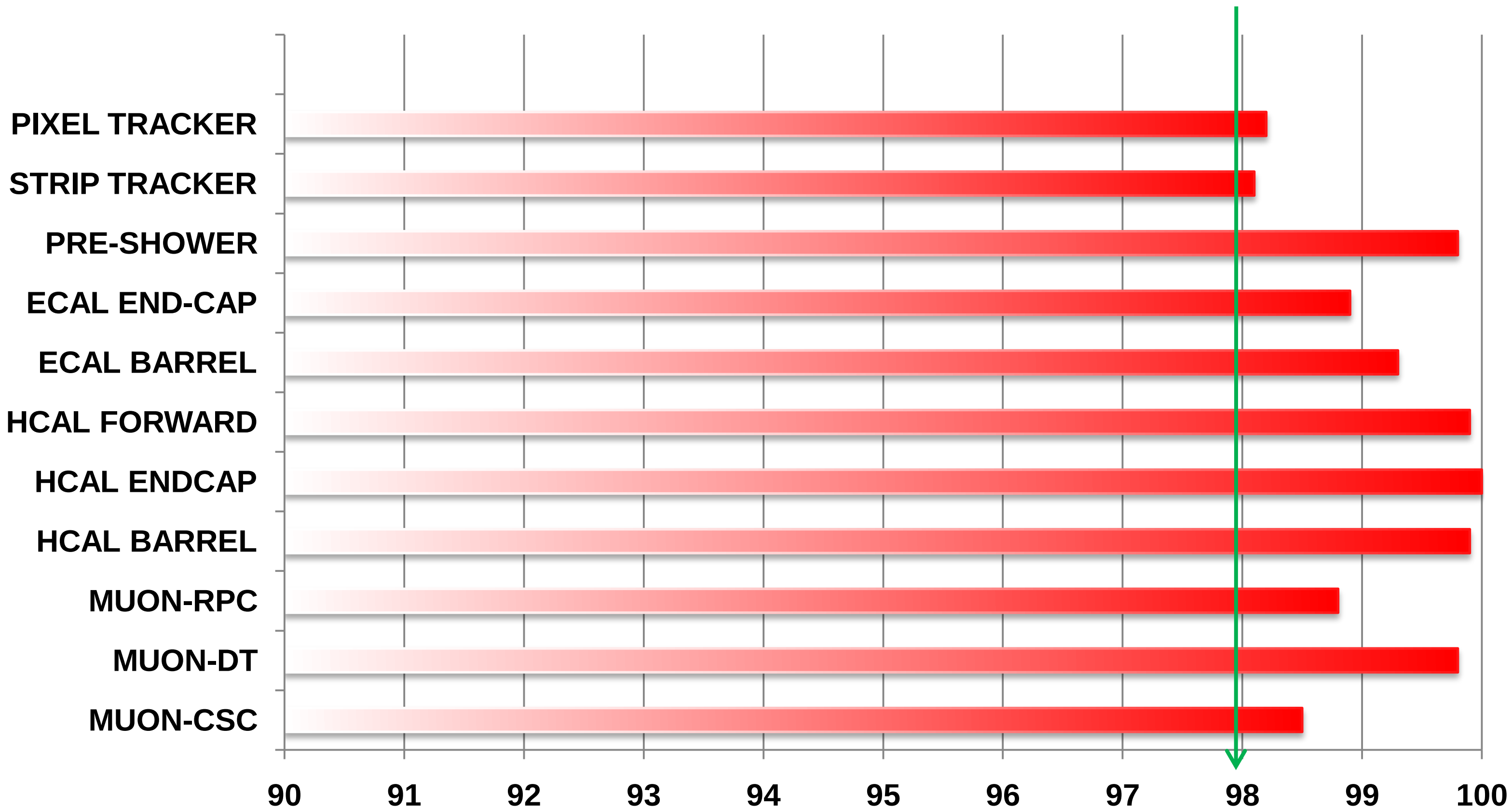
Each detector is like a 100 megapixel camera which takes 40 million pictures per second



- Highest energy proton collider
- 1 billion interactions per second
- First silicon pixels in a proton collider
- First all silicon tracker
- 100 million channels of radiation hard electronics
- Calorimeter with 60,000 PbWO4 crystals
- First use of accordion liquid argon calorimeter
- Largest magnetic toroids
- Largest magnetic solenoid
- Selection of one in 10 million interactions at a 40 MHz speed.
- Enormous data logging rate – 1 million CD per year
- Worldwide grid computing analysis



Detector Performance



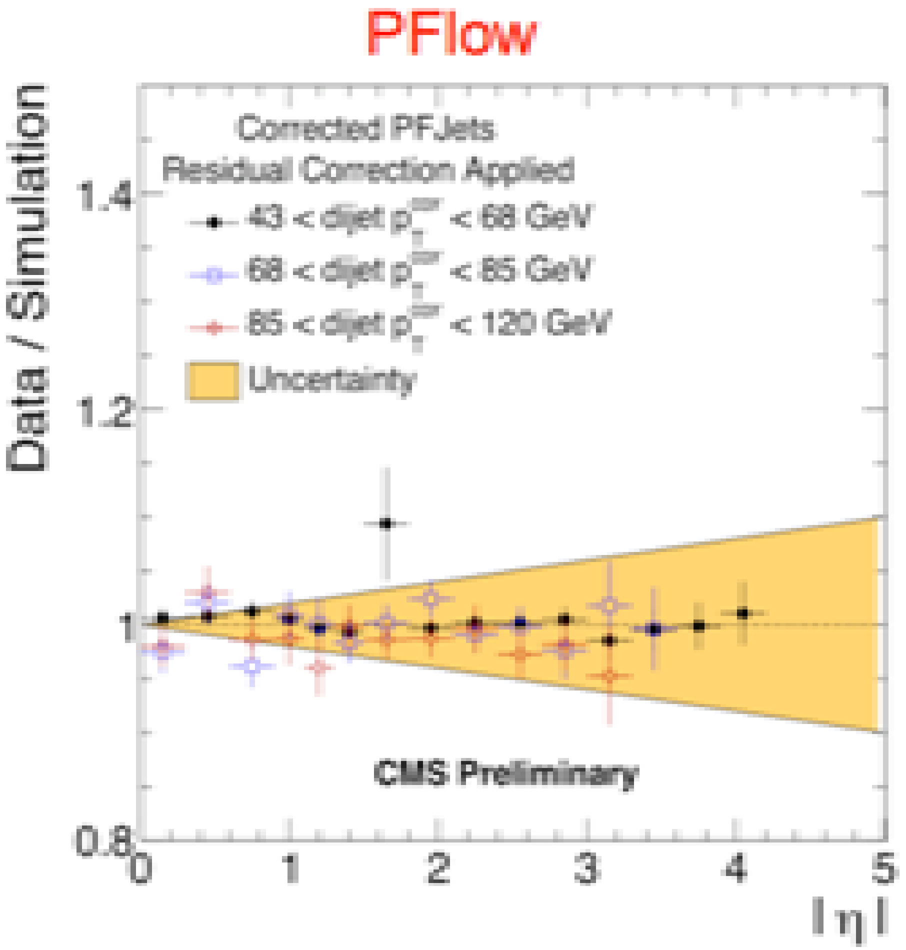
	MUON-CSC	MUON-DT	MUON-RPC	HCAL BARREL	HCAL ENDCAP	HCAL FORWARD	ECAL BARREL	ECAL END-CAP	PRE-SHOWER	STRIP TRACKER	PIXEL TRACKER	
Series1	98.5	99.8	98.8	99.9	100	99.9	99.3	98.9	99.8	98.1	98.2	

Progress on SM – Factor ~10^9

Process	SM Object	Techniques	Cross Section (pb)
Inclusive	MB, UE	Tracking, Λ, Ks, Ξ, Ω	7×10^{10}
Jets	u, d, s, g	Dijet balance, ϕ symmetry Single particle response	10^8 (< 20 GeV)
MET	Neutrinos: ν_e, ν_μ, ν_τ	Particle flow Calo + tracking Noise filters	10^5 (MB, > 50 GeV)
Decay Vertex	c b	D, D* Ptrel, vertex mass, secondary vertex	-- 10^6 (> 30 GeV)
ECAL	Photon γ	J + γ balance (JES) ϕ symmetry π , η	10^4 (< 30 GeV)
Dileptons	e μ	Ψ, Υ, Z Cosmics, beam halo	10^5, 3×10^3, 10^3 (Z)
Lepton + MET	W	Tag and Probe Z , Mass scale, mass resolution, trigger efficiency	10^4
Lepton + MET + Jet	τ	Z decay, "standard candle"	10^3
Lepton(s) + MET + Jet(s)	t	Lepton(s), μ,e, b tag, jets, MET	10^2
? ? ?	BSM	All of the above	??

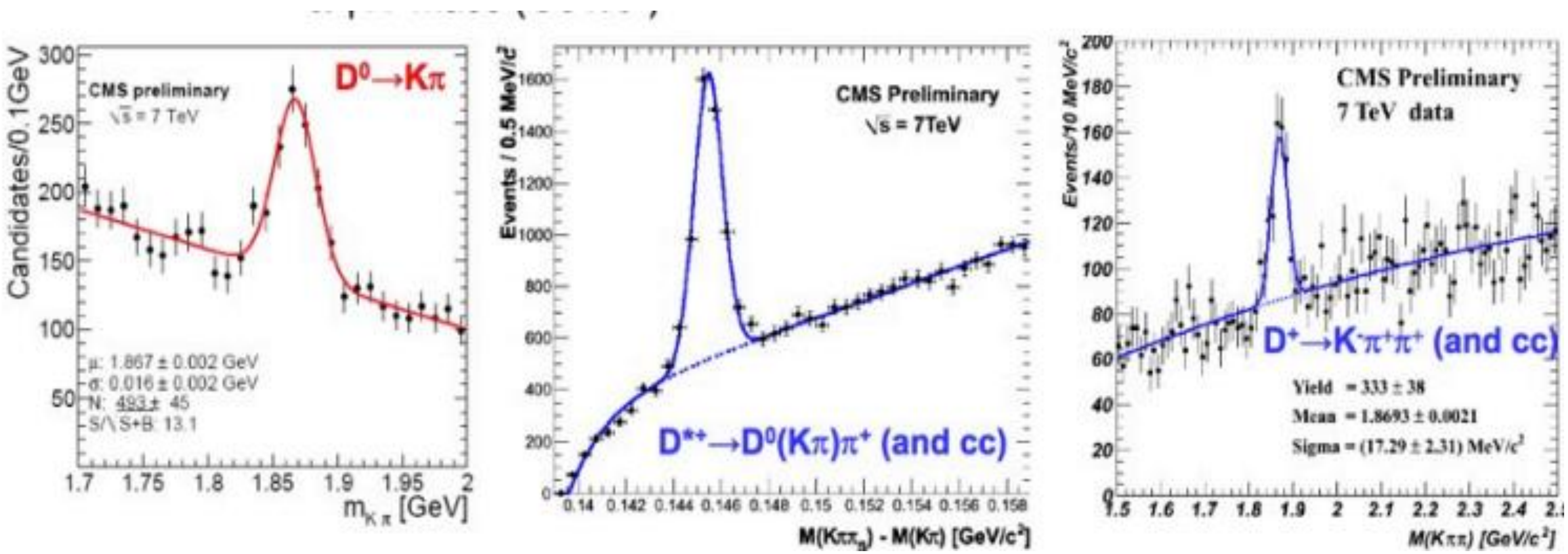
Order is that of observability – as the Luminosity increases

Jet Energy Scale



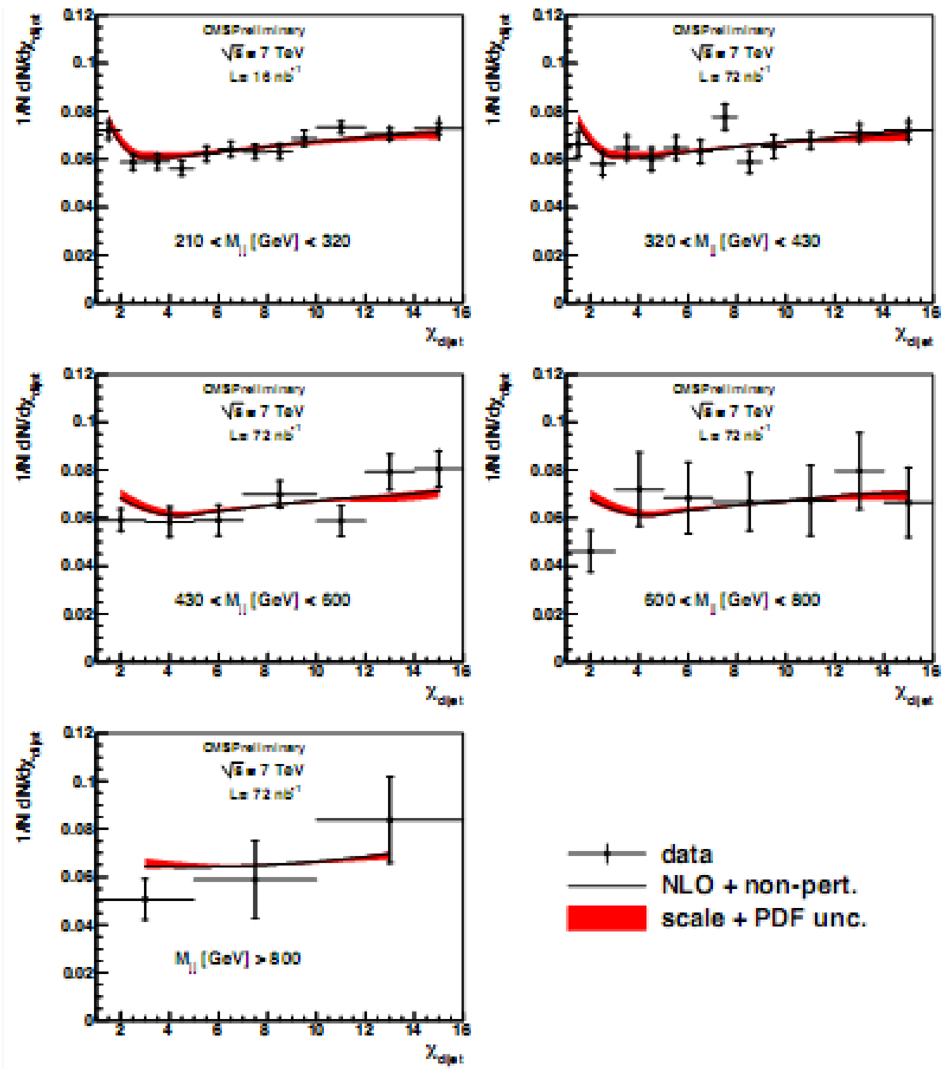
CMS calorimetry uses different technologies in different regions of |y|. Check that JES is well modeled and that CMS has a uniform calibration for jets over the full, |y| < 5 coverage.

Heavy Flavor "Tags" – c Quark

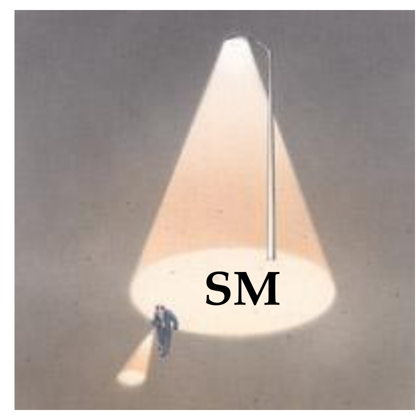


Use tracker secondary vertex finding. Tools are vertex mass, P_{trel} templates for u+d, c and b. Commission for c quark with D decay chains

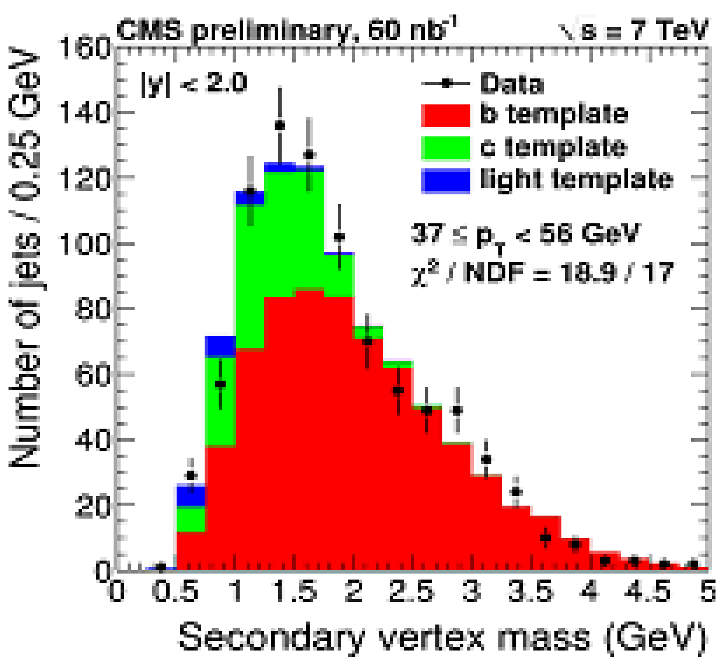
Jet Angular Distributions

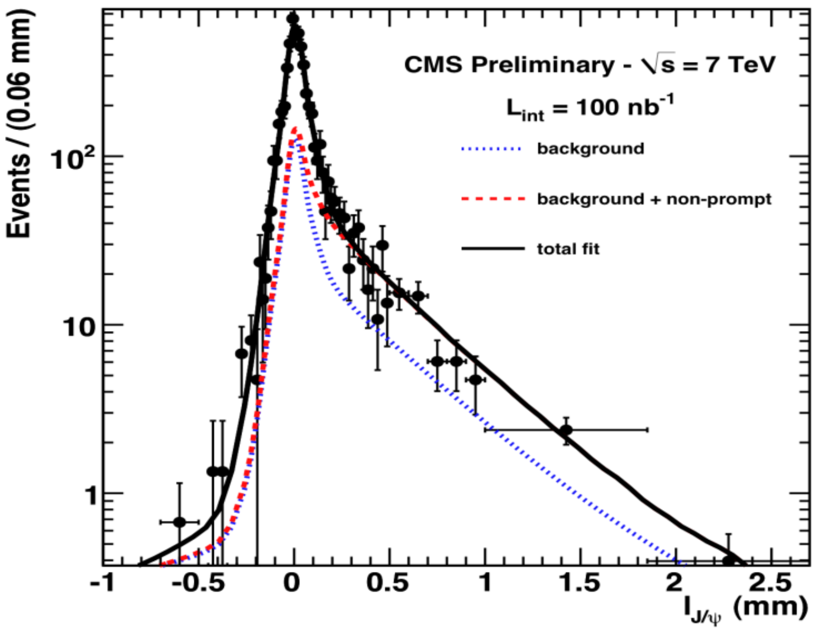


Look for more central, S wave, BSM effects. SM is t channel dominated -> flat chi distribution.



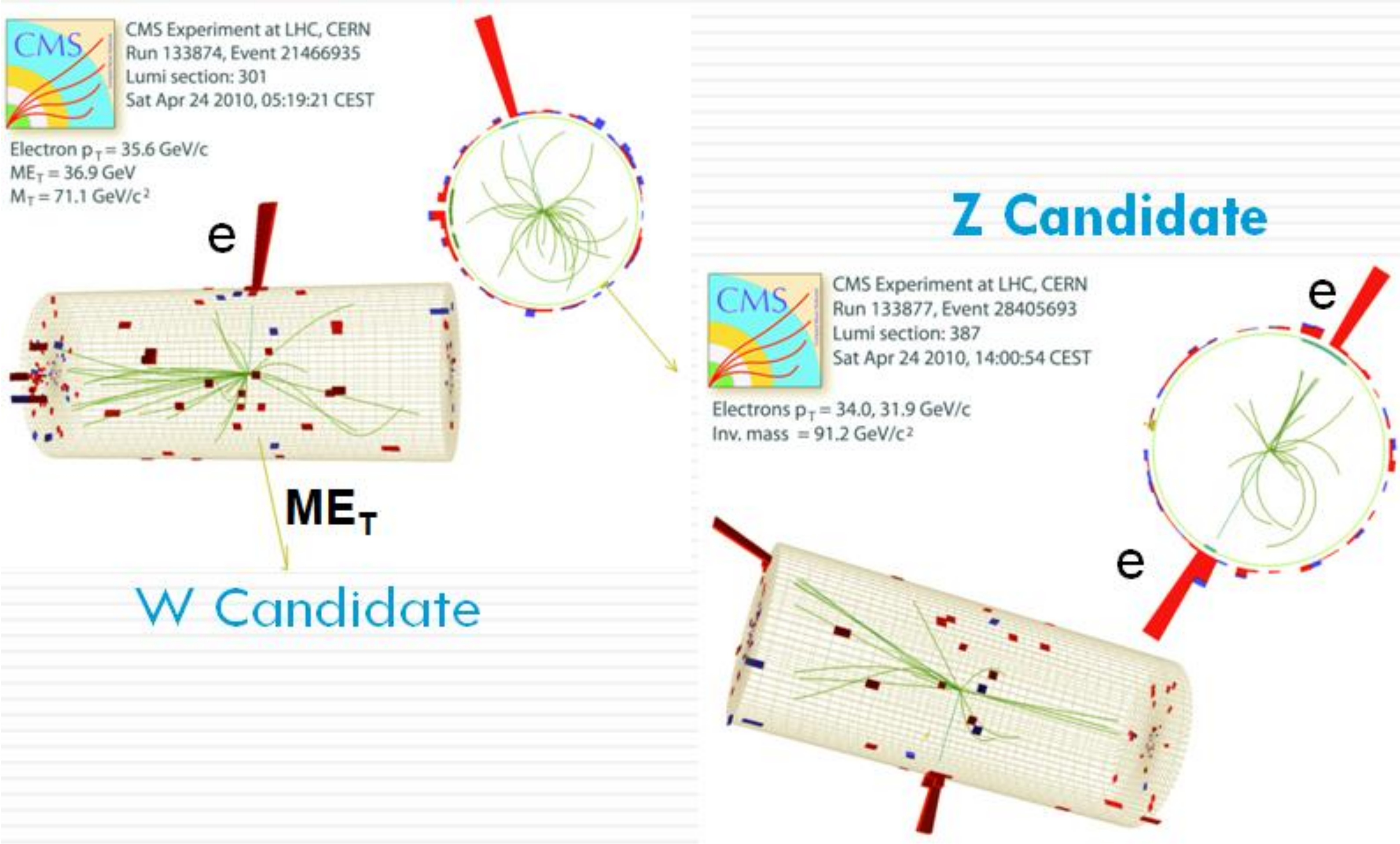
b Tags



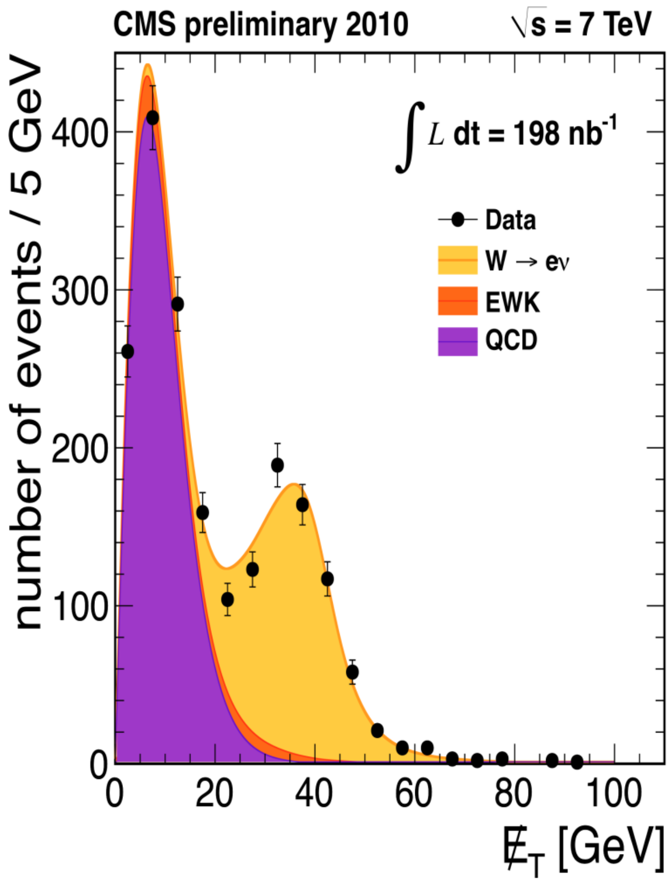


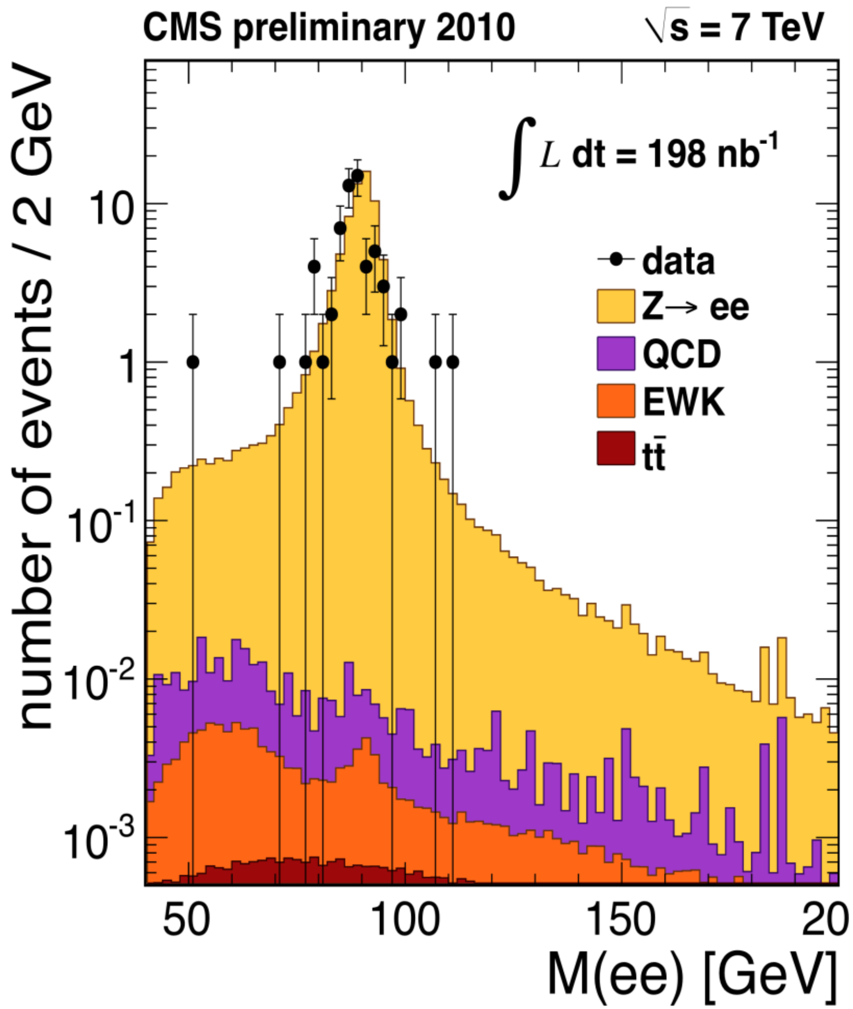
Many BSM scenarios, and top decays focus on third quark generation. Commission b tags with templates and vertexing.

EW Physics – W and Z, Electrons

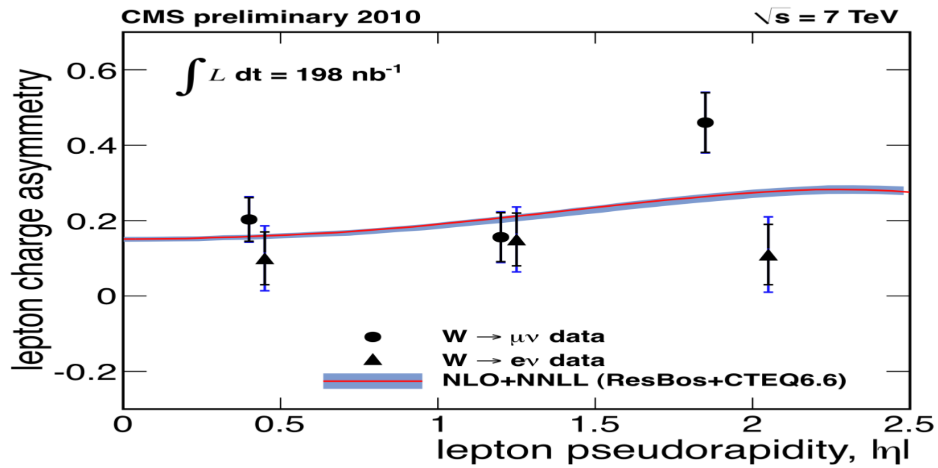


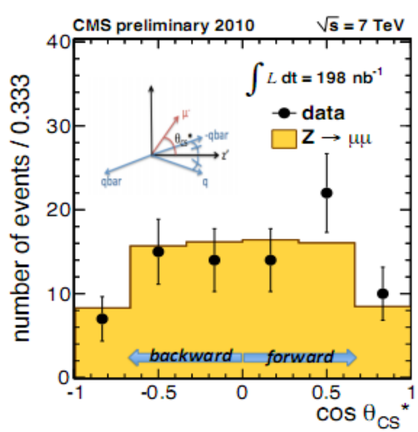
Electron Spectra or M_T and M

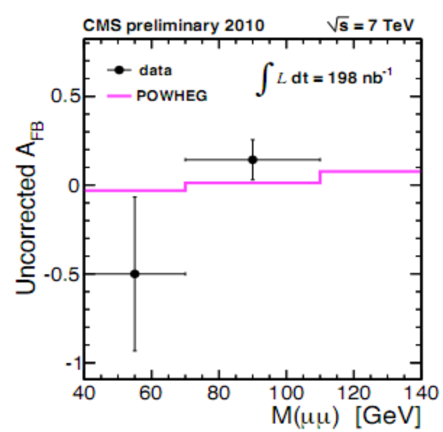




Decay Asymmetries – W and Z





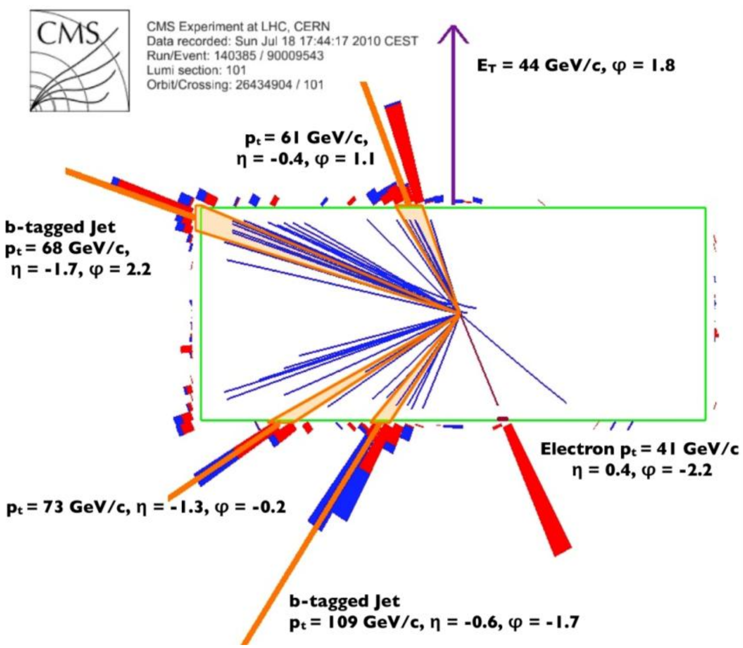


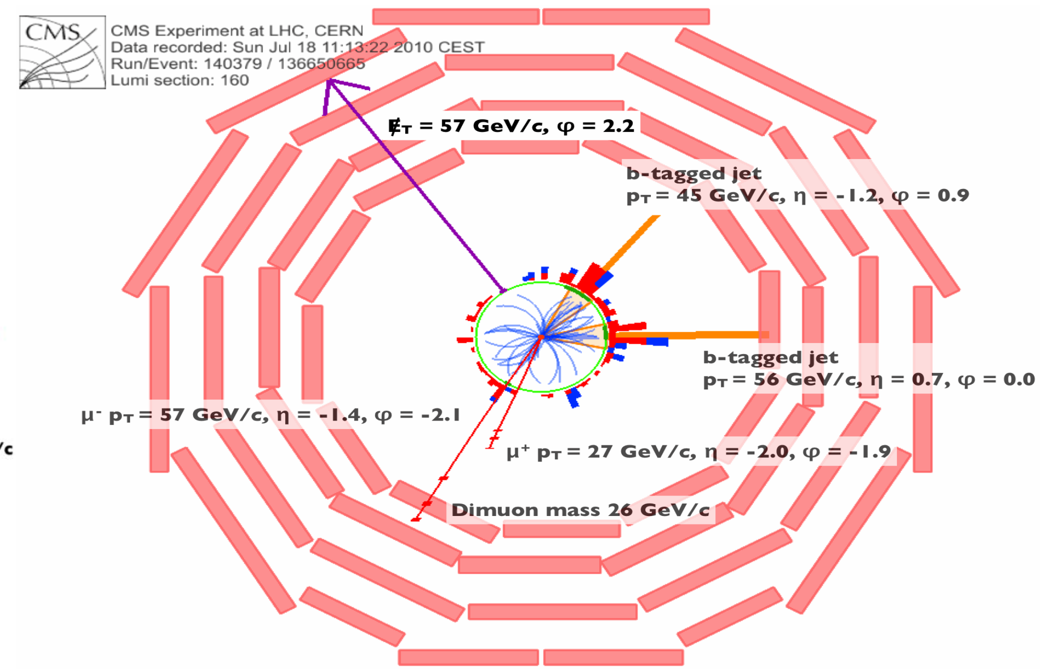
θ_{cs}* is defined in the Collins-Soper frame [1].

Mass bin [GeV]	[40-70]	[70-110]	[110-140]
# forward events	1	44	1
# backward events	3	33	0
Total # events	4	77	1

The uncorrected forward-backward asymmetry is measured to be -0.50 ± 0.4 in the mass range 40-70 GeV, and 0.14 ± 0.11 in the mass range 70-110 GeV using 198 nb^{-1} of data. The measured values are consistent with POWHEG + full CMS simulation predictions of -0.03 and 0.01 in these two mass bins [2].

Top Candidate - Electron

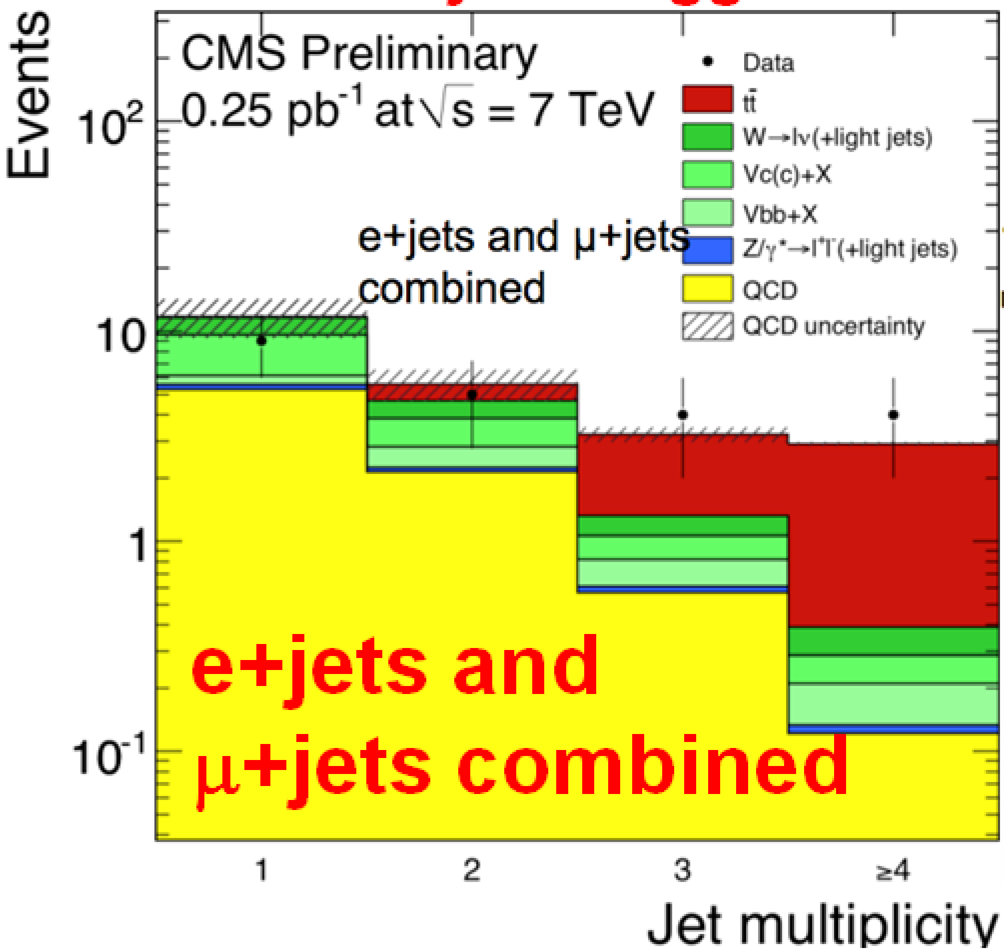




Two J tagged as b jets -> top signature

Top Candidates and b Tag

At least 1jet b-tagged



Because of rapid commissioning of b tagging, a clean top signal in lepton + > 2 jets with at least 1 b tag is possible.

Gluino Pair Production

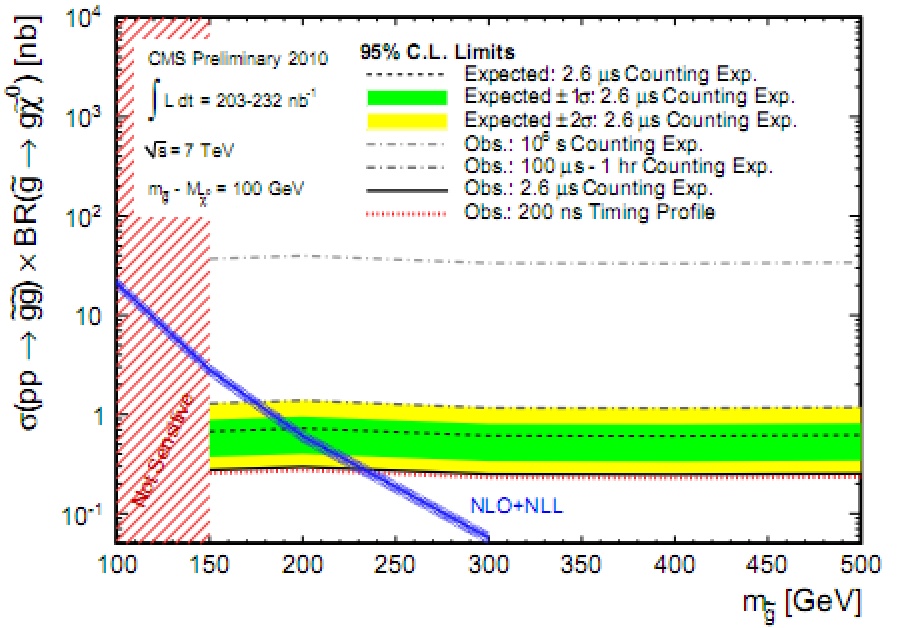
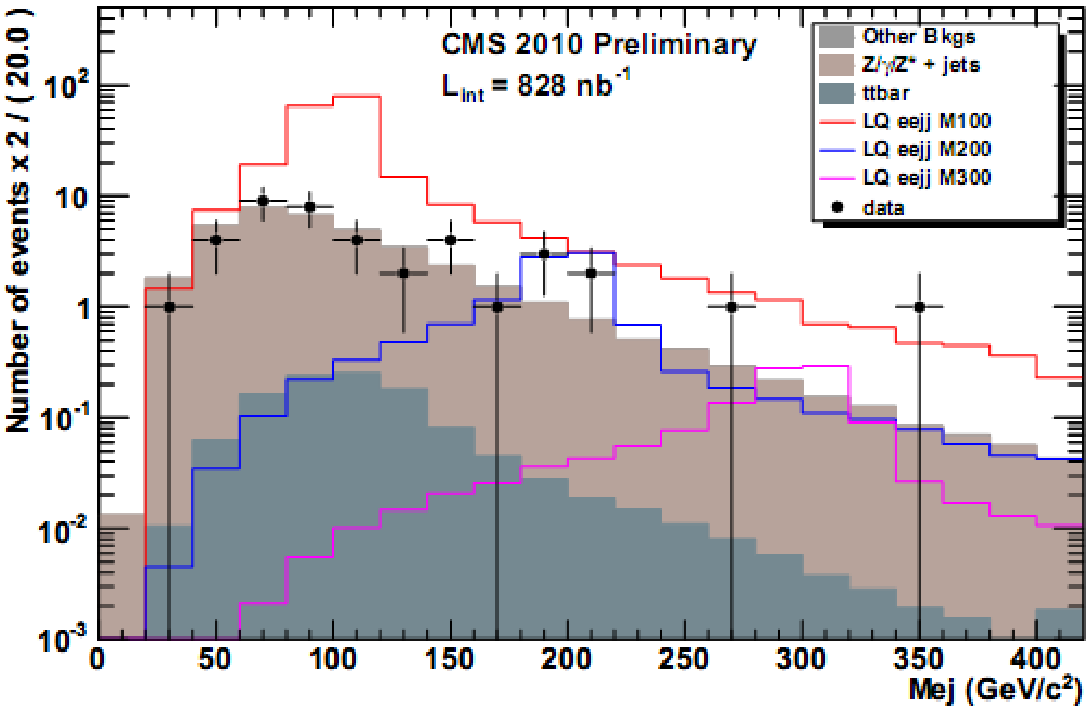


Figure 5: 95% C.L. limits on gluino pair production cross-section as a function of gluino mass assuming the "cloud model" of R-hadron interactions. The $m_{\tilde{g}} - M_{\tilde{\chi}^0_1}$ mass difference is maintained at 100 GeV; results are only presented for $M_{\tilde{\chi}^0_1} > 50$ GeV. The NLO+NLL calculation is from a private communication with the authors of [12]. The theoretical uncertainty on this calculation (represented by the blue band) is taken to be 15%. The lifetimes chosen are those for which the counting experiment and time profile analysis are most sensitive. With the counting experiment, we exclude $m_{\tilde{g}} < 225$ GeV$/c^2$ for a lifetime of 2.6 μs, and with the time profile analysis we exclude $m_{\tilde{g}} < 229$ GeV$/c^2$ for a lifetime of 200 ns.

Leptoquarks ?



Quarks and leptons are unified at some high mass scale. Implies "lepto-quarks". Look at q + l mass – bump hunting.

Heavy Stable Charged Particle

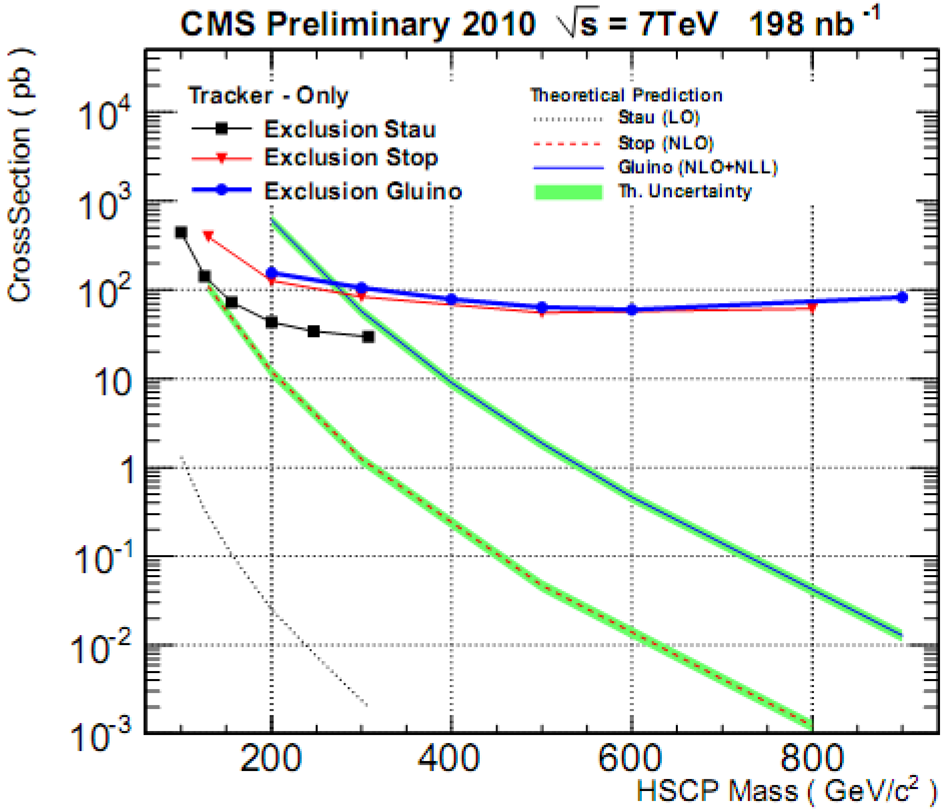
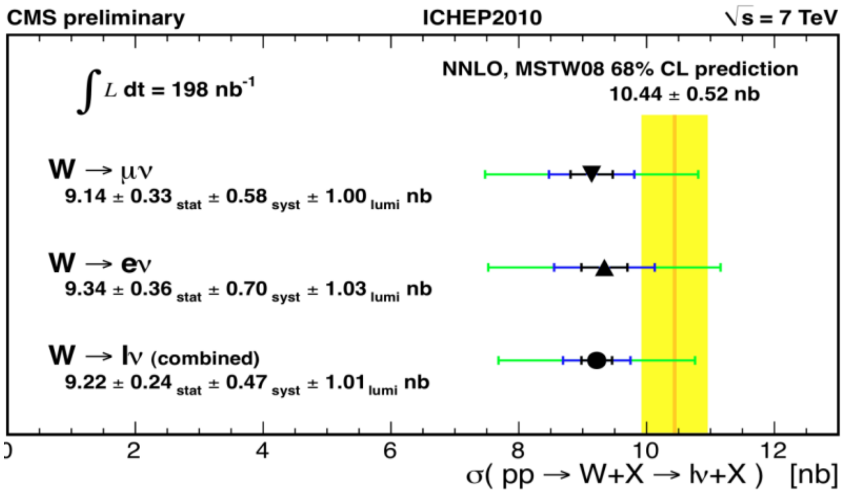
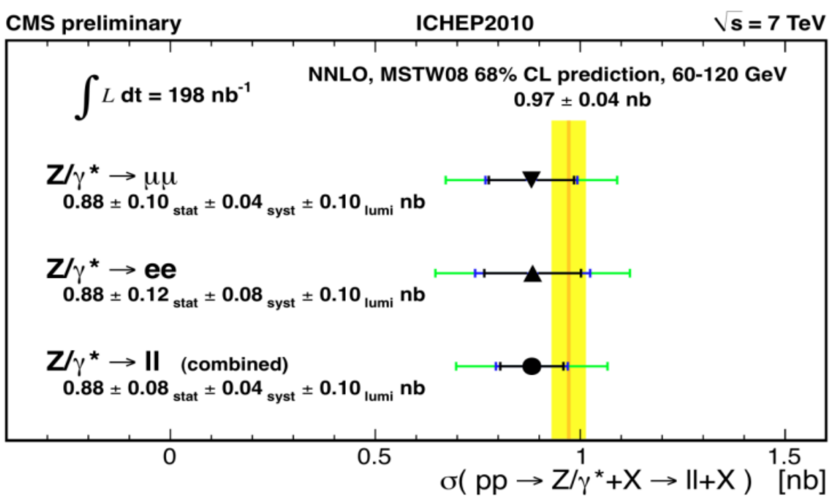


Figure 10: Observed 95% C.L. upper limits on the cross section for production of the different models considered and predicted theoretical cross sections. Upper: analysis of the muon identification plus tracker candidates; Lower: analysis of the tracker-only candidates. The bands represents the theoretical uncertainty on the cross section values.

Use tracker timing and dE/dx – and muon system timing. Tracker only here.

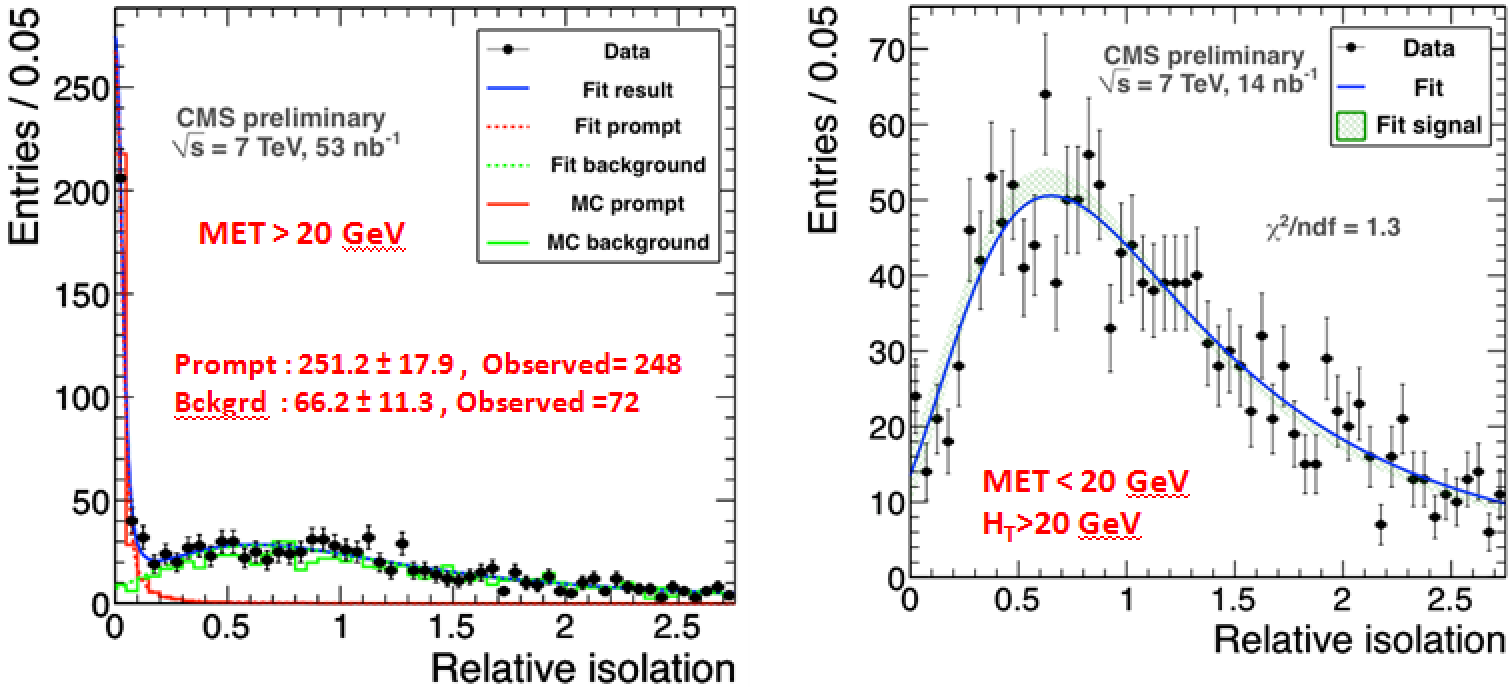
W, Z Cross Sections





SUSY and MET

- QCD contributes to ∫ + Jets+ MET signature :
  - mainly due to heavy-flavor decays to muons
  - A fit procedure for Relative Isolation to predict bckgrd from non-prompt muons



Prepare for SUSY searches by using data driven methods to predict the MET spectrum at large MET values

Dijet – Contact Interaction Limits

Expected contact interaction scale limits from dijet centrality ratio