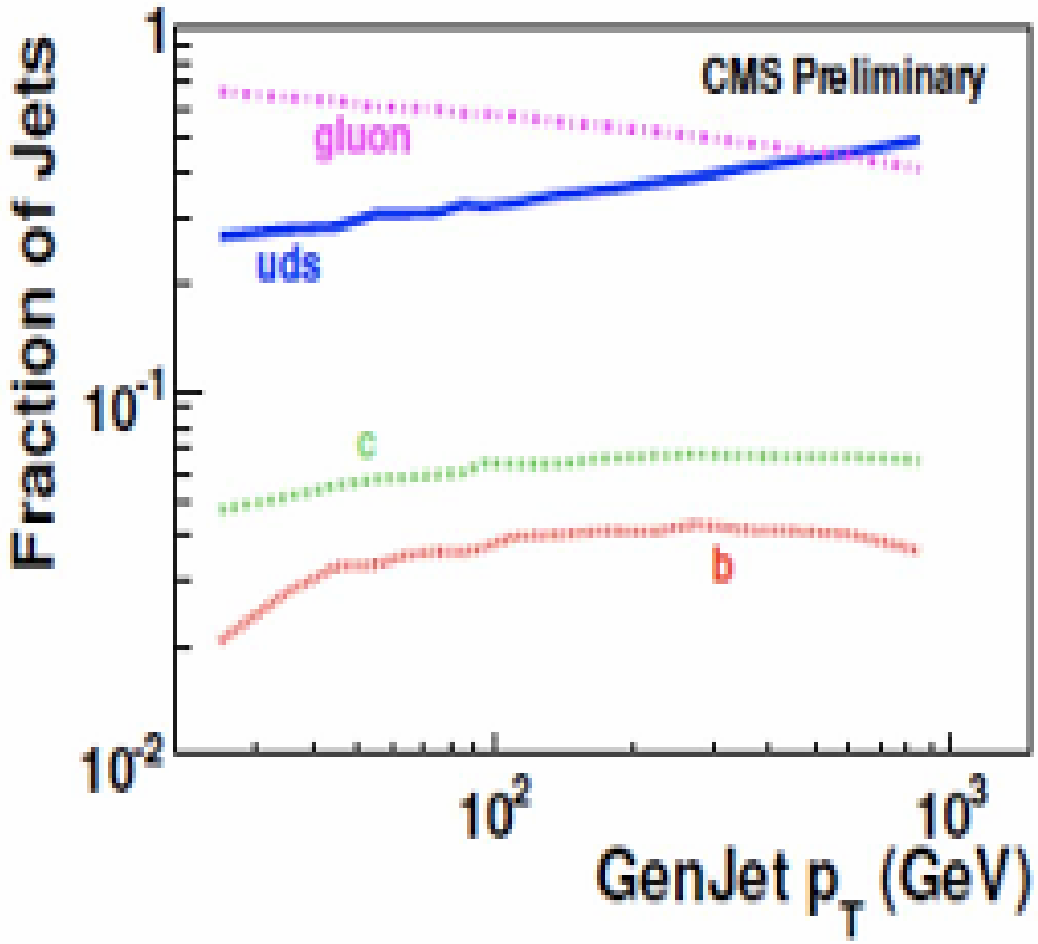
Outline – II, Early LHC Data

- Hi Pt Jets
  - Calibration and SM recovery
  - Di-Jets
  - Quark Composites?
- Exotics – Long Lived particles, Black-Holes
- Photons and Diphotons –
- b Tags
- ψ, Υ, W, Z, Z -> τ pairs : W' ? Z' ?
- V-V Pairs
- Top pairs, Z' ?

Jets – Gluon or Quark?



Jet composition depends on Pt. very roughly

$$< x > \sim M / \sqrt{s} \sim 2P_t / \sqrt{s}$$

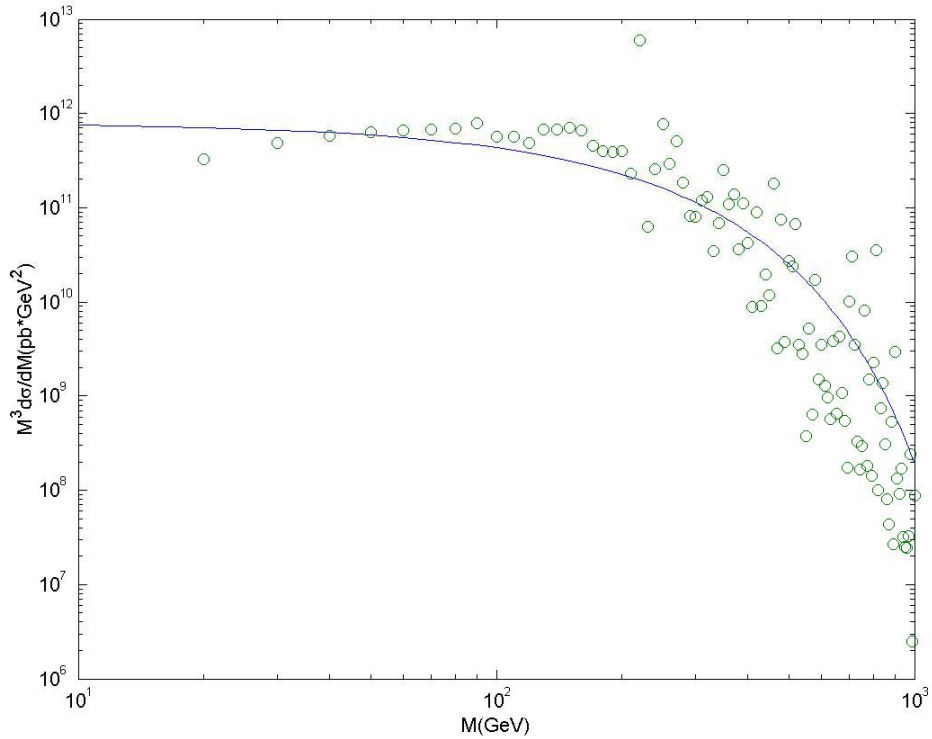
Recall that u > g for x > 0.2 or M > 2.8 TeV or Pt > 1.4 TeV

Most LHC processes are gluon initiated.

Jet-Jet Mass, 2 --> 2

Expect $1/M^3$ behavior at low mass. When $M/\sqrt{s}$ becomes substantial, the source effects will be large. E.g. for M = 400 GeV, at the Tevatron, $M/\sqrt{s}=0.2$, and

$(1-M/\sqrt{s})^{12}$ is ~ 0.07.

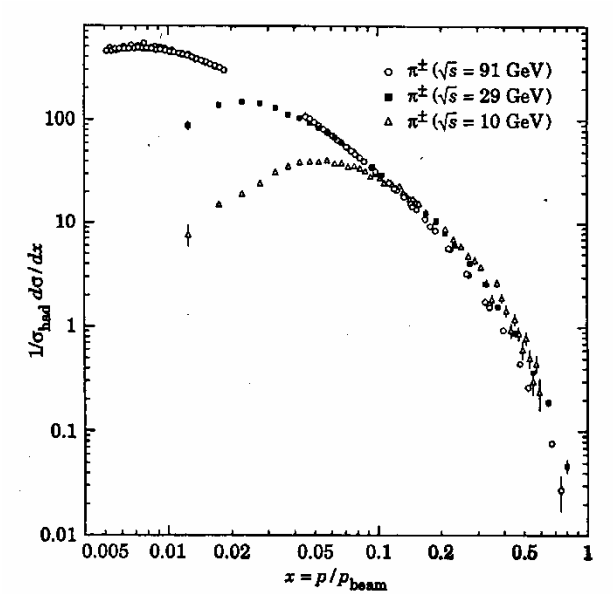


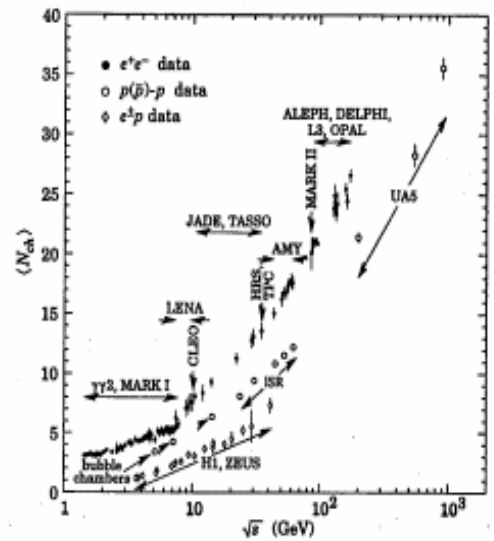
$$p + p \rightarrow g + g$$

$$xg(x) \sim 7/2(1-x)^6$$

$$M^3 d\sigma / dM \sim (1 - M/\sqrt{s})^{12}$$

Parton-->Hadron Fragmentation





For light hadrons (pions) as hadronization products, assume k_T is limited (scale ~Λ. The fragmentation function, D(z) has a radiative form, leading to a jet multiplicity which is logarithmic in E_T

$$z = k / P$$

$$z_{\min} < z < 1, \quad z_{\min} = m_\pi / P$$

$$zD(z) = a(1-z)^\alpha$$

$$< n >= \int D(z)dz \sim a \int_{m/P}^{1} dz / z \sim a \ln(P/m)$$

$$dy = dP_{\|} / E \sim dz / z$$

$$< n > \sim \Delta y \sim \ln(\sqrt{s} / M)$$

Plateau widens with s, <n>~ln(s)

Jets and Di-jets

- In the minbias calibration sample look for events passing jet algorithms. Get an estimate of the L1 and high level trigger and reconstruction efficiencies. For 10 million minbias have ~ 20,000 dijets with Et>30 GeV.
- As L rises, impose a Jet Trigger. Check the cross section vs Pt and Mass.
- Check the angular distribution.
- Establish the MET distribution. Check that tails are consistent with ISR, FSR.
- Use di-jets, when understood, to cross calibrate the η "rings" of the calorimetry using jet balance.
- Having established di-jets, launch a Jet – Jet mass search .

Jet Energy Resolution

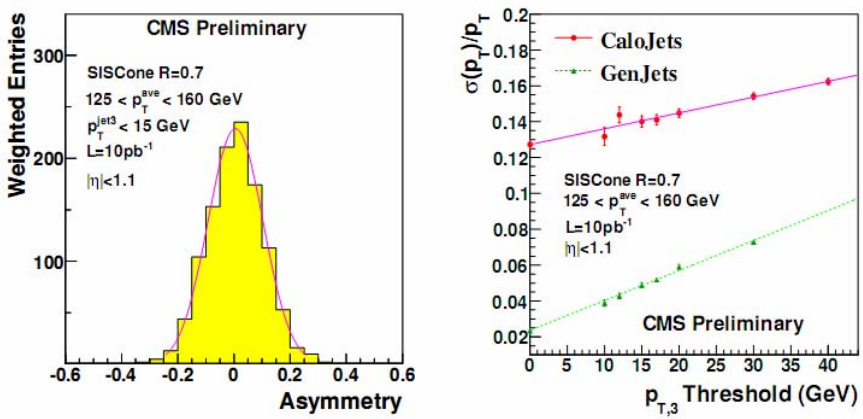


Figure 1: *Left:* Calorimeter asymmetry distributions with different p_T^{jet3} cuts for SISCone ($R = 0.7$) jets with $125 < p_T^{ave} < 160$ GeV and $|\eta| < 1.1$. *Right:* Extrapolation lines for both SISCone ($R = 0.7$) calorimeter jets and generated jets in the same p_T^{ave} and η range.

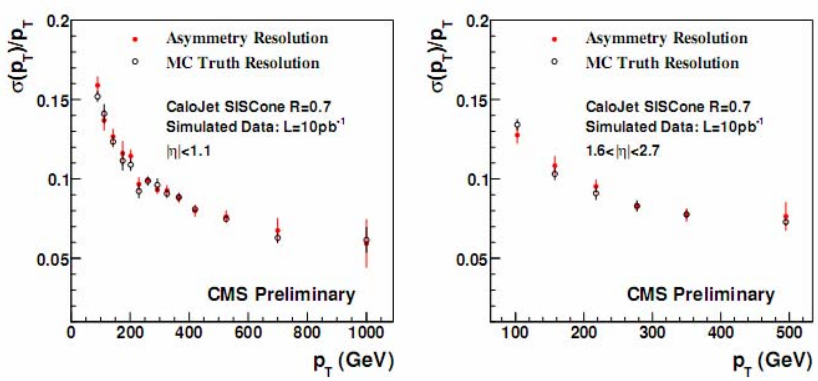
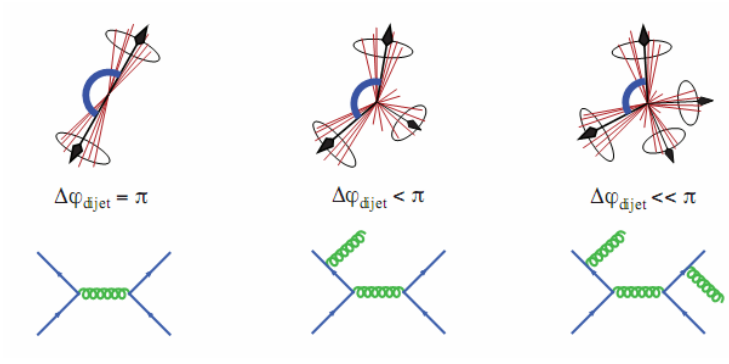
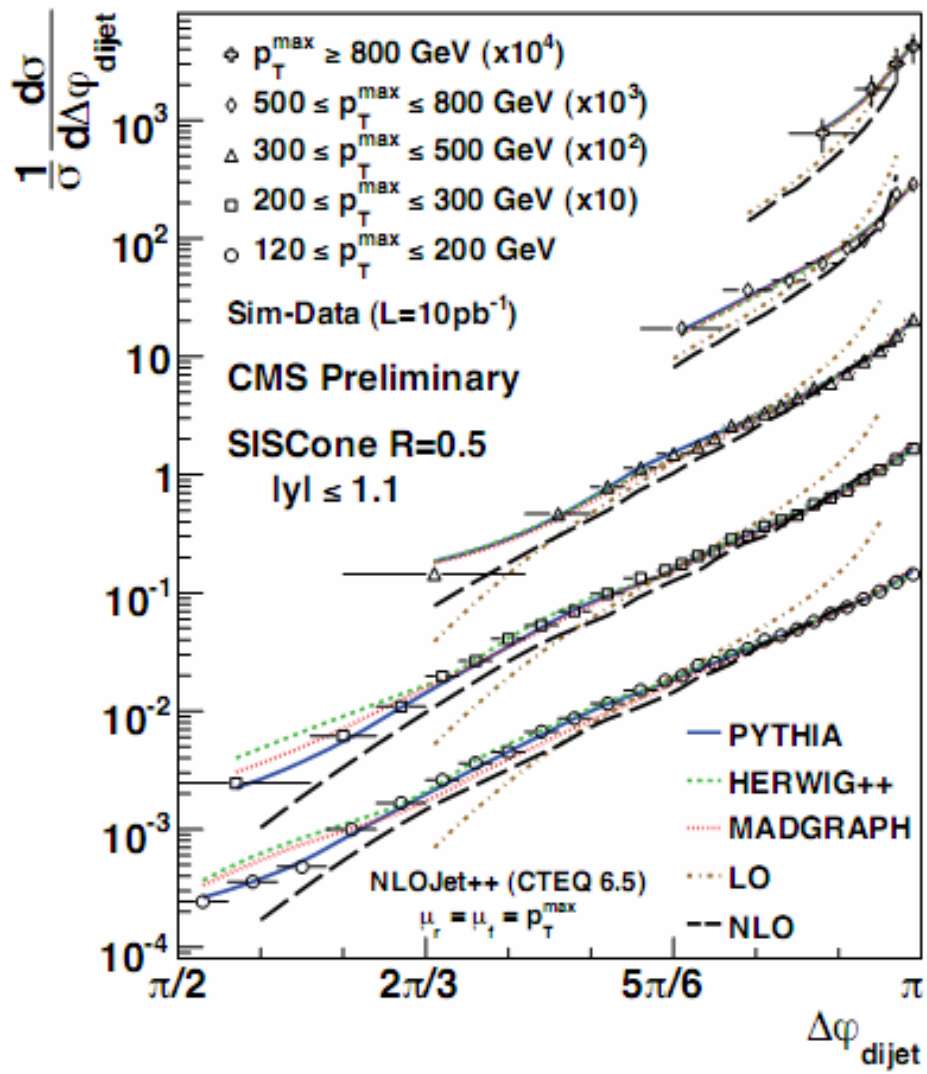


Figure 2: Comparisons of jet p_T resolutions from the asymmetry method and MC truth for SISCone $R = 0.7$ jets with $|\eta| < 1.1$ (left) and $1.6 < |\eta| < 2.7$ (right). The statistical uncertainties correspond to $10\,\mathrm{pb}^{-1}$ of data.

Determine Jet energy resolution from jet-jet energy asymmetry. Must cut on extra jets in the event and extrapolate. Force the dijets to be back to back

Dijet Azimuthal De-Correlation





An early measurement is the jet azimuthal decorrelation – due to ISR and FSR.

"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 $\sigma_{SM} \sim \alpha^2 / \hat{s}$

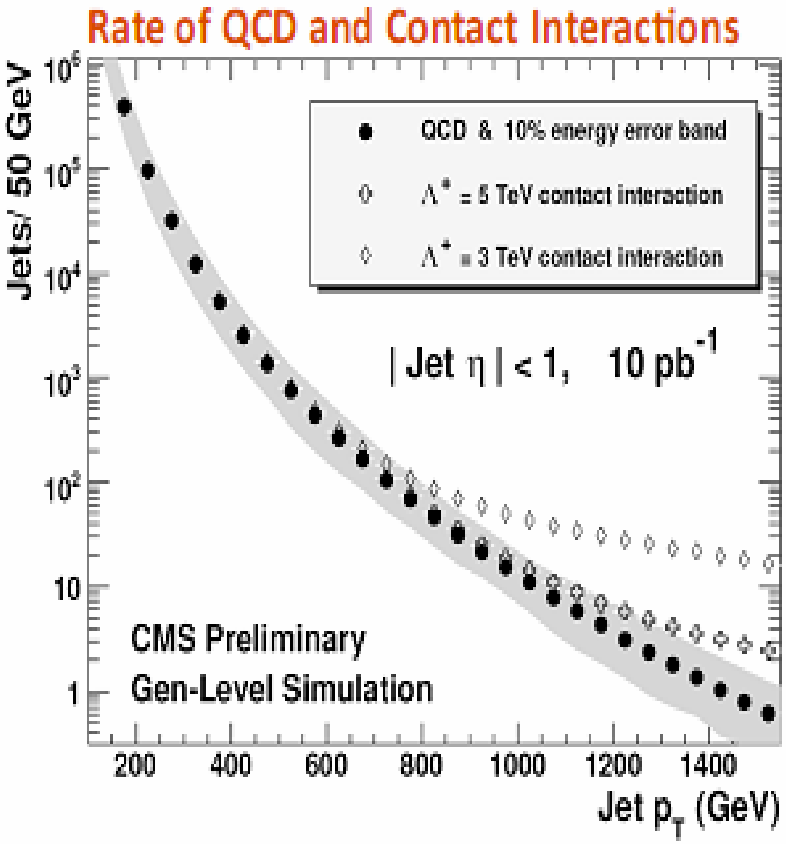
- The interference term would go roughly as

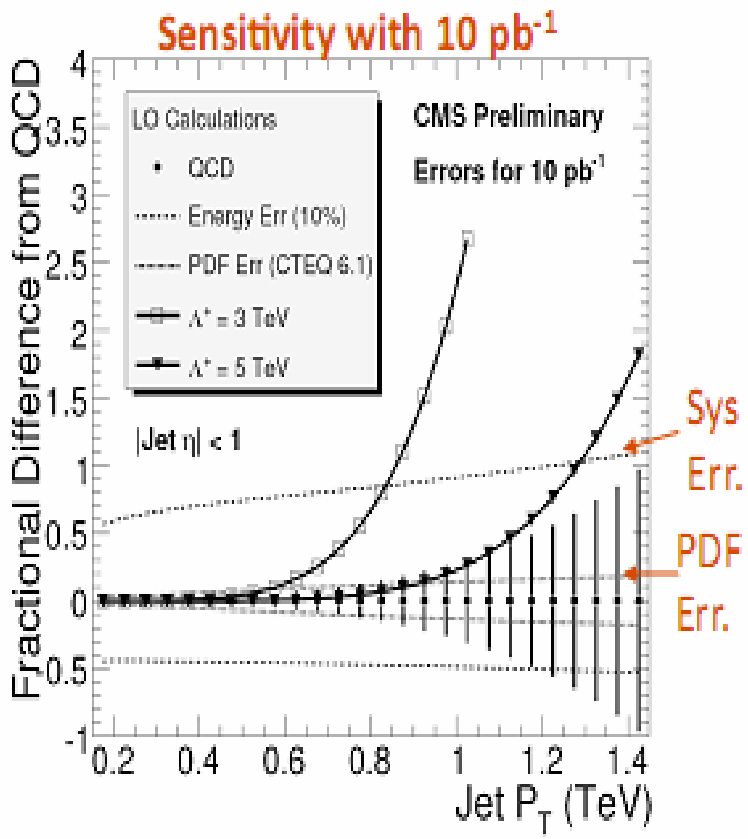
$$\pm\alpha\alpha_{new} / M^2_{new}$$

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

Look in the High Pt "Tail"

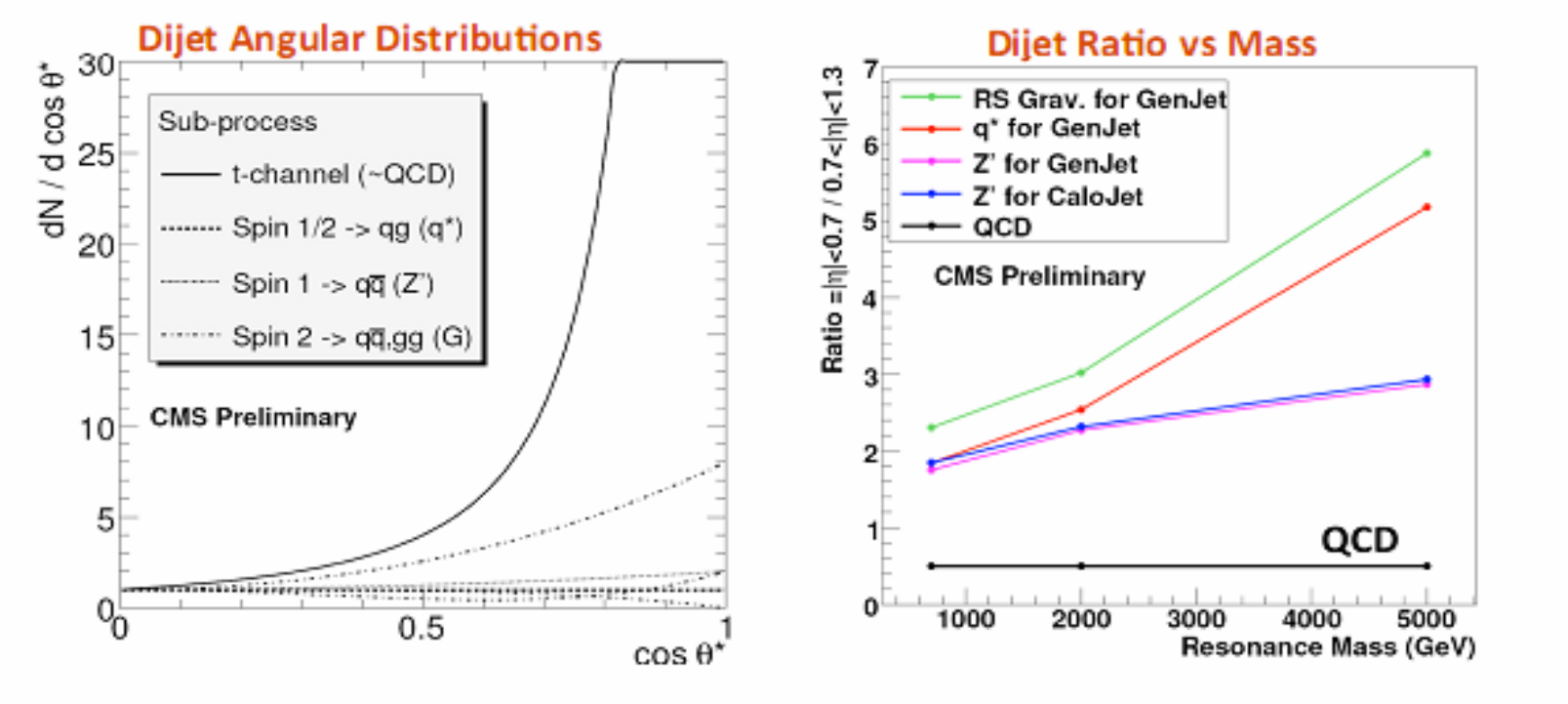
With 10 pb^{-1} we can see new physics beyond Tevatron exclusion of $L^{+} < 2.7$ TeV.





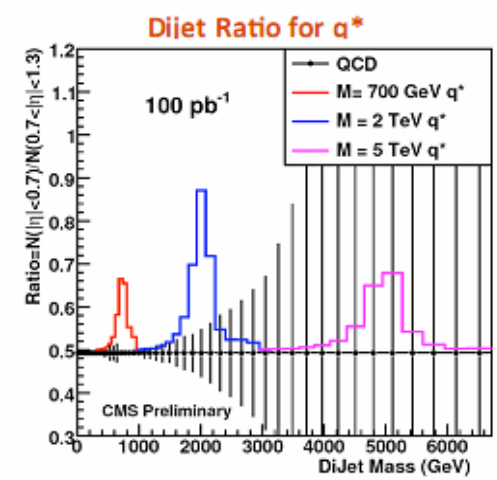
But worry about systematics – e.g. test beam data on pions only goes to ~ 300 GeV, or jets ~ 1.5 TeV

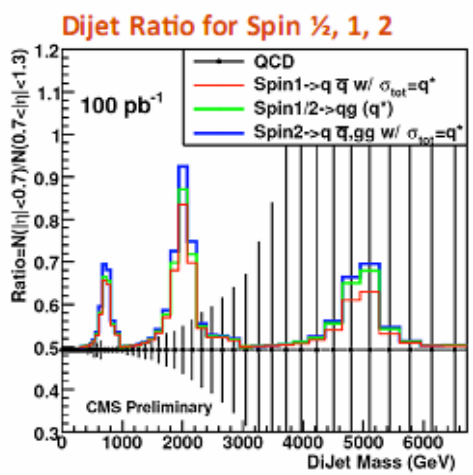
Angular Distributions

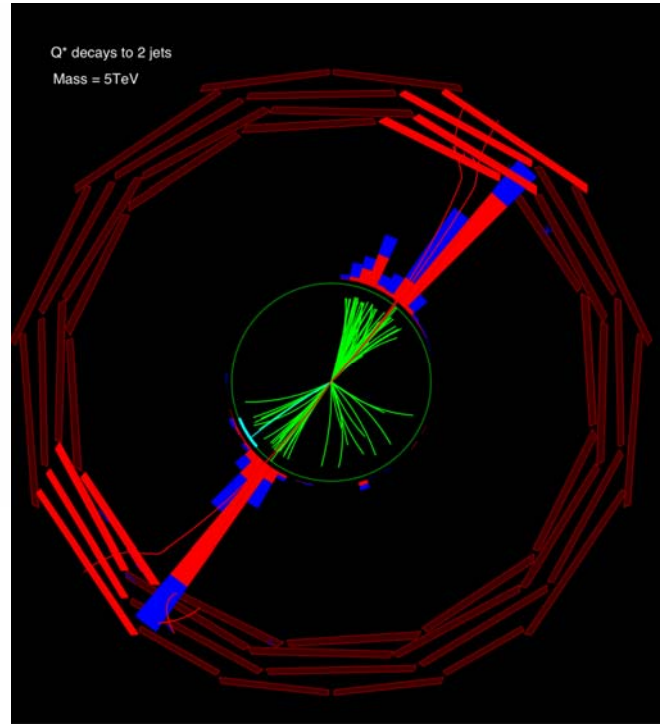


Establish low Pt cross section, mass distribution and angular distribution. Then look at high mass. Discovery possible very quickly - ~ 3 TeV for 100 pb^{-1}

Angular Ratios



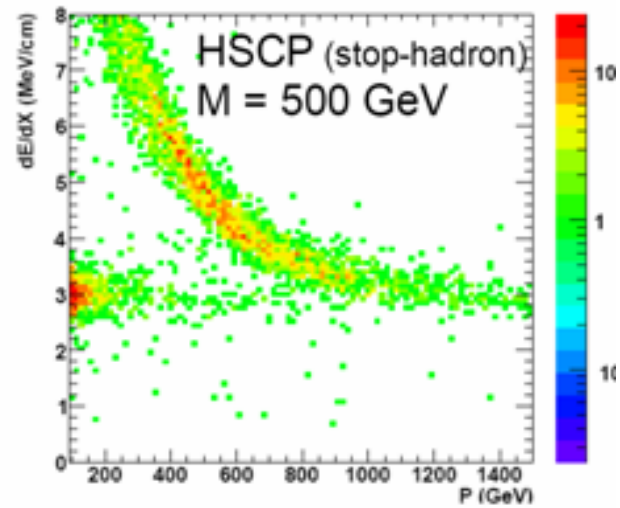


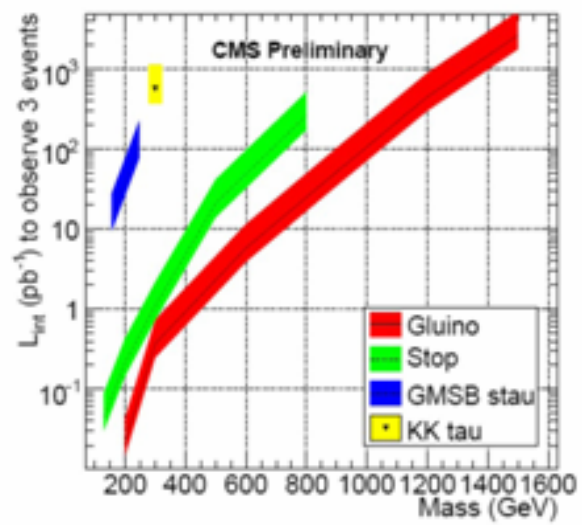


The di-jet mass searches for excited quarks or contact interactions or ? Will be the earliest LHC search – with fairly low luminosity.

Heavy Stable Particles?

- Several SUSY variants predict metastable or stable charged particles
  - Slepton: “heavy muons”
  - Gluino, squark: “R-hadrons”
    - nuclear interactions!
- Signatures: dE/dx, Time Of Flight
- dE/dx: Tracker
  - >10 independent samplings in Si
  - Estimate the Most Probable Value
- TOF: Muon Chambers
  - δt additional parameter in the track fit
  - Main bkg: cosmics



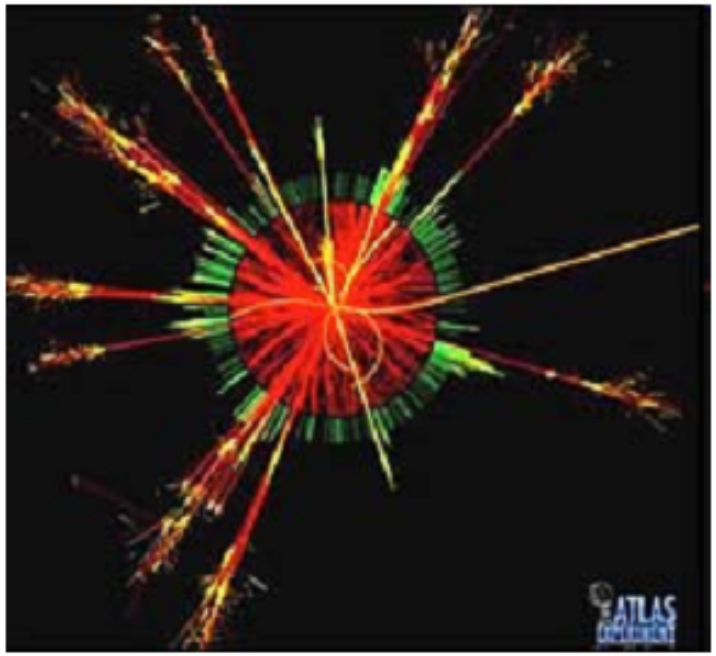


Black Holes

The Planck scale is the one at which gravitation interactions become large.
If gravity becomes strong at the TeV scale, the results could be quite exciting.
If there are extra dimensions, the formula for the Schwarzschild radius becomes

$$r_{s(4+n)} = \frac{1}{\sqrt{\pi} M_*} \left(\frac{M_{BH}}{M_*} \left(\frac{8\Gamma((n+3)/2}{n+2} \right) \right)^{1/(n+1)}$$

$$(M_* = 2TeV, M_{BH} = 4TeV, r = 100\, fm)$$



Cross section would be large at current limits on M*, n

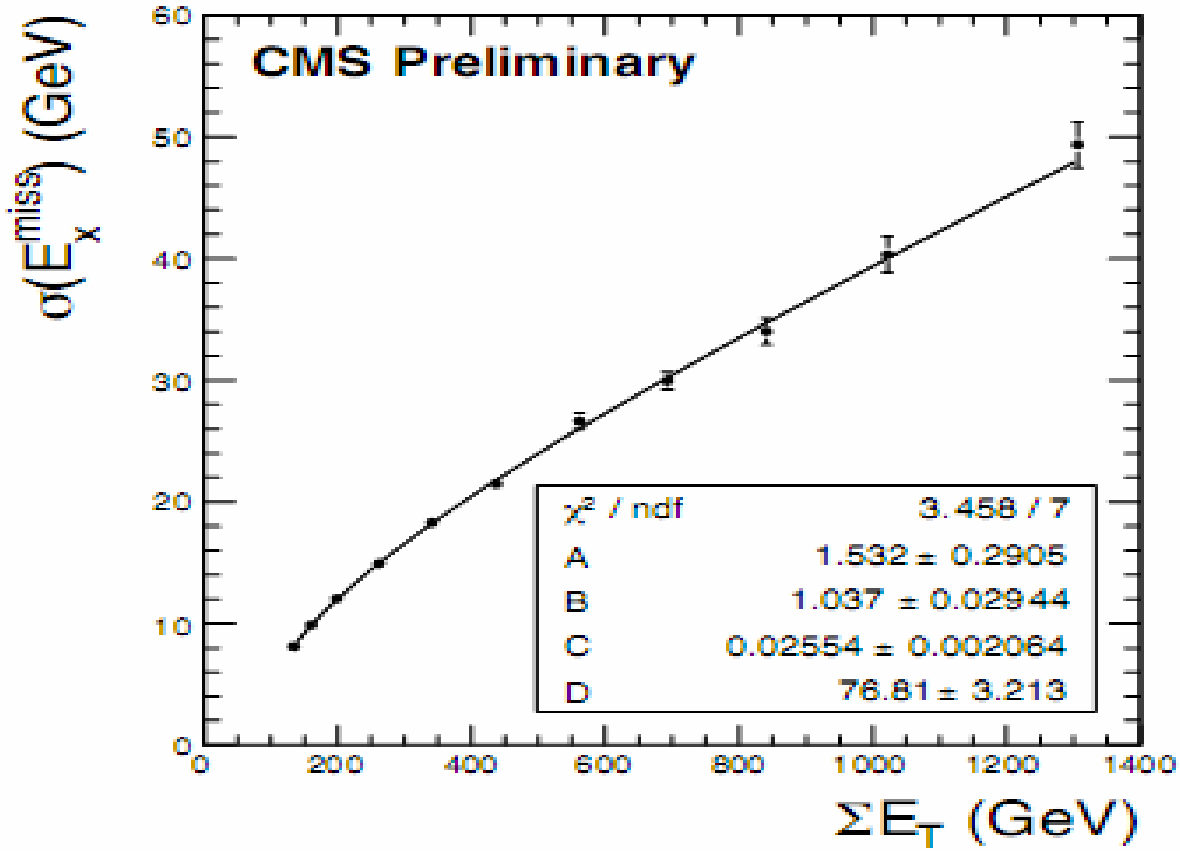
$\sigma = \pi r^2$

($300\, pb$ for example above without Voloshin damping factor $20\, pb$ with = 3000 events in 300 pb-1 (factor 2 from 14 to 10))

Since gravity couples universally to mass, black hole will emit all particles "democratically' Thus look for rare, weakly produced particles – W, Z, ….

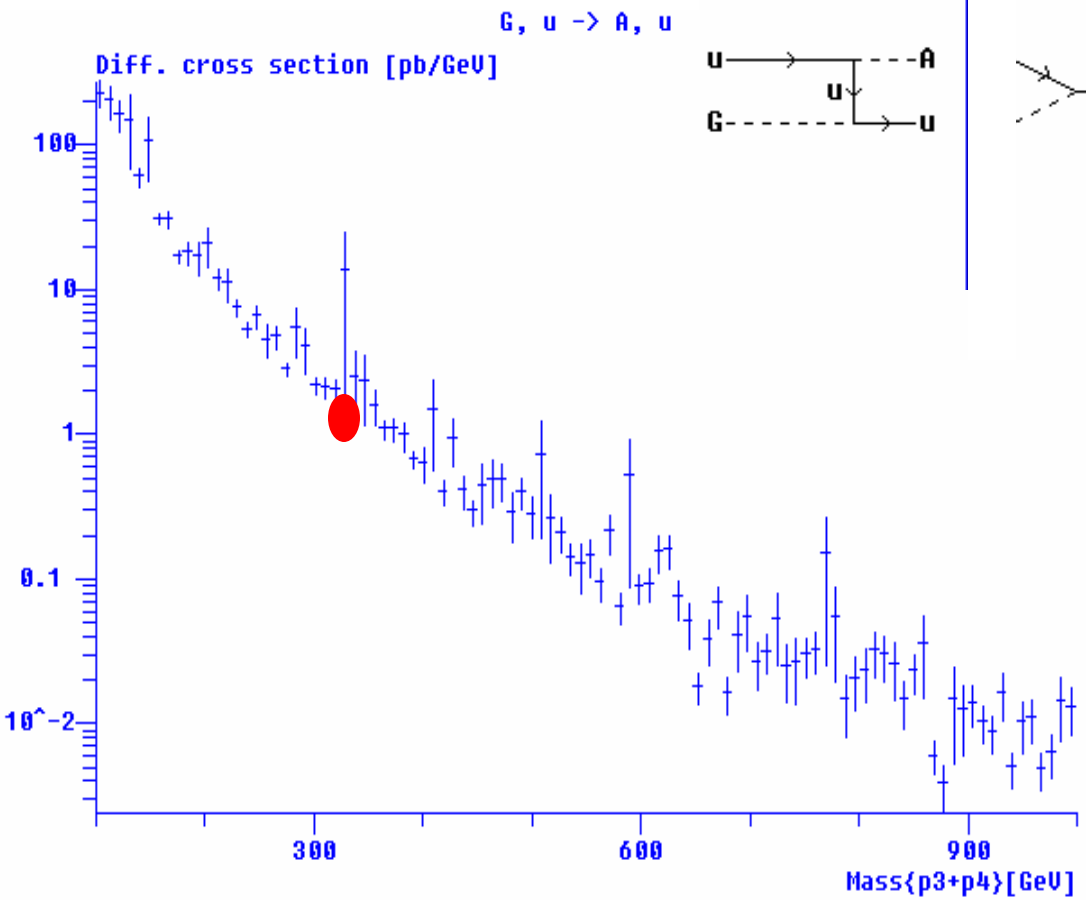
Establish MET – Jet Events

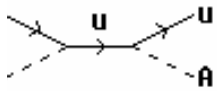
$$dE / E \sim a / \sqrt{E} \oplus b$$



Assume MET is due to mis-measures of jet energies. Extract MET resolution from Jet resolutions - tails.

Direct Photon Production–γ + J



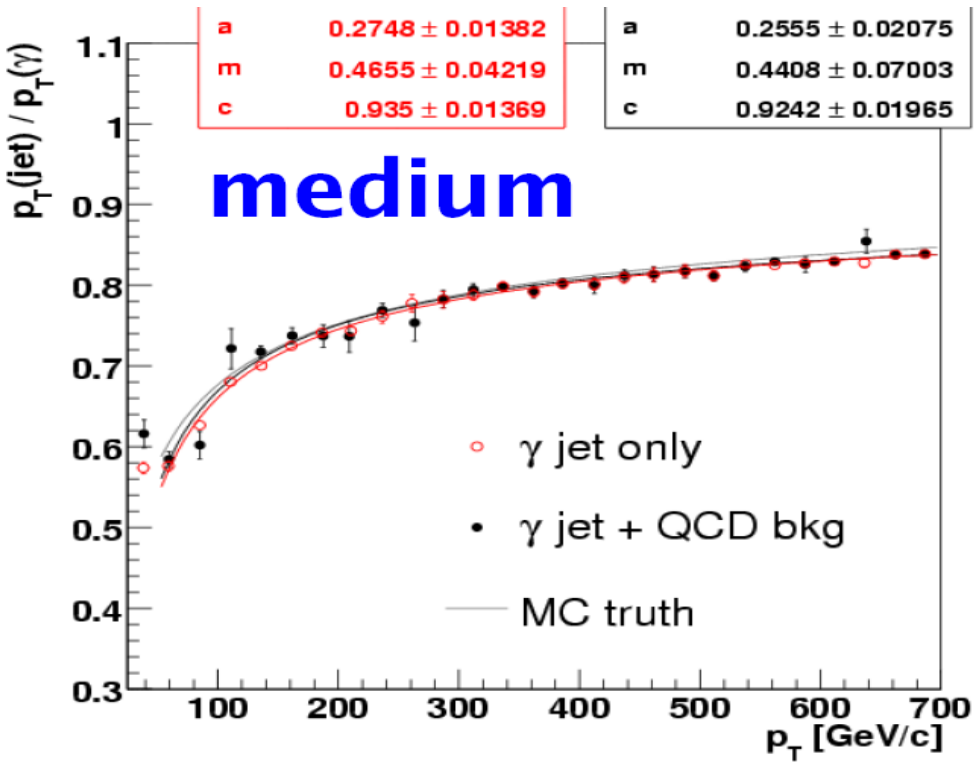


Compton scattering. Expect a similar spectrum to di-jets with a rate down by ratio of coupling constants and differences in u and g source functions. α/α_s~14

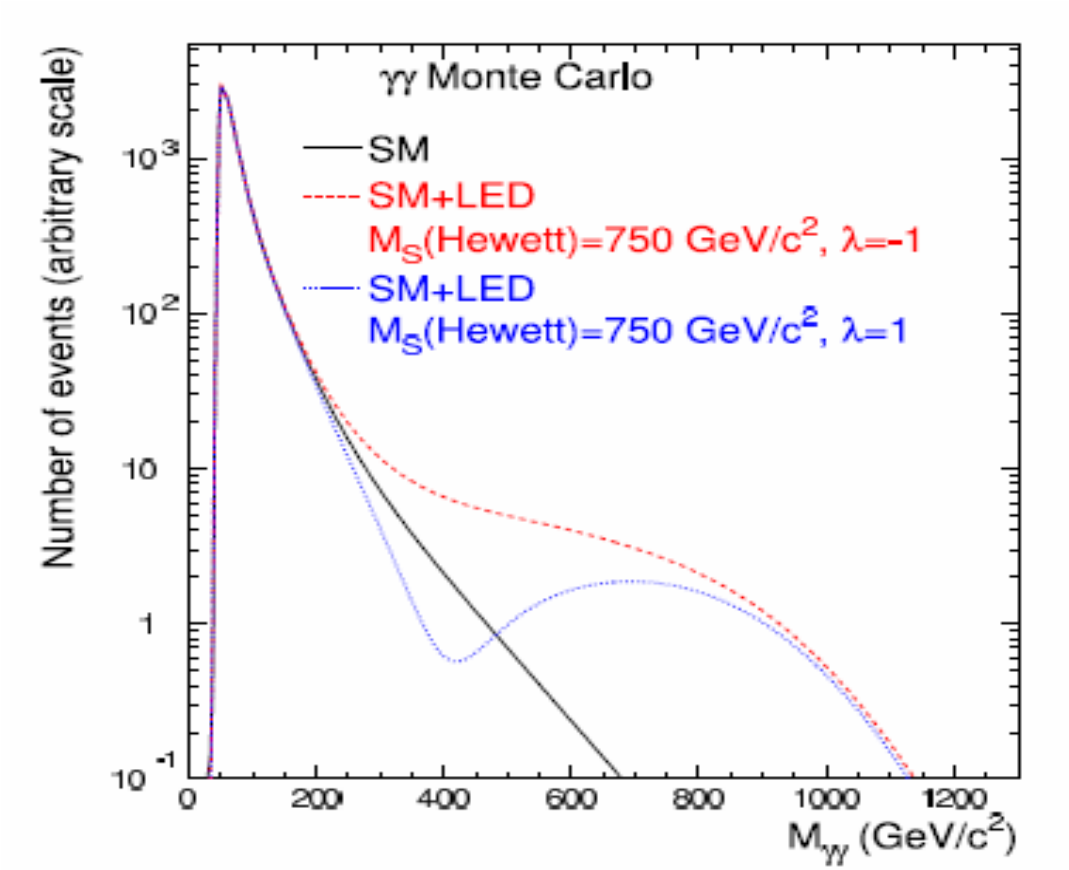
u/g~6 at x~0.

Photon + Jet Balance

- Photon + jet balance analysis
- Z + jet balance will give valuable confirmation but samples will be small



Di-photons at High Mass



Gravity couples to all mass "democratically". Therefore look at rare processes with SM weak couplings. LHC will be in new territory by 100 pb^{-1}.

KK Graviton in Di-Photons

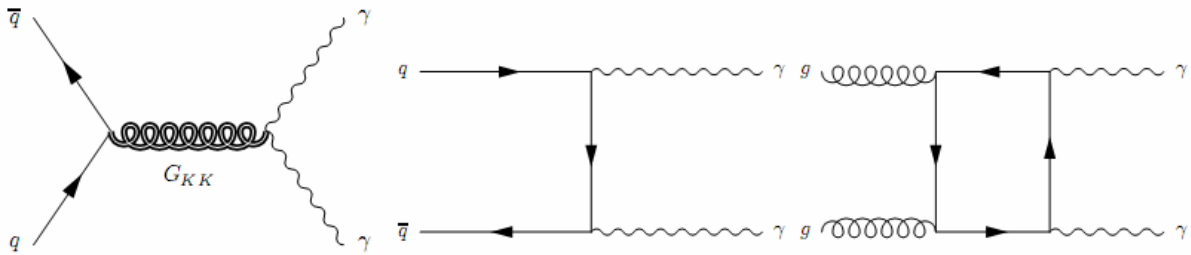
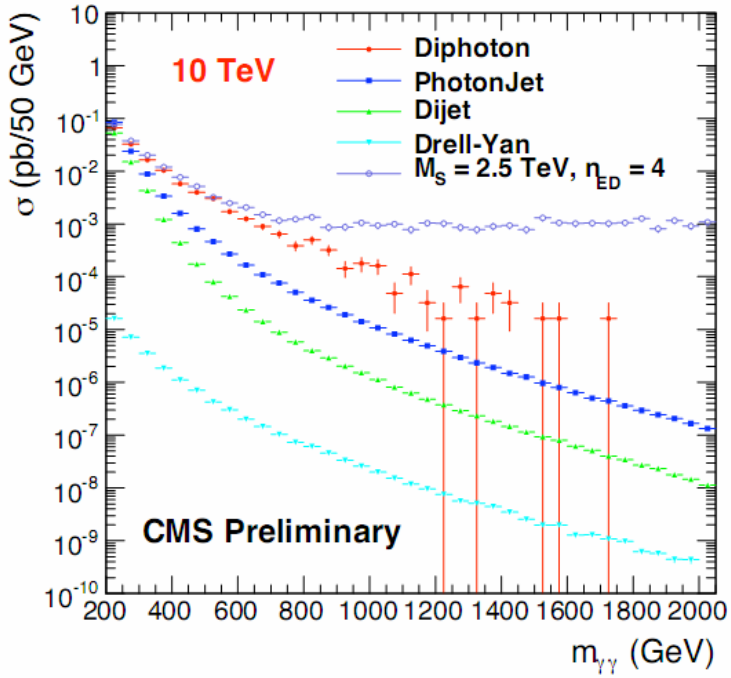


Figure 1: Feynman diagrams for virtual KK graviton production through $q\bar{q}$ annihilation decaying into two photons (left) as well as for SM diphoton production (last two diagrams).



RS Gravitons in Di-Photons

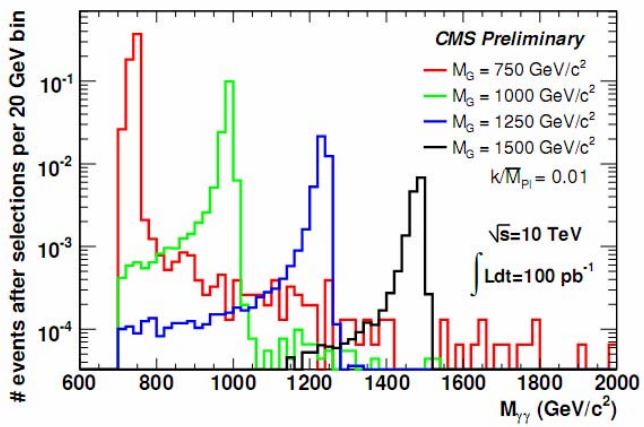
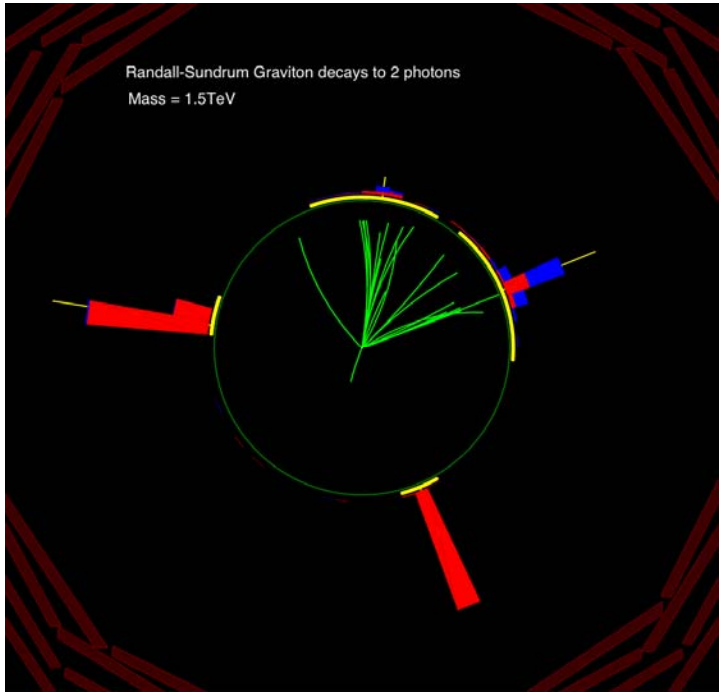


Figure 2: Diphoton invariant mass spectra after selection is applied, scaled to $100\,\mathrm{pb}^{-1}$ for $M_1 = 750, 1000, 1250$, and $1500\,\mathrm{GeV/c}^2$, $\tilde{k} = 0.01$ samples.

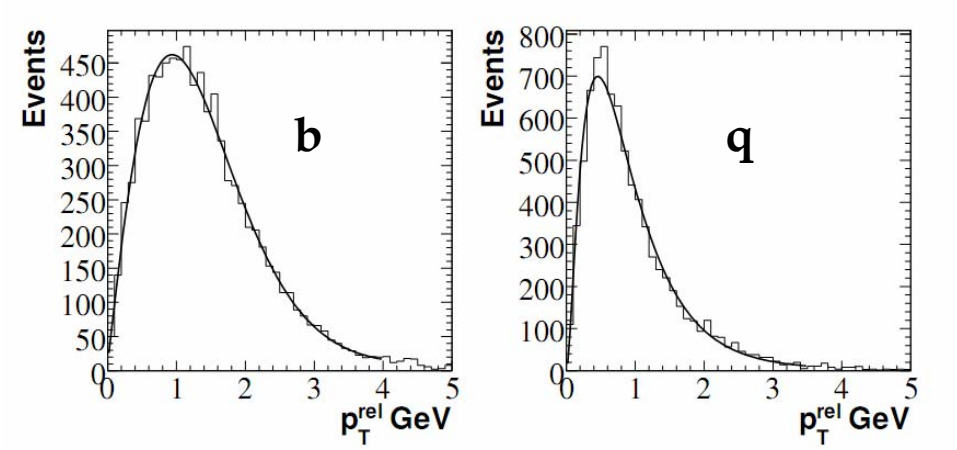


For 100 pb^{-1} there is a discovery reach for di-photon resonances.

LHC–2010 Run, First 100 pb^{-1}

L for 1 month run	Integrated L	Trigger	Process	Comments
10^{28}	$10nb^{-1}$	σ_{bB} ~ 600 nb. Setup – run single electron, muon, photon	g+g -> b+B ψ	900,000 JJ, 6000 bB, 1200 1μ, 60 2μ Establish μ jet tag 80 2e and 2μ events from ψ
10^{29}	100 nb^{-1}	Setup dimuon, dielectron $\sigma_{\mu\nu}$ ~ 10 nb	q+Q->W->μ+v (D-Y) Υ	1000 μ from W->μ + v Lumi – standard candle (look at high Mt tail) 100 2e and 2μ events from Υ
10^{30}	1 pb^{-1}	Run dilepton trigger $\sigma_{\mu\mu}$ ~ 1.5 nb σ_{tT} ~ 630 pb	q+Q->Z->μ+μ (D-Y) g+g->t+T	1500 dimuons from Z-mass scale, resolution Lumi- standard candle, high M 600 t + T produced
10^{31}	10 pb^{-1}	Setup, J*MET $\sigma_{q\mu\mu}$ ~ 40 pb $\sigma_{\gamma\gamma}$ ~ 24 pb	g+q->Z+q->μ+μ+q q+Q->γ+-γ (tree) τ	400 Z + J events with Z->dimuons – Z+J balance, calib Estimate J + MET (q + v) 240 diphoton events with M > 60 GeV 6000 t + T 150 Z->tau pairs into dileptons > 8 GeV * MET > 15 GeV
10^{32}	100 pb^{-1}	σ_{qQZ} ~ 170 pb σ_{qgZg} ~ 32 pb σ_{tT} ~ 630 pb	g+g->q+Q+Z g+q->q+g+Z+g	3000 J+J+Z->vv events, Pt>30 500 J+J+Z->μ+μ events, Pt>30 600 J+J+J+Z->vv events 10000 J+J+J+J+μ+v events
10^{33}	1 fb^{-1} (1% of design L for 1 yr) End of '08 Physics Run			M of dijet in 100000 top events, W-> μ +v – set Jet energy scale with W mass. Dimuon mass > 1 TeV, start discovery search, diphoton search, SUSY search

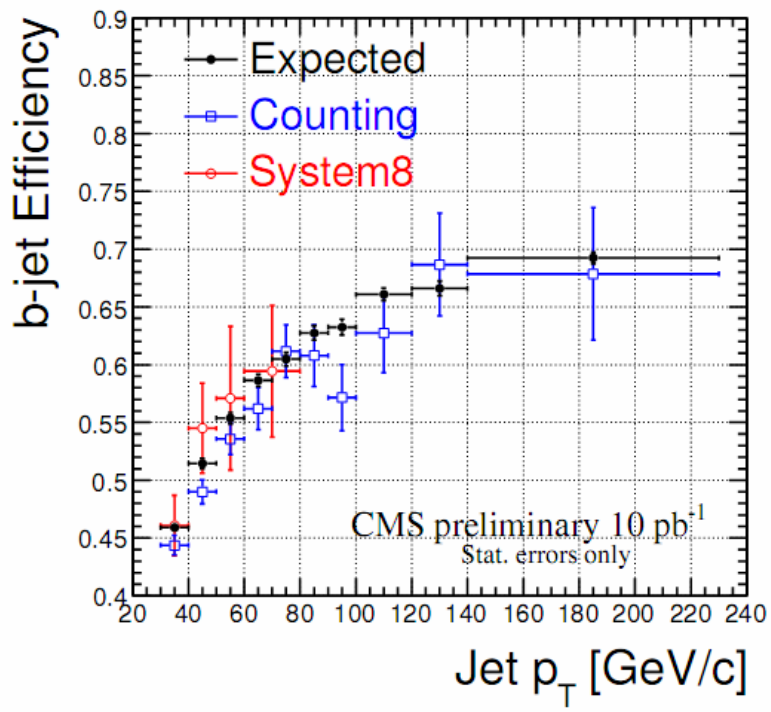
b Tagging



50% b

2% u,d

10% c



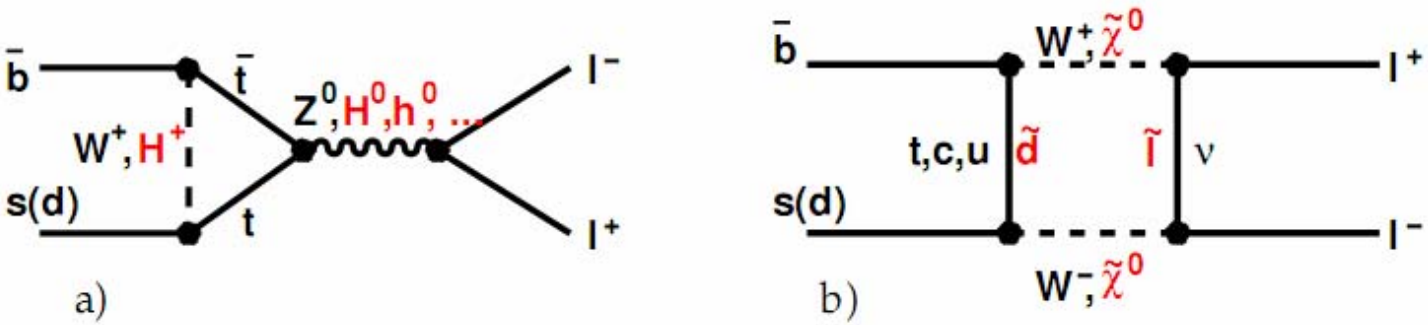
Identify b Jets using muon Pt relative to jet axis. Tracking alignment crucial.

Or impact parameter. Or secondary vertex.

Establish b tagging. Check with top pair events. Note that
Earliest attempt to establish b tags comes with b jet events.

$$(c\tau)_b \sim 450\mu m, (c\tau)_\tau \sim 87\mu m$$

BSM Search in Bs Decays

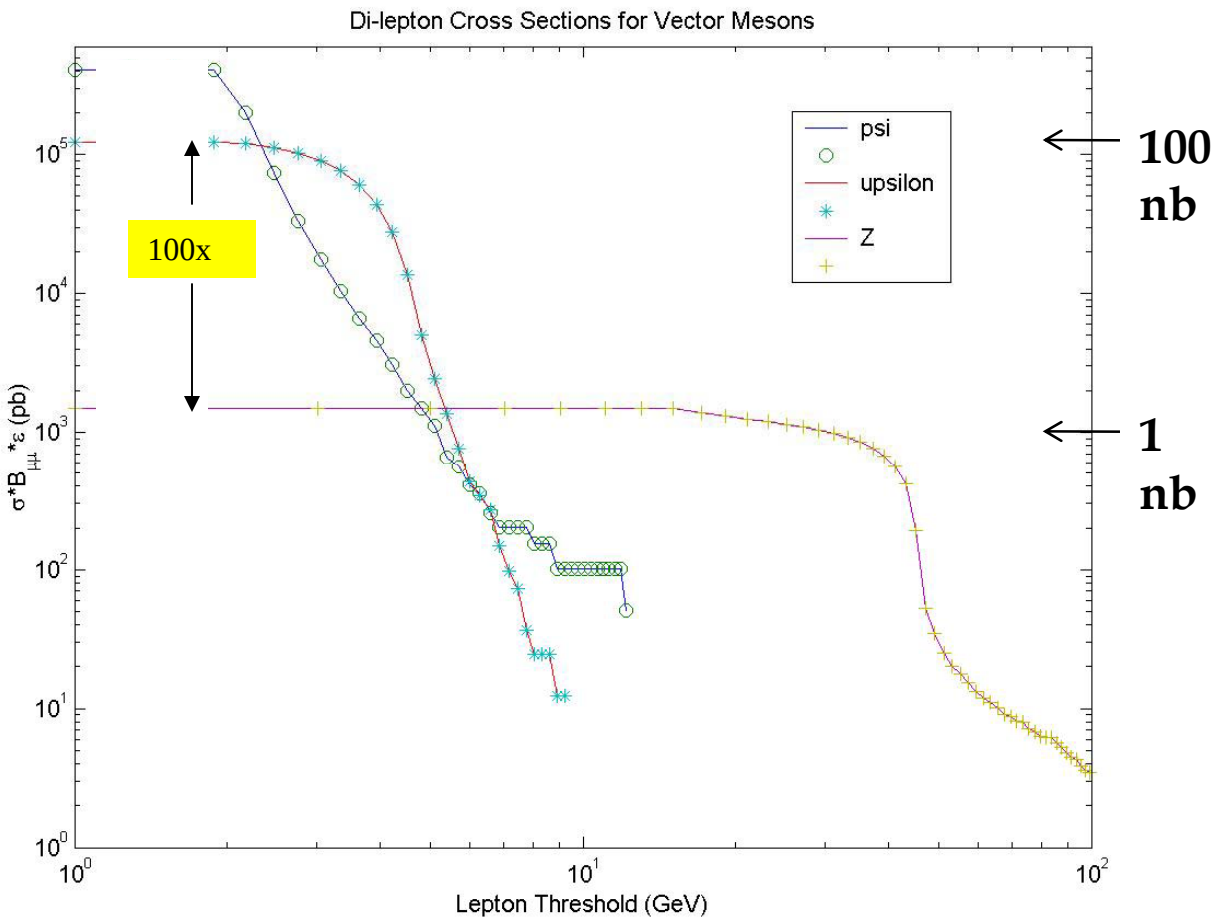


$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq 1.6 \times 10^{-8}.$$

At 95% C.L. the upper limit on the branching fraction is $\mathcal{B}(B_s^0 \to \mu^+\mu^-) \leq 1.9 \times 10^{-8}$.

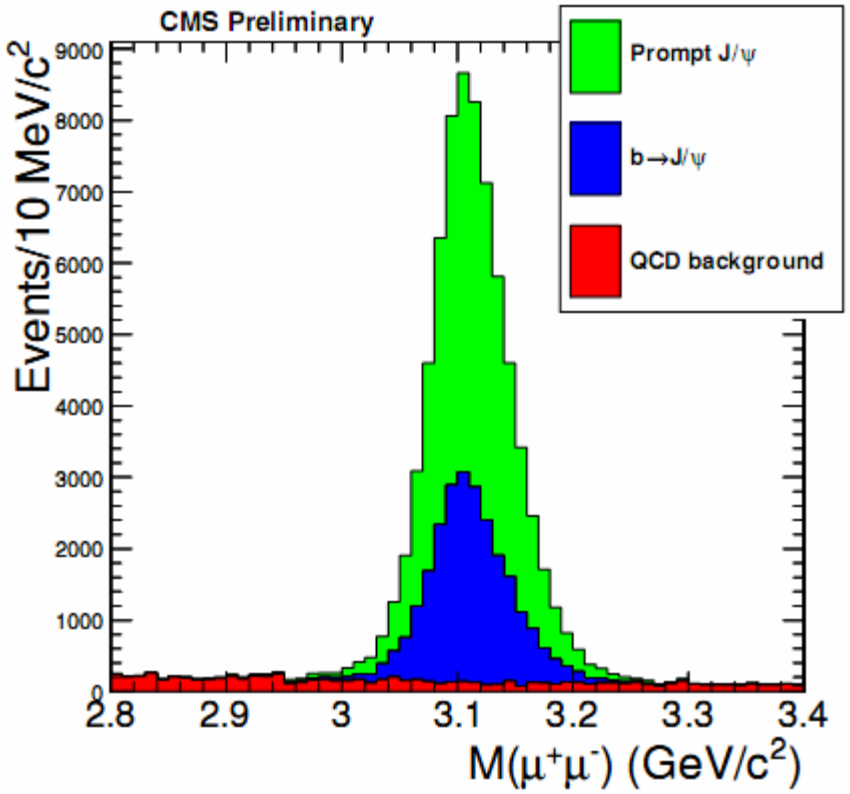
While this upper limit is about four times above the SM expectation, it allows already constraints on new physics models with the first $1.0\,\mathrm{fb}^{-1}$ of integrated luminosity. A better de-

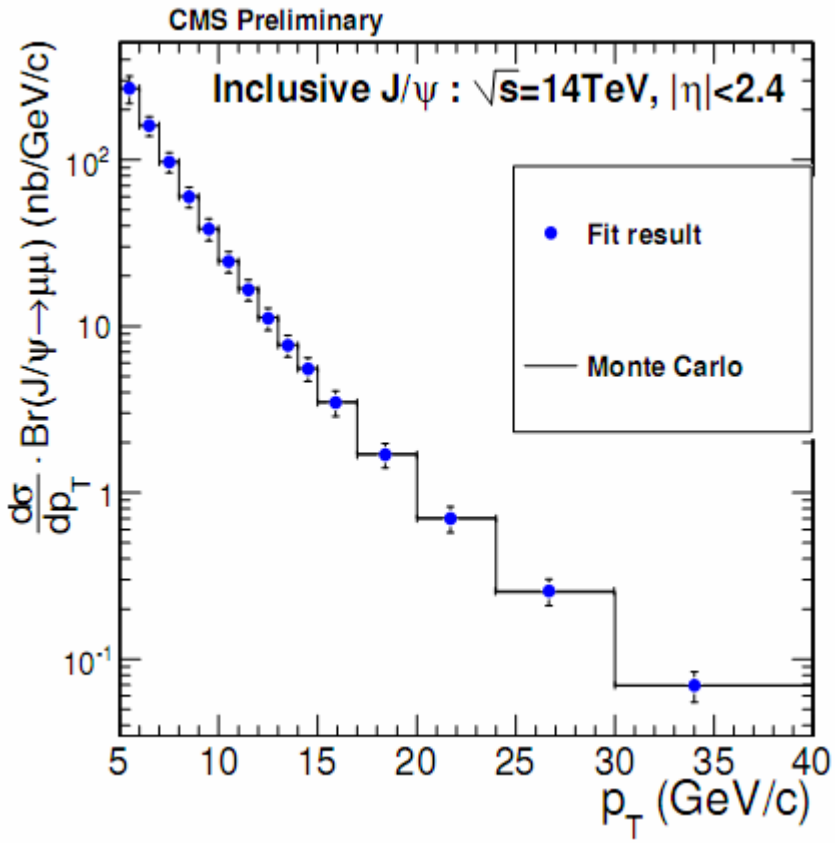
Dilepton Resonances - Thresholds



If thresholds of 3 to 4 GeV can be used in triggers, then high cross section resonances can be used to establish Tracker and Muon alignment and check the mass scale and resolution.

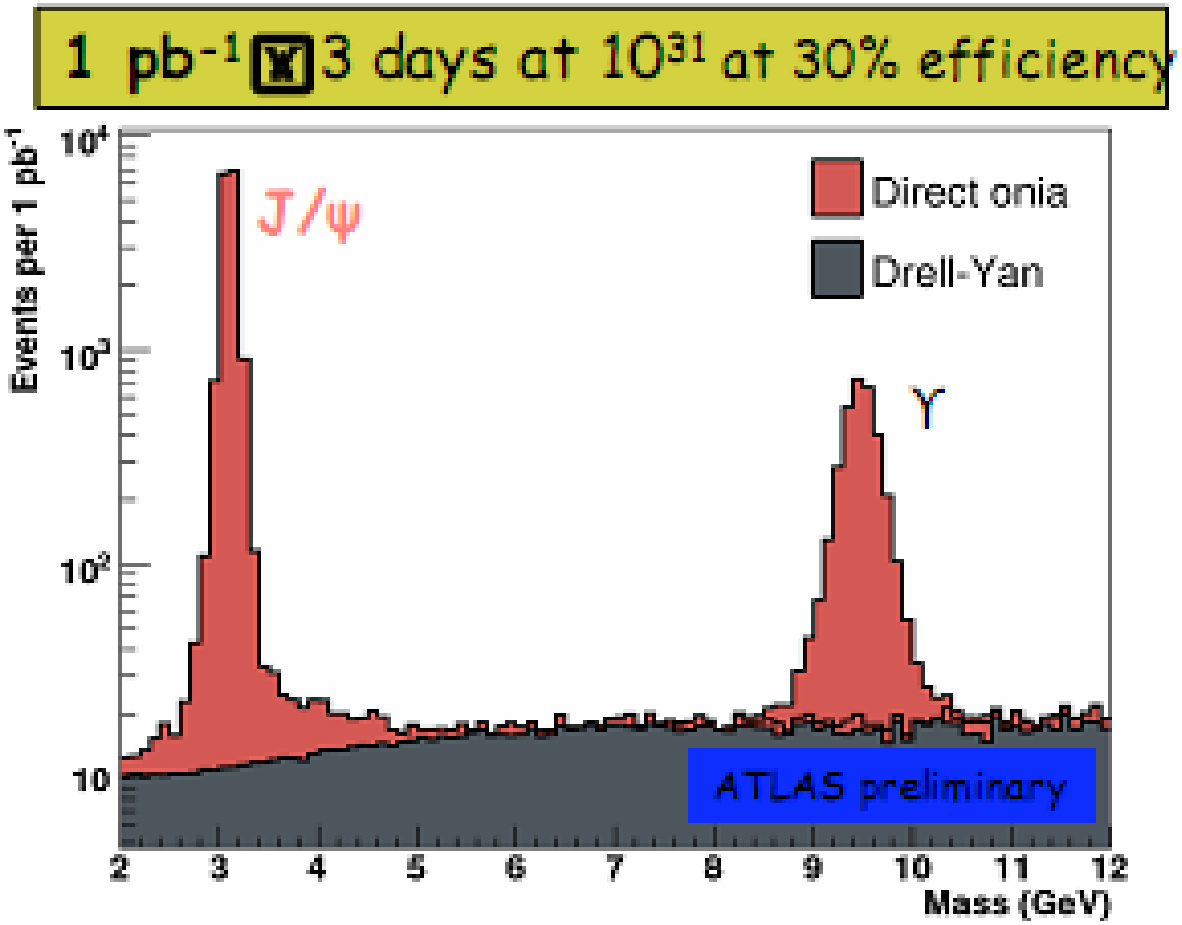
Psi Production





Largest cross section resonant dilepton state. Set momentum scale for tracker. Note the cross section scale is ~ 100 nb.

Upsilon Production



Use di-lepton resonances to check momentum scale and momentum resolution at 3, 10 and 91 GeV mass.

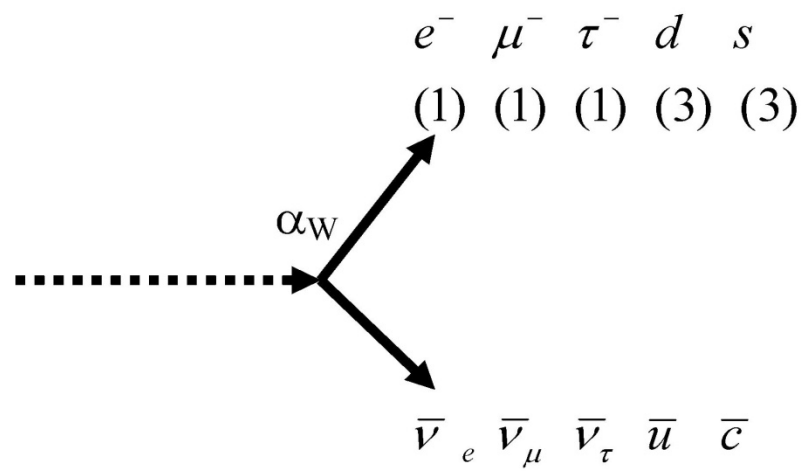
W - SM Mass and Width Prediction

Mass:

$$< \varphi >= 1/\sqrt{2G\sqrt{2}} = 174 \;\; GeV$$

$$G/\sqrt{2} = g_W^2 / 8M_W^2 \;\; , \;\; g_W \sin\theta_W = e$$

$$M_W^2 = 2\pi\alpha_W < \varphi >^2 , M_W \sim 80 \; GeV$$



Width;

$$\Gamma(W^- \to e^- + \bar{\nu}_e) = (\alpha_W / 12) M_W \sim 0.21 \;\; GeV$$

$$\Gamma_W \sim 9\Gamma(W^- \to e^- + \bar{\nu}_e)$$

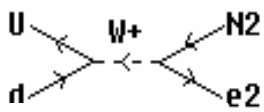
$$\Gamma(Z \to \nu_\ell \bar{\nu}_\ell) = [\alpha_W / 24][M_Z / \cos^2\theta_W] \sim 0.16 \;\; GeV$$

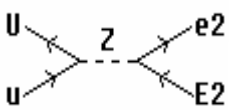
$$e^- + \bar{\nu}_e , \mu^- + \bar{\nu}_\mu , \tau^- + \bar{\nu}_\tau$$

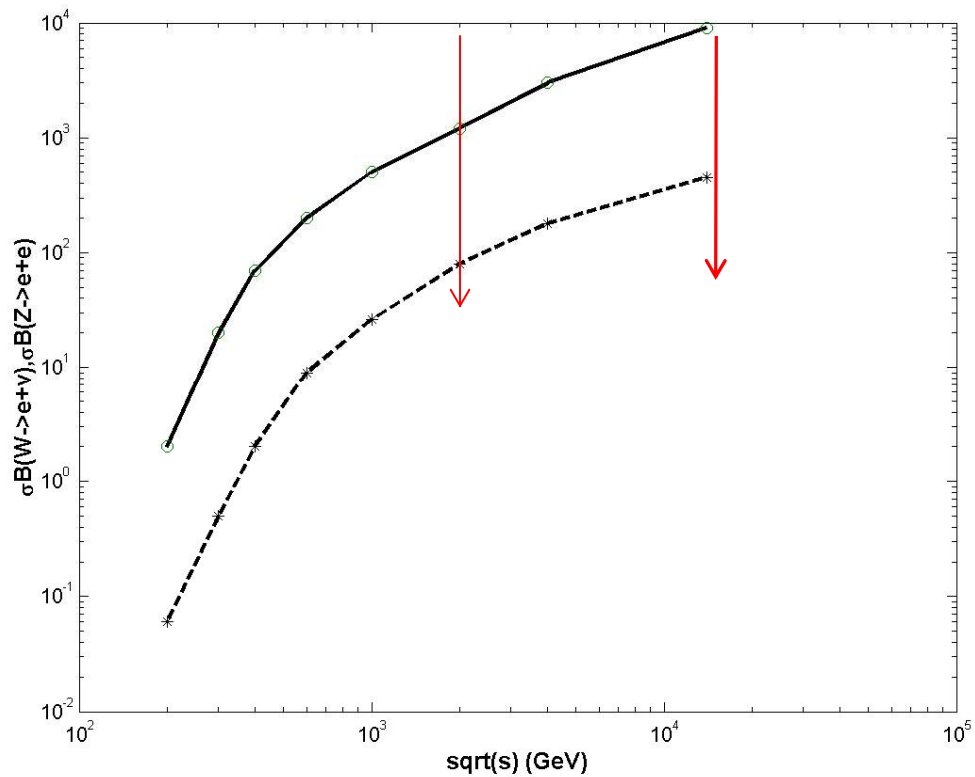
$$\bar{u} + d , \bar{c} + s$$

Color factor of 3 for quarks. 9 distinct dilepton or diquark final states.

DY Formation: 2 --> 1







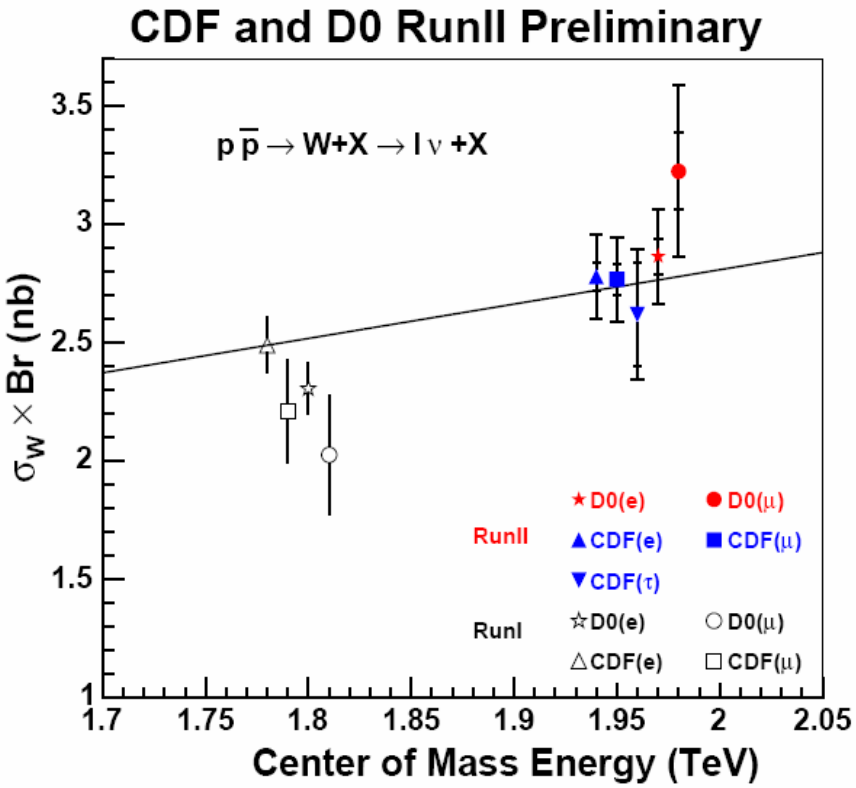
At a fixed resonant mass, expect rapid rise from "threshold" - $\Delta\sigma \sim$

$(1-M/\sqrt{s})^{2a}$

- then slow "saturation". $\sigma_W \sim$ 30 nb at the LHC

$$\bar{u} + u \rightarrow Z \rightarrow e^+ + e^-,\ \bar{u} + d \rightarrow W^- \rightarrow e^- + \bar{\nu}_e$$

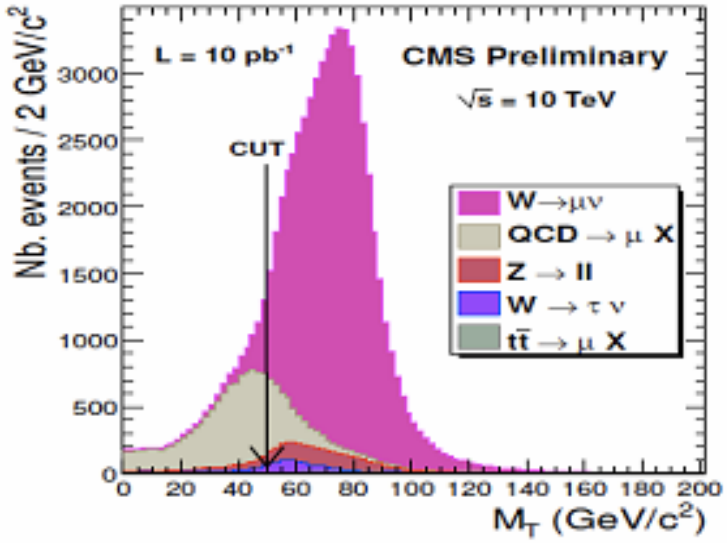
Standard W Candle?

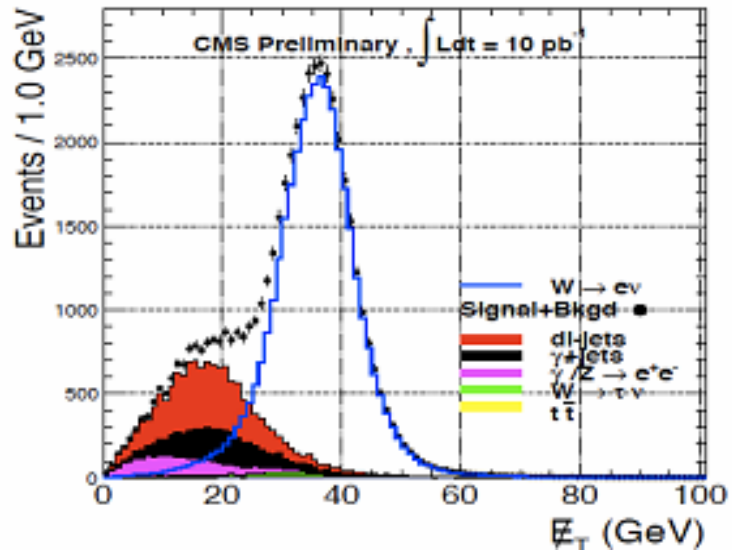


Use W -> μ + v as a "standard candle" to set the LHC luminosity? Expect ~ 2% accuracy on the predicted cross section. Cross section for W-> μ +v with |η|<2.5 * Pt > 15 GeV is ~ 10 nb. In isolated muon triggers look for MET and for Jacobean peak indicating cleanly identified W D-Y production. Once established, look at transverse mass tail in isolated leptons. In new territory above Run II mass reach – start a discovery search in 2010.

W Signals into Muons, Electrons

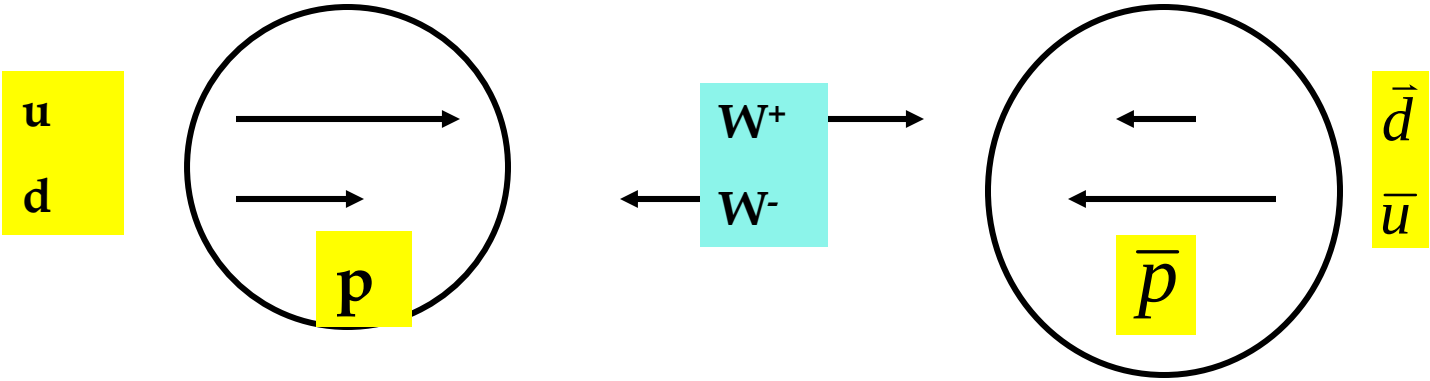
$$m_T = \sqrt{2 p_T \not{E}_T (1 - cos\Delta\phi_{\ell,\not{E}_T})}$$





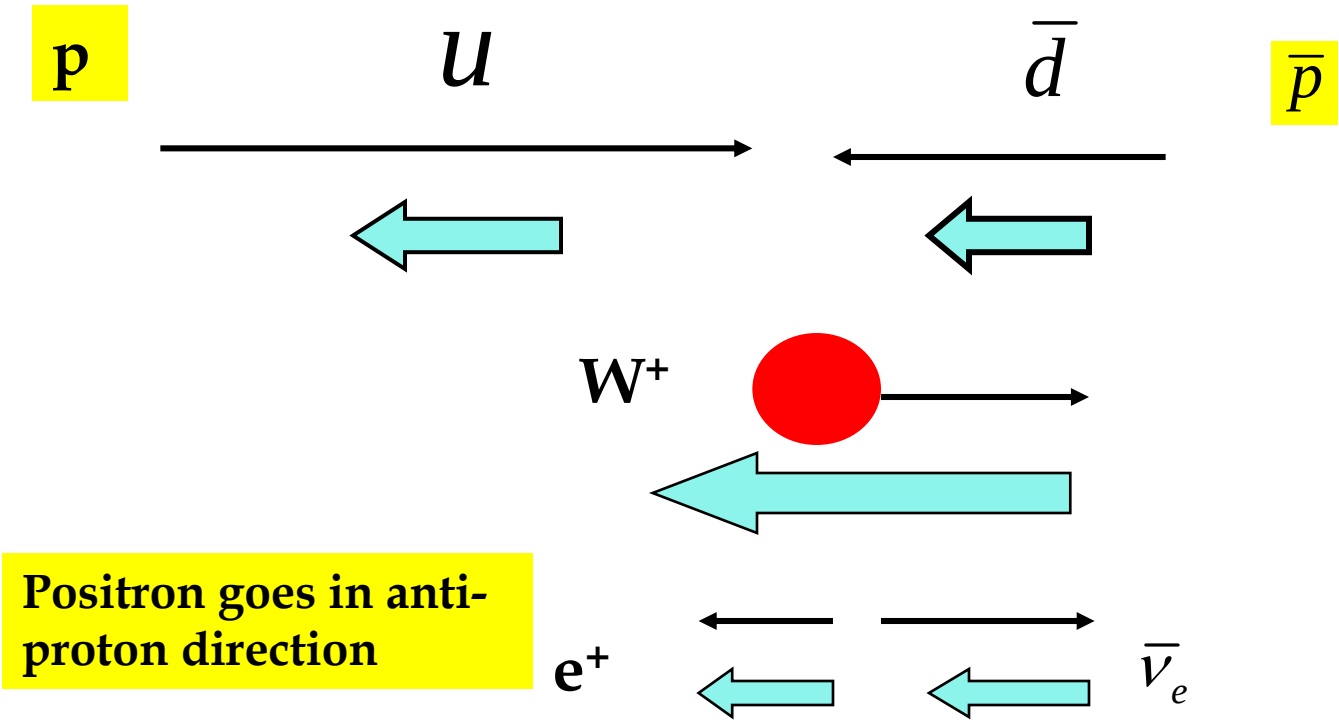
Very quickly the searches will be systematics dominated.

PDF u/d Ratio and W Asymmetry



At Tevatron, with valence quarks – since valence u is > valence d, the W+ goes in the p direction and the W- goes in the anti-proton direction. Sensitive to PDF valence distributions

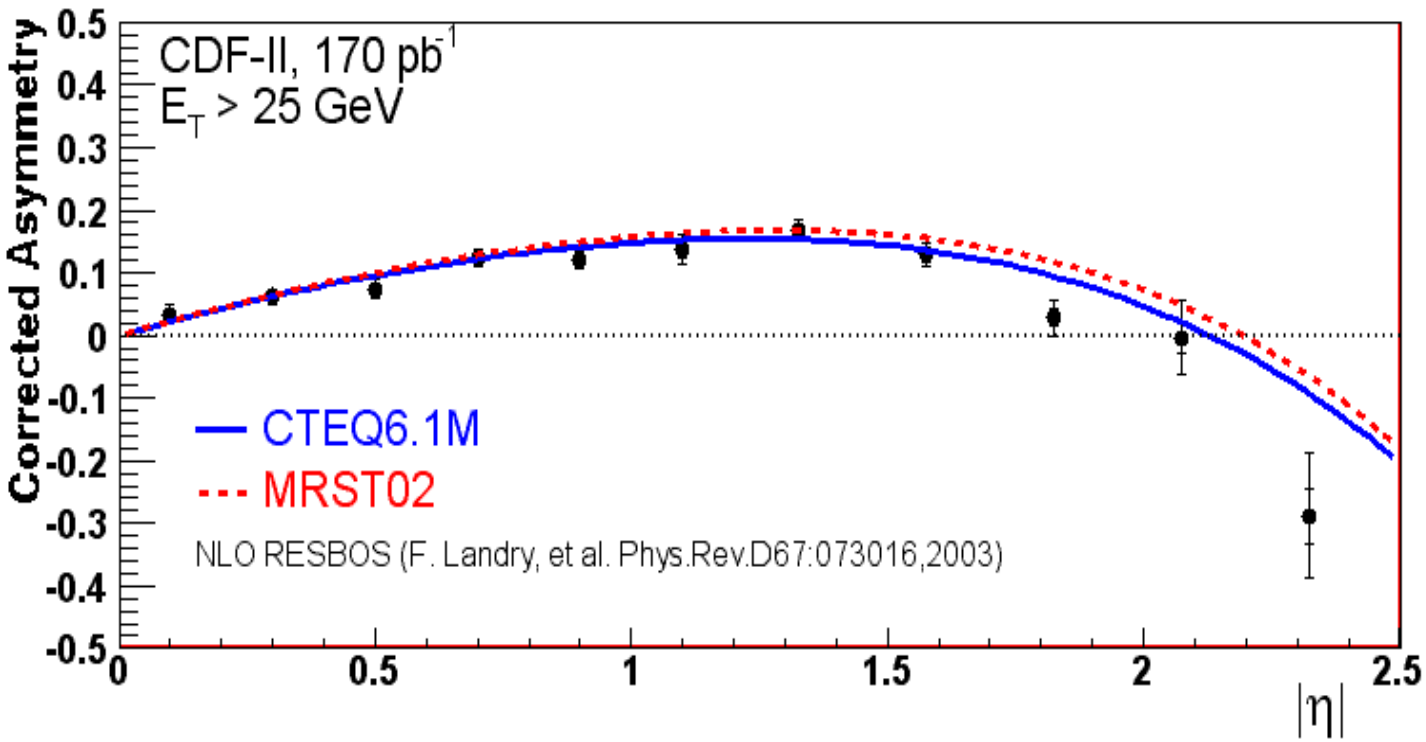
Lepton Asymmetry at Tevatron



Positron goes in anti-proton direction

We must simply assert that the V-A, parity violating, nature of the weak interactions makes light quarks and leptons, (u, d, e^-, ν_e in the first generation) left handed (negative helicity, where helicity is the projection of spin on the direction of the momentum) and the corresponding anti-particles, $\bar{u}, \bar{d}, e^+, \bar{\nu}_e$, right handed (positive helicity).

CDF – Lepton Asymmetry

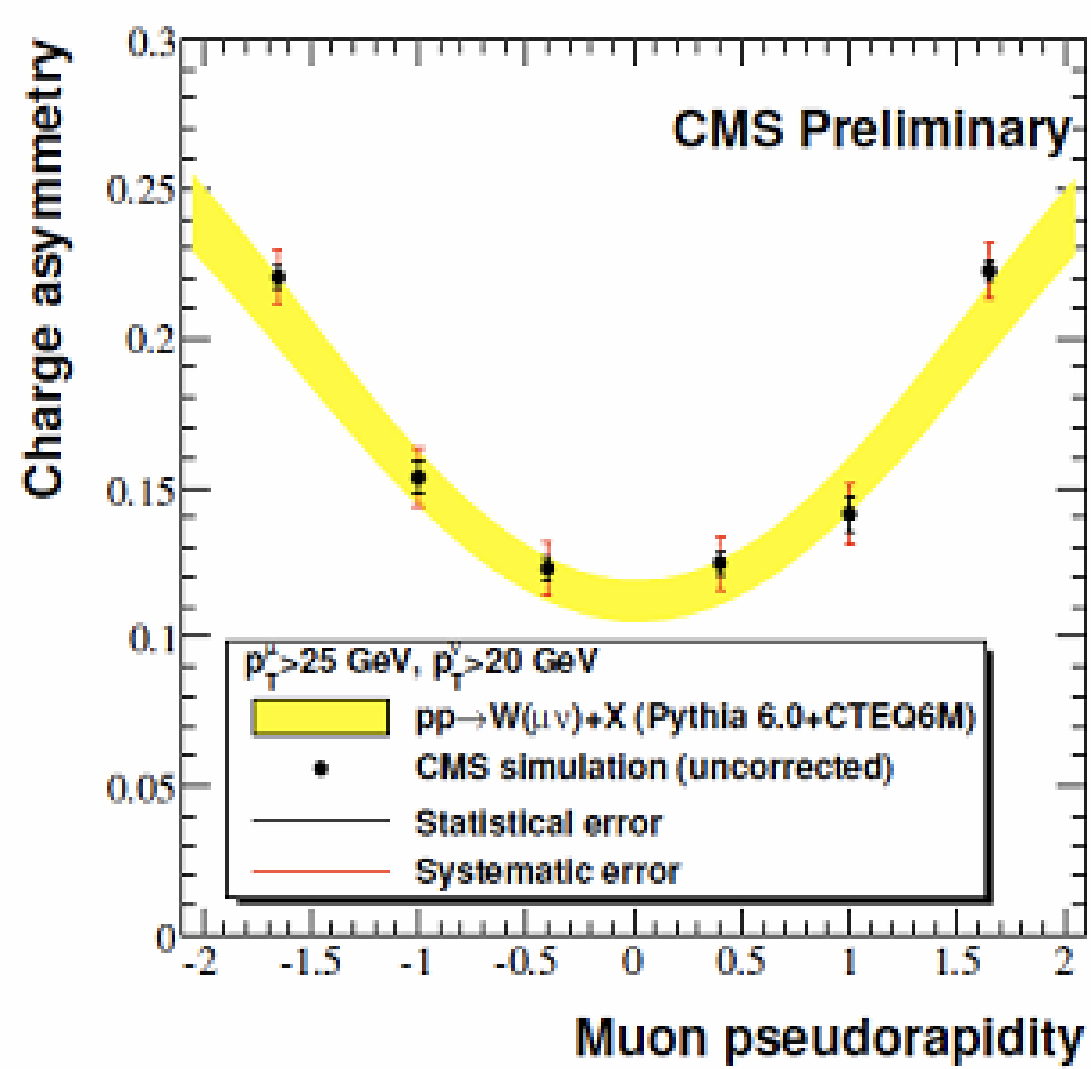


d/u ratio favors u ==> W+ in p direction

Positron goes in antiproton direction (lepton not W), electron goes in proton direction (2 competing effects)

➔ Charge asymmetry, constrains PDF (ratio – systematics robust)

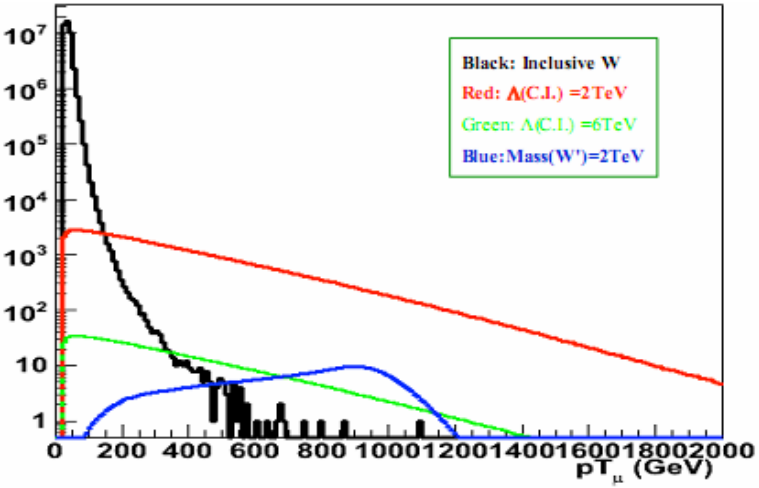
Muon Asymmetry at LHC



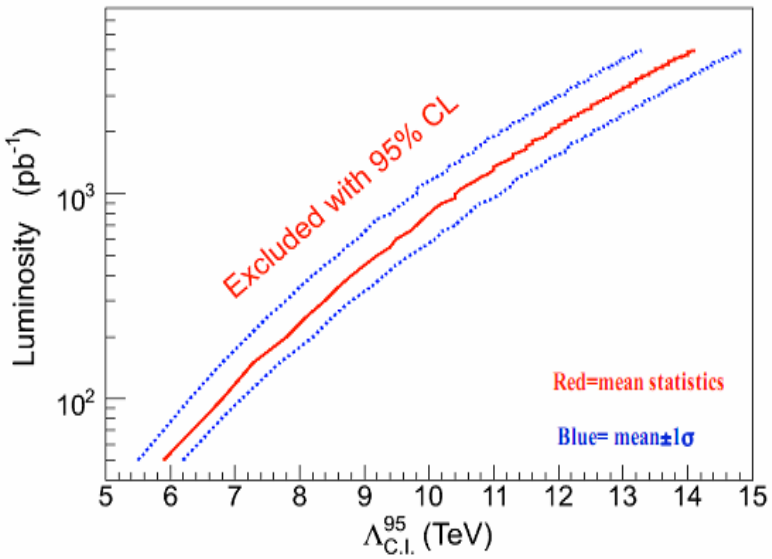
At LHC for 100 pb^{-1} begin to confront PDF uncertainties.

Backgrounds are small – QCD and D-Y.

Lepton Composites? Contact Interactions

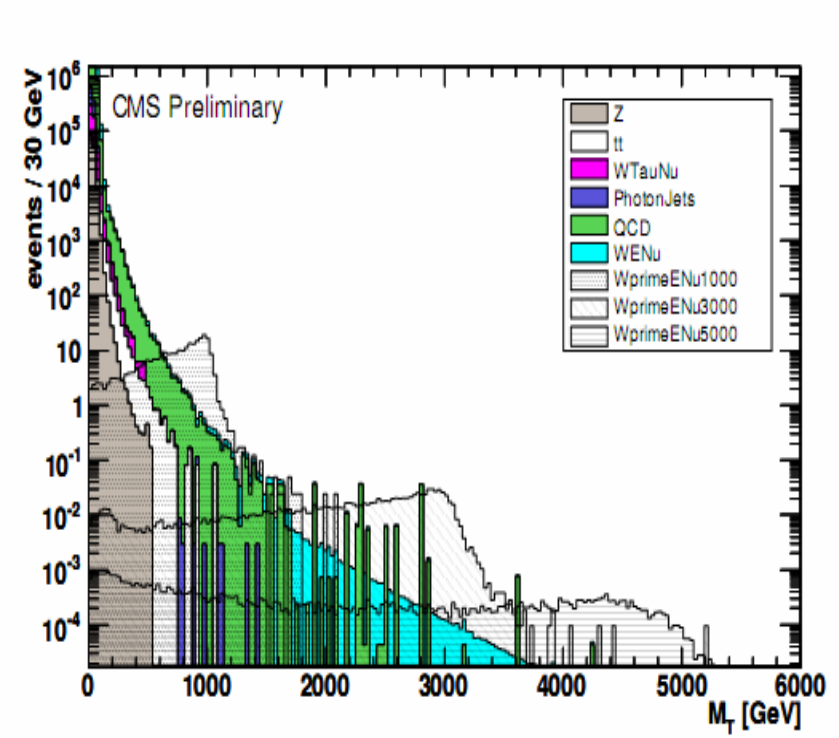


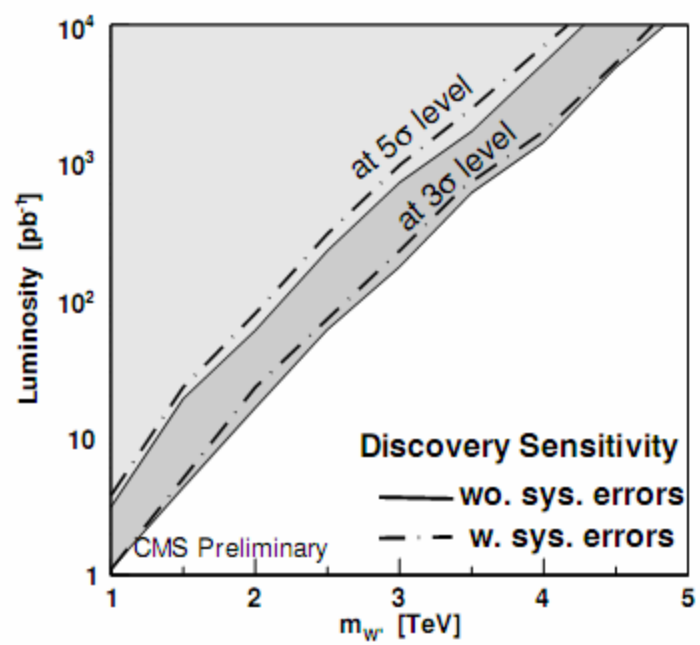
- Pythia6 in ROOT
- Helicity NonConserving (HNC) model



Once the W is established, look in the BW tail for discrepancies. Could be a resonance or a "contact interaction"

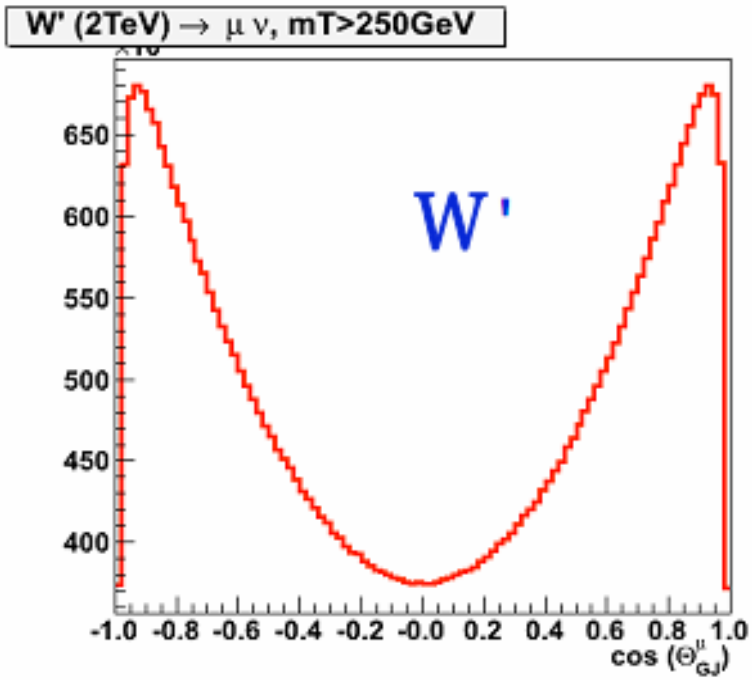
W' in BW Tail of the W?

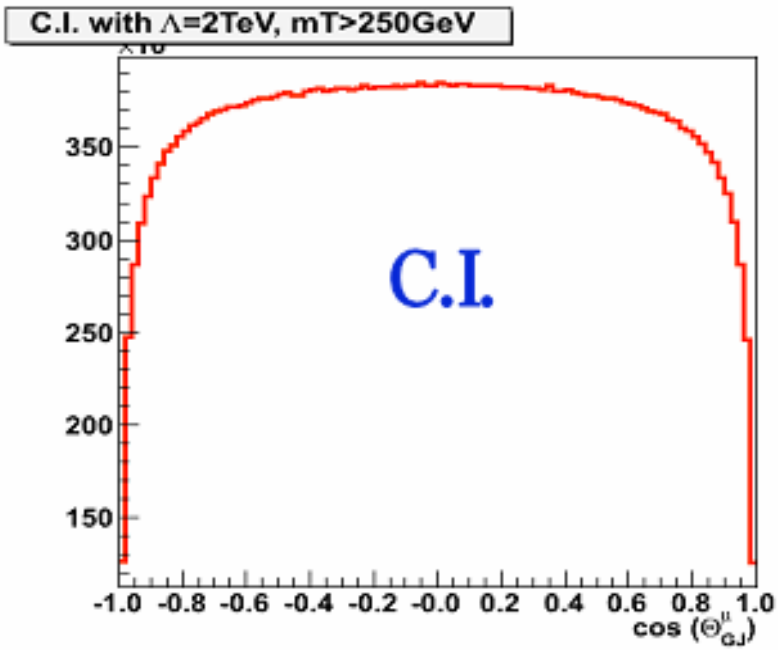




"Jacobean" peak for resonant W' is mass is accessible. Note the low mass tail due to FSR and due to PDF falling with x.

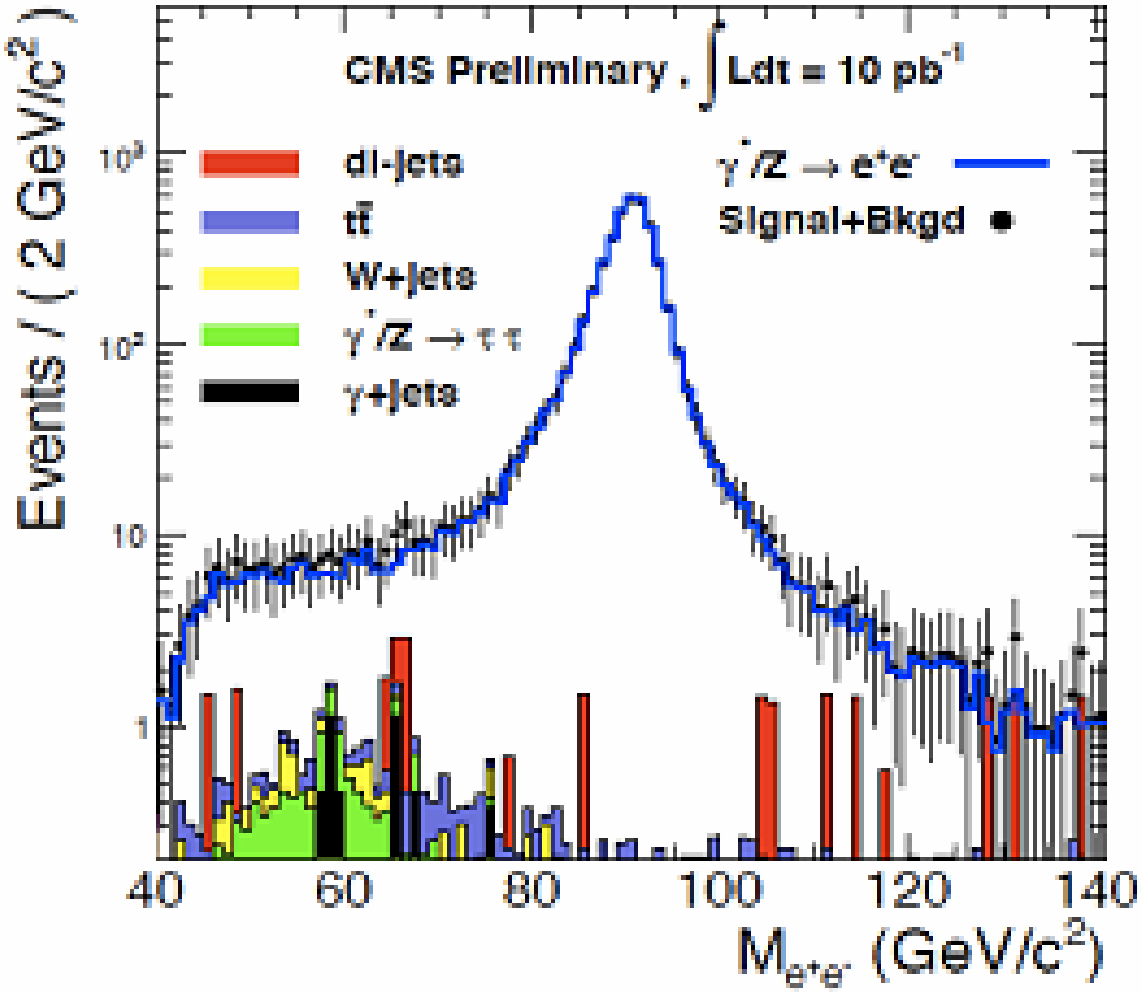
W' or Composite Lepton?





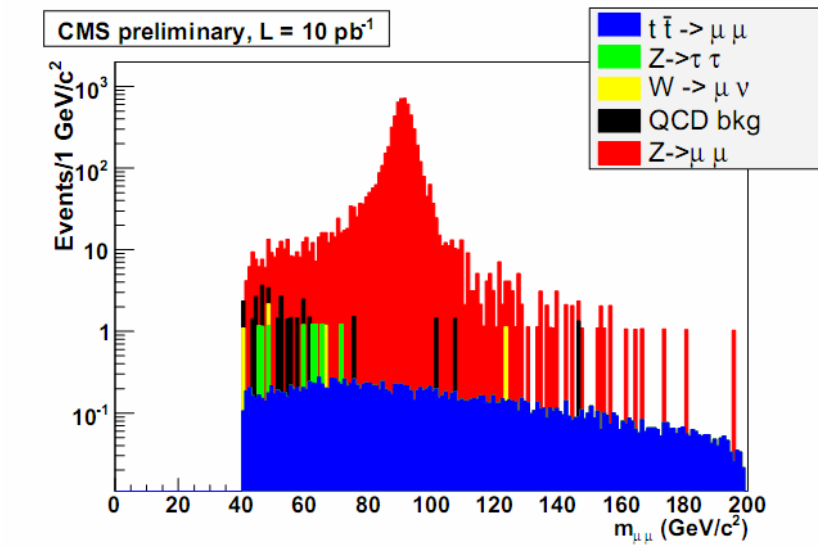
Must use the MET to reconstruct the W (quadratic ambiguity) . With parent u+v system, the decay angle can be reconstructed. This is a good discriminant.

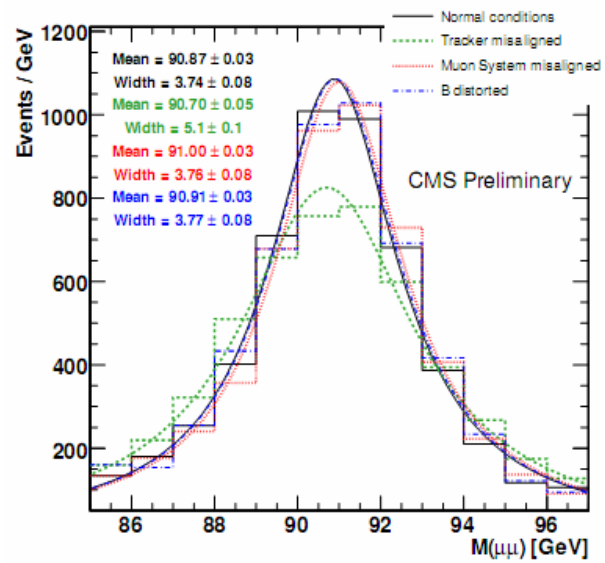
Z Decays into Electrons



The dilepton "tag and probe" – extract data driven efficiencies for leptons – e.g. e trigger efficiency. Backgrounds are small so purity for clean tagging is very high.

Z Production - Muons

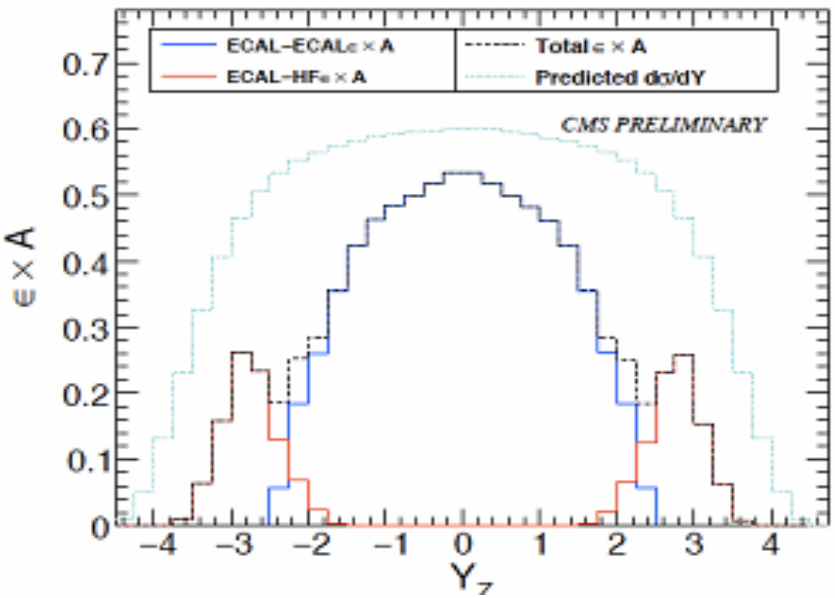


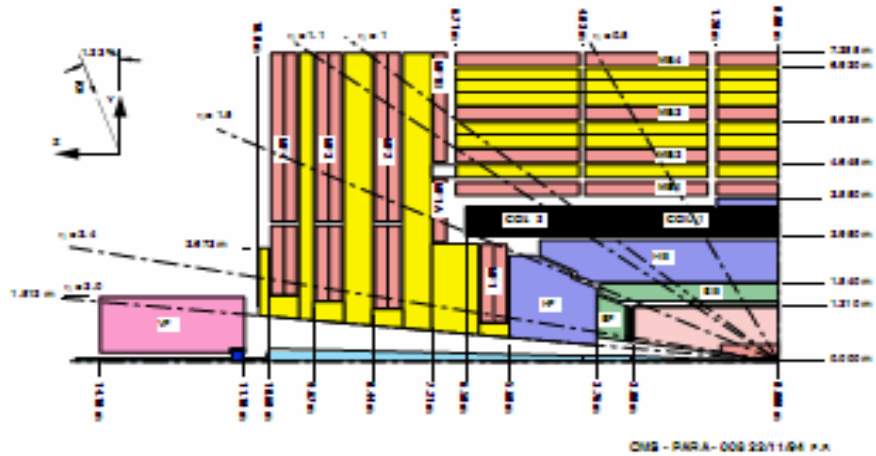


SM Z – check mass scale, Z resolution, width and FB Asymmetry. Use Z signal for "tag and probe" to get lepton efficiencies.

Using Forward Calorimetry

- Very unique technique: electron reconstruction with the CMS Forward Hadron(HF) detector, longitudinal shower information..



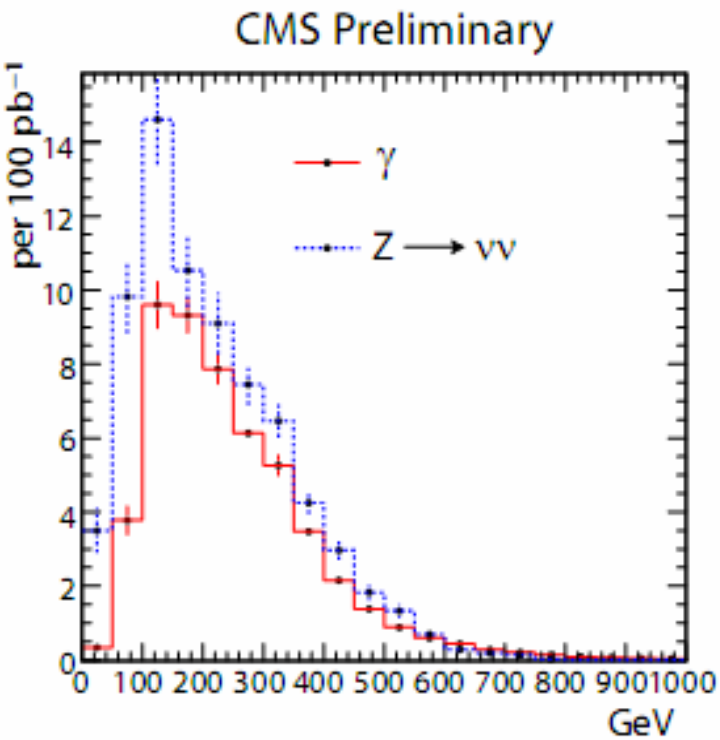


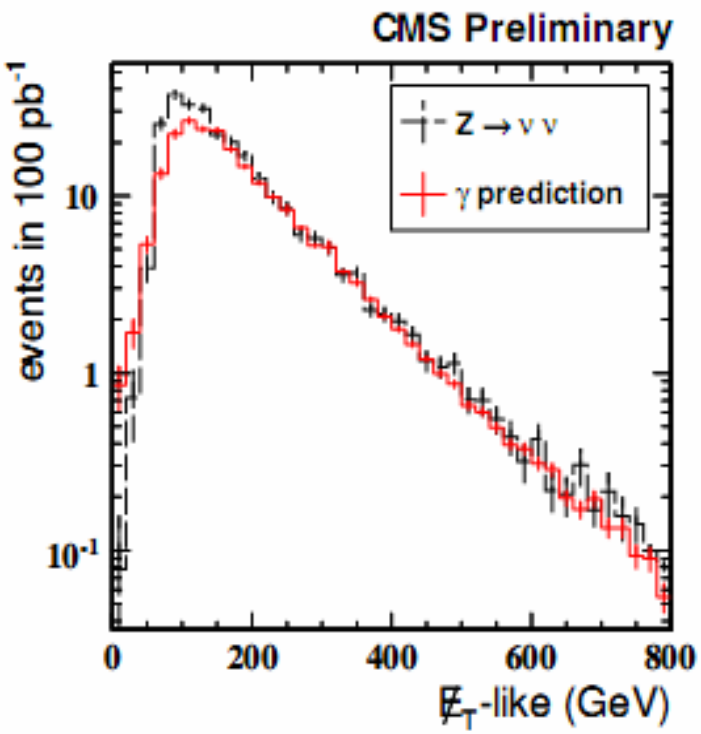
Largely extend the acceptance (rapidity from ~2.5 to ~4.0) →lower x in parton kinematics!

$$x_1 x_2 = M^2 / s$$

$$x_{1,2} = M / \sqrt{s}[e^{\pm y}]$$

Irreducible SM MET Background





Z -> v + v is irreducible. Use leptonic Z decay to estimate (low statistics) or use photon as a signal which is dynamically similar to Z.

Using Tracking in Jets

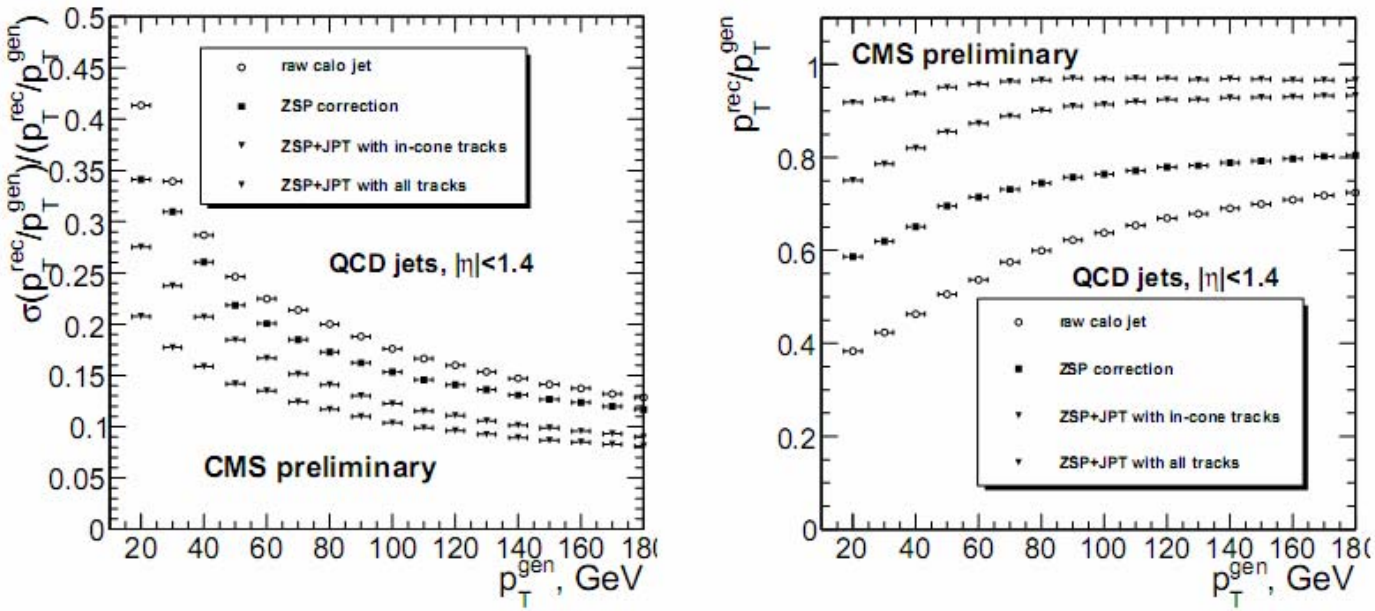
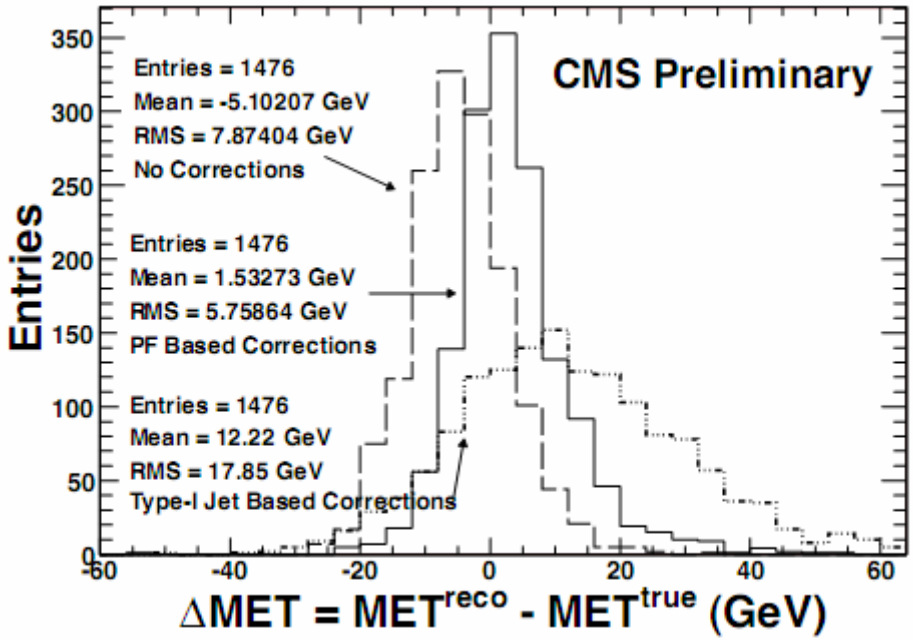


Figure 1: The transverse jet energy resolution (left) and JER (right) for raw calorimeter jets and for every step of algorithm described in sub-sections 2.1, 2.2 and 2.3.

Energy resolution can be improved using tracking by ~ 2 x at low jet energies. Linearity is also improved.

Missing Transverse Energy and PF



$$dP / P \sim P, \quad dE / E \sim a / \sqrt{E} \oplus b$$

Establish MET with SM processes: e.g. W leptonic decay, Z -> v + v and top decays. When validated use MET as a tool for probing new physics. Use particle flow and tracking information to improve MET resolution by ~ 2x.

EW Coupling of Fermions

$$Q = T_3 + Y/2$$

$$g_V^f = T_3/2 - x_W Q$$

$$g_A^f = -T_3/2$$

$$x_W = \sin^2\theta_W$$

$$g_A^u = -1/4 = -g_A^d = -g_A^e$$

$$g_V^u = 1/4 - 2x/3$$

$$g_V^d = -1/4 + x/3$$

$$g_V^e = -1/4 + x$$

$$g_V^2 + g_A^2 = 1/8[1 - 4|Q|x + 8Q^2x^2]$$

For EM processes, u quark dominates d by factor 4 in coupling. For EW processes, u and d quarks have ~ equal coupling strength.

Asymmetry at the Z depends only on known EW couplings. Prediction is quite solid at the LHC. In principle measure the Weinberg angle

Z Decays

- Off the Z peak there is a Z/γ D-Y interference.
- At the Z peak, the F/B asymmetry is non-zero due to EW P violation – V/A interference.

$$\alpha_{FB} \sim [g_V^\ell g_A^\ell][g_V^q g_A^q] / [(g_V^\ell)^2 + (g_A^\ell)^2][(g_V^q)^2 + (g_A^q)^2]$$

$$d\sigma / d\cos\theta \sim (1+\cos^2\theta) + 8\alpha_{FB}\cos\theta$$

- Integrating over the decay angles

$$\cos\theta > 0 - N_F,\ \cos\theta < 0 - N_B$$

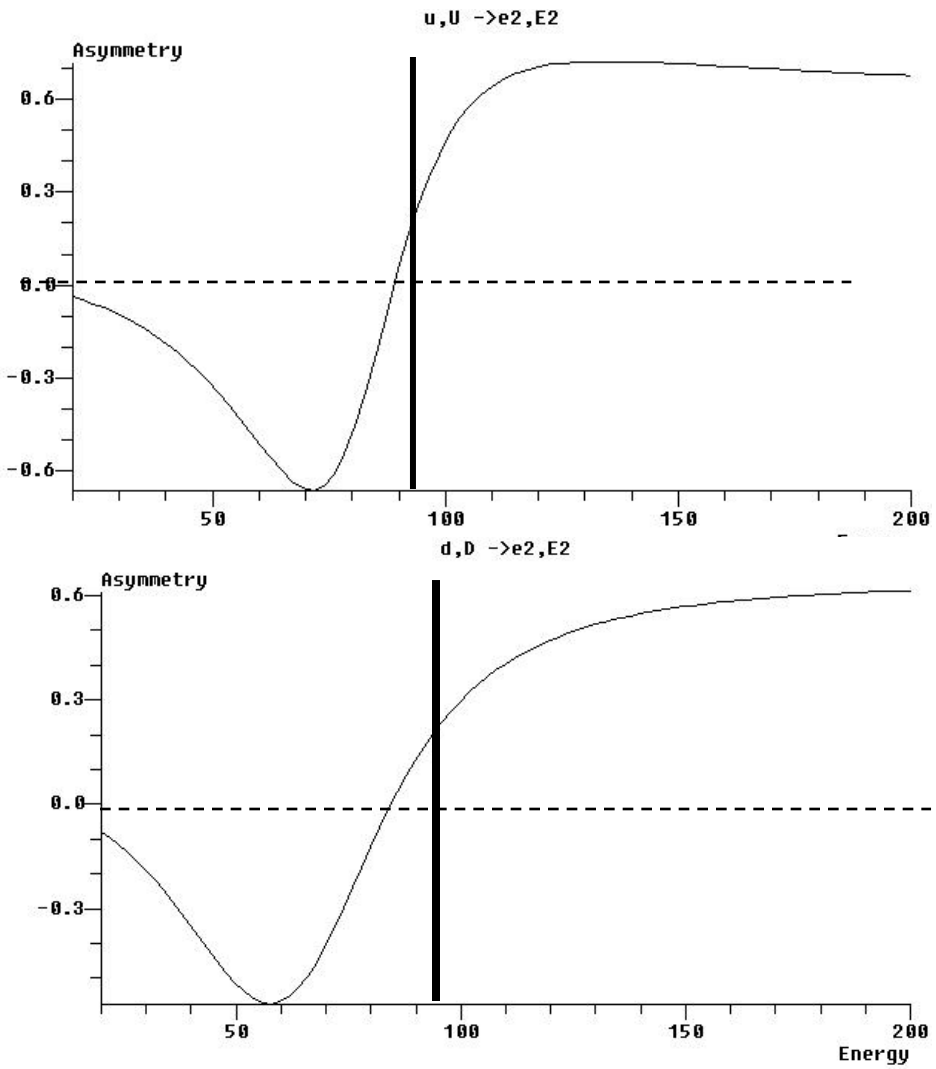
$$N_F = 4/3 + 4\alpha_{FB},\ N_B = 4/3 - 4\alpha_{FB}$$

$$A_{FB} = (N_F - N_B)/(N_F + N_B)$$

$$= 3\alpha_{FB}$$

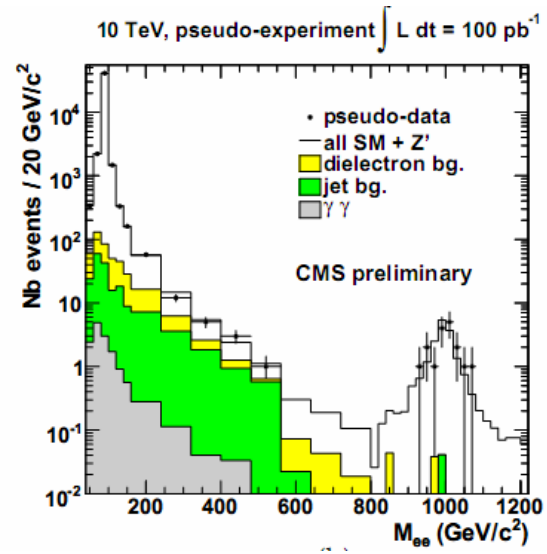
$$A_{FB}^u = 0.105,\ A_{FB}^d = 0.143$$

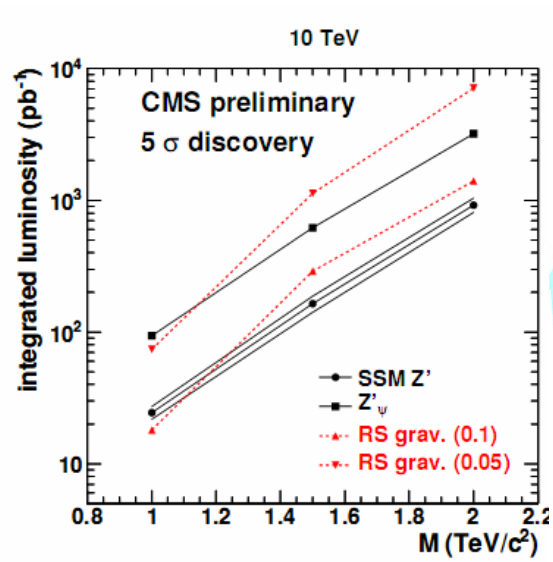
CALCHEP Asymmetry

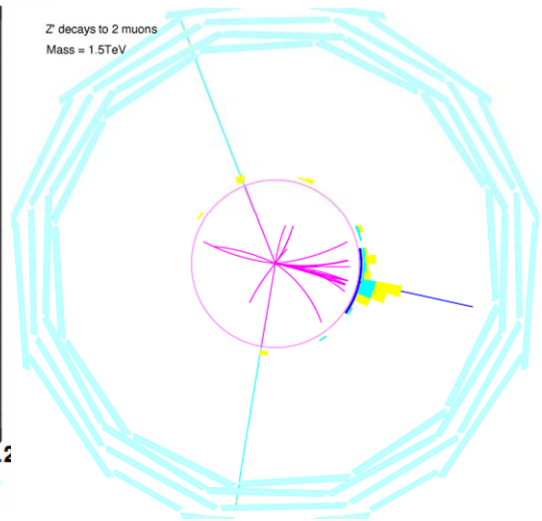


Asymmetries are large. The issue is that the LHC is a p-p collider and we need to find the direction of the quark and anti-quark. We ASSUME the quark is a valence quark and has higher momentum than the "sea" anti-quark. Take Z boost direction to be quark direction

Z' Search



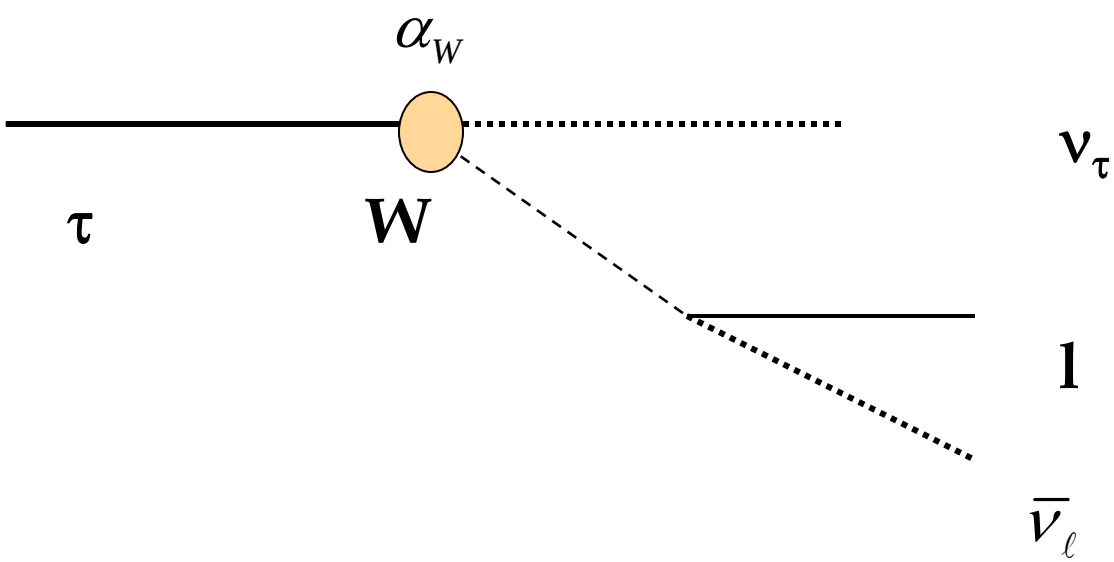




Having established Z decays into dileptons, (mass width, asymmetry, cross section), look in the BW tail of the Z for new physics. At 100 pb^{-1} start to probe the "terascale" – masses ~ 2 TeV.

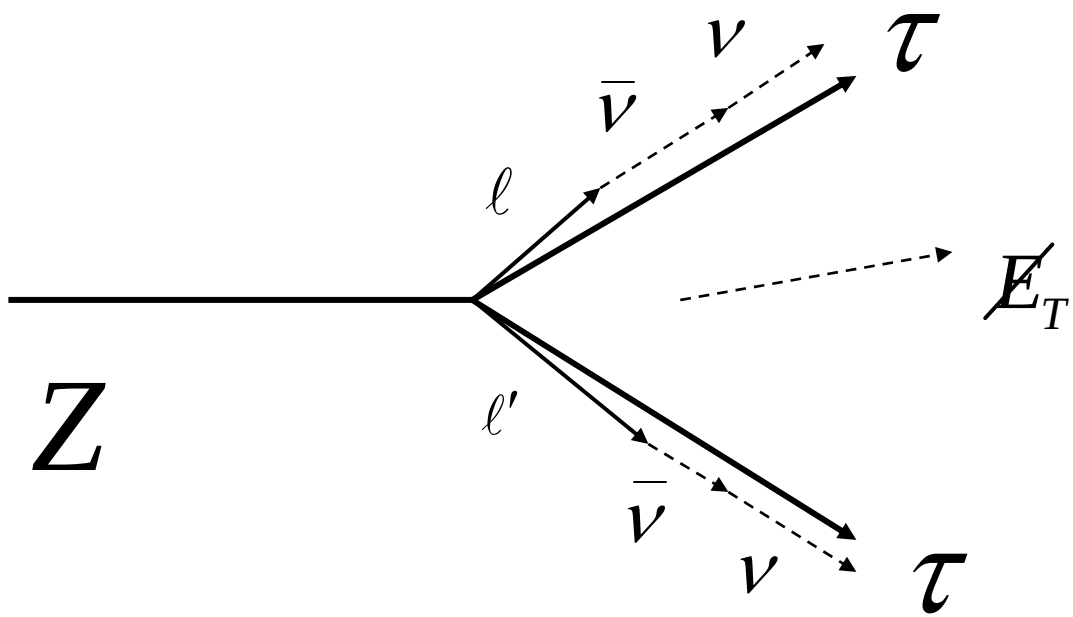
Establish tau in Z Decays

Z -> τ + τ decays as with muon and electron pairs.



Decays appear in dilepton trigger stream. BR is 35% for tau into muon or electron.

Z Decay to Tau Pairs - Collinear



$$M_{\tau\tau} \sim \sqrt{2(E_{\ell 1} + E_{\nu\nu 1})(E_{\ell 2} + E_{\nu\nu 2})(1 - \cos\theta_{\ell 1 \ell 2})}$$

$$METx = E_{\nu\nu 1}\alpha_{x\ell 1} + E_{\nu\nu 2}\alpha_{x\ell 2}$$

$$METy = E_{\nu\nu 1}\alpha_{y\ell 1} + E_{\nu\nu 2}\alpha_{y\ell 2}$$

SM "candle" for tau – third generation lepton important in many BSM scenarios.

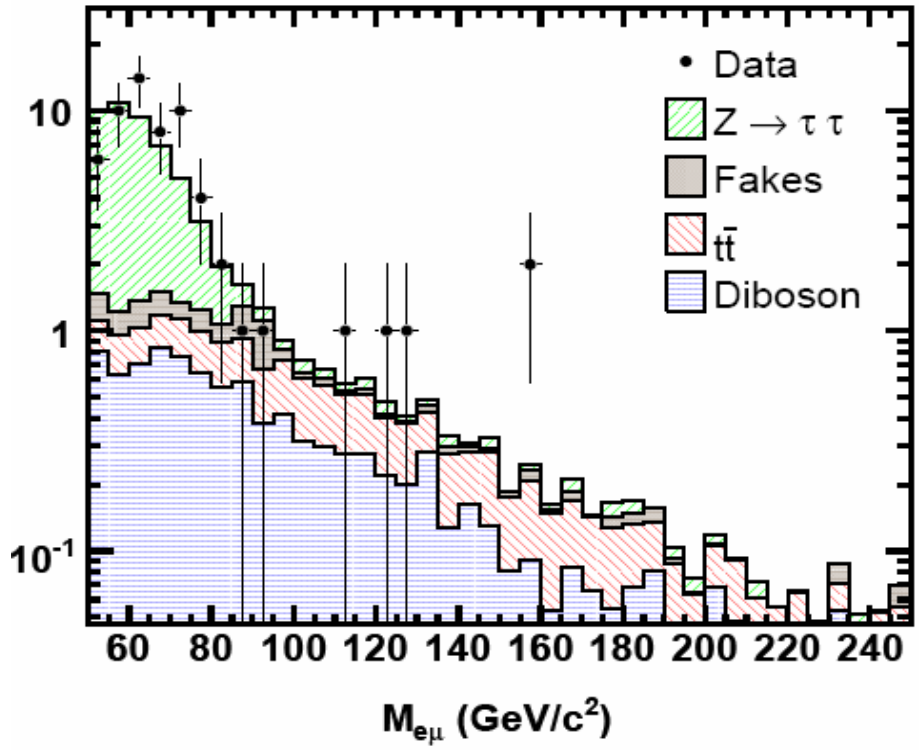
Assume collinear neutrinos. Then have 2 Eqs in 2 unknowns. Must cut on determinant

$$\det = \sin\theta_{\ell 1}\sin\theta_{\ell 2}\sin(\phi_{\ell 1} - \phi_{\ell 2})$$

|det|>0.005 is ~ 70% efficient after cuts on Pt of the leptons and MET.

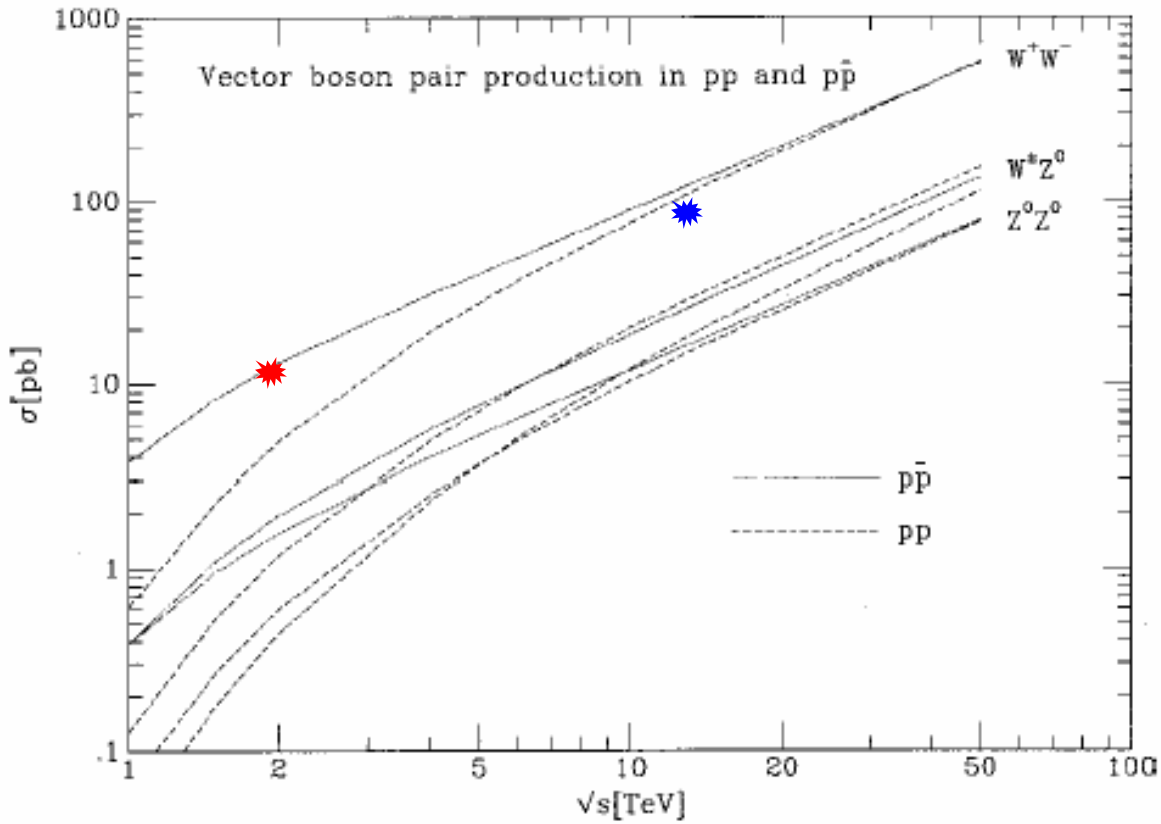
Di-lepton Search for Z -> $\tau + \tau$

Tevatron



Having established clean electron, muon and tau "objects" a look at di-lepton masses can be taken with some confidence. The top pair background dominates the dilepton mass spectrum at high masses - SUSY.

WW Cross Section Measured at CDF

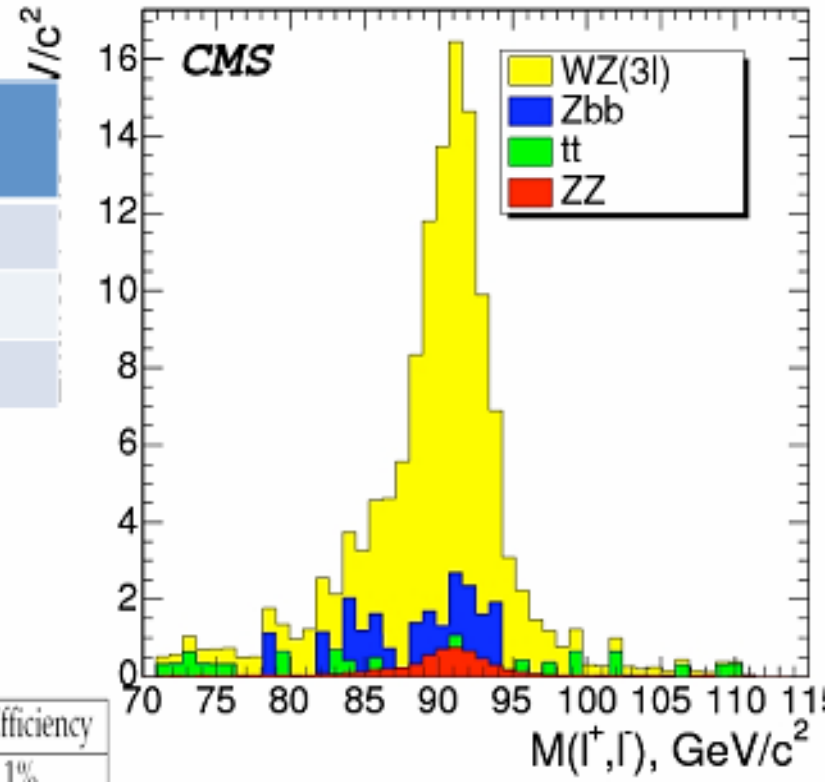


Extrapolate to LHC energy. COMPHEP gives a D-Y WW cross section at the LHC of 72 pb.

Combined Vector Bosons - WZ

"at least 1 lepton"

Channel	Xsect (14 TeV) (pb)	BR >1 e or mu	Events in 300 pb-1
WW	112	0.4	13k
WZ	48	.26	4k
ZZ	15	.12	0.5k



WZ with 3 leptons, 350 pb-1

	$e^\pm e^+ e^-$	$\mu^\pm e^+ e^-$	$e^\pm \mu^+ \mu^-$	$\mu^\pm \mu^+ \mu^-$	Total	Efficiency
$W^\pm Z^0 \to \ell^\pm \ell^+ \ell^-$	14.8	26.9	28.1	27.0	96.8	6.1%
$Z^0 Z^0$	0.63	1.54	1.50	1.51	5.18	4.7%
$t\bar{t}$	0.93	1.55	-	0.31	2.79	0.02%
$\mu^+\mu^- b\bar{b}$	-	-	6.54	4.9	11.4	0.005%
$e^+e^- b\bar{b}$	1.21	1.82	-	-	3.03	0.005%

Combined Vector Bosons - WW

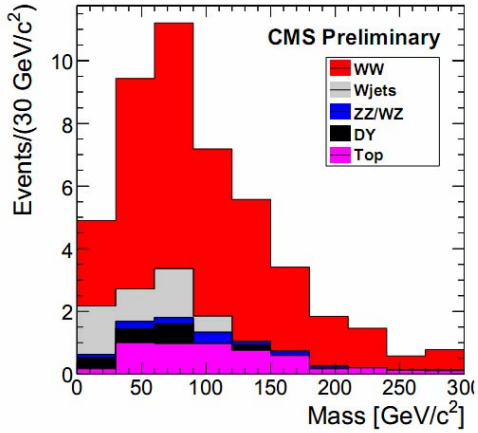


Figure 4: Dilepton mass distribution for the final event selection scaled to 100 pb^{-1} of integrated luminosity

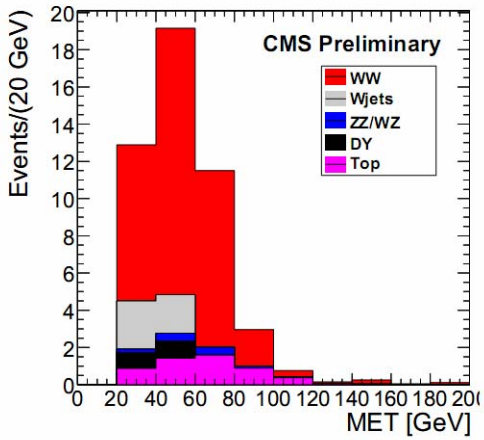


Figure 5: Missing transverse energy distribution for the final event selection scaled to 100 pb^{-1} of integrated luminosity

No Z peak in this case. Backgrounds from single W, VV, DY and Top. Clear signal for 100 pb^{-1}. Start to study V-V scattering at the LHC

Technicolor in WZ?

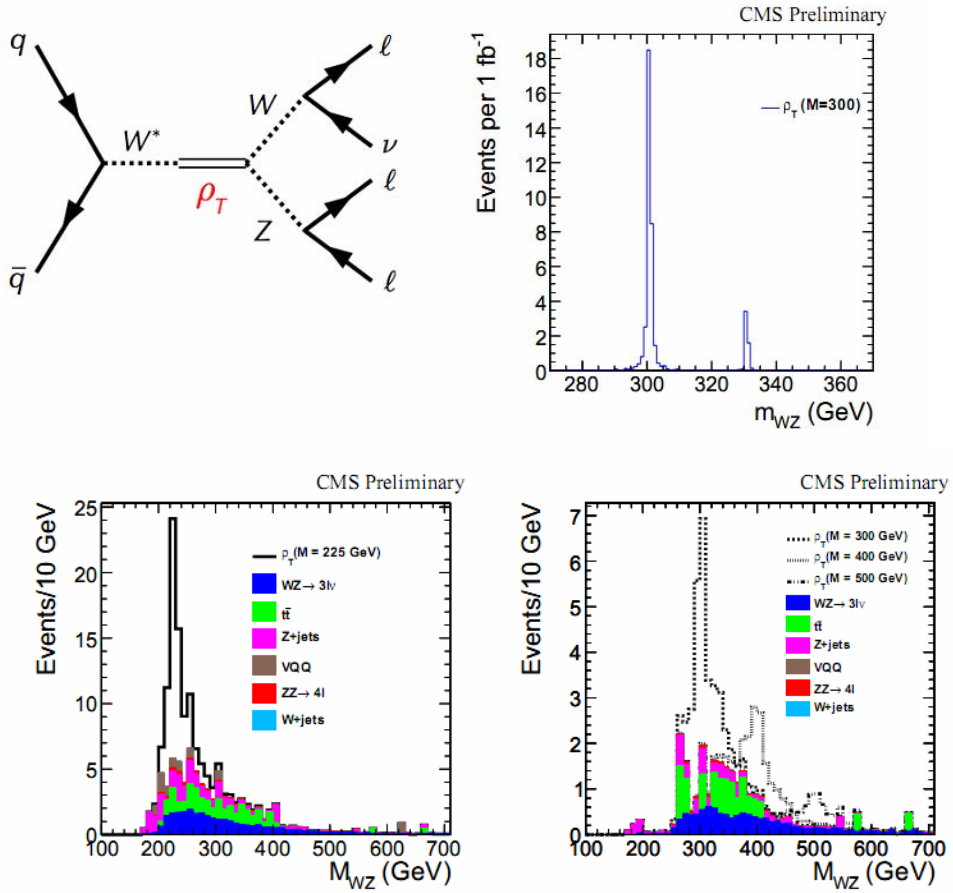


Figure 14: WZ invariant mass distributions for signal ($\rho_T = 225$ GeV) and background samples (left). WZ invariant mass distributions for signal (ρ_T in the range 300–500 GeV) and background samples (right). The distributions are normalized to an integrated luminosity of 1 fb^{-1} in order to improve visualization.

The Higgs is a hypothesis not a fact . Higgs could be a dynamical object - top pair , deeply bound condensate in analogy to superconductivity – from Landau-Ginzberg to Cooper pairs. New force for binding, technicolor. Find strongly interacting bound states.

Top Dileptons

Top dileptons

No b tagging
10 pb^{-1}
14 TeV
CMS

2 iso l $P_T > 20$
2 jets $P_T > 30$
$|M_{ee,\mu\mu} - M_Z| > 15$
$MET > 30$
$MET > 0.6|\vec{P}_T^{ll}|$ or MET not along $-\vec{P}_T^{ll}$

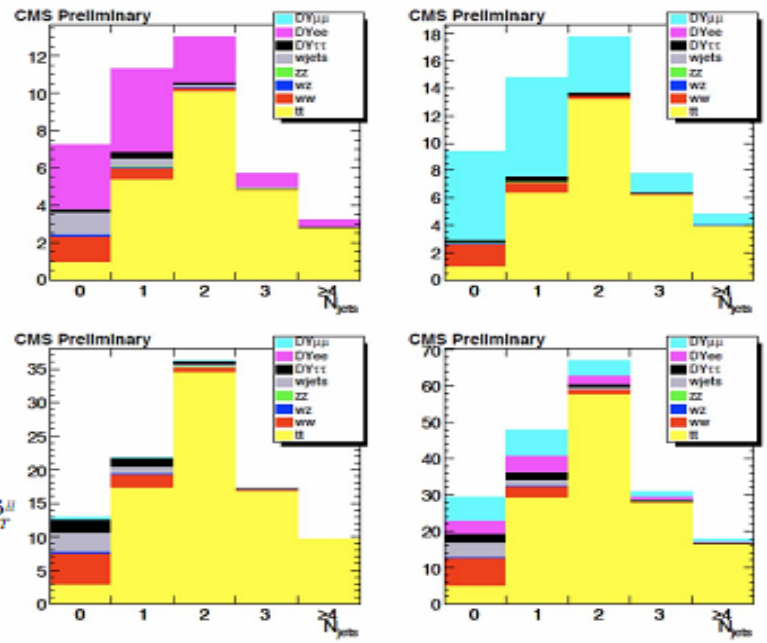
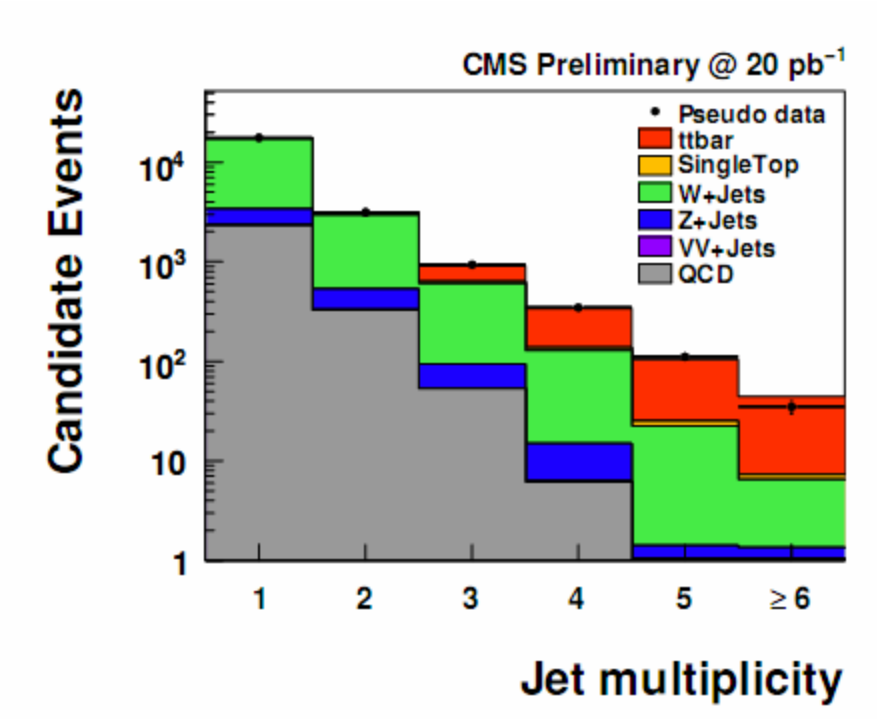
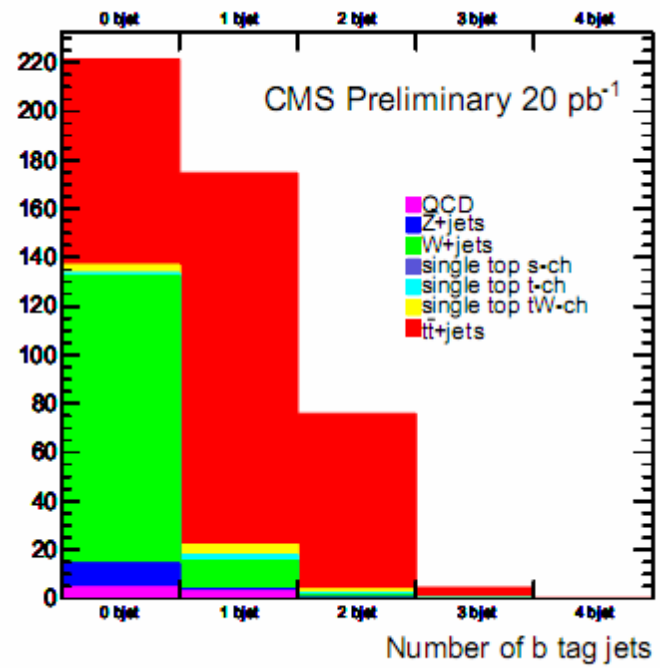


Figure 2: The expected number of dilepton events in 10 pb^{-1} as a function of jet multiplicity in ee (top left), $\mu\mu$ (top right), $e\mu$ (bottom left), and all channels combined (bottom right). The figures show contributions from $t\bar{t}$ (yellow), WW (red), WZ (dark blue), ZZ (green), W+jets (gray), DY→ $\tau\tau$ (black), DY→ ee (magenta), and DY→ $\mu\mu$ (cyan).

Establish top pair SM signal in dilepton final state – clean but low statistics. Top has SM "candle" with leptons, jets, MET and b jets.

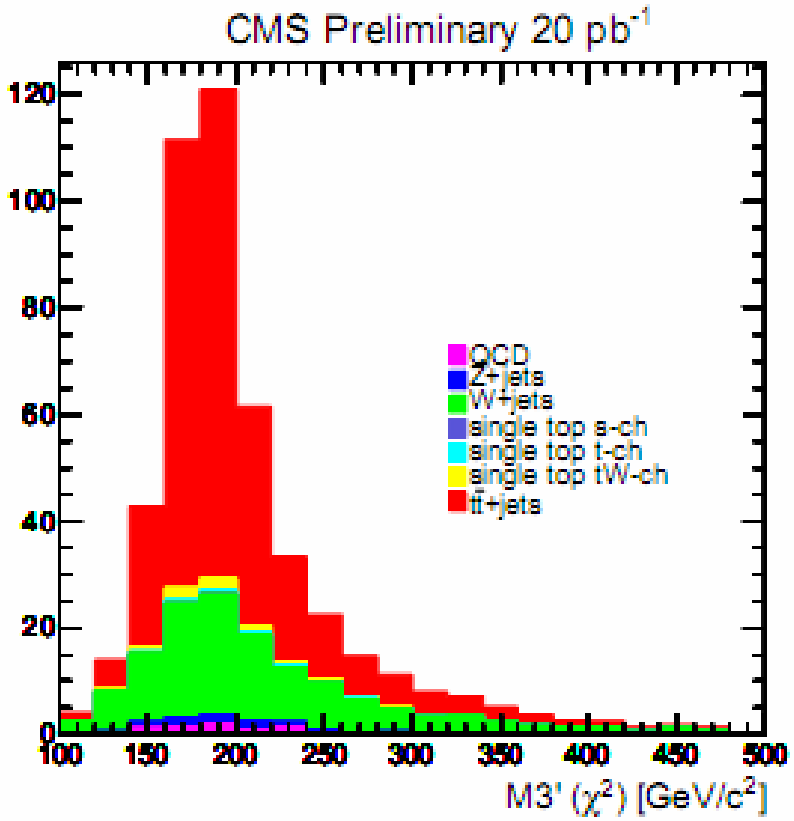
Top – Single leptons





Ask for a lepton plus jets. Background from W+nJ is largest. If b tags available early, then S/B will be quite small.

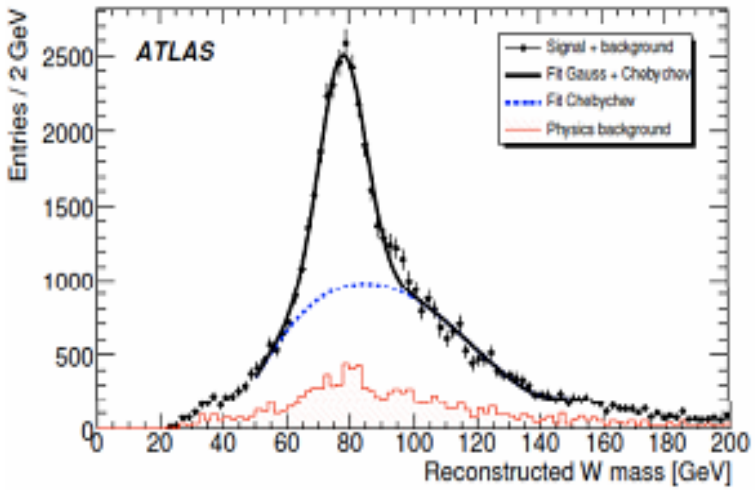
Reconstructed Top Mass



Check jet energy scale with hadronic decay of the W. Check b tag efficiency with 2 b in final state. Establish MET scale. Top is a very useful SM "standard candle"

Jet Energy Scale from W in Top

Light Quark calibration



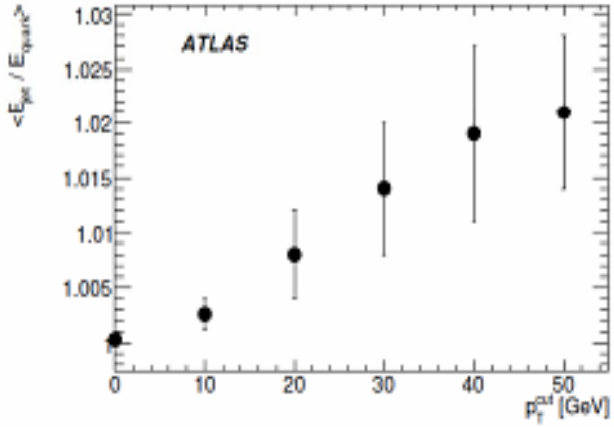
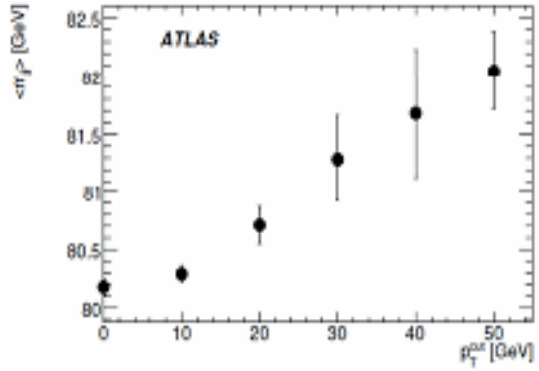
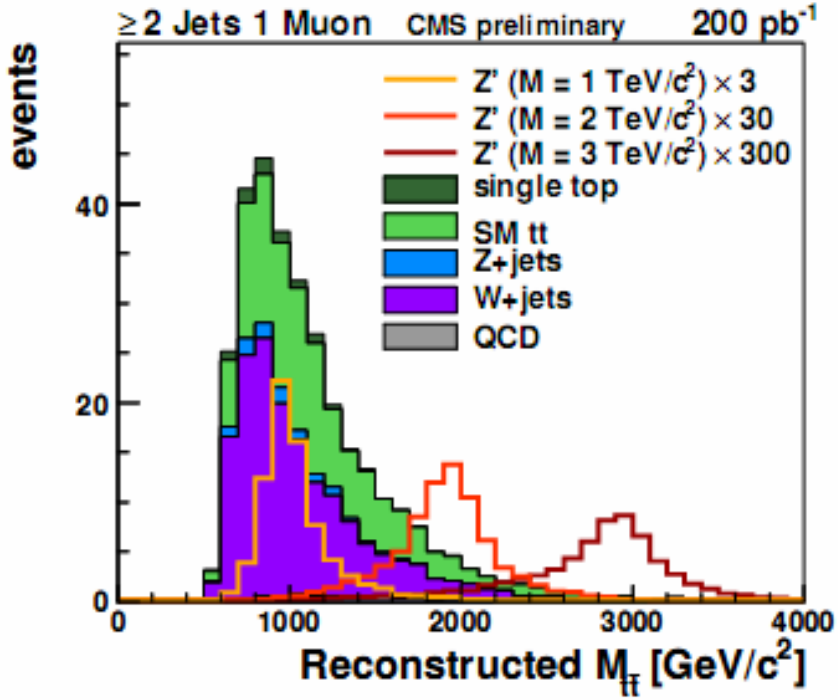


Figure 12: structed jet 20%. This



Z' in Top Pairs?



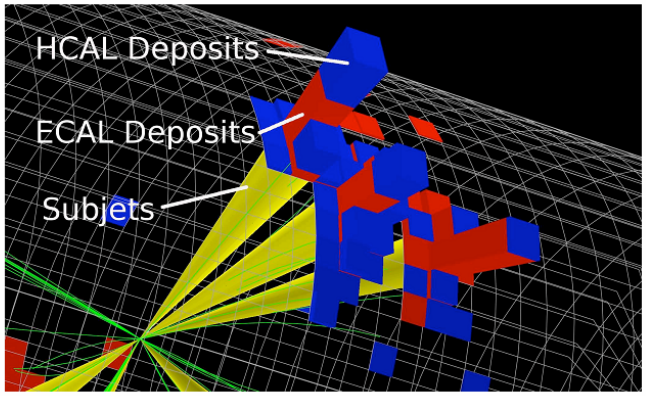


Figure 1: Reconstructed top-quark jet in cylindrical view with $p_T = 800$ GeV/c. The cones represent the subjets. The HCAL and ECAL deposits, and the subjets are indicated on the figure.

Many new physics models have resonances decaying to top pairs. At high mass the top decay products merge into a single jet. Need to develop tools to discriminate between a QCD jet and a top jet -> b + W -> b + u + d.

Problems - II

1. Find the W and Z branching ratios using Calchep and W->2*x, Z->2*x
2. Find the cross section for u+U->A+A. Compare to Figure in the lecture.
3. Evaluate the p+p cross section of top pairs as a function of CM energy.

LI – formalism and introduction
LII – rediscover SM -> LIII Higgs → LIV – SUSY ED etc…