Physics Analysis

Bing Zhou

The University of Michigan

CCAST Workshop @Tsinghua University

Nov. 6-10, 2006

Outline

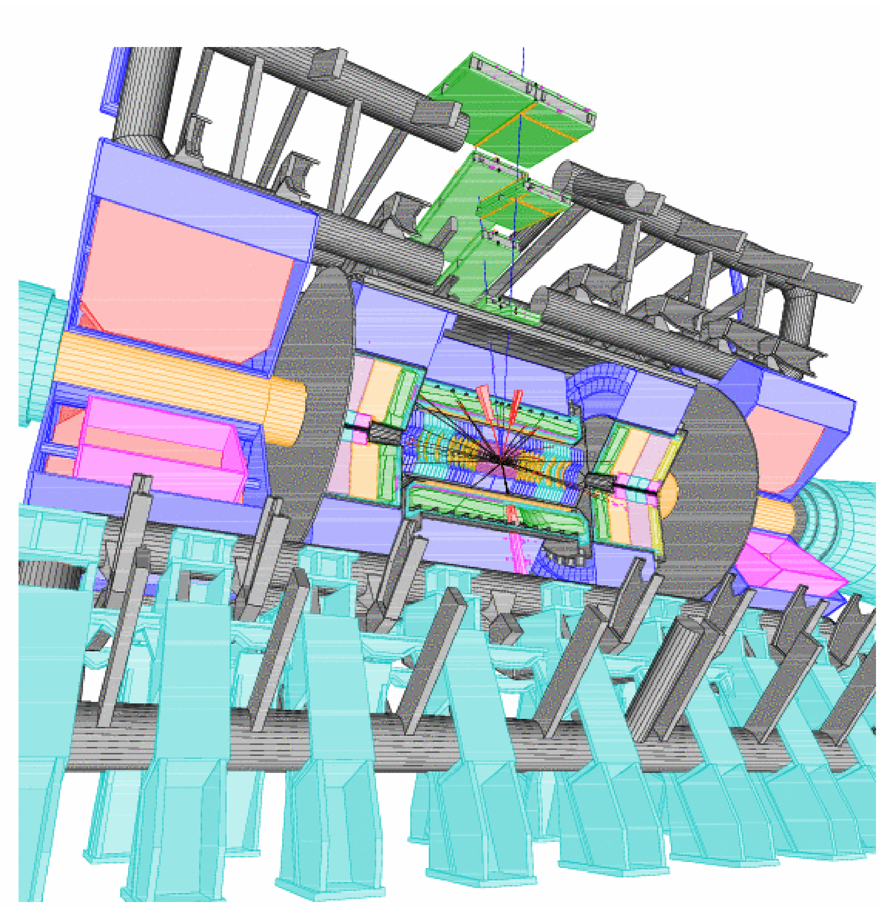
- Collider physics analysis basics
- Monte Carlo Tools
- Physics Objects Reconstructions
- LHC Physics potential of ATLAS, CMS

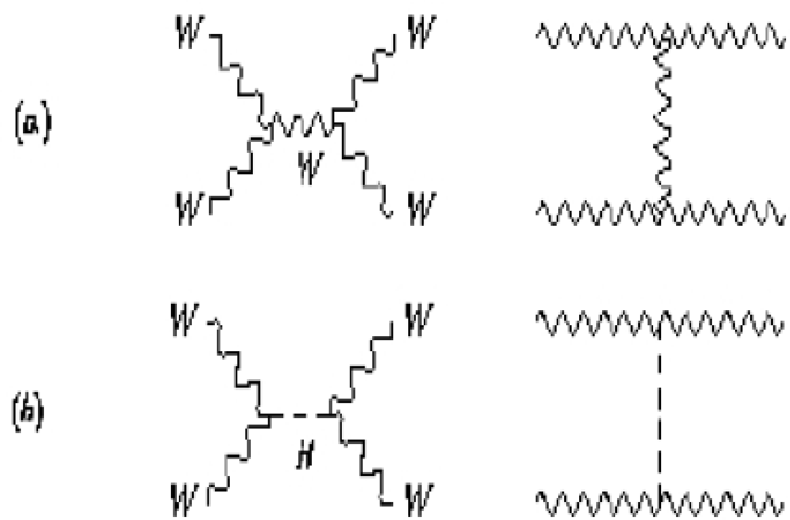
Basics

- Hadron Colliders - especially those that allow access to a new energy regime – are machines for discovery
  - In the case of the TeV scale, this is reinforced by the fact that the know SM forces and particles violate unitarity at ~ 1 TeV: there must be some thing new (if only a SM Higgs)
- Discovery means producing convincing evidence of some thing new.
- New physics models: produce visible new phenomena
- Goals of analysis in this case: produce the evidence"
  - Separation os a signal from the background
  - Need to show that the probability of the 'signal' from known sources is small
    - **Must demonstrate that the backgrounds are well understood**
    - **Uncertainties: statistics and systematic**

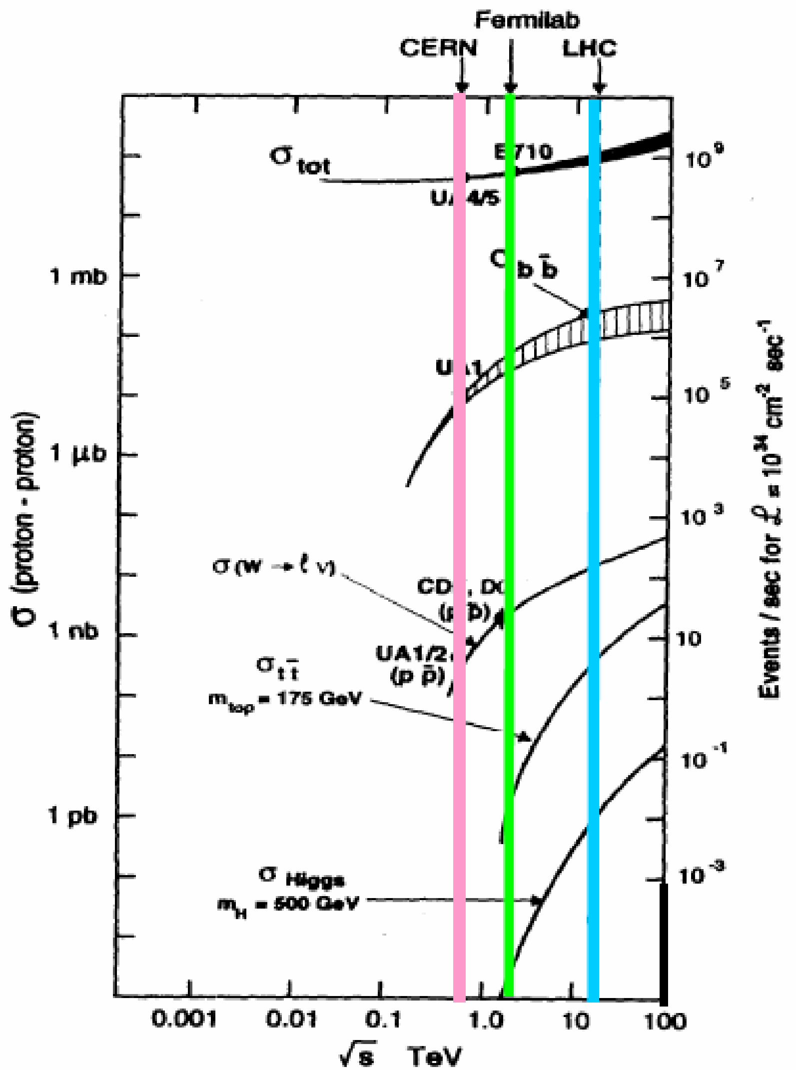
Physics Analysis Goal

Translate from measurement To Physics process



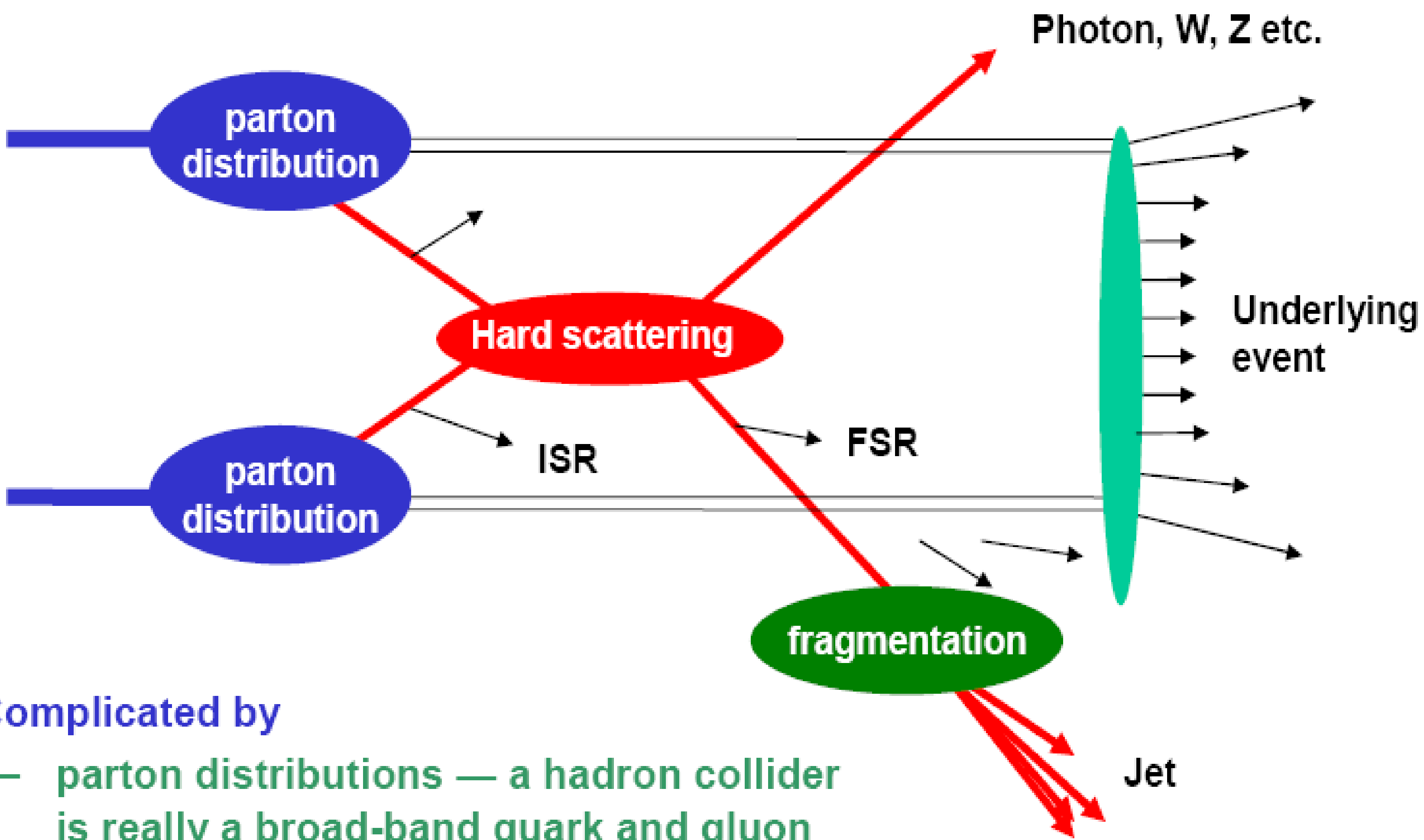


Collider Basics: Cross section



- Rates Determined by:
  - Hard Scattering σ
  - Parton Luminosity
- QCD Processes Dominate
  - EW rates lower by α / α_{strong}
- Cross Sections Decrease Rapidly with s
  - Heavy particles difficult to produce

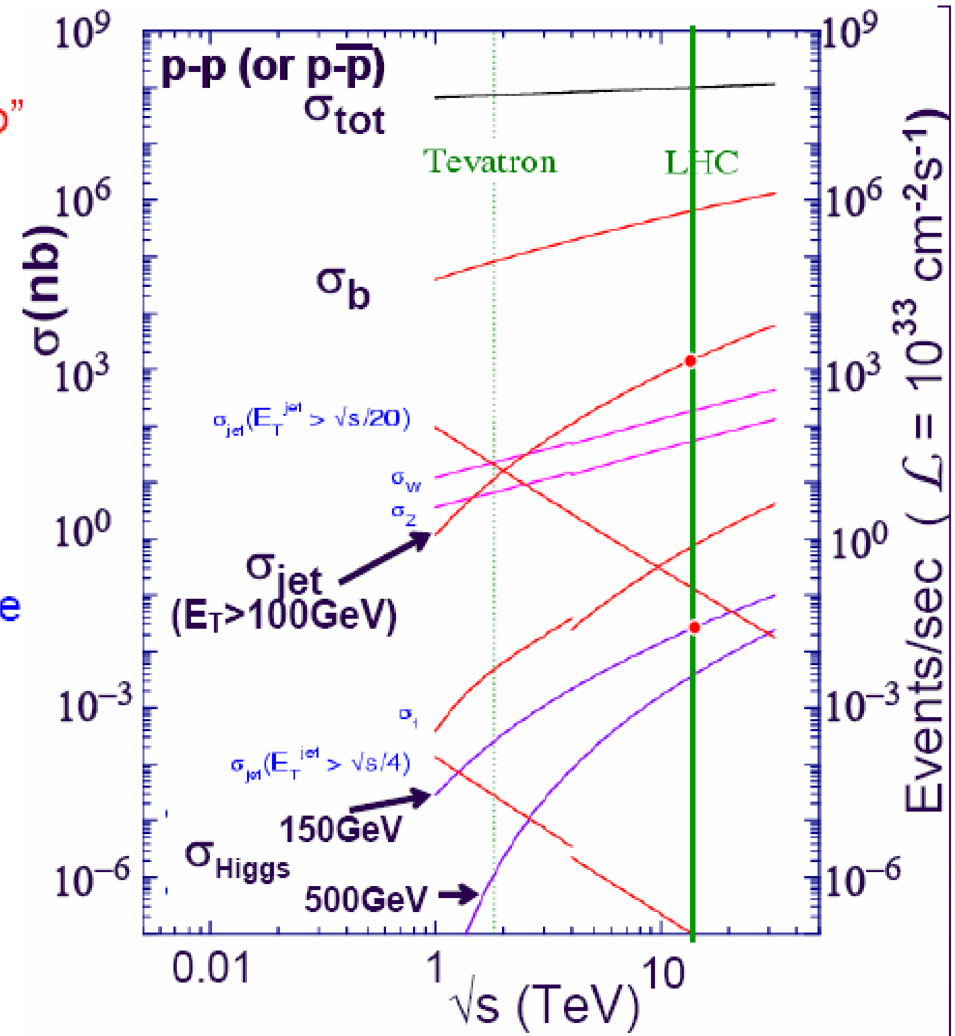
Basics: Hadron Collision Processes



- Complicated by
  - parton distributions — a hadron collider is really a broad-band quark and gluon collider → different from e+e- collisions

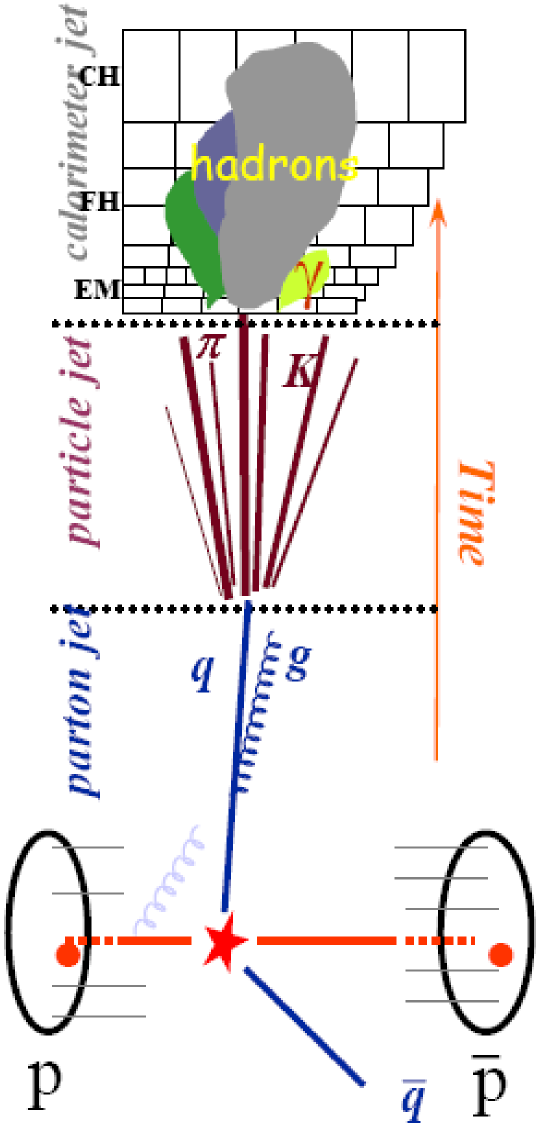
Implications at LHC

- Something happens every crossing
  - 25 inelastic evts/crossing at 10^{34} "Pile-up"
- Must Select Events of Interest: Trigger
  - Must know what you've thown out
  - Analysis must be trigger-aware
- Jets Dominate Hard Scattering Rate
  - Can isolate EW processes only they have something besides jets, eg leptons
  - Potential source of bckgnd "Fakes"
  - Detector mis-measurements can induce false signals
- W, Z: Bckgnd for Top, Higgs, SUSY



Simulation Tools

- A "Monte Carlo" is a Fortran or C++ program that generates events
- Events vary from one to the next (random numbers) — expect to reproduce both the average behavior and fluctuations of real data
- Event Generators may be
  - parton level:
    - Parton Distribution functions
    - Hard interaction matrix element
  - and may also handle:
    - Initial state radiation
    - Final state radiation
    - Underlying event
    - Hadronization and decays
- Separate programs for Detector Simulation
  - GEANT is by far the most commonly used



Event Generators

- LO: **Pythia, Herwig** (include hardronization and ‘soft jets’)
- ‘Underline’ -- **Jimmy**
- Improved generators (NLO)
  - **MCFM, RESBOS, ALPGEN:** these go beyond the PYTHIA/HERWIG models and include real matrix element calculations. They are being improved today.
  - **MC@NLO, CKKW:** generate inclusive jets at NLO
  - **MadGraph/MadEvent, WhiZard/O'Mega, Sherpa/Amegic++ :** these are very complete and sophisticated event generators for MSSM processes.
    - spin amplitudes!
    - efficient generation of codes for reduced CPU load
    - multi-channel adaptive sampling of phase space
    - structure functions for incoming partons
    - interface to, e.g., PYTHIA for hadronization (Sherpa does this itself)
    - These three programs have been shown to agree! (hep-ph/0512012)

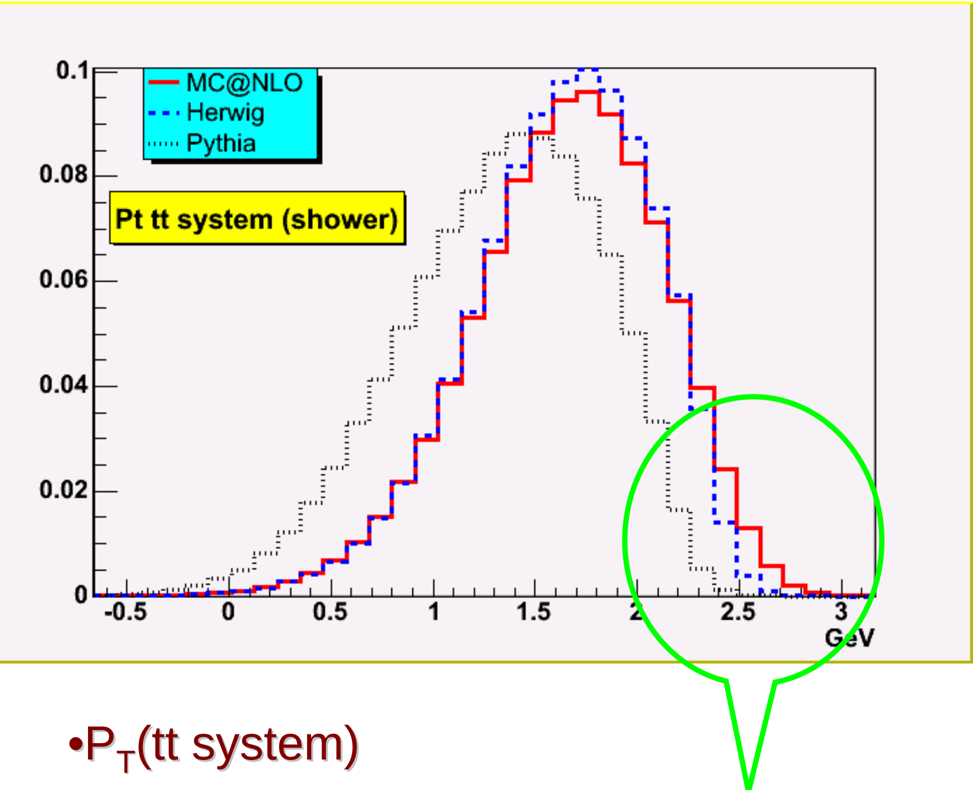
How Much Can We Trust MC

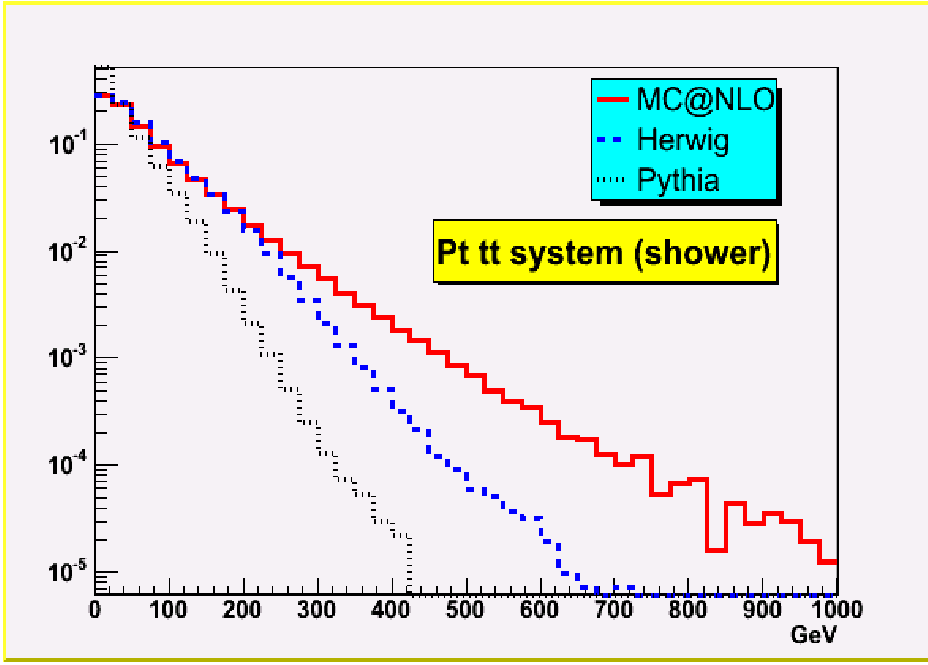
- PDF and Underline modeling need data to fit
- Event generators
  - May or may not generate additional jets through parton showering
  - May or may not treat spins properly
  - May or may not get the cross section right
    - NLO much better than LO – but sometimes no choice!
- It’s not simple
  - One can not necessarily just add (for example) a W+1 jet simulation and W+2 jets and W+3 jets to model W+n jets signal. Likely to be double counting.
  - One can not necessarily just run a W+ 1 jet simulation and generate the extra jets through parton showering either…

Generators: MC@NLO, Herwig, Pythia

Example: distributions on top-anti-top characteristic – P_T of the whole system

P_T of t-tbar system is balanced by ISR & FSR



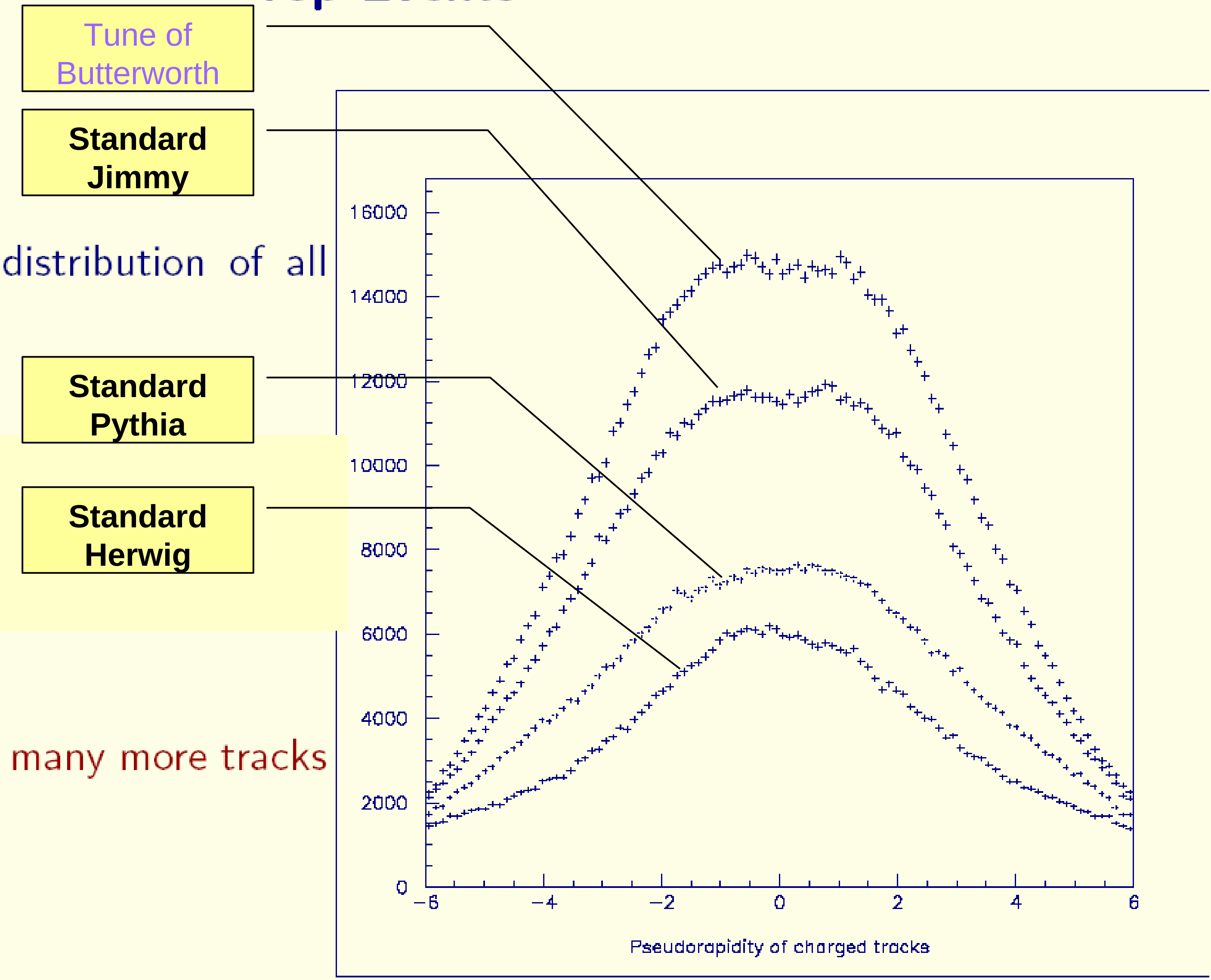


- P_T(tt system)
  - **Herwig & MCatNLO agree at low P_T,**
  - **At large P_T MCatNLO 'harder'**

Underlying event (UE) / minimum bias

- Extremely difficult to predict the magnitude of the UE at LHC
  - Will have to learn much more from Tevatron before startup
- Various models exists
  - Herwig's UE and minimum bias shows much less activity compared to Pythia.
    - This has always been a problem in Herwig.
  - Jimmy is developed as alternative model for UE at ep collisions
    - Various 'tunings' exist – leading to wildly different results

Top Events



Plot shows rapidity distribution of all charged tracks

Note that Jimmy has many more tracks

How Well Can We Simulate Detector?

- Detector Simulation – is only as good as the geometrical modeling of the detector – are all the cables and support structure in your model?
- Short time structure in current detector adds another dimension – nuclear de-excitations, drift charge in argon can be slower than beam bunch crossing time!
- Do not blindly trust tails of the distributions or rare processes
  - Random number may not populate them fully
  - Modeling not verified at this level -- e.g. MC estimate the probability for a jet to be reconstructed as a photon – a 10^{-3} or 10^{-4} probability

Analysis Strategy at LHC

- Characterize Bulk of Cross Section "Soft Physics"
  - Tracks
- Identify Dominant $2 \rightarrow 2$ QCD Processes
  - Jets
- Develop Strategies for Selecting EW Processes
  - e, μ, τ, ν. γ
- Reconstruct Heavy Objects Produced Strongly
  - Top, SUSY(?)
- Understand Discovery Potential for Low Rate EW Processes
  - Higgs

Offline Data Process for Analysis

- LHC reconstruction very complex
  - Many channels, many hits: Reconstruction is slow
- Large data collection rate and large event size
  - TB of storage required
- Cannot support bulk reconstruction by individual physicists
- Organized Production effort

  RAW $\rightarrow$ RECO $\rightarrow$ AOD $\rightarrow$ TAG $\rightarrow$ NTUPL
- Results available through Data Delivery System
  - "Analysis" is performed on output of Offline reconstruction

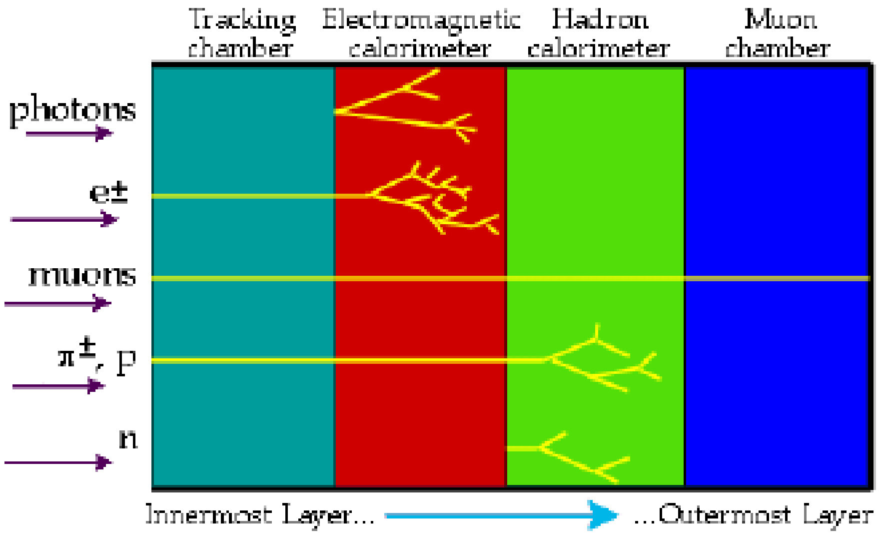
Reconstructed Physics Objects

- Collections of Candidate Objects
  - Tracks, Jets, Electrons, μ, τ, vertices, missing energy, heavy flavor
- Selections Performed Using Loose Criteria
  - Can tighten during analysis phase
- No attempt to uniquely identify objects
  - Same energy deposition may appear as jet, e and γ candidate
- Support for multiple algorithms
  - Best jet algorithm for Top analysis may not be the best algorithm for QCD studies

Physicists impost consistent interpretation during analysis phase

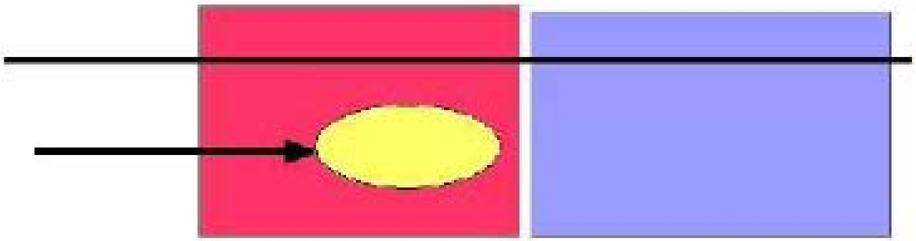
Electron Identification

- Electrons signature:
  - Energy Deposition in EM Calorimeter
  - Track pointing at the energy deposition and with momentum consistent with calorimeter energy
  - Little or no energy in hadron calorimeter

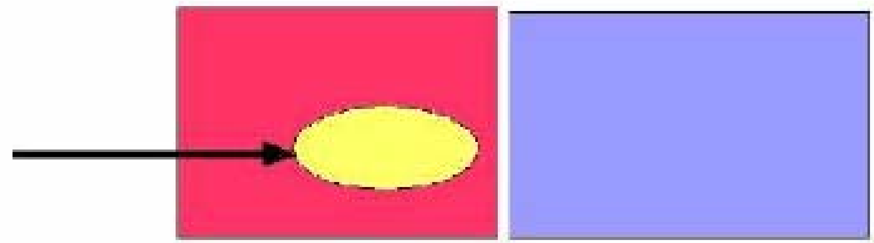


Background for Electron ID

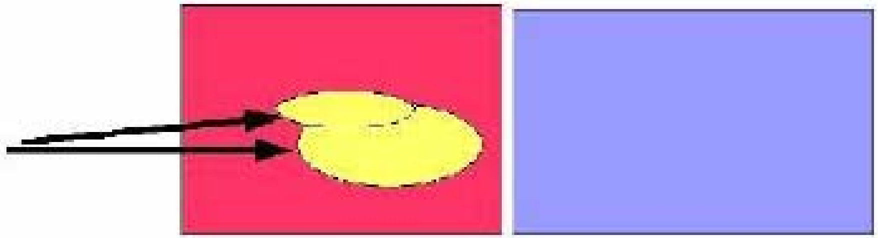
π^0 and non-interacting π^+



Early showering π^+



Photon Conversions

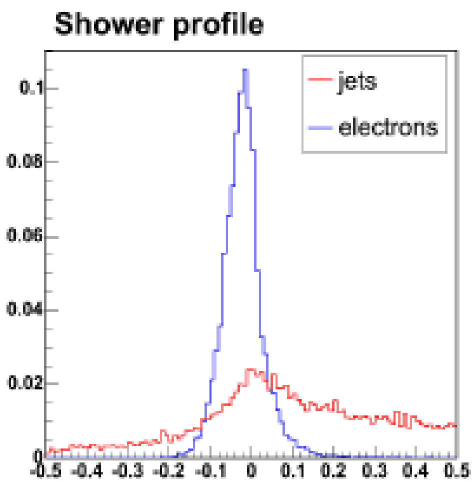


Reject Electron Background (I)

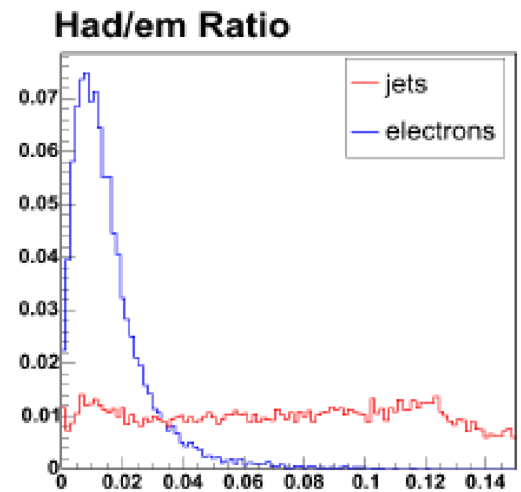
Choice of variables depends on detector. Some possibilities:

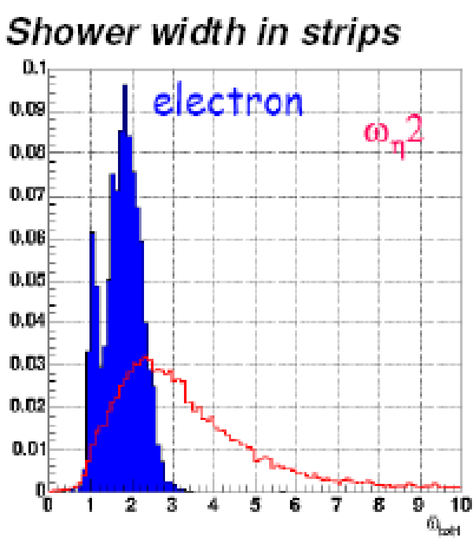
- Shower Shape Variables:
  - Longitudinal shape: ratio of energy in depth segments of calorimeter
  - Transverse shape: Hadron showers typically wider than electrons (also rejects π^0 π^+ overlap)
  - Had/EM: Expect very little energy deposit in HAD calorimeter

Shower Shape Distributions: Electron vs. Jets

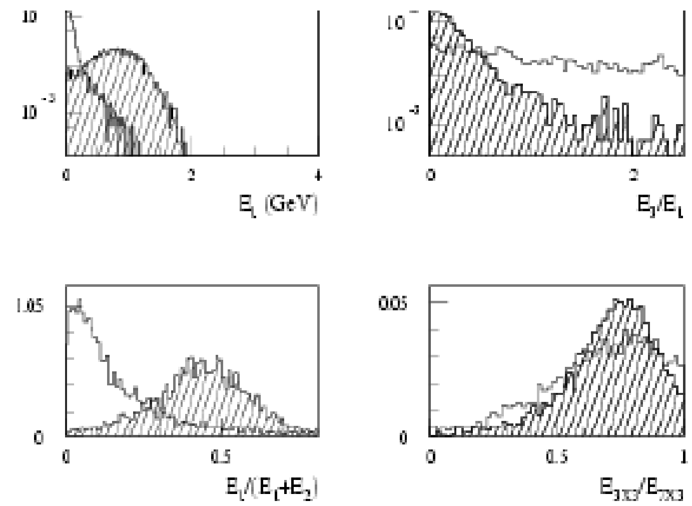


CDF





ATLAS



Reject Electron Background (II)

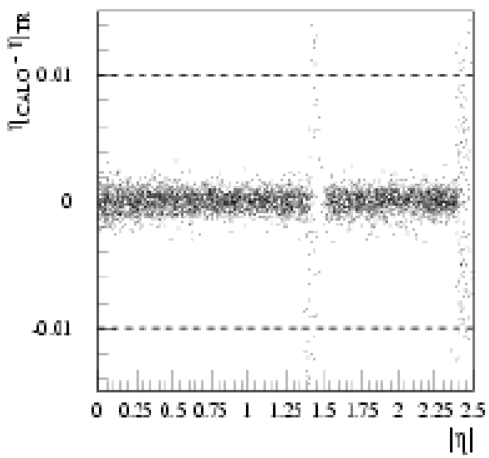
- Track-Shower Matching:
  - E/P: Ratio of energy in calorimeter to momentum in tracker
  - Pointing: Compare extrapolated position of track to position of EM cluster

Caution:

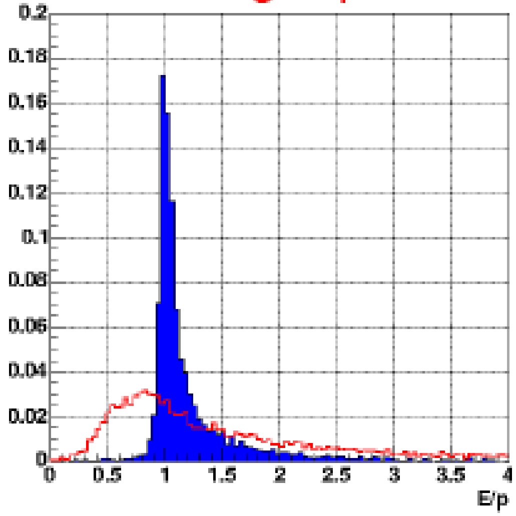
- Significant material in LHC trackers means electron bremstahlung
- Correct modeling of material distribution necessary both for defining selection criteria and for estimating efficiency

Track Matching - E/P

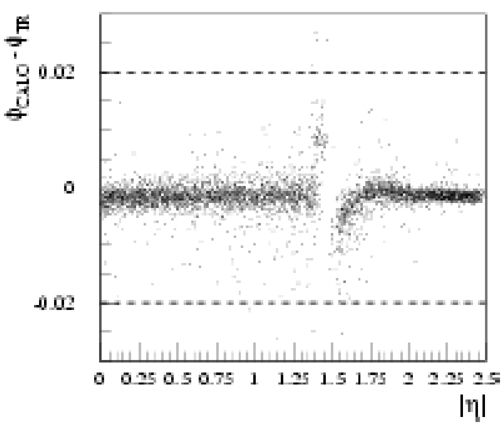
Matching in η



Matching E/p



Matching in ϕ



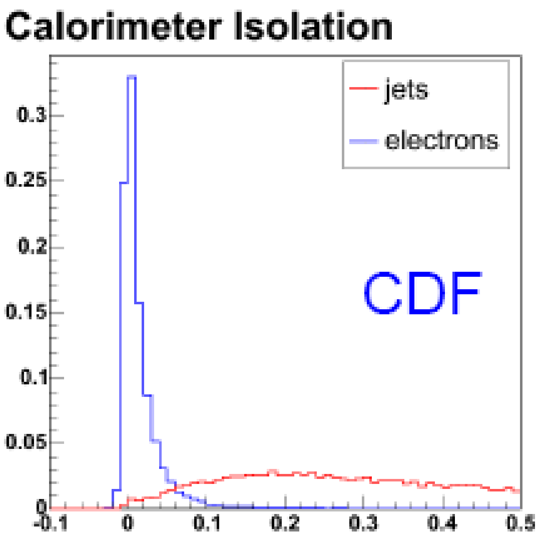
Reject Electron Background (III)

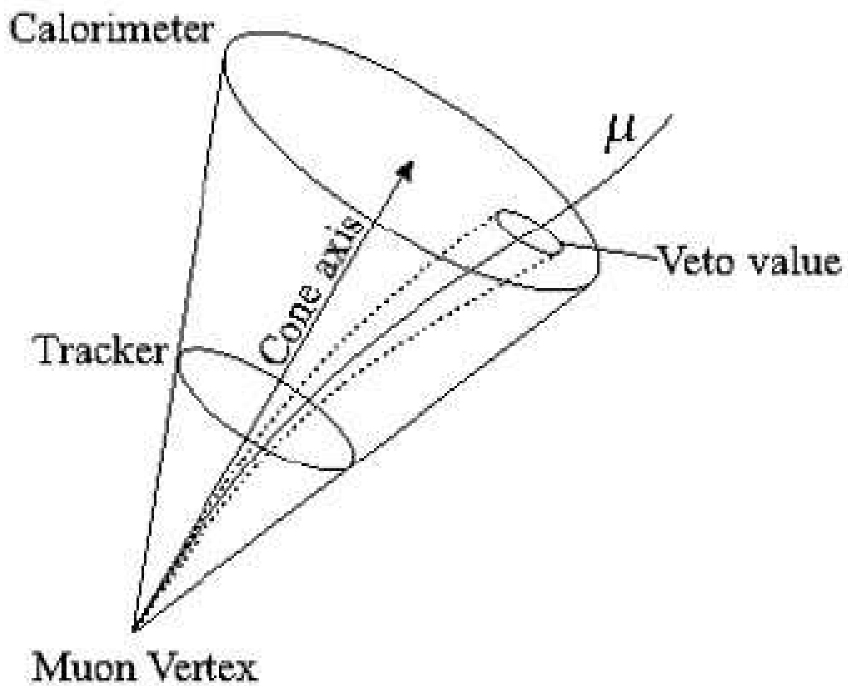
- Large amount of material also means photon conversions are an issue (photons from π^0)
  - Explicit removal of conversions:
    - Require hits in pixel layer (most of material outside this)
    - Look for second track from conversion: cut on reconstructed mass and angle

Reject Electron Background (IV)

- Isolation:
  - Study ratio of energy in annulus round electron to enegy of electron
  - As noted above: Does not work for all physics processes
- Transitions Radiation and dE/dx:
  - CDF drift chamber measures dE/dx: sensitive to particle velocity: helps for low momentum e
  - Atlas tracker has TR function: Can require high energy deposition hit, at cost of efficiency

Lepton Isolation

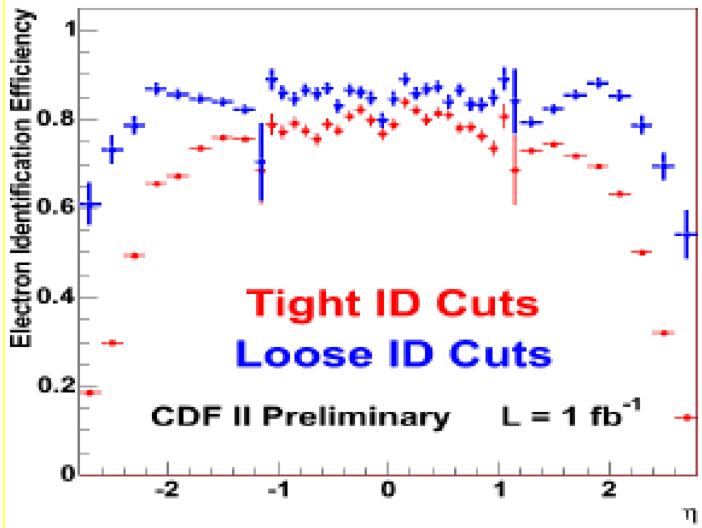


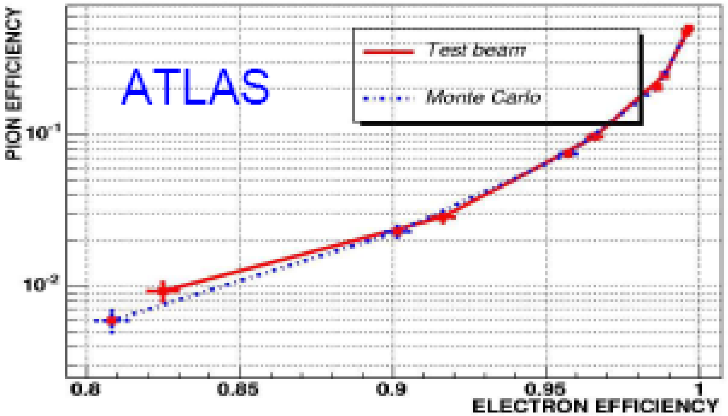


- Sum of Et in calorimeter in a cone
- Sum of Pt in Tracker in a cone

Overall Efficiency of Electron ID

- Measure when possible using real data:
  - W from no-track trigger to measure tracking efficiency
  - Z with one tight electron and with loose selection
- Use simulation to extrapolate kinematics and correct for environmental issues (eg isolation)





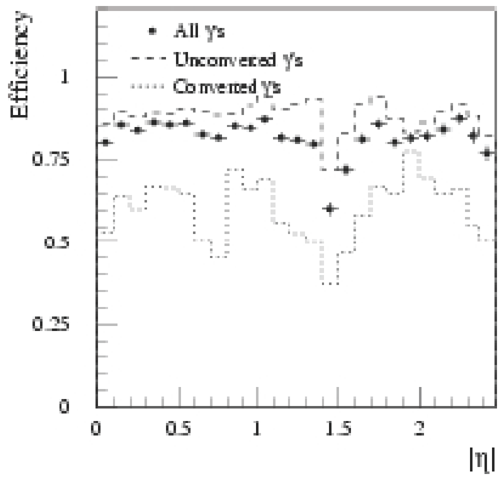
Photon Identification

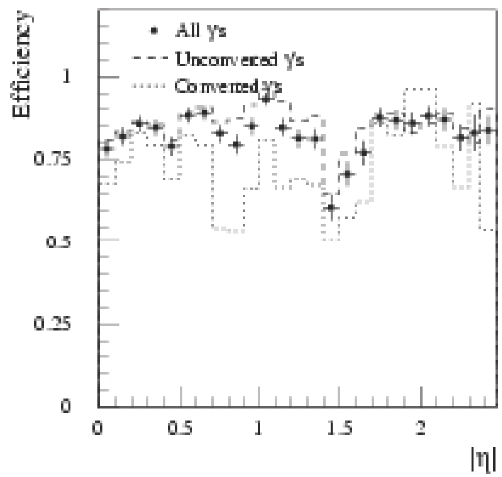
- Use same variables as for electron selection, with tighter cuts
  - Unconverted photons have track veto
  - Converted photons independently analyzed by looking for the second track
  - Emphasis on shower shape variables
    - Photons shower later than electrons
    - π^0 decay to 2γ so probability of early shower twice as large
- Isolation is critical

ATLAS and CMS have different emphasis due to different detector designs, but overall performance for Higgs similar

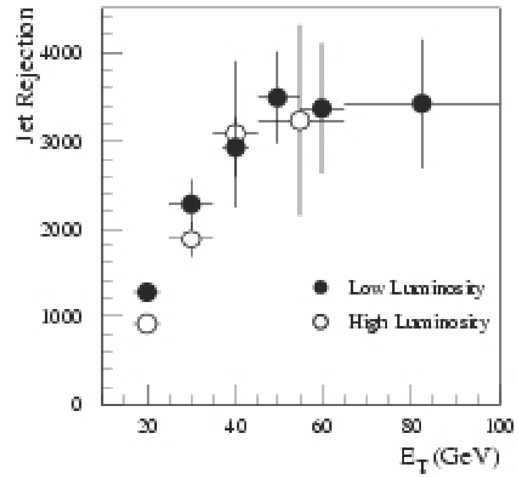
Photon ID efficiency and Background Rejection

Atlas: Efficiency: Low and High Luminosity

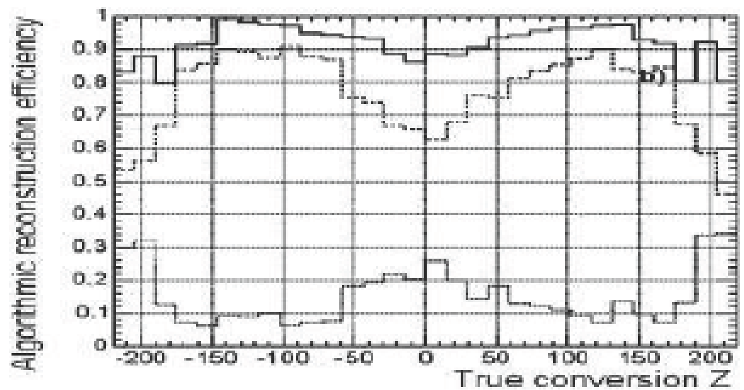




Atlas Jet Rejection

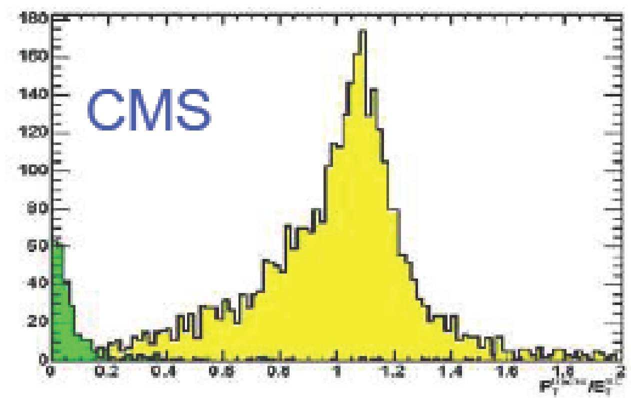


CMS



Conversion Probability vs η

CMS

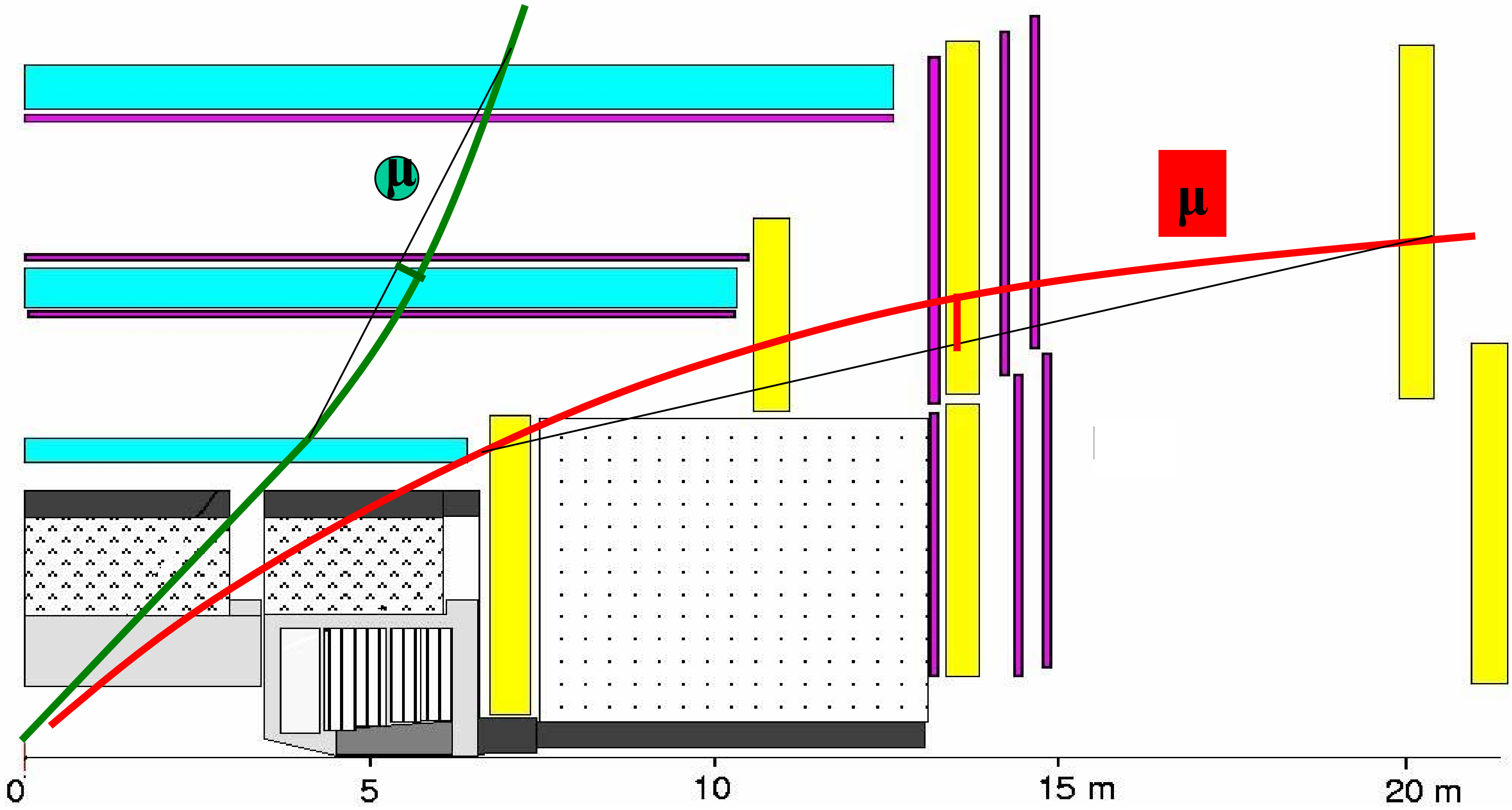


Pt Tracks/Et ECAL

ATLAS Muon Momentum Measurement

1 TeV muon sagitta ~ 500 μm

Sagitta measurement precision ~ 50 μm



ATLAS Muon Reconstruction and Identification

Muonboy : Muon Reconstruction in the Muon System, +back-fit to IP

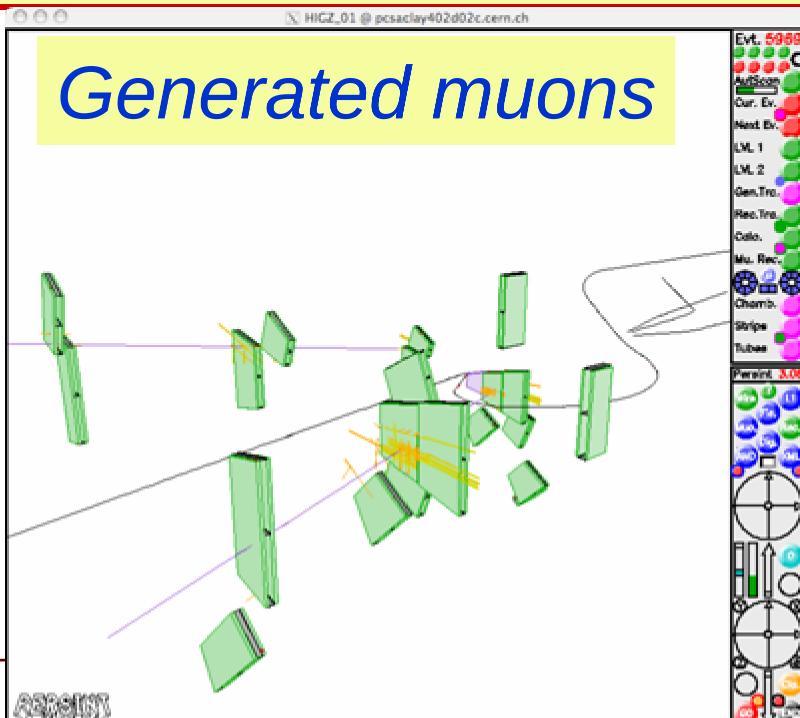
STACO : Statistical Combination of the Inner Detector and the Muon System

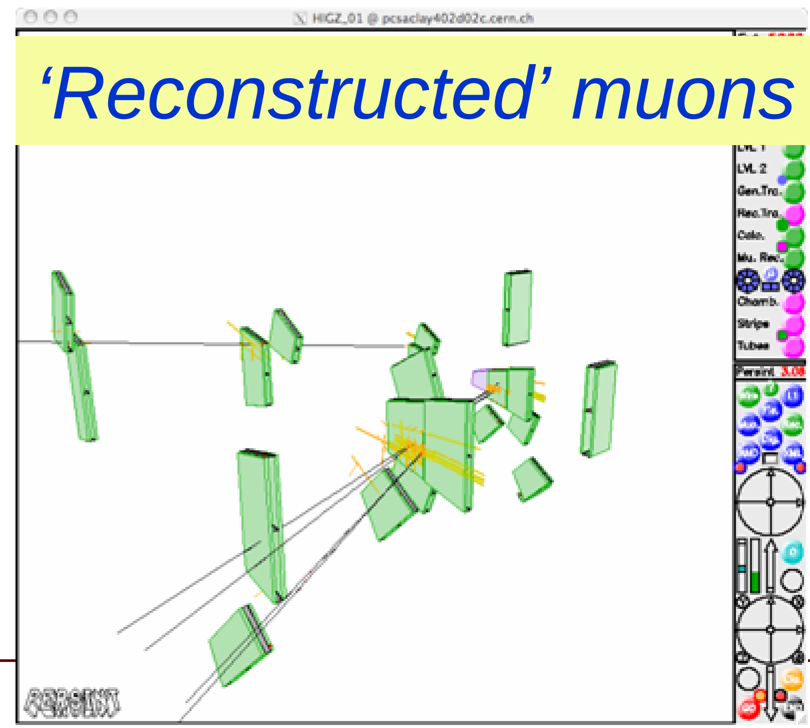
MuTag : Tag of ID tracks using Inner Stations Segments

MOORE : Muon Reconstruction in the Muon System

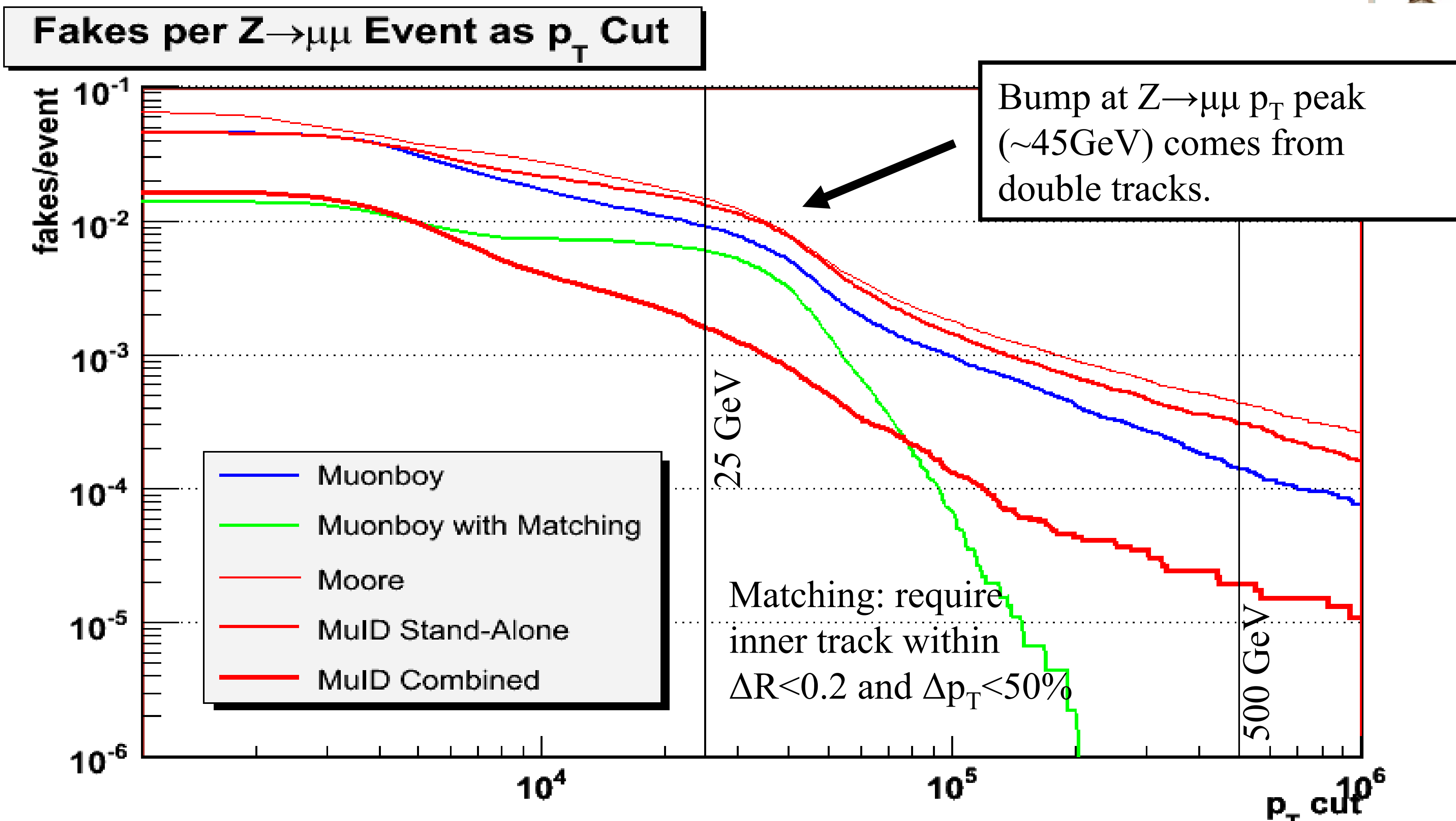
MuonID Standalone : back-fit from moore reconstruction to IP

MuonID Combined: Combine Inner tracker and the Muon System





Fake rate as a function of muon Pt cut



For p_T > 500 GeV,
MuonBoy fake rate ~0.15%

MuID S-A fake rate ~0.3%
MuID Combined fake rate ~0.015%

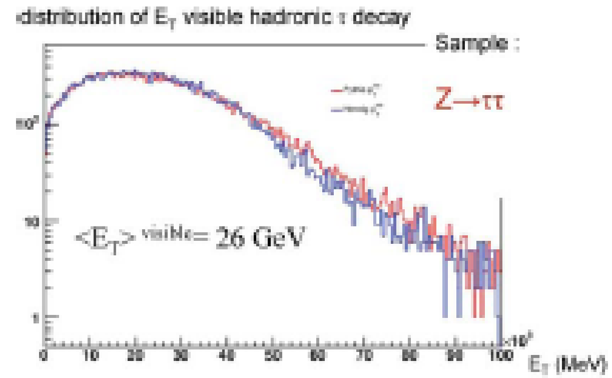
Tau Decay Modes

τ Decays

- τ decay modes
  - Leptonical decay modes: ~35%
    - $\tau \rightarrow \nu_\tau + \nu_e + e$ (17.4%)
    - $\tau \rightarrow \nu_\tau + \nu_\mu + \mu$ (17.8%)
  - Hadronical decay modes: ~65%
    - 1 prong
      - $\tau \rightarrow \nu_\tau + \pi^\pm$ (11.0%)
      - $\tau \rightarrow \nu_\tau + \pi^\pm + \pi^0$ (25.4%)
      - $\tau \rightarrow \nu_\tau + \pi^\pm + \pi^0 + \pi^0$ (10.8%)
      - $\tau \rightarrow \nu_\tau + \pi^\pm + \pi^0 + \pi^0 + \pi^0$ (1.4%)
      - $\tau \rightarrow \nu_\tau + K^\pm + \nu\pi^0$ (1.6%)
    - 3 prong
      - $\tau \rightarrow \nu_\tau + 3\,\pi^\pm + \nu\pi^0$ (15.2%)

77% (1 prong)

23% (3 prong)



1 track, impact parameter
Shower shape, energy sharing

3 tracks, impact parameter
Secondary vertex
Shower shape, energy sharing

ATLAS Tau Identification

τ-jet Reconstruction

- Tau Candidate Reconstruction
  - Identification

    Well-collimated Calorimeter Cluster with a small number of associated Charged Tracks

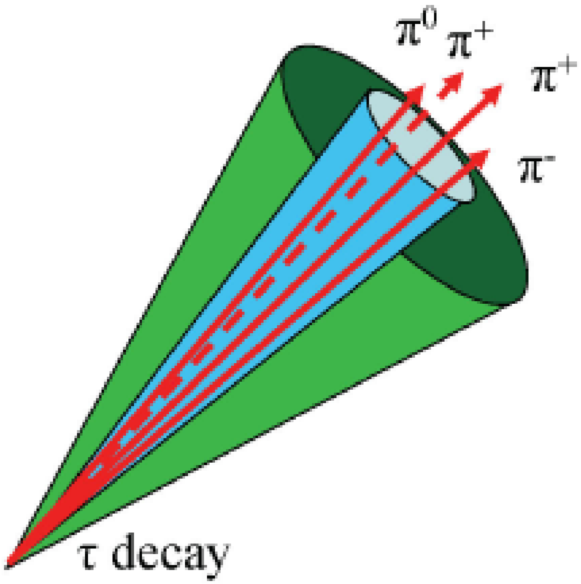
  - Distinguishing variables

    R_{em} = EM jet radius

    ΔE_T^{12} = fraction of E_T in EM/hadronic calorimeters within $0.1<\Delta R< 0.2$

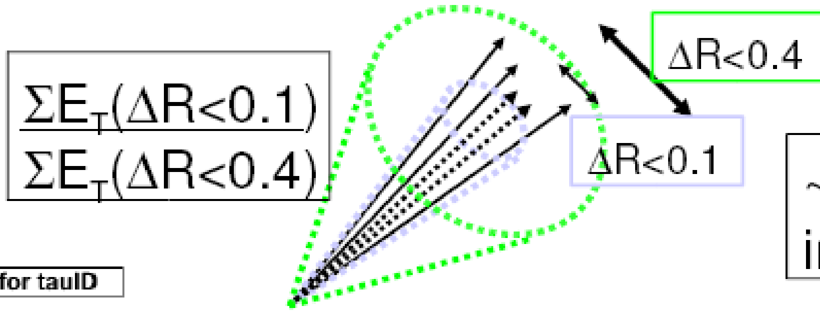
    N_{tracks} ,Charge, Impact Parameter,

    With of the energy deposition in the η-Strips



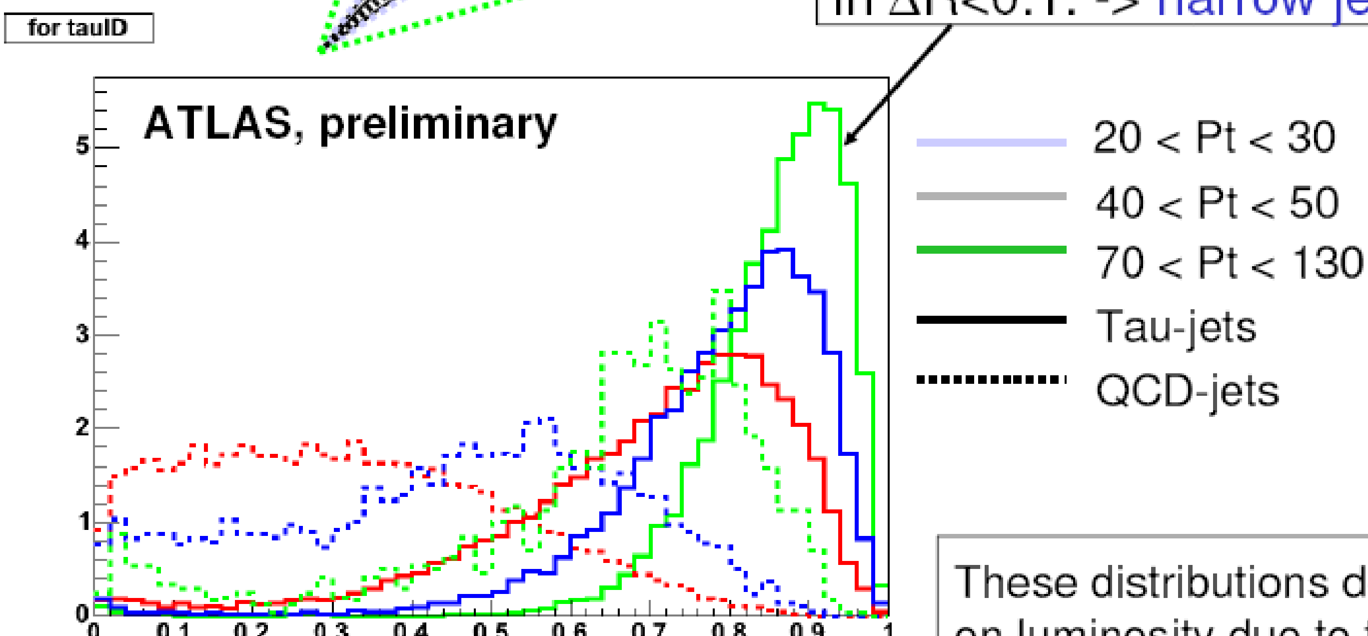
- Backgrounds misidentified as Taus
  - QCD Jets
  - Electrons that shower late or with strong Bremstrahlung
  - Muons interacting in the Calorimeter

Tau: Fraction of Energy in ΔR<0.1



(transverse energy)

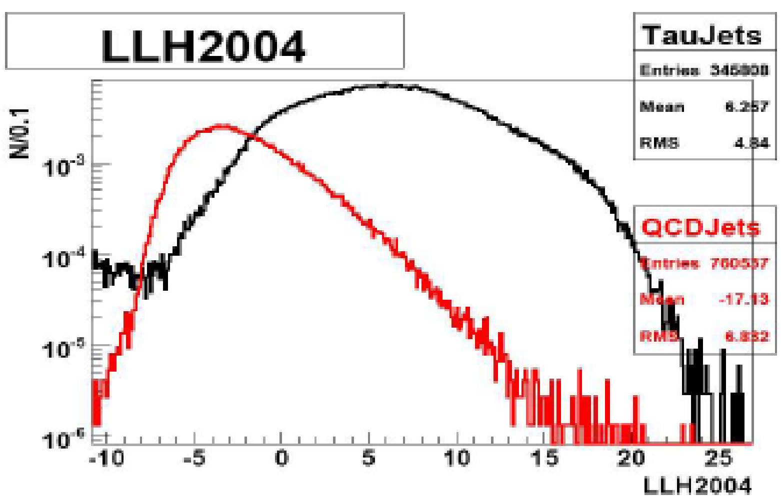
~90% of energy are deposited in ΔR<0.1. -> narrow jet



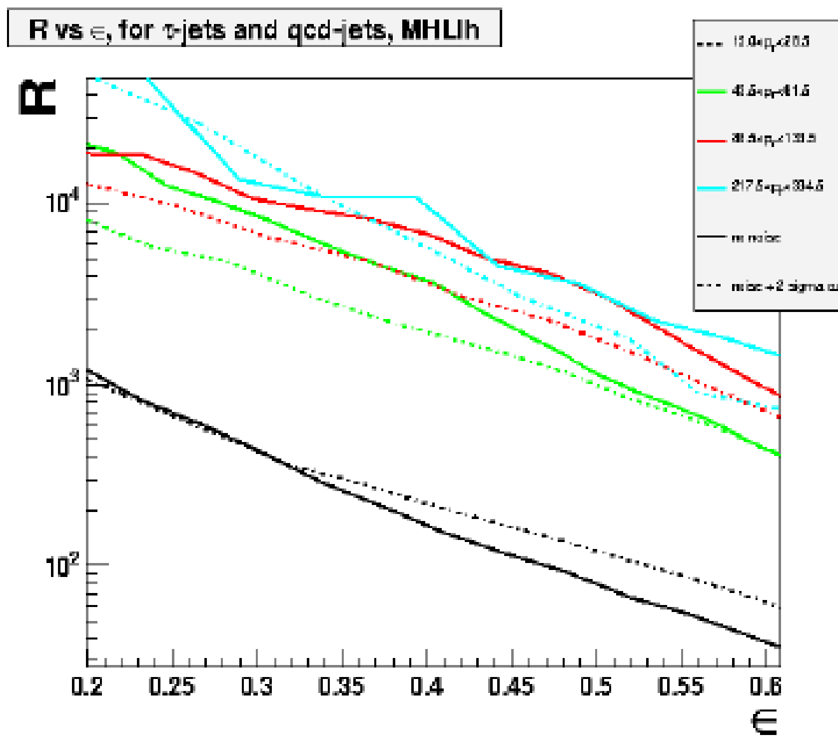
These distributions depend on luminosity due to the pile-up.

A Likelihood approach to τ-ID

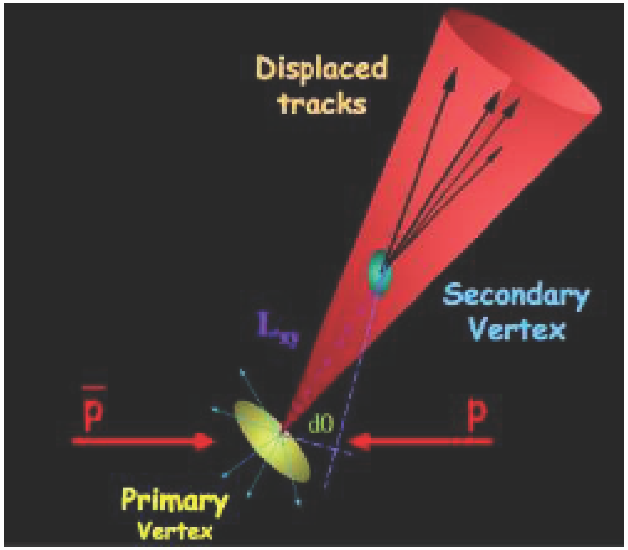
- Construct variable that combines all cut variables
- Compare signal and bckgnd
- Can vary cut to get need rejection



ATLAS



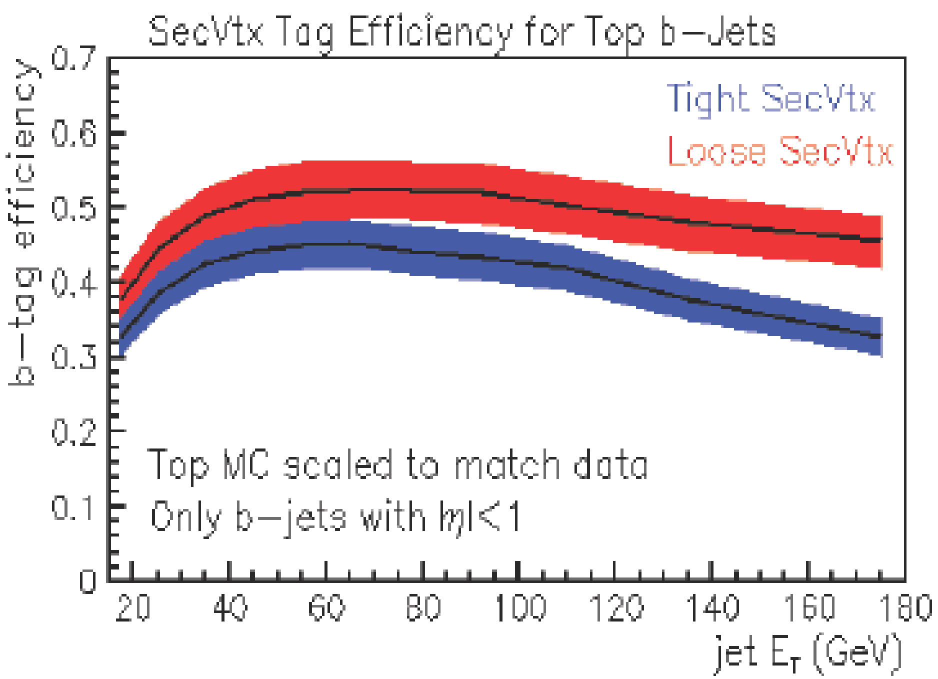
B-jet Identification

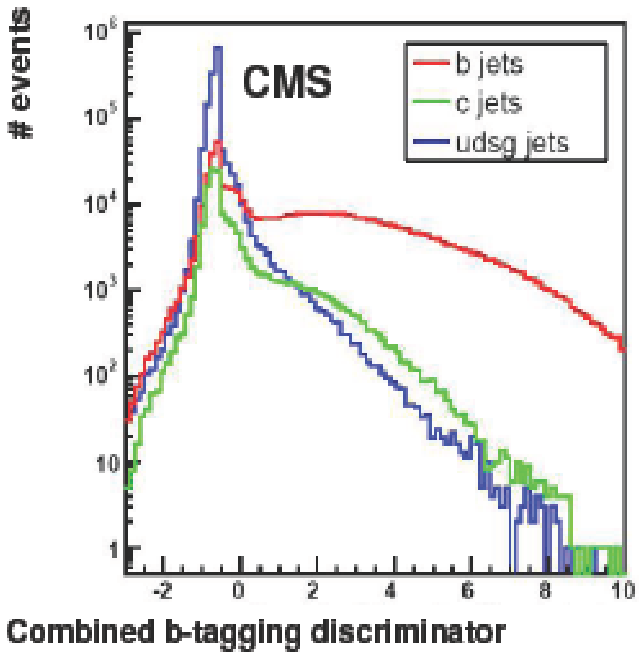


- Characteristics of B decays:
  - B lifetime long: $c\tau \sim 460\ \mu$
  - Semileptonic BR 10% per lepton species
- Two methods of b-tagging
  - Displaced vertex (or track from it)
  - “Soft” leptons close inside jets
- Vertex tagging has higher efficiency and better purity
  - But can combine both techniques

B-tagging efficiency Depends on Background

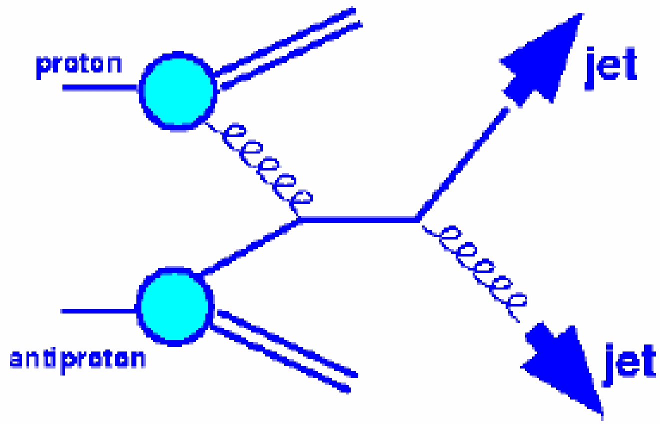
- Charm also long-lived: less rejection
- Performance E_T dependent

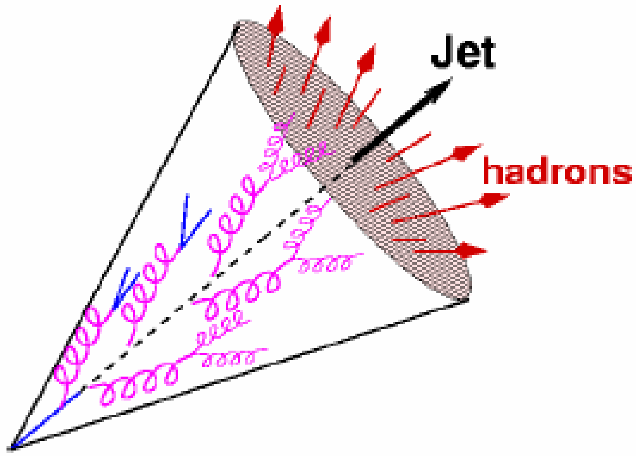




QCD Jet

- 2 → 2 elastic scattering of quarks and gluons





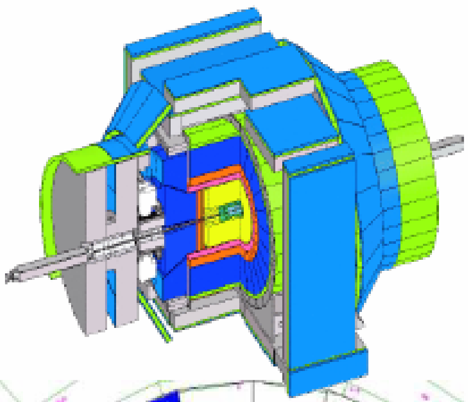
- Strategy
  - Calorimeter based pattern recognition
  - Associate tracks with the jets after calorimeter jet found
  - Primary vertex needed to calculate p_T

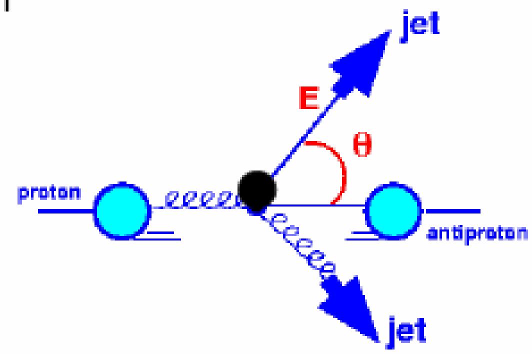
A ‘Cone’ Jet Reconstruction Algorithm

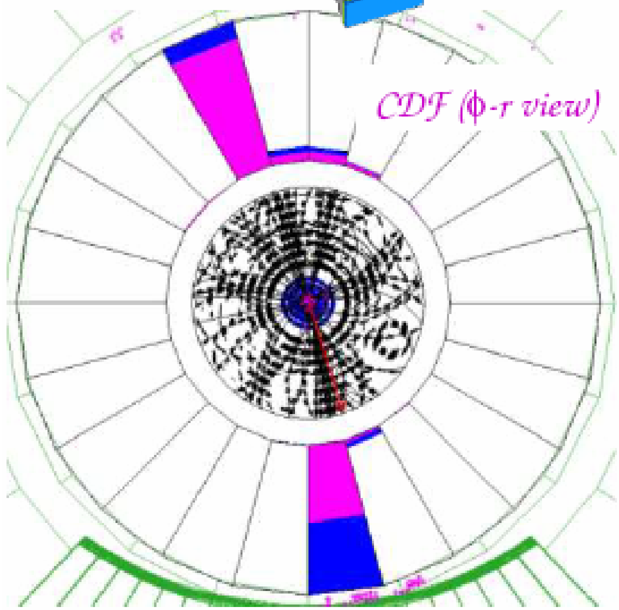
- Jets are circles when projected in $\eta - \phi$ space
- To reject fluctuations in underlying event and pileup:
  - Start with a “seed” tower above fixed E_T (E_{ESeed})
  - Draw a circle in $\eta - \phi$ space (Cone Size: 0.4 to 1)
  - Include all towers with above a fixed E_T (E_{tmin})
  - Calculate E_T centroid
  - Iterate list of towers until stable
- This is the “pattern recognition” phase

What Do Jets Look Like ?

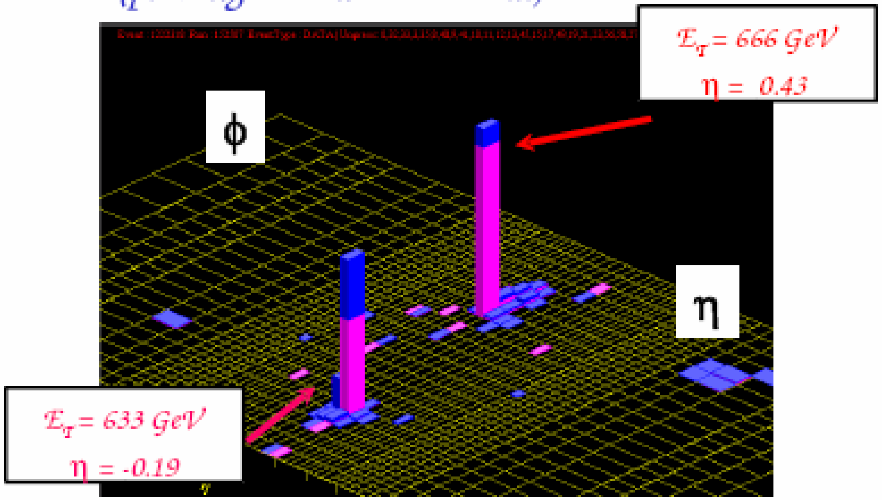
(the highest P_T jet event from CDF)







Dijet Mass = 1.36 TeV
(probing distance ~10^{-19} m)



Jet Energy Scale

The jet energy scale is the dominant uncertainty in many measurements of the top quark.

CDF and DØ use different approaches to determine the jet energy scale and uncertainty:

- **CDF:**
  Scale mainly from single particle response (testbeam) + jet fragmentation model
  Cross-checked with photon/Z-jet p_T balance
  - ~3% uncertainty, further improvements in progress.

- **DØ:**
  Scale mainly from photon-jet p_T balance.
  Cross-checked with closure tests in photon/Z+jet events
  - Run II calibration uncertainty ~ 2%

Missing E_T (ν) Reconstruction

- Use same technique as for jets
  - Create a grid of calorimeter towers
  - Treat each tower as a massless particle with momentum direction normal to the tower

Define $\not{E}_T$ (2 vector)

$$\not{E}_T = -\sum_{\text{Towers}} E_{iT}\hat{n} = -\sum E_i \sin\theta_i \hat{n}$$

Similarly total E_t

$$E_t = \sum_{\text{Towers}} |E_{iT}| = \sum |E_i| \sin\theta_i$$

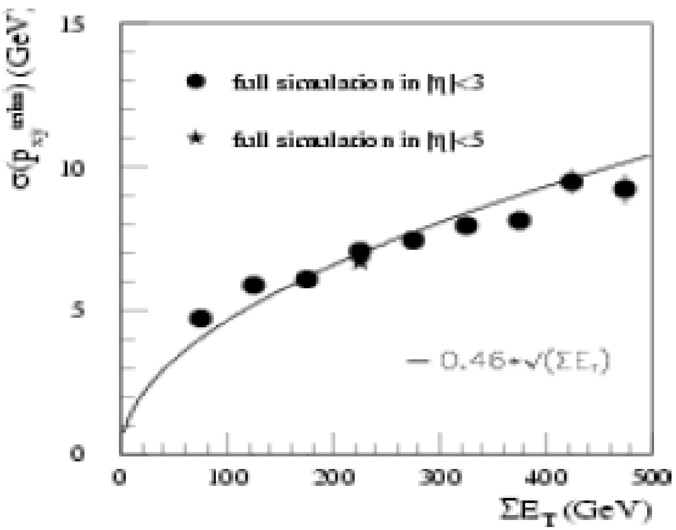
Calorimeter "Tower"

Missing E_T Resolution

- Calorimeter resolutions depend on energy deposition

$$\sigma_{\not{E}_T} \propto \sqrt{E_T}$$

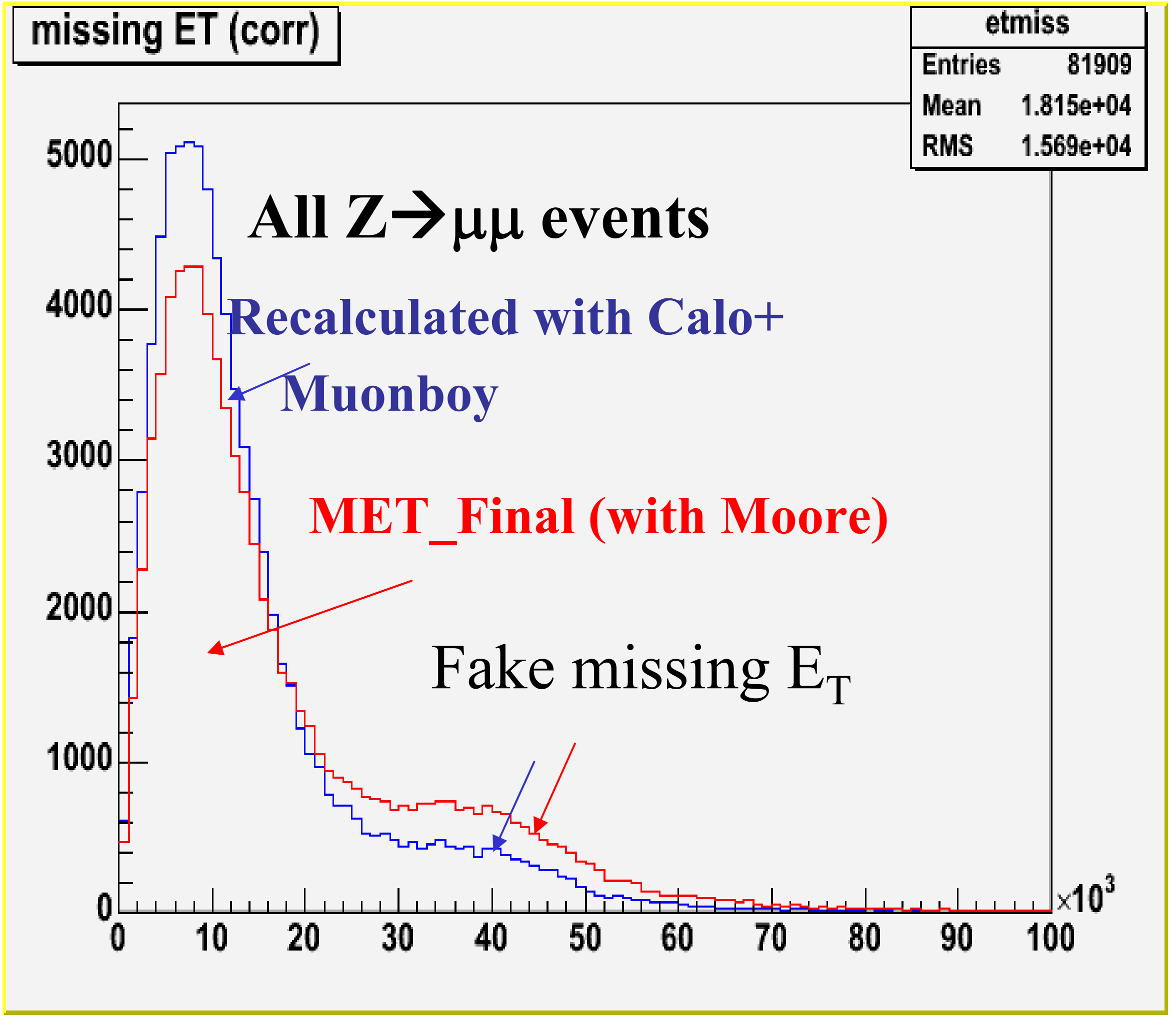
- Measurement is also sensitive to detector imperfections (cracks) and noise
- Degrades with pile-up



ATLAS TDR

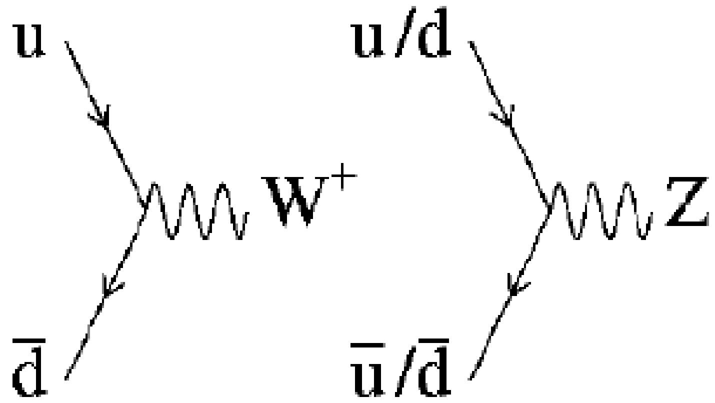
Comment: Muon ineff. -> Fake Missing E_T

(ATLAS: Z->μμ MC sample, recon 10.0.1)



W and Z Production in Hadron Collider

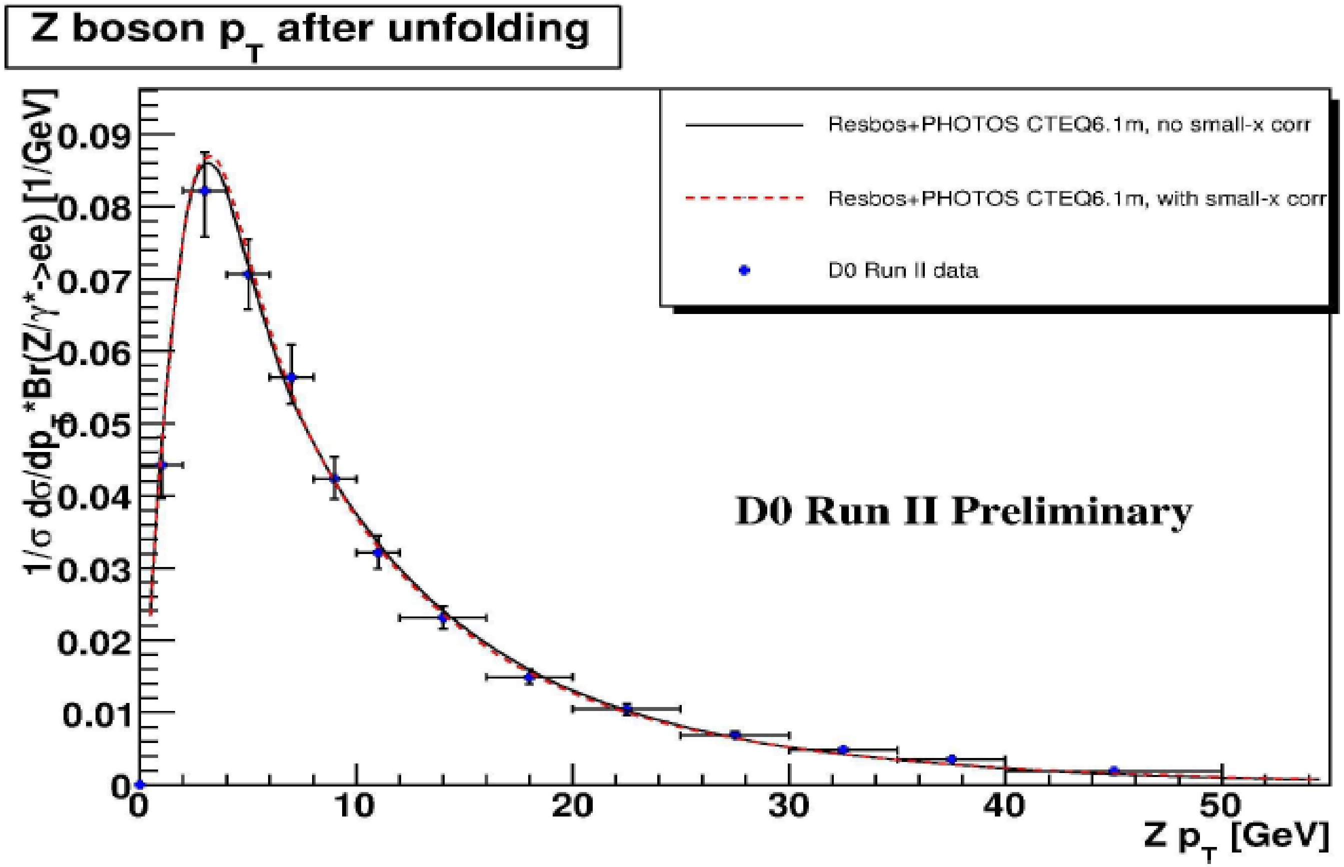
- Lowest order diagram: quark annihilation
- W and Z obtain P_T via initial state gluon emission



Lowest order production:

W and Z produced with 0 PT

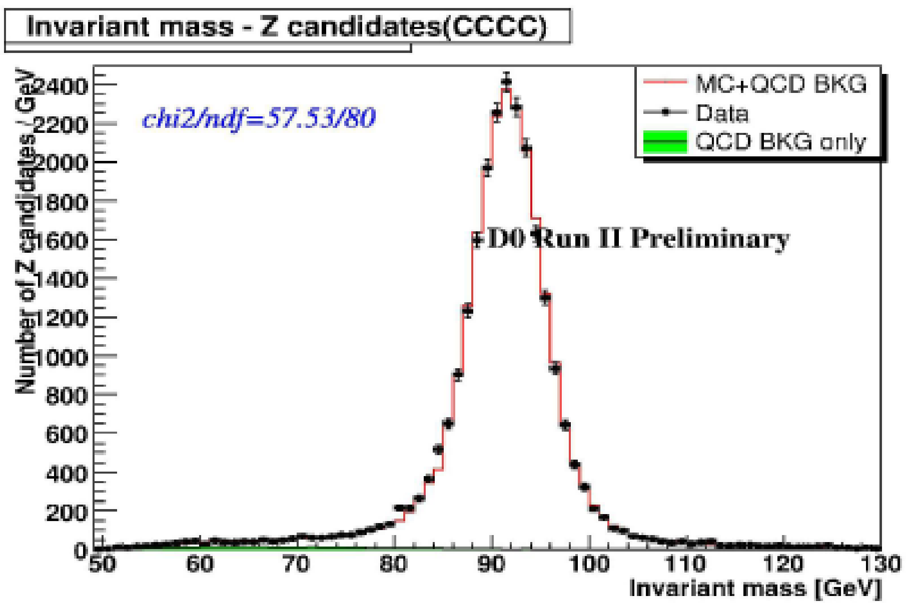
Full QCD Calculation: V-Boson Pt Remains Small



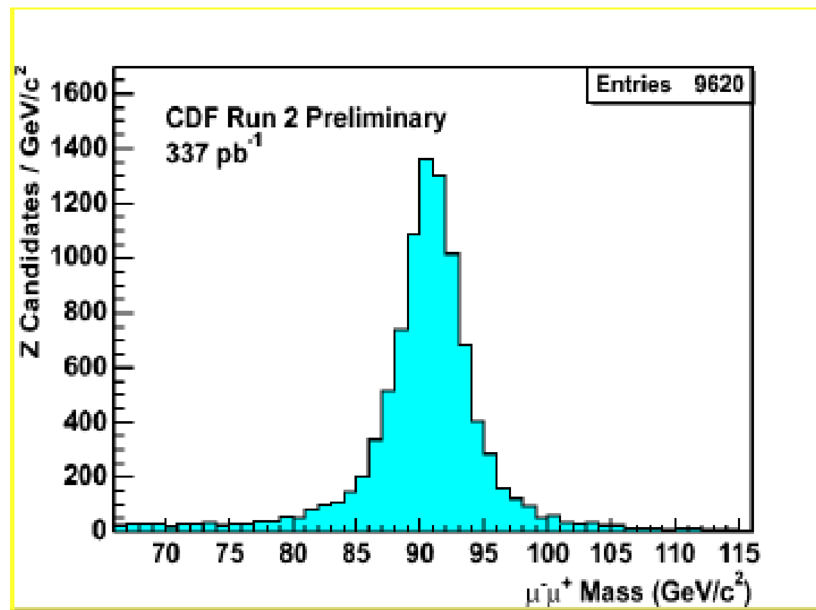
Distribution dominated by multiple soft gluon emission

Reconstruction of Z

- Limited to leptonic modes unless you trigger on b-jets
- Two high P_T leptons, nearly back-to-back in ϕ
- Reconstruction straightforward, background small



$Z \rightarrow ee$



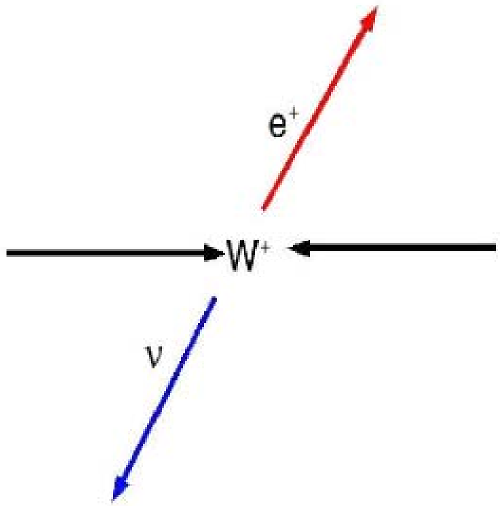
$Z \rightarrow \mu\mu$

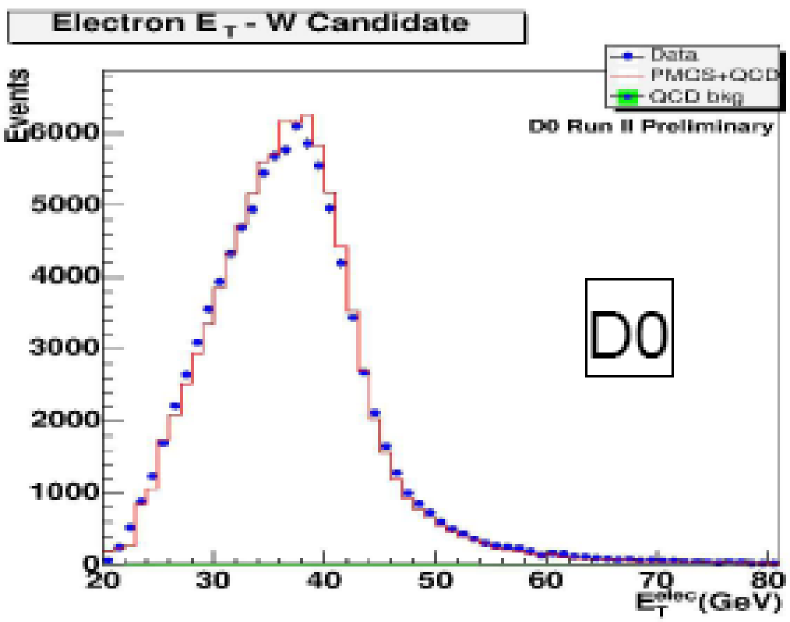
Reconstruction of W→ lepton+neutrino

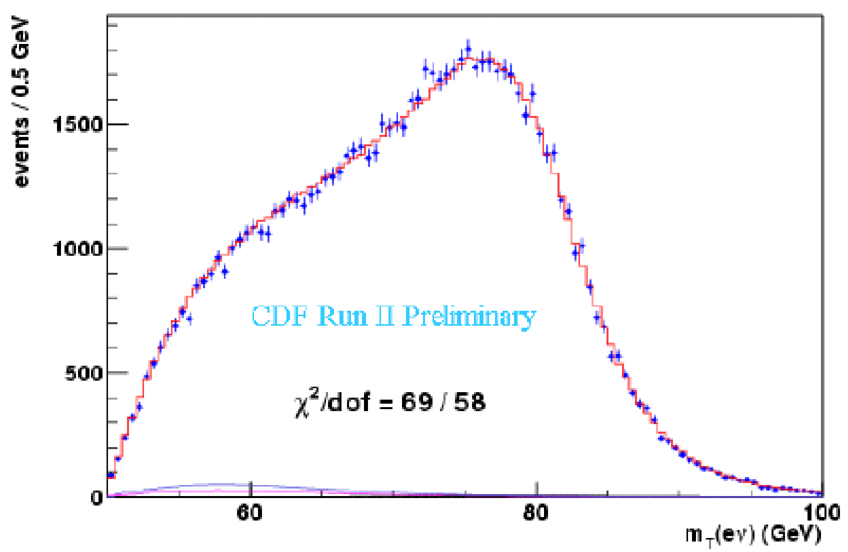
- Select W event:

  isolated high P_T e or muon

  large missing E_T (> 20 GeV)

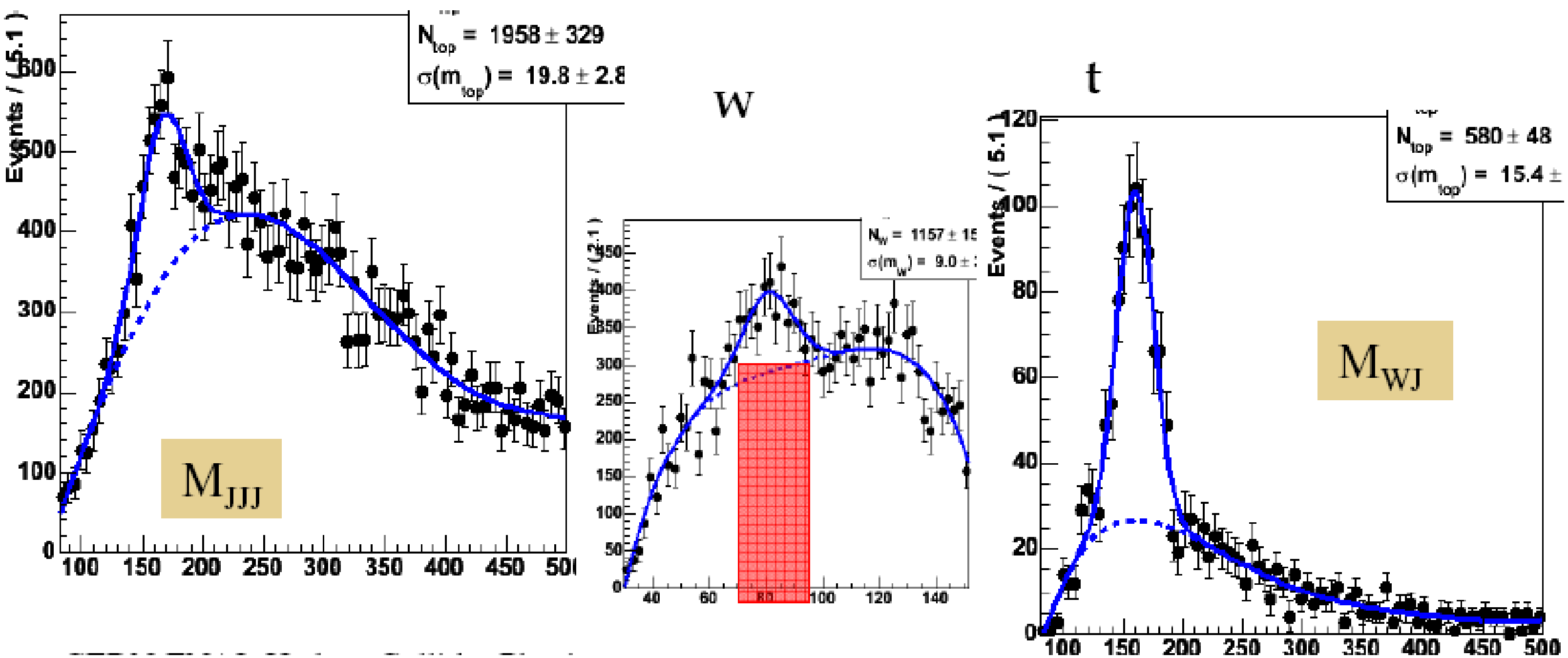






Top Identification

Three jets with highest vector-sum P_T as the decay products of the top – lepton trigger. Two jets in hadronic top with highest momentum in reconstructed J+J+J C.M. frame. Lumi = 300 /pb. Top mass with cut on W in M_{JJ}.



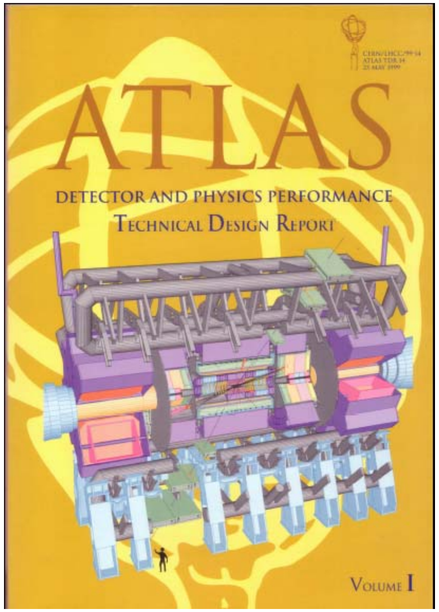
Physics Discovery Potential at LHC

Bing Zhou

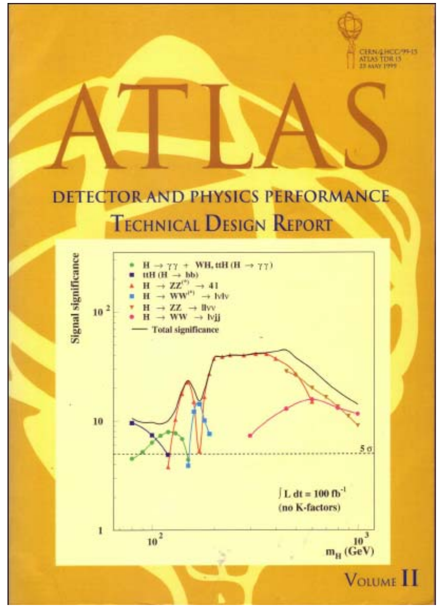
The University of Michigan

CCAST Workshop @Tsinghua University

Nov. 6-10, 2006



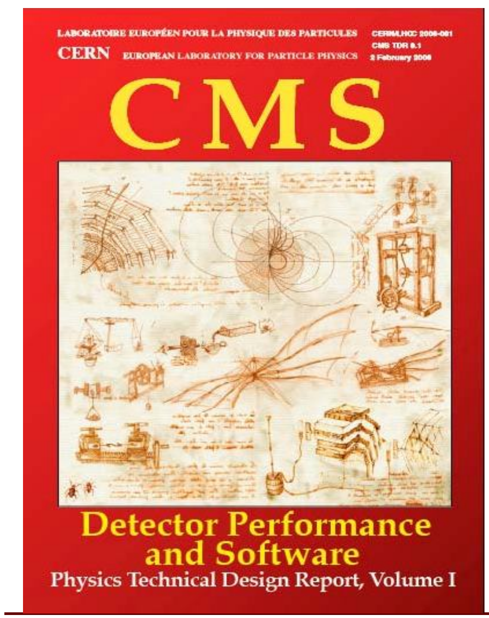
May 1999



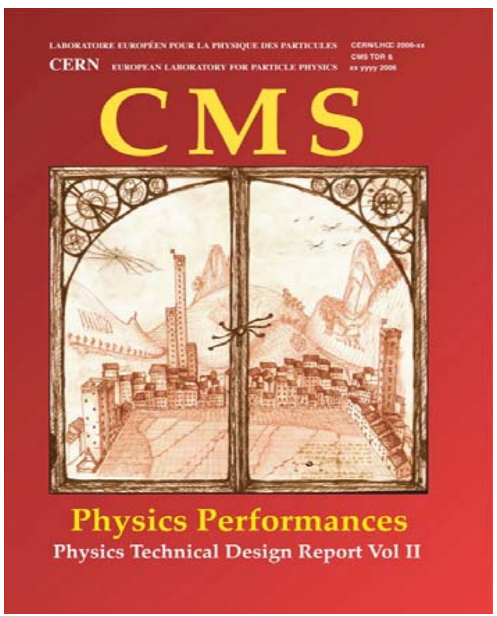
May 1999

Physics TDRs

CSC (Computing System Commissioning) notes are to be produced in spring 2007, covering software and physics analysis validation for the early physics run with 0.1 fb^{-1} and 1 fb^{-1}.



Feb. 2006



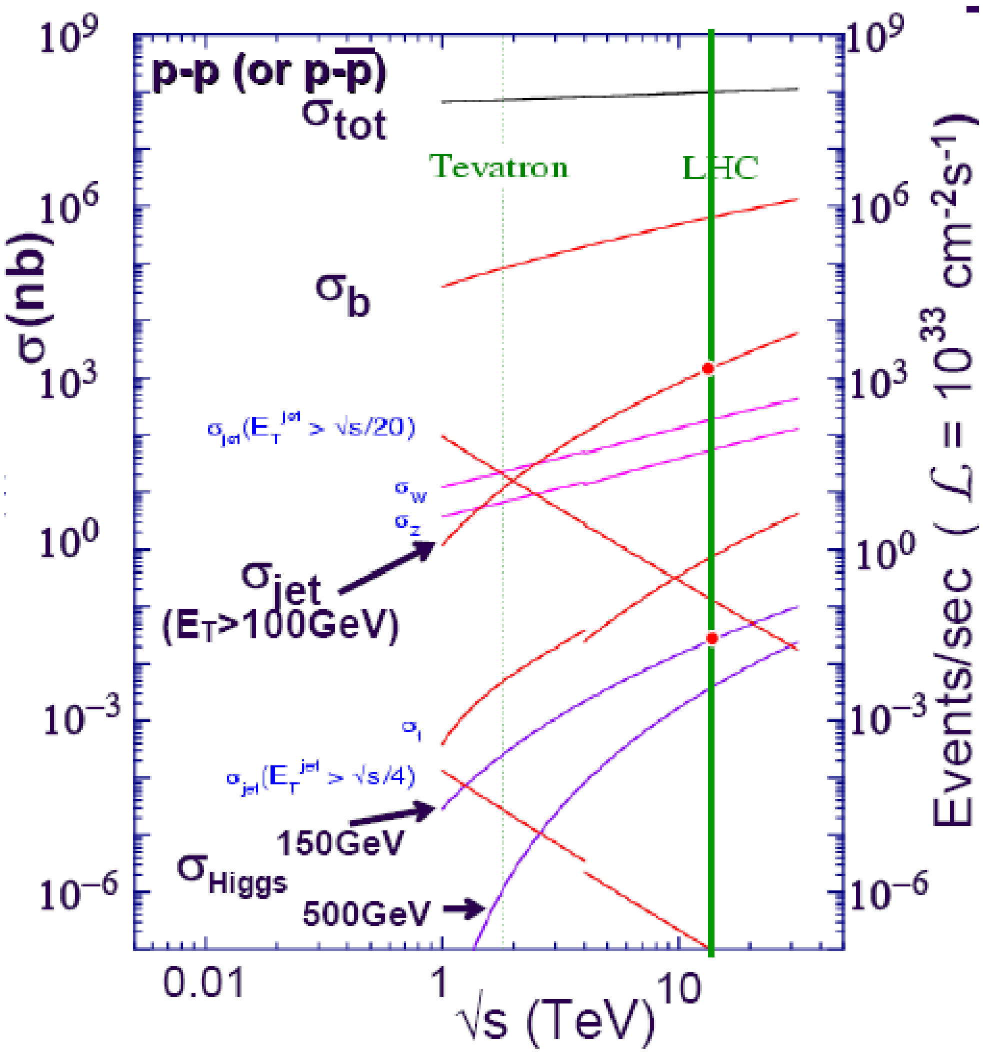
Jun. 2006

Instead of 3-rd vol. of TDR, short notes on startup will be submitted to LHCC in summer 2007, along with the very early physics reach with 0.1 fb^{-1} and 1 fb^{-1}.

http://cmsdoc.cern.ch/cms/cpt/tdr/

First Step of Campaign at the LHC

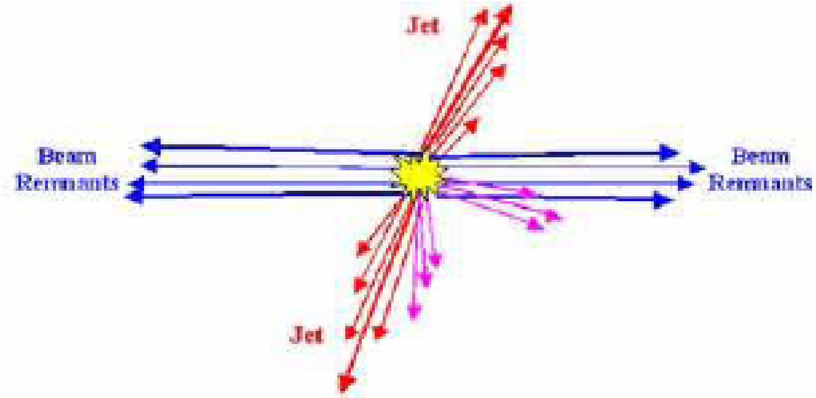
1) MC Models and Re-establish the SM processes



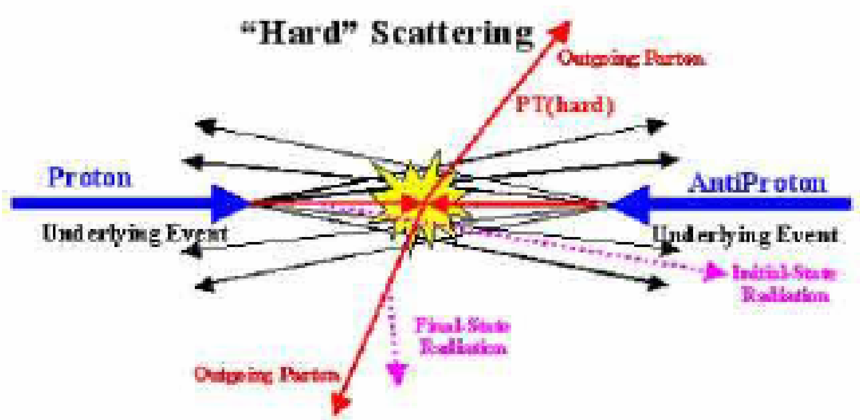
Channel	Recorded [1 fb^{-1}]
$W \rightarrow \mu\nu$	7×10^6
$Z \rightarrow \mu\mu$	1×10^6
$tt \rightarrow \mu + X$	0.1×10^6
Jets p_T>150GeV (if 10% bandwidth)	$\sim 10^6$
Min Bias (10% bandwidth)	$\sim 10^6$ (can be larger)
$\tilde{g}\tilde{g}$ (M~1 TeV)	10^2-10^3

Underlying Event and ISR Modeling

- Hard Collision leaves remnants of incoming p's moving in Beam Direction



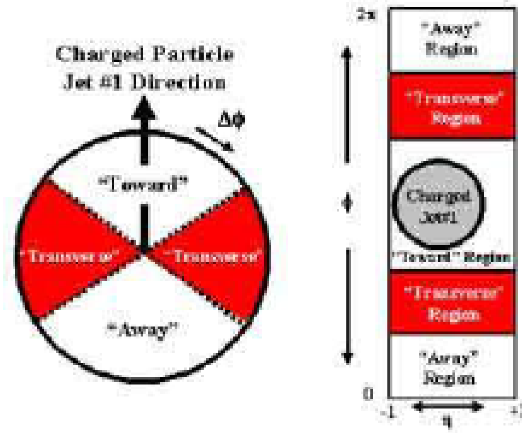
- "Initial State" gluon radiation largely co-linear with incoming partons: same basic structure



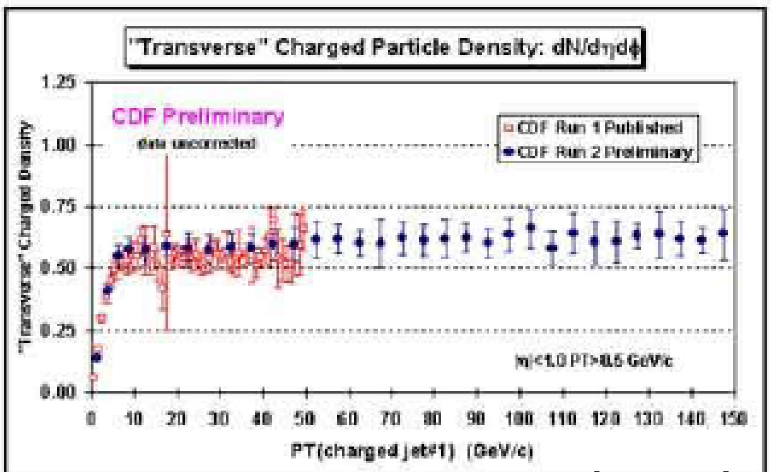
Soft particles distributed uniformly in η

Track Distributions from Underlying Events

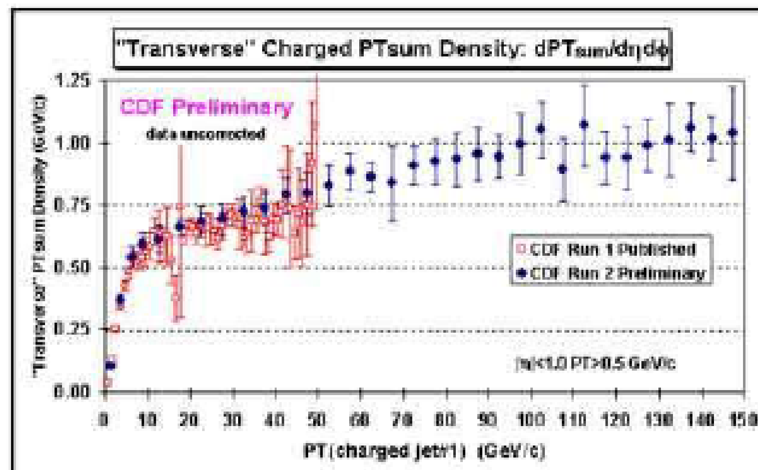
- Look at 90° from jet direction



dN/dηdφ



Pt (GeV)

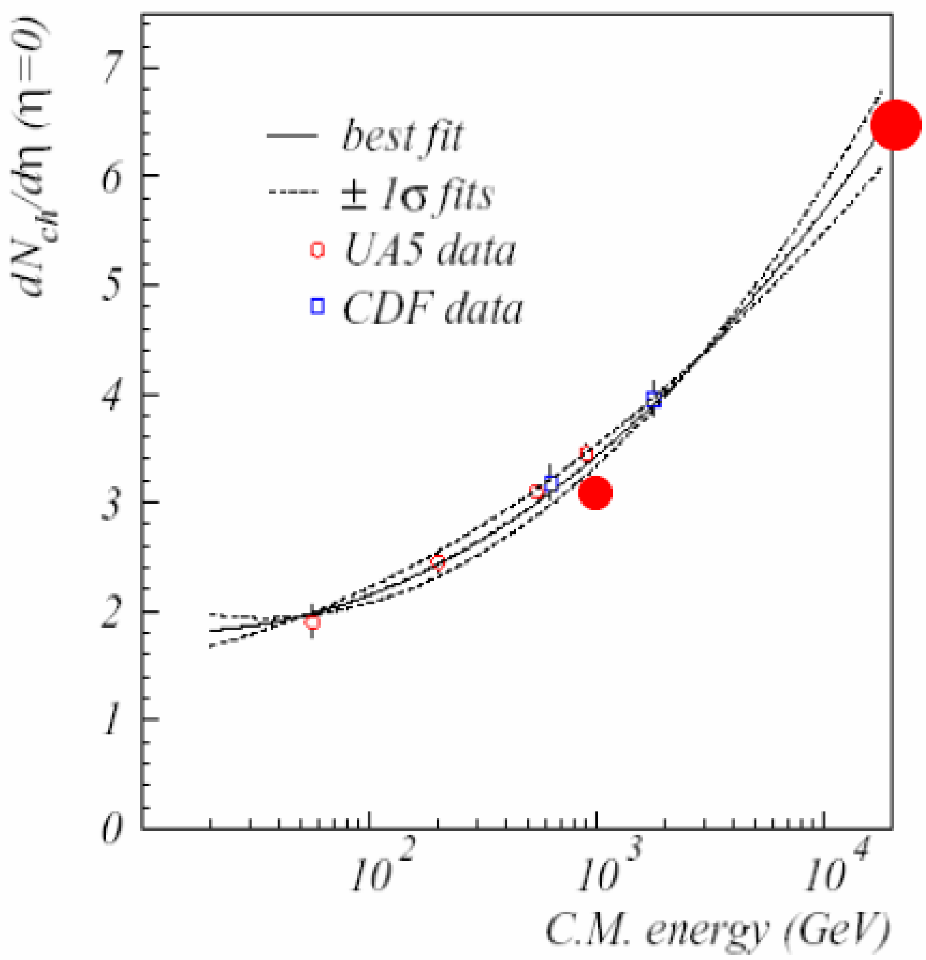


•Approx constant Particle multiplicity

•Energy density increases with hard scattering scale

Pt (GeV)

MinBias Density Extrapolate



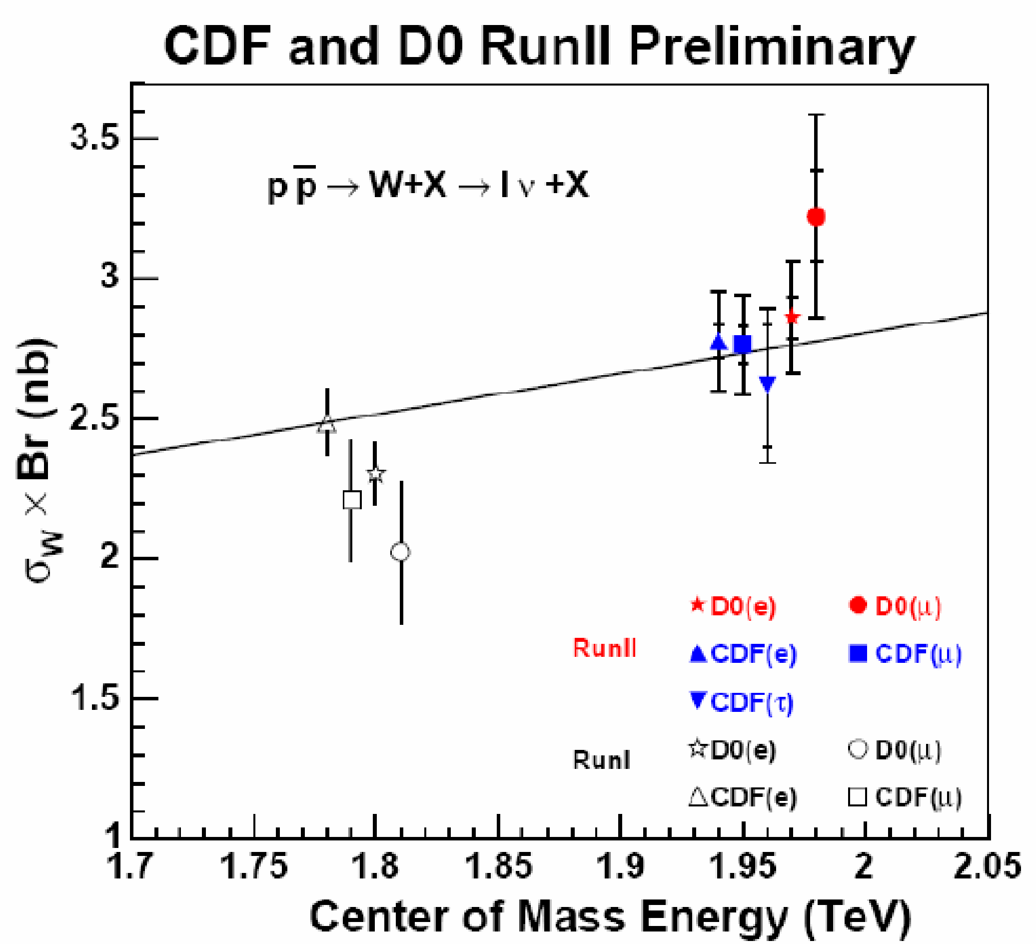
Using data from 0.2 to 1.8 TeV to extrapolate the plateau rapidity density. For all pions expect

$$\rho = 1/\sigma(d\sigma/d\eta) \sim 9$$

$$\pi^+ = \pi^- = \pi^o$$

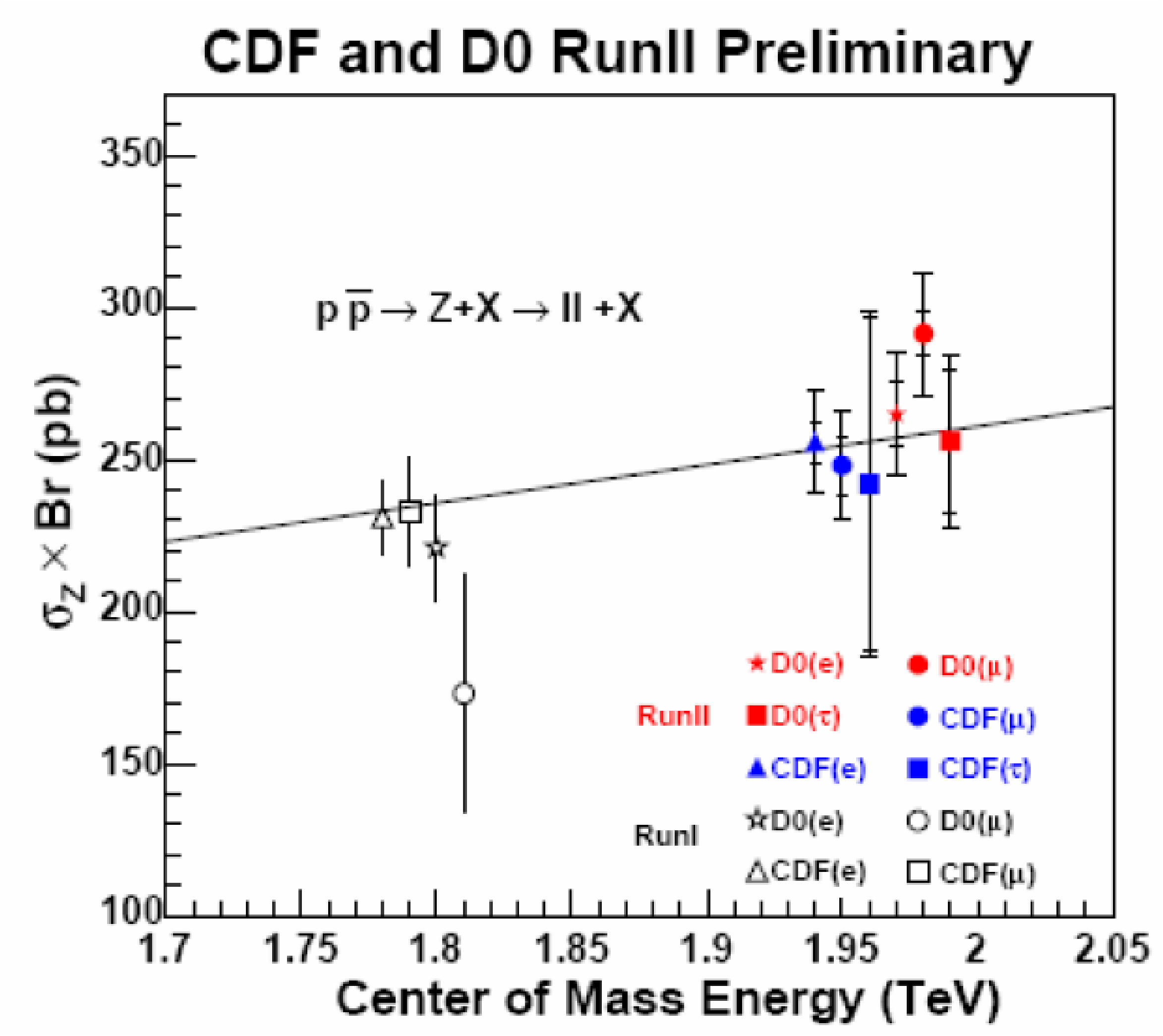
Note – 2x extrapolation from 0.9 TeV

Standard W Candle



Use W -> μ + ν as a "standard candle" to set the LHC luminosity? Expect ~ 2% accuracy on the predicted cross section. Cross section for W-> μ +ν 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 2008.

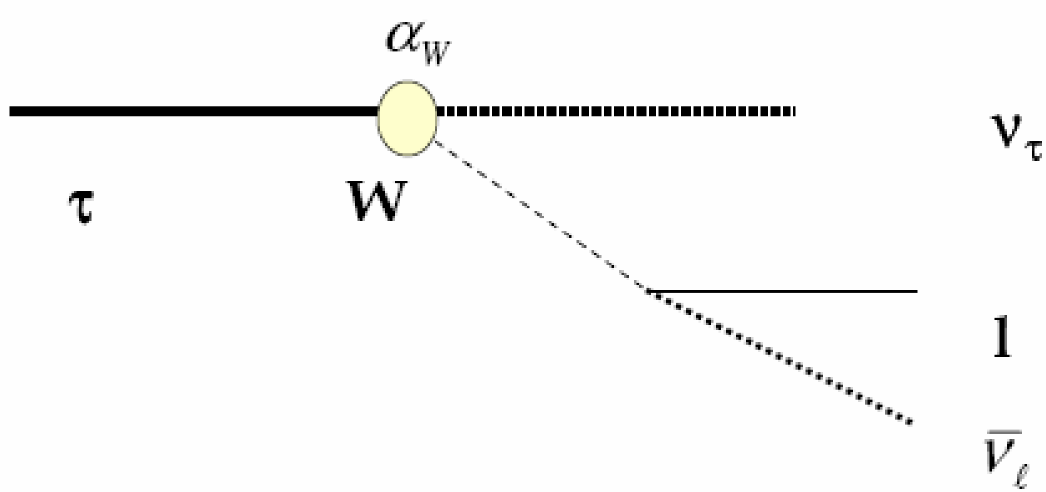
Standard Z Candle



Use Z-> μ+μ as second "standard candle" to determine the LHC luminosity. Expect ~ 2% accuracy in cross section prediction. Find cross section for Z-> μ+μ decay with |η|<2.5 * Pt > 15 GeV is ~ 600 pb. Note slow rise from Run II cross section values.

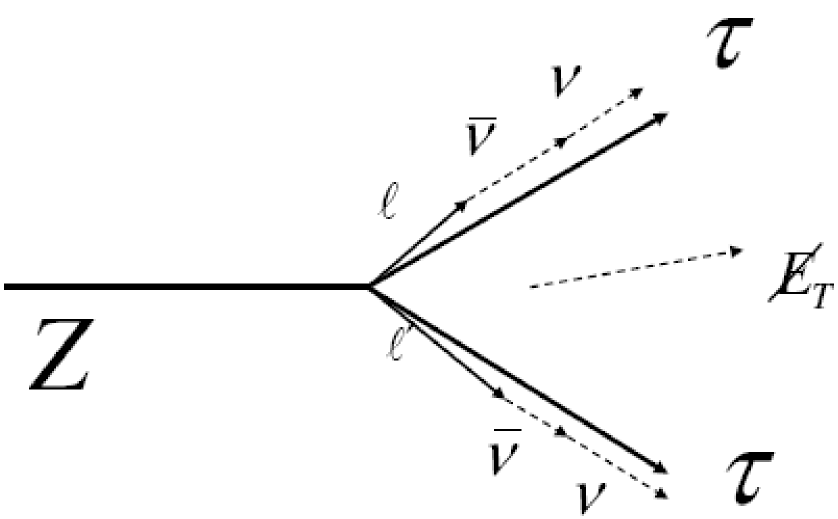
Establish Z→ ττ

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→ ττ : Colinear



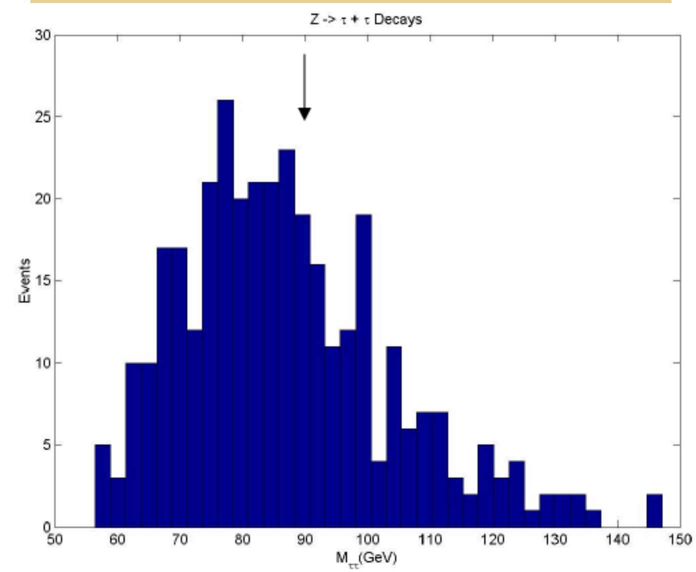
$$M_{\tau\tau} \sim \sqrt{2(E_{\ell 1}+E_{\nu\nu 1})(E_{\ell 2}+E_{\nu\nu 2})(1-\cos\theta_{\ell 1\ell 2})}$$

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

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.

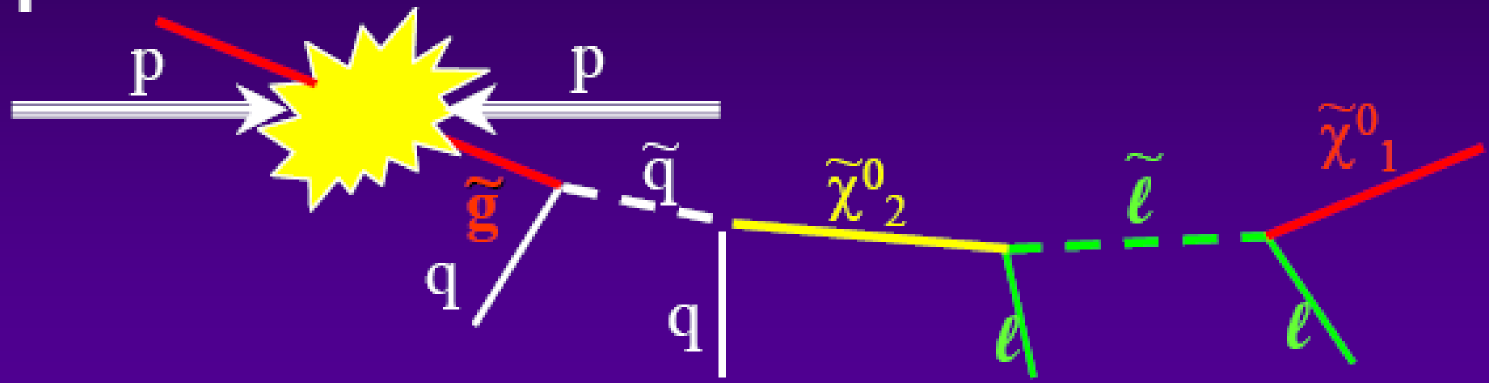


Establish SM as a Baseline in Early LHC ($10 – 500\ pb^{-1}$)

- Use SM processes to understand the detector and calibrate detector in early running
  - **Lepton energy scale from Zs**
  - **Jet energy calibration from g-j; b-j**
  - **Luminosity from W+Z rates**
  - **Tuning of Monte Carlos**
- Understand SM background processes
  - **Minimum bias and underlying event**
  - **Establish limits of knowledge of SM processes**
- Aim to study SM Physics topics
  - Cross section measurements (W, Z, Di-jets, Di-boson)
  - **Precision EW measurements: Mw, $\sin^2\theta_w$ and gauge couplings**
  - **QCD measurements: as(Q2) and PDFs**

Quick Discovery of SUSY Particles?

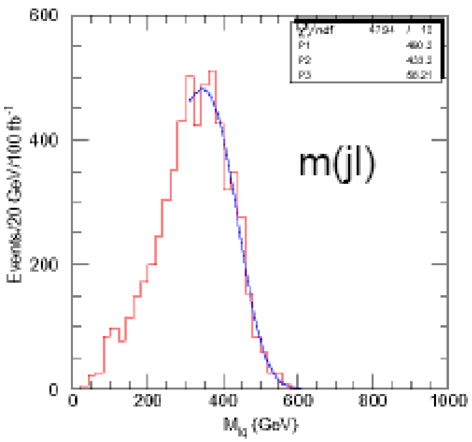
Typical SUSY event at LHC:

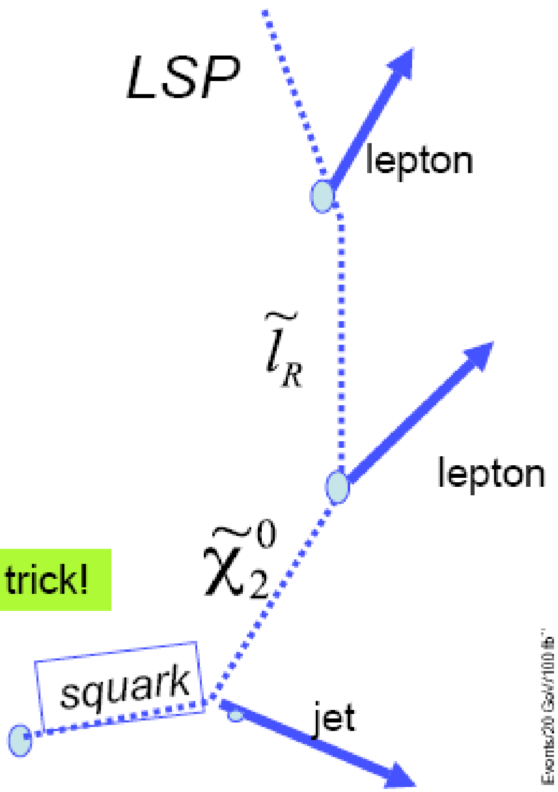


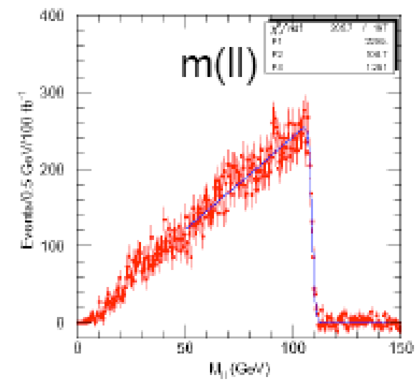
- Strongly interacting sparticles (squarks, gluinos) dominate production
  - Can have high cross-sections $\Rightarrow$ good candidate for early discovery
- sleptons, gauginos etc. $\tilde{g}$ cascade decays to LSP.
- Long decay chains and large mass differences between SUSY states
  - Many high pT objects observed (leptons, jets, b-jets).
- If R-Parity conserved LSP stable and sparticles pair produced.
  - Large ETmiss signature
- Closest equivalent SM signature $t \rightarrow Wb$ with $W \rightarrow \ell\nu$

Mass Reconstruction

determination of the boundary of phase space
for mass determination.



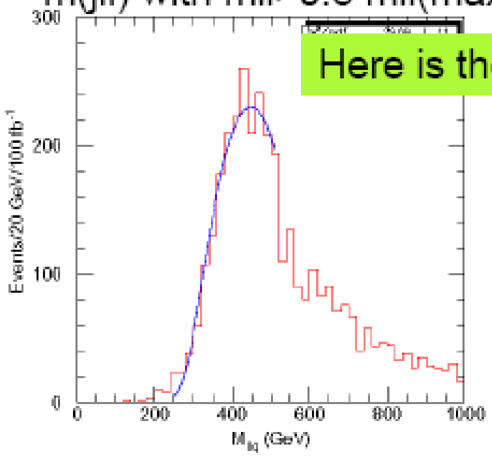


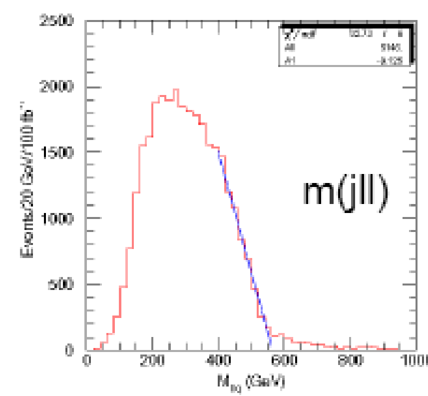


ee+μμ-eμ subtraction
is effective to select
single channel

m(jll) with mll>0.5 mll(max)

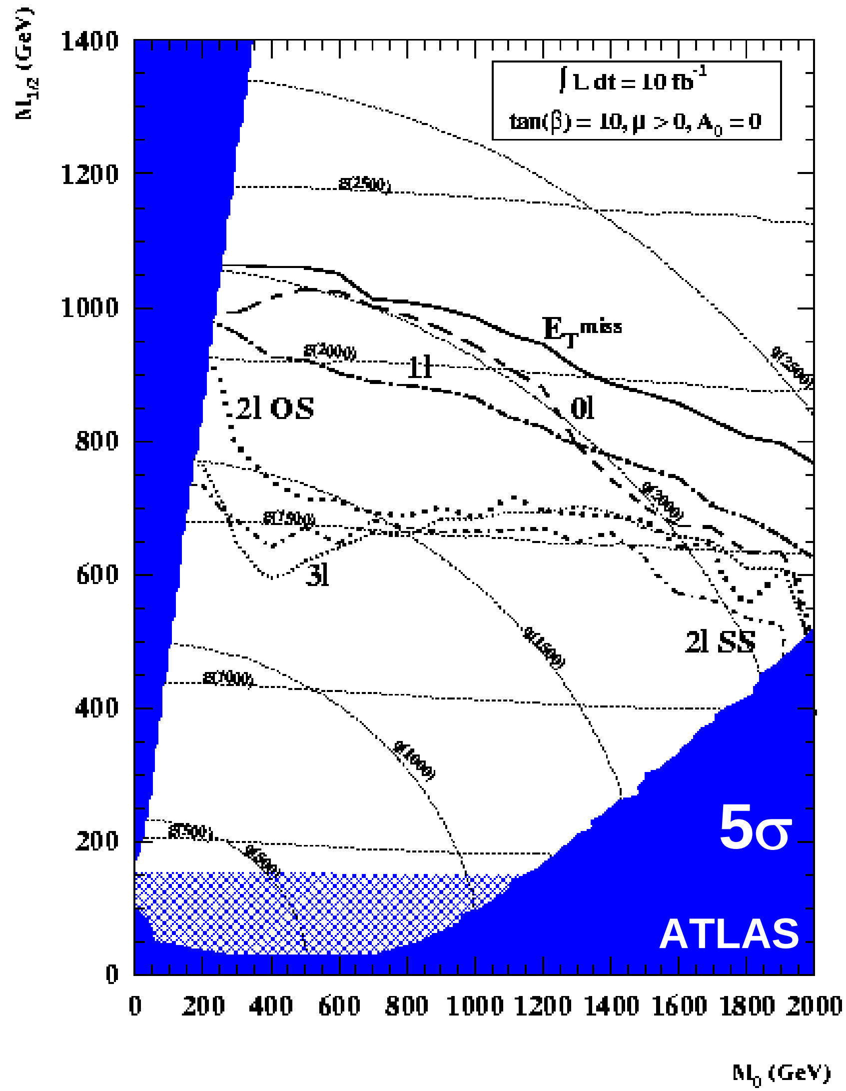
Here is the trick!





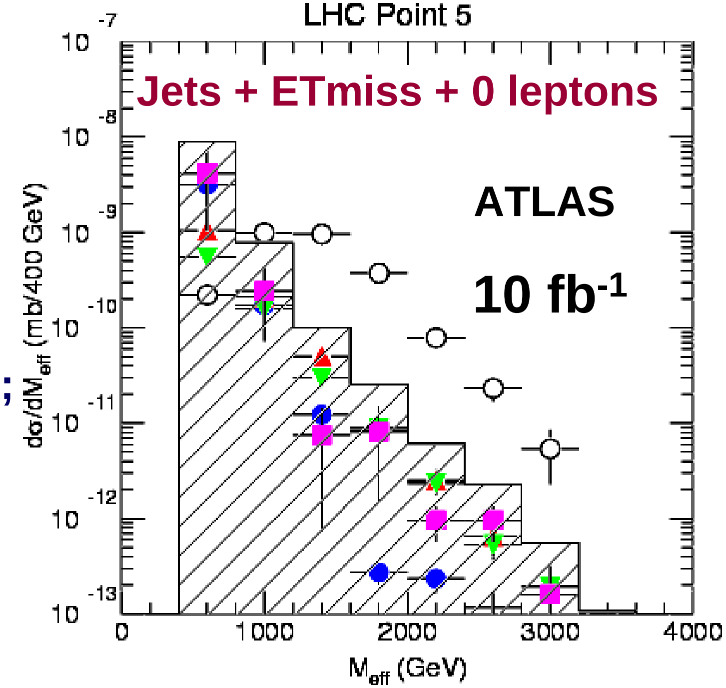
SUSY Search (ATLAS)

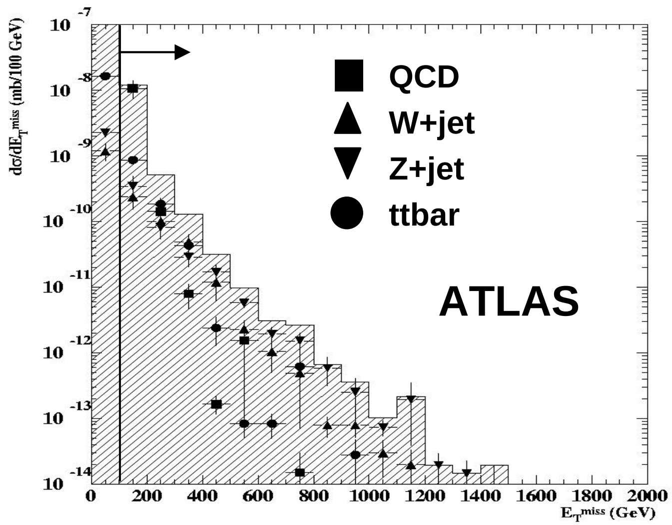
- R-Parity conserving SUSY search channels:
  - **Large E_T^{miss};**
  - **Large jet multiplicity;**
  - **Large E_T^{sum}.**
- Will need convincing estimates of backgrounds with as little data as possible.
- Background estimation techniques will change depending on integrated lumi.
- Ditto optimum search channels & cuts.
- Aim to use combination of
  - **Fast/'brisk'-sim;**
  - **Full-sim;**
  - **Estimations from data.**
- Use comparison between different techniques to validate estimates and build confidence in (blind) analysis.



Strategy

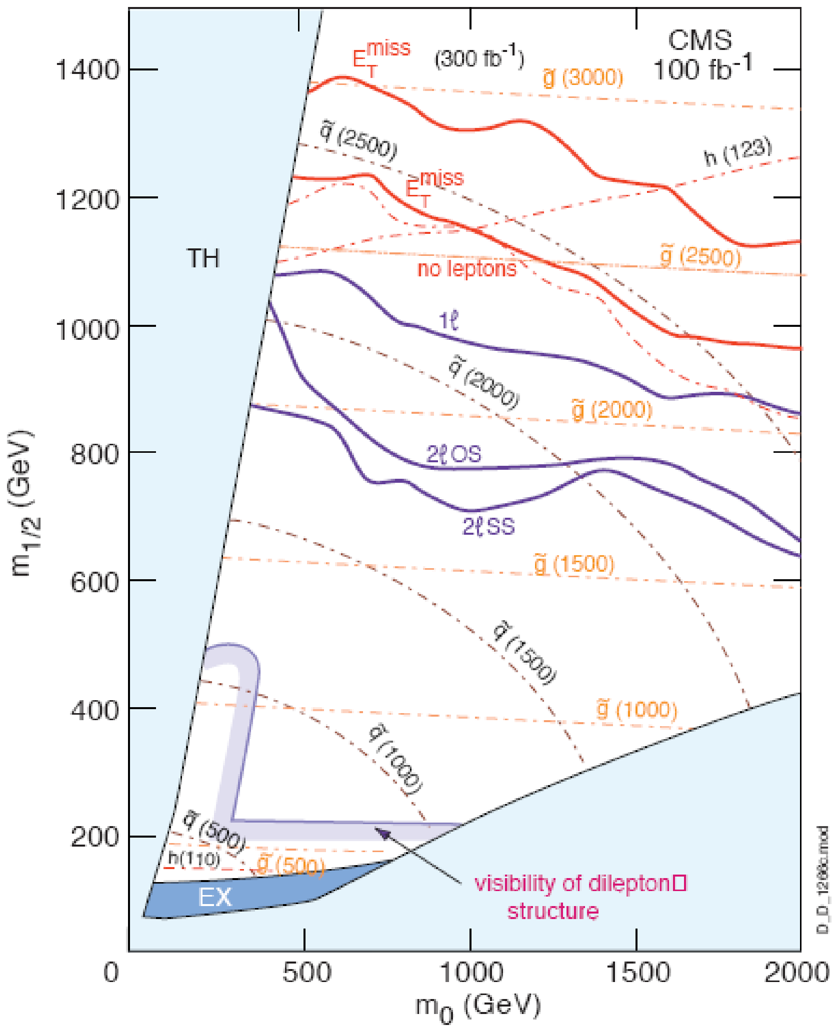
- **Main backgrounds:**
  - Z + n jets
  - W + n jets
  - ttbar
  - QCD
- **Also:**
  - Single top
  - WW/WZ/ZZ
- **Generic approach :**
  - Select low E_T^{miss} background calibration samples;
  - Extrapolate into high E_T^{miss} signal region.





- **Used by CDF / D0**
- **Extrapolation non-trivial.**
  - Must find variables uncorrelated with E_T^{miss}
- **Several approaches developed.**

SUSY Discovery Potential (CMS)

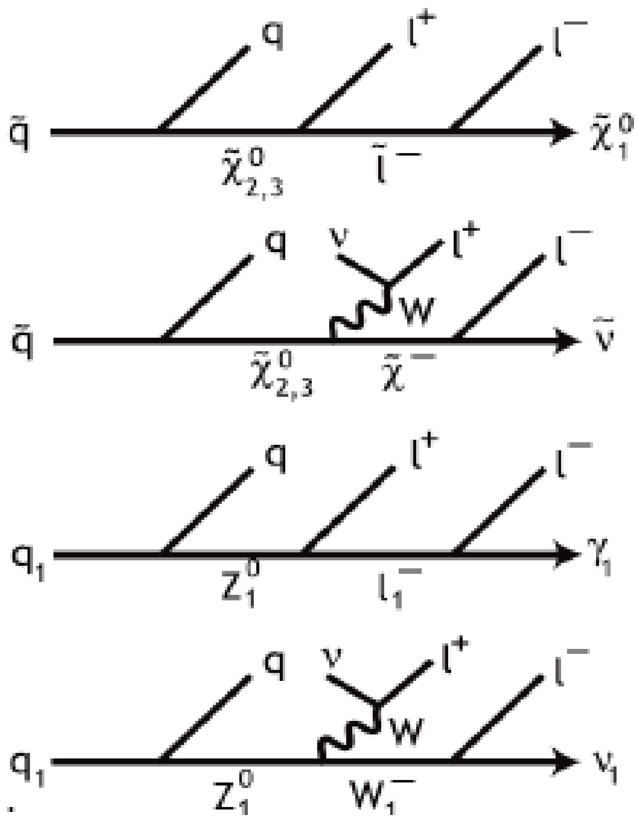


CMS 5σ reach for R-parity conserving mSUGRA in various inclusive channels:

- $\not{E}_T$
- $\not{E}_T$ with lepton veto
- One lepton channel
- Two opposite sign (OS) leptons
- Two same sign (SS) leptons

Do we understand what the new physics is?

Many ways to produce a ‘signature’ in l^+l^- jet + $\not{E}_T$(dark matter signature)



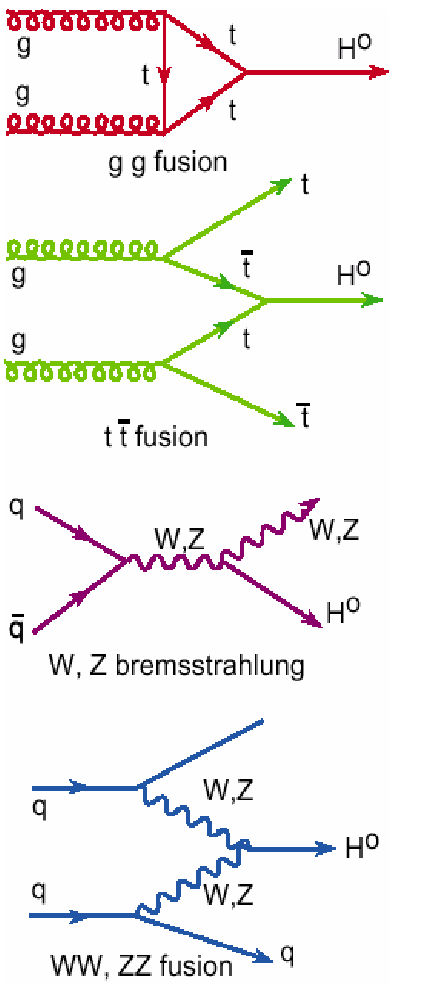
SUSY LSP = neutrolino

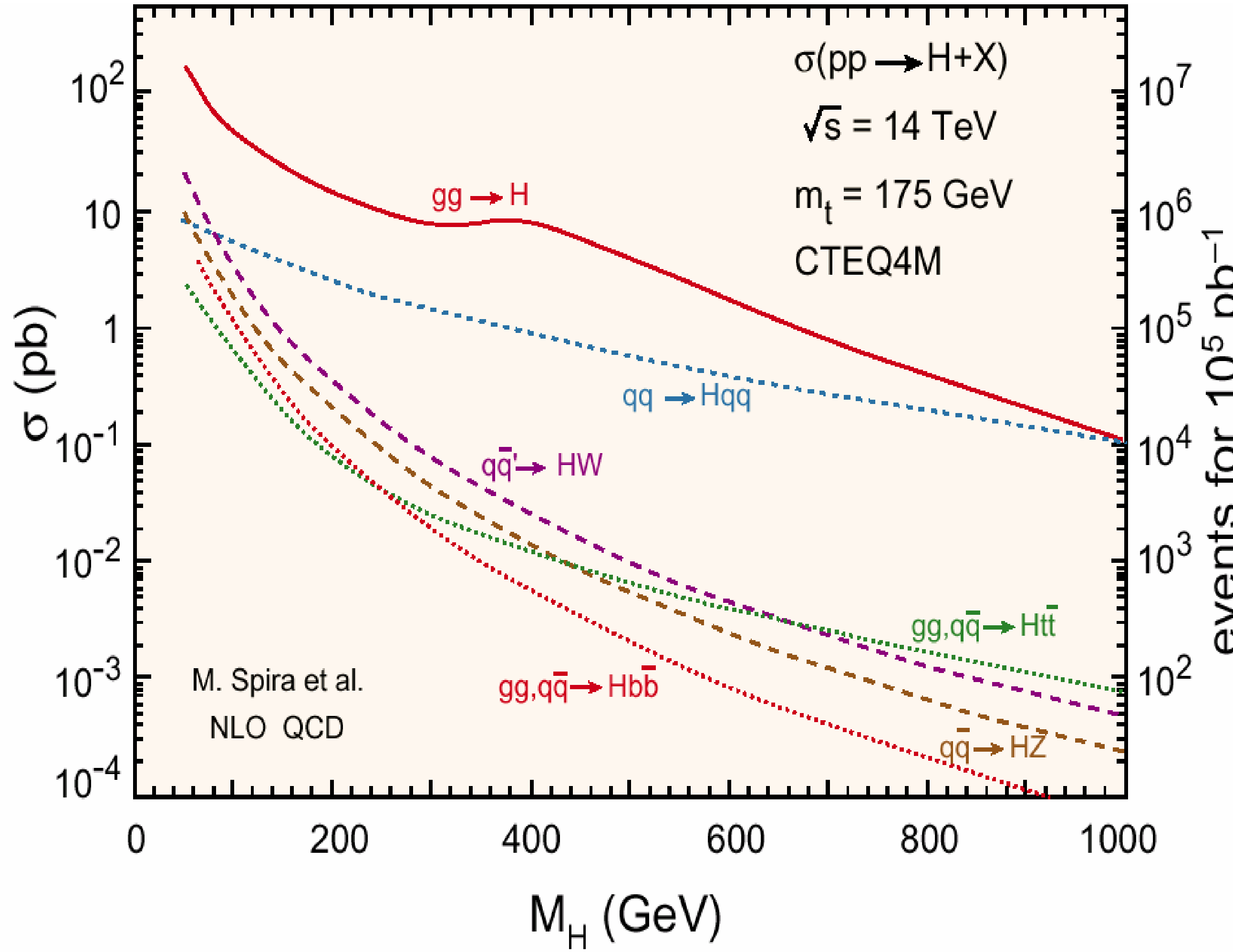
SUSY LSP = scalar neutrino

X – dimension model variants

LHC can’t distinguish these interpretations. At ILC, the cross-sections and angular distributions for different initial state polarizations tell us which is happening.

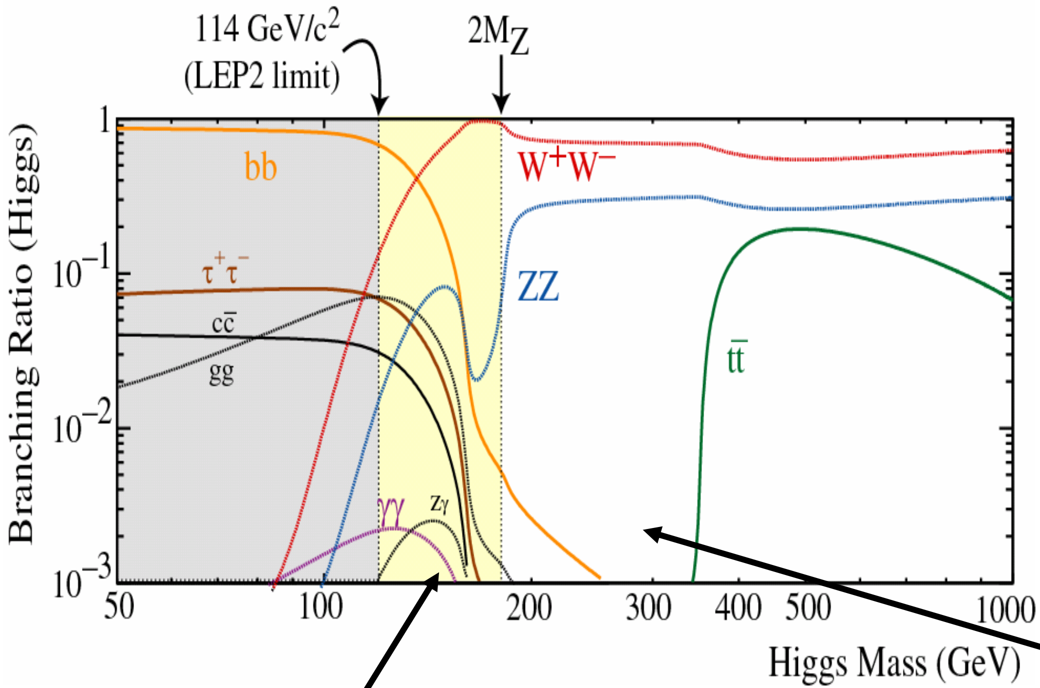
Higgs Production Mechanism @ LHC





4 production mechanism ➡ key to measure H-boson parameters

Higgs Discovery Channels at LHC



Dominant BR for $m_H < 2m_Z$:
$\sigma(H \to bb) \approx 20$ pb;
$\sigma(bb) \approx 500\ \mu b$
for m(H) = 120 GeV
→ no hope to trigger or extract fully hadronic final states
→ look for final states with ℓ, γ (ℓ = e, μ)

Low mass region: m(H) < 2 m_Z :

$H \to \gamma\gamma$: small BR, but best resolution

$H \to bb$: good BR, poor resolution ➔ ttH, WH

$H \to ZZ^* \to 4\ell$

$H \to WW^* \to \ell\nu\ell\nu$ or $\ell\nu jj$: via VBF

$H \to \tau\tau$: via VBF

m(H) > 2 m_Z :

$H \to ZZ \to 4\ell$

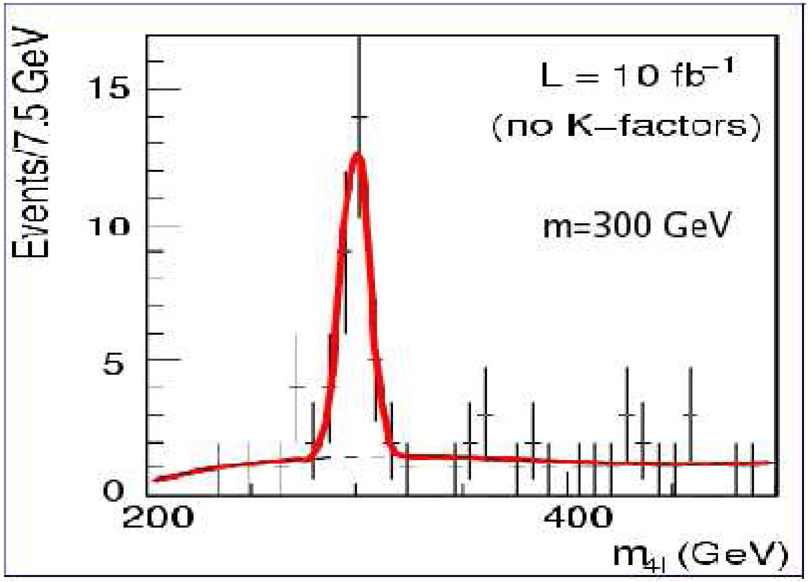
$qqH \to ZZ \to \ell\ell\ \nu\nu$ *

$qqH \to ZZ \to \ell\ell\ jj$ *

$qqH \to WW \to \ell\nu jj$ *

* for m_H > 300 GeV forward jet tag

Light SM Higgs Search

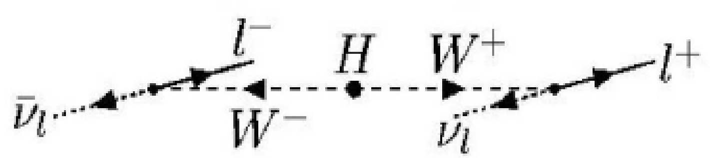


- Most important backgrounds:
  - ZZ production. Irreducible.
  - $t\bar{t}$ and Zbb, with two semi-leptonic b-quark decays.

- The $ZZ \rightarrow 4\ell$ very clean signal.
  - Also use $ZZ \rightarrow \ell\ell qq, \ell\ell\nu\nu\ldots$
- All of the Higgs boson's decay products are reconstructed.
- Very good sensitivity in this channel for $m_H \geq 130$ GeV.
- For $m_H > 2m_Z$ this becomes the "gold plated channel".
- Dominant background from continuum ZZ production.
  - Can be estimated from sidebands in data.

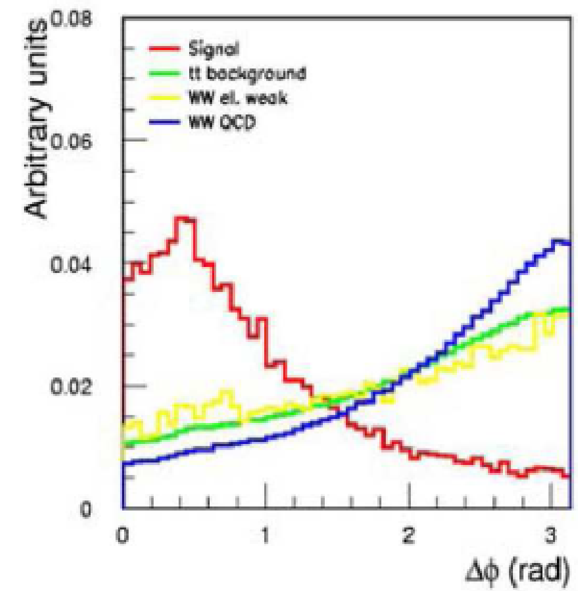
H → WW

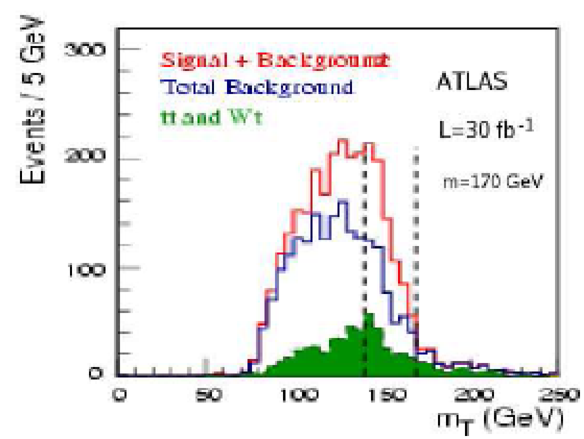
- $BR(H \to WW)$ is nearly 98% for a Higgs boson with $m_H \approx 160$ GeV.
- Backgrounds from WW, $t\bar{t}$, WZ.
- Use the lepton spin correlations:



- No mass peak, have to use m_T:

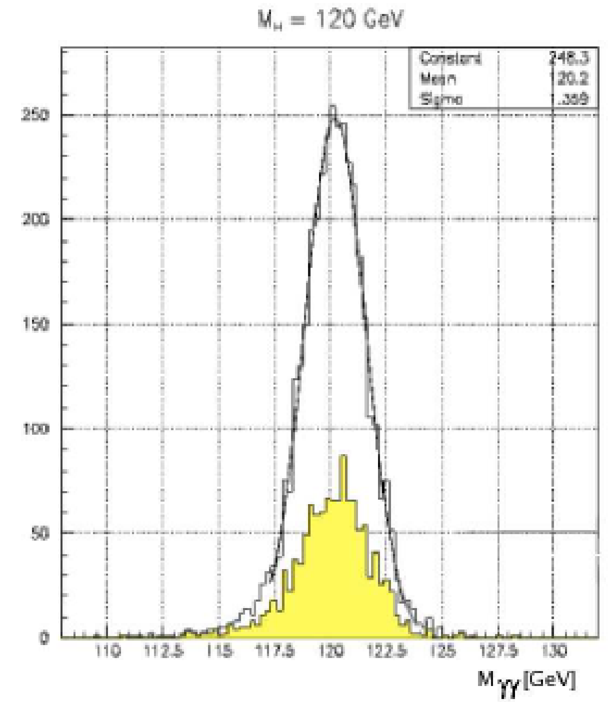
$$m_T = \sqrt{2 p_T^{\ell\ell} \not{E}_T (1 - \cos \Delta\phi)}$$





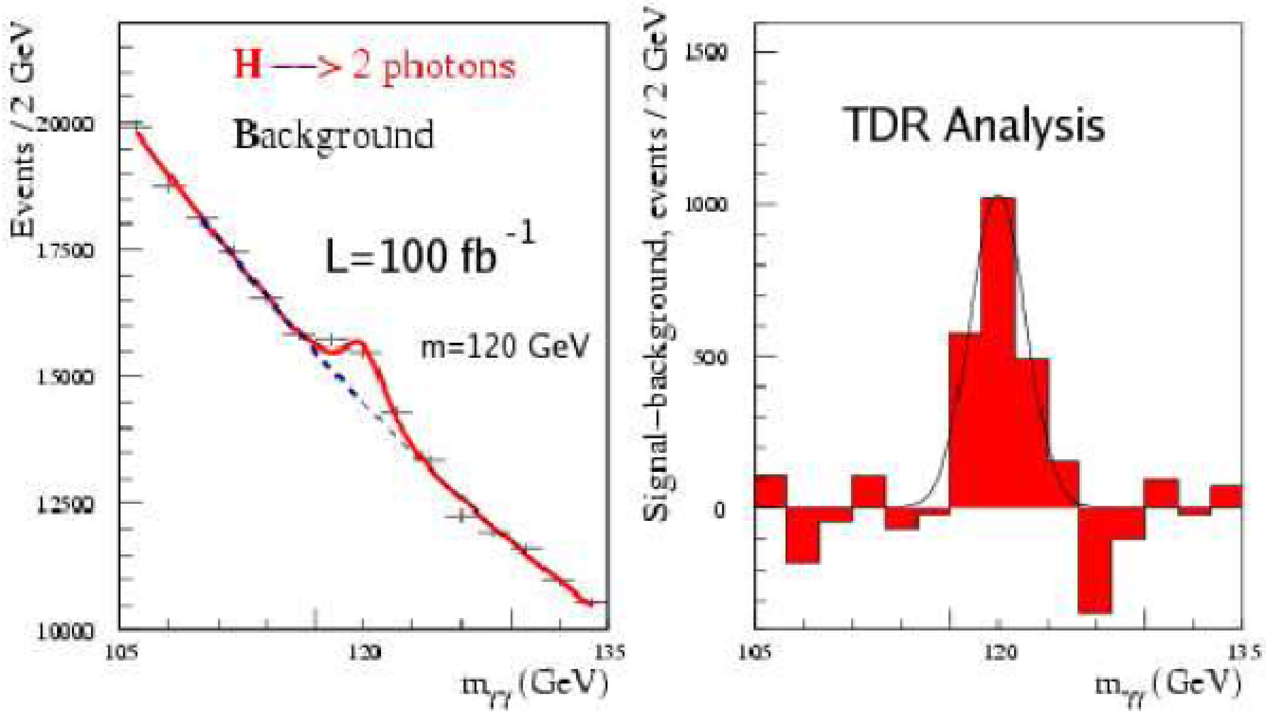
H → γ γ

- Typical event selection criteria:
  - Two isolated photons with $p_T > 40$ and $p_T > 25$.
  - Both photons within $|\eta| < 2.4$, excluding gaps.
  - Invariant mass of the photons: $M_H - 2 < M_{\gamma\gamma} < M_H + 2$ GeV.
- Mass resolution $\sigma(M_{\gamma\gamma}) \approx 1.36$ GeV.
- Photons conversions taken into account ($\sim 40\%$ of the events).
- EM calorimeter is crucial:
  - Energy and angle resolution.
  - Photon acceptance.
  - γ/jet and γ/π^0 rejection.



H → γγ Background

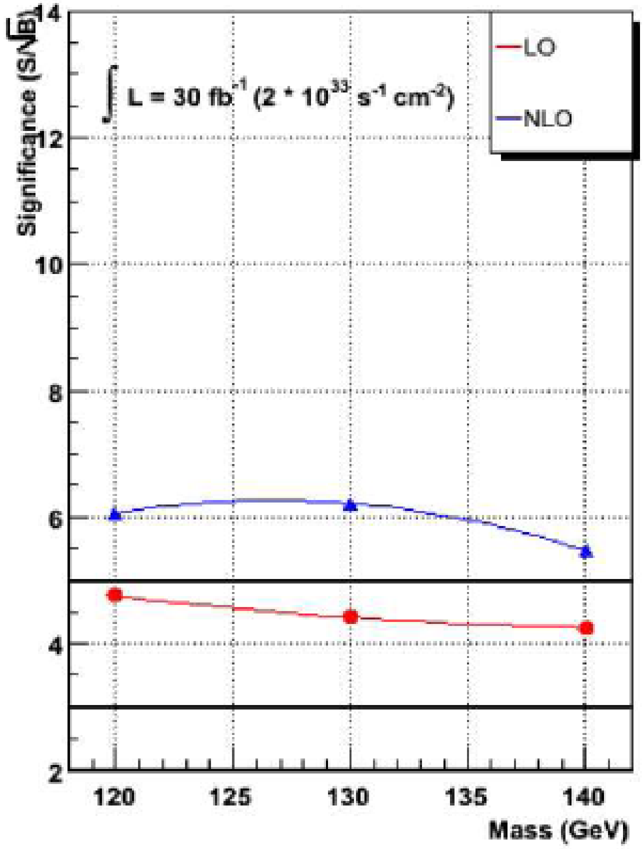
- The largest background comes from irreducible $\gamma\gamma$ production. $\sigma_{\gamma\gamma} \approx 125$ fb/GeV. Need mass resolution $\sigma(M_{\gamma\gamma})/M_{\gamma\gamma} \approx 1\%$.
- Reducible background from jets misreconstructed as photons. $\sigma_{\gamma j} \approx 8 \cdot 10^2 \cdot \sigma_{\gamma\gamma}$ and $\sigma_{jj} \approx 2 \cdot 10^6 \cdot \sigma_{\gamma\gamma}$. Need rejection $R_j > 10^3$.



Significance with NLO Calculation

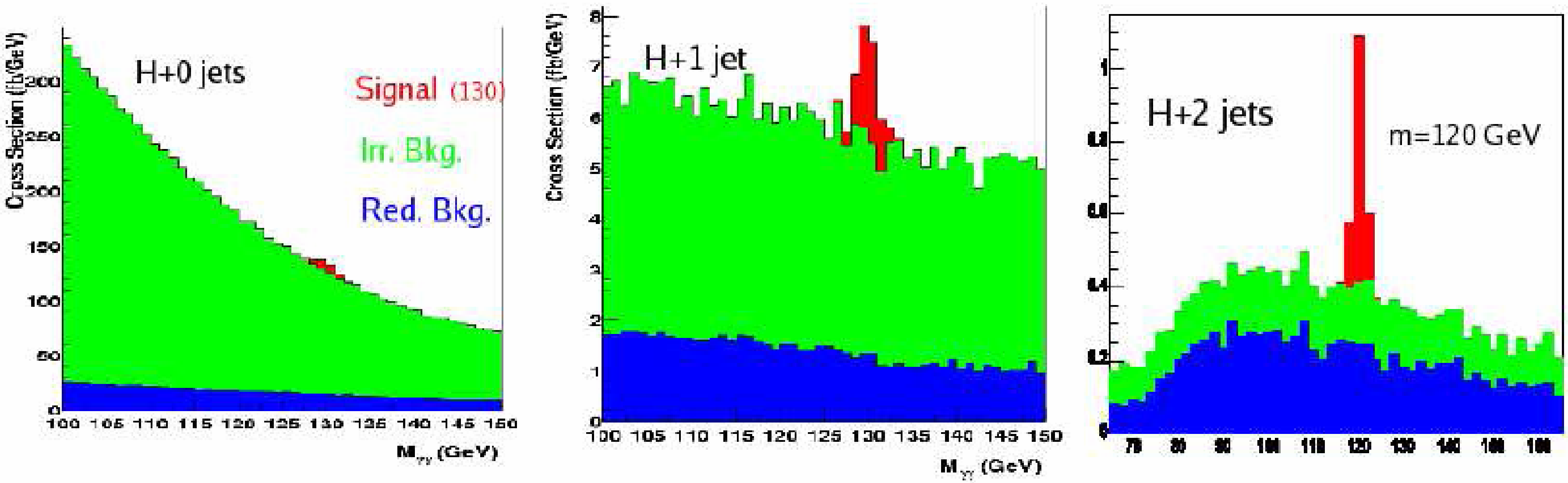
- Cross sections calculated at NLO:
  - $K \sim 1.8$ for $gg \to H$.
  - The full $\mathcal{O}(\alpha_S)$ calculation, plus box diagram, for the $\gamma\gamma$ background.
  - $K \sim 1.7$ for γj and jj backgrounds.

Event yield (at NLO) for 30 fb^{-1}		
m_H	120 GeV	130 GeV
$H \to \gamma\gamma$	815	758
$\gamma\gamma$	14100	9552
$\gamma j, jj$	3967	3396
$S/\sqrt{B}$	6.06	6.22



- Gives dramatic improvement in sensitivity.

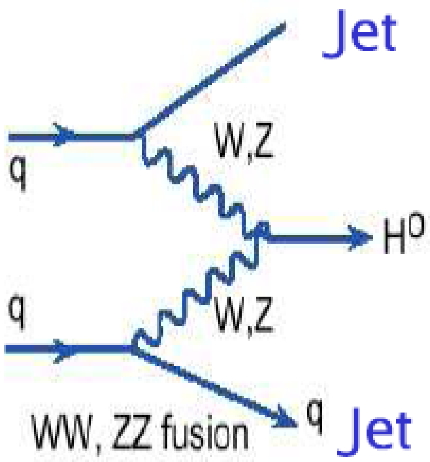
Combination of H + n-jets Analysis



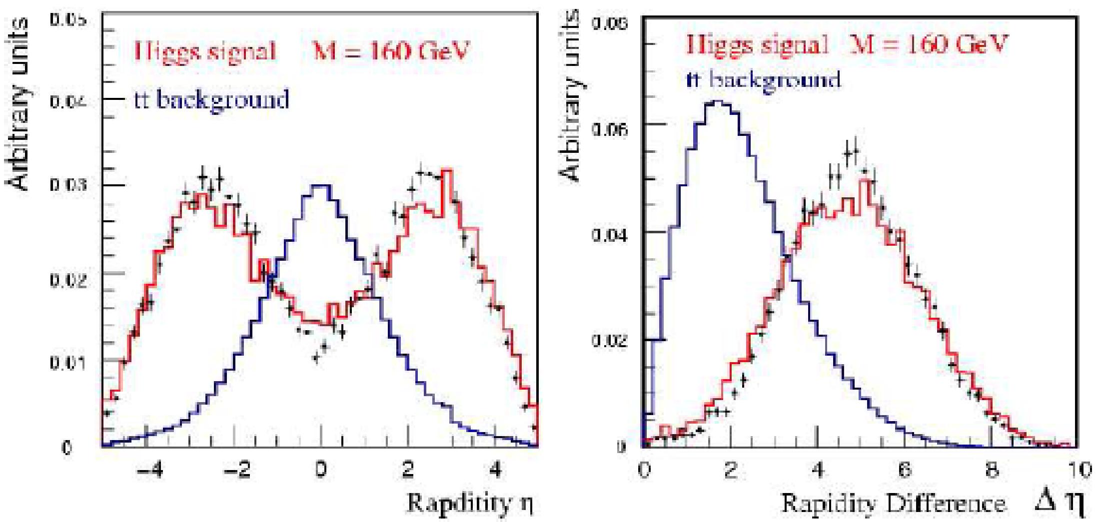
- Do inclusive analysis. Use a combination of all jet multiplicities.
  - $H + 0$ jets from $gg \to H$.
  - $H + 1$ jet at NLO, plus VBF production with one lost jet.
  - $H + 2$ jets from VBF.
- Decrease in signal, increase in S/B with jet multiplicity.
  - Decrease in systematic uncertainty?
- This is a preliminiary study.
  - Looks promising.

Signal with VBF Events

- Typical selections for tag jets:
  - $p_T > 40$ and $p_T > 20$ GeV.
  - $\Delta\eta > 3.8$ between the tag jets.
- Apply a central jet veto:
  - No central jets with $p_T > 20$ GeV.
  - H decay products between tag jets.



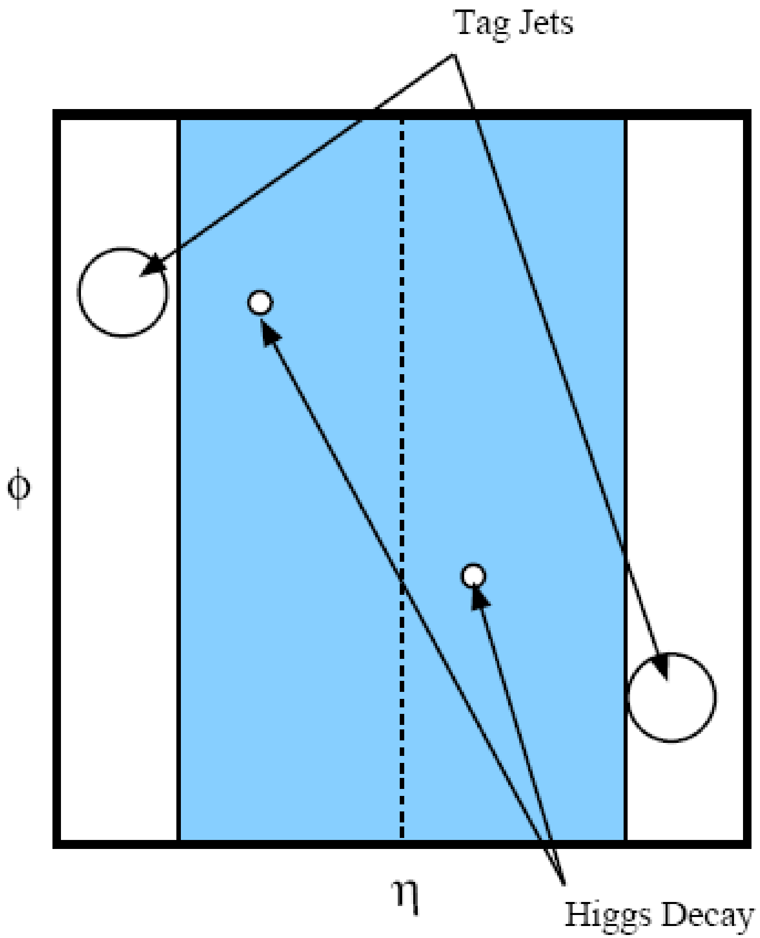
- Powerful way to reduce backgrounds.
- Uncertainty from underlying and overlapping event, pile-up.



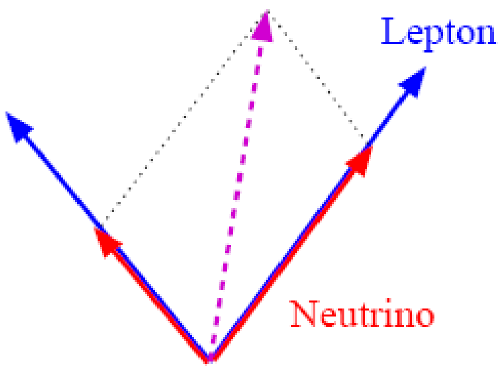
H→ ττ and H→WW in VBF production

- At low Higgs masses the largest sensitivity search channels are found in the vector boson fusion production mode.

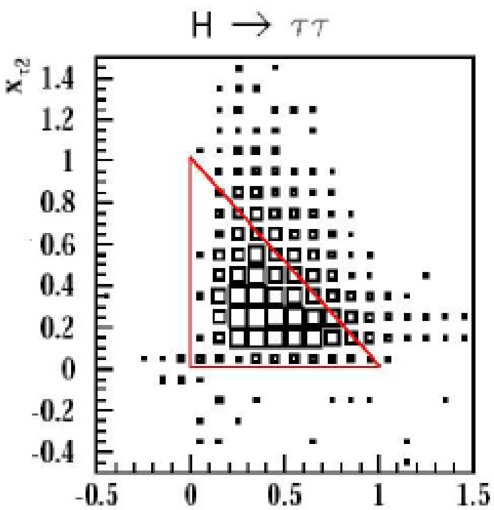
- At least one of the W/τ's have to decay leptonically.
- Main backgrounds are $t\bar{t}$, Wt, WW+jets, γ^*/Z+jets.
- Some selection criteria ($e\mu$):
  - $p_T^e > 15$ GeV, $p_T^\mu > 10$ GeV.
  - $|\eta_\ell| < 2.5$ and $M_{\ell\ell} < M_H/2$.
  - Tag jet cuts, central jet veto.
- τ reconstruction provide extra sensitivity or rejection.

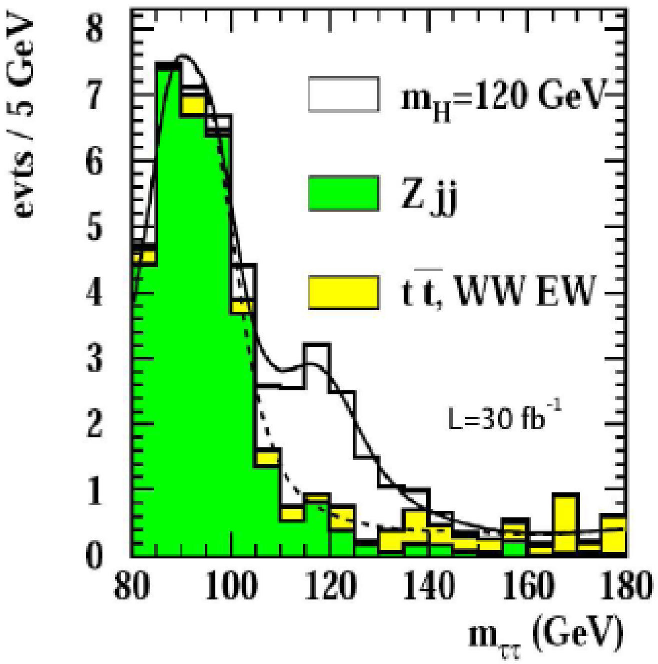


VBF H→ ττ Reconstruction



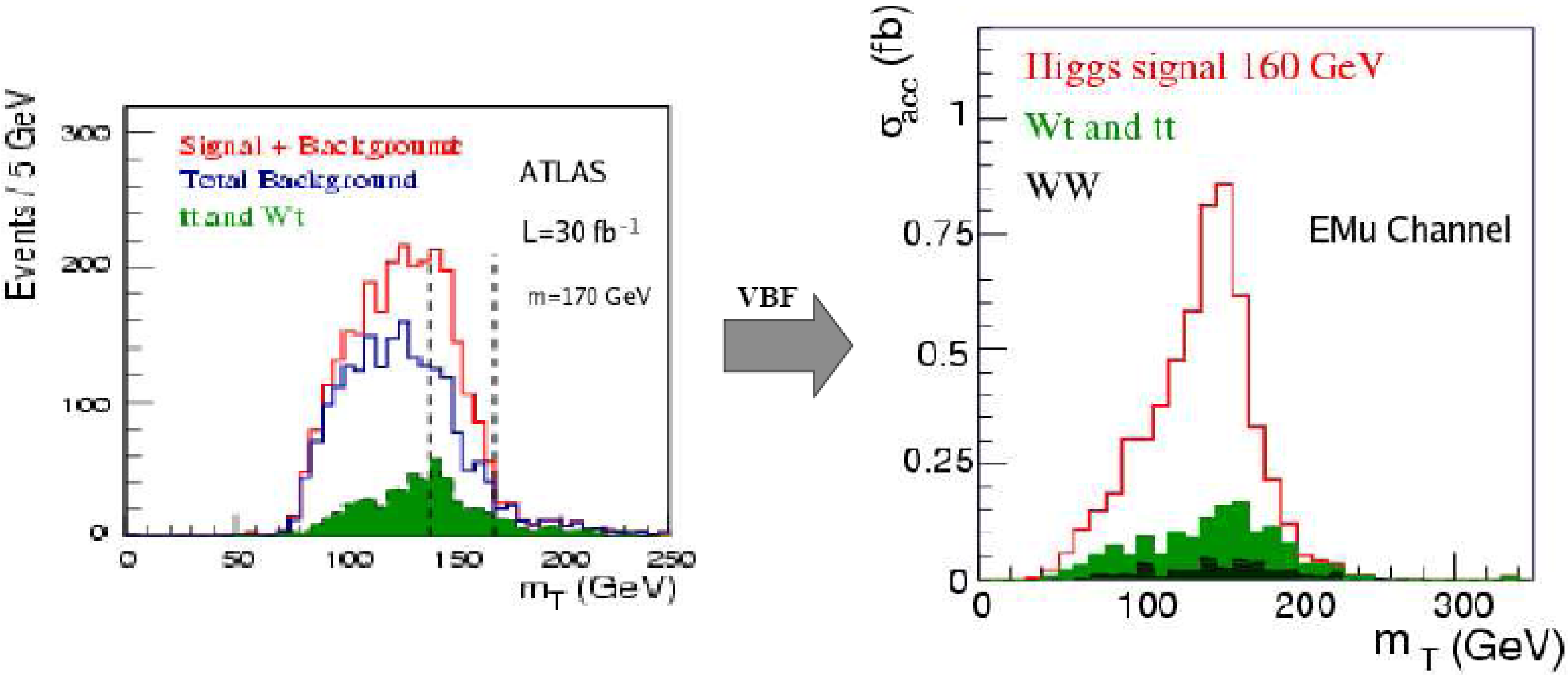
- Assume ℓ and ν's from $\tau \to \ell\nu\nu$ are collinear.
- Label visible energy fractions x_{τ_1} and x_{τ_2}.
- Assume $\not{p}_T$ vector comes from the ν's, and solve the equations for x_{τ_1} and x_{τ_2}.





VBF H→ WW Reconstruction

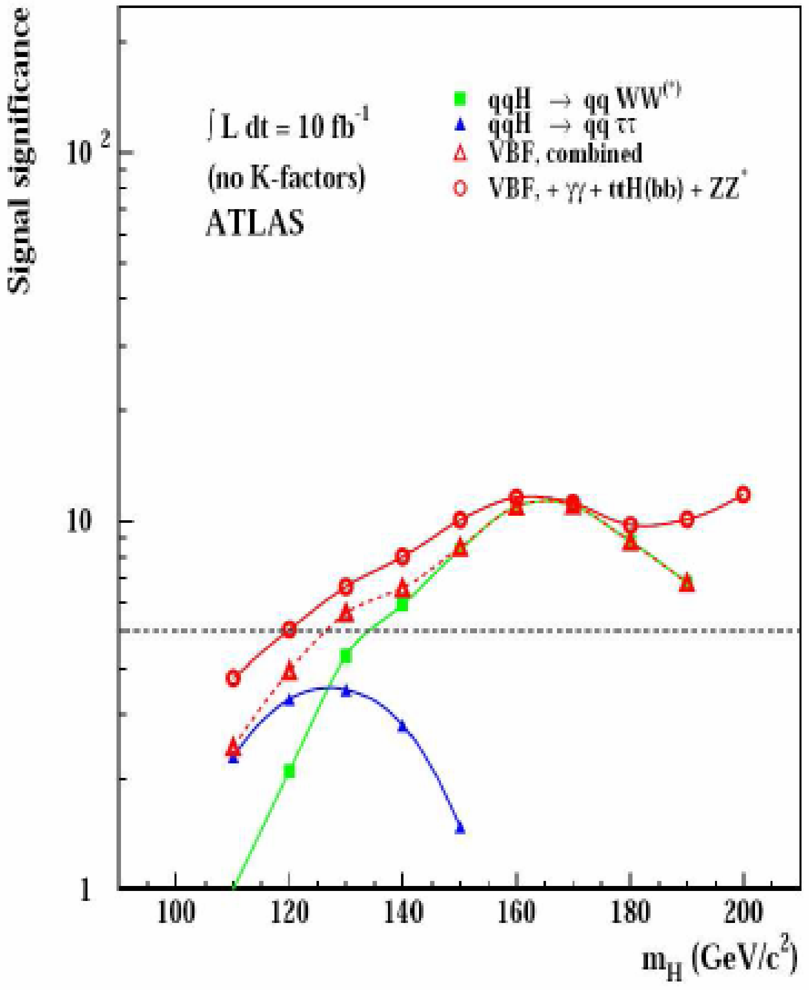
- As in the inclusive WW analysis, spin correlations between the leptons are used to enhance the signal fraction.



- Signal to background in the VBF channel increases to ~ 3.6.

Sensitivity of VBF Channels

- Both $H \to \tau\tau$ and $H \to WW$ are sensitive for low Higgs masses.
- $H \to \tau\tau$:
  - $m_H \lesssim 145$ GeV.
- $H \to WW$:
  - $125 \leq m_H \leq 200$ GeV.
- If the two channels are combined, a 5σ discovery is possible for $m_H \gtrsim 130$ GeV with 10 fb^{-1}.



Most Challenge Channel H+ ttbar

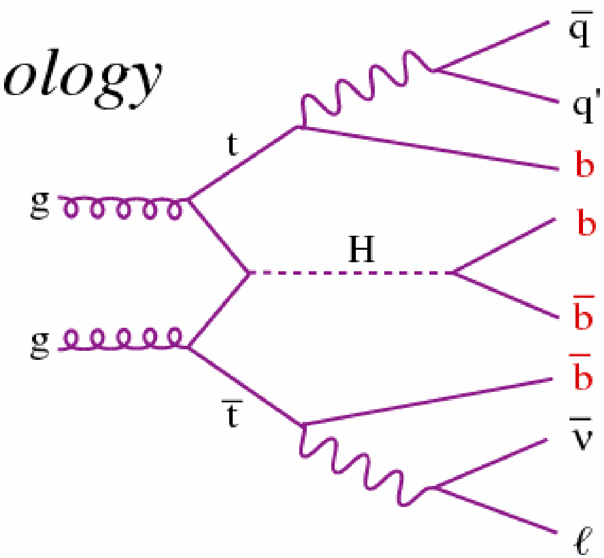
Challenging and complex topology

4 b-jets, 2 jets, 1 lepton

$H \to bb$

$t \to bqq'$

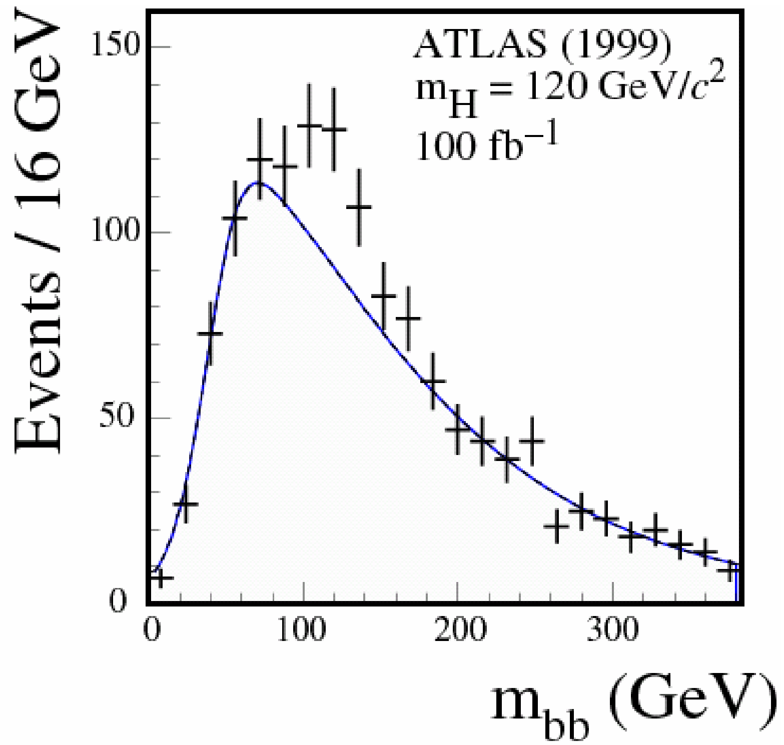
$t \to b\ell\nu$



- Spectacular, very energetic, final state!
- The ℓ from the t decay allows for triggering, even though $H \to b\bar{b}$.
- Dominant background is from non-resonant $ttbb$ production.
  - Smaller backgrounds from ttZ, $ttjj$, $WWbbjj$ ...

Need a lot of Luminosity for H ttbar detection

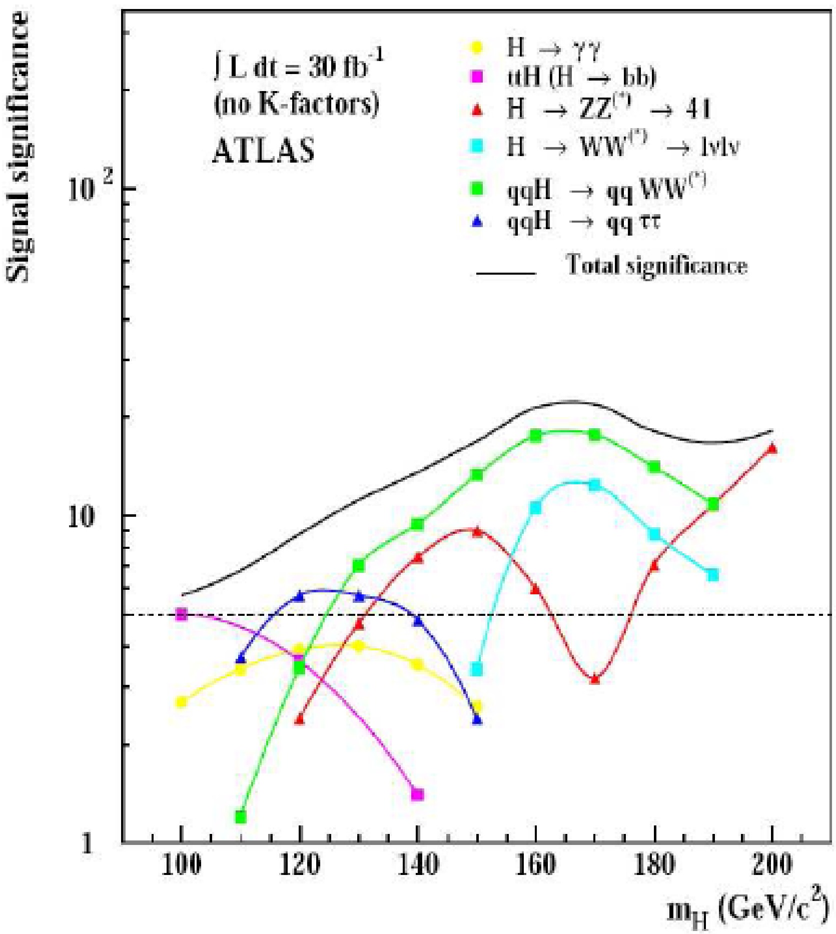
- To extract the signal:
  - Reconstruct all six jets.
  - Exactly 4 b-tagged jets.
  - Reconstruct the two t quarks.
  - Determine invariant mass of b-jets from the Higgs decay.



Signal significance (5σ) :

mH < 120 GeV needs 100 fb^{-1}

Combined Sensitivity



- Only LO results shown in plot.
- Full mass range covered after a few years of running.
- Several channels available for any given Higgs mass.
- VBF channels play important role for low Higgs masses.
- For $m_H \leq 120$ GeV three complementary channels:
  - $H \to \gamma\gamma$ ($M_{\gamma\gamma}$ resolution).
  - $t\bar{t}H$ (b-tagging).
  - $qqH \to qq\tau\tau$ (large $|\eta|$ jets).

Search for MSSM Higgs(es)

Complex analyses; 5 Higgses: h0, H0, A0, $H^{\pm}$

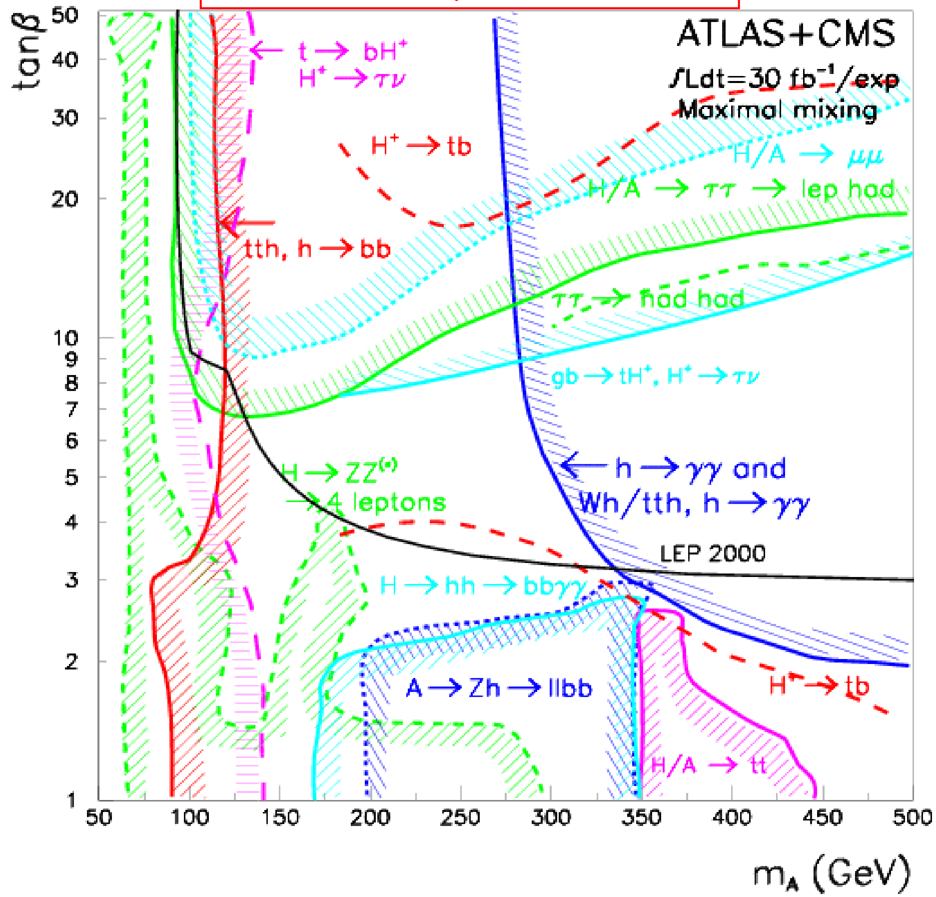
- *At tree level, all masses and couplings depend on: M_A and tanβ*

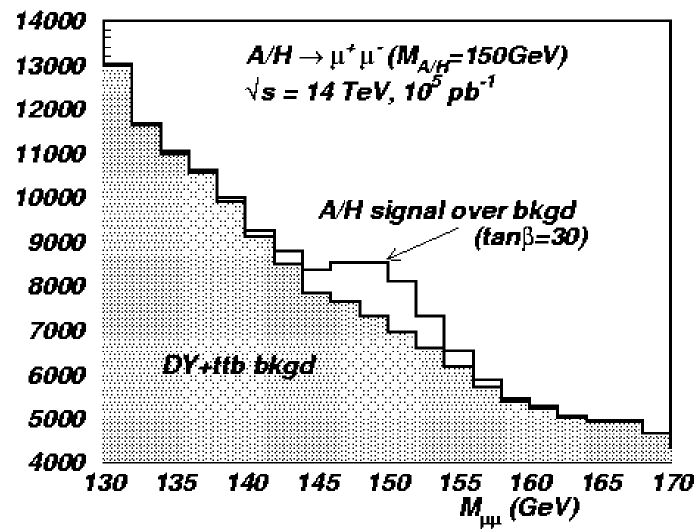
- **Large variety of observation modes**
  - if SUSY particles heavy
    - **SM-like: $h \to \gamma\gamma$, bb; $H \to 4\ell$**
    - **MSSM-specific: $A/H \to \mu\mu$, $\tau\tau$, tt ; $H \to hh$, $A \to Zh$; $H^{\pm} \to \tau\nu$**
  - if SUSY particles accessible:
    - **$H/A \to \chi^2_0 \chi^2_0 \to 4\ell$ + missing Energy**
    - **h produced in cascade decays (e.g. $\chi^2_0 \to h\, \chi^1_0$)**
- **Studies performed in two steps:**
  1. SUSY particles are heavy: no contribution to Higgs production/decay
  2. SUSY particles contribute in production/decays
     - **Impact on Higgs decay to SM particles generally small**
       - **$h \to \gamma\gamma$ 10% smaller**
       - **$A/H \to$ SM at most 40% smaller**

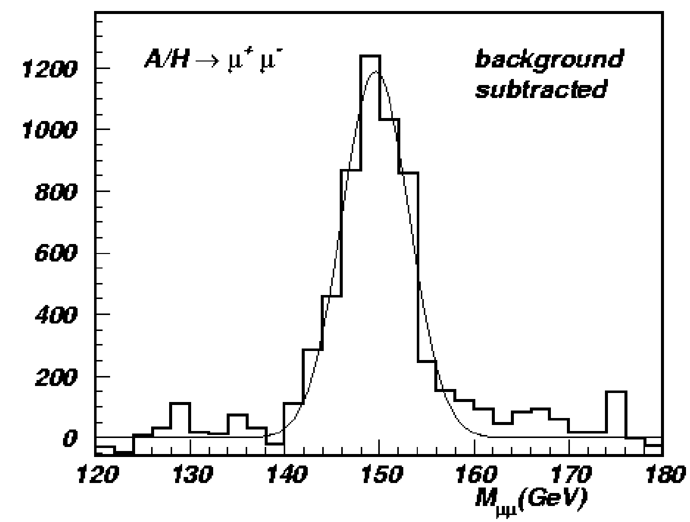
MSSM Higgs Discovery Potential

- ✓ Plane fully **covered** with **30 fb^{-1}**
- ✓ 2 or more Higgses observable in large fraction of plane

5σ discovery contours







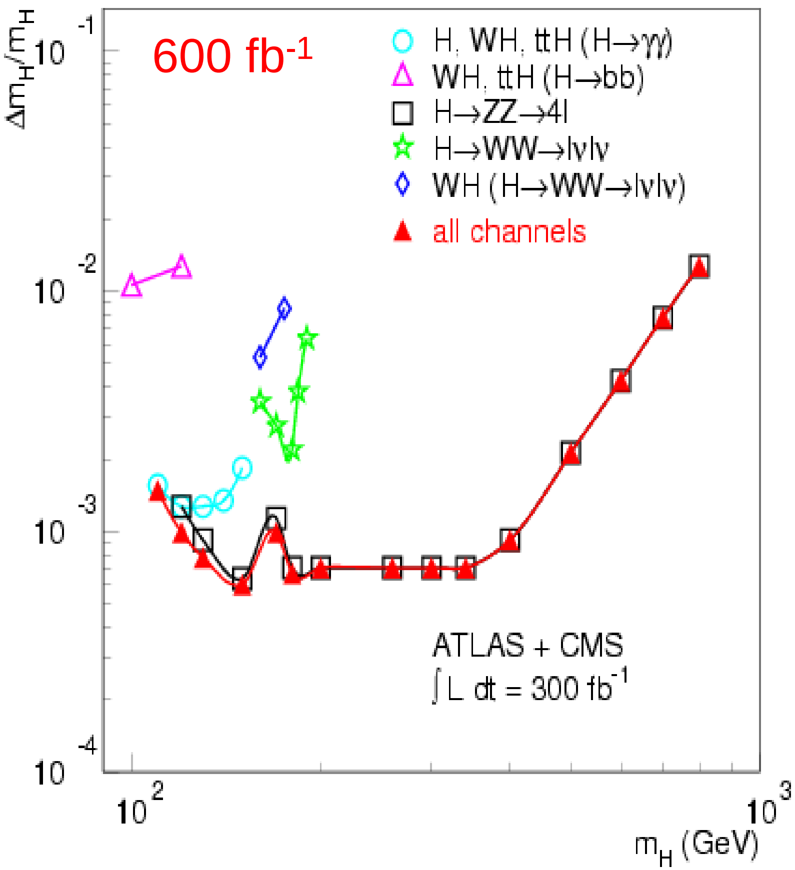
Higgs Boson Parameters: Mass

SM

✓ Limited by absolute energy scale
- 0.1% for ℓ/γ ($Z \to \ell\ell$ calibration)
- 1% for jets

✓ Resolutions:
- For $\gamma\gamma$ & $4\ell \approx 1.5$ GeV/c^2
- For bb ≈ 15 GeV/c^2

✓ At large masses: decreasing precision due to large Γ_H



MSSM

✓ h as in SM case
✓ H/A: 0.1 - 0.5% in modes $\gamma\gamma$, 4ℓ, $\mu\mu$
✓ 1 - 2% in modes bb, bb$\gamma\gamma$ (hh), bb$\ell\ell$ (Zh)

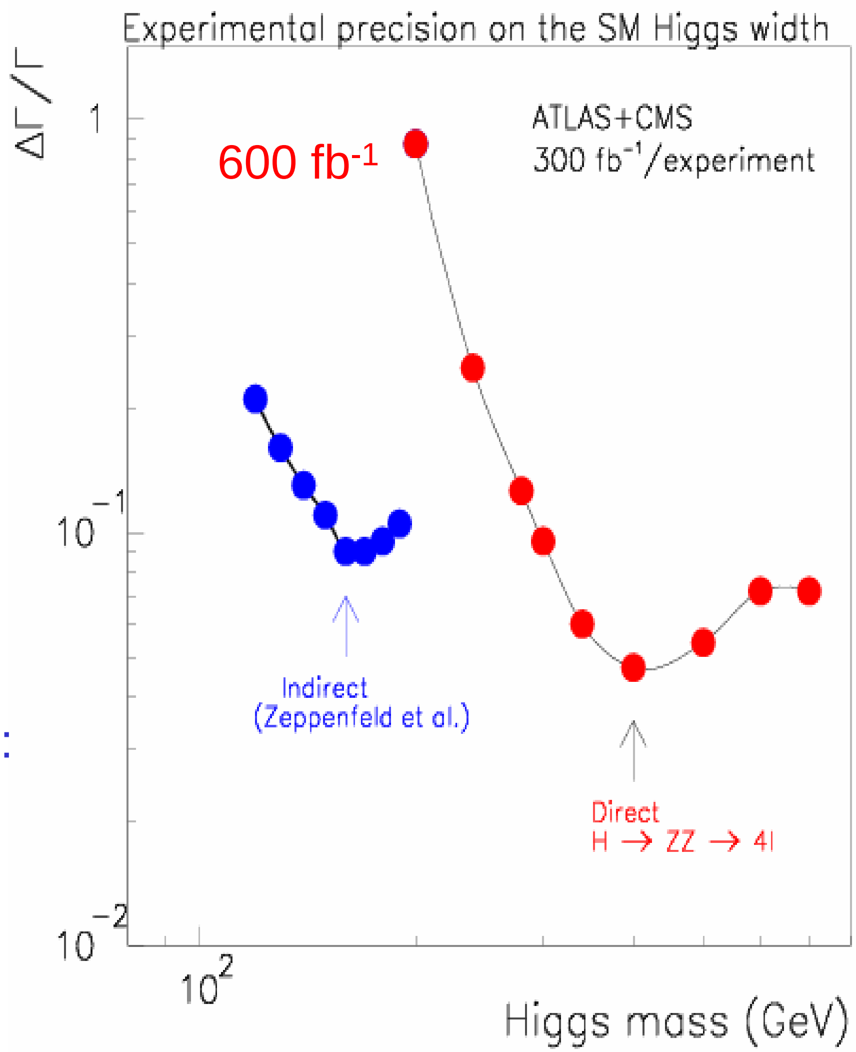
Higgs Parameters: Width

- Direct width measurement:
  - Mass peak width of $H \to ZZ \to 4\ell$ channel

    for $M_H > 200$ GeV

    ($\Gamma_H > \Gamma_{exp}$ in SM)
  - Systematics: radiative decays (1.5%)
- Indirect width measurement:
  - Comparison of rates in channels:
    - $qq \to qqH$, $H \to \gamma\gamma, \tau\tau, WW$
    - $gg \to H$, $H \to \gamma\gamma, ZZ^*, WW^*$
  - Assumption:

    o BR($H \to$ cc, non-standard) < 10%



Higgs Parameters: Couplings (1)

Ratio of boson-boson couplings

Direct: ratio between W and Z partial width

$$\frac{\sigma \times BR(H \to WW^*)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_W}{\Gamma_g \Gamma_Z} = \frac{\Gamma_W}{\Gamma_Z}$$

QCD correction cancel

VBF: ratio between W and Z partial width

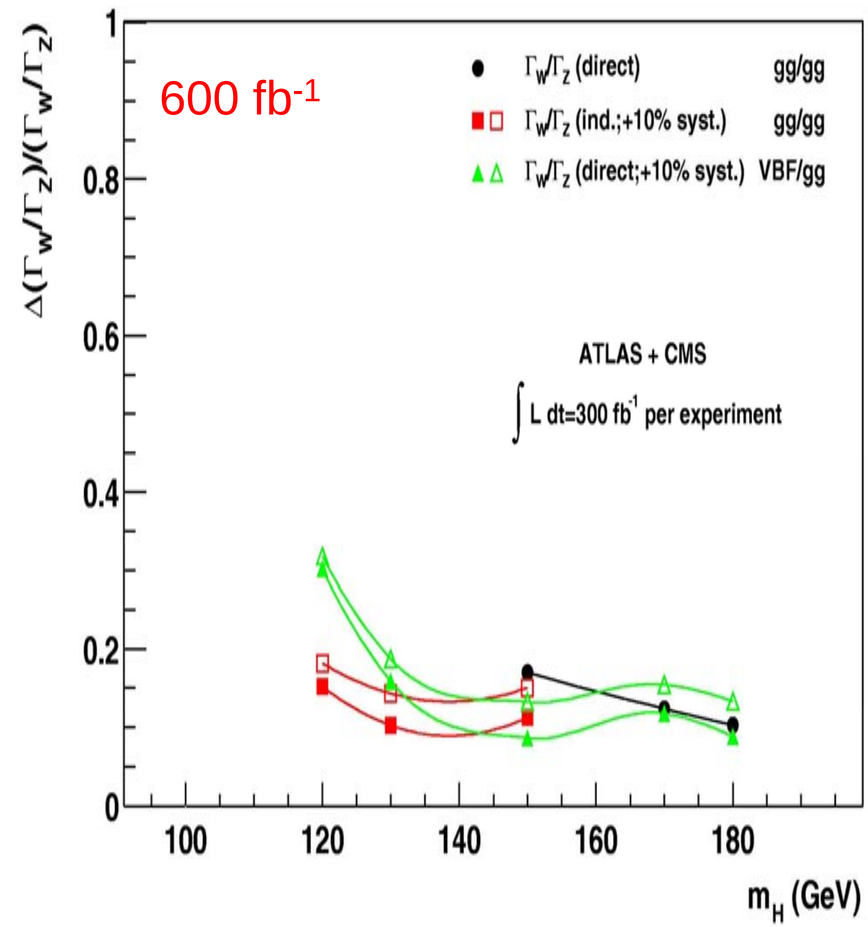
$$\frac{\sigma \times BR(qqH \to qqWW^*)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_W}{\Gamma_Z}$$

different processes, QCD corrections do not cancel, i.e. add. uncertainty

Indirect: ratio between γ and Z partial width

$$\frac{\sigma \times BR(H \to \gamma\gamma)}{\sigma \times BR(H \to ZZ^*)} = \frac{\Gamma_g \Gamma_\gamma}{\Gamma_g \Gamma_Z} \approx \frac{\Gamma_W}{\Gamma_Z}$$

Use proportionality between G_W and G_γ, Needs theoretical input, 10% uncertainty assumed



Higgs Parameters: Couplings (2)

Ratio of boson-fermion couplings

VBF: allows a direct measurement of G_W/G_t in the mass range 120 – 150 GeV

Direct :

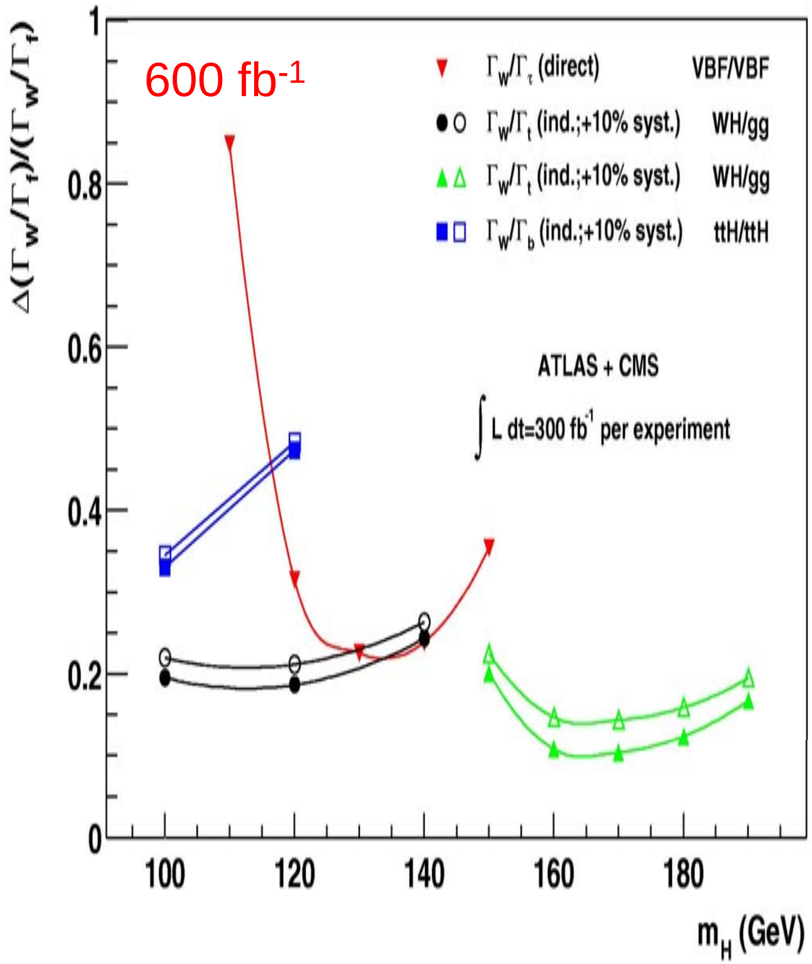
$$\frac{\sigma \times BR(qqH \rightarrow qqWW)}{\sigma \times BR(qqH \rightarrow qq\tau\tau)} = \frac{\Gamma_W \Gamma_W}{\Gamma_W \Gamma_\tau} = \frac{\Gamma_W}{\Gamma_\tau}$$

Indirect :

$$\frac{\sigma \times BR(WH \rightarrow W\gamma\gamma)}{\sigma \times BR(H \rightarrow \gamma\gamma)} \sim \frac{\Gamma_W}{\Gamma_t} \cdot C_{QCD}$$

$$\frac{\sigma \times BR(WH \rightarrow WWW)}{\sigma \times BR(H \rightarrow WW)} \sim \frac{\Gamma_W}{\Gamma_t} \cdot C_{QCD}$$

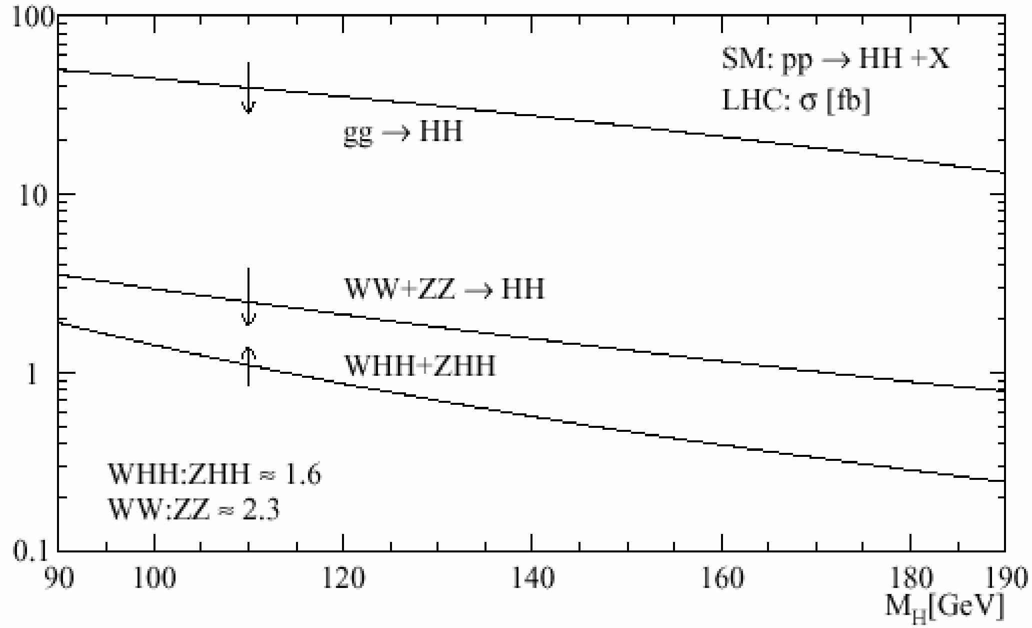
$$\frac{\sigma \times BR(ttH \rightarrow ttbb)}{\sigma \times BR(ttH \rightarrow tt\gamma\gamma)} \sim \frac{\Gamma_b}{\Gamma_W}$$



Higgs Parameters: Self-couplings

Cross section of the Higgs pair production at LHC

Hep-ph/0204087



Need Super LHC to measure
Higgs self-interaction couplings:

$$\lambda^{SM}_{HHH} = 3\,\frac{m_H^2}{v}\,, \qquad \lambda^{SM}_{HHHH} = 3\,\frac{m_H^2}{v^2}$$

Table 8: Expected numbers of signal and background events after all cuts for the $gg\to HH\to 4W\to \ell^+\ell'^+4j$ final state, for $\int\mathcal{L} = 6000$ fb^{-1}.

m_H	Signal	$t\bar{t}$	$W^\pm Z$	$W^\pm W^+W^-$	$t\bar{t}W^\pm$	$t\bar{t}t\bar{t}$	$S/\sqrt{B}$
170 GeV	350	90	60	2400	1600	30	5.4
200 GeV	220	90	60	1500	1600	30	3.8

$$gg\to HH\to W^+W^-\,W^+W^-\to \ell^\pm\nu jj\ell^\pm\nu jj$$

Strongly-Coupled Vector Boson System

No light Higgs boson? Study Longitudinal gauge boson scattering in high energy regime (the L-component which provides mass to these bosons).

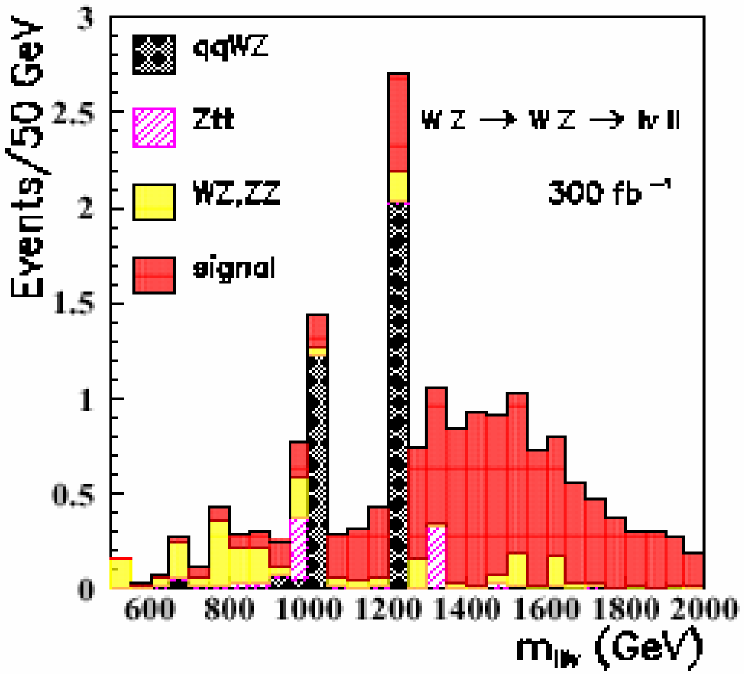
$W_L Z_L \longrightarrow W_L Z_L \longrightarrow l\,\nu\,ll$

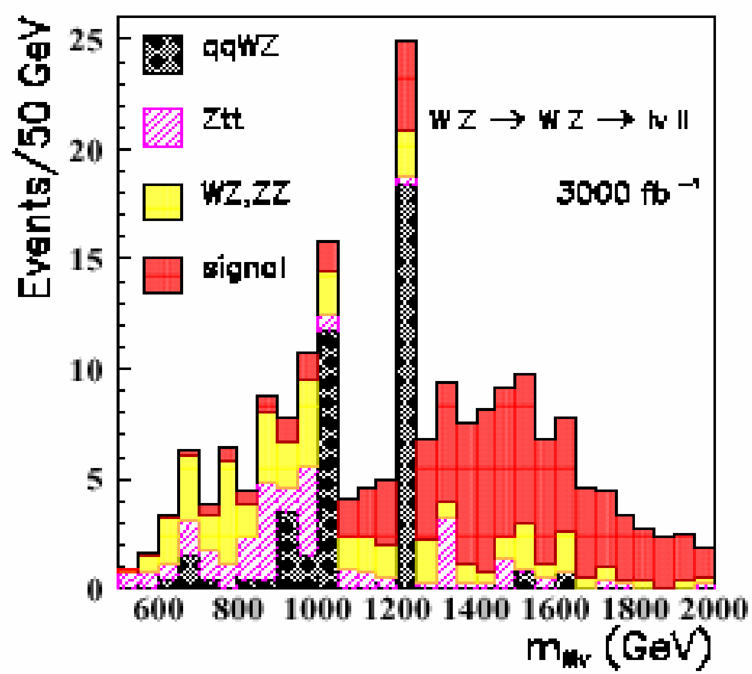
(Hep-ph/0204087)

$$p_T(\ell_1) > 150\ \text{GeV}, \quad p_T(\ell_2) > 100\ \text{GeV}, \quad p_T(\ell_3) > 50\ \text{GeV}$$
$$|m(\ell_1\ell_2) - m_Z| < 10\ \text{GeV}$$
$$E_T^{miss} > 75\ \text{GeV}$$

S / B = 6.6/2.2

$S/\sqrt{B}$ **~ 10**

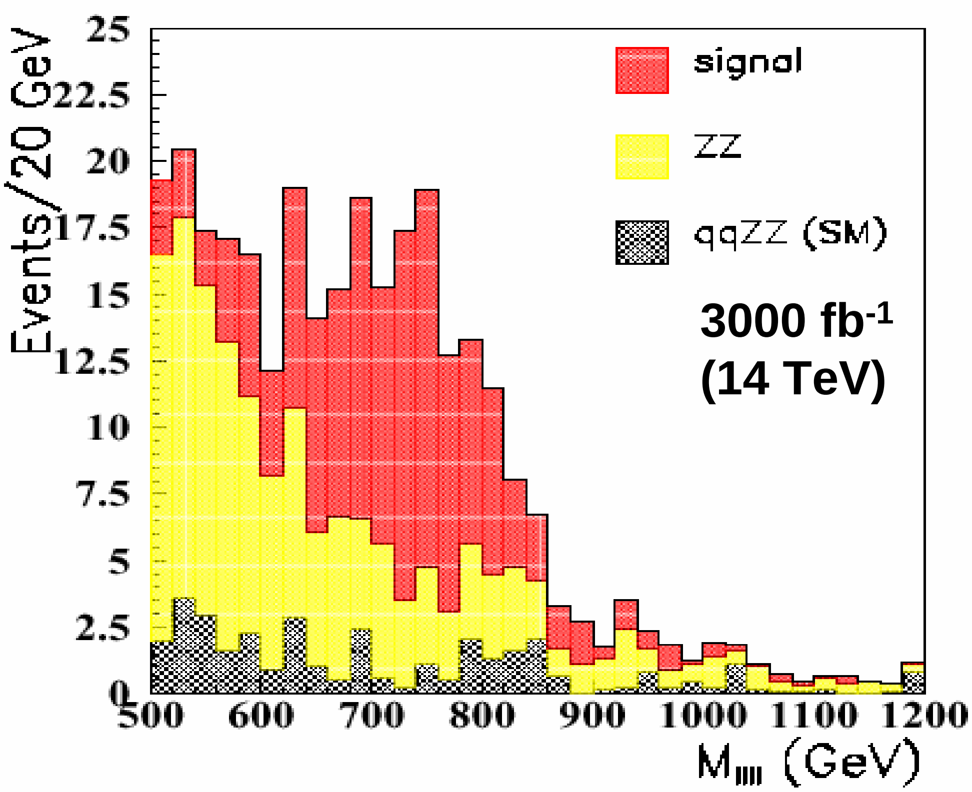




Z_L Z_L Scalar Resonance

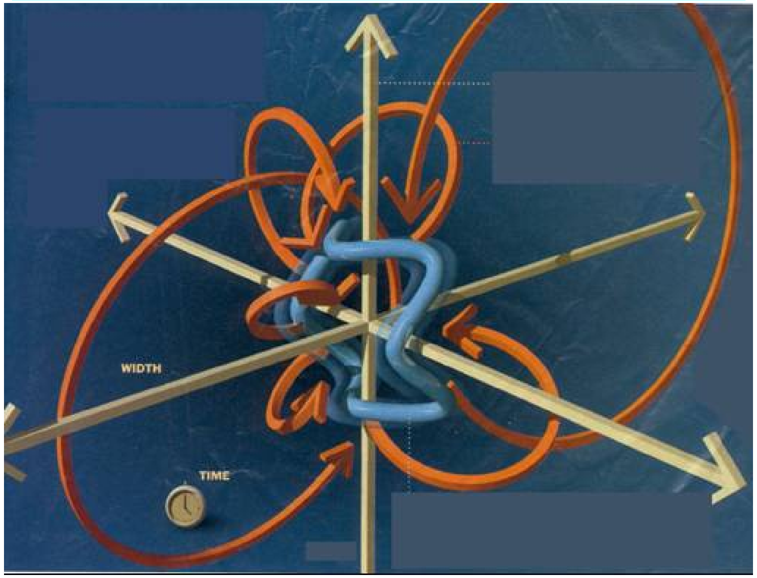
W_L W_L -> Z_L Z_L-> 4 leptons
Z_L Z_L -> Z_L Z_L-> 4 leptons

(Hep-ph/0204087)



→ Search for new resonances
(which could regularize vector boson scattering Xsection)

Extra Dimensions



Large Extra Dimensions (ADD)

- Gravity in bulk / flat space
- Missing energy / interference / black holes

Warped Extra Dimensions (RS)

- Gravity in bulk / curved space
- Spin 2 resonances in >TeV range / black holes

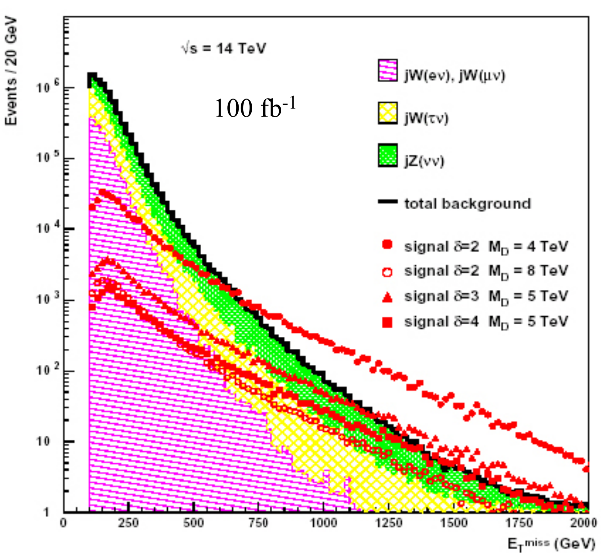
TeV Scale Extra Dimensions

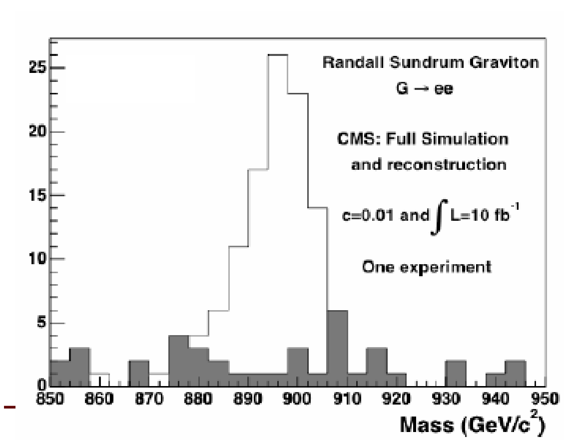
- Gauge bosons / Higgs in bulk
- Spin 1 resonances in >TeV range
- Interference with Drell-Yan

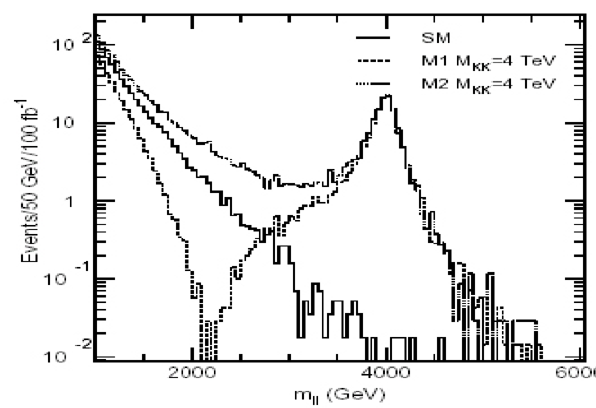
Universal Extra Dimensions

- Everybody in the bulk!
- Fake SUSY spectrum of KK states

E_T(jet) > 1 TeV





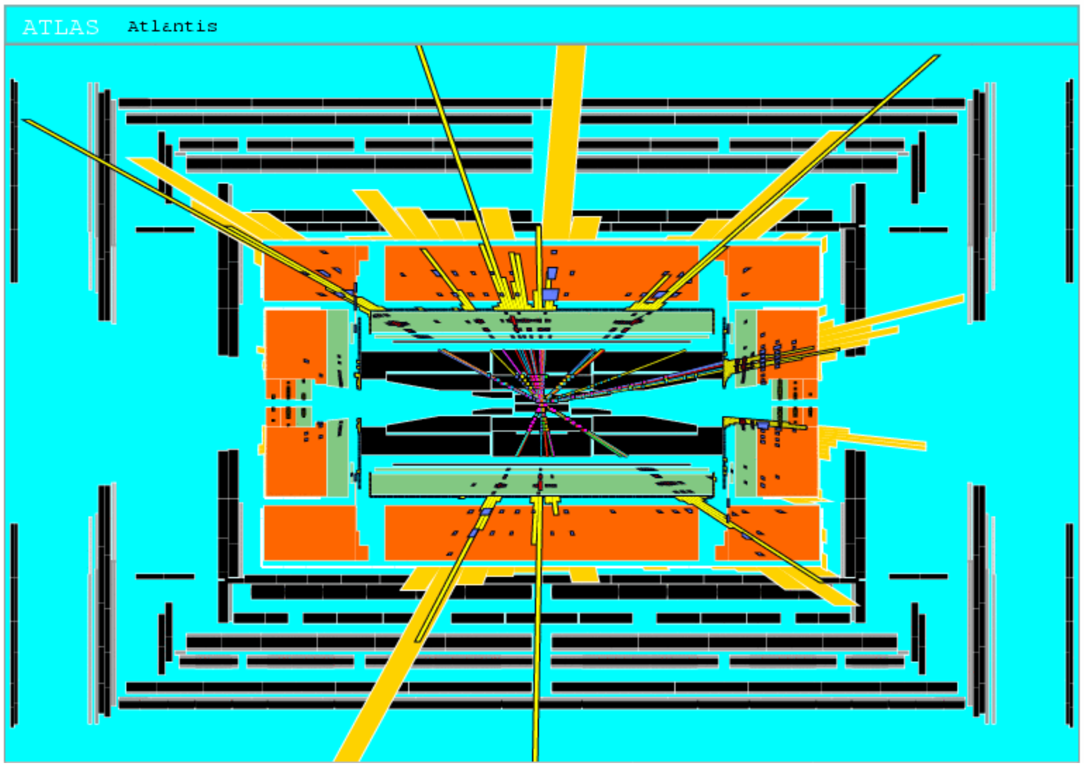


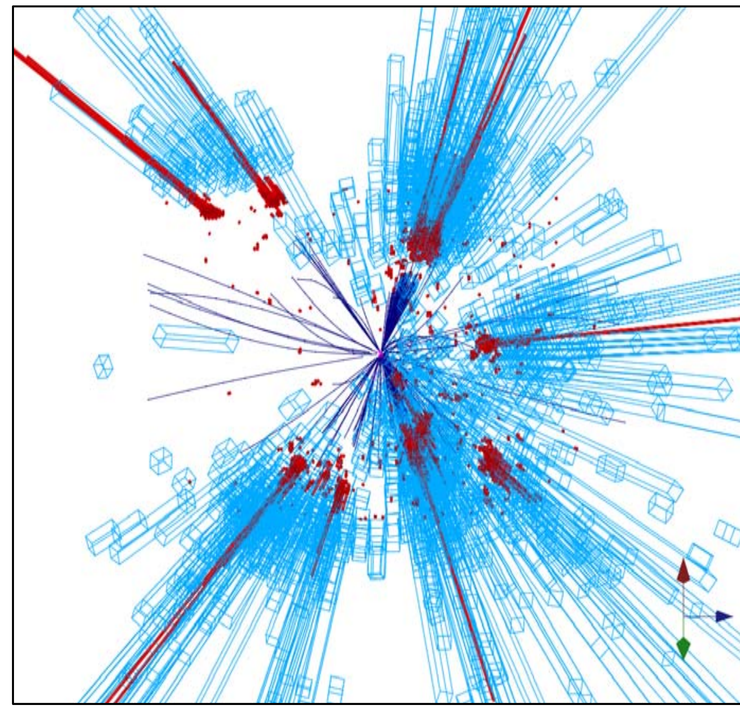
Extra Dimensions:

What if Planck Scale in TeV Range?

Simulation of a mini black hole event with M_{BH} ~ 8 TeV in ATLAS

… and in CMS





Narrow Graviton Resonance: Spin of G

B. C. Allanach, K. Odagiri, A. Parker and B. Webber, *JHEP 9 (2000) 19*

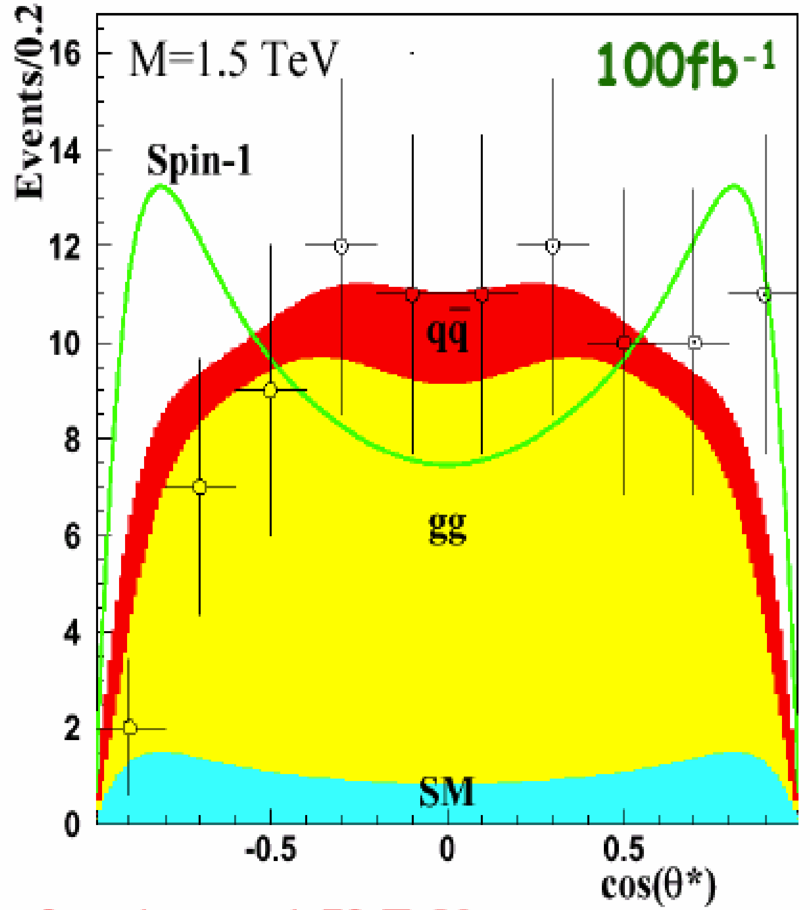
$gg\ (q\bar{q}) \rightarrow G \rightarrow e^+e^-$

Calculations made using HELAS customed for spin-2

Angular distributions

- $qq \rightarrow G \rightarrow ff: 1 - 3\cos^2\theta + 4\cos^4\theta$
- $gg \rightarrow G \rightarrow ff: 1 - \cos^4\theta$
- $qq \rightarrow G \rightarrow VV: 1 - \cos^4\theta$
- $gg \rightarrow G \rightarrow VV: 1 + 6\cos^2\theta + \cos^4\theta$
- DY background: $1 + \cos^2\theta$

Signature : graviton has spin 2

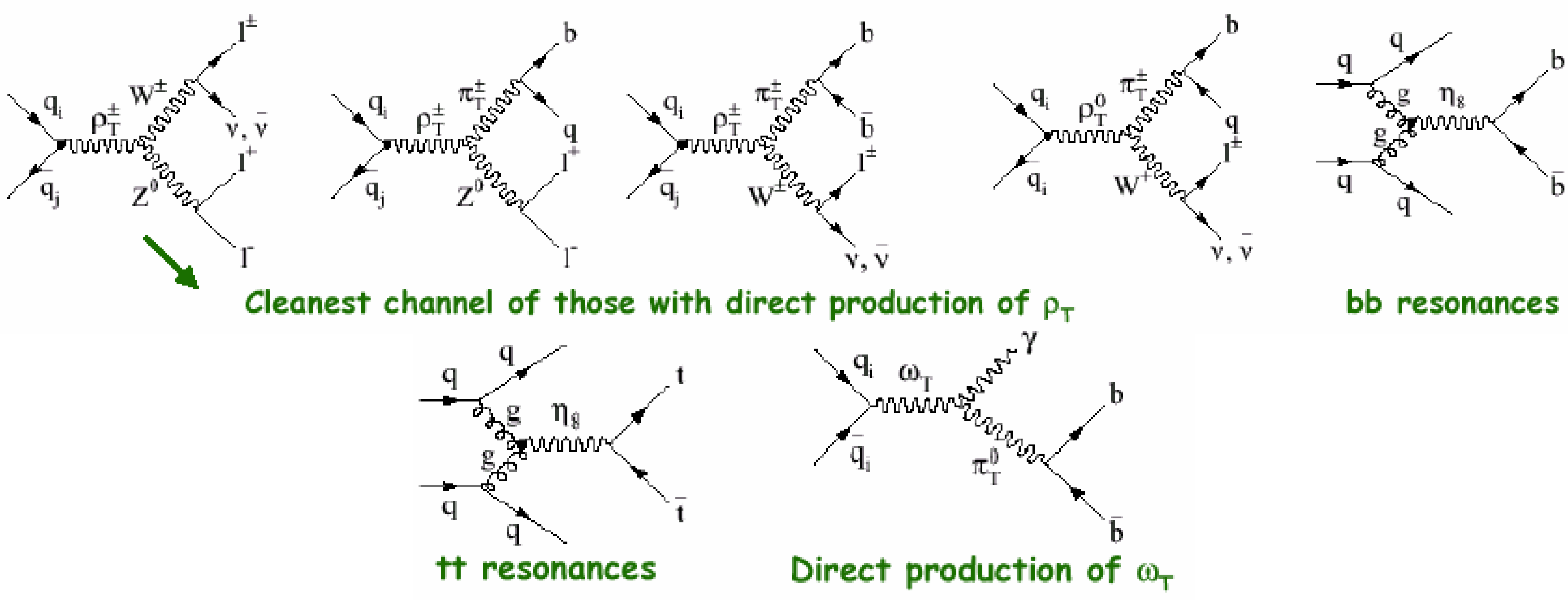


ATLAS can distinguish spin 2 vs 1 up to 1.72 TeV

Strong Symmetry Breaking
Technicolor

No fundamental scalar Higgs (it is a new strong force bounded state)
Technicolor predicts existence of technihadron resonance

Technicolor channels investigated

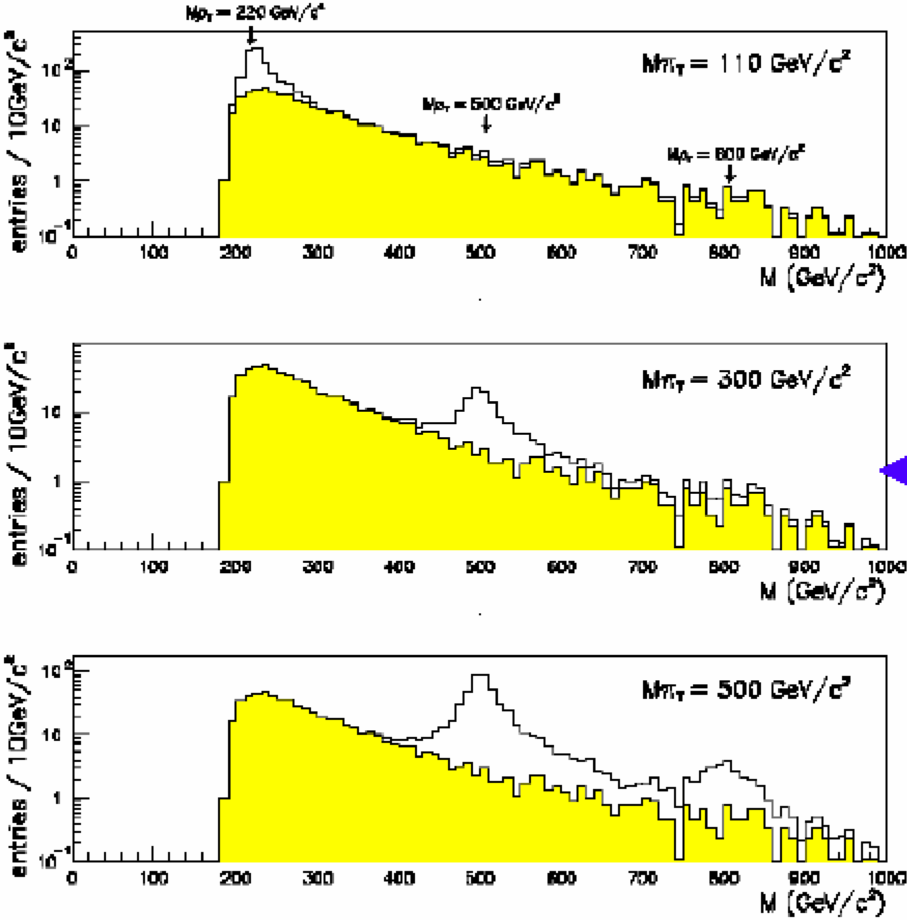


Main background for signals: Z + jets (qq->gZ, gg-> qZ, qq->ZZ)
tt, WZ continuum production

Signals of the Technicolor

Examples

Reconstructed invariant mass for $\rho_T \to WZ \to l\nu ll$ channel.
Solid line is signal. Filled area is background.



Lower limits required for 5σ significance with 30 fb^{-1} :
in some cases,
signals are below observability,
but combination of signals
could provide strong evidence.

$\rho_T \to WZ \to l\nu ll$ for 30 fb^{-1}
(a) $\sigma \times BR_{model}$ = 0.16 fb
$\sigma \times BR_{5\sigma\ discovery}$ = 0.025 fb

$\rho_T \to W\pi \to l\nu bb$ for 30 fb^{-1}
(c) $\sigma \times BR_{model}$ = 0.064 fb
$\sigma \times BR_{5\sigma\ discovery}$ = 0.15 fb

Summary of New Physics Reach at LHC

Any one of those would change the understanding of our universe !

SM Higgs	100 GeV ~ 1 TeV
MSSM Higgs	covers full (m_A, tanβ)
SUSY (squark, gluino)	2.5 - 3 TeV (300 fb^{-1})
New gauge bosons (Z')	< 4.5 TeV (100 fb^{-1})
Quark substructure (Λ_C)	< 25/40 TeV (30/300 fb^{-1})
q*, l*	< 6.5/3.4 TeV (100 fb^{-1})
Large ED (M_D for n=2,4)	< 9/5.8 TeV (100 fb^{-1})
Small ED (M_C)	< 5.8 TeV (100 fb^{-1})
Black holes	< 6 ~ 10 TeV
M(top quark)	σ_M ~ 1 GeV (~ 0.5 %)
M_W	σ_M ~ 15 MeV
CP-violation in B-decay	$\sigma(\sin 2\beta)$ ~ 0.016 (30 fb^{-1})
Rare B-decay ($B_S \rightarrow \mu\mu$)	~ 5σ (130 fb^{-1})

→ Discovery for sure + some measurements (SM Higgs)

→ can say "final word" about (low E) SUSY

Both experiments can cope with the new physics possibilities which were not foreseen at the beginning of the project.

Cosmological Connection

- Extremely tempting to assume that EWSB and Dark Matter characterised by the same energy scale
- Likely that new physics contains a stable particle that can be copiously produced at the LHC

There are counterexamples, but

if above true => large cross sections for jets + missing energy events at the LHC

=> LHC will provide data for astrophysics

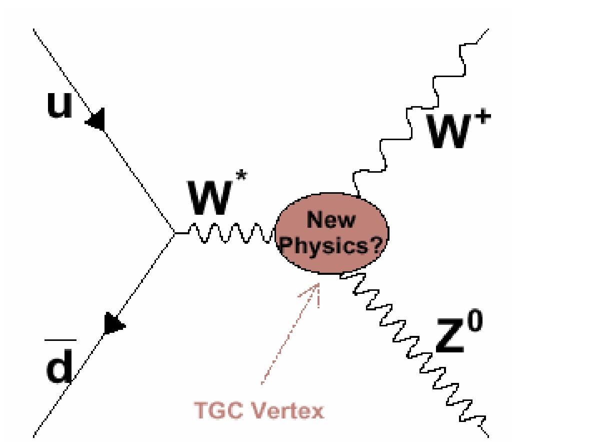
=> infer DM properties from masses and cross sections

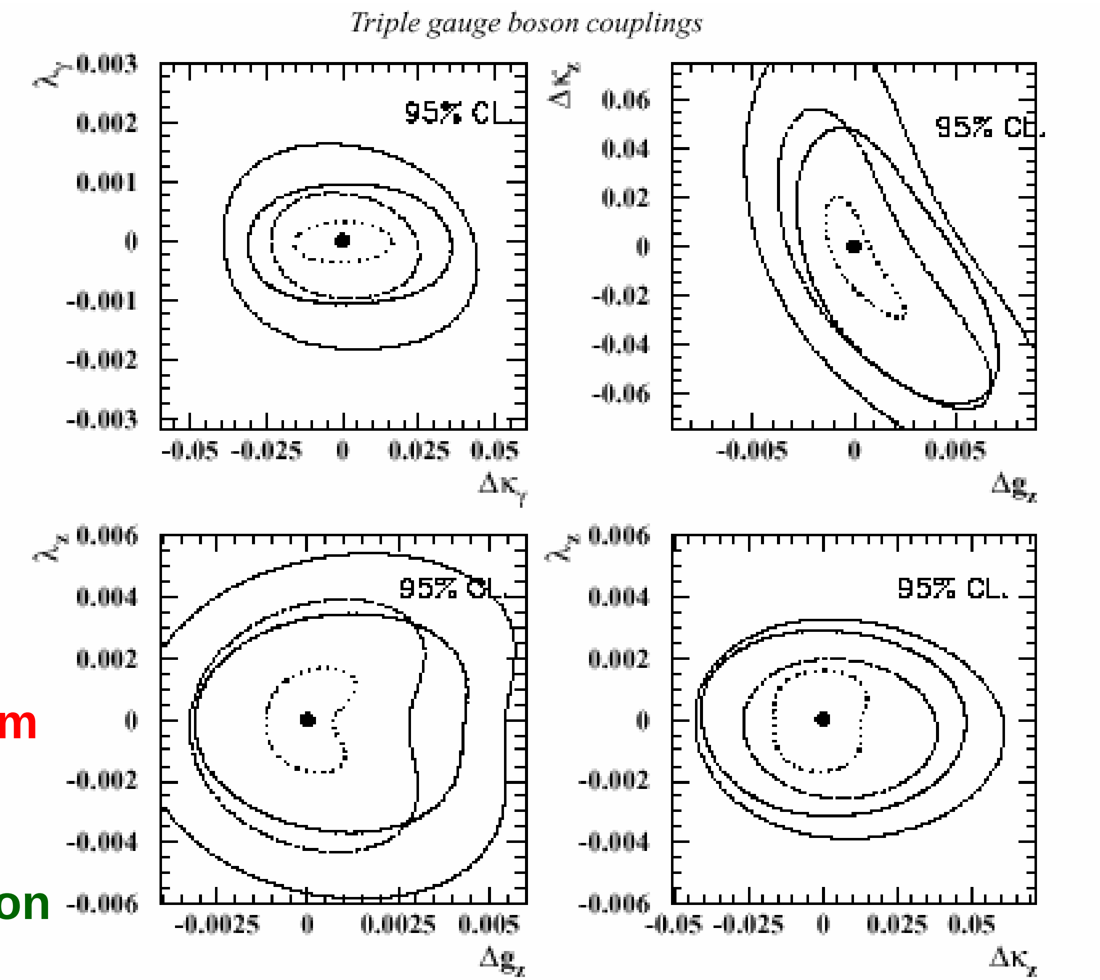
Relic density $\Omega_X h^2 \sim 3 \times 10^{-27}\ cm^3 s^{-1} / \langle\sigma v\rangle$

requires typical weak interaction annihilation cross sections

How well $\langle\sigma v\rangle$ can be predicted from LHC depends on model for NP

Triple Gauge Boson Couplings





non-abelian $SU(2)_L \times U(1)_Y$ gauge group (foundation of SM!)

Open window to electroweak Symmetry breaking mechanism

LHC: orders of magnitude Improvement over LEP/Tevatron

Expected 95% C.L. constrains contours (outer-> inside):

(14TeV, 100fb^{-1}), (28TeV, 100fb^{-1}), (14TeV, 1000fb^{-1}), (28TeV, 1000fb^{-1})