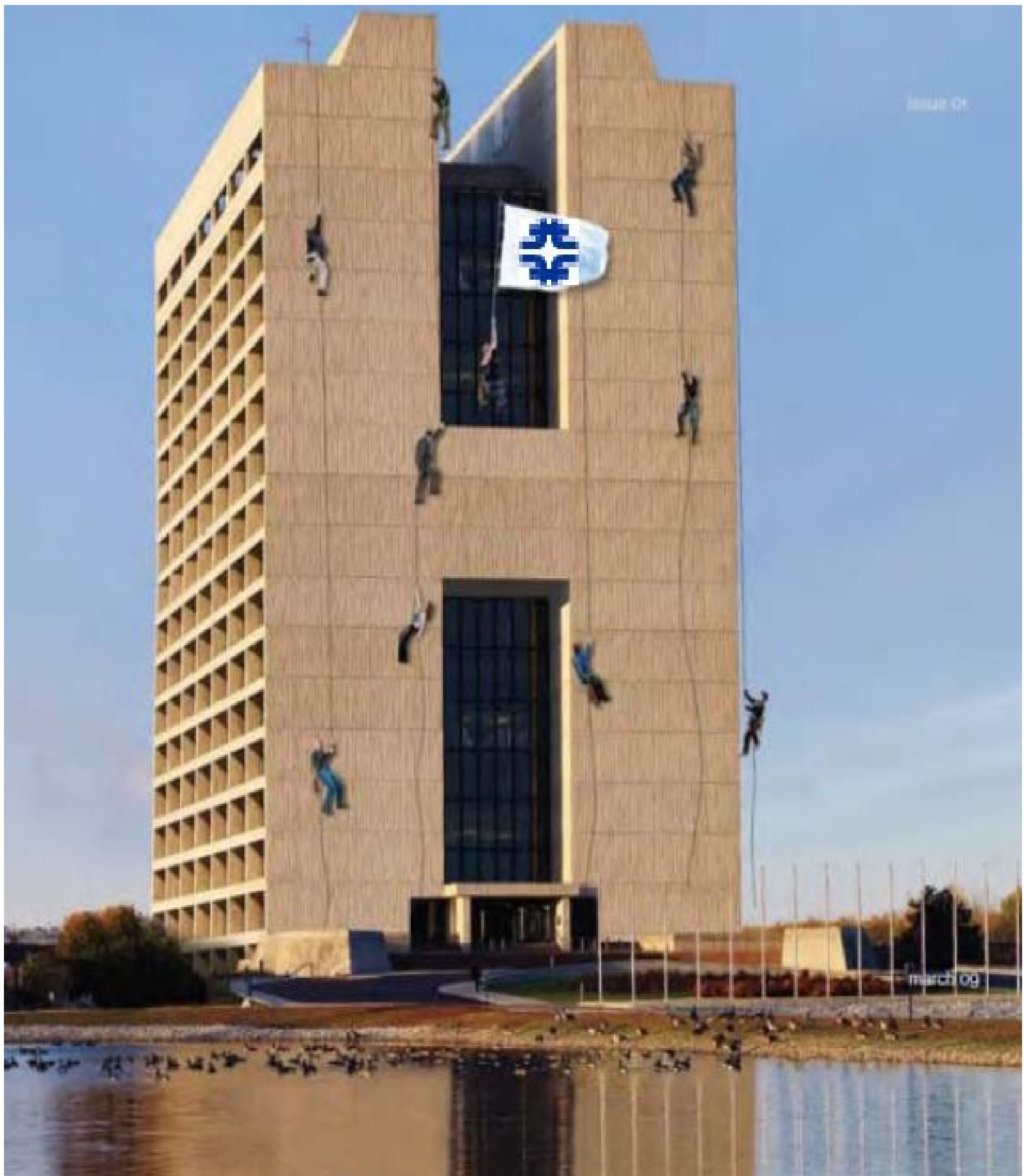
Higgs Bosons at the Tevatron and at a Future Muon Collider

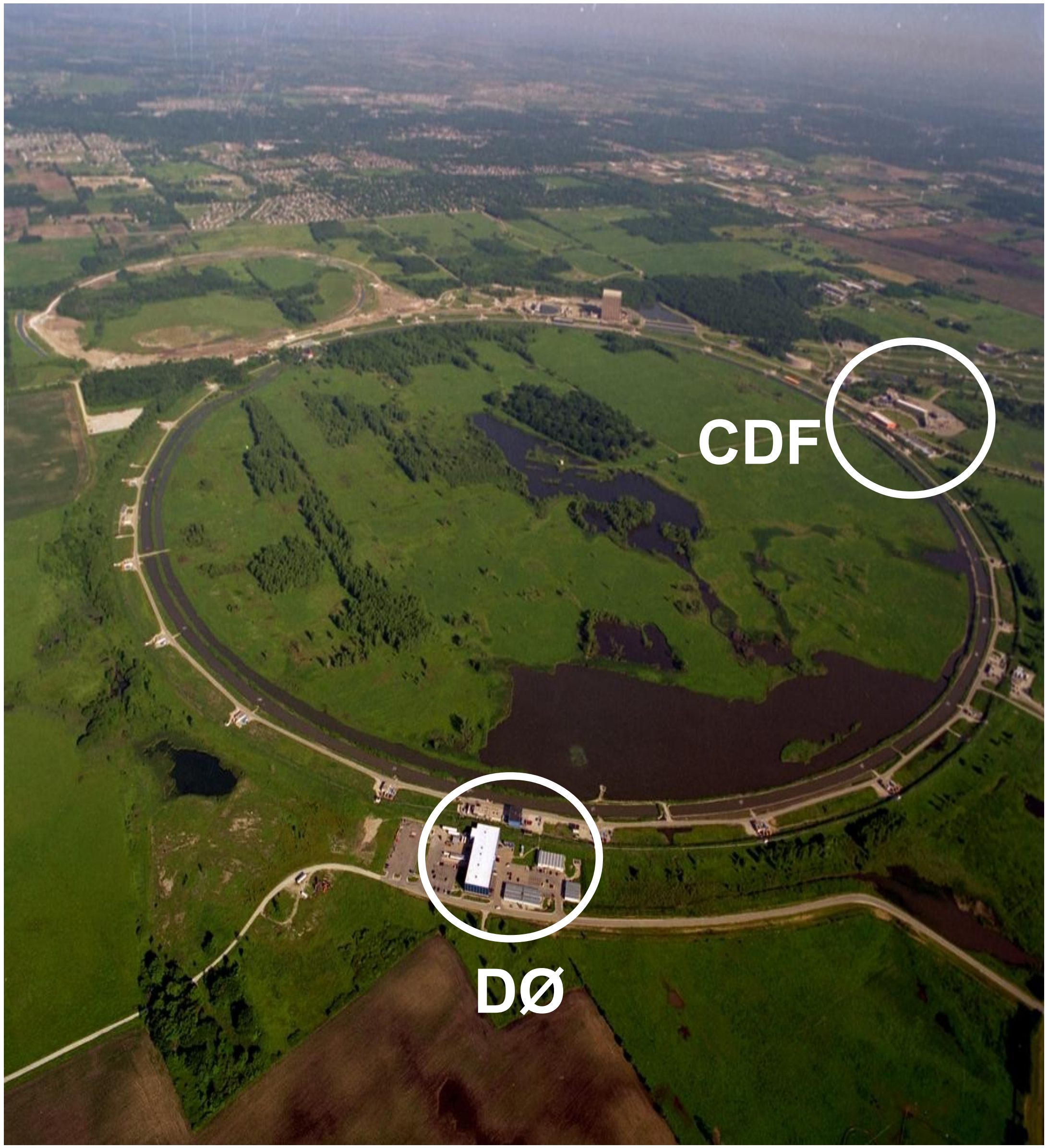


Marc Buehler
University of Virginia

Outline

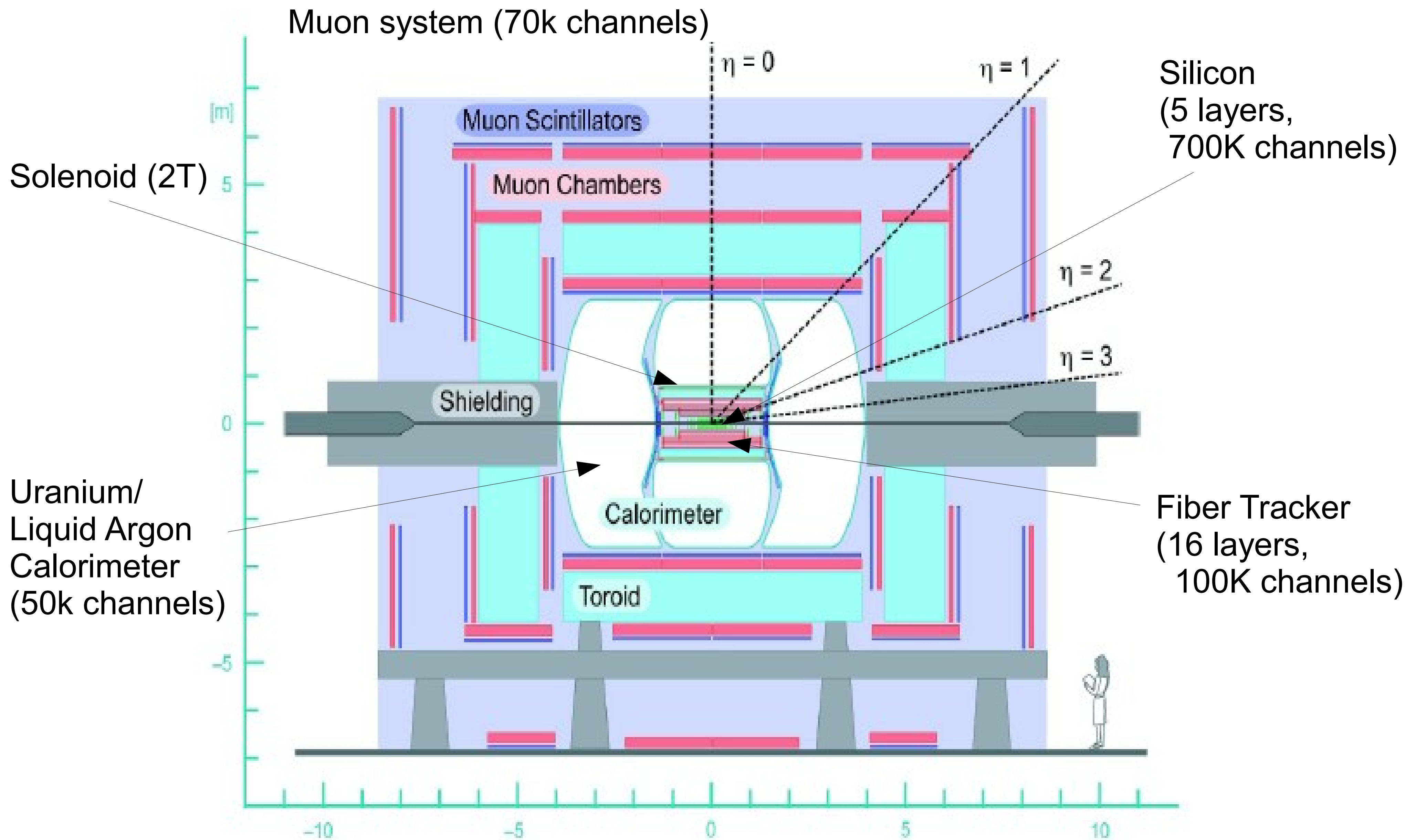
- DZero Detector Overview:
  - Triggering
  - Central Track Trigger (CTT)
- Higgs at the Tevatron
  - $H \rightarrow WW \rightarrow l\nu jj$
  - Higgs Combinations
- Higgs at a Muon Collider

Tevatron Collider in Run II



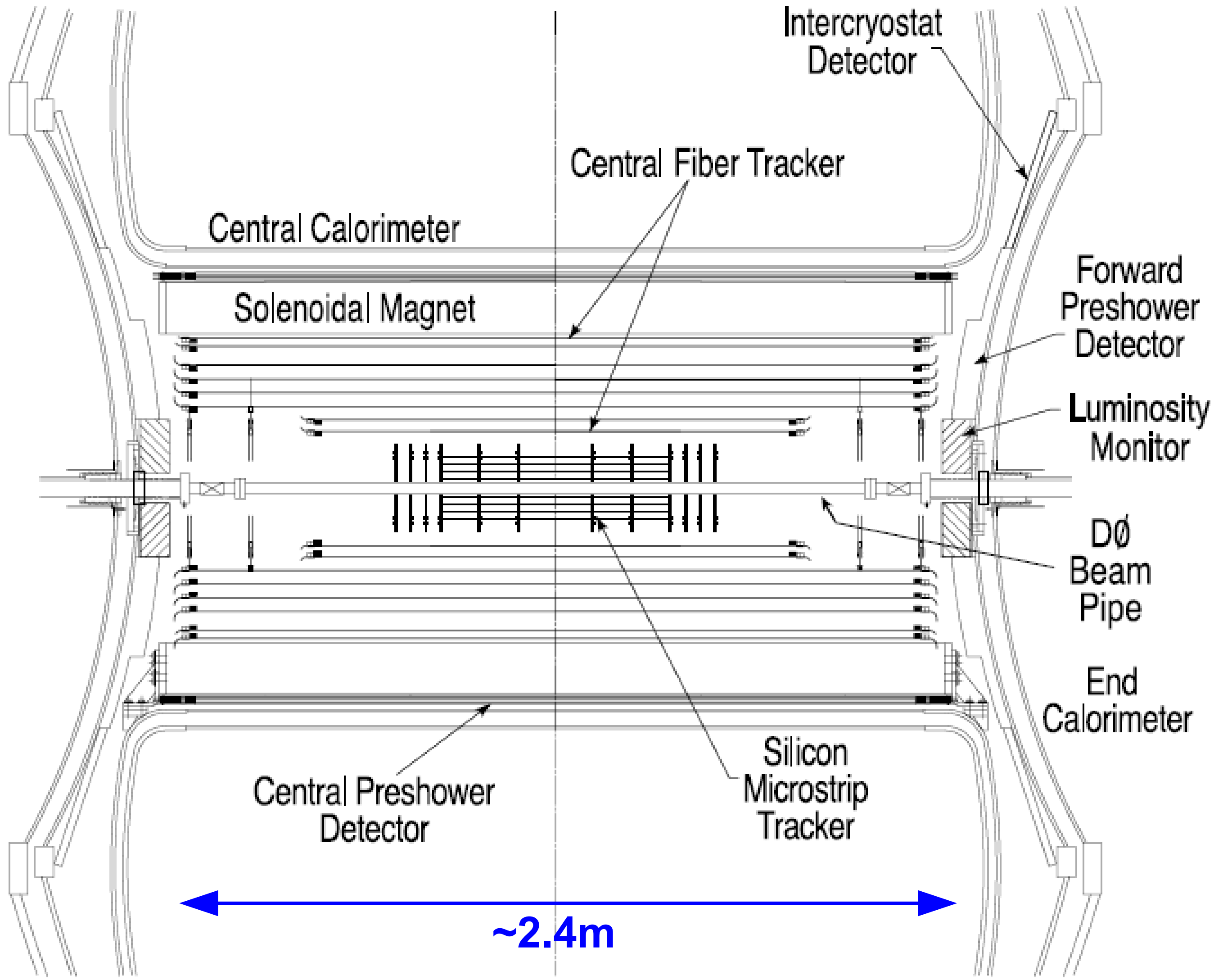
- Highest energy proton-antiproton collider
- Colliding protons and antiprotons at $\sqrt{s}$=1.96TeV
- Delivers a dataset equal to Run I (~100pb^{-1}) every 2 weeks per detector
- Total delivered integrated luminosity for Run II is ~11fb^{-1} per detector

The DZero Detector



The DZero Detector

Central Tracking System



High Luminosity Challenges

Trigger system is crucial when dealing with high instantaneous luminosities

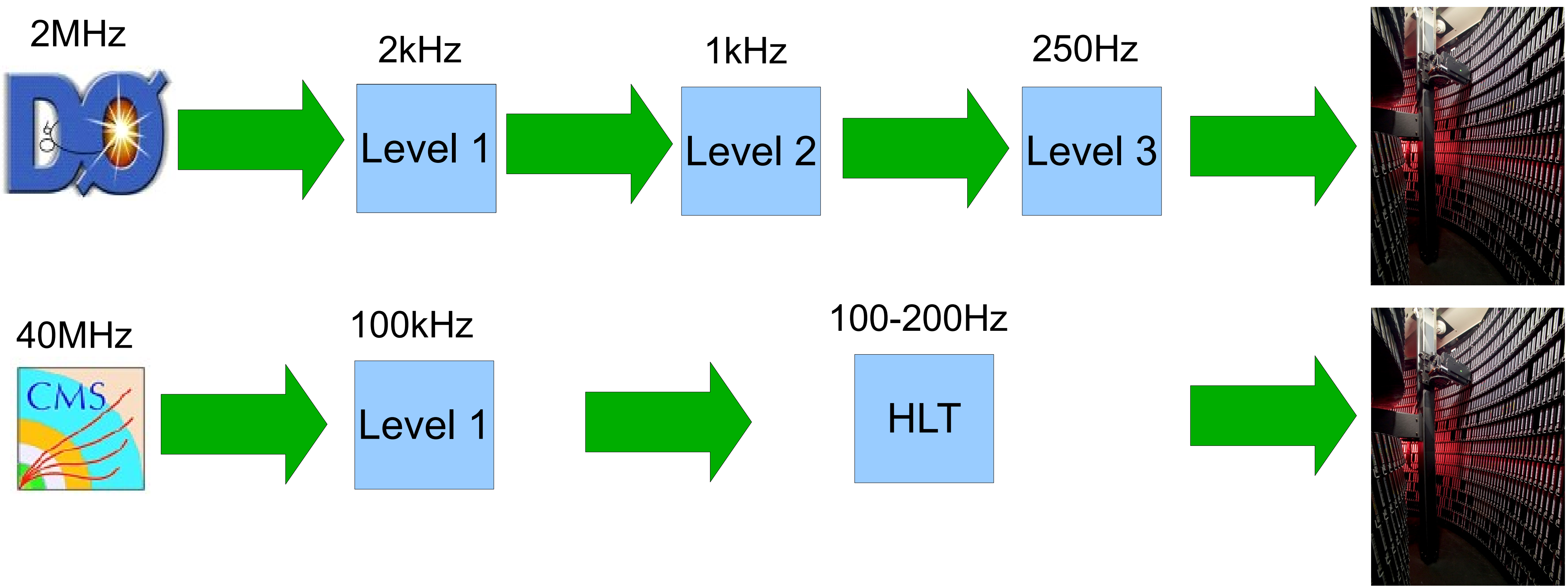
"The Trigger does not determine which physics model is right. The Trigger only determines which physics model is left."

DZero three-tier trigger system:

L1: Fast/coarse filtering. Hardware & firmware implementation

L2: Forms simple physics objects using dedicated SBCs

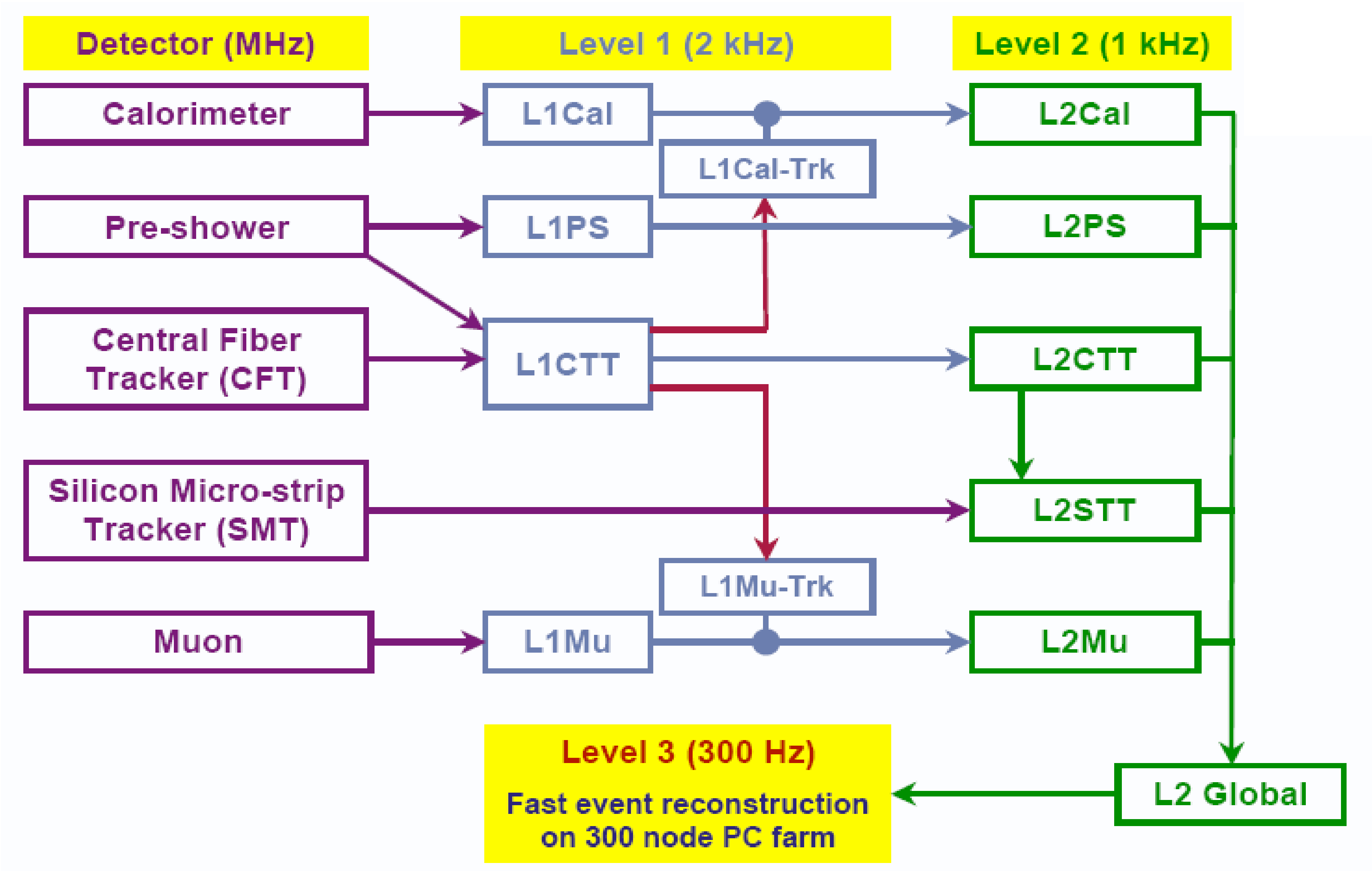
L3: Uses full detector readout and event reconstruction on a filter farm



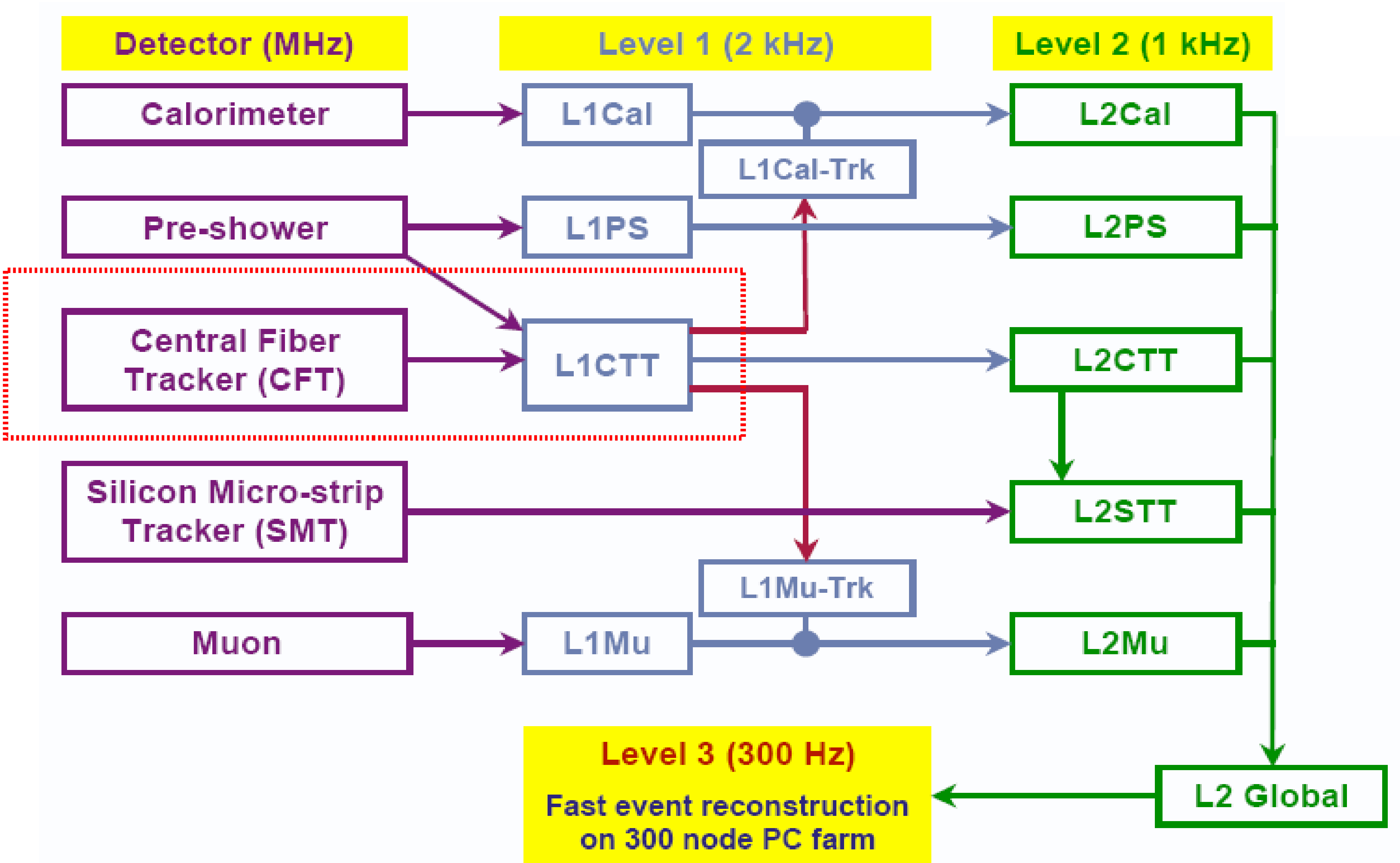
Trigger Strategy

- Object oriented:
  - Muons, electrons, taus, jets, MET, …
- General purpose triggers shared among physics groups
  - Each group gets their ”fair share” of the bandwidth
- High efficiency and redundancy
  - Various combinations of tight and loose conditions
- Keep high p_T “core” triggers unprescaled at high luminosities
  - Most B physics and QCD triggers prescaled at high luminosity
  - B physics and looser versions of core triggers turn on as luminosity drops during a store
- Rate “guidelines”
  - Keep L1/L2/L3 rates below their technically allowed values with room to spare:
    - L1/L2 < 1800/900Hz
    - Rate to tape kept at a store average value of 100Hz (up to 250Hz at high instantaneous luminosities)

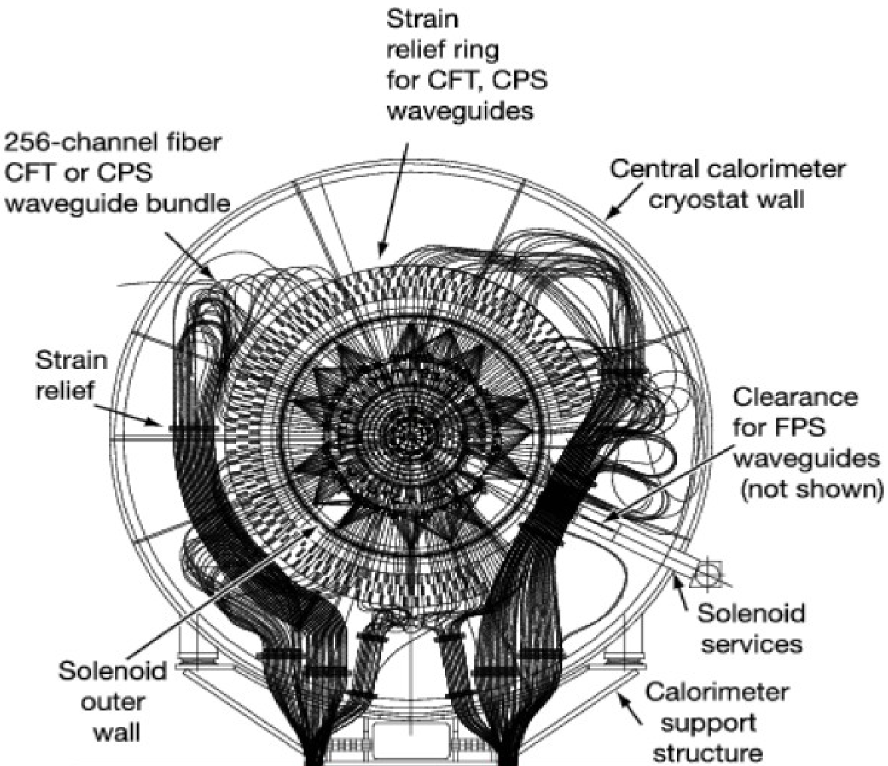
The DZero RunIIb Trigger



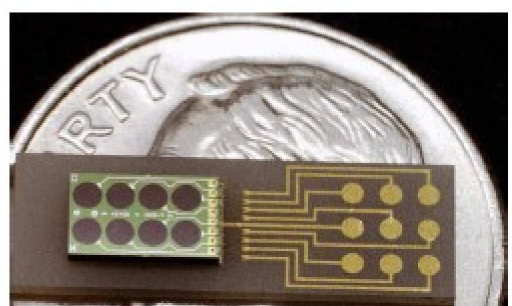
The DZero RunIIb Trigger



Central Fiber Tracker (CFT)

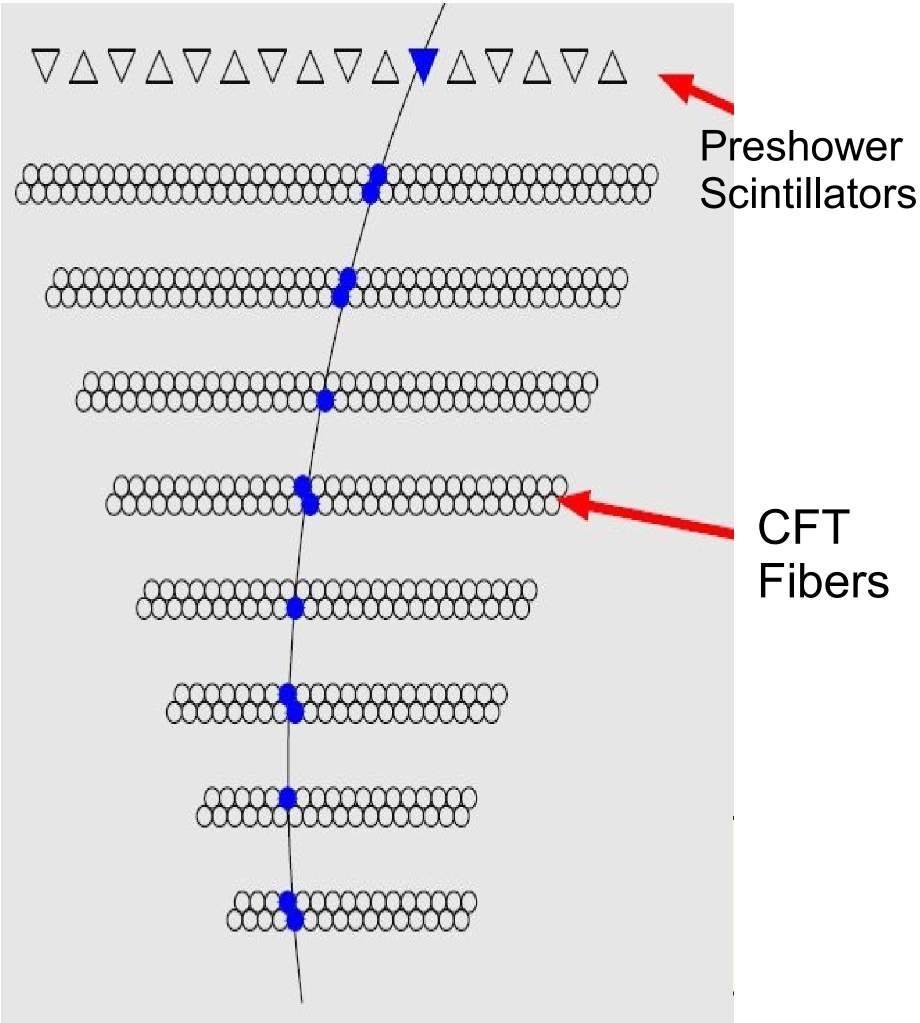


- Provides inputs to Central Track Trigger (CTT)
- Located between silicon tracker and 2T solenoid
- Surrounded by pre-shower detectors
- Covering $|\eta|<1.7$
- Length ~2.4m
- 76,800 fibers in 8 axial and stereo doublet layers with radii from 20 to 52 cm
- Light from scintillating fibers converted into electrical signals by Visible Light Photon Counters (VLPC)
- AFEIIt boards generate discriminator inputs for CTT



VLPC: solid state photo-detector with 8 input pixels 1mm in diameter each

Central Track Trigger (CTT)

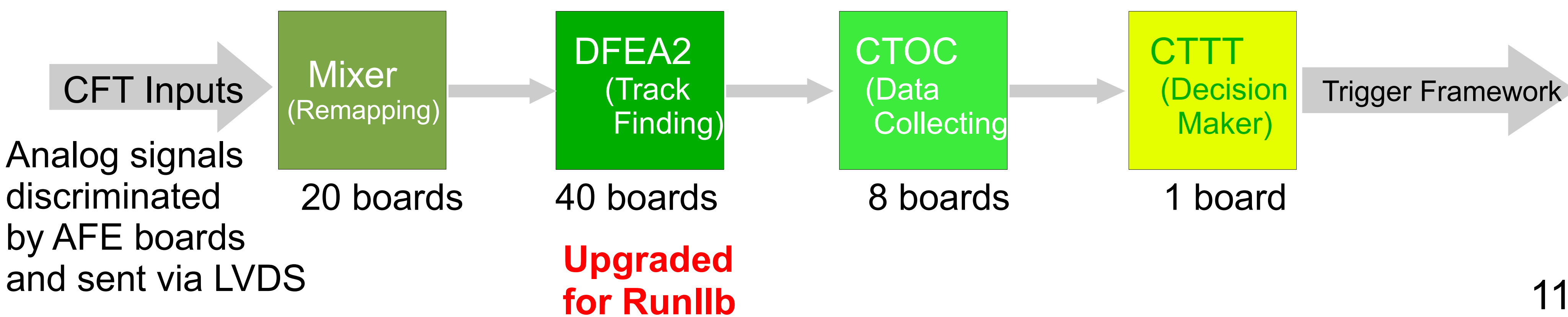


4.5° Trigger Sector

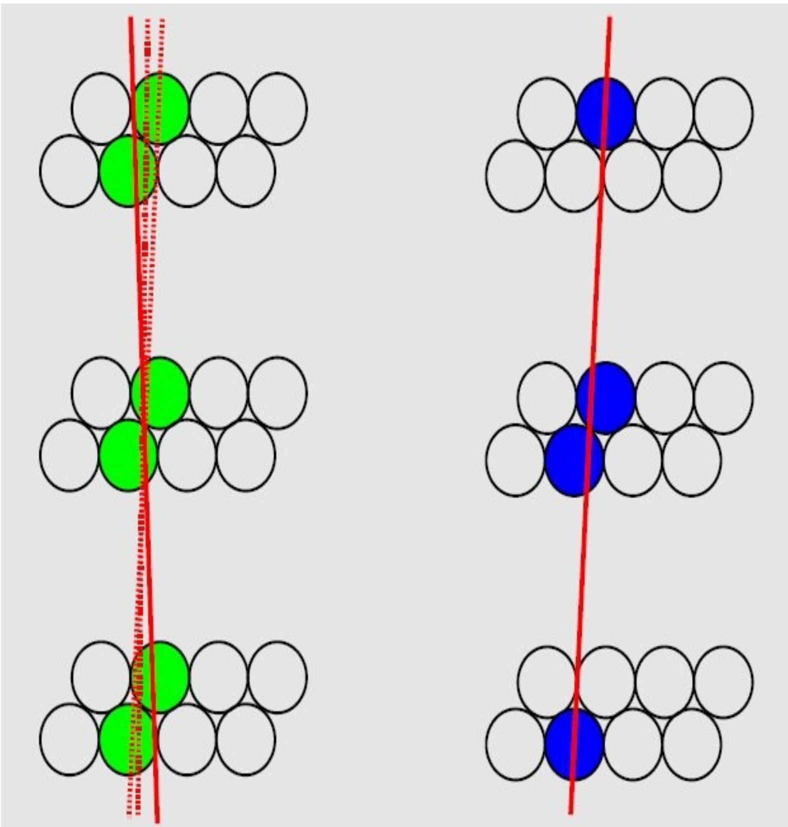
- Hardware trigger at level 1 (L1) running at 7.6MHz (132ns/decision)
- Uses hit patterns from CFT axial layers to find tracks in azimuthal plane with 4 different p_T thresholds: 1.5, 3, 5, 10 GeV
- All probable CFT hit patterns consistent with tracks (*track equations*) are stored in FPGAs
- For triggering purposes the azimuthal plane is segmented into 80 4.5°-wide *trigger sectors*
- Provides additional information on isolation and & pre-shower match
- Provides outputs to multiple downstream trigger components:
  - L1 Muon
  - L1 CalTrack
  - L2 silicon track trigger

CTT System Overview

- CTT hardware is located in the collision hall underneath the detector ⇒ need reliable control and monitoring for remote operations
- Consists of >100 custom built processing cards distributed over multiple crates
- Communication path to the DZero control room via 1553/Gigabit Ethernet
- Signal processing chain for CTT track triggering:



CTT Track Finding Upgrade

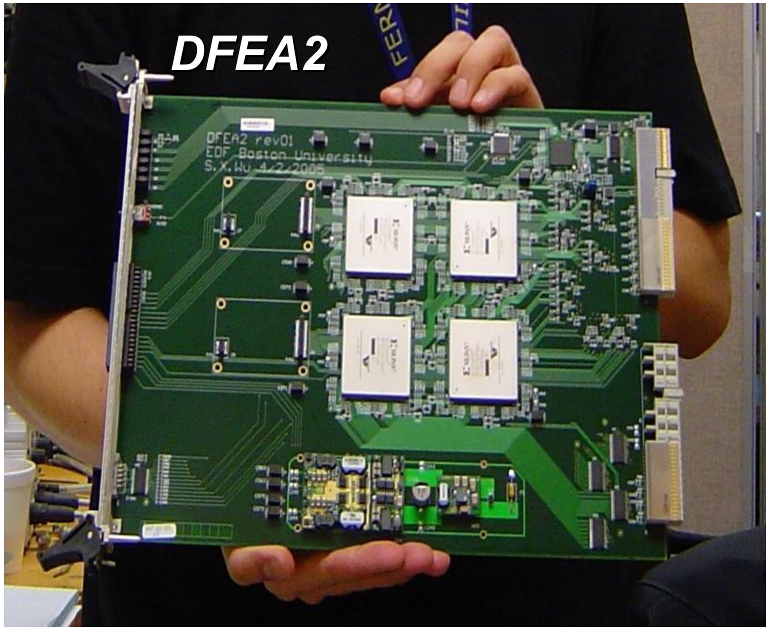


Doublets
(Run IIa)

Singlets
(Run IIb)

- Run IIa hardware limited number of fiber track equations
  - Combining 2 fibers into one doublet space-point
  - With increasing occupancy, the fake track rate dominates due to combinatorics
- For Run IIb the solution was to use the full granularity of the CFT using singlet fiber hits (≥ 8)
  - Increases number of track equations from 16k to 50k per sector
  - Needs larger FPGA with faster download for track equations

CTT Hardware Upgrade



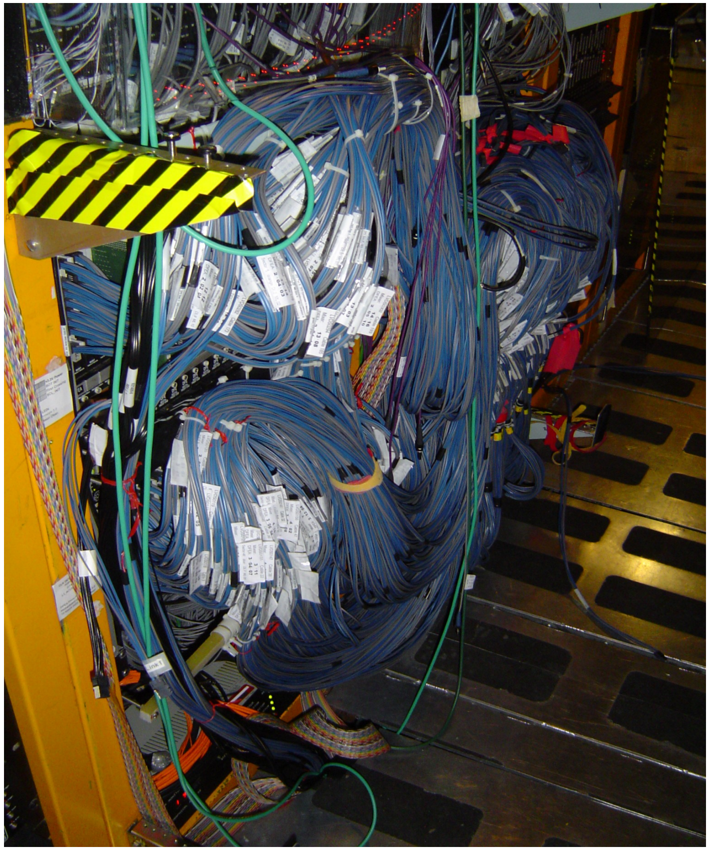
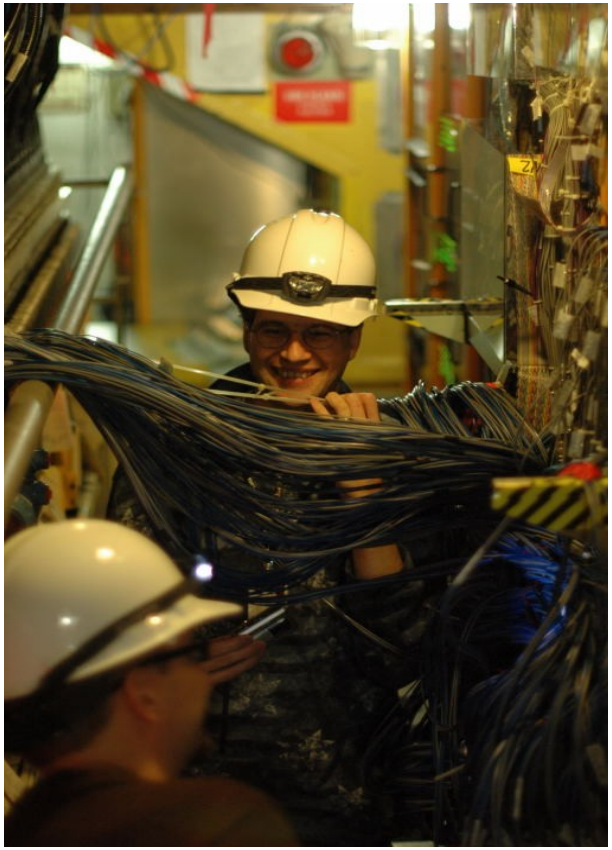
- Track finding hardware (DFEA2)
  - 4 large Xilinx Virtex II FPGAs
  - Front panel designed to provide complete test and diagnostic information
  - Custom backplane
  - Processing two trigger sectors per board
  - 8 (4) x 1.5Mbps bus LVDS inputs (outputs)
  - Two 1-Gigabit coaxial copper outputs
  - Designed at Boston University
- New crate controller
  - Gigabit optical Ethernet connection
- Improved infrastructure
  - New redundant power distribution
  - New crate design to improve cable routing

Test connector for logic analyzer or oscilloscope

Multipurpose LED display

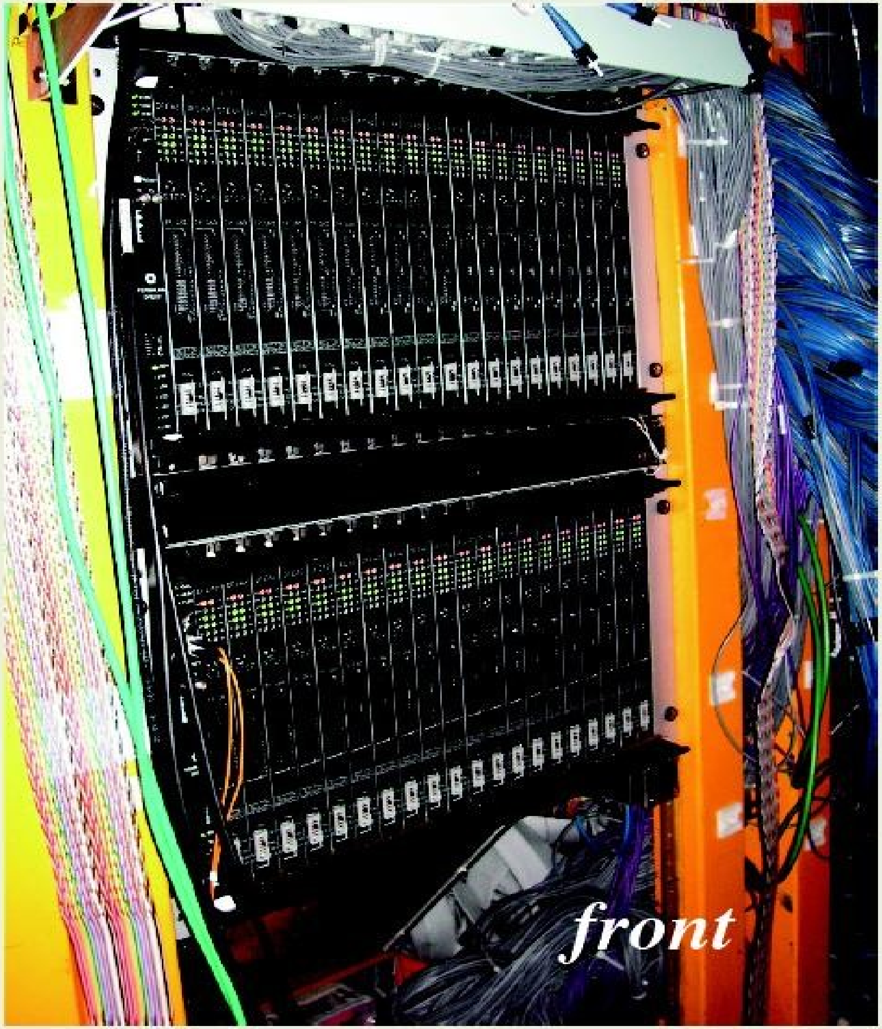
JTAG for FPGA testing and programming

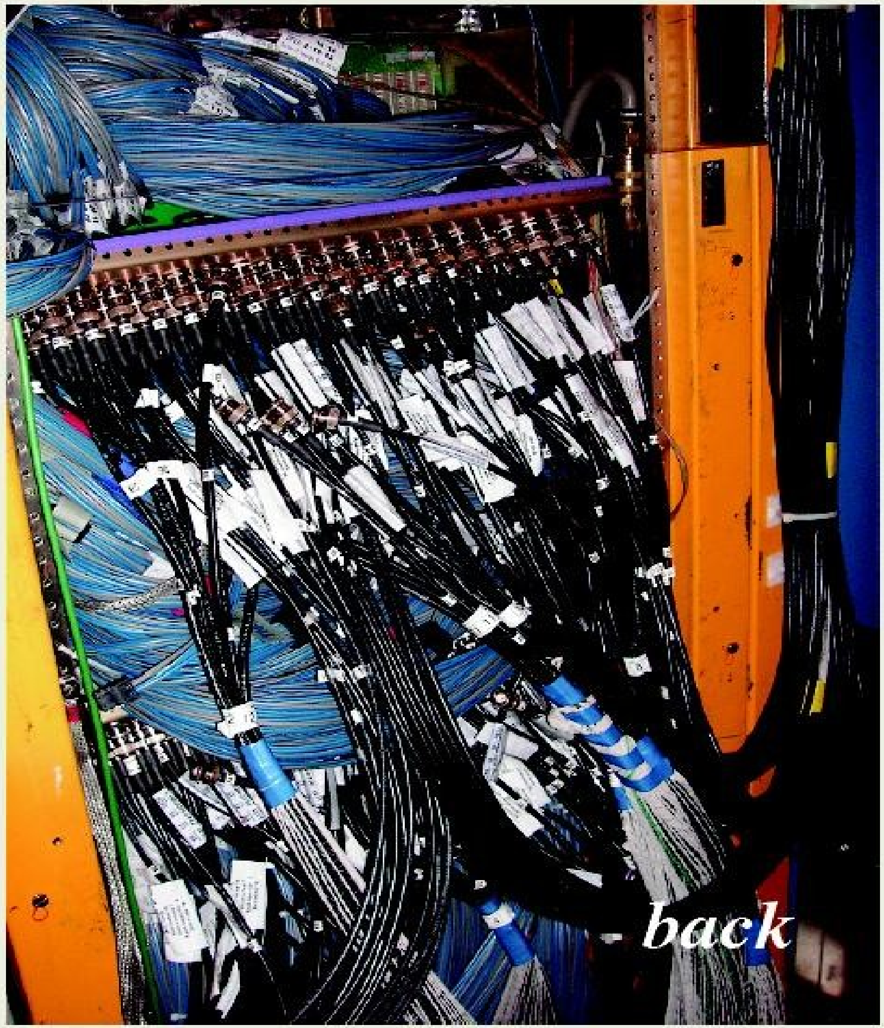
Hardware Installation


- Installation of DFEA2 boards and cabling (lots of cabling ...) during the Spring 2006 Run IIb upgrade shutdown

Hardware Installation

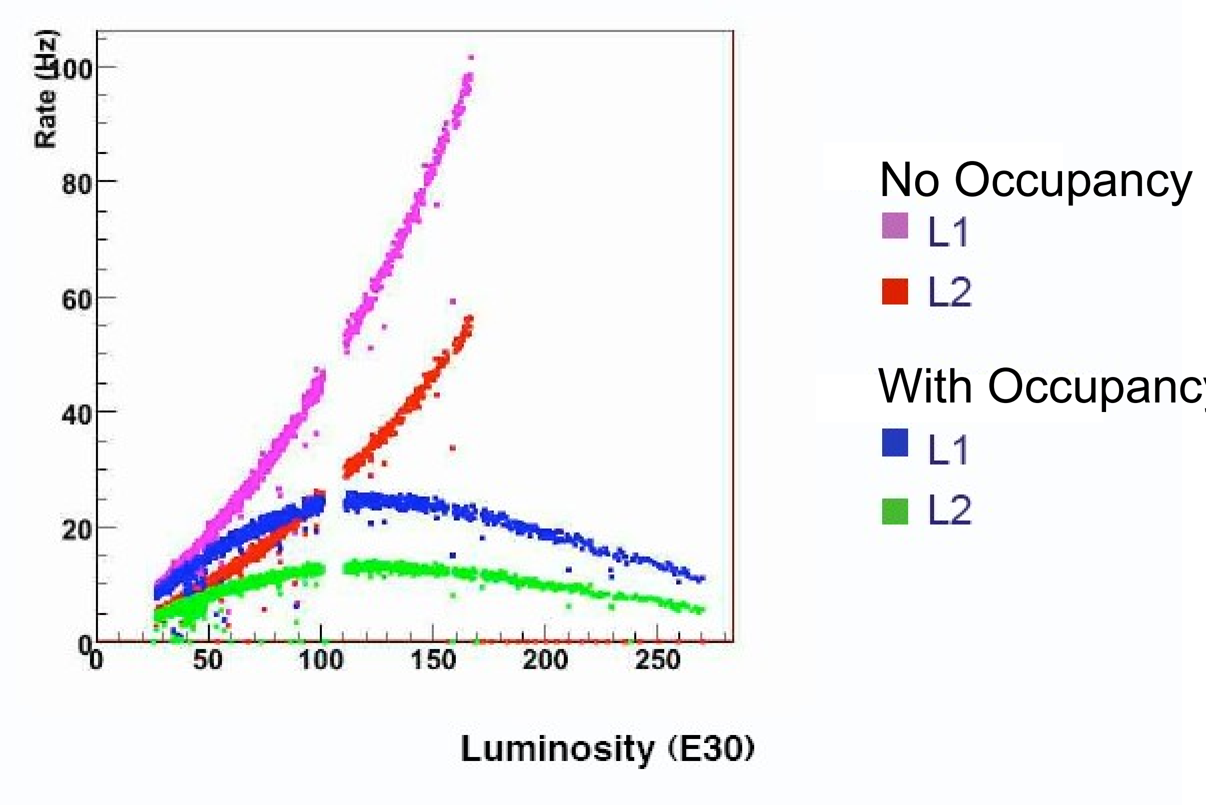




- New crate design allows easy maintenance access to DFEA2 boards
- All I/O cabling is done through the backside of the crates

CTT Occupancy Veto Terms

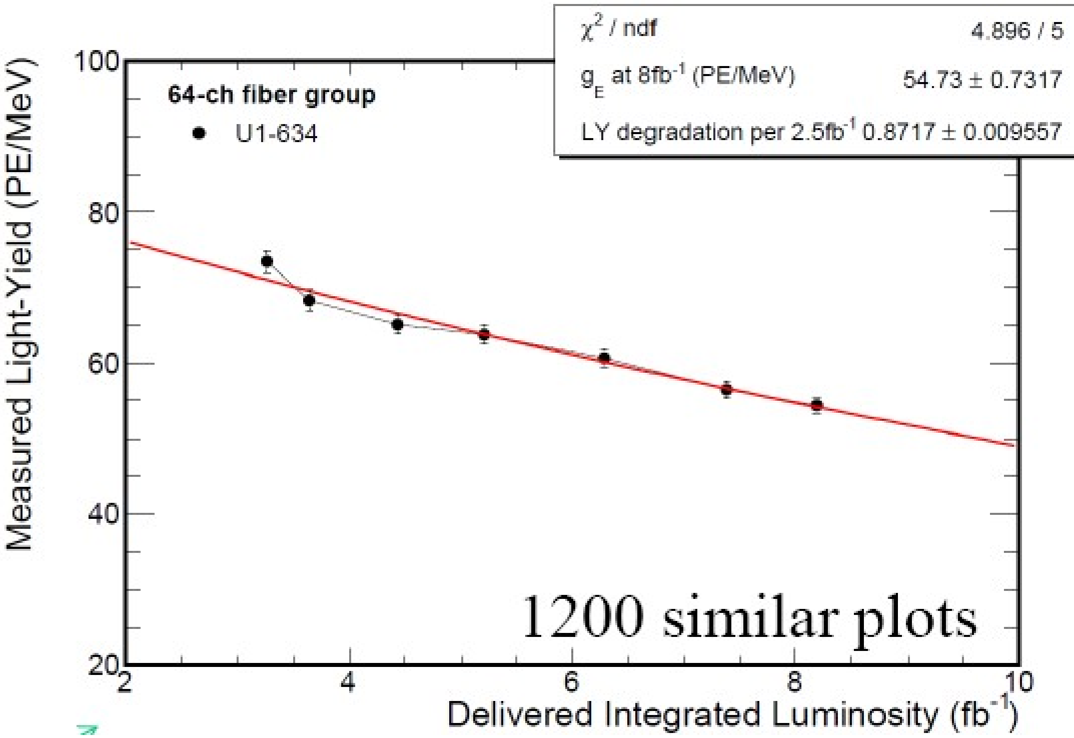
At peak luminosities CFT occupancies reach levels where CTT track finding is dominated by fake tracks.
Use occupancy veto terms to select events with low CFT occupancies



L1 and L2 trigger rates for Di-Muon triggers
→ Previously turned off at 160E30 w/o occupancy vetoes
→ Now running up to 350E30 with occupancy vetoes

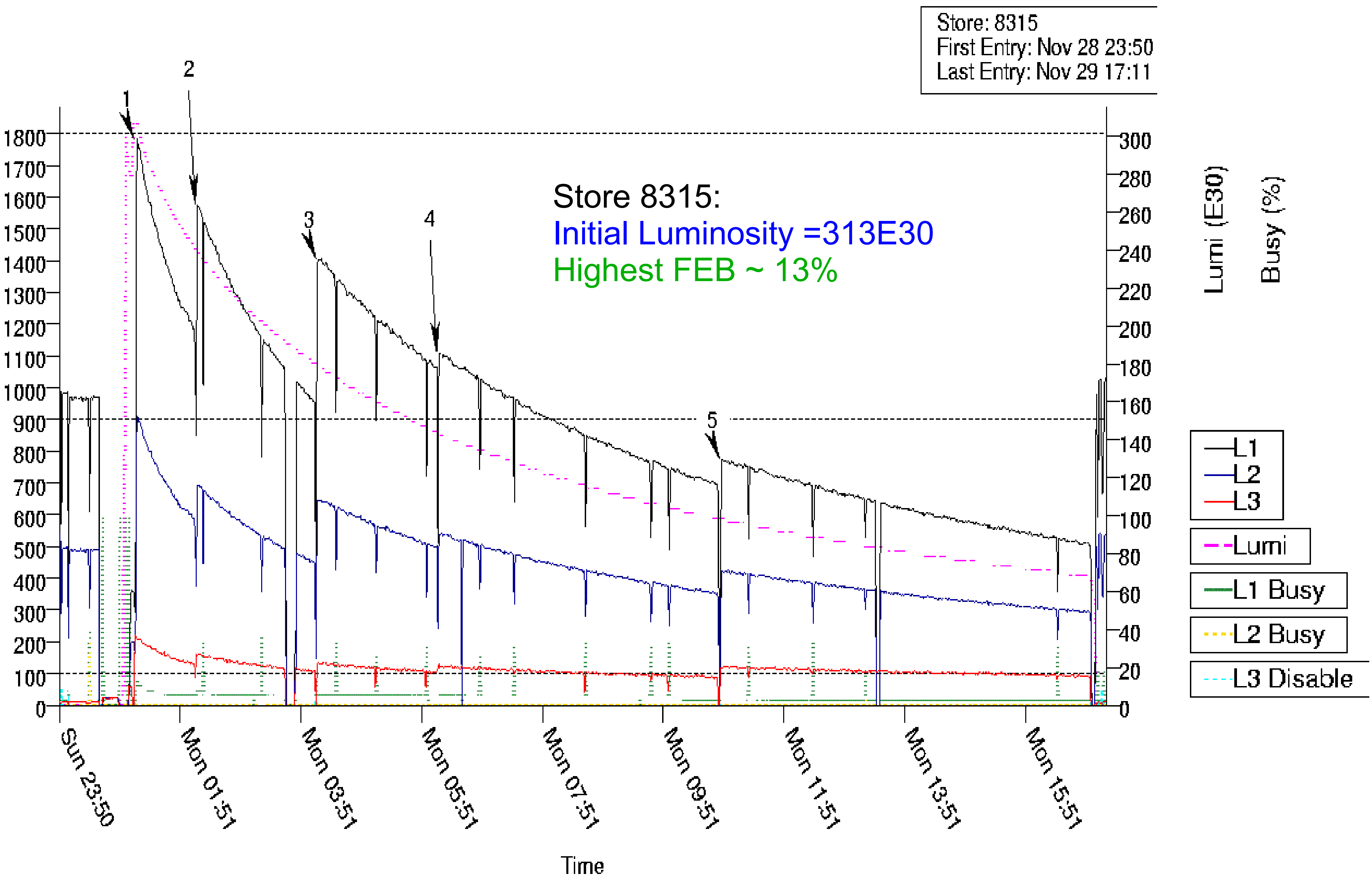
Light Yield vs Integrated Luminosity

- Fiber light yields decrease with accumulated radiation dose
- Options to boost CTT efficiencies:
  - Smarter track equations:
    - Improved algorithms
    - Better modeling
  - Firmware re-arrangement
    - Re-allocate more logic resources for high p_T tracks
  - Invest in better hardware
    - Develop entirely new hardware
- **Were able to maintain efficient triggering**

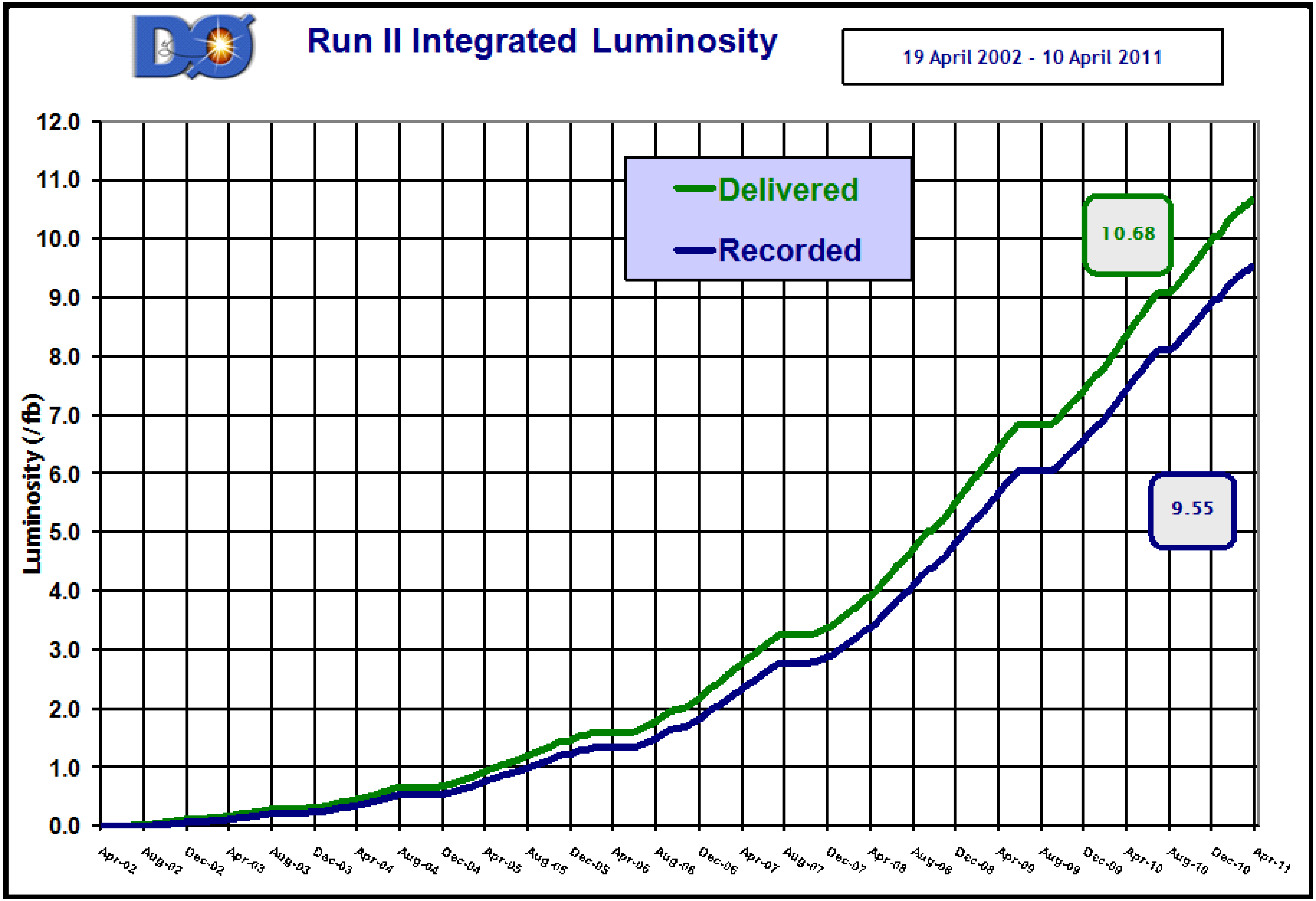


(G.Wilson)

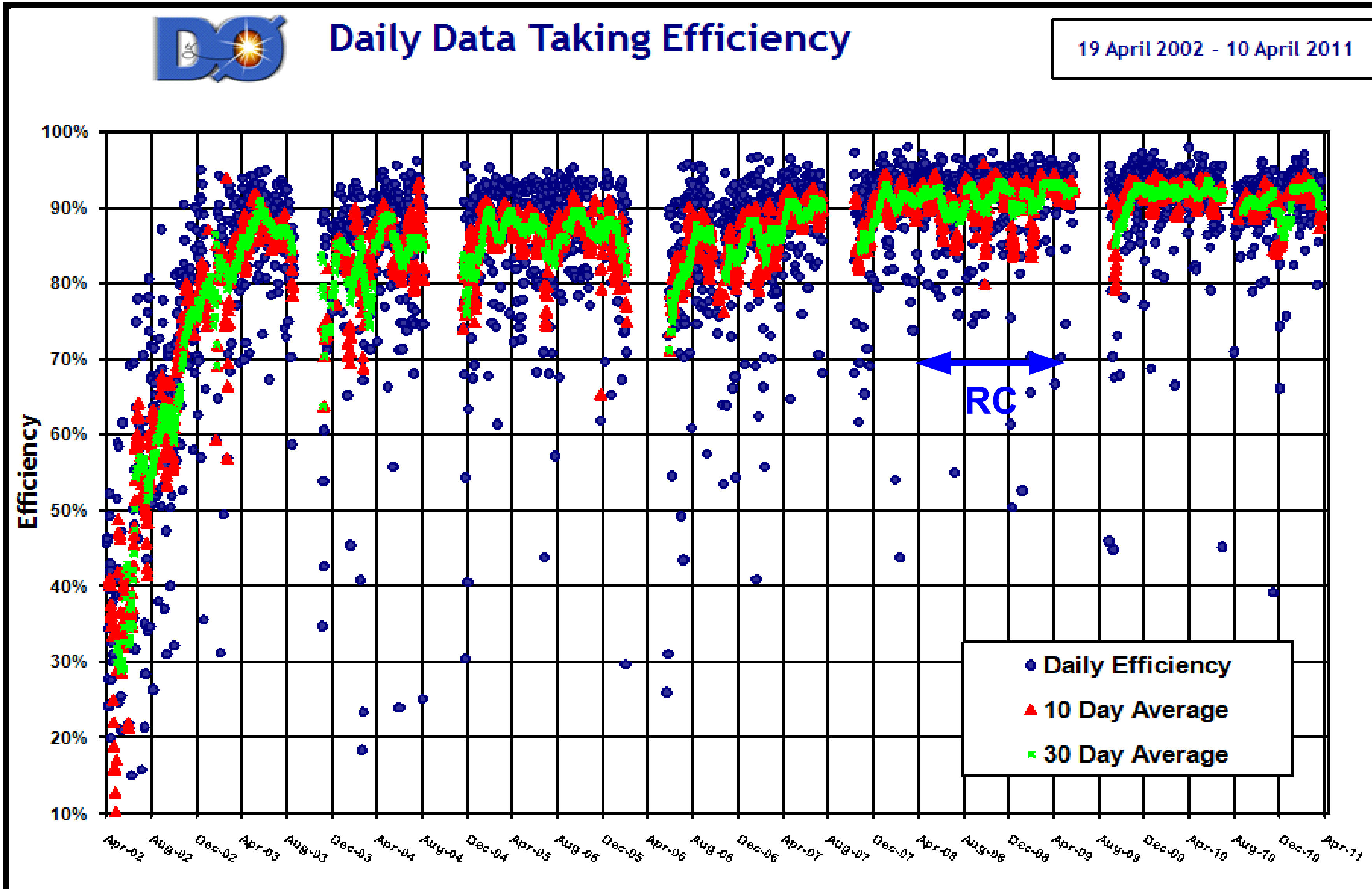
A High Luminosity Store



DZero Data Taking



DZero Data Taking

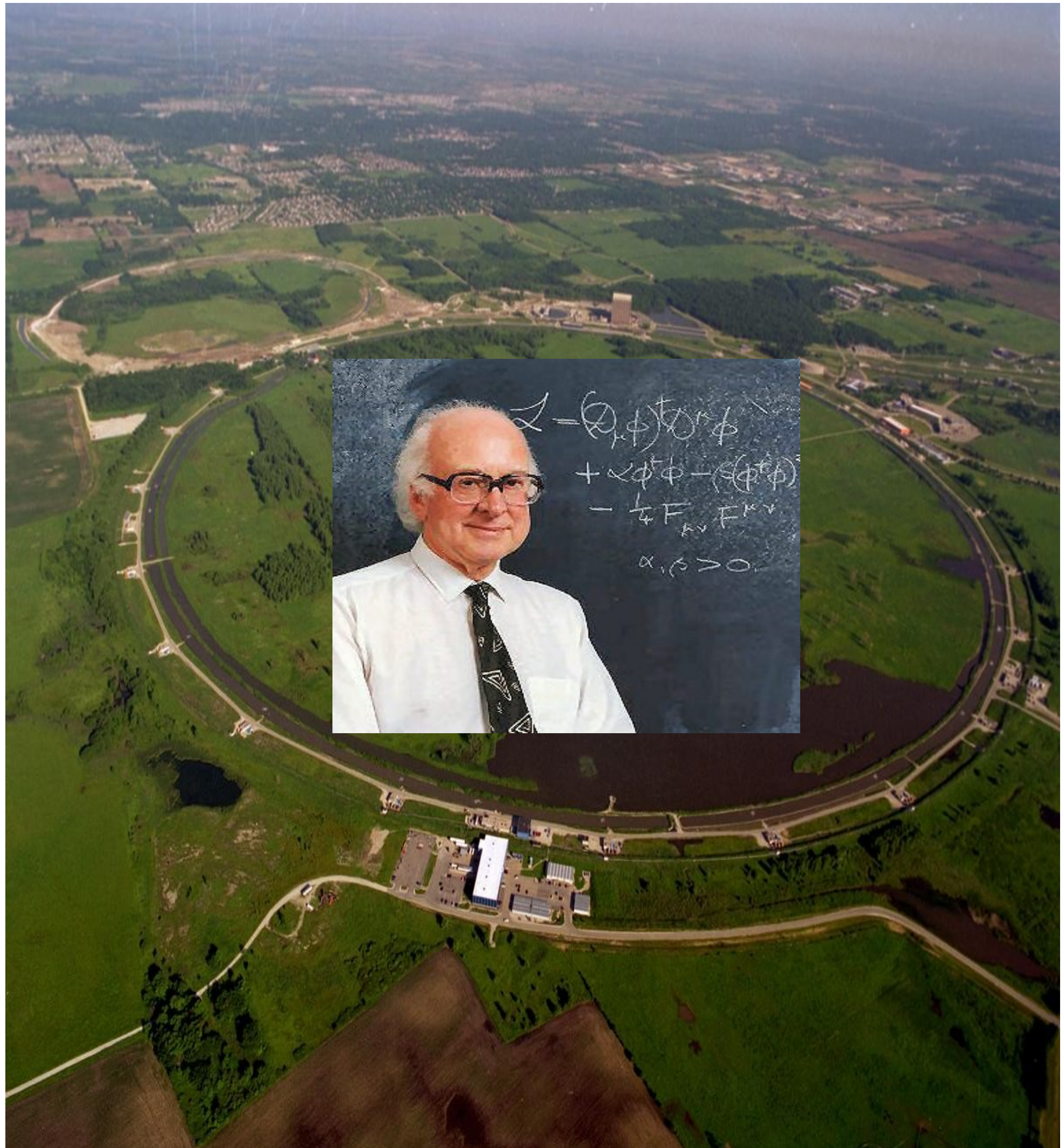


Running with high operating efficiency (>90%)

No operational issues anticipated until the end of Run II

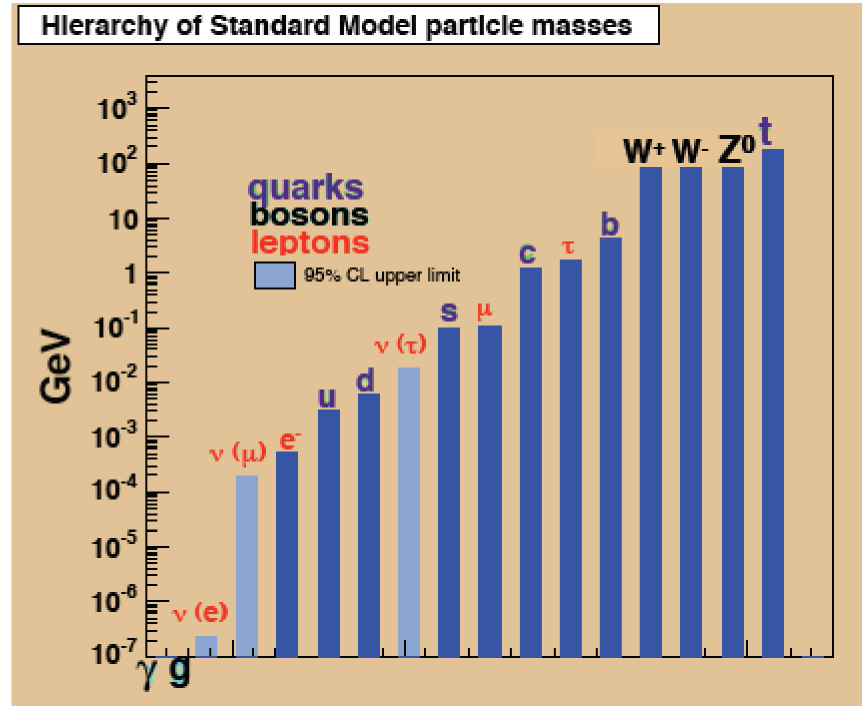
Expect to have ~10fb^{-1} on tape by the end of Run II

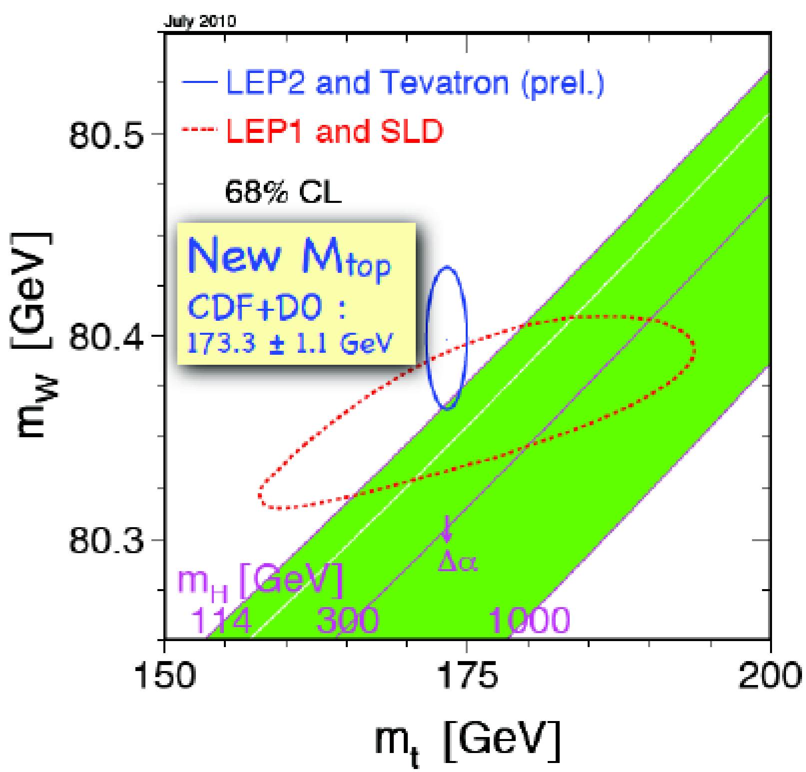
Higgs at the Tevatron



Higgs Introduction

- Higgs Mechanism predicts the existence of a new particle
- Generates Fermion masses through interaction with Higgs field
- Breaks electroweak symmetry (W/Z bosons acquire mass) through degrees of freedom of Higgs field
- We don't know exactly what the mass (m_H) of the Higgs boson is



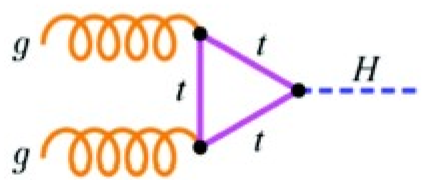


- Direct search at LEP found excess around 115GeV, but not statistically significant
  - $M_H \geq 114.4$GeV @ 95% CL
- M_W and M_t constraints and indirect constraints on M_H from global EW fits prefer a light Higgs boson:
  - $M_H = 87^{+35}_{-26}$ GeV
  - $M_H < 186$ GeV @ 95% CL

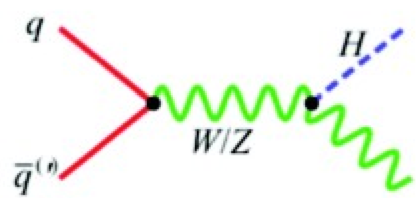
Low vs High Mass

Higgs production
at the Tevatron:

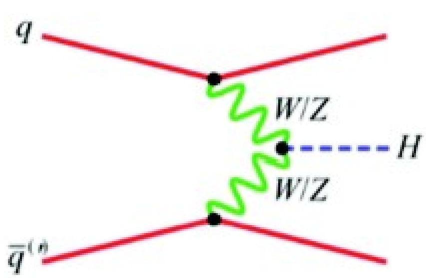
$$\sigma(gg \rightarrow H) = 0.2 \ - \ 1 \text{ pb}$$

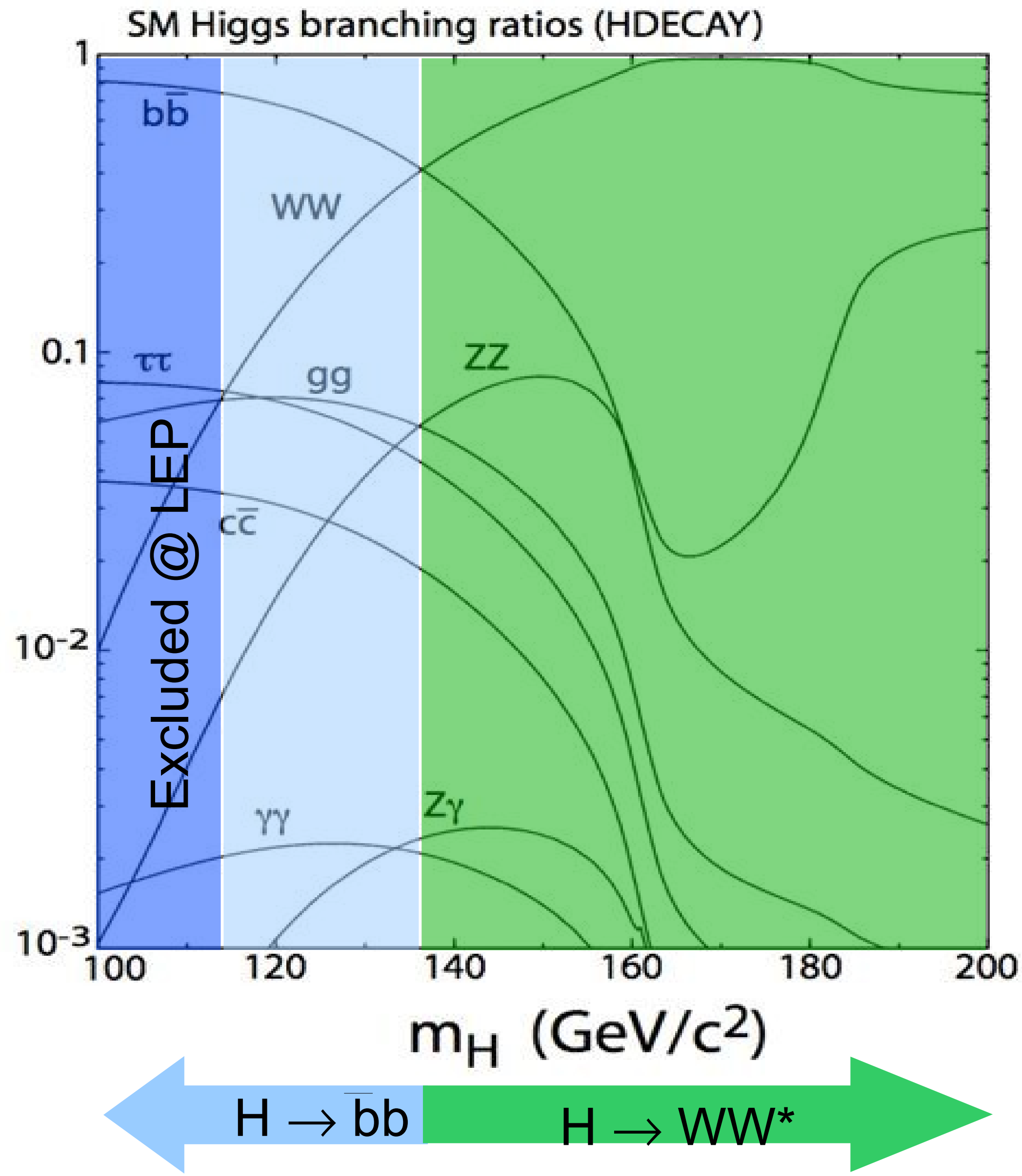


$$\sigma(q\bar{q} \rightarrow VH) = 0.01 \ - \ 0.3 \text{ pb}$$



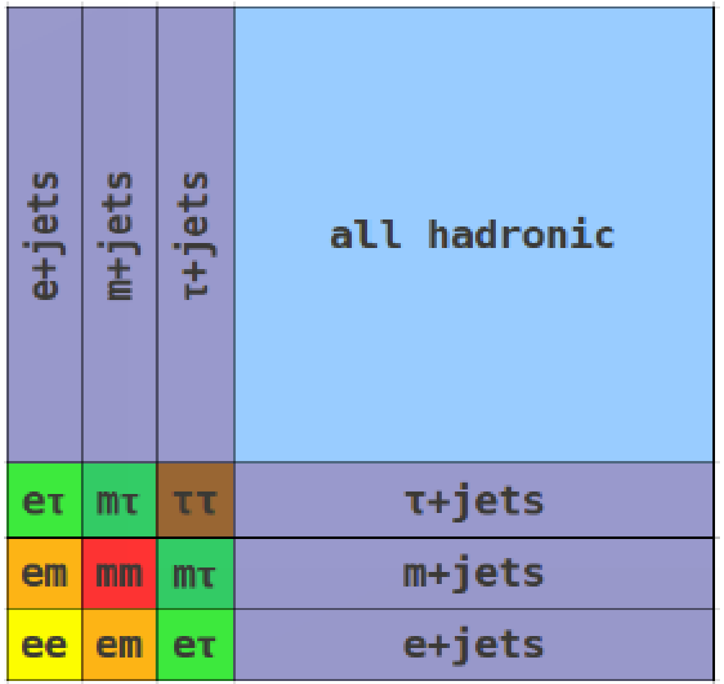
$$\sigma(q\bar{q} \rightarrow q\bar{q}H) = 0.01 \ - \ 0.1 \text{ pb}$$





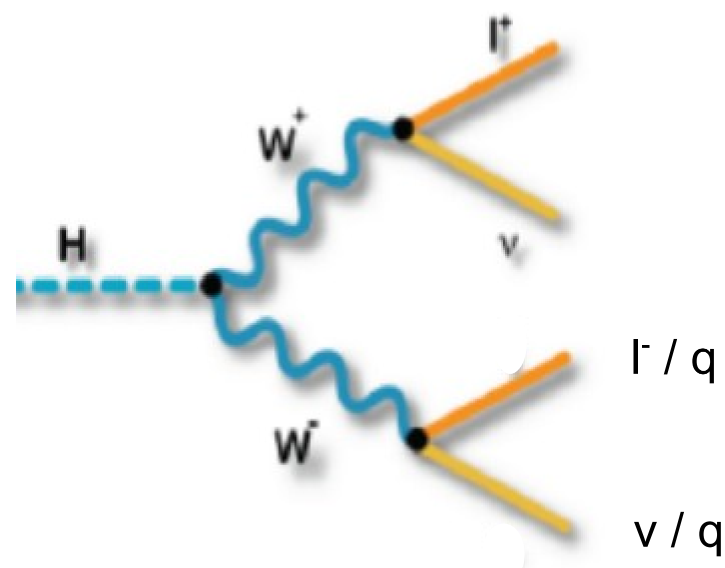
H→WW* dominant for M_H>135GeV
Tevatron definition of "High Mass"

H→WW* Final States



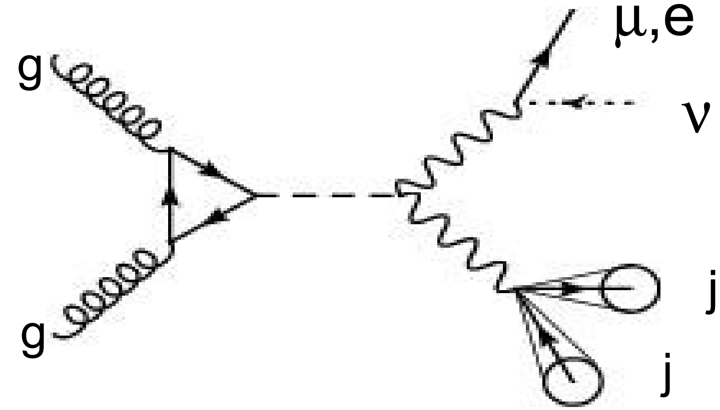
- *"Leave no stone unturned"*
- Hadron collider environment requires that at least one W decays leptonically
- Most sensitive channel is lνlν
- We recently included lνqq

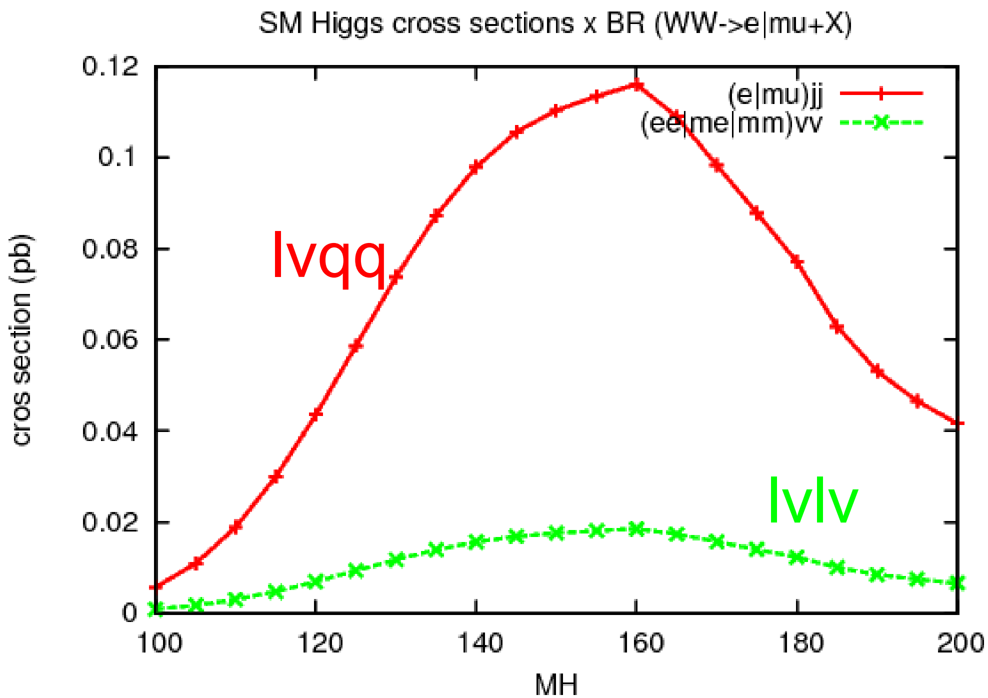
- "All leptonic" final state (lνlν) has a small BR but provides a very clean signal: 2 high p_T leptons and missing E_T
- "Semi leptonic" final state (lνqq) has a large BR but much larger backgrounds which are more difficult to model



H→WW→lνjj Introduction

- H→WW is the most sensitive search channel at the Tevatron
- DZero has reached SM sensitivity
- Until recently only leptonic final states: H→WW→lνlν
- This analysis looks at semi-leptonic final states H→WW→lνjj (l=μ,e):
  - 5.4fb^{-1} data set
  - H production via gluon-fusion
  - Large branching fraction for hadronic W decays
  - Factor of ~6 increase in xsection * BR
  - Large backgrounds from W+jets
- Use W mass constraint to reconstruct neutrino p_Z. For m_H>160GeV possible to extract the mass of Higgs



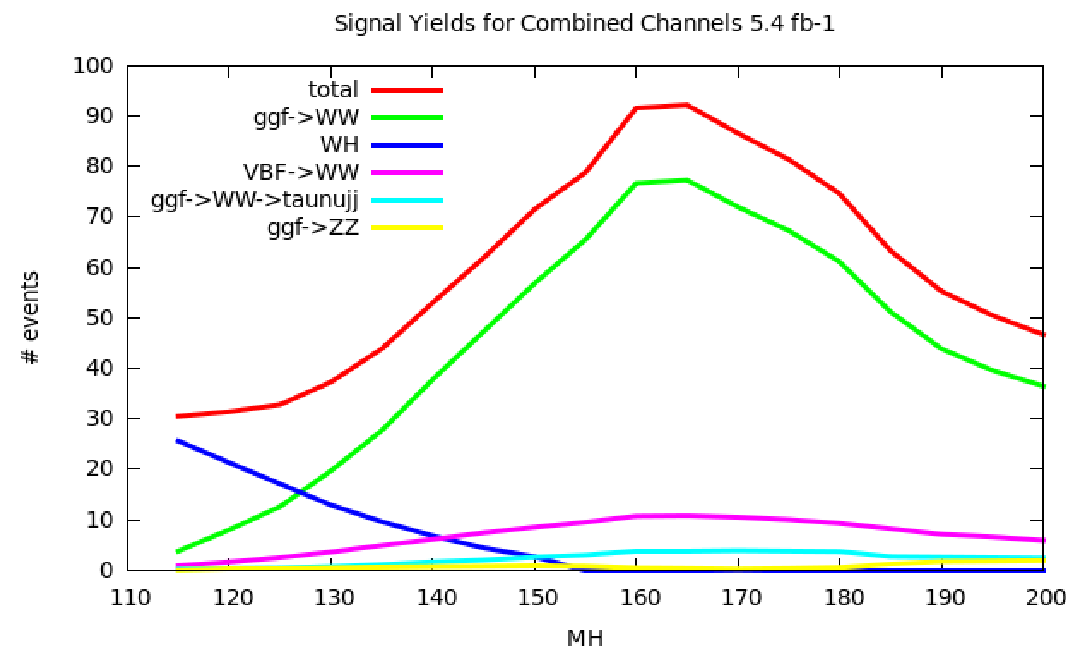


Signal & Background

Channel	$gg \to H$	$qq \to qqH$	WH	V+jets	Multijet	Top	VV	Total Background	Data
Electron	11.2/46.3/27.8	2.1/6.4/4.2	7.2/0/0	52158	11453	2433	1584	67627	67627
Muon	9.5/34.7/20.4	1.5/4.4/2.9	5.7/0/0	47970	2720	1598	1273	53562	53562

- Signal Processes (PYTHIA):
  - gg→H→WW→e/μνjj
    - Dominates above m_H=125GeV
  - gg→H→WW→τνjj & gg→H→ZZ :
    - Contributes little after pre-selection
  - WH→lνbb:
    - Contributes at low mass
    - Different kinematic shape
  - Vector Boson Fusion qqH→qqWW:
    - Contributes at medium and high mass
    - Different kinematic shape

- Backgrounds:
  - W/Z+Jets: Alpgen
  - Multijet ("QCD"): derived from data
  - Di-bosons (WW,WZ,ZZ): Pythia
  - Top (ttbar, single-top): Alpgen, CompHEP



Event Selection

Triggers:
Electron channel: Single-Lep and Lep+Jets triggers, >90% efficiency
Muon channel: SingleMuon triggers, efficiency ~79%(74%) Run2a(b)

- **Leptons**:
  - $p_T > 15$ GeV
  - e:$|\eta_{det}| < 1.1$, mu:$|\eta_{det}| < 1.6$
- MET > 15 GeV
- Triangle Cut:
  $M_{trans\ W} > 40 - MET/2$

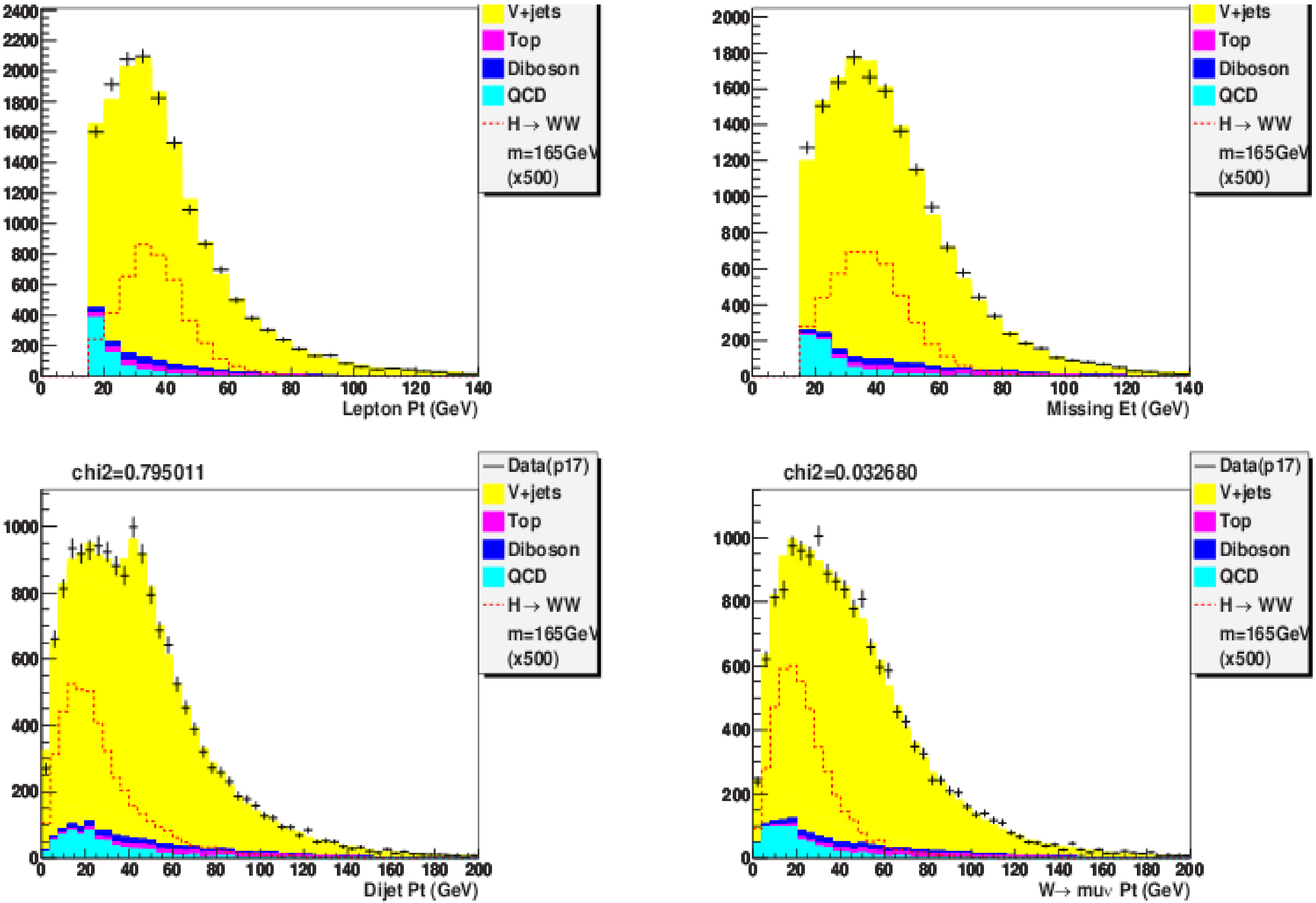
- **Jets**:
  - ≥2 jets
  - Vertex-confirmation
  - JCCB
  - $p_T > 20$ GeV
  - $|\eta| < 2.5$

Analysis Strategy

- Very low S/√B ratios make it impossible to perform cut-based analysis, i.e., no counting experiment : S/√B~0.18
- Requires the use of Multivariate Analysis Techniques (MVA) for signal extraction:
  - Random Forest (RF)
  - RF optimized for each sub-channel and Higgs mass hypothesis
  - Input parameters: event topology, kinematics, …
  - RF outputs are used as input to derive limits
- 4-step process:
  - Step 1: Use simple cuts (pre-selection) and optimize data modeling
  - Step 2: Select variables that show good signal vs background discrimination
  - Step 3: Feed variables into Random Forest to separate signal from background
  - Step 4: Use Random Forest outputs to set cross section limits

Data Modeling (1)

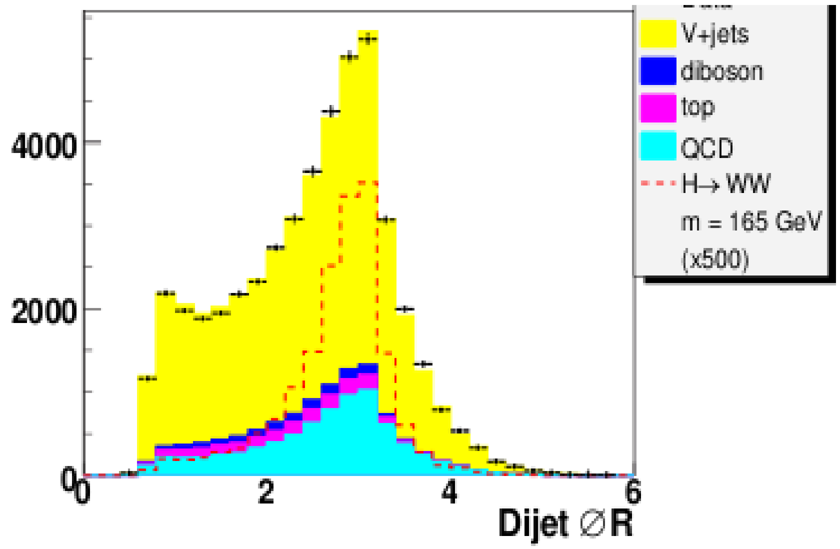
Scores of distributions were examined and after corrections to MC, generally excellent agreement is observed between data and background models.

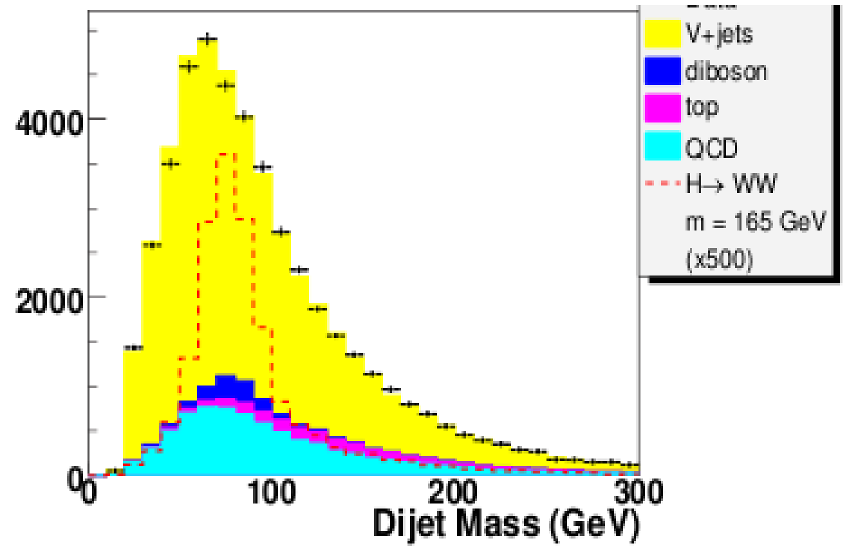


Muon Channel

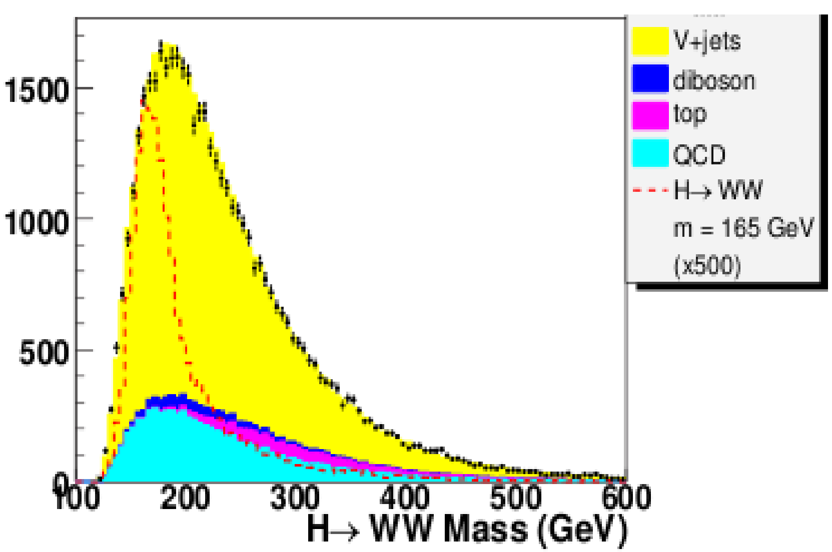
Data Modeling (2)

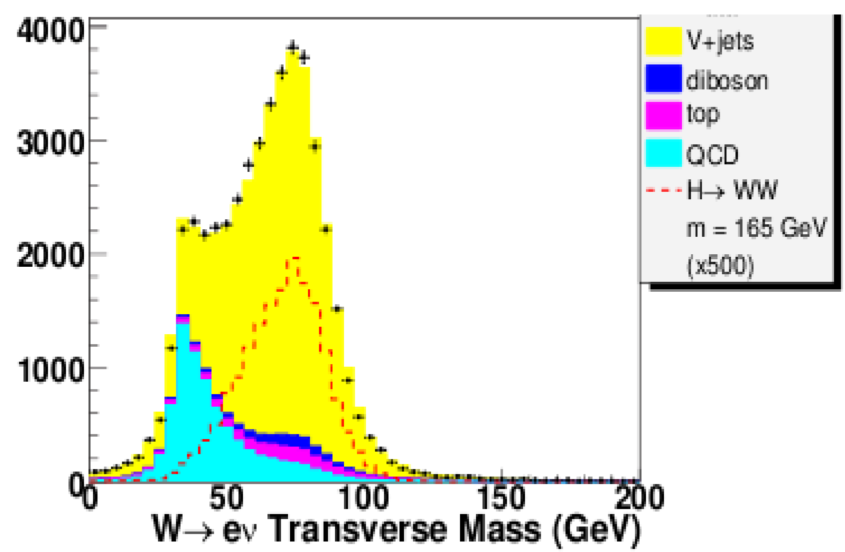
Scores of distributions were examined and after corrections to MC, generally excellent agreement is observed between data and background models.





Electron Channel





Selection of Distributions for Analysis

Variables satisfying a χ^2 probability requirement of 2% in data/MC comparisons are selected as possible discriminants

Normalized signal shapes were compared to the dominant background from V+jets using a KS test.

Those variables with the largest KS distance were selected to use in constructing our MVA.

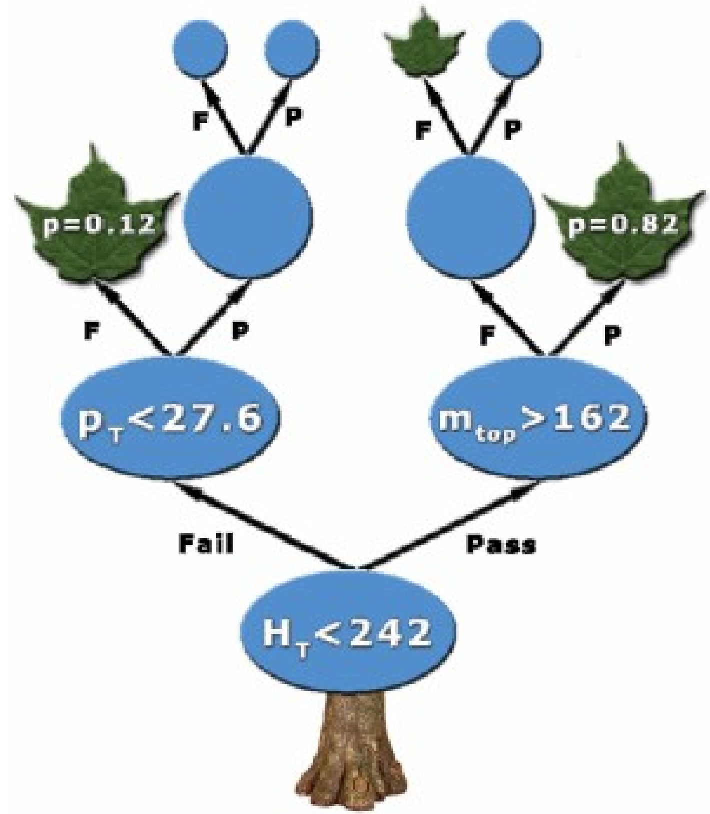
Roughly 30 variables were selected per channel (object and event kinematics, angular variables)

Large number of inputs reflects the fact that different distributions show sensitivity at different mass ranges and any single variable is a very weak classifier.

Random Forest Description

We use a Random Forest (RF) classifier to improve separation between signal and background.

RF is composed of a collection of (50) Decision Trees

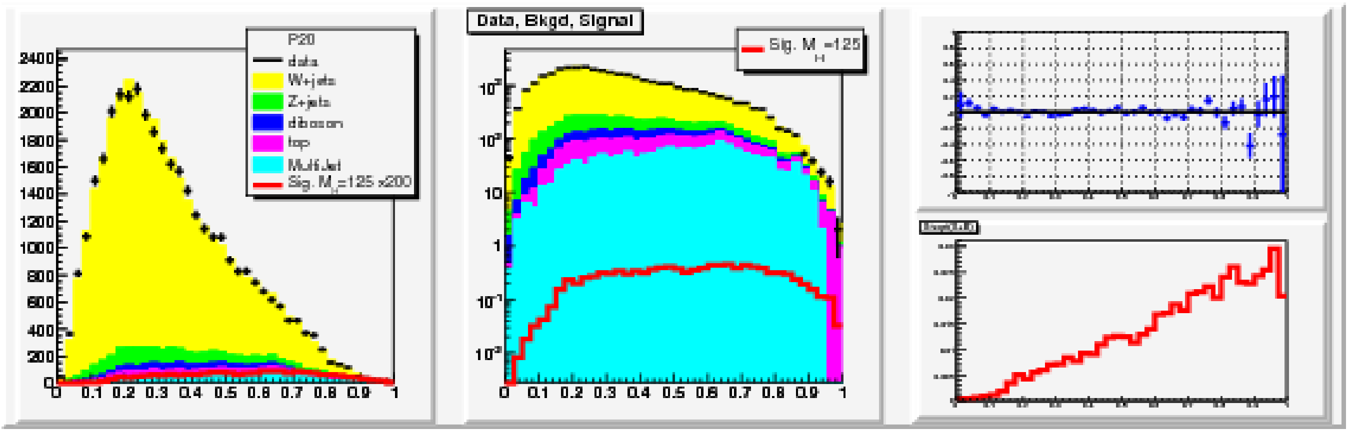


Building a Decision Tree, Example:
- Start with one node containing entire training sample (signal + background)
- Find single variable cut that yields best separation between signal and background
- Now there are two nodes: repeat on each node
- A node becomes a leaf when a stopping criterion is reached: minimum number of signal/background events, or maximum tree depth
- Pass event to classify through tree, and assign purity from leaf

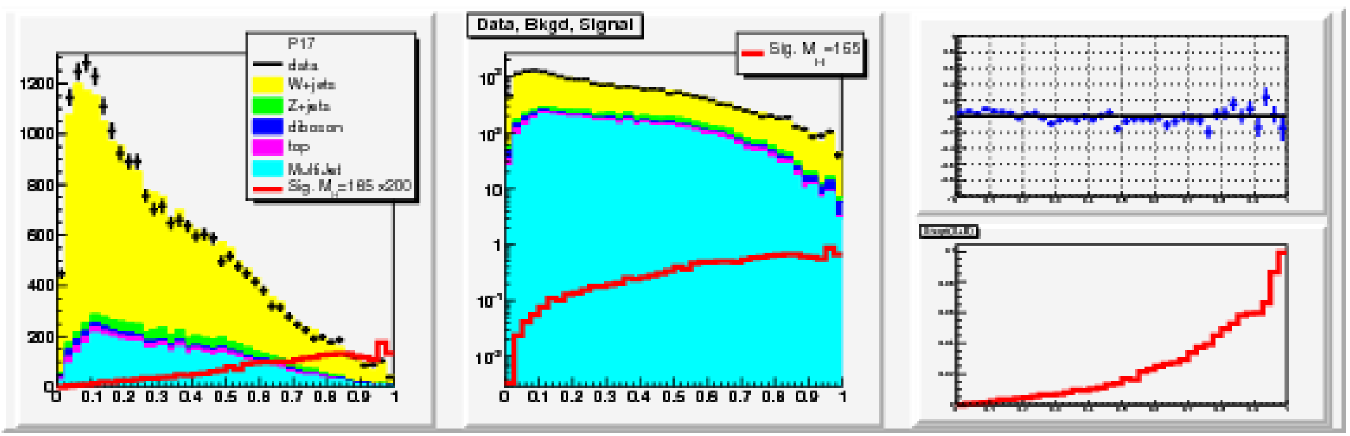
Boosting is used to reweight mis-classified events:
self correcting

Combine multiple Decision Trees into a Random Forest:
For a given event the output of the forest is the combined average output of all trees

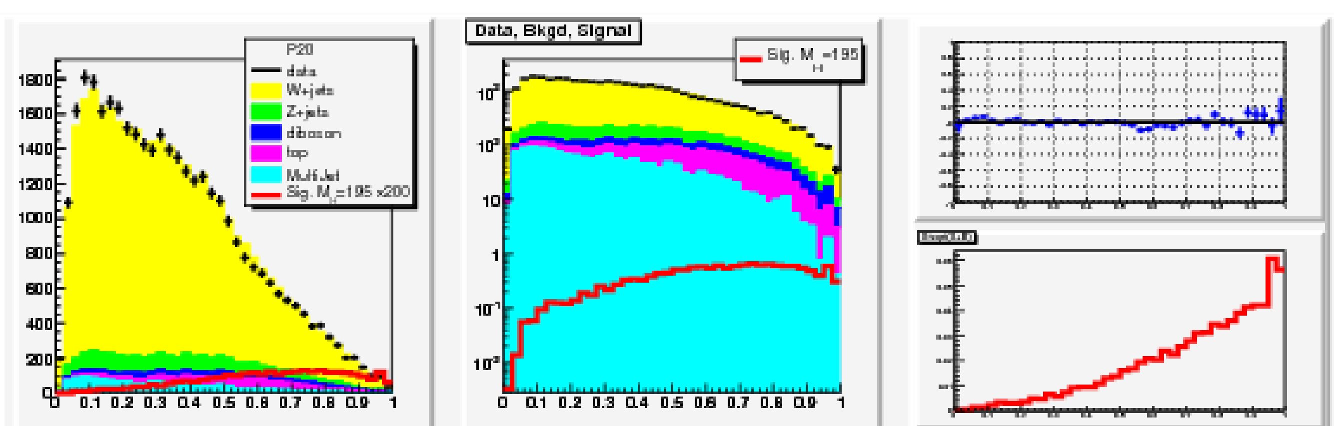
Random Forest Outputs



125 GeV: Muon Channel



165 GeV: Electron Channel



195 GeV: Muon Channel

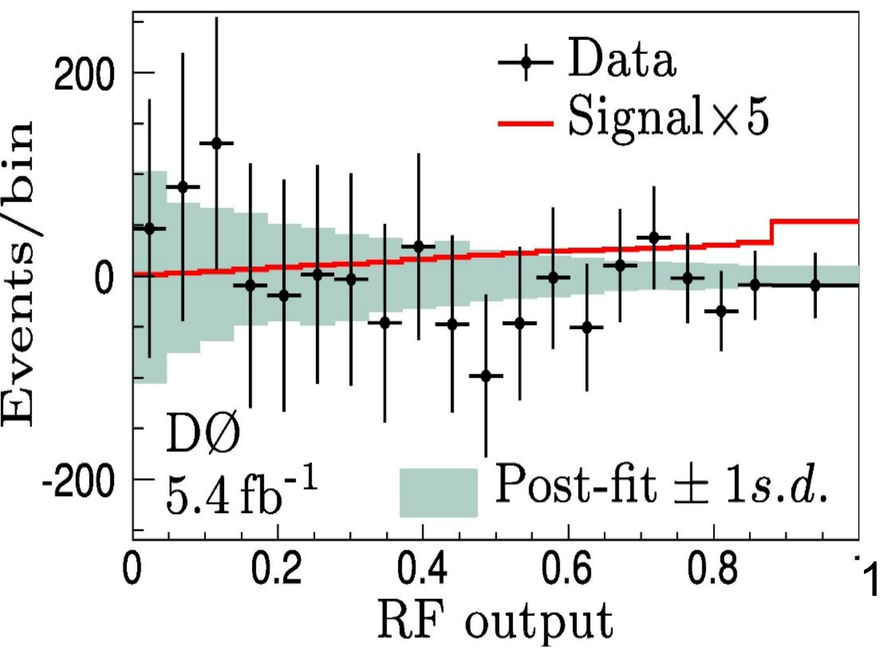
Systematic Uncertainties

Can affect both shape and overall normalization of final discriminant

Uncertainties listed are relative changes in normalization

Contribution	Shape	W+jets	Z+jets	Top	Diboson	$gg \to H$
Jet energy scale	Y	shape only	shape only	±6.0	$\binom{+3.3}{-3.5}$	$\binom{+3.3}{-2.0}$
Jet identification	Y	shape only	shape only	±3.3	±1.3	±3.5
Jet resolution	Y	shape only	shape only	$\binom{+0.5}{-0.3}$	$\binom{+1.0}{-0.5}$	$\binom{+2.0}{-1.8}$
Association of jets with PV	Y	shape only	shape only	±3.8	±3.8	±4.8
Luminosty	-	-	±6.1	±6.1	±6.1	±6.1
Muon trigger	Y	±0.5	±0.5	±0.5	±0.25	±0.25
Electron identification	-	±4.0	±4.0	±4.0	±4.0	±4.0
Muon identification	-	±4.0	±4.0	±4.0	±4.0	±4.0
ALPGEN tuning	Y	shape only	shape only	-	-	-
Cross Section	-	±6.0	±6.0	±10.0	±7.0	±10.0
PDF	Y	$\binom{+3.5}{-2.5}$	$\binom{+8.0}{-1.5}$	$\binom{+2.3}{-3.6}$	±0.25	$\binom{+1.8}{-3.8}$

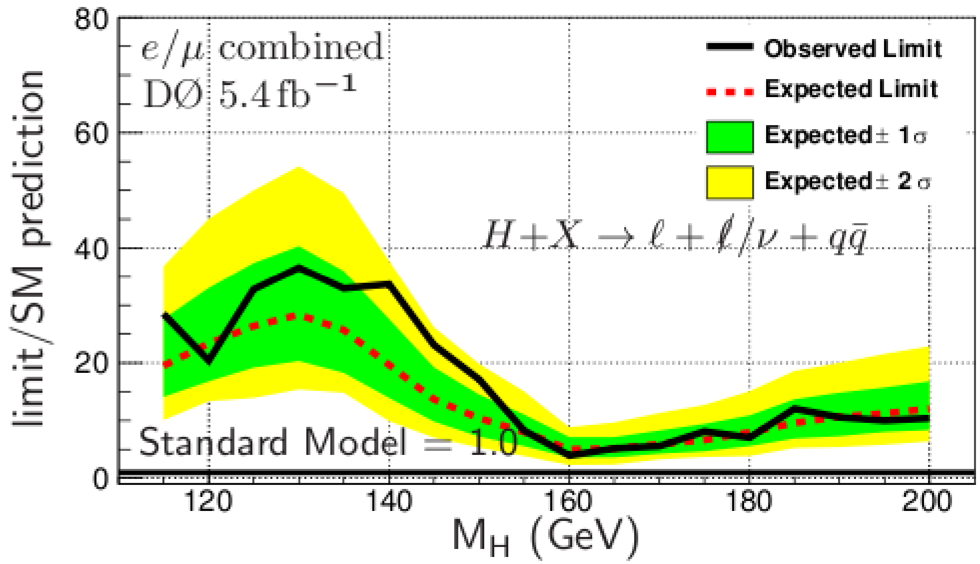
		Multijet background	
		Electron channel	Muon channel
Multijet background	Y	±6.5	±26.2

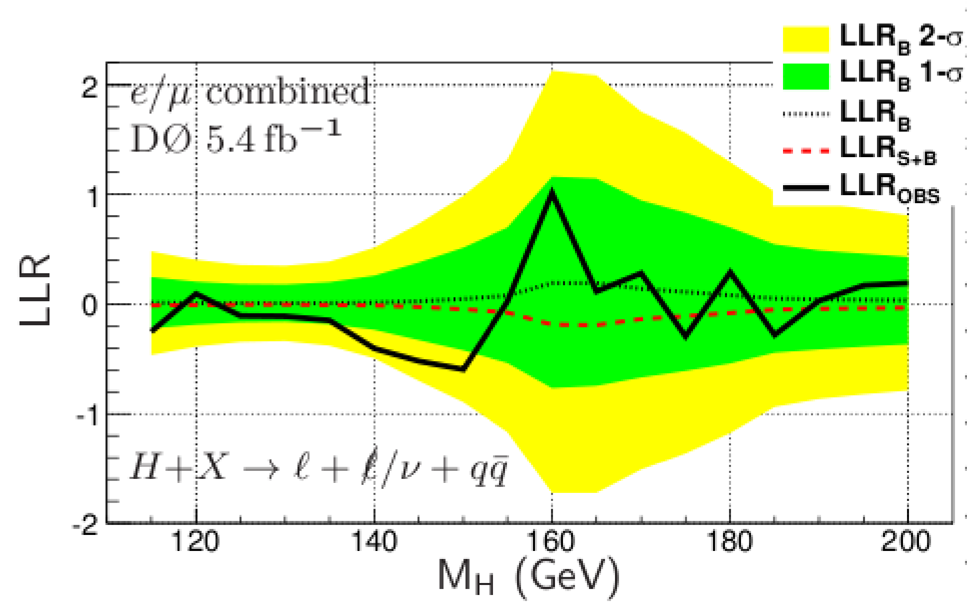


Background subtracted data (points),
1s.d. uncertainty on background (blue band),
M_H=160GeV signal x5 (red)

H→WW→lνjj Limits

No significant excess of signal-like events is observed
RF outputs used to set exclusion limits at 95% CL
Combining electron and muon channel



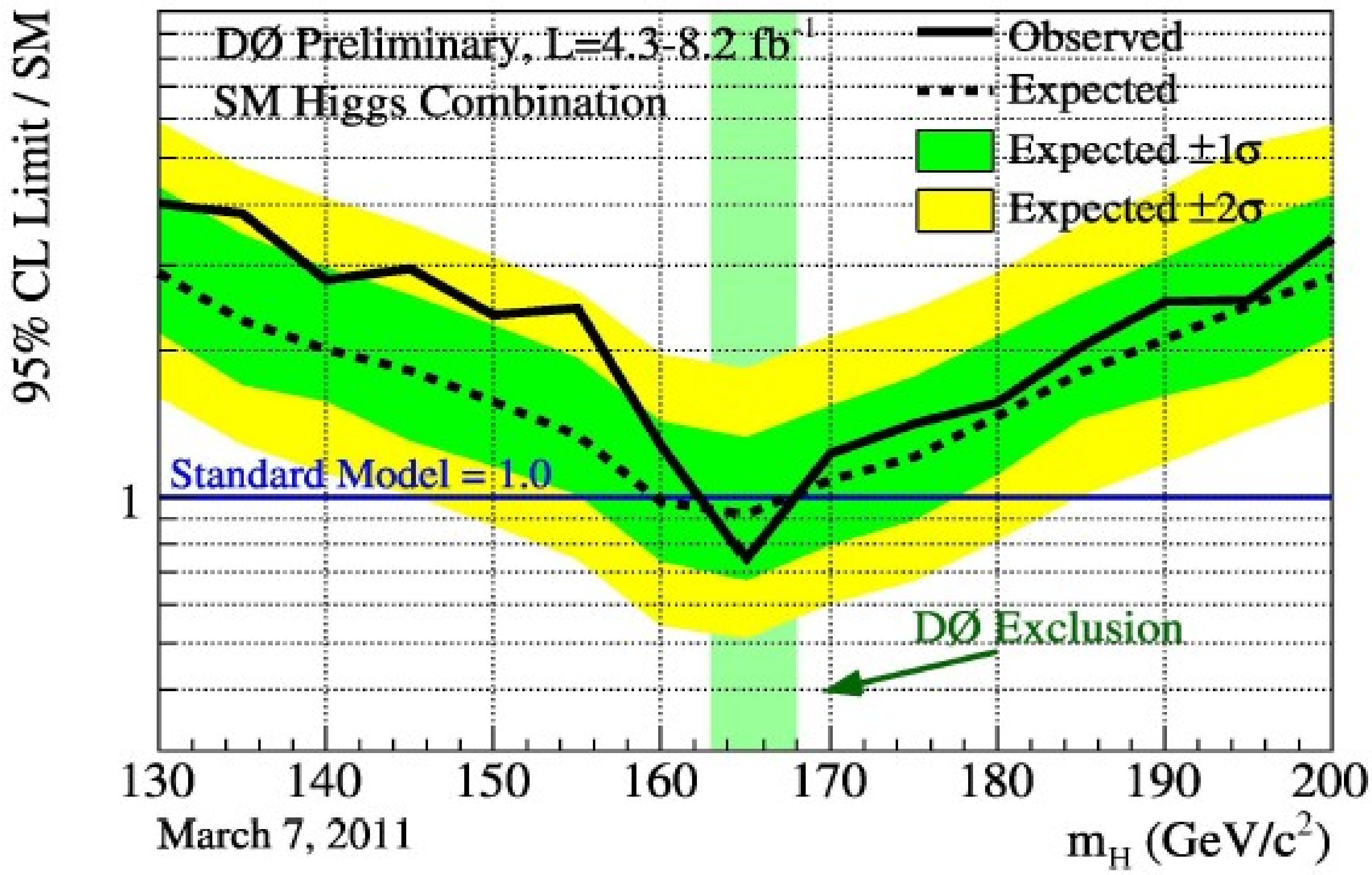


M_H (GeV)	115	120	125	130	135	140	145	150	155	160	165	170	175	180	185	190	195	200
Observed	28.5	20.4	32.8	36.6	33.0	33.7	23.1	17.1	8.3	3.9	5.2	5.6	8.2	7.1	12.0	10.6	10.0	10.4
Expected	19.5	23.4	26.4	28.4	25.7	19.7	13.7	10.4	8.0	5.0	5.1	5.9	6.7	8.0	9.6	10.7	11.2	12.1

Submitted to Physical Review Letters (PRL) January 2011: arXiv:1101.6079v2[hep-ex]
Accepted by PRL on March 24, 2011

DZero Combined Limits

Combined with all other high mass analysis channels (mainly $H \to WW \to l\nu l\nu$)



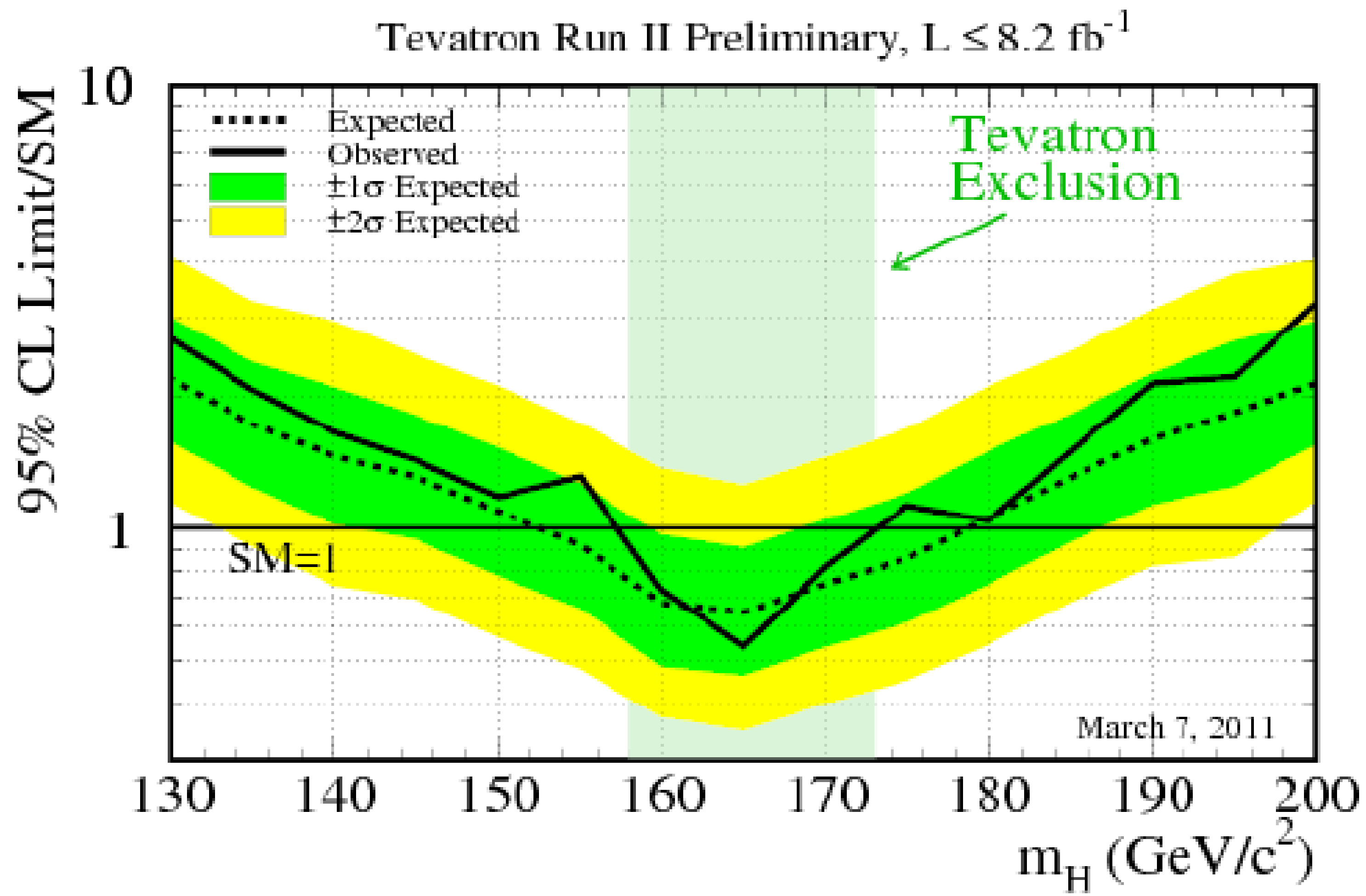
Single experiment exclusion:

SM Higgs excluded at 95%CL for **$163 < m_H < 168$ GeV**

Expected exclusion at 95%CL for **$160 < m_H < 168$ GeV**

Tevatron Limits

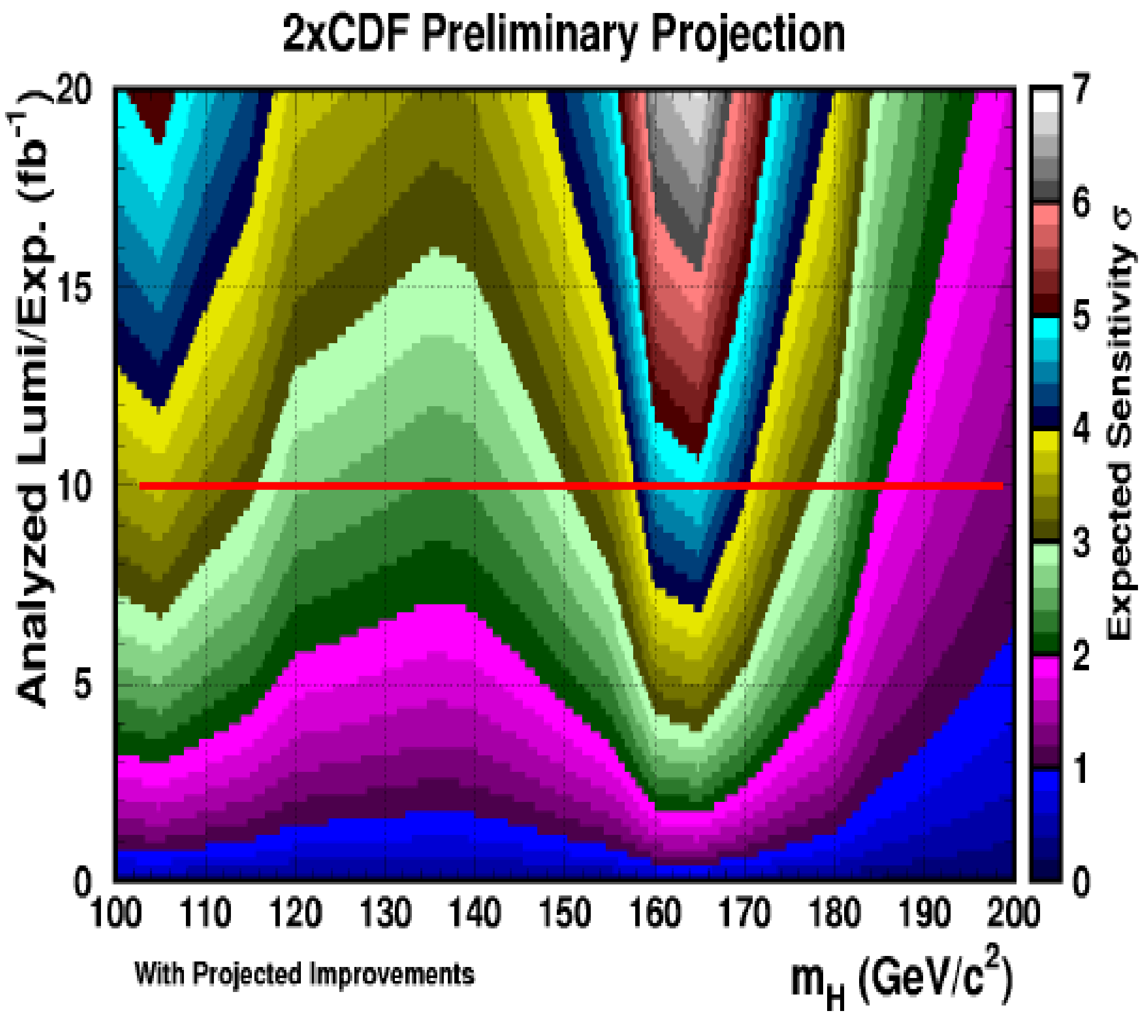
Combining DZero with CDF:



SM Higgs excluded at 95%CL for **158 < m_H < 173 GeV**

Expected exclusion at 95%CL for **153 < m_H < 179 GeV**

Future Prospects

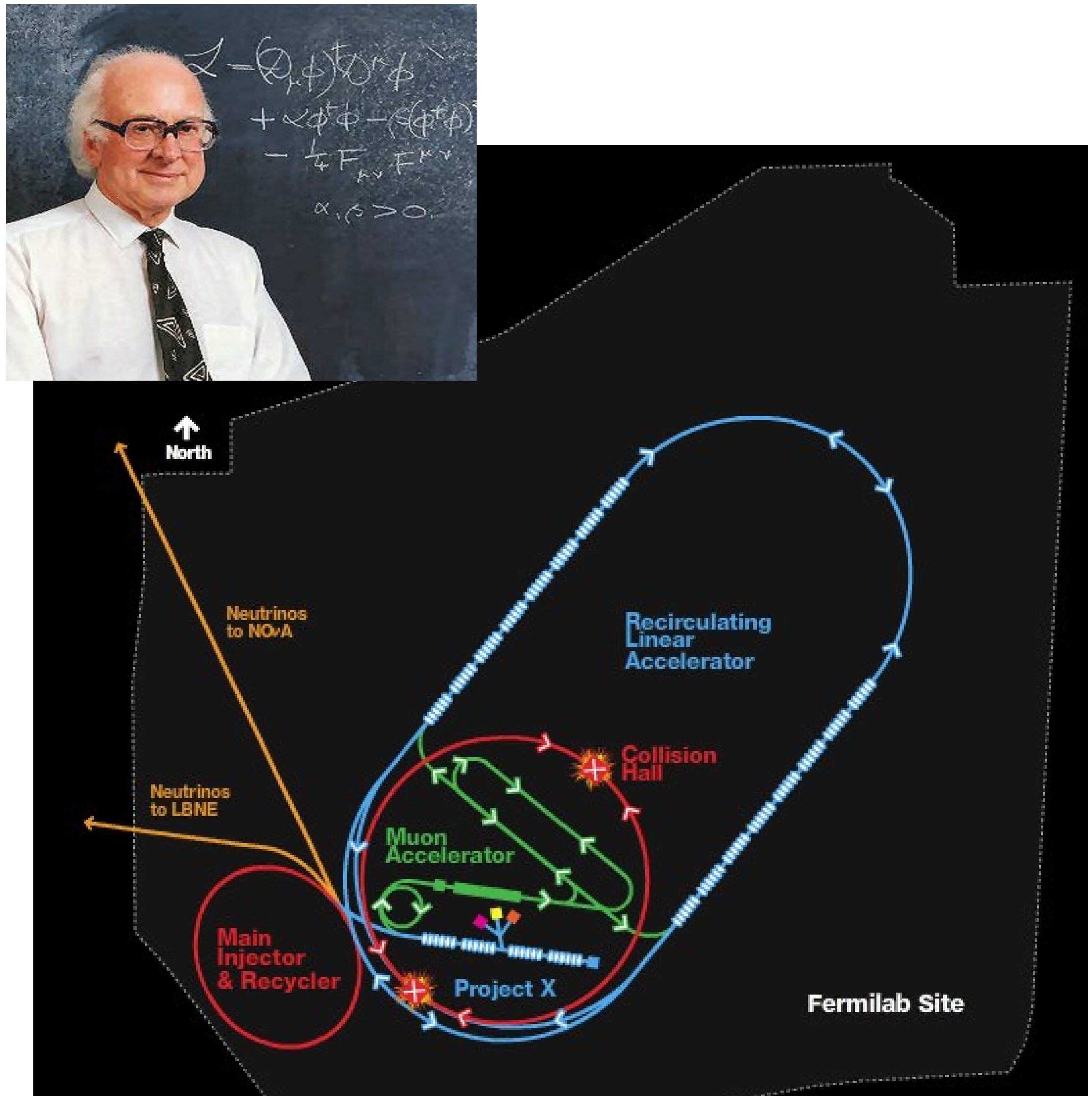


Projected expected limits for SM Higgs vs integrated luminosity

No extension of Tevatron RunIIb ⇒ 10fb^{-1} will be our final data set

- **>2.4σ expected sensitivity across entire mass range**
- **3σ at 115GeV**

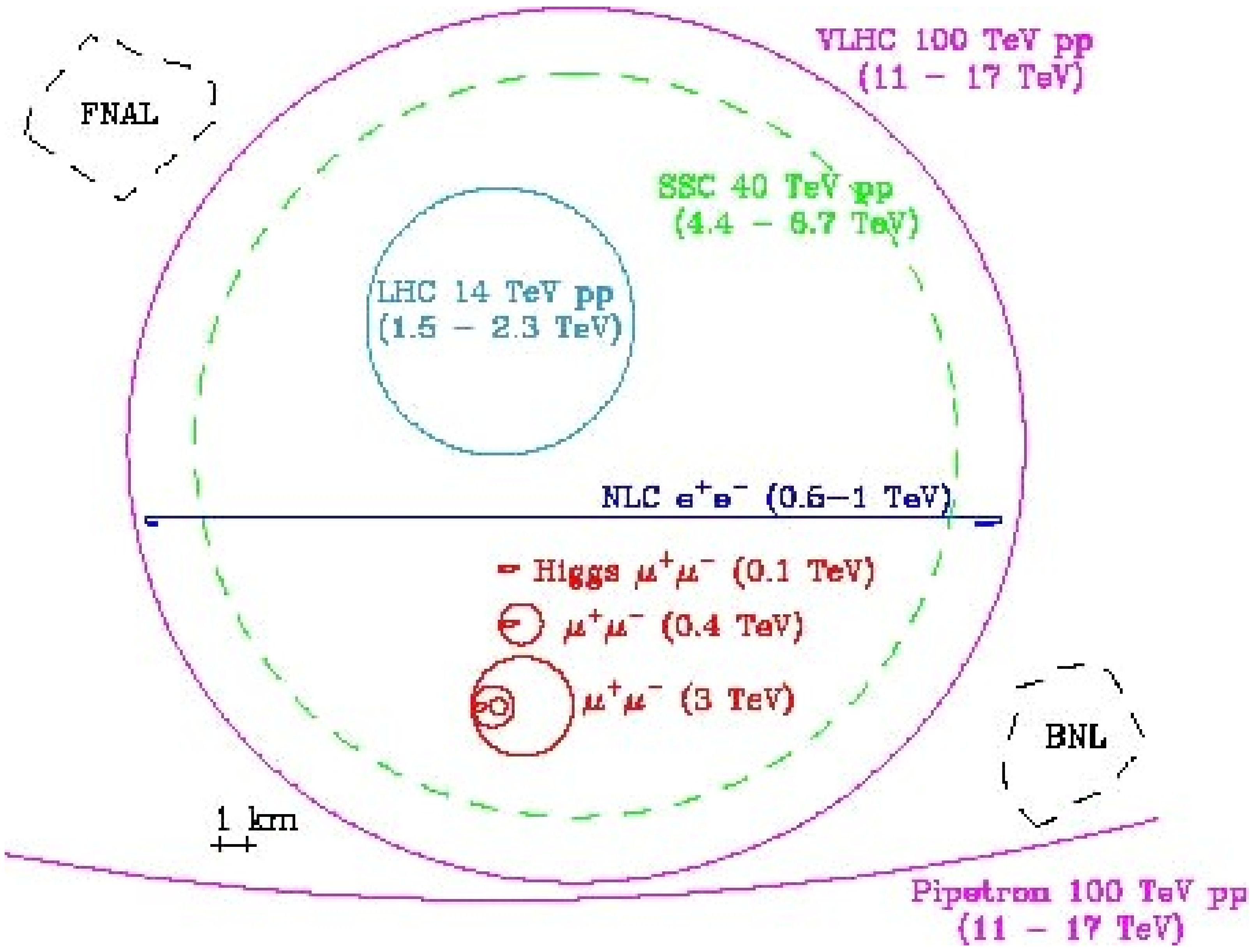
Higgs at a Muon Collider



The Case for a Muon Collider

- Muons are fundamental particles
  - Energy of interaction is the full energy of particle
  - At a hadron collider partons only carry a fraction of the hadron momenta
  - LHC @ 14 TeV → parton-parton collisions at ~2 TeV
- Muons are heavier than electrons: $m_\mu \sim 200 \times m_e$
  - For a lepton with mass *m* the radiative energy losses are $\sim 1/m^4$
  - Lost energy must be put back in via RF power (cost of operation)
  - Severely limits the COM energy achievable with a LEP-like collider
  - Solved by using heavy leptons
  - Size of a muon collider ring is much smaller
- Physics advantages:
  - Small radiative losses → small beam-energy spread (as low as $\Delta p/p$=0.003%)
  - Small beam-energy spread + precise COM energy determination allows precision measurements of new resonant states
  - Neutrinos from muon decays can be used for precision neutrino cross section measurements and long-baseline experiments (Neutrino Factory)

Comparison of High Energy Colliders

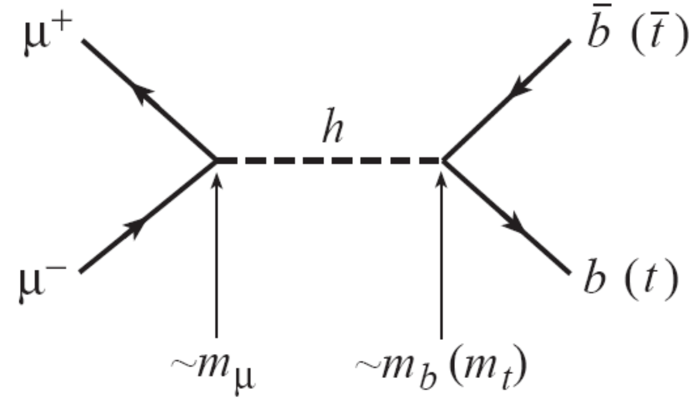


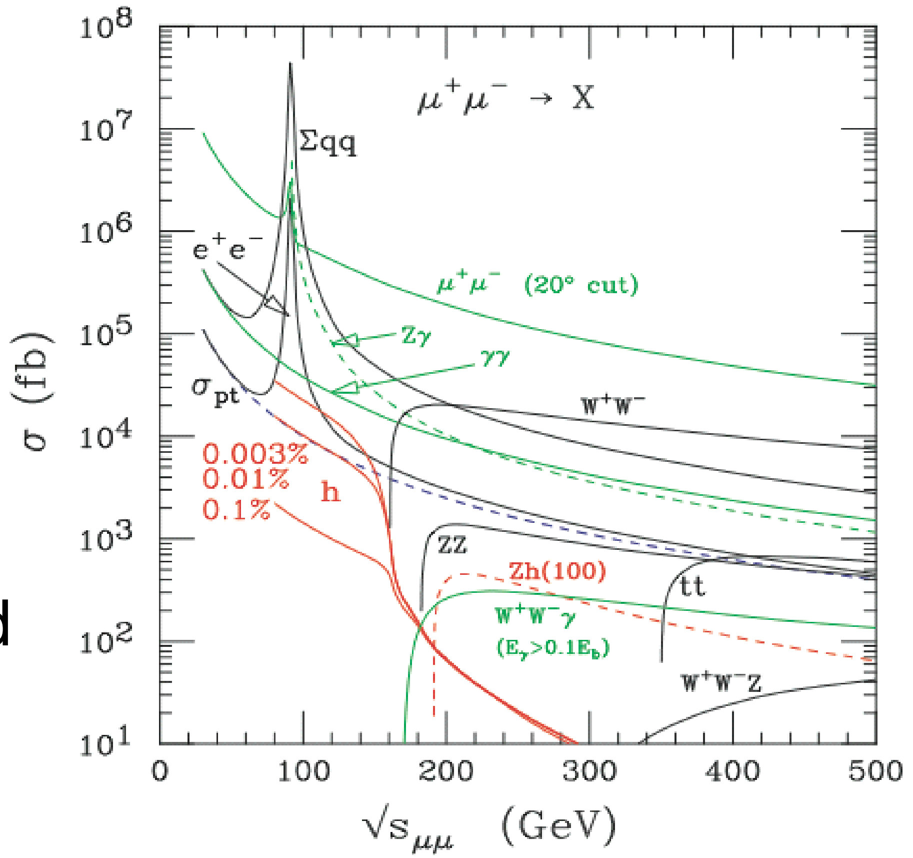
Technical Feasibility

- Some technical problems arise when dealing with muons:
  - Need to **generate**, **accelerate** and **collide** muon bunches within the muon liftetime of 2.2μs
- Muon cooling:
  - Transform a diffuse muon cloud into a bright bunch with small longitudinal and transverse dimensions
  - Must be done in a short time, i.e., stochastic cooling or electron cooling won't work
  - Use ionization cooling
- Backgrounds:
  - Huge detector backgrounds from large flux of electrons produced in muon decays
  - Loss of forward region and impact on physics potential
- Polarization
  - Should be studied

Higgs Bosons at a Muon Collider

- Expect a light SM(-like) Higgs Boson
- Possible to produce with high rates directly via *s* channel process:
  - Good energy resolution: few MeV
  - Little Bremsstrahlung
  - No Beamstrahlung smearing
  - Precise tuning of beam energy: $\Delta E \sim 10^{-6} E$
- Measure Higgs mass, width and BRs with high precision
  - Distinguish between SM Higgs and supersymmetric Higgs (MSSM)





From Phys. Rev. Spec. Topics – Accelerators and Beams, Vol.2, 081001 (1999)

Light SM-like Higgs Boson

Assuming Tevatron (unlikely) or LHC (more likely) discovered a light SM-like H: $m_H \approx 110$GeV

Looking for $\mu\mu \rightarrow H \rightarrow bb$

Tune MC $\sqrt{s}$ to m_H and perform scan

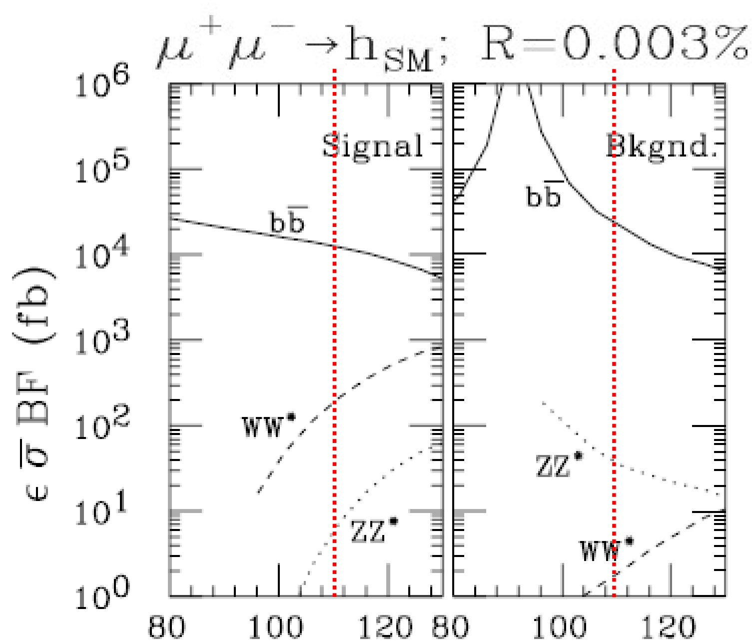
Assume gaussian beams with RMS energy resolution of R=0.003%

Corresponding RMS spread in COM energy is ~2 MeV

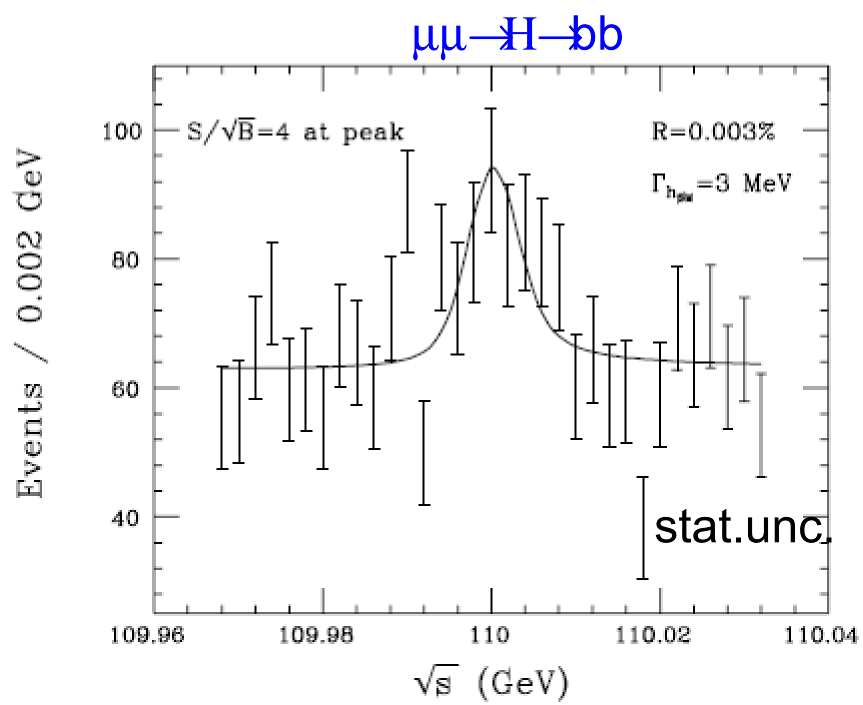
Need enough statistics for each scan point to have good $S/\sqrt{B}=4$

Assuming MC delivers $1.5\times10^{31}cm^{-2}s^{-1}$ ($0.15fb^{-1}$/yr)

After one year of running we can measure the Higgs mass to an accuracy of Δm_H~1MeV



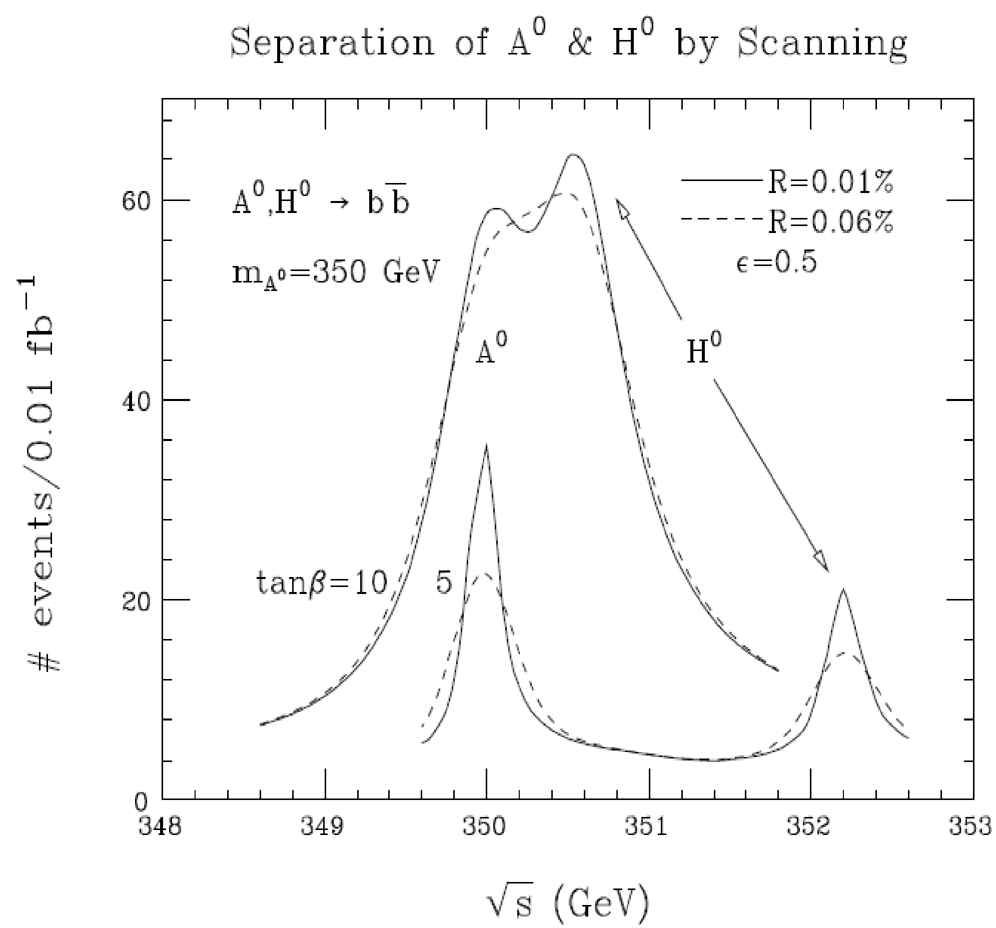
SM signal/background xsections for bb, WW, ZZ vs m_H [GeV]



From Phys. Rep. 286, 1 (1997)

MSSM Higgs Bosons

- Supersymmetric models can generate multiple physical Higgs bosons
- MSSM (Two Higgs Doublets):
  - h^0 couplings close to SM values (low mass)
    - Measure Higgs width with high accuracy to distinguish between h_{SM} and h^0
    - Ratio r=BF(WW)/BF(bb) is sensitive to m_{A0}
  - H^0, A^0 nearly degenerate in mass at high $\tan\beta$
  - H^0, A^0 widths are broader (Γ~30MeV) than for h^0 → less challenging
- **Can be done with *s* channel scan at a Muon Collider to disentangle**



From Phys. Rep. 286, 1 (1997)

The next 20 years

- Muon Collider is probably not going to be operating within the next 20 years
- By then the LHC will have (hopefully) made basic discoveries
- Not a very strong case for a MC if we only find a low mass SM Higgs boson.
  - We want something exotic!
- LHC is a discovery machine
  - Hard to make precision measurements
  - Low signal/background
  - Many interactions per crossing
- A Muon Collider may be needed to complement LHC discoveries

Summary

- Showed an overview of the DZero detector
- Presented results from the DZero high mass SM Higgs searches
  - DZero has reached single-experiment SM sensitivity
- Possibilities for Higgs searches at a future Muon Collider
- Now waiting for the LHC to make discoveries
- Exciting times ahead!

Backup

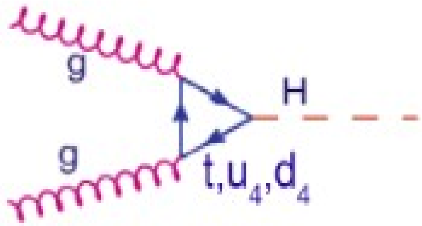
Random Forest Inputs

Object Kinematics	
Lepton energy	E^{ℓ}
Lepton/jet transverse momentum	$p_T^{\ell}, p_T^{j_1}, p_T^{j_2}$
Angular Variables	
Azimuthal angles	$\Delta\phi(j_1, j_2), \Delta\phi(\ell, \not{E}_T)$,
	$Min(\Delta\phi(\not{E}_T, j_1), \Delta\phi(\not{E}_T, j_2)), Min(\Delta\phi(\ell, j_1), \Delta\phi(\ell, j_2))$
	$\Delta\phi(\text{bisector of dijet pair}, \not{E}_T)$
Polar angles	$\Delta\eta(j_1, j_2)$
3D angles	$\Delta R(j_1, j_2), Max(\Delta R(\ell, j_1), \Delta R(\ell, j_2)), Min(\Delta R(\not{E}_T, j_1), \Delta R(\not{E}_T, j_2))$
	$\angle(j_1, j_2)^{\dagger}, \angle(j_1, W \to \ell\nu)^{\dagger}, \angle(\ell, \text{dijet system})$
Event Kinematics	
Lorentz factor	$\beta(\text{dijet system})$
Transverse momentum sums	
vector	$\not{E}_T, p_T(\text{dijet system}), p_T(W \to \ell\nu)$
scalar	$H_T(j_1, j_2)$, $H_T(\text{all jets})$, $H_T(j_1, j_2, \ell)$, $H_T(j_1, j_2, \ell, \not{E}_T)$
Event shapes	$aplanarity(j_1, j_2, \ell, \nu)$
	$centrality(\ell, j_1, j_2)$, $centrality(\ell, \text{all jets})$
	$sphericity(\ell, j_1, j_2)$, $sphericity(\ell, j_1, j_2, \not{E}_T)^a$
N-body masses	$M(j_1, j_2)$, $M(j_1, j_2, \ell)$, $M(WW)$, $M(j_1, j_2, \ell, \not{E}_T)$
Transverse masses	$M_T(j_1, j_2)$, $M_T(W \to \ell\nu)$, $M_T(WW)$
Ratio of jet energies	$E^{j_2}/E^{j_1\,\dagger}$
$KT^{max/min}$	$\Delta R(j_1/j_2) \times E_T(j_1/2)/(E_T^{\ell} + \not{E}_T)$
Other combinations	dot product of $\not{E}_T$ and angular bisector of dijet pair
	$\Delta\phi(W^{Lep.}$, bisector of dijet system)
	Magnitude of $p_T{}^{j_1}$ perpendicular to dijet system
Scaled $\not{E}_T$	$\sum_{\text{all jets}} [\sqrt{E^{j_i}} sin(\theta^{j_i}) cos(\Delta\phi(j_i, \not{E}_T))]^2$

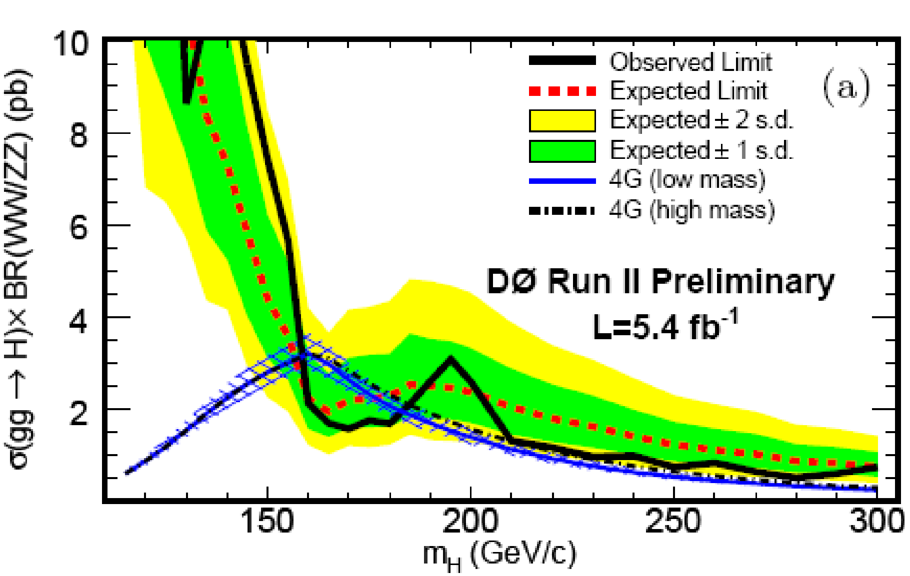
[a] For descriptions of the event shape variables see: V.D. Barger and R.J.N. Phillips, Collider Physics, Addison-Wesley, Reading, MA, 1987.

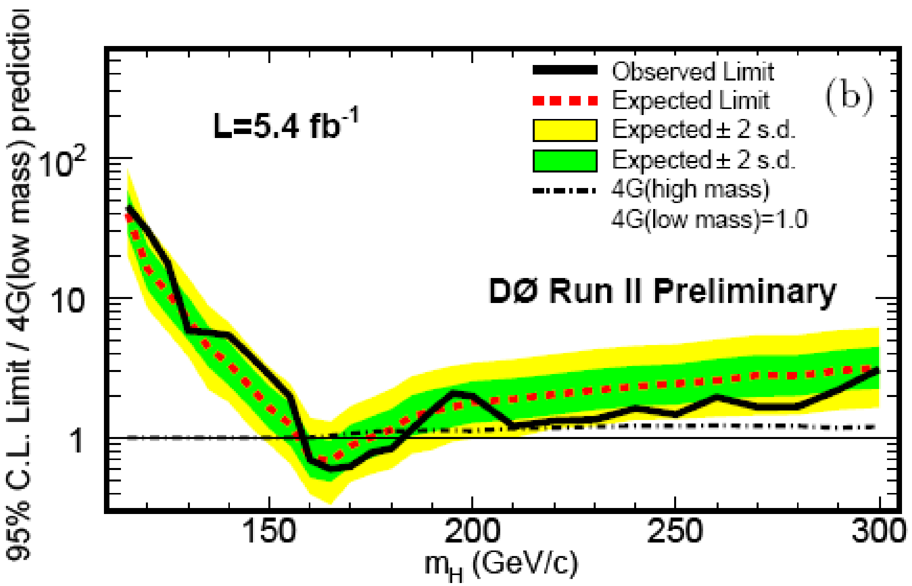
4^{th} Generation Interpretation

New heavy quark generation hypothesis
- ggH coupling is 3 times bigger than SM
- 9 times larger production cross section



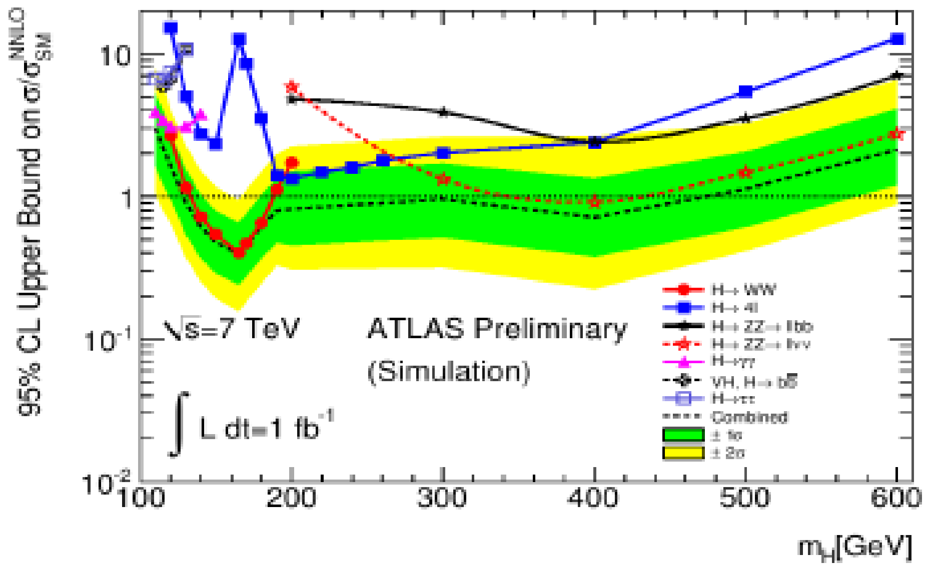
SM analysis re-optimized for higher m_H ranges



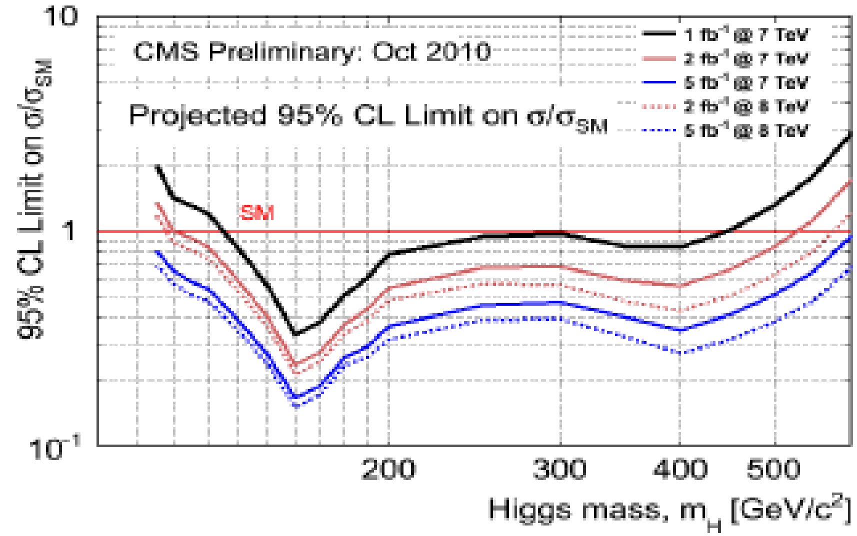


Projections for 2011-2012

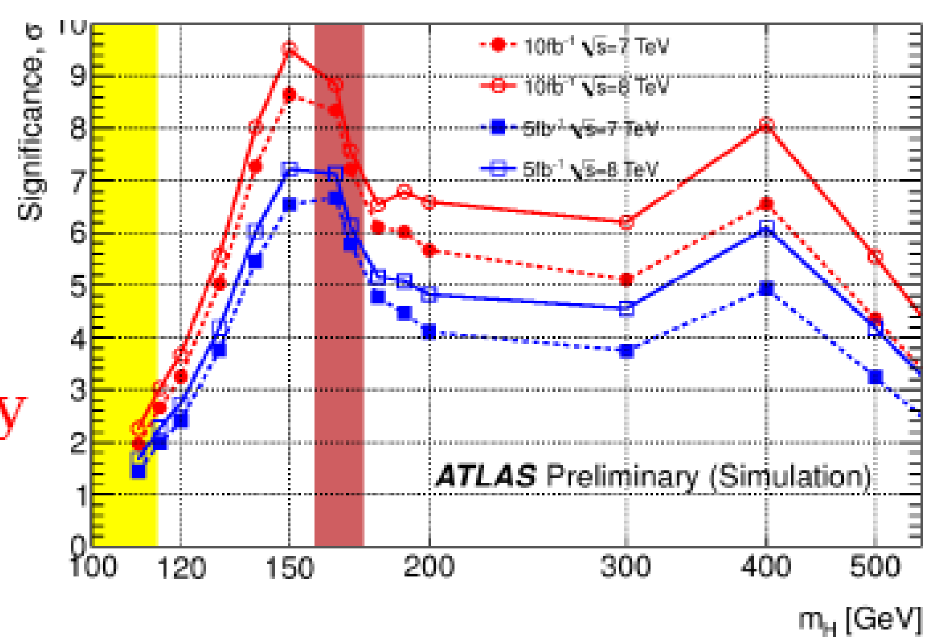
ATL-PHYS-PUB-2010-015



CMS NOTE 2010/008



- Both experiments expect to exclude a SM Higgs in ~130<M_H<460 GeV w/ 1fb^{-1}
- With 5-10 fb^{-1} at 8 TeV, exclude full mass range up to 600 GeV, or reach 5σ discovery if there is a SM Higgs in 130<M_H<500 GeV
- 114-130 GeV is challenging



ATL-PHYS-PUB-2010-015

Limit Setting

Using the RF output for signal, background and data we have 2 hypotheses:
H0: The data includes only SM background processes
H1: The data includes both the SM backgrounds and a Higgs signal (parametrized by mass)

To test which hypothesis is more probable, we construct a likelihood ratio:

s = # of signal evts
b = # of background
d = # of data evts

$$Q = \frac{e^{-(s+b)}(s+b)^d}{d!} \Big/ \frac{e^{-b}(b)^d}{d!}$$

Likelihood(sig+back) Likelihood(back only)

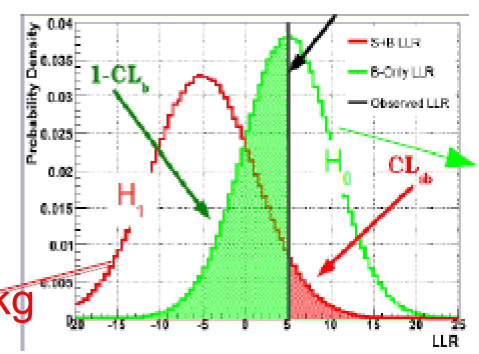
Results from different channels can be combined by multipliying: $Q' = \prod_i Q_i$

Rewrite Q in the form of a Log Likelihood Ratio: $(\mathrm{LLR}) = -2\ln(Q)$

Generate many pseudo-experiments for both H0 and H1

Plot the frequency of LLR values for each Higgs mass point

LLR from data



LLR bkg only

LLR H+bkg

CL_{s+b} is the fraction of H1 that is more background-like than data
CL_b is the fraction of H0 that is more background-like than data

Signal-like Background-like

Define ratio: $CL_s = \frac{CL_{s+b}}{CL_b}$

Increase rate of signal until
$1\text{-}CL_s = 0.95$
to get limit at 95% CL

Search Channel Summary

$m_H = 165$ GeV/c^2	Exp.	Obs.
CDF		
OS - 0 jet 5.9 - fb^{-1}	1.67	2.39
OS - 1 jet	2.35	2.46
OS - 2+ jets	3.16	6.14
low $M_{\ell\ell}$	11.2	7.21
Same Sign	4.86	5.92
Trileptons (noZ)	7.37	7.85
Trileptons (Z - 1j)	31.8	36.4
Trileptons (Z - 2+j)	9.16	10.4
hadronic τ	14.5	23.5
D0		
$ee + \mu\mu + e\mu$ - 5.4 fb^{-1}	1.36	1.55
$e\mu$ - 6.7 fb^{-1}	1.93	1.99
Same Sign	7.0	7.2
$\ell\nu jj$	5.5	3.8

TABLE I. Baseline parameters for high energy and low energy muon colliders. Higgs/yr assumes a cross section $\sigma = 5 \times 10^4$ fb; a Higgs width $\Gamma = 2.7$ MeV, 1 yr = 10^7 s.

COM energy (TeV)	3	0.4		0.1	
p energy (GeV)	16	16		16	
p's/bunch	2.5×10^{13}	2.5×10^{13}		5×10^{13}	
Bunches/fill	4	4		2	
Rep. rate (Hz)	15	15		15	
p power (MW)	4	4		4	
μ/bunch	2×10^{12}	2×10^{12}		4×10^{12}	
μ power (MW)	28	4		1	
Wall power (MW)	204	120		81	
Collider circum. (m)	6000	1000		350	
Ave bending field (T)	5.2	4.7		3	
rms $\Delta p/p$ (%)	0.16	0.14	0.12	0.01	0.003
6D $\epsilon_{6,N}$ $(\pi \mathrm{m})^3$	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}	1.7×10^{-10}
rms ϵ_n (π mm mrad)	50	50	85	195	290
β^* (cm)	0.3	2.6	4.1	9.4	14.1
σ_z (cm)	0.3	2.6	4.1	9.4	14.1
σ_r spot (μm)	3.2	26	86	196	294
σ_θ IP (mrad)	1.1	1.0	2.1	2.1	2.1
Tune shift	0.044	0.044	0.051	0.022	0.015
n_{turns} (effective)	785	700	450	450	450
Luminosity ($\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$)	7×10^{34}	10^{33}	1.2×10^{32}	2.2×10^{31}	10^{31}
Higgs/yr			1.9×10^3	4×10^3	3.9×10^3