In Search of New Physics with Higgs at DØ

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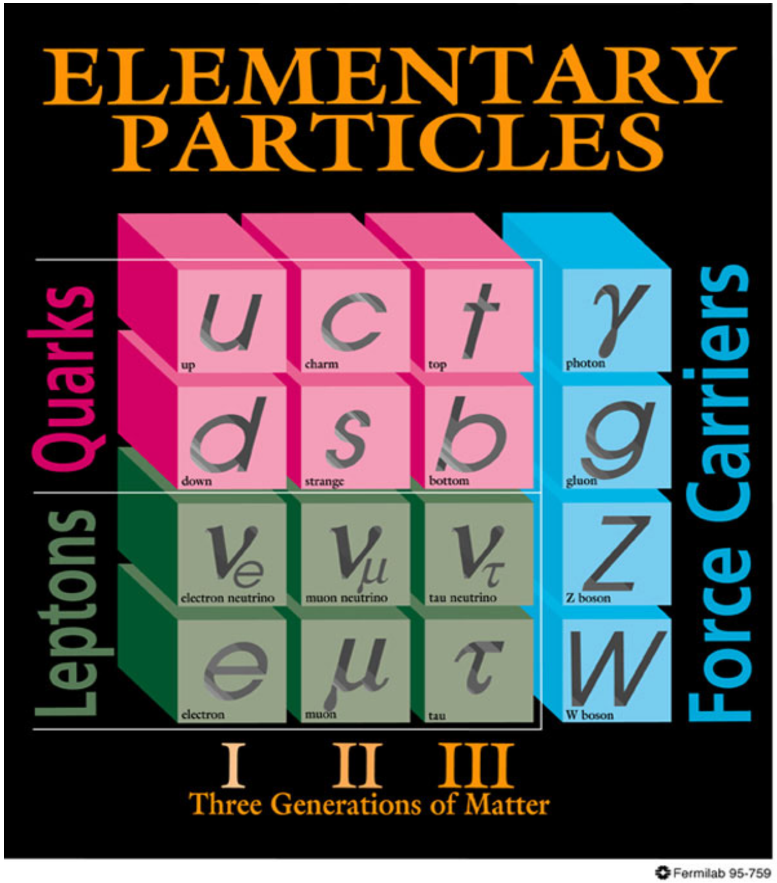
$SU(3)_C \times SU(2)_L \times U(1)_Y$

Fundamental particles:

Fermions
(half-integer spin)

- quarks
- leptons

Building blocks of matter
(1st generation)



Fundamental forces mediated by:

Bosons
(integer spin)

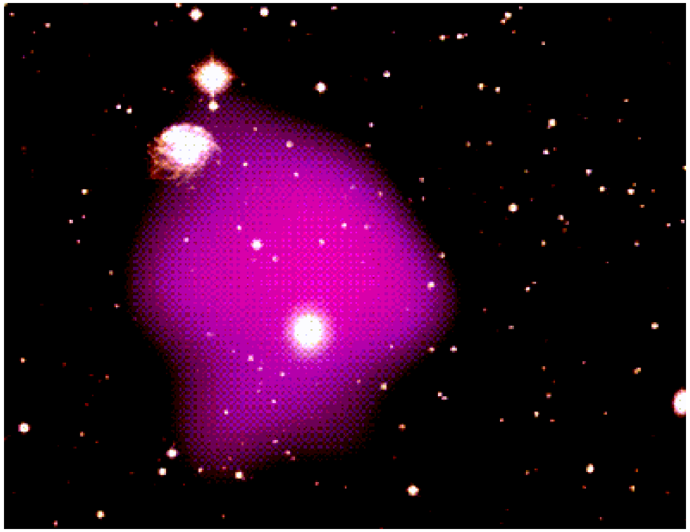
- gluons QCD
- photon, W/Z EW

Gravity not included

What about mass?

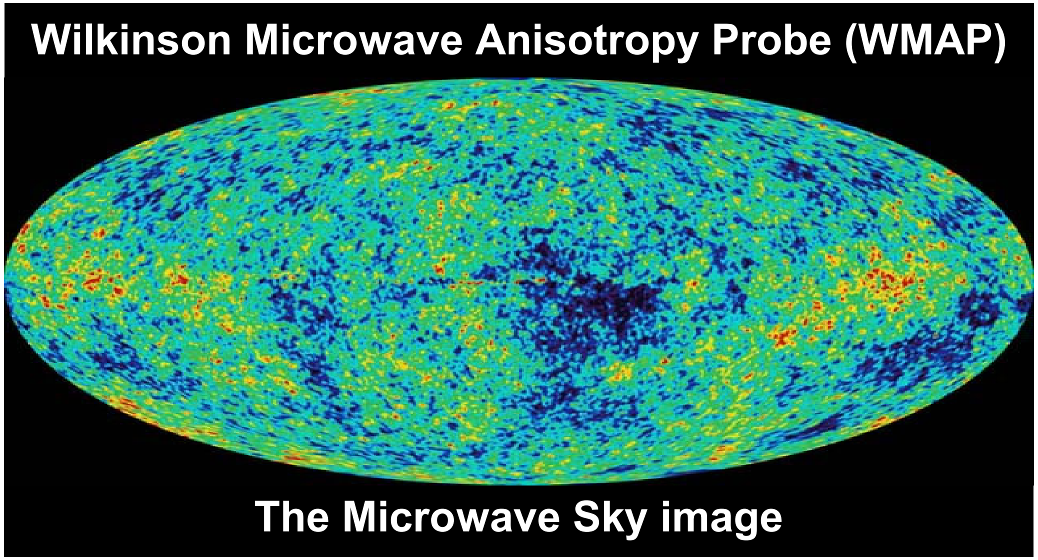
Mass without Matter

- The bulk of the mass in the universe does not appear to be due to ordinary matter



- There are many reasons to believe that the universe is full of "dark matter"
- One recent piece of evidence: Superposed on an optical picture of a group of galaxies is an X-ray image taken by ROSAT. The presence of confined hot gas (which produces X-rays) highlighted in (false) red color indicates that the gravity exerted in groups and clusters of galaxies is larger than that expected from the observed galaxies

- Latest WMAP 2003 results from power spectrum of CMB
  - 4% atoms, 23% Cold Dark Matter, and 73% Dark energy in the universe
  - quintessence (negative-pressure energy field) is not ruled out, but Dark-E seems more like a “cosmological constant”
  - first stars ignited early – fast ν’s don’t play any major role in the evolution of structure in the universe

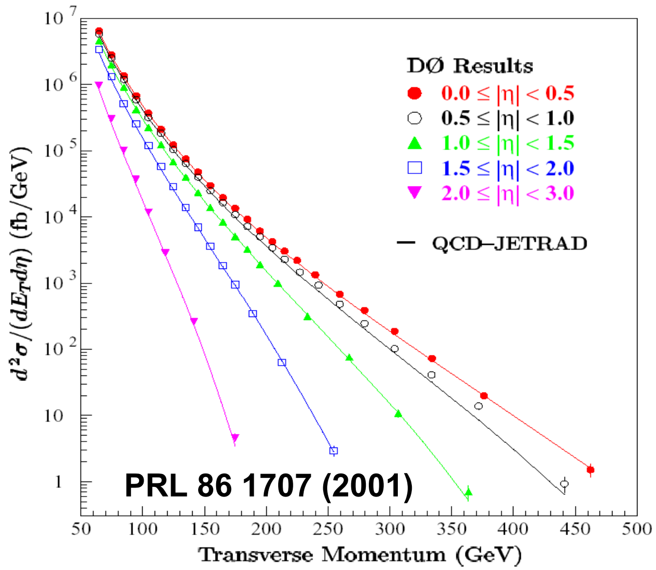


Mass without Mass

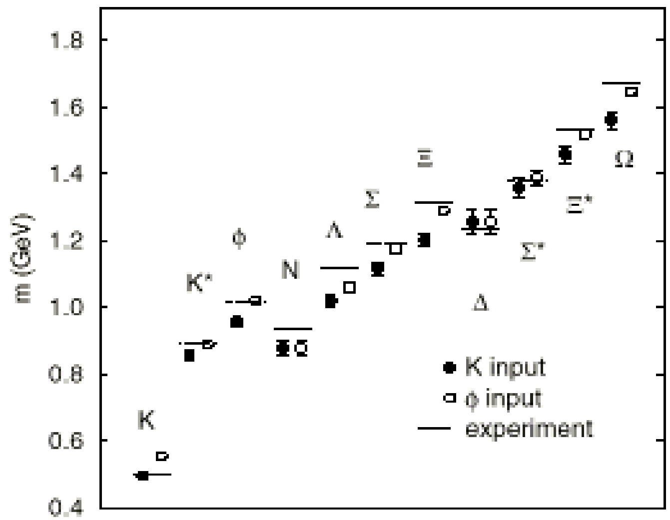
- The bulk of the mass of ordinary matter (better than 99%) from protons and neutrons
- Masses of p(uud) and n(udd) due to 'binding energy' – $m_{u/d}$ negligible (if non-zero)
- Carriers of this binding energy, $SU(3)_c$ gluons, are <u>massless</u>
- QCD provides understanding of >99% of all visible mass in the universe

  ⇒ So, $E = mc^2$ or $m = E/c^2$?

- Precisely testable QCD calculations are available for high momentum transfer processes at particle accelerators
  - e.g. production of jets of high momentum hadrons through quark-antiquark scattering in $\bar{p}p$ collisions



- Soft QCD is calculable only numerically – lattice gauge theory
  - initially somewhat disappointing
  - recent advances in computing, and in the techniques used, lead to reasonably credible results: predicted and measured hadron masses



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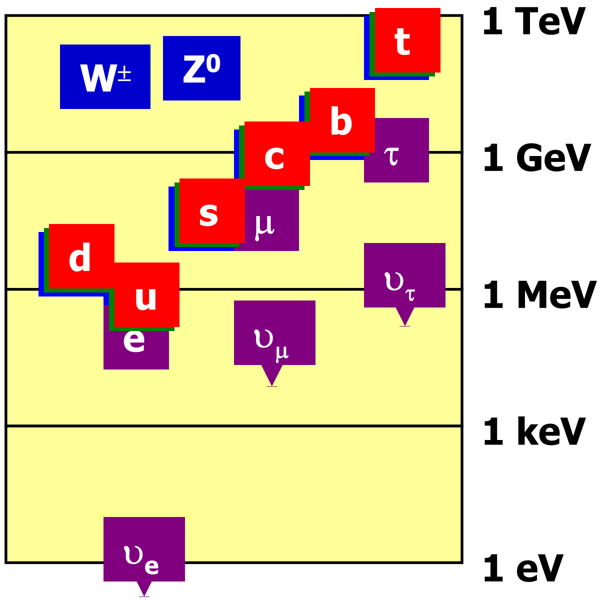
Mass and the Standard Model



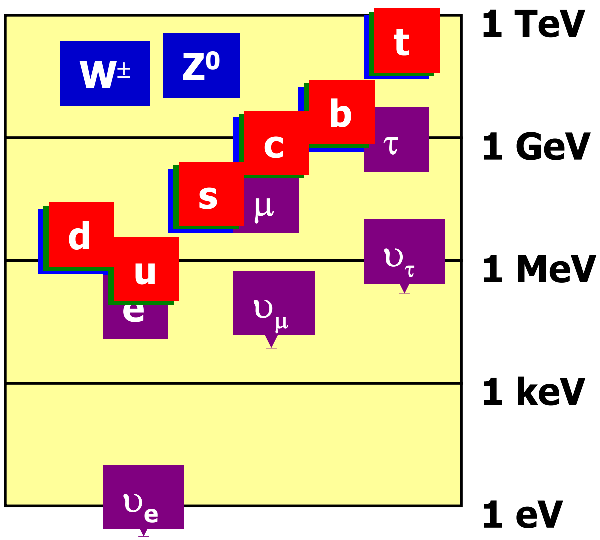
- How can mass arise in the SM?
- Local quantum field theory + gauge (historical misnomer for phase) invariance
- Global gauge symmetry (Noether): $\psi(x) \to \psi(x) e^{i\varphi}$
  - conservation laws (e.g. N of particles, charge)
- Local gauge symmetry: $\psi(x) \to \psi(x) e^{i\varphi(x)}$
  - Dirac $\psi(i\not{\partial} - m)\psi \Rightarrow$ need A_μ = QED, good news!
  - bad news: no terms like $m\psi\psi$, m^2A^2 allowed, i.e. only massless gauge and fermion fields…
- Sure, have massless γ and g leading to extremely successful theories of QED and QCD…
- … and possibly also massless graviton…
- But what about all the rest?

Gauge vs Mass?

- Does local gauge invariance really forbid mass?
- Not really, e.g. consider (2+1) dimensions
  - Chern-Simons term $\varepsilon^{\mu\nu\alpha} F_{\mu\nu} A_\alpha$ along with the familiar Maxwell $F_{\mu\nu}{}^2$ term allowed
  - Does not spoil gauge invariance (induces dynamically)
  - In 4-d: $\varepsilon^{\mu\nu\alpha\beta} F_{\mu\nu} F_{\alpha\beta} = 4\partial_\mu(\varepsilon^{\mu\nu\alpha\beta} A_\nu \partial_\alpha A_\beta)$
  - Topologically massive gauge theories
  - Successful applications to high-temperature superconductivity, quantum Hall effect, etc.
  - Ongoing efforts to introduce this mechanism in 4-d by means of auxiliary field
- Or other mechanisms such as
  - Technicolor theories
  - Dynamical symmetry breaking via *tt* condensate in analogy with BCS or the NJL (with 4-f interactions)

Mass Hierarchy

- Why this hierarchy of masses?



- Nambu, not so long ago (99?):

$\Rightarrow m = 2^n m_0$, with $m_0 \approx 5$ MeV

n	(0)		(8)		(15)
q	u	6+2 →	c	6+1 →	t
m	5		1280		164000

n	(1)		(5)		(10)
q	d	6-2 →	s	6-1 →	b
m	10		160		5100

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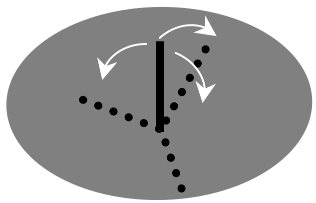
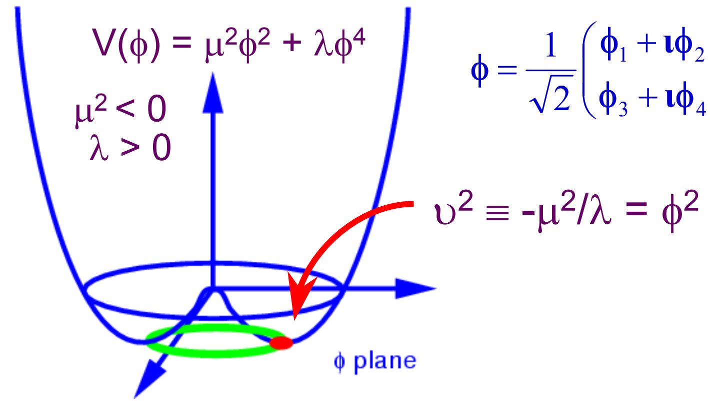
How to Pull a Rabbit out of Your Hat

- An attractive mechanism for inducing mass in the SM can be based on SSB



- Ground state breaks the symmetry of interaction
- Classic example is a ferromagnet: below T_c one direction of spin alignment is picked out
- What happens when a symmetry is hidden in a gauge invariant theory?
  - Global gauge symmetry ⇒ massless Goldstone Boson
  - Local gauge symmetry?

- To the massless SU(2)×U(1), add a complex scalar doublet ϕ with $V(\phi)$



$$\phi = \frac{1}{\sqrt{2}}\begin{pmatrix}\phi_1 + i\phi_2 \\ \phi_3 + i\phi_4\end{pmatrix}$$

- Arbitrarily pick $\phi_3^2 = \upsilon^2$ (SSB), expand around this vacuum (υ+h), and…
  - Photon remains massless, $m_\gamma = 0$
  - $M_W = \frac{1}{2}\upsilon g$ $g = e/\sin\theta_W$
  - $M_Z = \frac{1}{2}\upsilon (g^2+g'^2)^{1/2}$ $g' = e/\cos\theta_W$
  - Induces fermion masses $m_f = G\upsilon/\sqrt{2}$
  - Induces $\psi\psi h$ interactions $\propto m_f / \upsilon$
- Higgs field, m_h and λ; υ fixed from the μ lifetime (G_F) → $\upsilon = (G_F\sqrt{2})^{-1/2} \approx 246$ GeV
- And the theory remains renormalizable!

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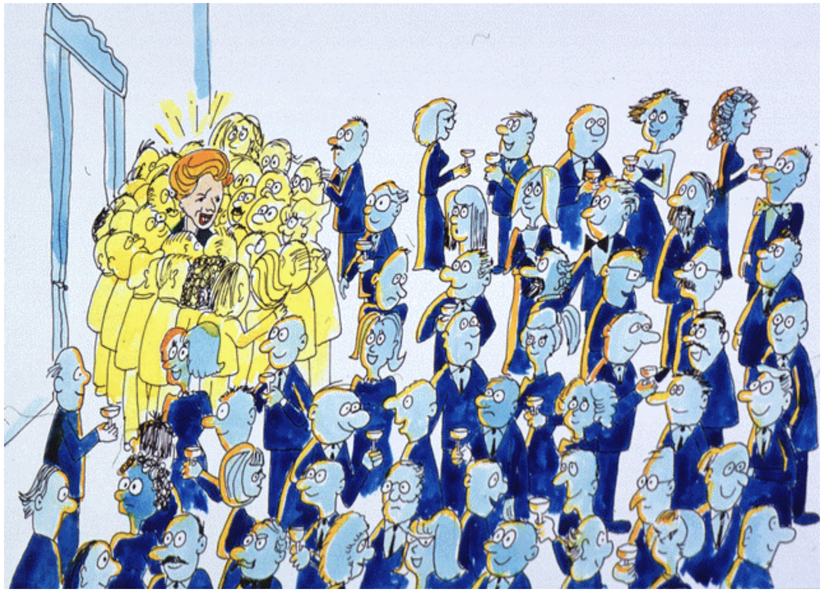
A Cute, Quasi-Political Explanation

Imagine a cocktail party with uniformly distributed people chatting with their neighbors…

Then the Ex-Prime Minister enters and crosses the room…

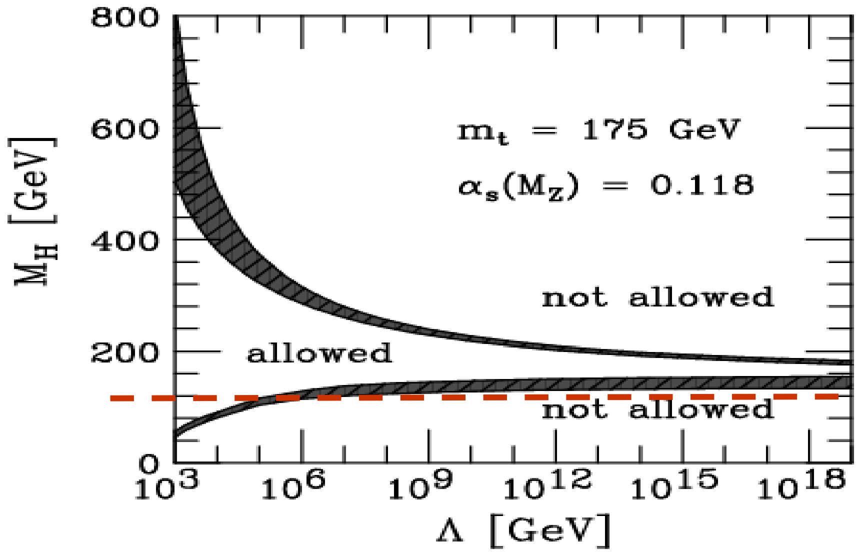


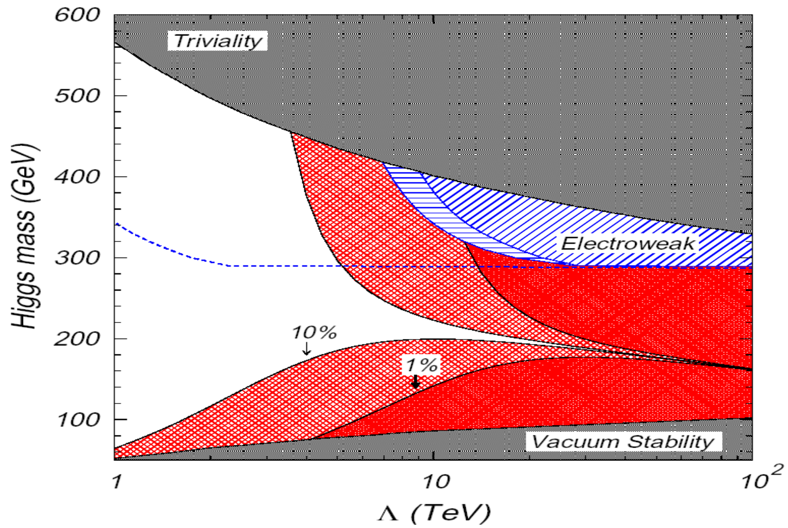
People are attracted to her, and so she is followed by a knot of people clustered around herself.

It can be said that she thereby acquires greater mass than normal, at least in the sense of inertia – once moving she is harder to stop, and once stopped she is harder to get moving again.

From David J. Miller, University College London

Theoretical Constraints on the Higgs





- Unitarity ("tree-level") from VV/HH scattering
  - lighter than ~780 GeV or new physics below Λ_U ~ 1.2 TeV
- Triviality $\Lambda \le M_H \exp\left(\frac{4\pi^2 v^2}{3M_H^2}\right)$
  - $\lambda\phi^4$ theory possibly trivial, i.e. $\lambda \to 0$ as $\Lambda_{UV} \to \infty$, numerical calculations, etc.
  - sometimes under control in theories with interactions…
- Vacuum stability $M_H^2 > \frac{3G_F\sqrt{2}}{8\pi^2} F \log\left(\Lambda^2 / v^2\right)$
  - for very small m_h, λ can be driven negative, i.e. vev falls of to infinity
  - tunneling rates vs the lifetime of universe
- Naturalness and fine-tuning
  - stability of the EW scale (i.e. parameter μ^2 with respect to radiative corrections
  - introduces stronger constraints
- Bottom line?: discovering Higgs with m <~130 GeV would suggest the onset of new physics at a scale below Λ_{GUT} ~ 10^{16} GeV… will come back to this…

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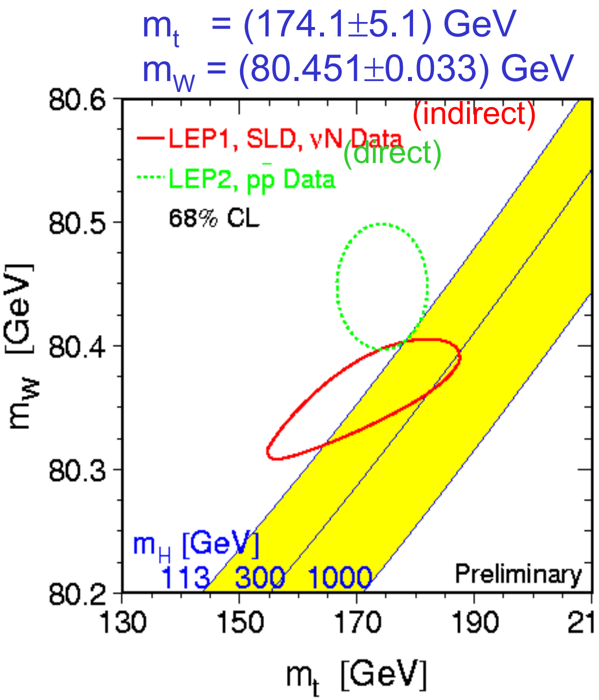
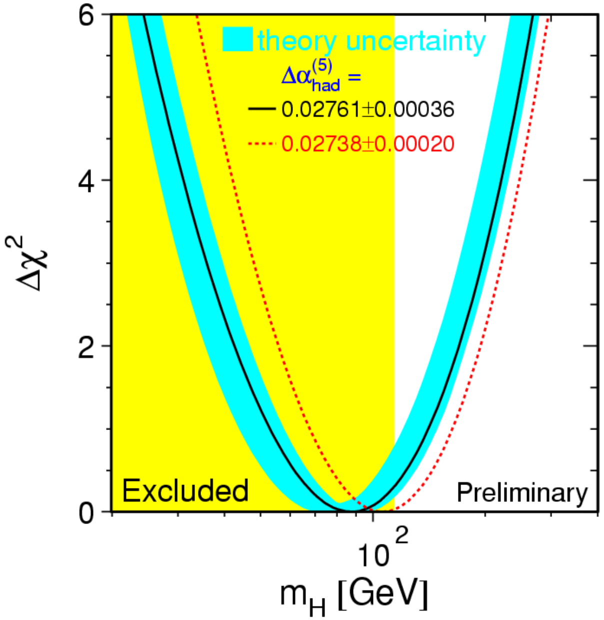
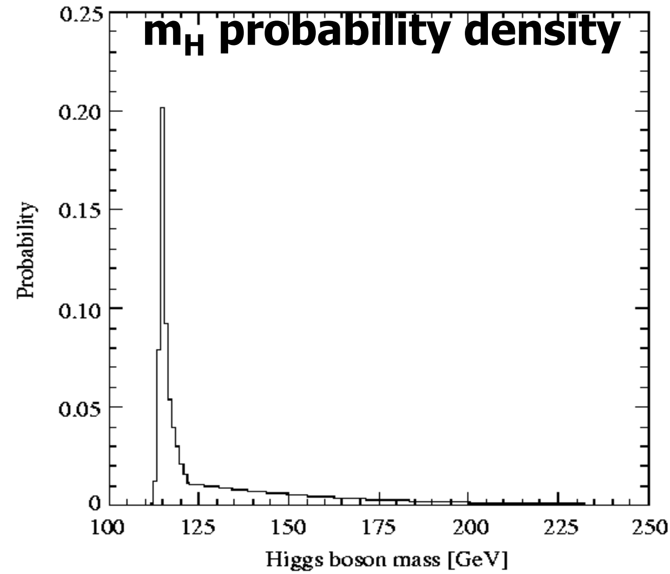
In Search of Higgs







- In the SM, top and W masses constrain m_H via Δr
  e.g. m_W mass is $\propto m_t$ via *tb* loops and
  also is $\propto \ln(m_H)$ via Higgs loops
- Direct limit on m_H from LEP is 113.5 GeV, with a 2.2σ hint at 115 GeV
- Combined constraints from Z, t, W, νN require SM Higgs to have m_H < ~200 GeV

Finding Higgs is the highest priority of worldwide HEP program

Physics Challenges → the Upgraded Tevatron

Physics goals for Run 2

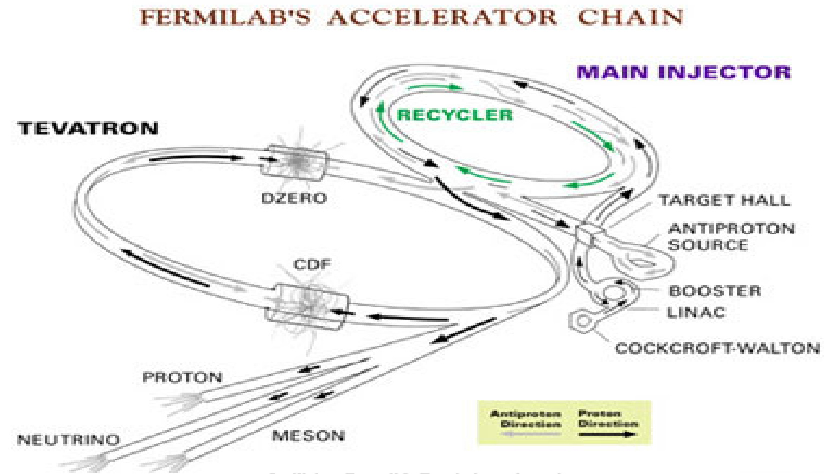
- precision studies of weak bosons, top, QCD, B-physics
- searches for Higgs, supersymmetry, extra dimensions, other new phenomena

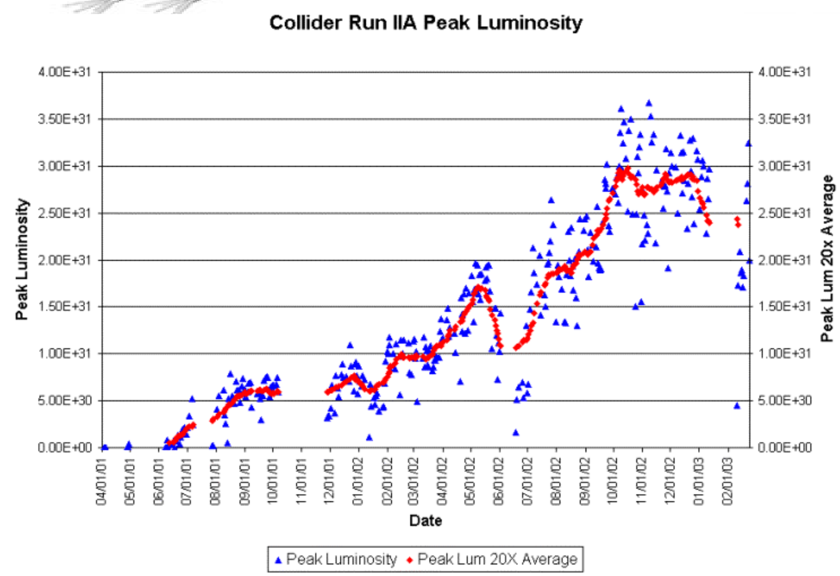
require

- electron, muon, and tau identification
- jets and missing transverse energy
- flavor tagging through displaced vertices and leptons
- luminosity, luminosity, luminosity…

	Run 1b	Run 2a	Run 2b
Bunches in Turn	6×6	36×36	140×103
$\sqrt{s}$ (TeV)	1.8	1.96	1.96
Typical L ($cm^{-2}s^{-1}$)	1.6×10^{30}	8.6×10^{31}	5.2×10^{32}
$\int$ Ldt (pb^{-1}/week)	3.2	17.3	105
Bunch xing (ns)	3500	396	132
Interactions / xing	2.5	2.3	4.8

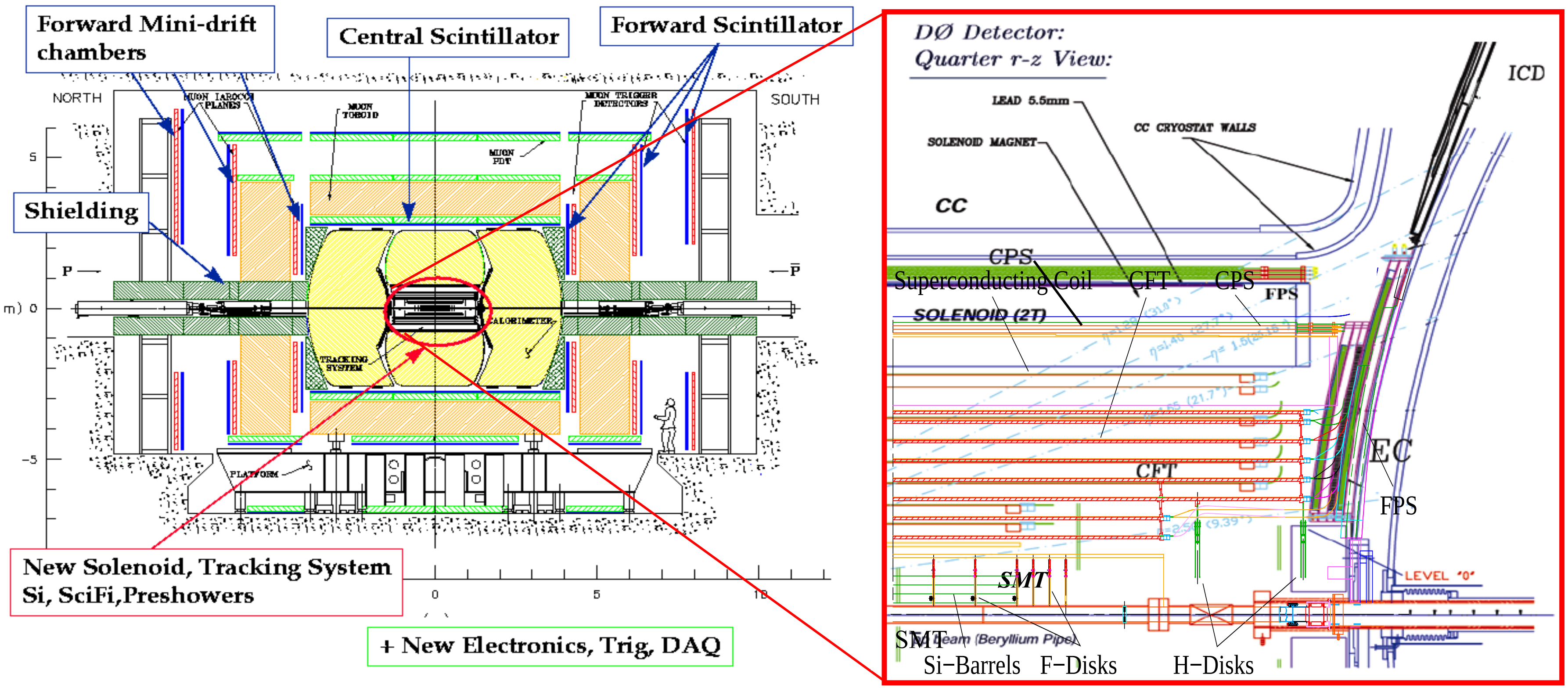
Run 1 → Run 2a → Run 2b
0.1 fb^{-1} → 2–4 fb^{-1} → 15 fb^{-1}





Peak Lum. achieved over 3×10^{31} $cm^{-2}s^{-1}$
Planned to reach Run 2a design
by Spring/Summer 2003

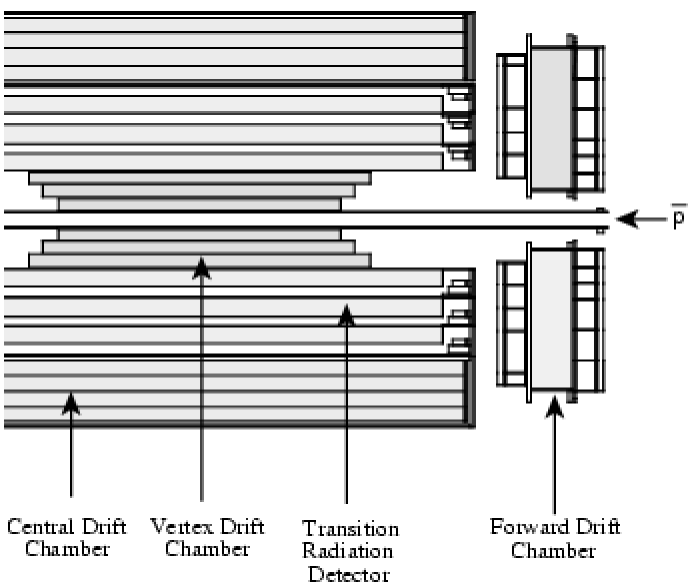
Physics Challenges → the Upgraded Detector



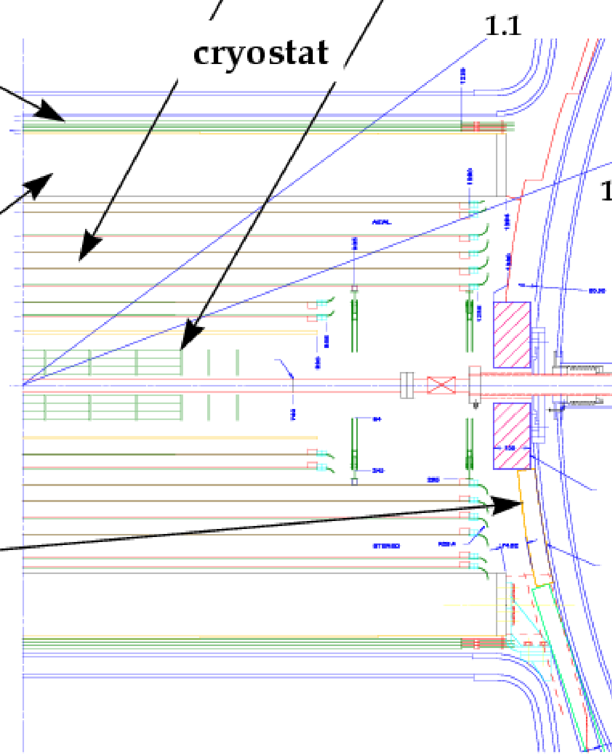
- New tracking devices, Silicon (SMT) and Fiber Tracker (CFT), placed in 2 T magnetic field
- Upgraded Calorimeter electronics readout and trigger
- Added PreShower detectors, Central (CPS) and Forward (FPS)
- Significantly improved Muon System
- New forward proton spectrometer (FPD)
- Entirely new Trigger System and DAQ to handle higher event rate

DØ Run II Tracking Detectors

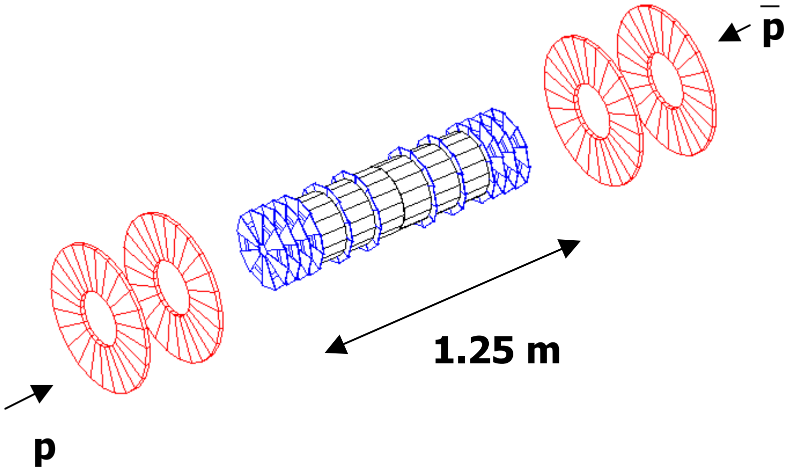
Run I: no magnet; drift chamber tracking with TRD for electron ID

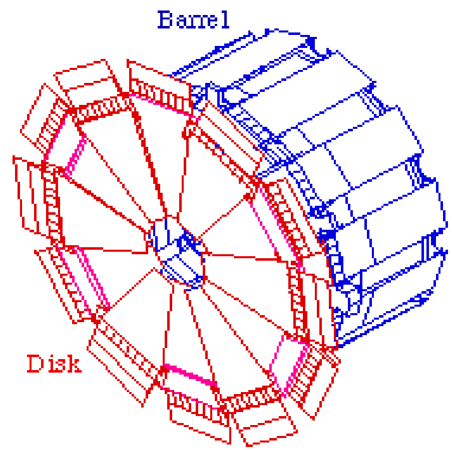


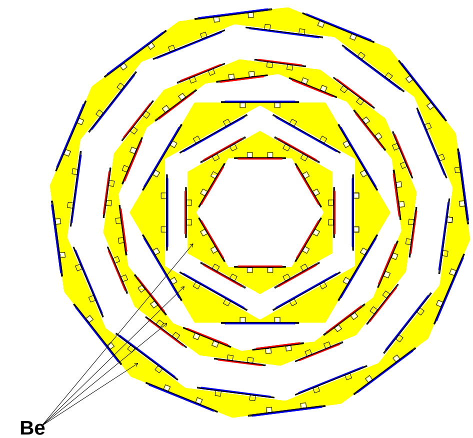
- **Silicon Tracker**
  - Four layer barrels (double/single sided)
  - Interspersed double sided disks
  - 840,00 channels
- **Fiber Tracker**
  - Eight layers sci-fi ribbon doublets (z-u-v, or z
  - 74,000 830um fibers w/ VLPC readout
- **Central Preshower**
  - Scintillator strips, WLS fiber readout
  - 6,000 channels
- **Solenoid**
  - 2T superconducting
- **Forward Preshower**
  - Scintillator strips, stereo, WLS readout
  - 16,000 channels



Silicon Microstrip Tracker







- 6 barrels (4 layers each) and 16 disks, coverage for $|\eta|< 3$
- Single (axial) and double sided (axial+stereo) detectors
- 3D track reconstruction capabilities
- ~800k channels of electronics
- Hit resolution: 10 μm, impact parameter resolution: 30 μm
- Tagging efficiency at p_T = 50 GeV/c
  - ~ 55% for *b*-quark jets, ~15 % for *c*-quark jets
  - ~ 0.5% fake tag rate for u,d,s quark jets
- Currently: ~95% of SMT channels available for readout

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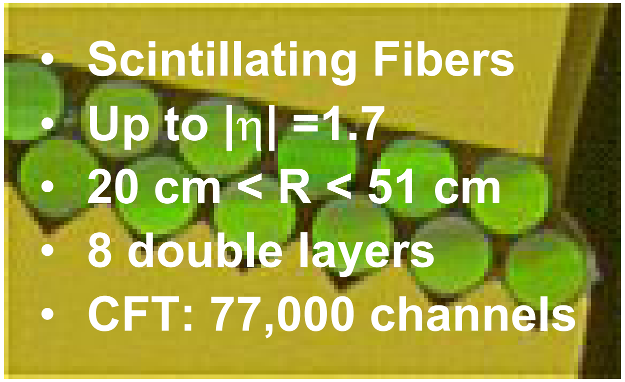
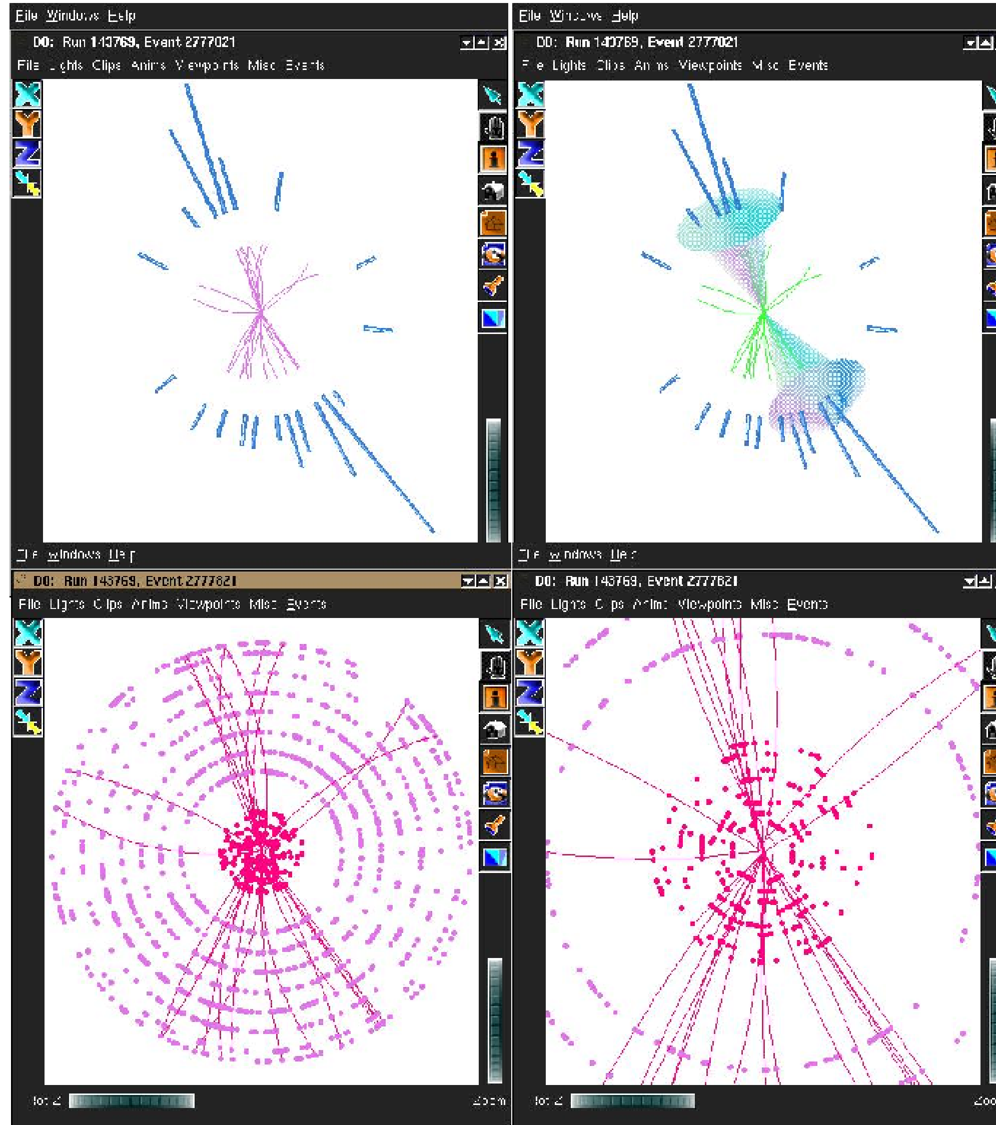
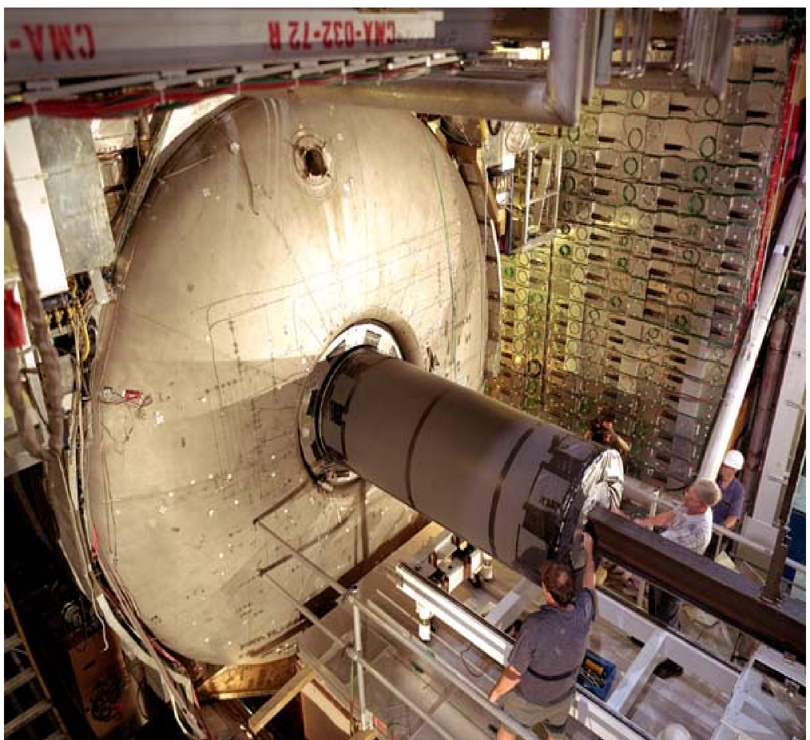
Central Fiber Tracker



- Scintillating Fibers
- Up to |η| =1.7
- 20 cm < R < 51 cm
- 8 double layers
- CFT: 77,000 channels

Zoom in to run 143769 event # 2777821





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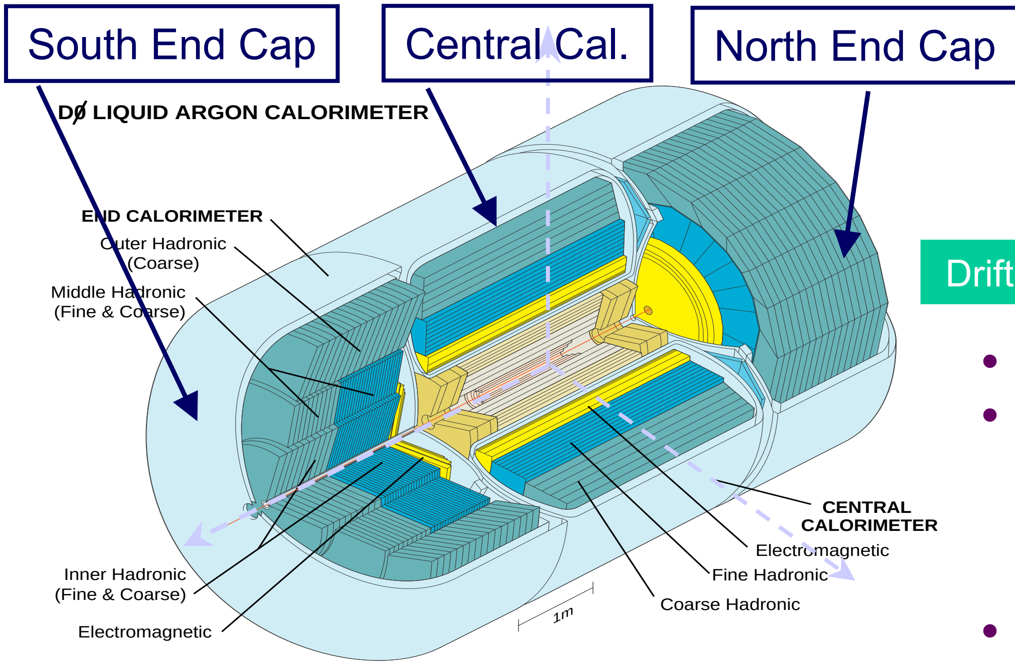
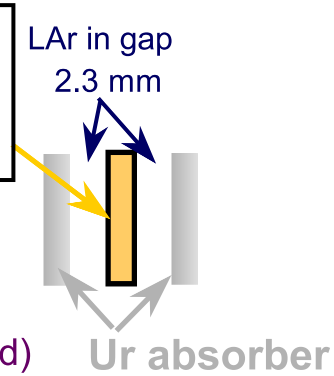
Calorimeters



Readout Cell

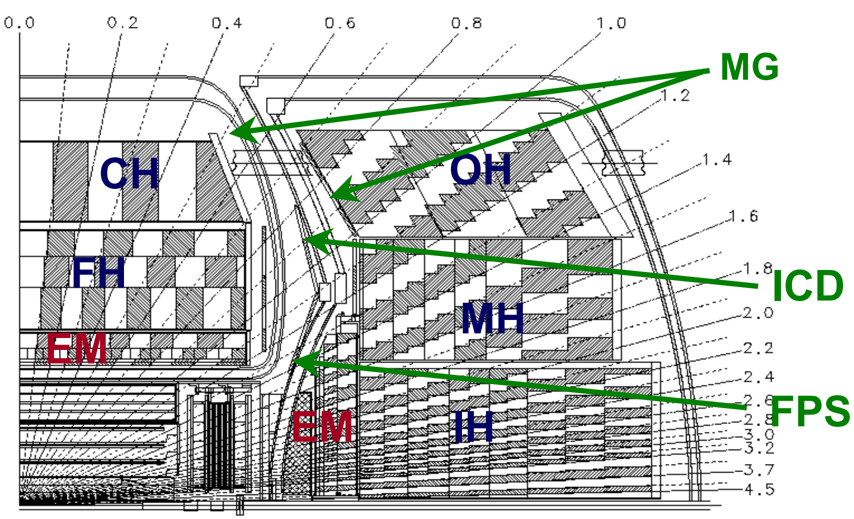
Cu pad readout on 0.5 mm G10 with resistive coat epoxy



Drift time ~430 ns

- 50k readout cells (< 0.1% bad)
- Fine segmentation
  - 5000 pseudoprojective towers (0.1×0.1)
  - 4 EM layers, shower-max (EM3): 0.05×0.05
  - 4/5 Hadronic (FH + CH)
- L1/L2 fast Trigger readout 0.2×0.2 towers

- Liquid Argon sampling
  - uniform response, rad. hard, fine spatial segmentation
  - LAr purity important
- Uranium absorber (Cu/Steel CC/EC for coarse hadronic)
  - nearly compensating, dense $\Rightarrow$ compact
- Uniform, hermetic with full coverage
  - $|\eta| < 4.2$ ($\theta \approx 2^o$), $\lambda_{int} \sim 7.2$ (total)
- Single particle energy resolution
  - e: $\sigma/E = 15\% / \sqrt{E} \oplus 0.3\%$ π: $\sigma/E = 45\% / \sqrt{E} \oplus 4\%$



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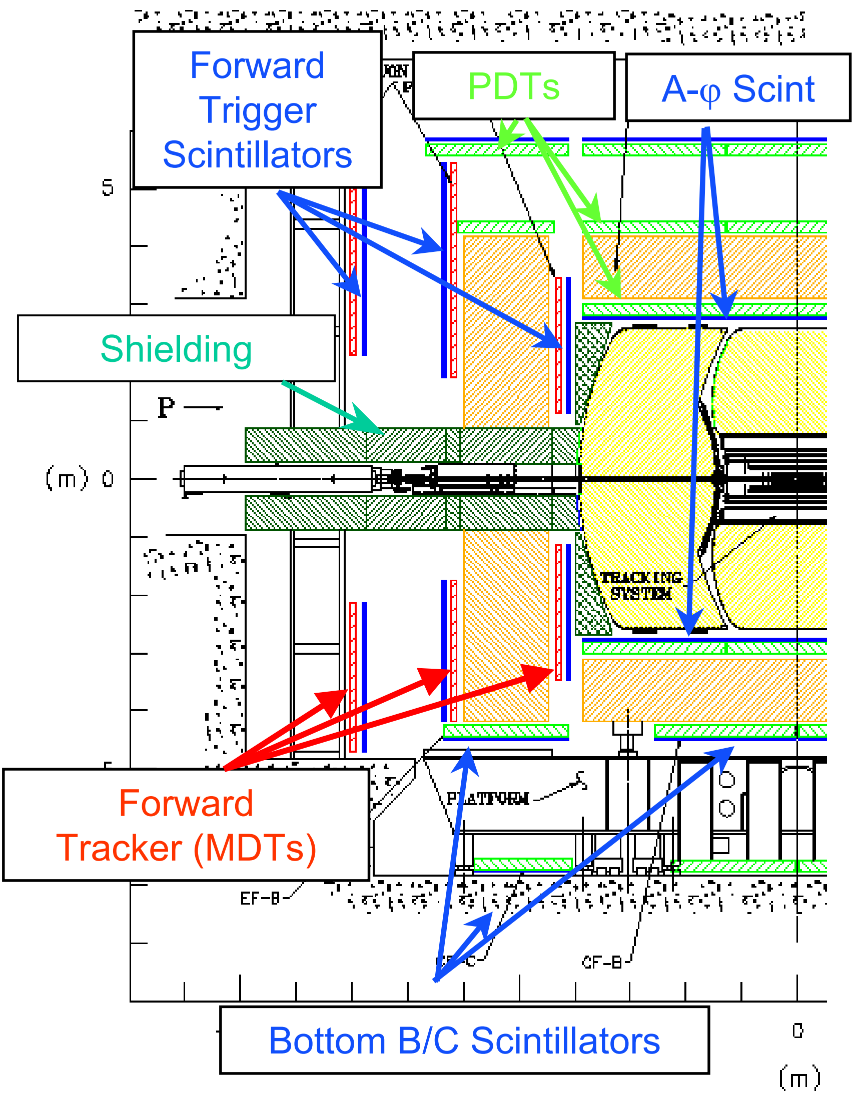
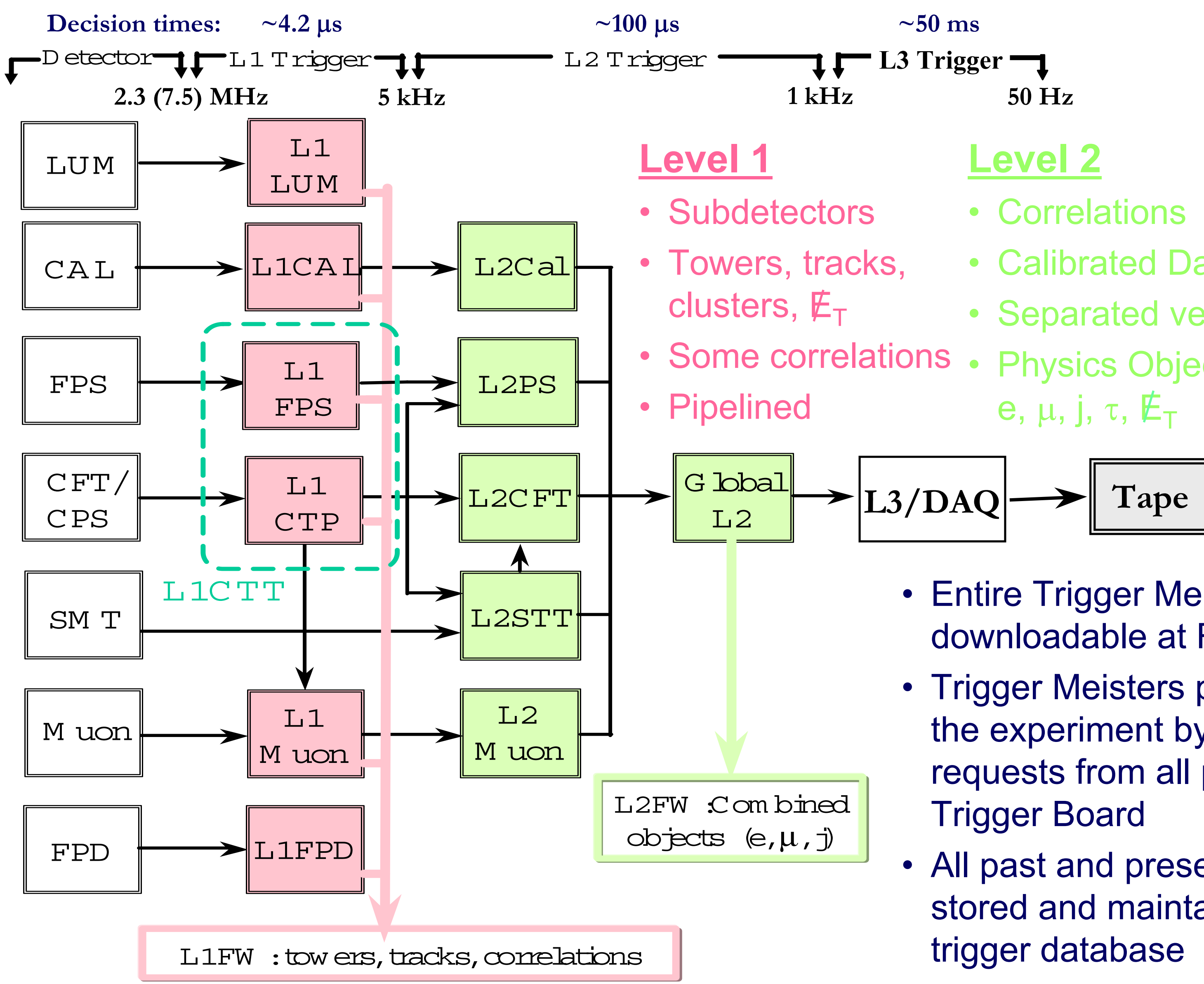
Muon System



- Central and Forward regions, coverage up to $\eta = \pm 2$
- Three layers: one inside (*A*), two outside (*B*, *C*) the toroid magnets
- Consists of scintillators and drift tubes
- Central Proportional Drift Tubes (PDT's)
  - 6624 drift cells (10.1 × 5.5 cm) in 94 three- and four-deck chambers
- Central Scintillation Counters
  - 360 "cosmic ray" counters outside the toroid ($\Delta\varphi$ = 22.5°)
  - 630 "A–φ" counters inside ($\Delta\varphi$ = 4.5°), $\Delta\eta$ = 0.1
- Forward Mini Drift Tubes (MDT's)
  - 6080 8-cell tubes in 8 octants per layer on North and South side, cell cross-section 9.4 × 9.4 mm
- Forward Scintillation Counters (Pixels)
  - 4214 counters on the North and South side
  - $\Delta\varphi$ = 4.5° matches the MDT sector size

DØ Trigger System



Level 1
- Subdetectors
- Towers, tracks, clusters, $\not{E}_T$
- Some correlations
- Pipelined

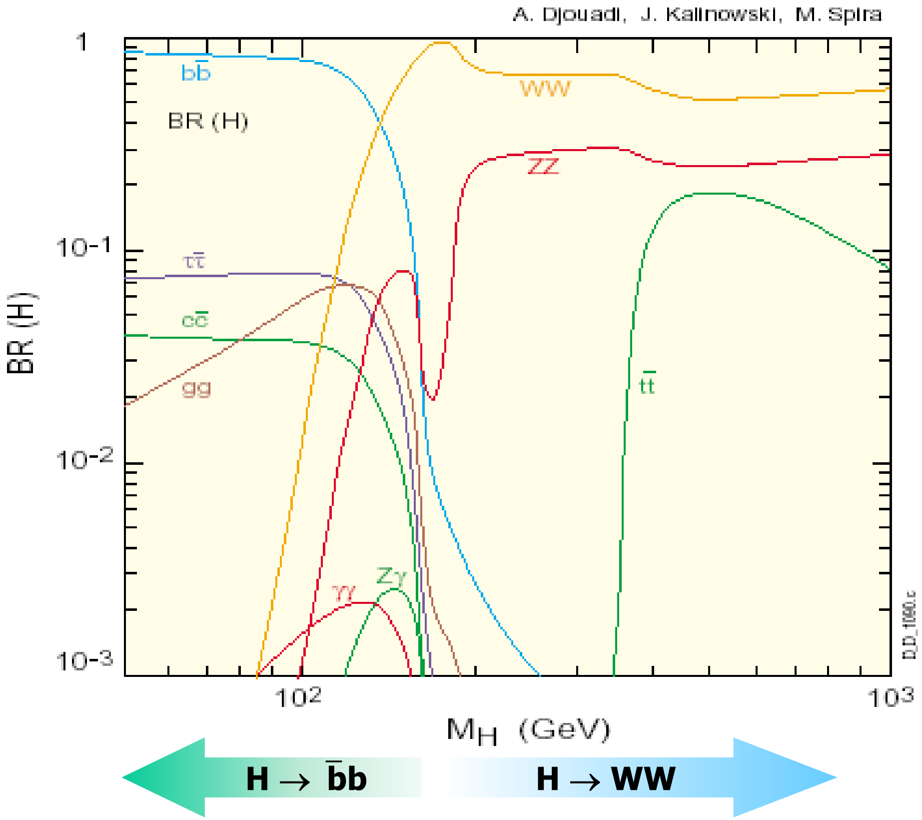
Level 2
- Correlations
- Calibrated Data
- Separated vertex
- Physics Objects e, μ, j, τ, $\not{E}_T$

Level 3
- Simple Reconstruction
- Physics Algorithms

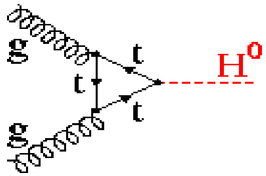
- Entire Trigger Menu configurable and downloadable at Run start
- Trigger Meisters provide trigger lists for the experiment by collecting trigger requests from all physics groups in the Trigger Board
- All past and present trigger lists are stored and maintained in the dedicated trigger database

Properties of the Higgs

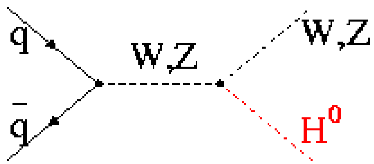
- The Higgs mass is the only SM parameter for which there is no direct measurement
- Behavior is completely determined once M_H is specified (production rates, decay modes are all calculable)
- The Higgs decays into the heaviest available particles



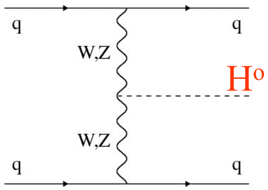
Higgs Production at the Tevatron



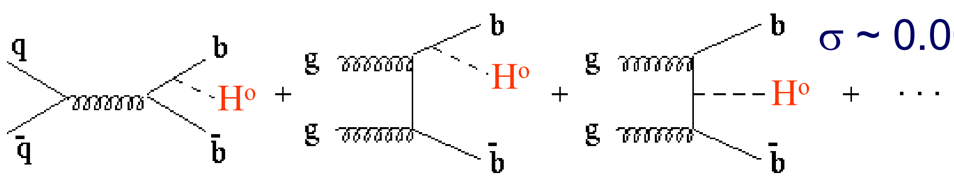
σ ~ 0.70 pb
for MH = 120 GeV/c²
(with QCD NLO)



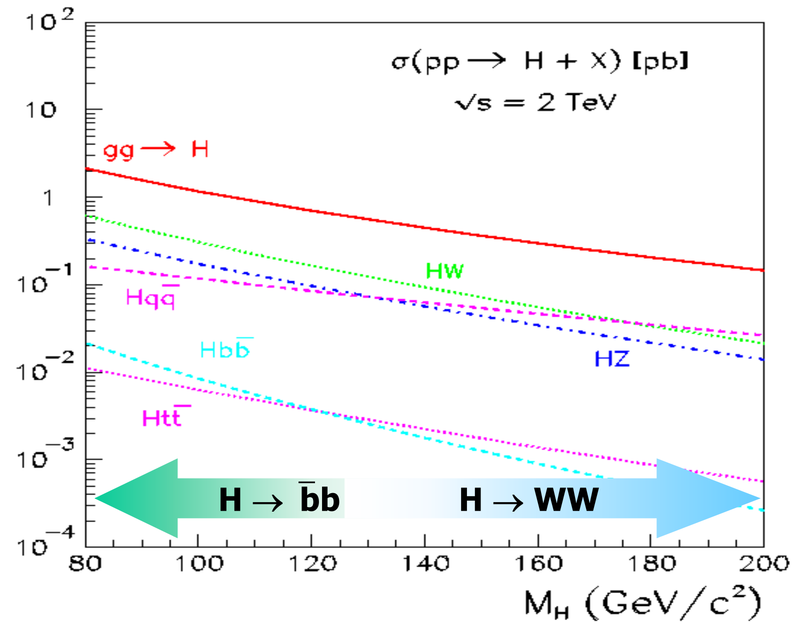
WH: σ ~ 0.16 pb
ZH: σ ~ 0.10 pb



σ ~ 0.10 pb



σ ~ 0.004 pb



- Inclusive Higgs production XS ~1pb (1000ev/year)
- For light Higgs, main decay mode is into *bb* and so the dominant process is swamped by QCD background
- So, consider Higgs production in association with a W or a Z (XS ~0.2 pb) with H→*bb* to make use of leptonic decays of gauge bosons for triggering

  lν (bb), l⁺l⁻(bb), νν(bb), lν (ττ), qq(bb)

- with backgrounds themselves interesting processes

  W*bb*, Z*bb*, *tt*, ZZ, WZ, W*→ *tb*

- For heavier Higgs, use *gg* production with H →WW* with either one or both of W's decaying leptonically. Can also consider WH(H→WW*) →WWW* where trilepton signal is smaller than like-sign dilepton one

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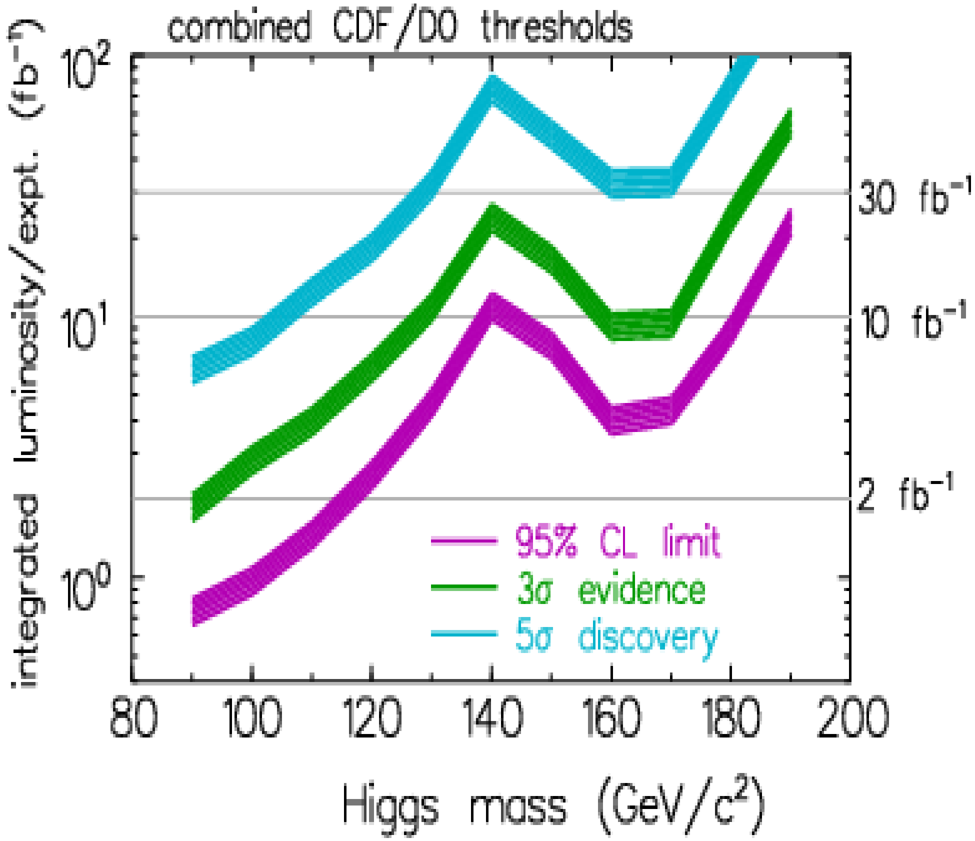
Higgs Mass Reach at the Tevatron

- MC results with fast, parameterized detector simulations
- 2 experiments (with Bayesian combination)
- ~30% improvement from Neural Network techniques
- Bands show syst. errors ~30%
- If LEP indication not true, will rule it out with 2 fb^{-1}
- SM-like M_H~115 GeV Higgs evidence (3σ) with 5 fb^{-1}
- If no SM Higgs, will exclude it up to M_H=190 GeV with 10 fb^{-1}
- Will observe the SM-like Higgs up to M_H=190 GeV with 30 fb^{-1}



The Bottom-line Plot Revisited

- At the behest of Ray Orbach, Director DOE Office of Science DØ and CDF just very recently formed a joint Higgs Sensitivity Study group

- The charge: re-evaluate Tevatron Higgs sensitivity
  - many assumptions go into making the bottom-line plot
  - address *b*-tagging, trigger efficiencies, jet-jet resolution, background estimation, effects of multiple interactions (396 vs 132 ns running)
  - use data as much as possible, split channels between CDF and DØ, extrapolate to all channel

- The results due by the June-July DOE accelerator review, so time is very short!

$W(\rightarrow e\nu/\mu\nu)H(\rightarrow bb)$ Associated Production

- Final states are characterized by
  - isolated lepton, e or μ
  - two *b*-jets
  - missing E_T

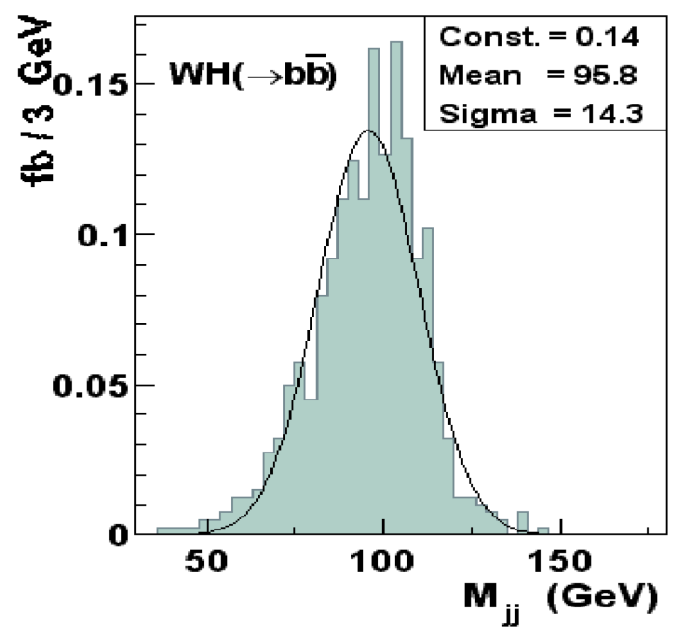
- Signal acceptance/rate based on detailed simulation

- Detailed background studies are underway

- Example of m_h = 115 GeV

- Selections similar to Fermilab Higgs Working Group (HWG):
  - E_T (e/μ) > 20 GeV in $|\eta| < 2.5$
  - E_T (jet1/2) > 15 GeV in $|\eta| < 2$ and tagged as *b*-jets

- Invariant mass of two leading jets



- Get relative resolution $\sigma/M \approx 15\%$
  - calorimeter response correction only
  - close to HWG results
- Expected number of signal events comparable to HWG estimations of 4 events per fb^{-1}

Z($\rightarrow$ee/$\mu\mu$/$\nu\nu$)H($\rightarrow$*bb*) Associated Production

Z($\rightarrow$ee/$\mu\mu$)H($\rightarrow$*bb*)

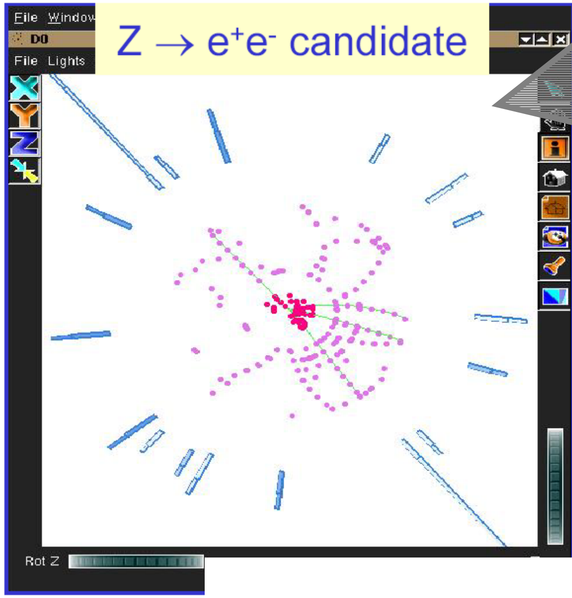
- Final states are characterized by
  - two isolated lepton, e or μ
  - M_{l+l-} consistent with M_Z
  - two *b*-jets

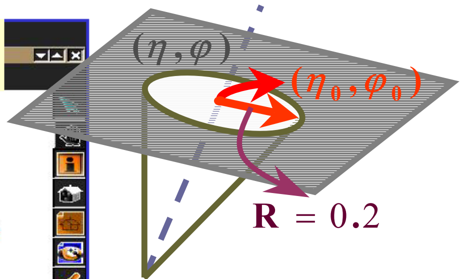
Z($\rightarrow\nu\nu$)H($\rightarrow$*bb*)

- Final states with
  - large missing E_T
  - two *b*-jets

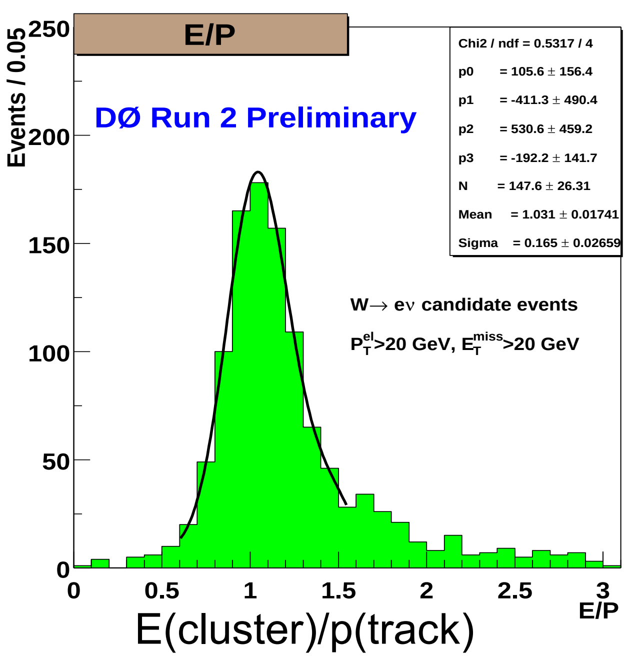
- In both cases the signal acceptance and rate calculations are based on detailed simulations
- Detailed background studies Z*jj*/*cc*/*bb*, ZZ, *tt*, QCD are underway
- Selection criteria similar to HWG
- Higgs mass resolution and expected number of events are similar to the WH($\rightarrow$*bb*) case and HWG estimations of 4.7 events per fb^{-1}

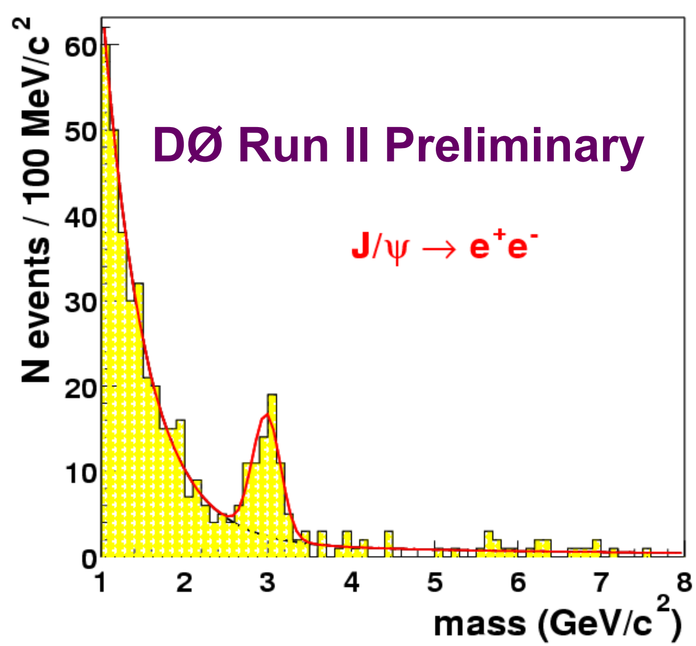
Electron Identification





- Simple fixed cone-size R = 0.2 clusters of energy (non-linearity corrections)
- Electromagnetic fraction > 0.9
- Isolation: less than 15% of energy in 0.2 < R < 0.4
- Require the calorimeter shower shape of the cluster to match that of an EM object
- Require a track matching the cluster
- Typically require p_T > 20 GeV for e's from W/Z's





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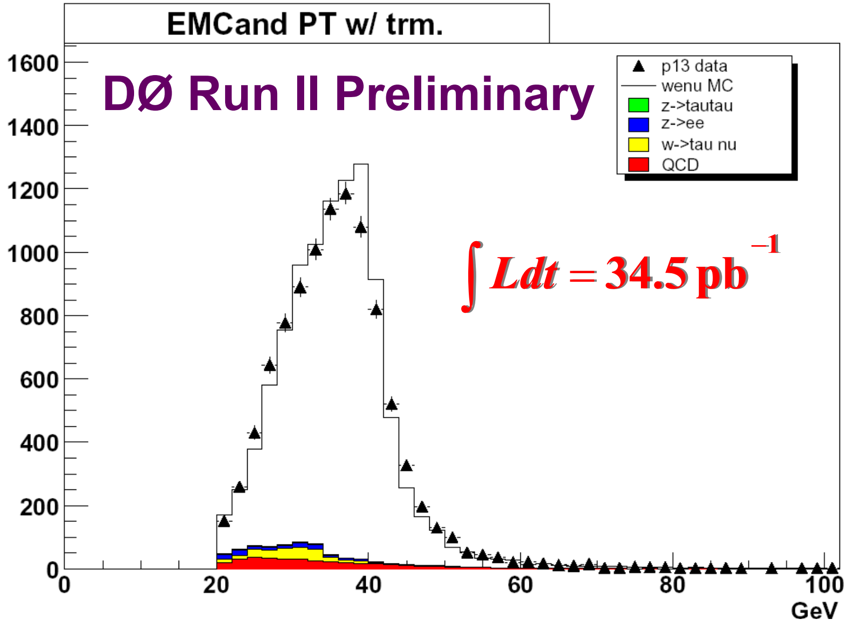
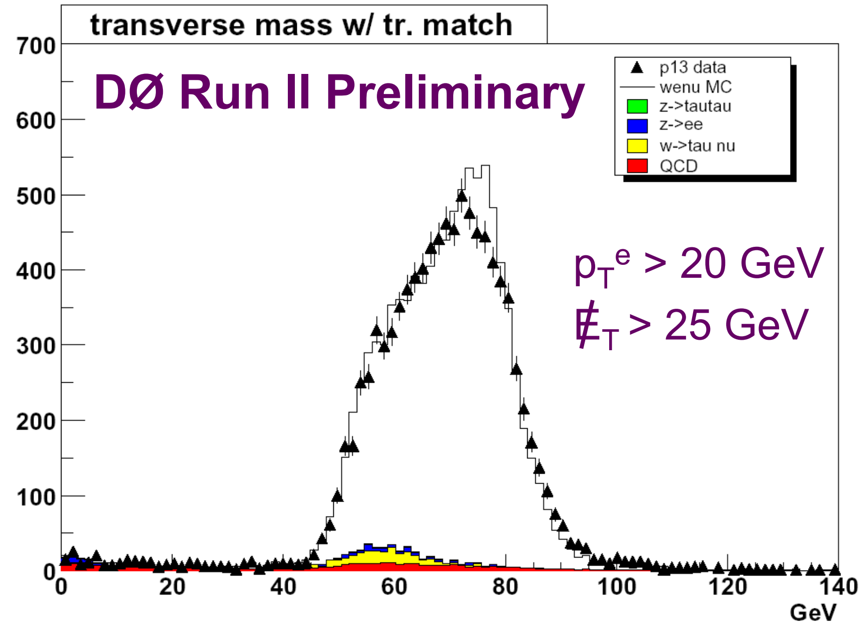
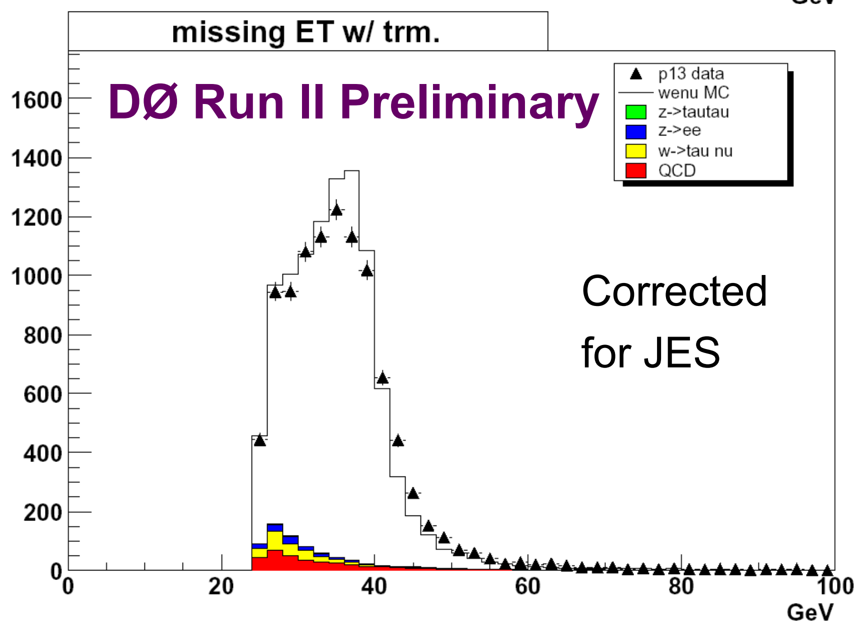
W(→eν)'s in Data







- W transverse mass

$$M_T^W = \sqrt{2E_T^e \not{E}_T \left(1 - \cos\Delta\varphi_{e\nu}\right)}$$

- QCD background from data
- Good agreement between data and MC

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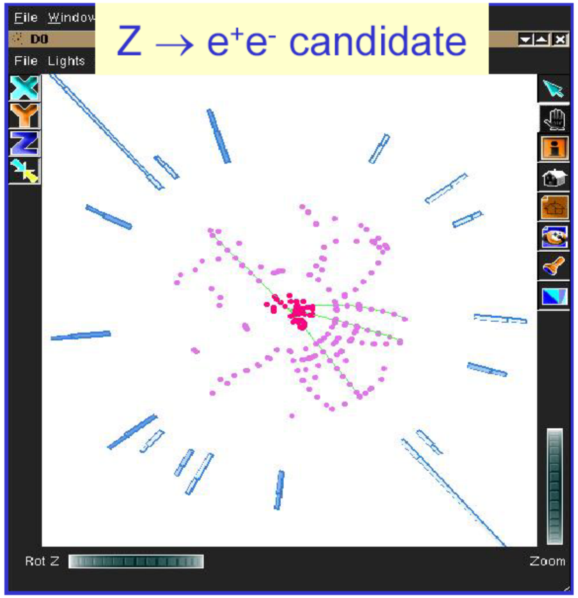
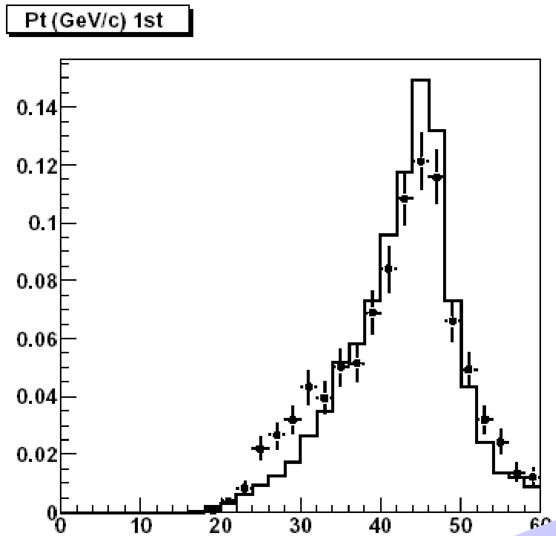
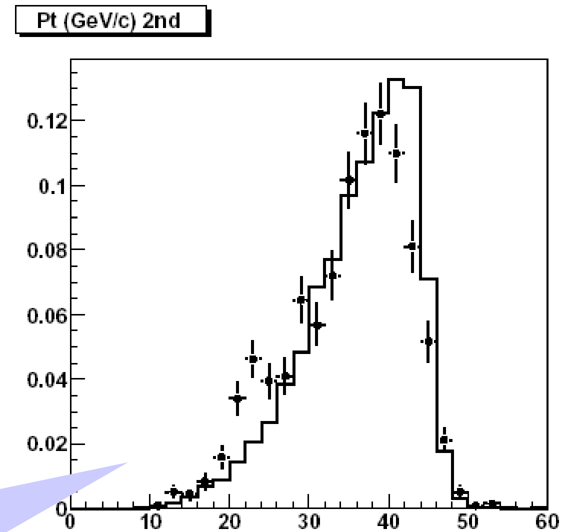
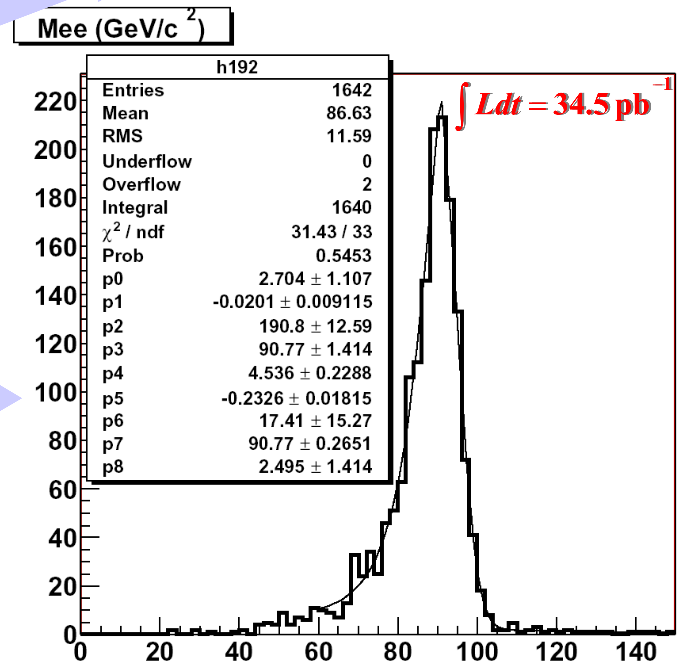
$Z(\to ee)$'s in data







- p_T distributions of the two electrons
- Fair agreement between data and MC
- Fit to a skewed Gaussian + BW + exponential background
  - low side tail due to electrons pointing to cracks, etc.
  - $p_T^e > 20$ GeV in $|\eta| < 2.5$



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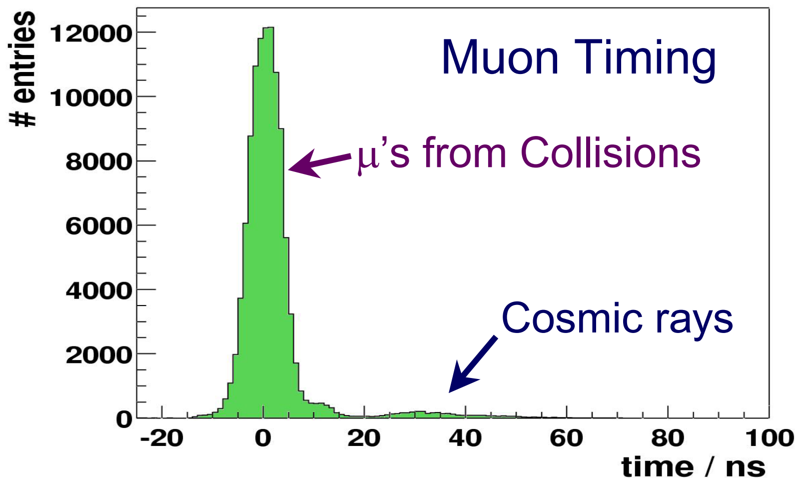
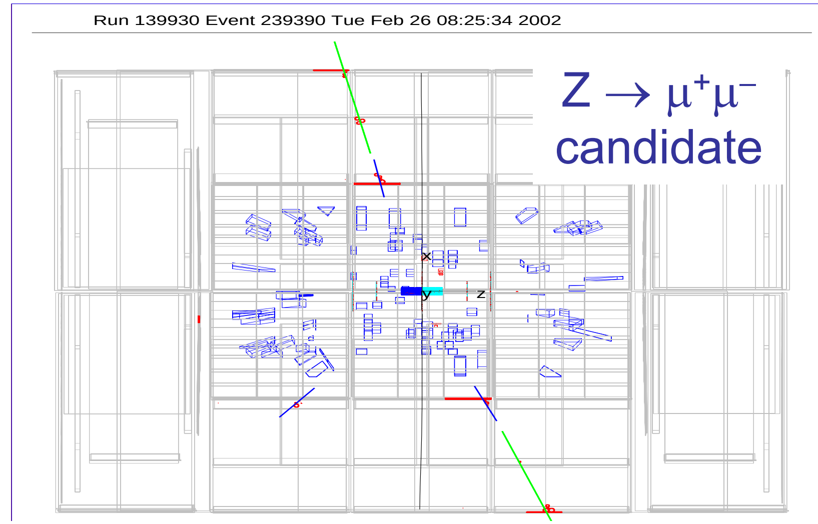
Muon Identificatoin



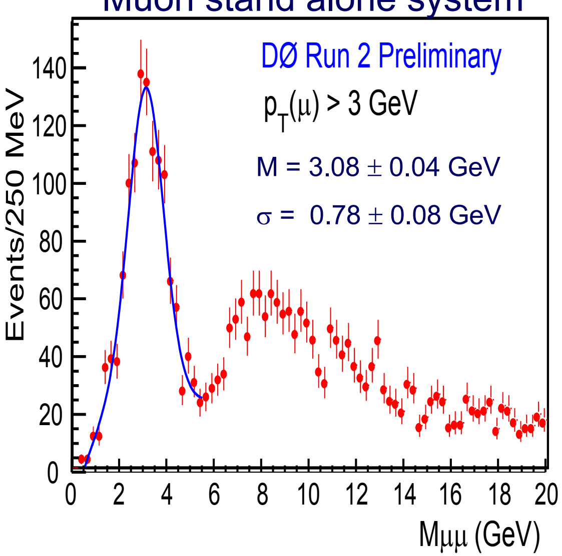
Timing cuts reduce cosmic bckg., could aid in detection of slow moving particles



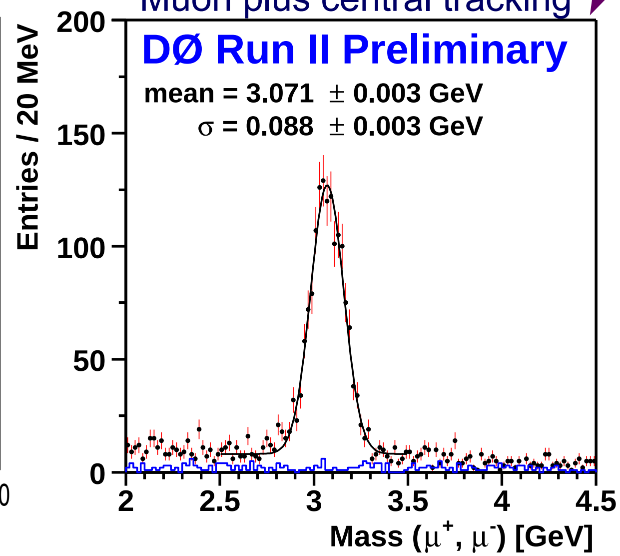
Matching of central tracks to μ's improves momentum resolution

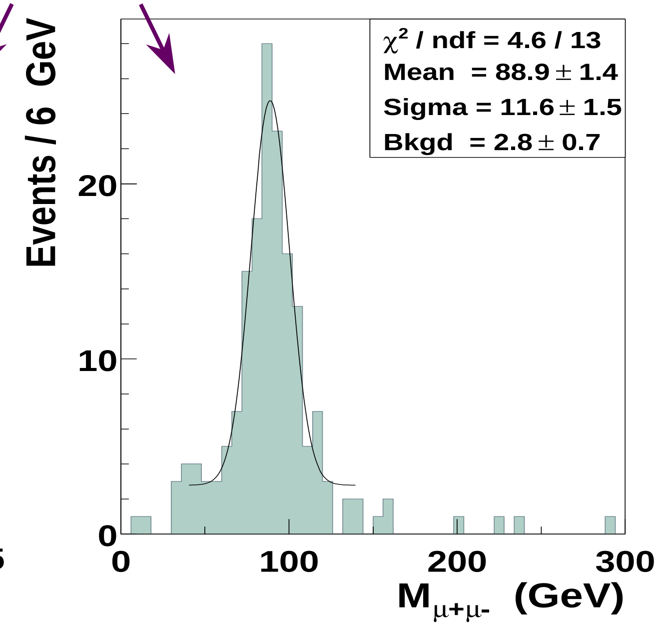
J/Ψ invariant mass

Muon stand alone system

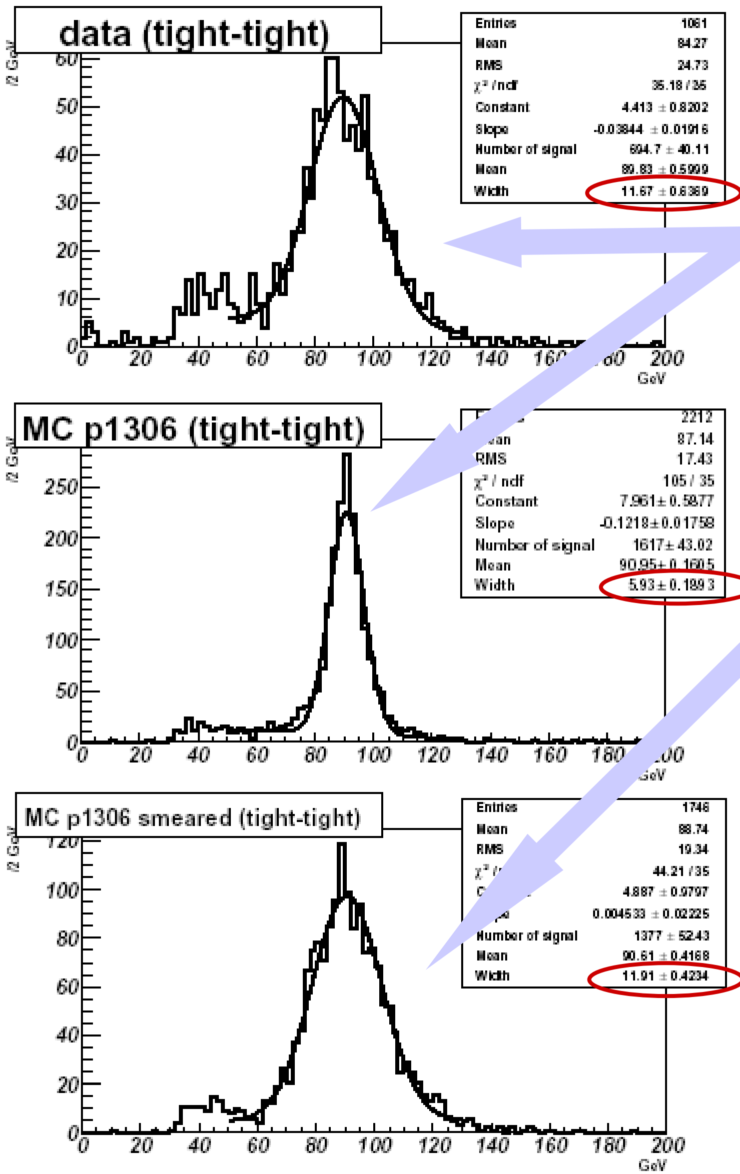


Muon plus central tracking

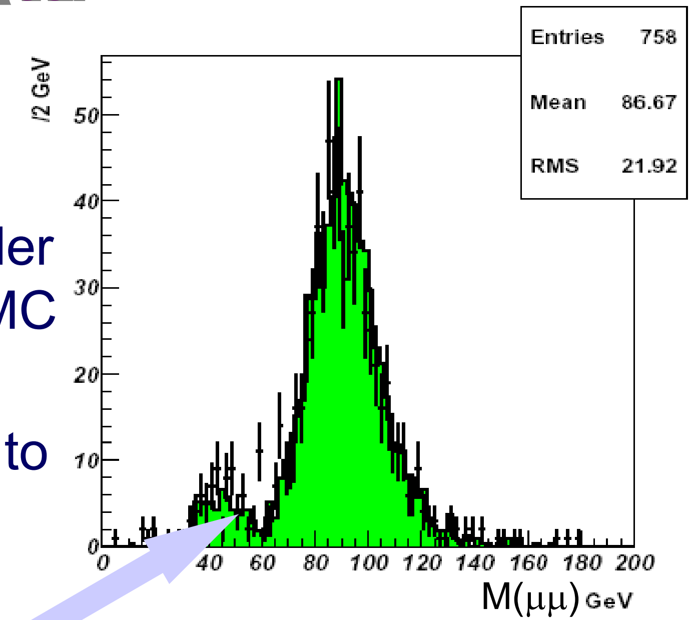


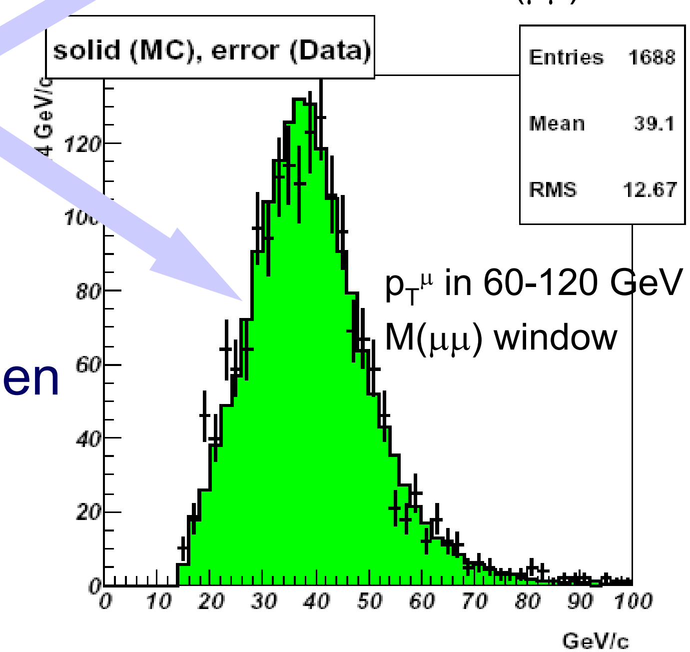


Z(→μμ)'s in data



- Z width x ~2 wider in data than in MC
- Smear tracks in MC additionally to match the data
- Alignment is a suspect
- After additional smearing good agreement in shapes is observed between data and MC





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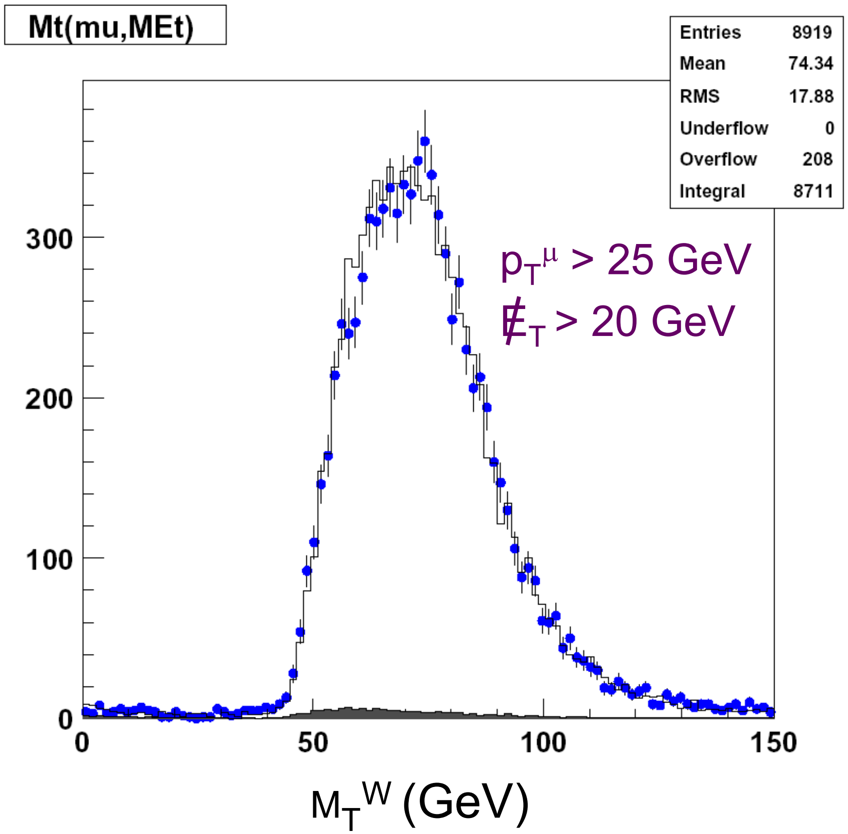
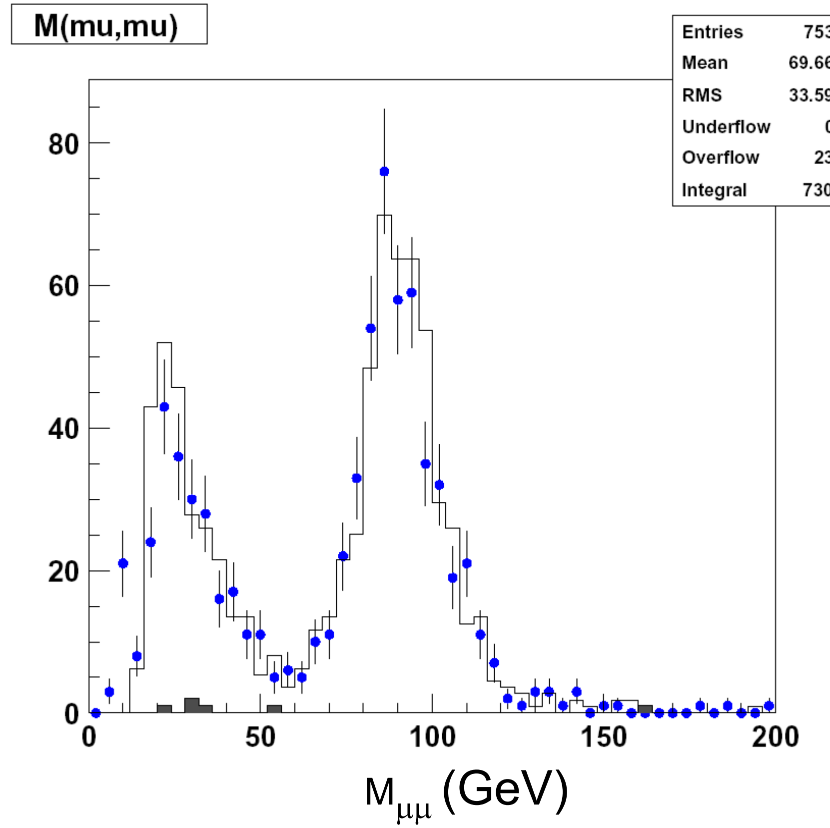
W(→μν)'s in Data

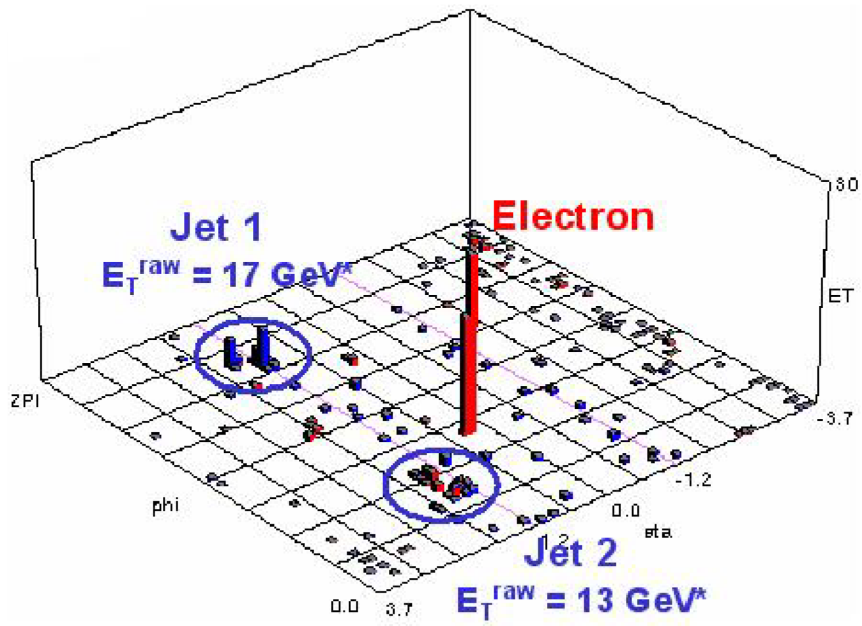




- Again, very good agreement between data and MC
- Track p_T has been additionally smeared in MC to match Z width in data

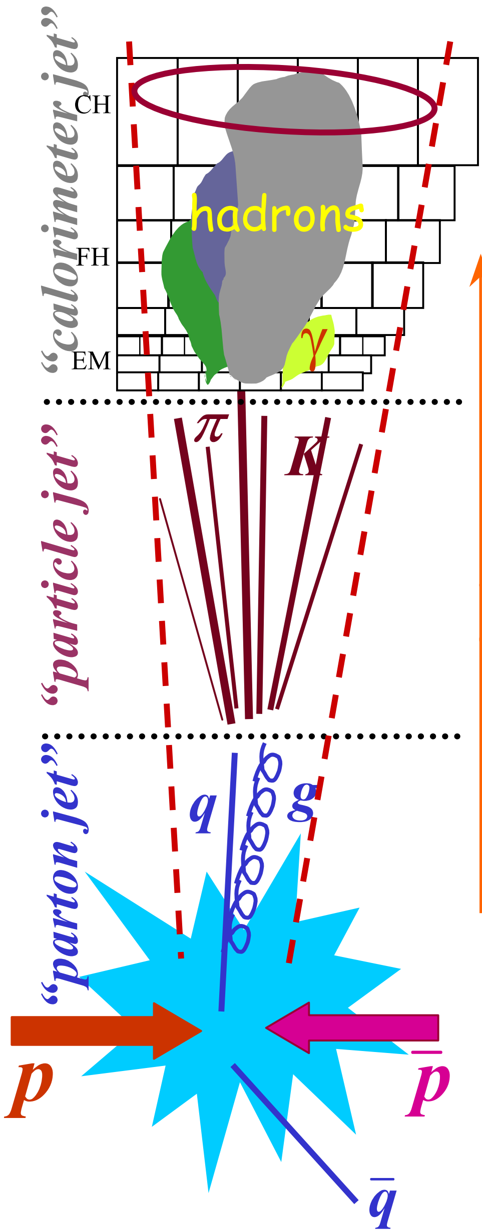
Towards (W/Z)*bb*: W/Z + Jets in Data

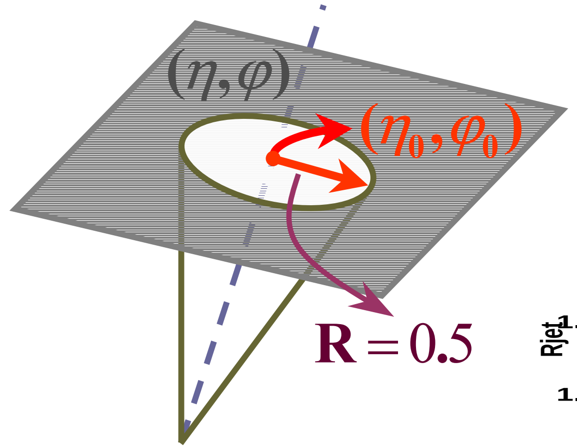
• a W + 2jet Higgs candidate (just for fun!)



*) Jet energies not calibrated

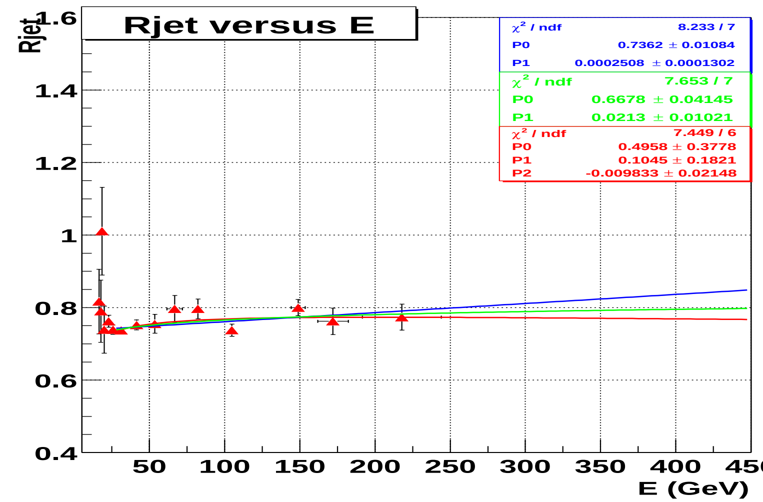
Jet Reconstruction and Calibration



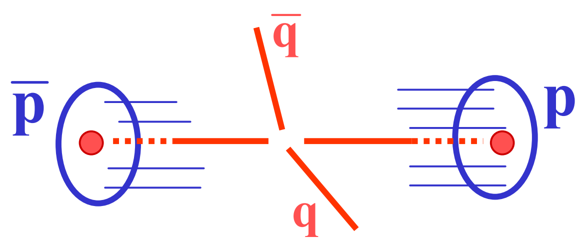


$$E_{jet}^{ptcl} = \frac{E_{jet}^{meas} - O}{R_{jet}\, S_{cone}}$$

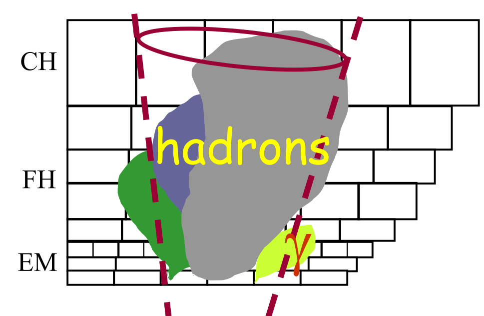
- Response (R_{jet}): E_{meas}/E_{true} (from E_T balance in γ-jet data)



- Offset (O): Ur noise, pileup, underlying event



- Showering ($1/S_{cone}$): out-of-cone shower losses



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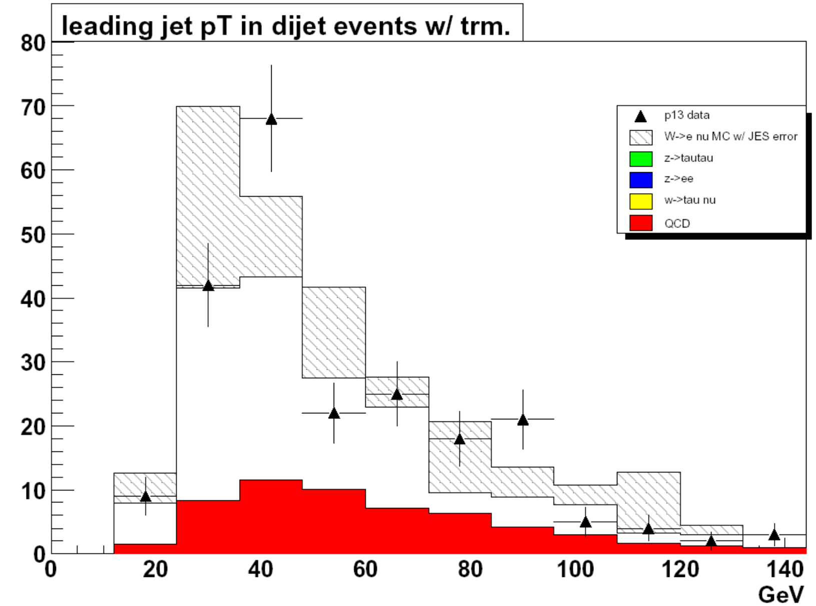
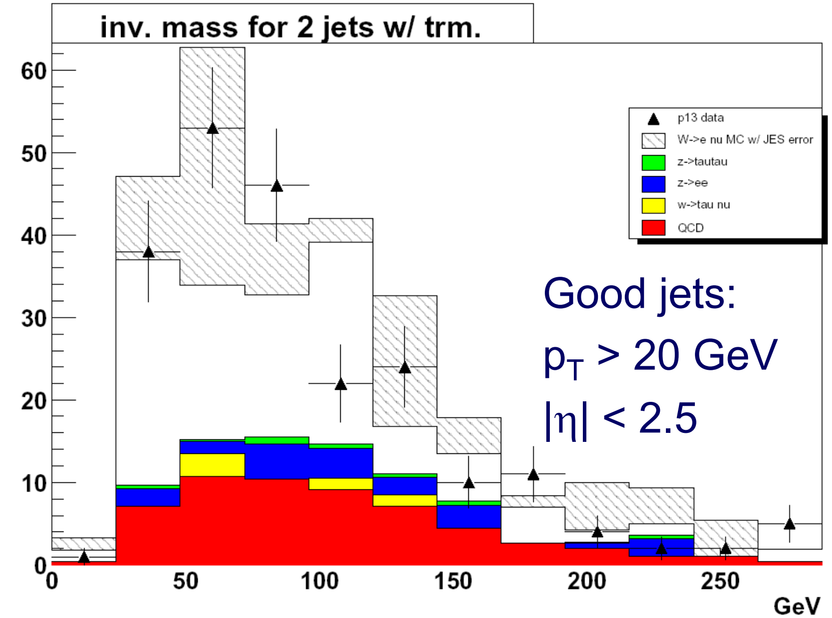
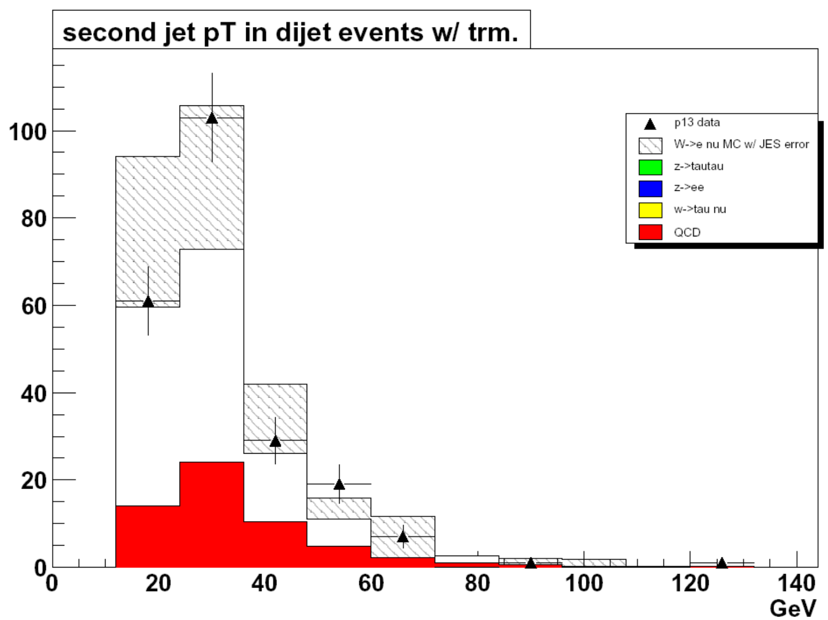
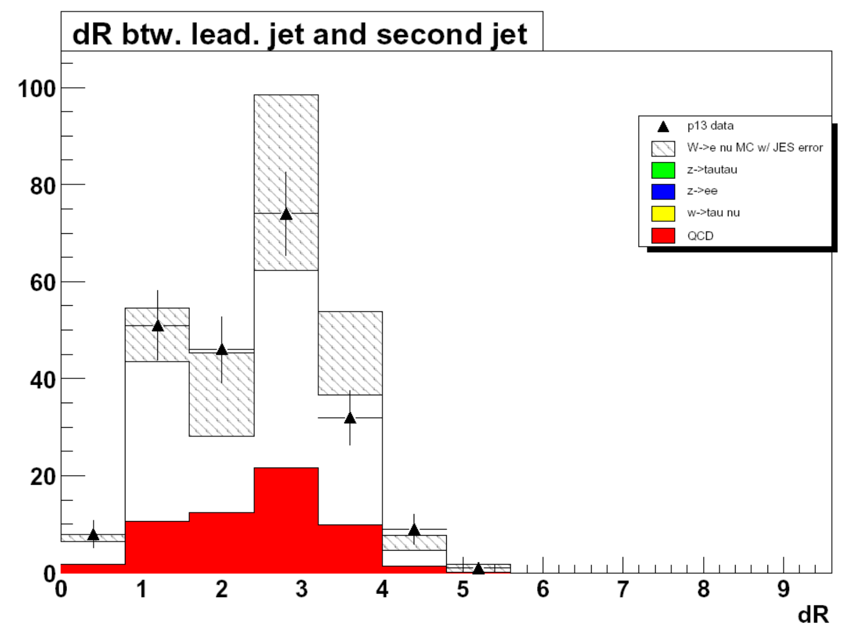
W(→eν) + dijets









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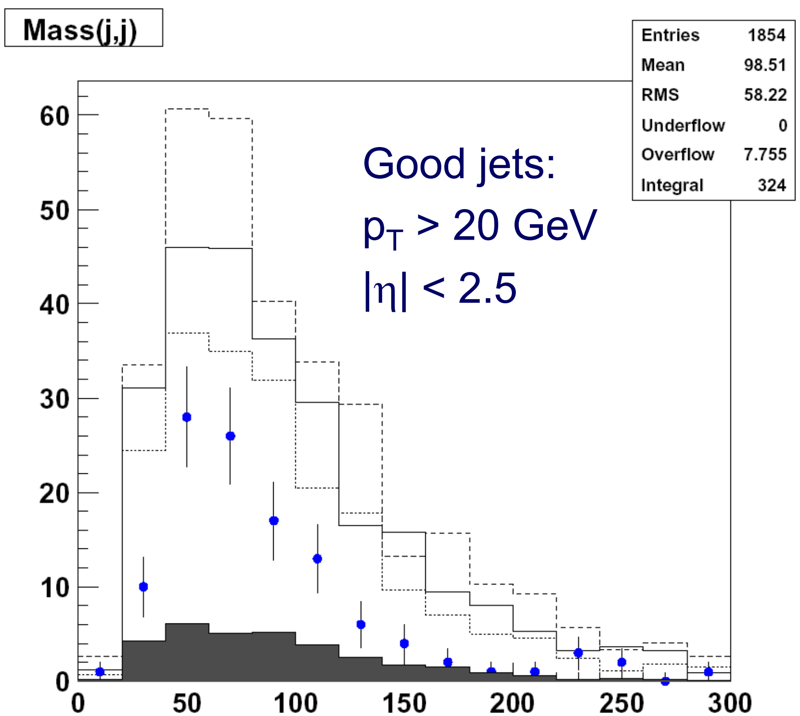
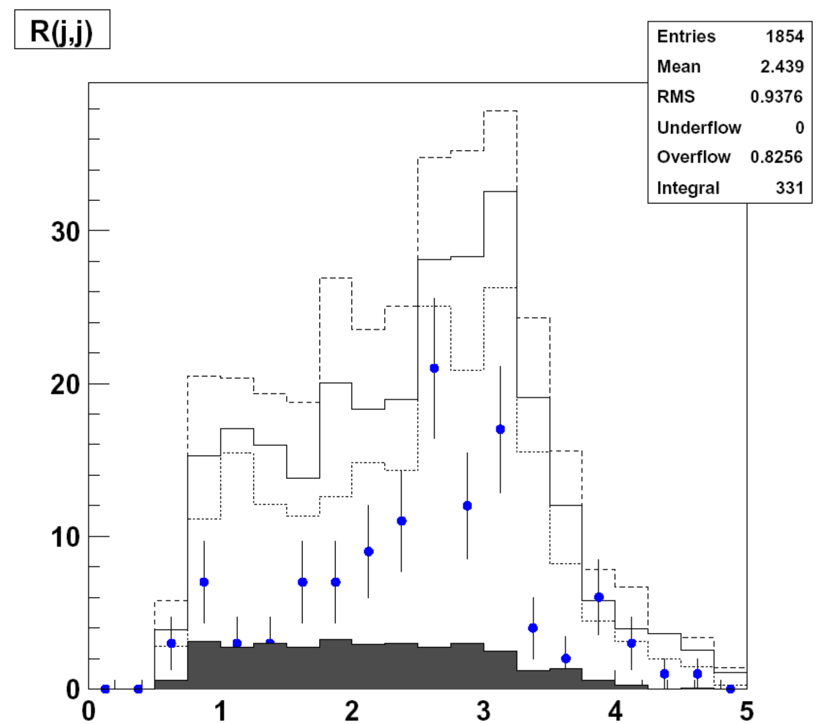
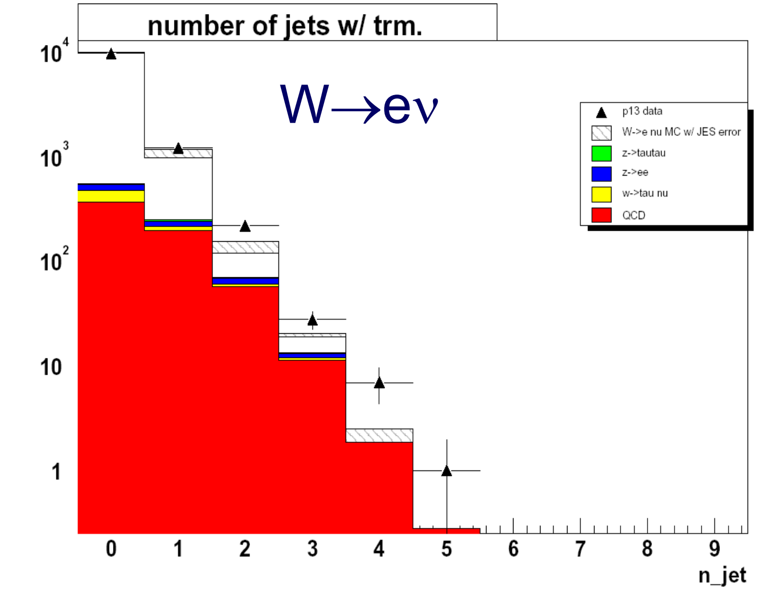
W(→μν) + dijets



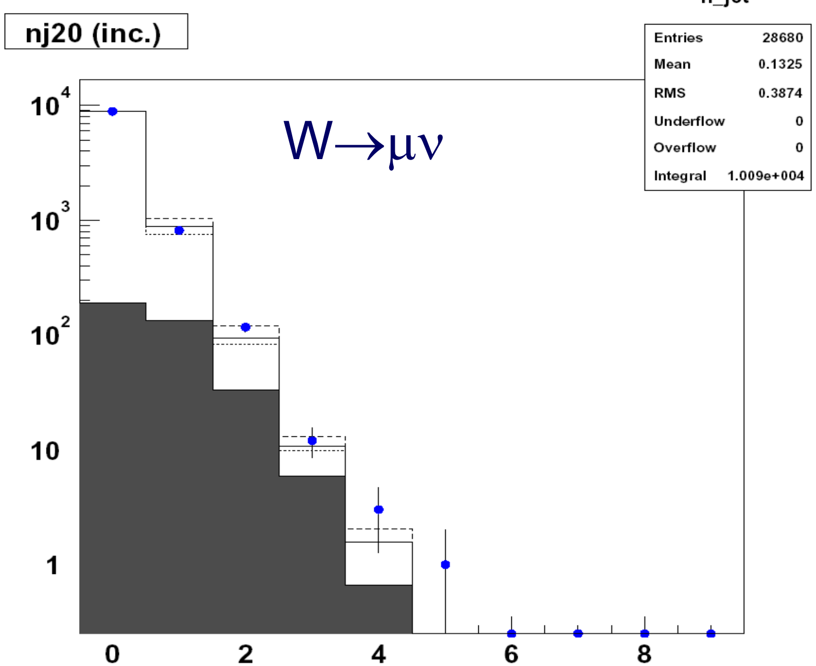


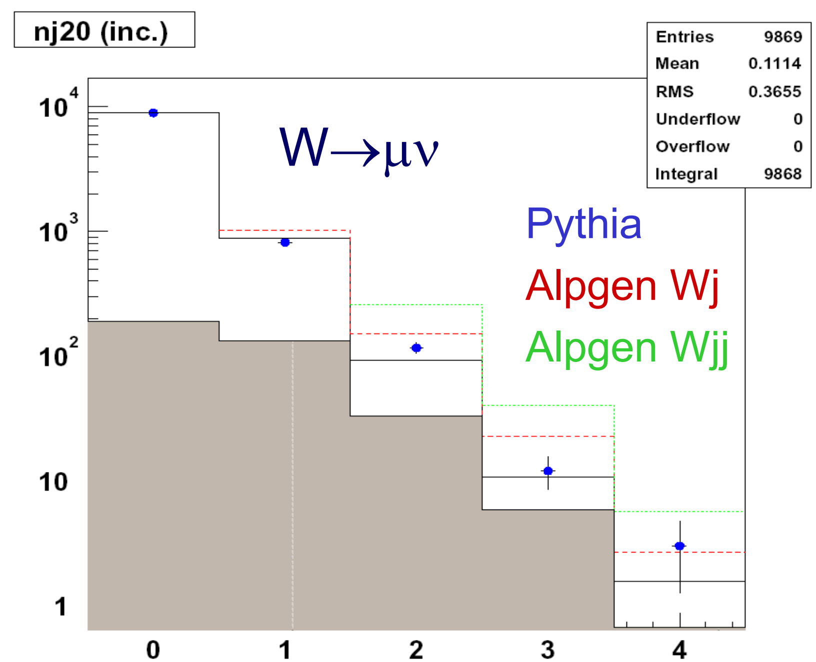
Distributions here not normalized, good agreement in shape

W(→eν/μν) + jets



- Number of inclusive jets in W→eν and W→μν events
- p_T (jet) > 20 GeV
- Good agreement with Pythia in 0 and 1 jet bins, disagreement is seen in higher multiplicities (as expected)
- ALPGEN seems to be doing better…





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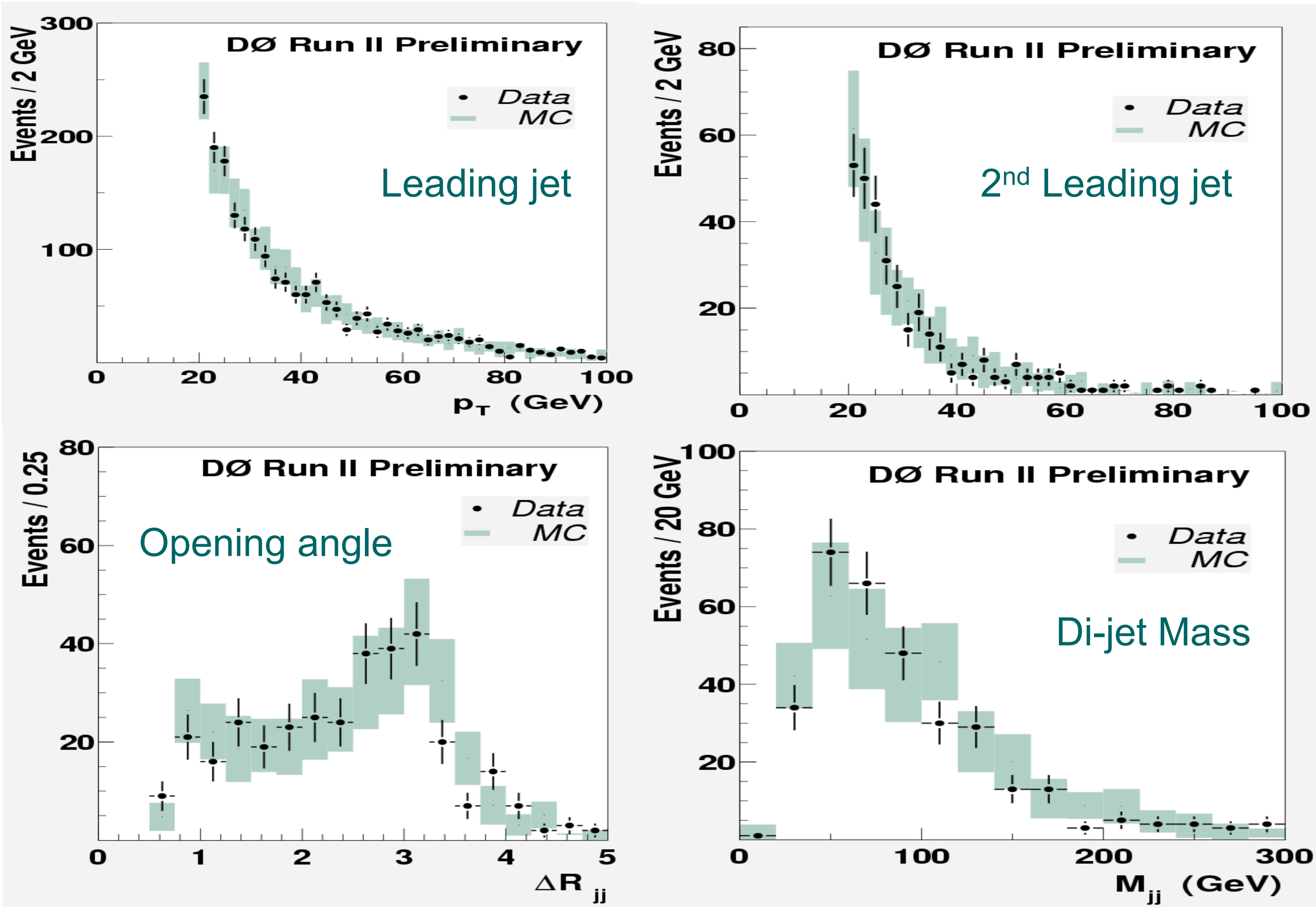
W(→e/μ) + jets



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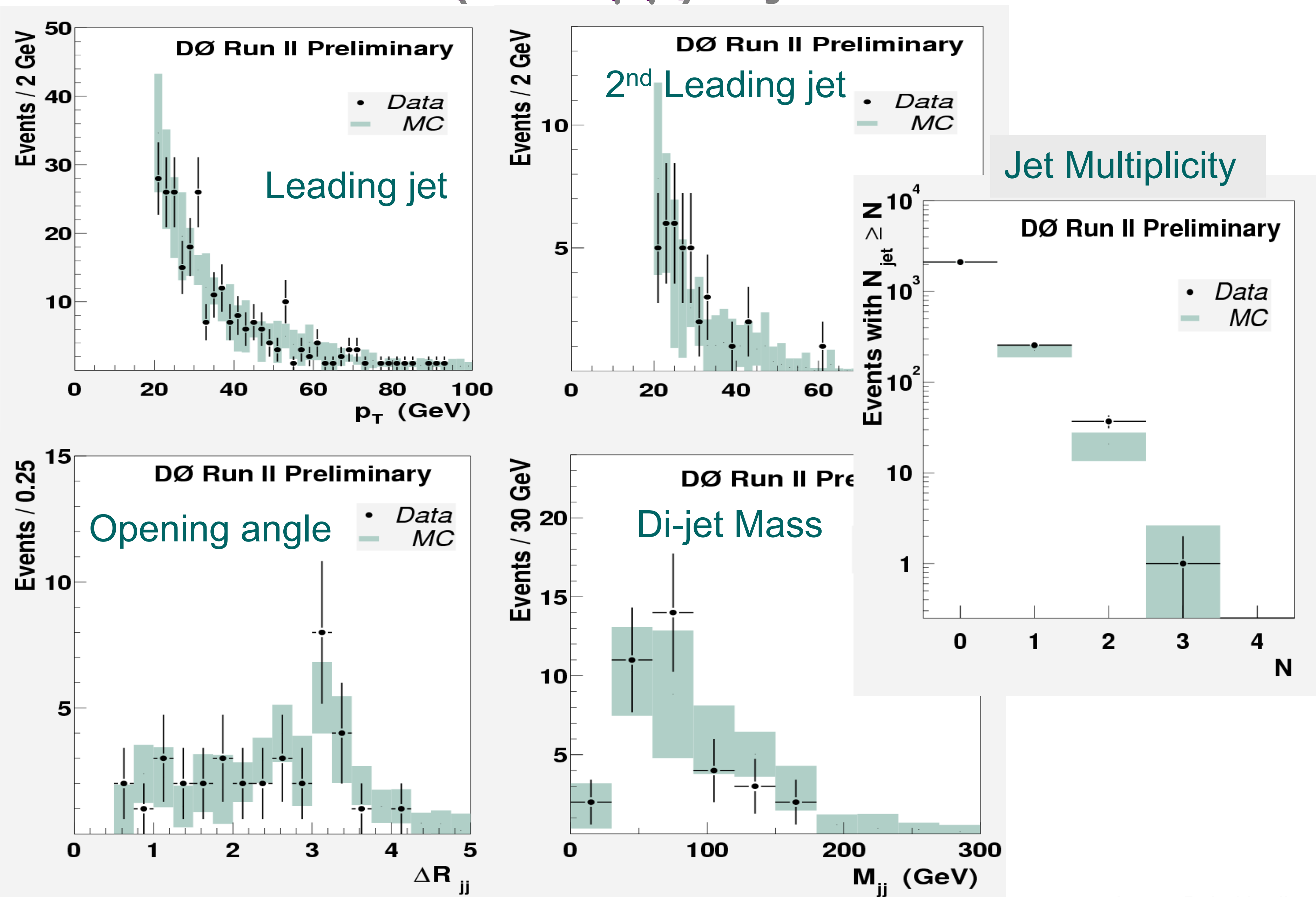
Z(→ee/μμ) + jets



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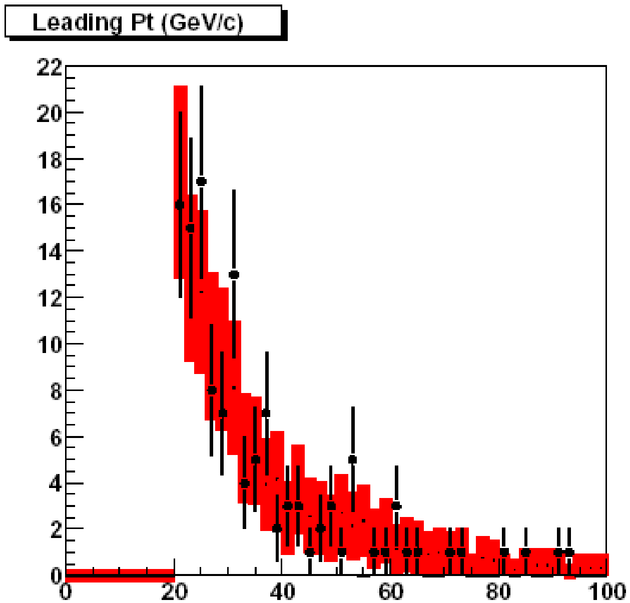
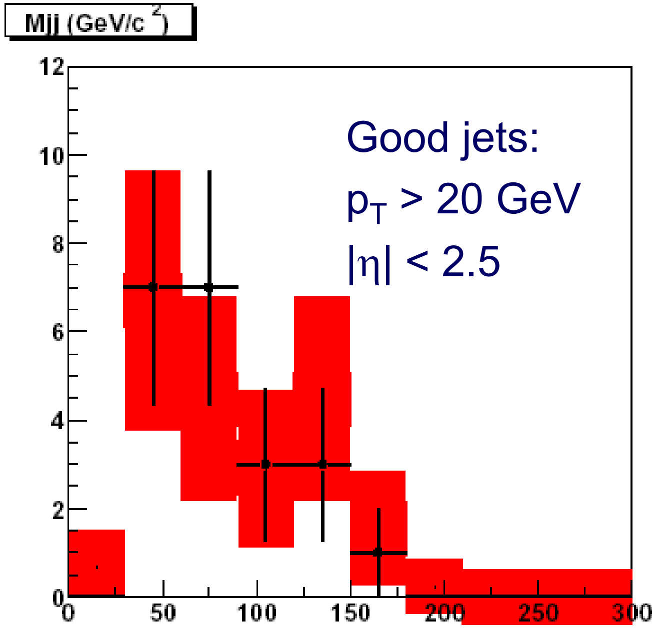
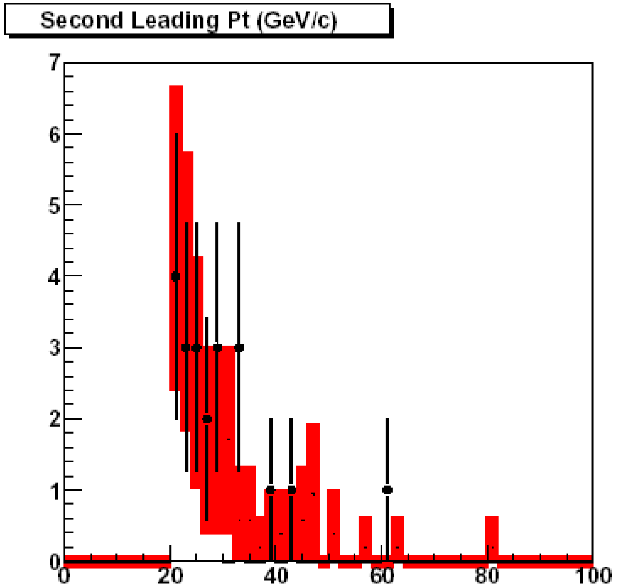
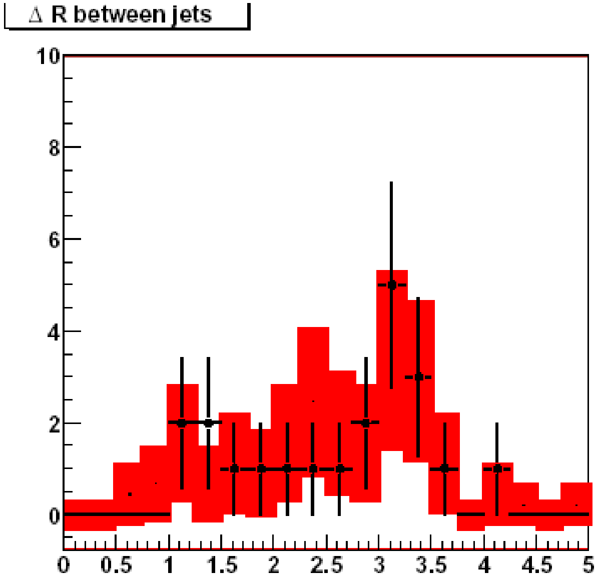
Z(→ee) + dijets









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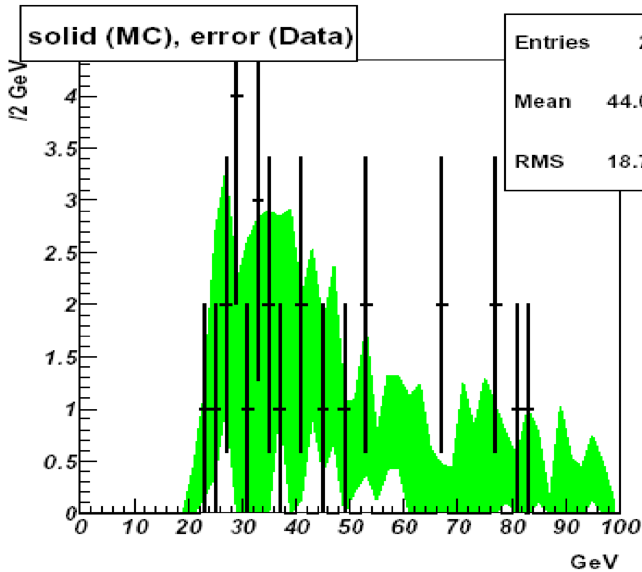
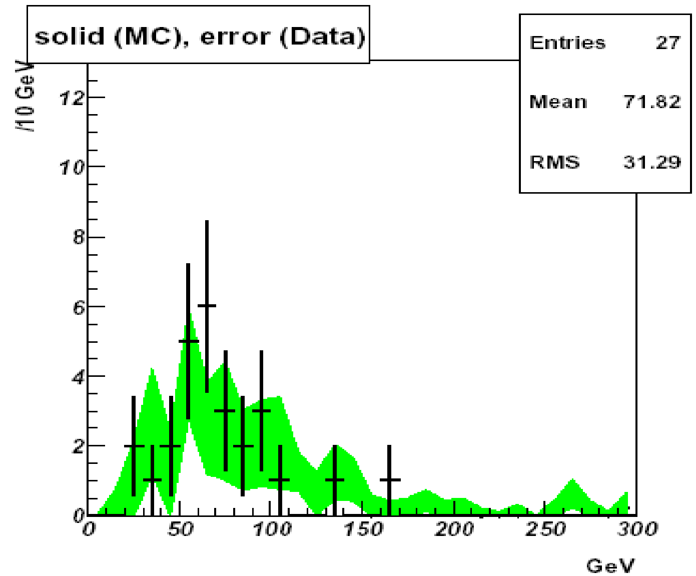
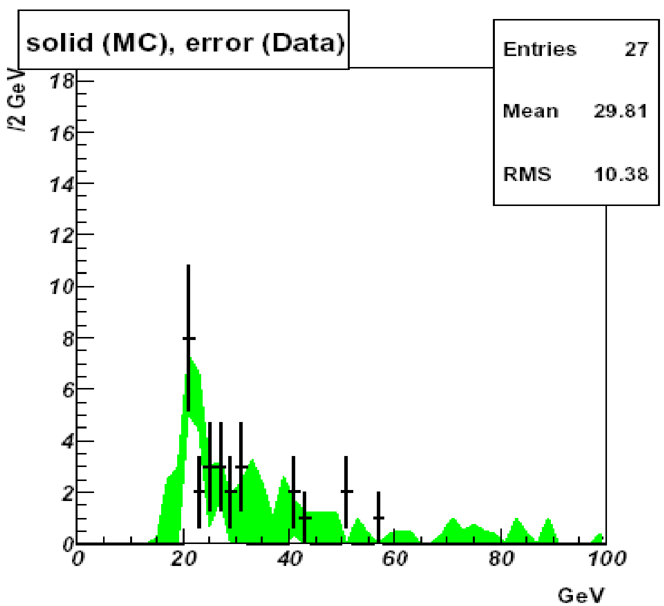
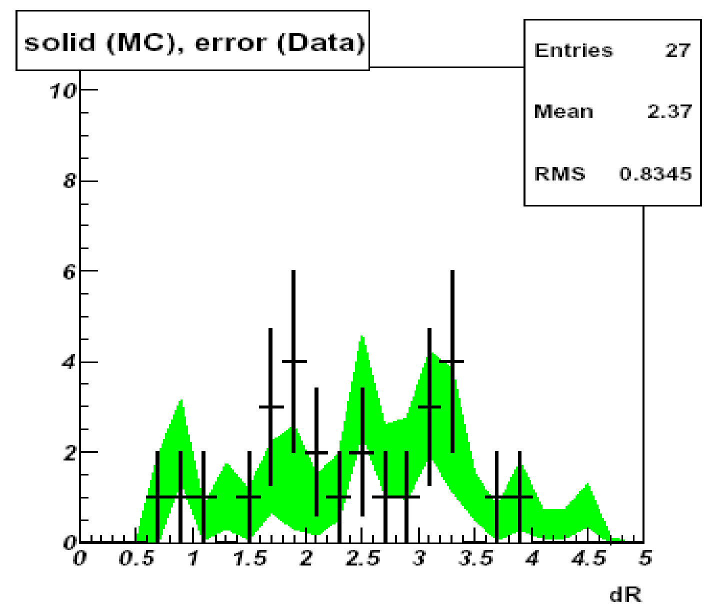
Z(→μμ) + dijets

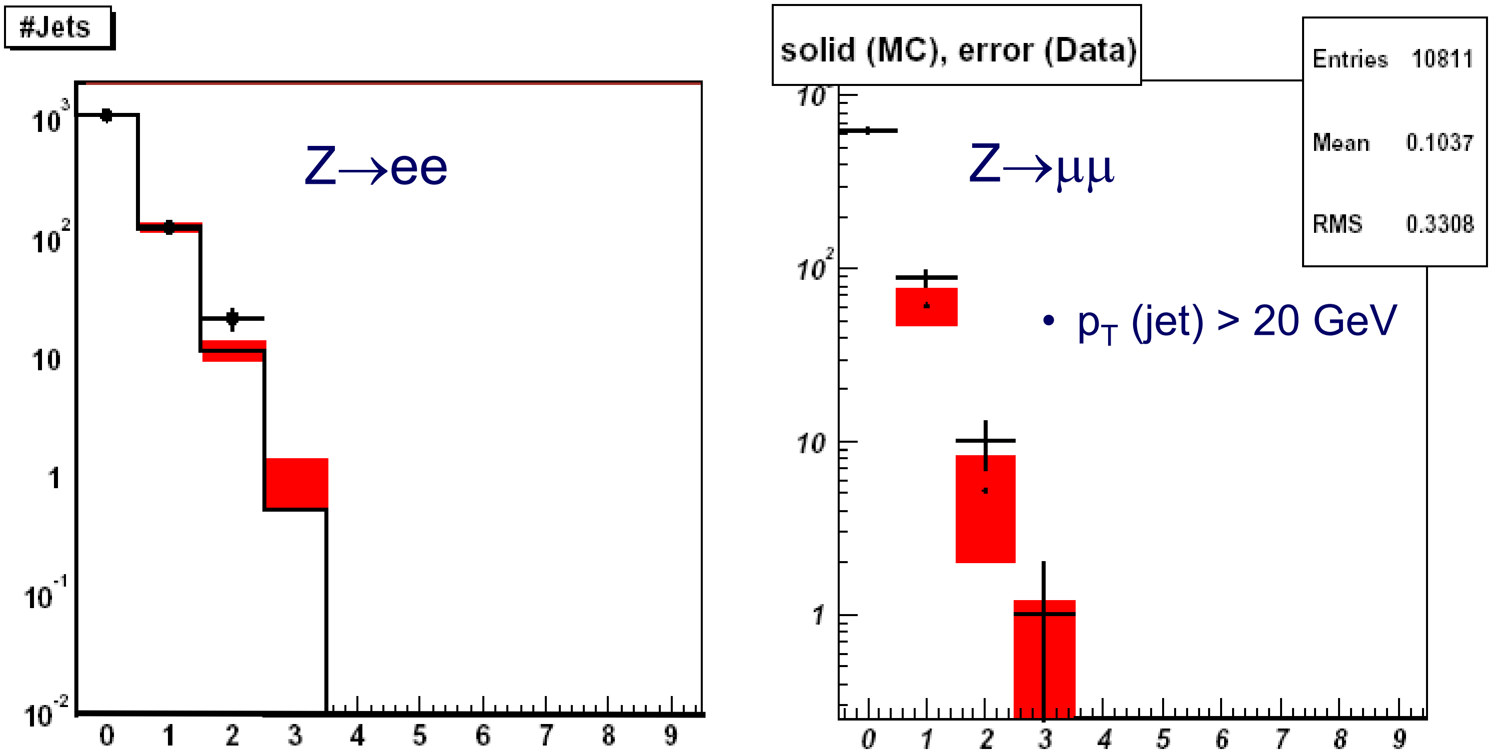

solid (MC), error (Data)
Entries 27
Mean 44.06
RMS 18.72
/2 GeV
GeV


solid (MC), error (Data)
Entries 27
Mean 71.82
RMS 31.29
/10 GeV
GeV


solid (MC), error (Data)
Entries 27
Mean 29.81
RMS 10.38
/2 GeV
GeV

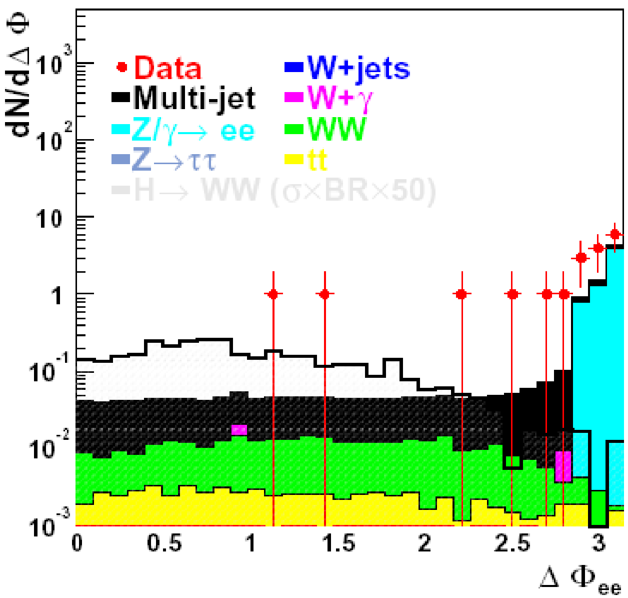

solid (MC), error (Data)
Entries 27
Mean 2.37
RMS 0.8345
dR

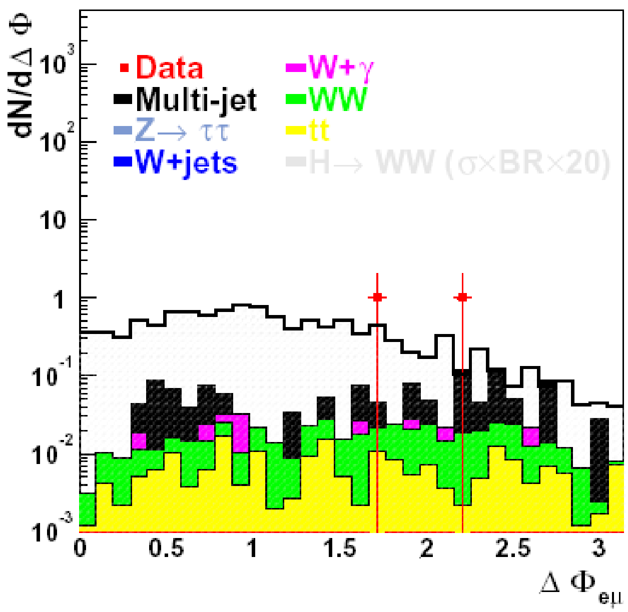
Z(→ee/μμ) + jets

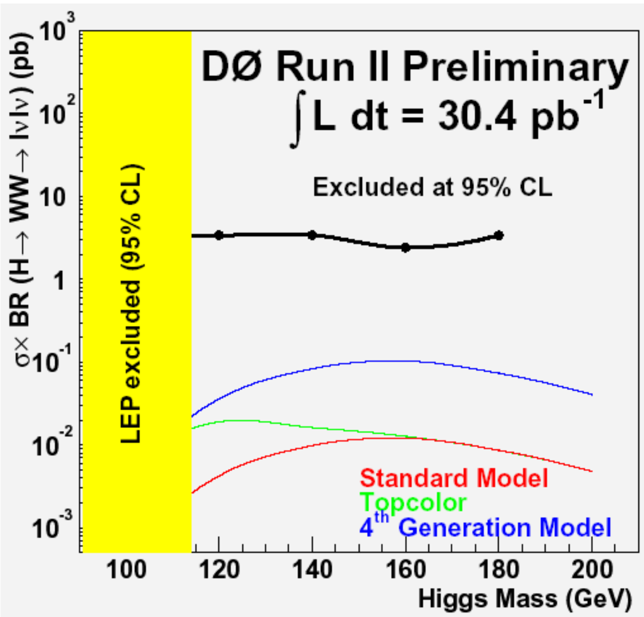


- Distributions of number of inclusive jets in Z→ee and Z→μμ events
- Uncertainty dominated by JES
- Again, fair agreement with Pythia in 0 and 1 jet bins, disagreement is seen in higher multiplicities (as expected)

$H \rightarrow WW \rightarrow l^+l^-\nu\nu$







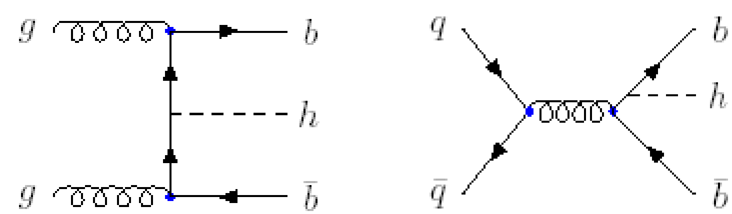
- Mass reconstruction not possible due to neutrinos
- Background processes
  - WW, *tt*, W/Z+jets, QCD/instrumental
- Employ spin correlations
  - $\Delta\Phi$(ll) variable is particularly useful
- $\Delta\Phi$ distributions after basic e/μ ID and kinematic cuts $p_T > 20$ GeV in $|\eta| < 2.5$
- ee and eμ channels so far

- Require good e^+e^-, missing E_T, no jets
- In the SM, of interest for high m_H
- 4th generation models Higgs production enhanced by ~8.5 in the mass range of 100 – 200 GeV
- Also in fermiophobic/topcolor BR($H \rightarrow WW^*$) > 98% for m_H > 100 GeV
- Current reach limited by recorded integrated luminosity

Higgs Associated Production with Beauty

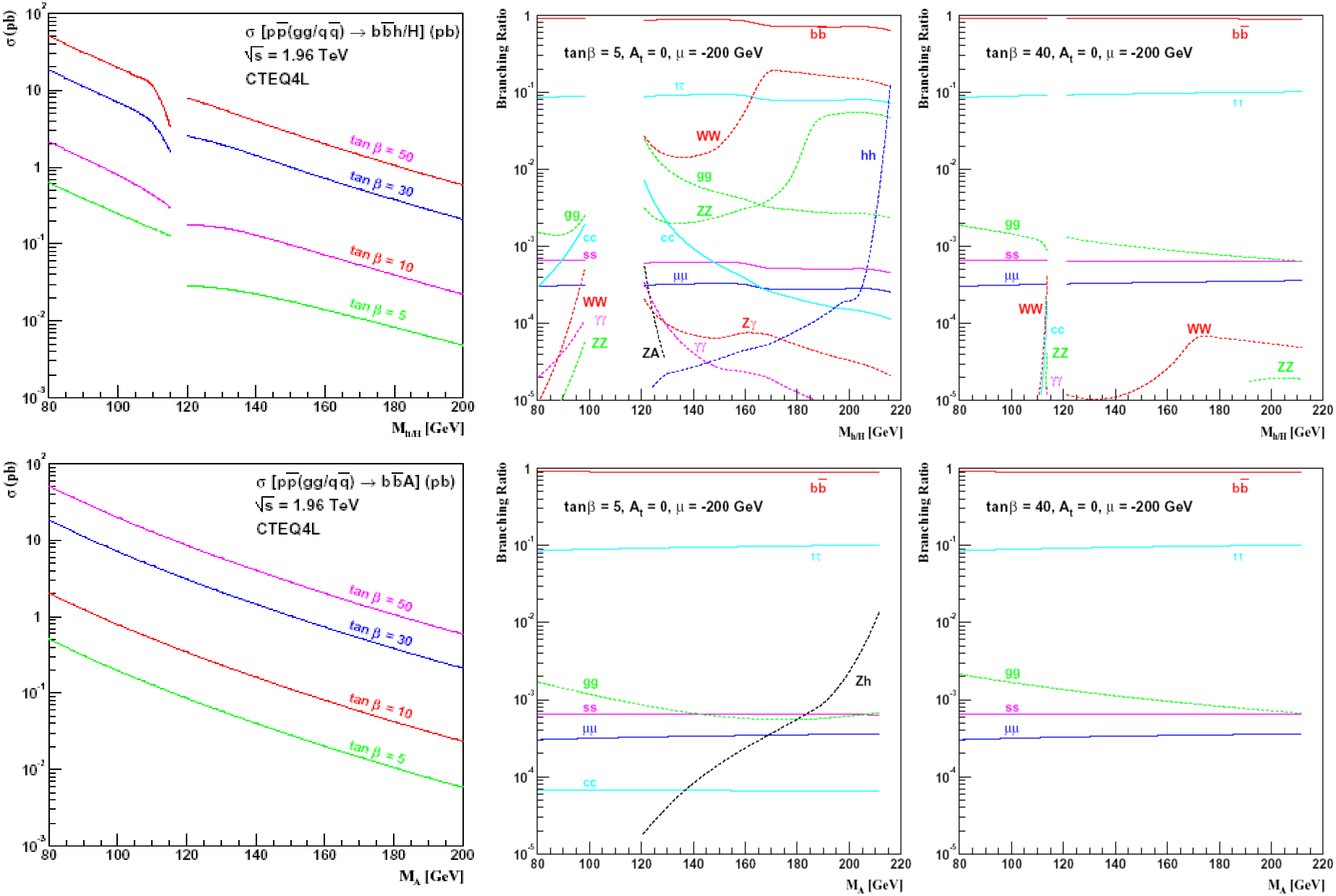
- In the SM, *bb*h coupling is weak $\propto m_b/vev$
- However, enhancement of *bb*h coupling is natural in Two Doublet Models for large $\tan\beta \equiv vev_t/vev_b$ $(vev_t^2 + vev_b^2 = vev^2_{SM})$
- Values of $\tan\beta$ as large as m_t/m_b are motivated in simplest versions of SO(10) GUTs
- SUSY models with two doublets are special cases of Two Doublet models
- After EWSB, end up with three neutral $\varphi(\equiv h, H, A)$ and two charged $H^{\pm}$ Higgses
- In SUSY, the Higgs sector is fully defined by two parameters, e.g. $\tan\beta$ and m_A
- For the minimal SUSY, $m_h <\sim 135$ GeV
- In general, in SUSY, $m_h <\sim 210$ GeV

- Yukawa *bb*A coupling is $\propto \tan\beta$ and so the $pp \to bb\varphi$ production gets enhanced by as much as $\tan^2\beta$
- Moreover, at high $\tan\beta$, either $m_h \approx m_A$ or $m_H \approx m_A$ with BR(*bb*) ~90%
- Typical leading order Feynman diagrams



- So, $pp \to bb\varphi \to bbbb$ could be enhanced at the Tevatron by as much as $\tan^2\beta$ and thus could well be observed or ruled out (certain models) with rather moderate luminosities, $\sim< fb^{-1}$

φ Production and Decays



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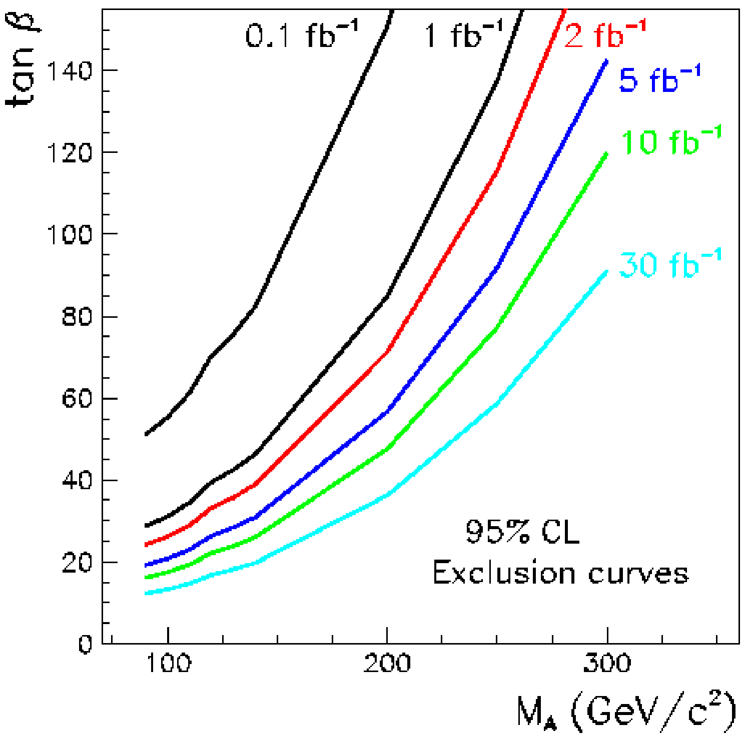
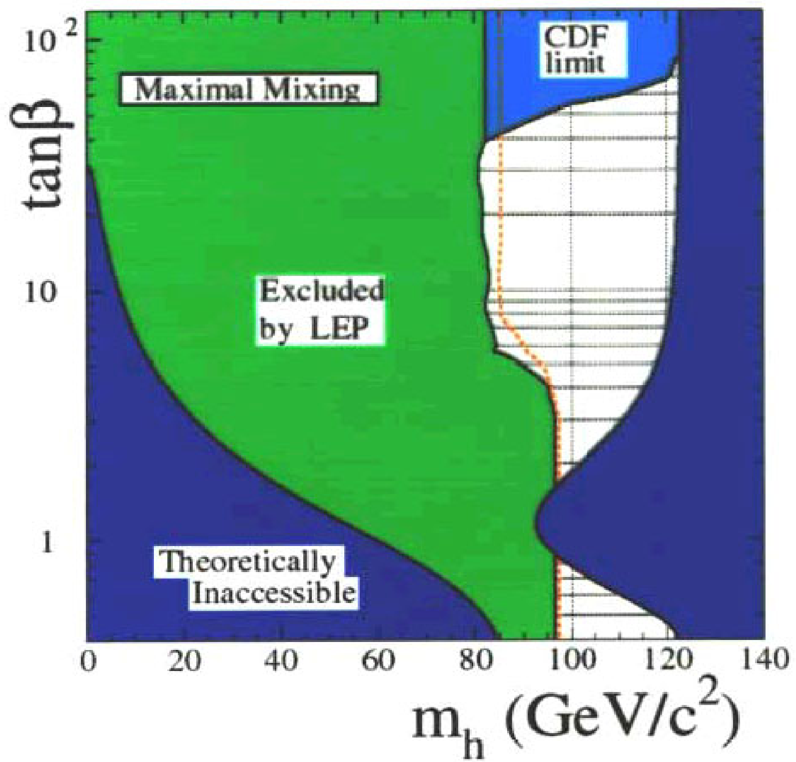
*bb*φ(→*bb*) Search in 4 *b*-jet Final States

- Spectacular 4 *b*-jet signature
  - major bckg QCD *bb*jj, *bbbb*
  - also (Z/W)*bb*/*cc*, *tt*
  - require 3 *b*-tagged jets, M_{bb} cut
  - *b*-tagging in trigger?

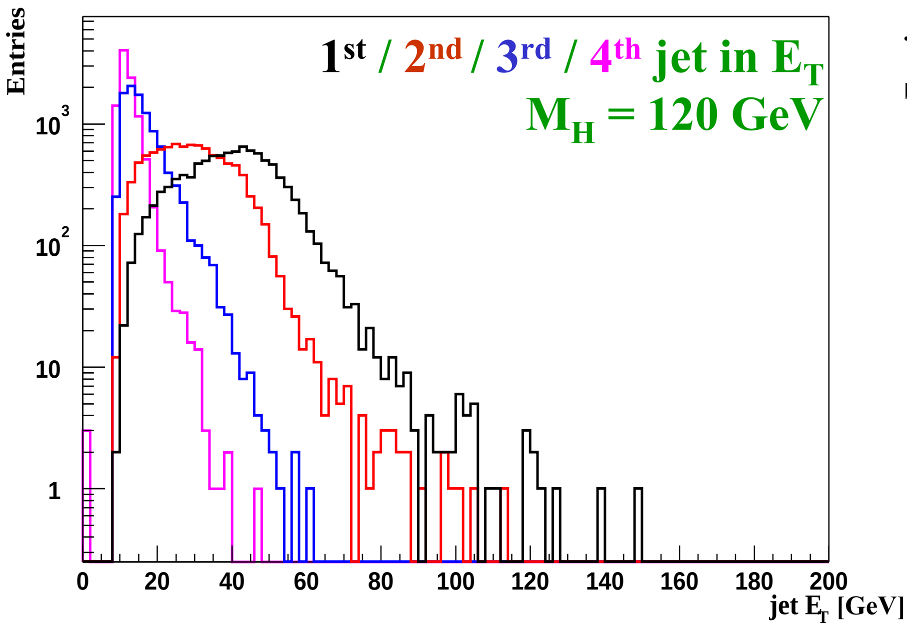
- Interesting exclusion regions at large tanβ, complementary to LEP
- Major issues thus are:
  - *b*-tagging
  - trigger efficiency (CDF's Run I, just a few percent !)
  - QCD backgrounds (eventually from data)

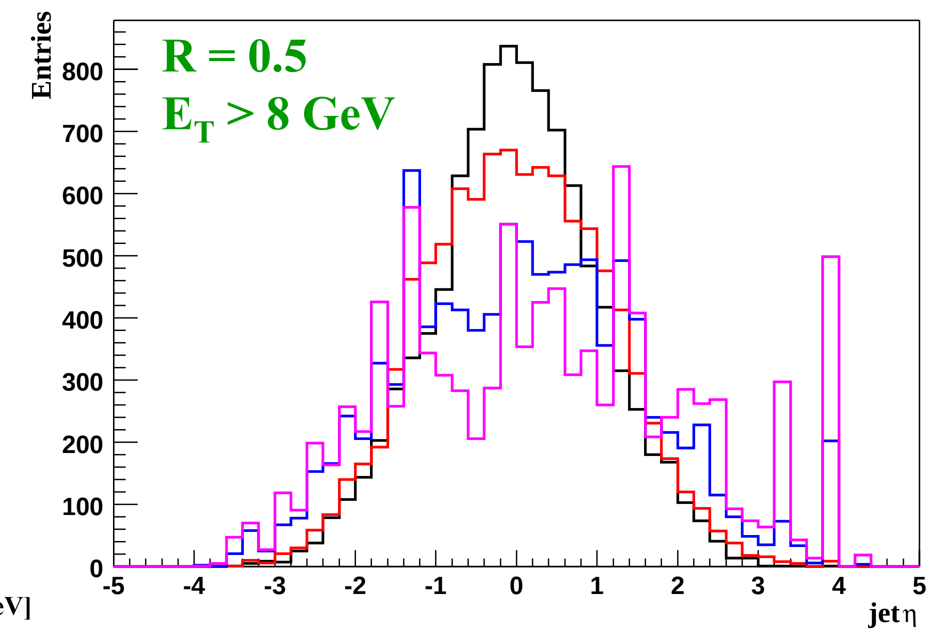




bbh(→*bb*) Kinematics

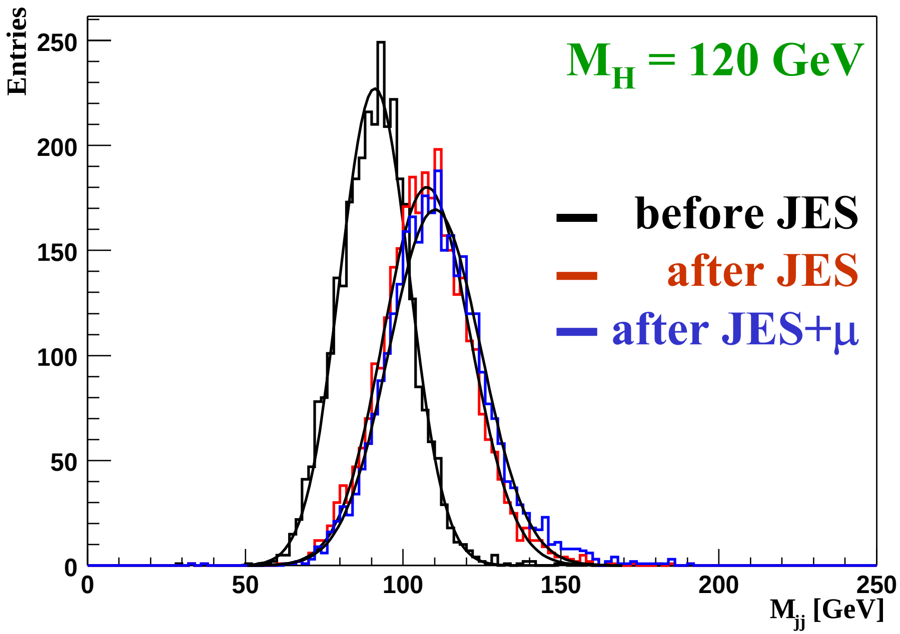
- Events generated with Pythia v6.155, detailed detector simulations
- Have checked and for *bbh* Pythia & CompHEP agree well at parton level
- Large signal samples ~50k per several Higgs mass values
- Also have ~50k each *ddh(→dd)* & *cch(→cc)* for mistag rate studies
- Backgrounds (QCD, *tt*, Z*bb*/*cc*, W*bb*/*cc*) either generated or in progress

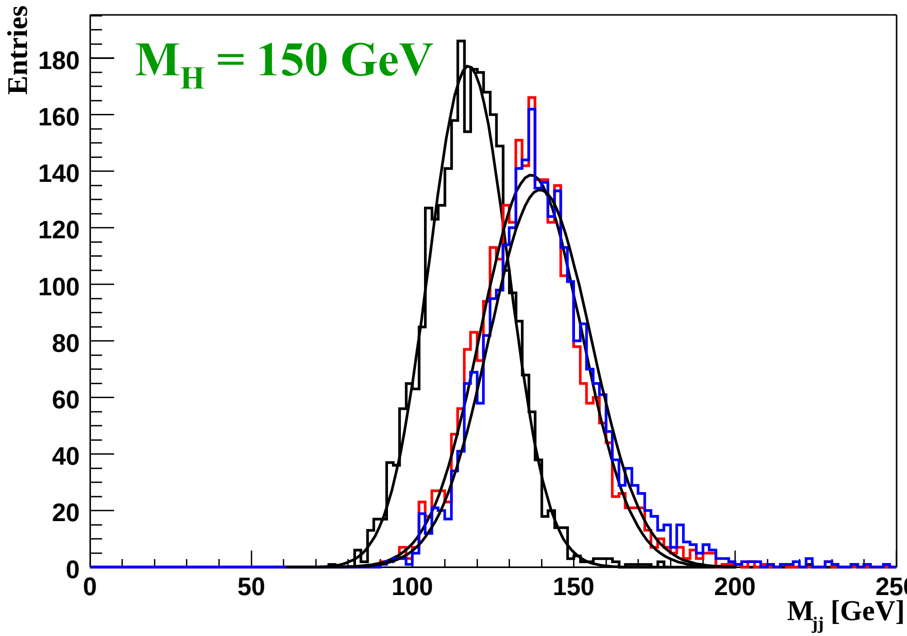




- The jets are not of high p_T (at least not for the Higgs masses where this channel is of interest), especially the forward jet(s), and this poses challenges, also for triggering in the environment of enormous QCD background

Higgs Mass Resolution (1)



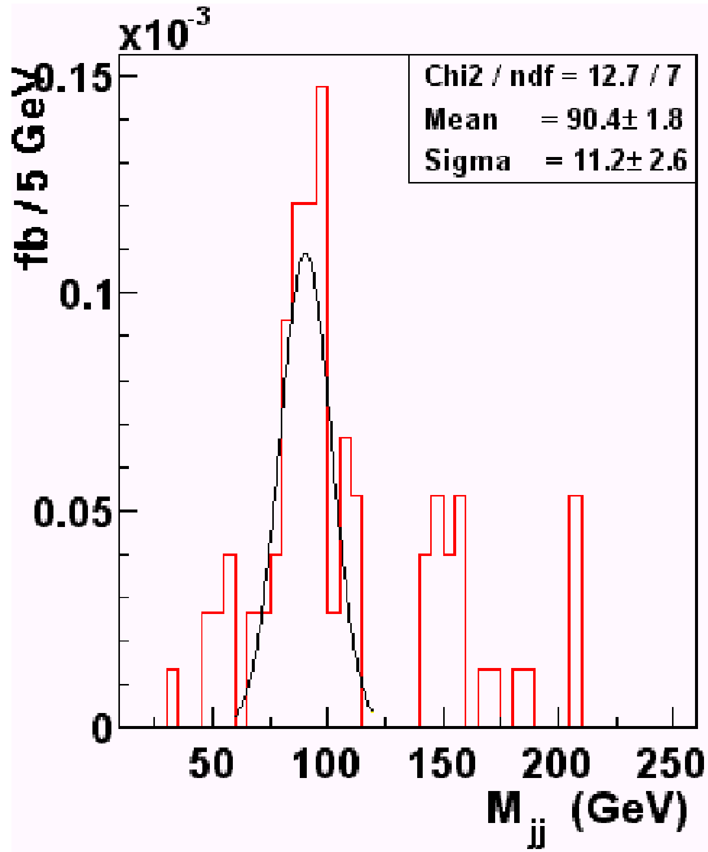


- Before JES correction
  - m = 91 GeV, σ = 11 GeV, σ/m = 12%
- After default JES correction
  - m = 107 GeV, σ = 14 GeV, σ/m = 13%
- After default JES + μ correction
  - m = 110 GeV, σ = 14 GeV, σ/m = 13%

- Before JES correction
  - m = 117 GeV, σ = 12 GeV, σ/m = 10%
- After default JES correction
  - m = 137 GeV, σ = 15 GeV, σ/m = 11%
- After default JES + μ correction
  - m = 140 GeV, σ = 16 GeV, σ/m = 11%

Higgs Mass Resolution (2)

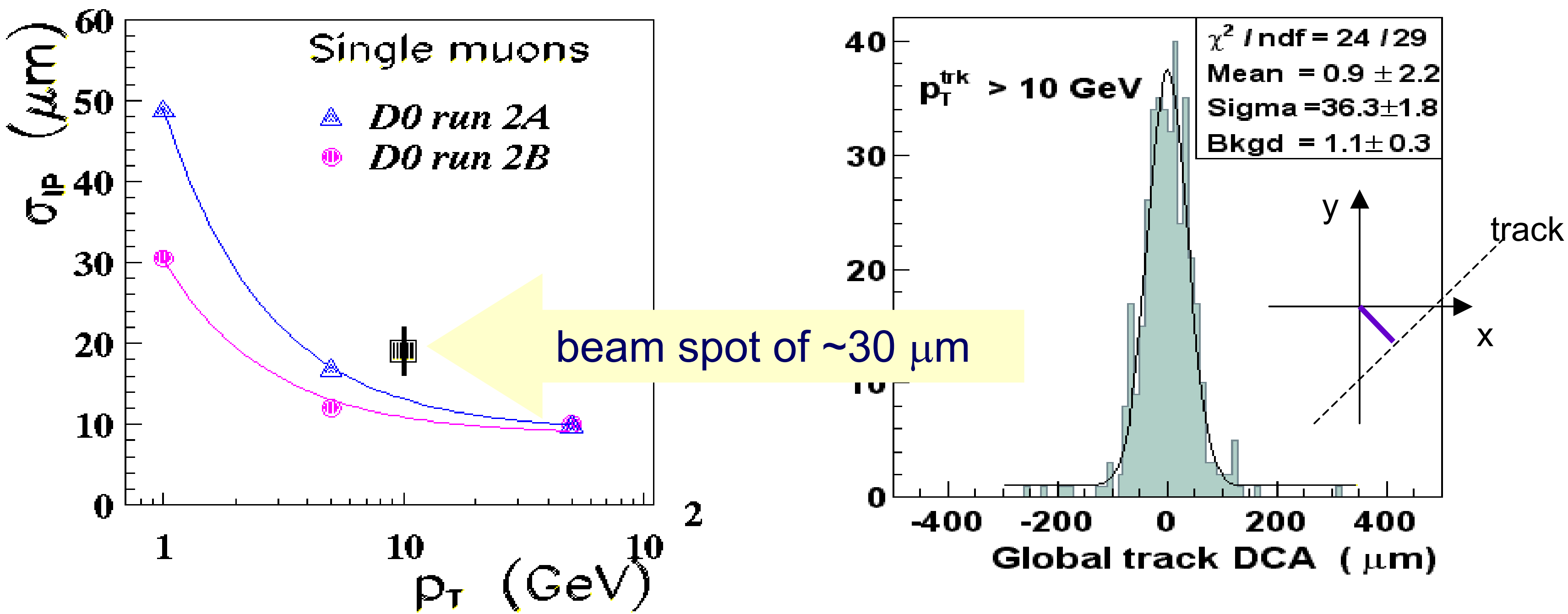
- First pass optimization on kinematic selection to maximize S/sqrt(B)
- For m_h = 120 GeV
  - 1^{st} jet E_T > 55 GeV
  - 2^{nd} jet E_T > 40 GeV
  - 3^{rd} and 4^{th} jets with E_T > 30 GeV
  - $|\eta| < 2$
  - require at least 3 b-tagged jets
  - considered all permutation (have to deal with combinatorial background)
  - rate normalized to SM XS, BR(*bb*)=1
- Relative resolution $\sigma/M \approx 12\%$



b-tagging (1)

- Crucial to keep signal efficiency high and suppress non-*b* jets
- Efficiency/fake rates determined by Impact Parameter (IP) resolution

- Measured IP resolution almost on target
  - 1st pass in SMT alignment
  - No CFT alignment



- Run IIb SMT design performs much better at low p_T directly relevant to b-tagging capability

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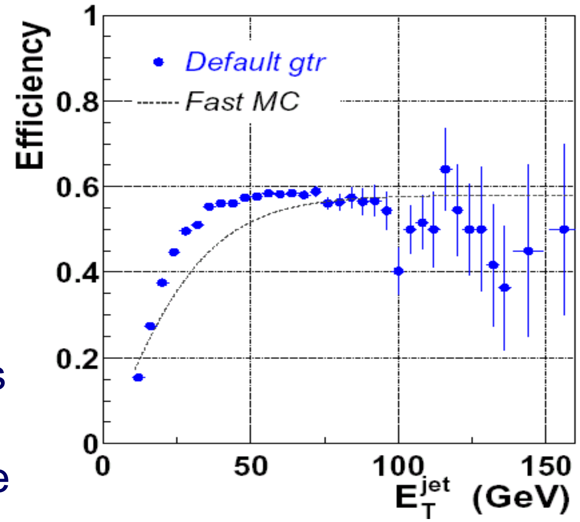
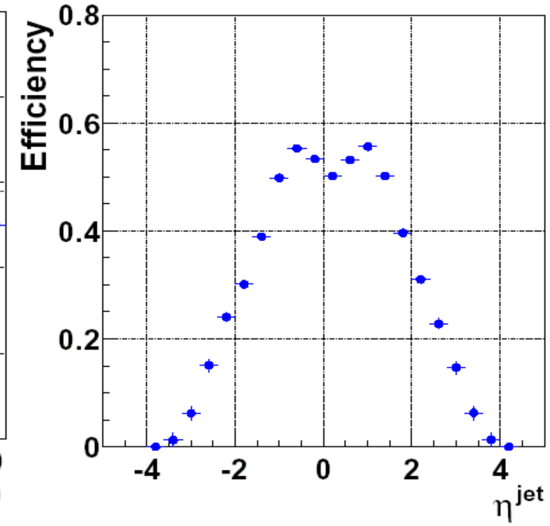
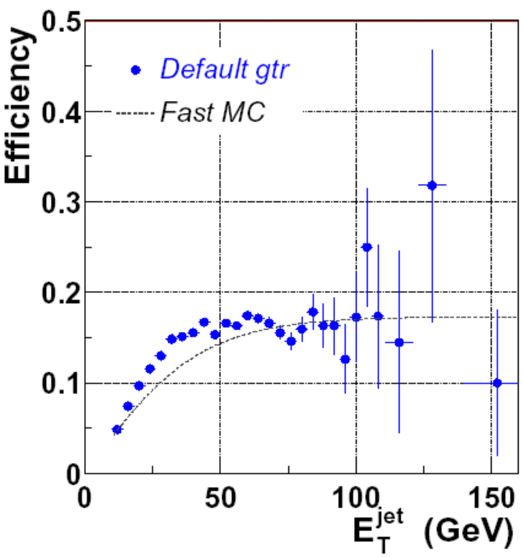
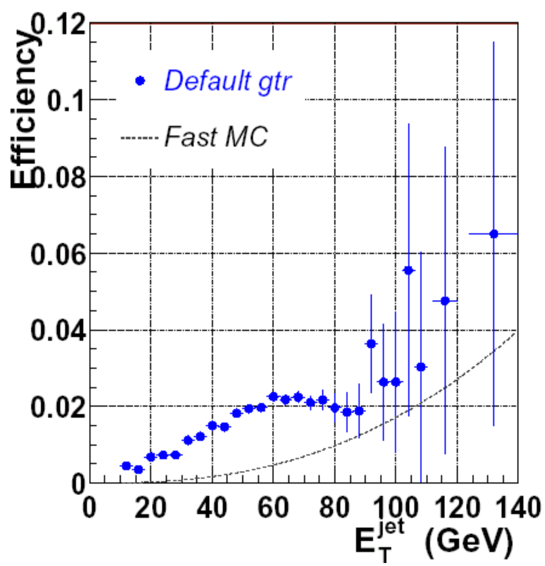
b-tagging (2)

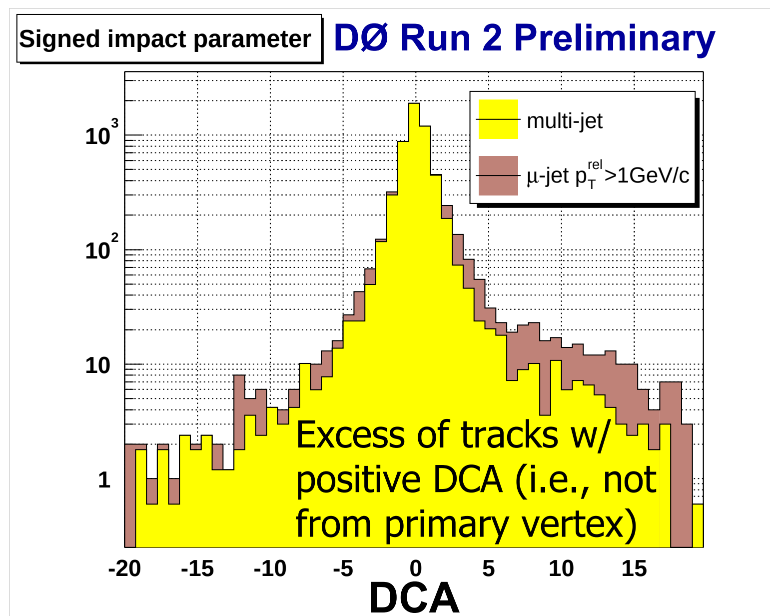
- Detailed detector simulations
  - not fully optimized yet
- Preliminary results indicate
  - *b*-tagging efficiency as high as 60% can be achieved
  - mistagging rate for *c*-jets is less than 15-20% depending on E_T, while light quark tag rate can be kept at a few percent level











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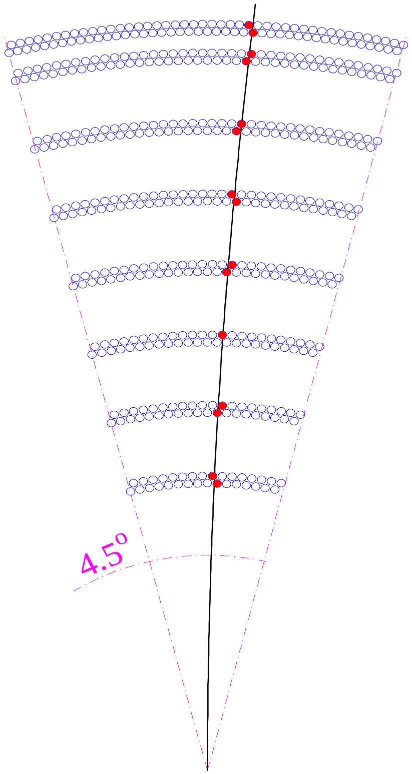
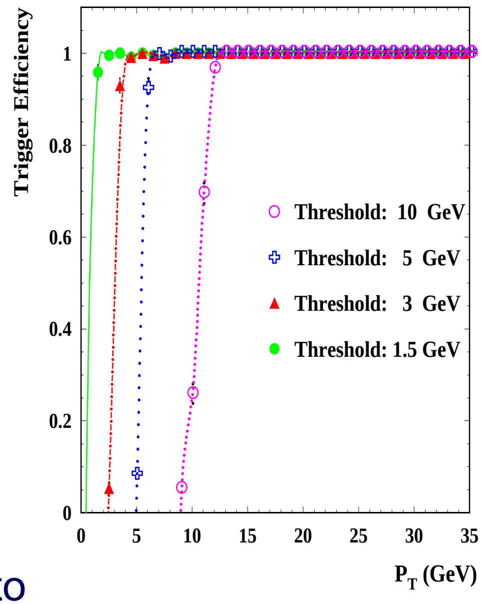
CTT + STT = Displaced Vertex Trigger



- Provides charged lepton id in Level 1 by finding tracks in 4.5° azimuthal trigger sectors of CFT
- Helps with EM-id in Level 1 by reconstructing clusters of energy in CPS scintillator strips
- Helps with Muon-id in Level 1 by sending 6 highest p_T tracks to L1Muon in about 900ns
- Helps with EM-id in forward regions $|\eta| < 2.6$ by reconstructing clusters of energy in FPS strips
- Helps with charged lepton id in forward regions by confirmation in pre-radiator layers of FPS
- Facilitates matching of preshower and calorimeter objects at quadrant level
- Upgrade to use narrower roads (from doublets to singlets) to control fake rates at high luminosities

Sharp efficiency turn-ons



- Helps with displaced vertex id in Level 2 Silicon Track Trigger by providing the Level 1 CFT tracks for global SMT+CFT track fitting
- In L1, cruder p_T bins are used, more detailed info on tracks sent to L2 where performance is critical e.g. in STT

Muon p_T, GeV	$\Delta p_T / p_T^2$	$\Delta\varphi_0$, mR	IP res, µm
2	1%	1	40
5	0.7%	0.6	25
50	0.3%	0.4	20

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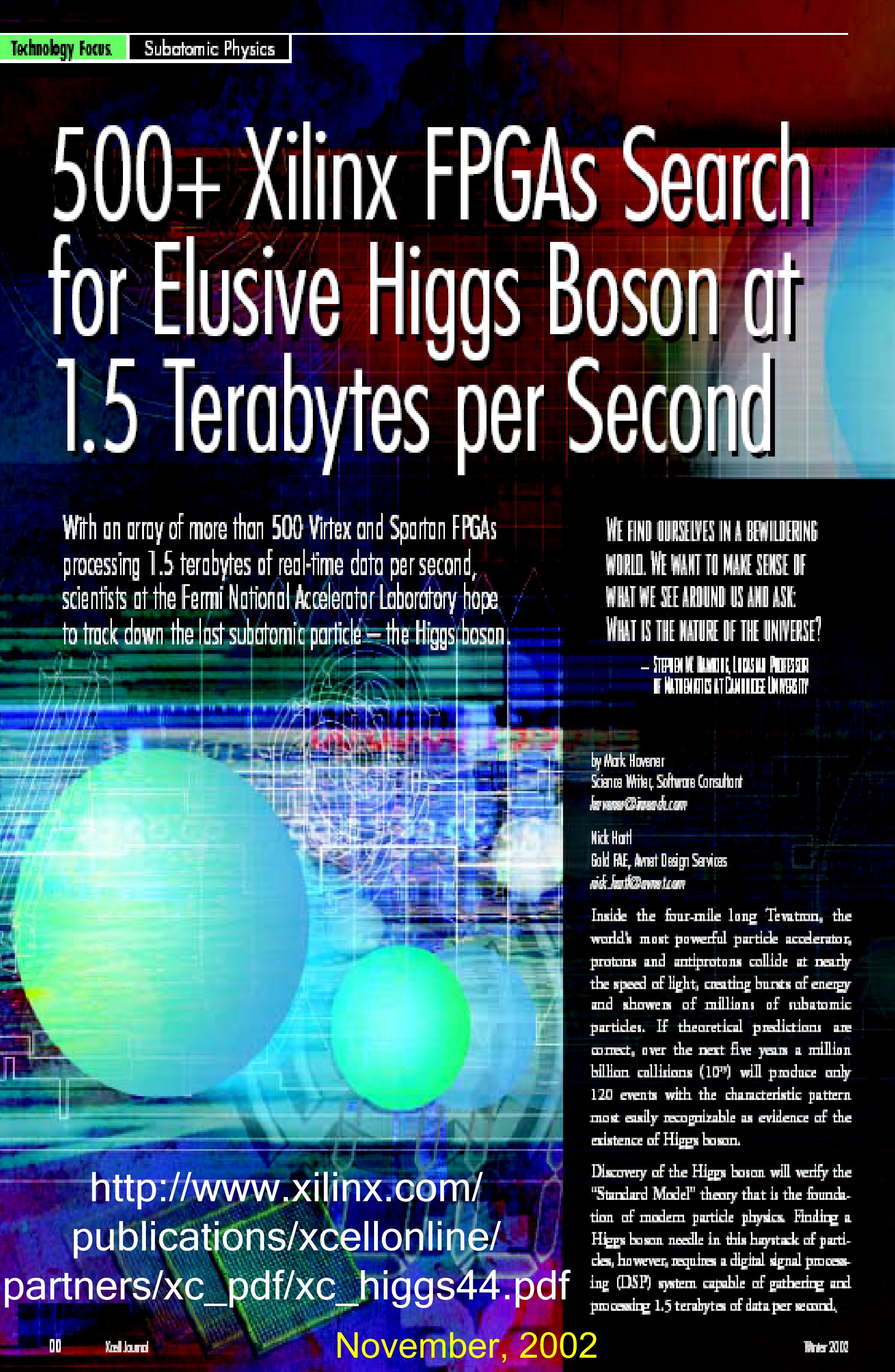


Technology Focus Subatomic Physics

500+ Xilinx FPGAs Search for Elusive Higgs Boson at 1.5 Terabytes per Second

With an array of more than 500 Virtex and Spartan FPGAs processing 1.5 terabytes of real-time data per second, scientists at the Fermi National Accelerator Laboratory hope to track down the last subatomic particle – the Higgs boson.

WE FIND OURSELVES IN A BEWILDERING WORLD. WE WANT TO MAKE SENSE OF WHAT WE SEE AROUND US AND ASK: WHAT IS THE NATURE OF THE UNIVERSE?

– STEPHEN W. HAWKING, LUCASIAN PROFESSOR OF MATHEMATICS AT CAMBRIDGE UNIVERSITY

by Mark Hovener
Science Writer, Software Consultant

Nick Hartl
Gold FAE, Avnet Design Services

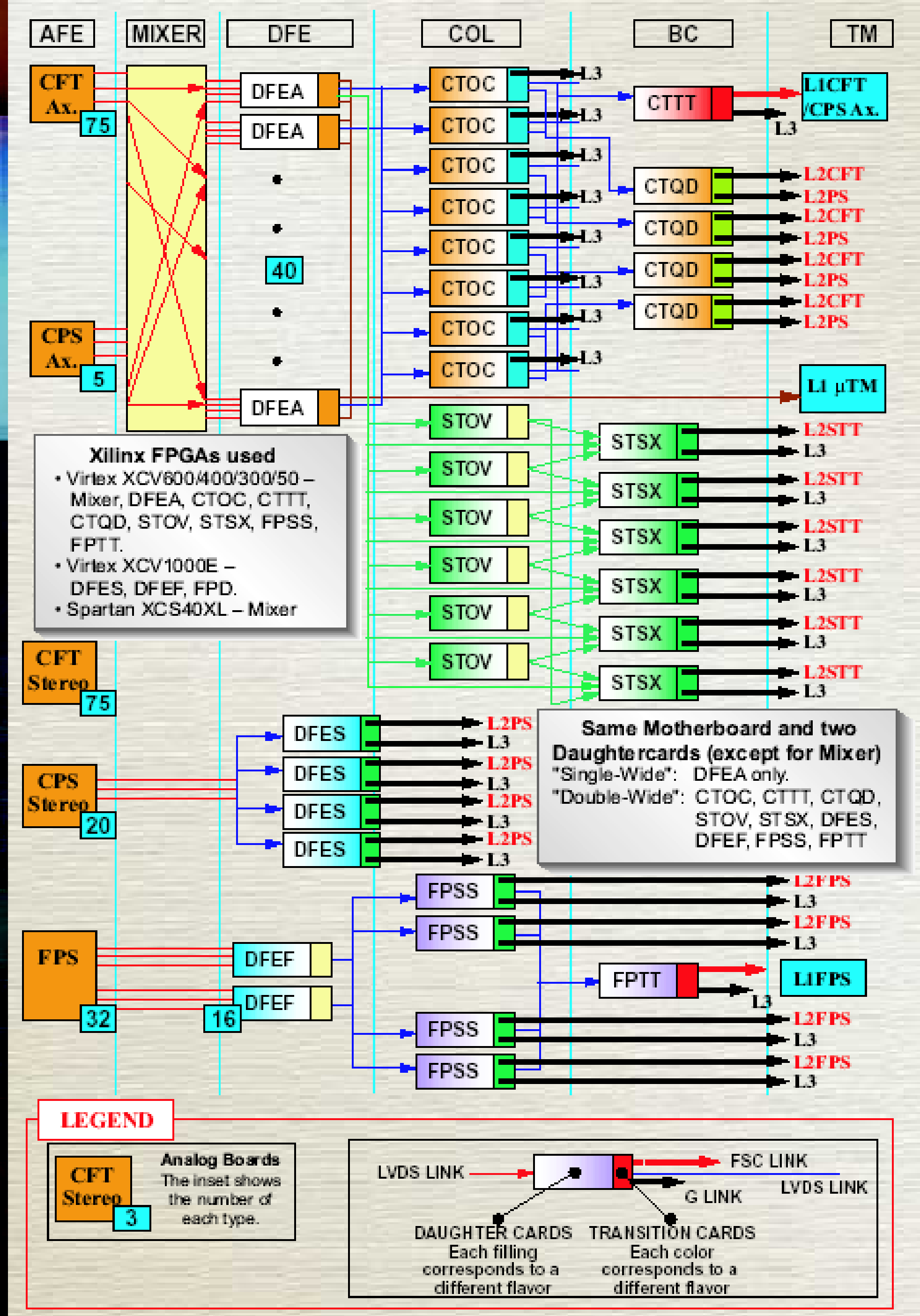
Inside the four-mile long Tevatron, the world's most powerful particle accelerator, protons and antiprotons collide at nearly the speed of light, creating bursts of energy and showers of millions of subatomic particles. If theoretical predictions are correct, over the next five years a million billion collisions (10^{15}) will produce only 120 events with the characteristic pattern most easily recognizable as evidence of the existence of Higgs boson.

Discovery of the Higgs boson will verify the "Standard Model" theory that is the foundation of modern particle physics. Finding a Higgs boson needle in this haystack of particles, however, requires a digital signal processing (DSP) system capable of gathering and processing 1.5 terabytes of data per second.

http://www.xilinx.com/publications/xcellonline/partners/xc_pdf/xc_higgs44.pdf

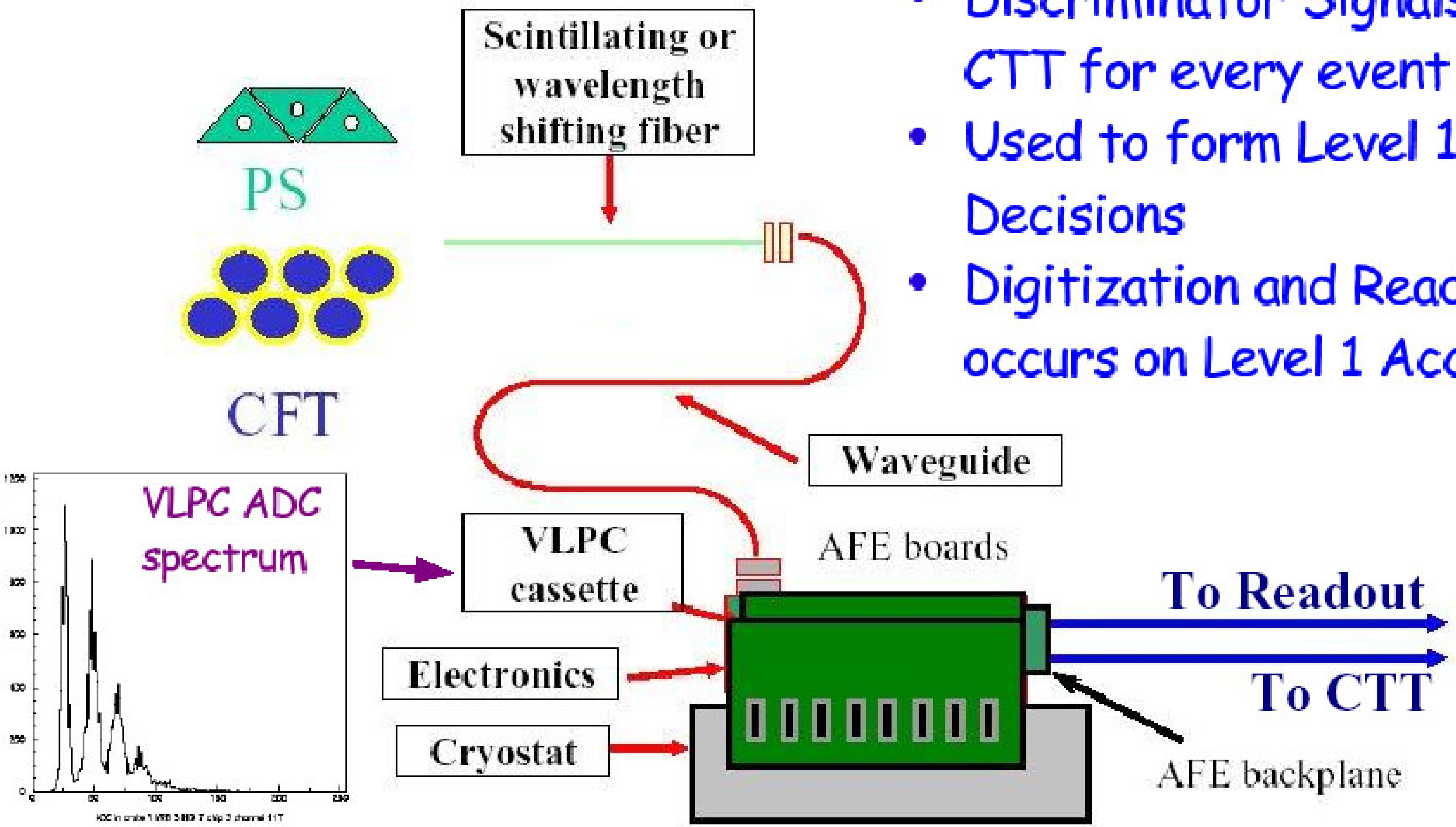
November, 2002

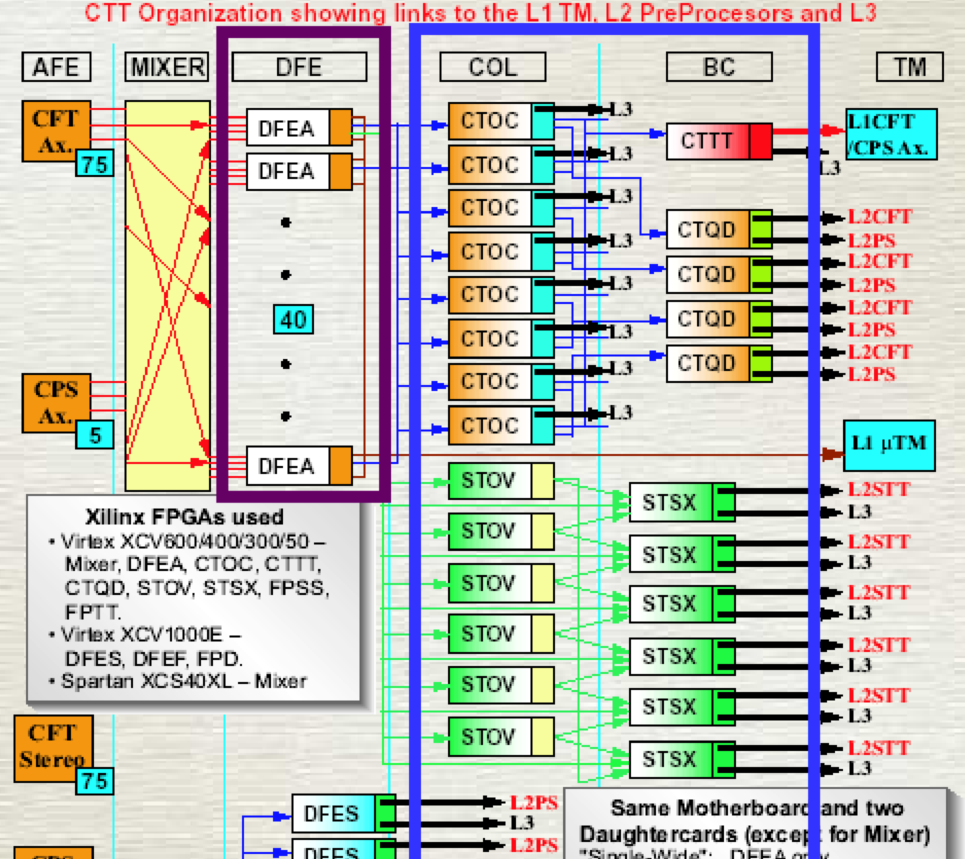
CTT Organization showing links to the L1 TM, L2 PreProcesors and L3



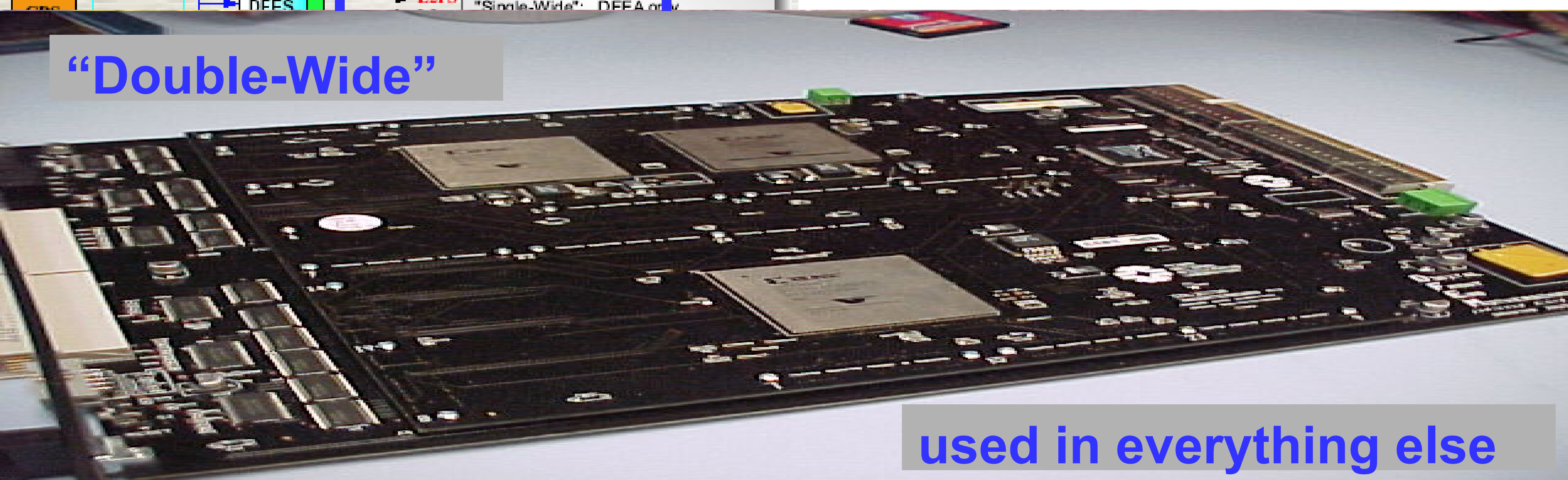
Electronics – Tracking & Triggering with Light

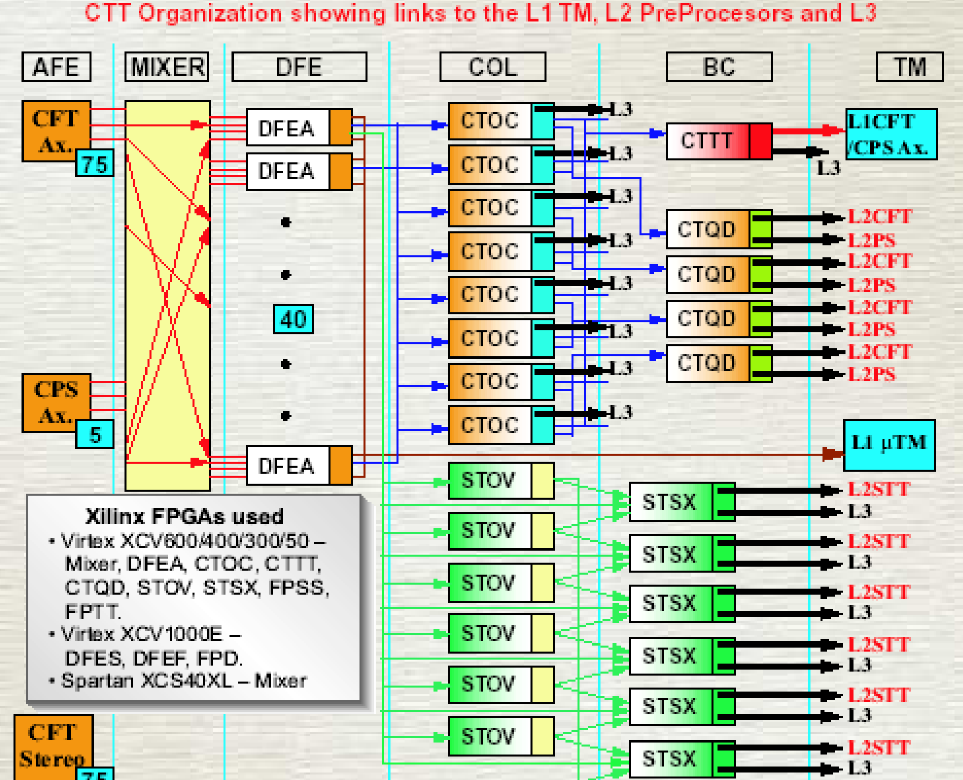
- Discriminator Signals sent to CTT for every event
- Used to form Level 1 & 2 Decisions
- Digitization and Readout occurs on Level 1 Accept

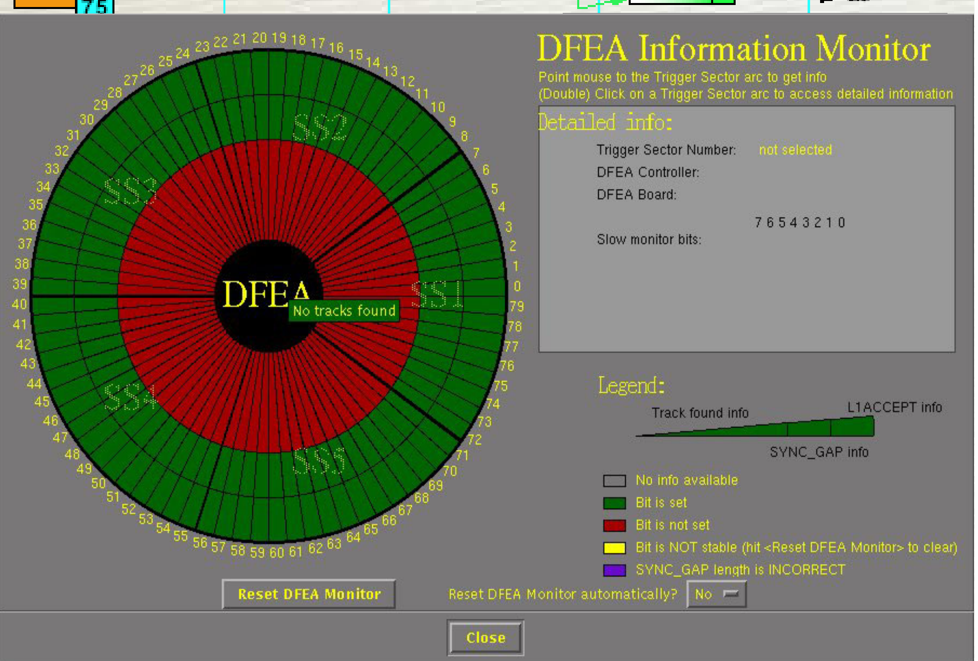




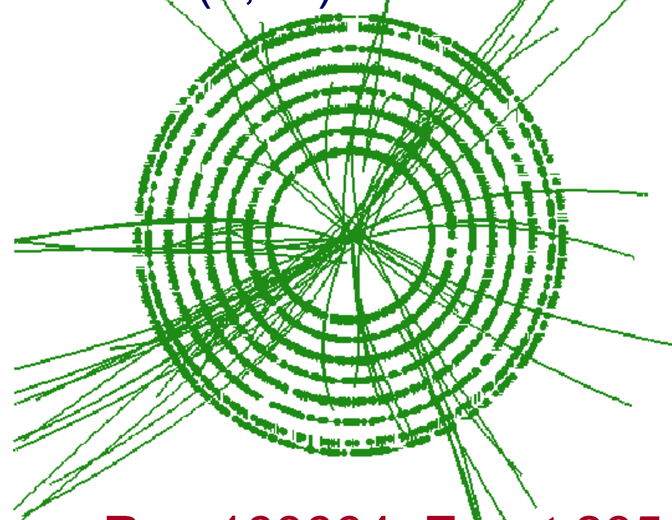
- 100+ digital boards, same platform motherboard
- 2 flavors of daughtercards
  - ➢ "single-wide" – DFEAs only
  - ➢ "double-wide" – everywhere else
- 500+ Xilnix Virtex FPGAs programmed using VHDL



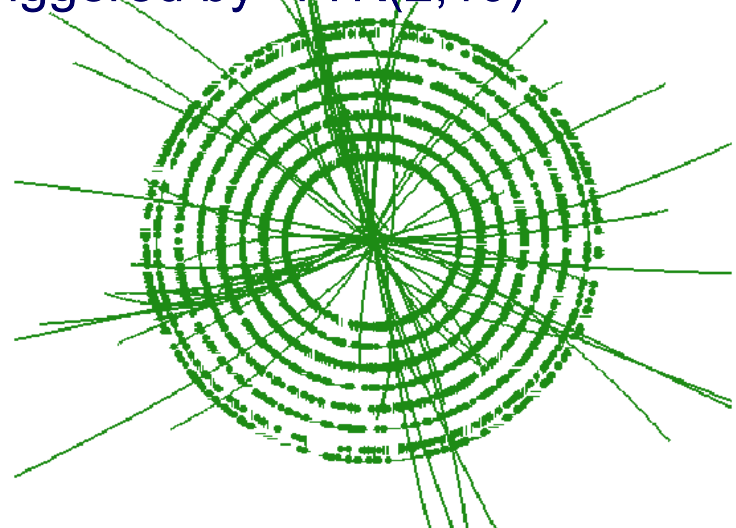




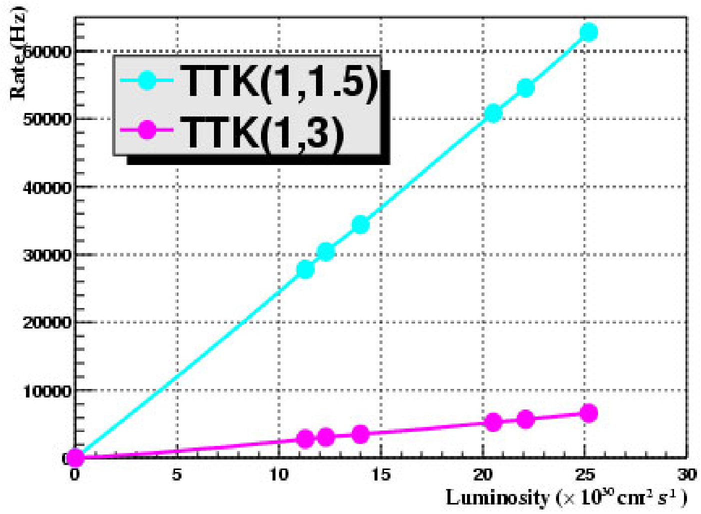
- Run 168664, Event 28548088
- Triggered by TTK(1,10) and TTK(2,10)

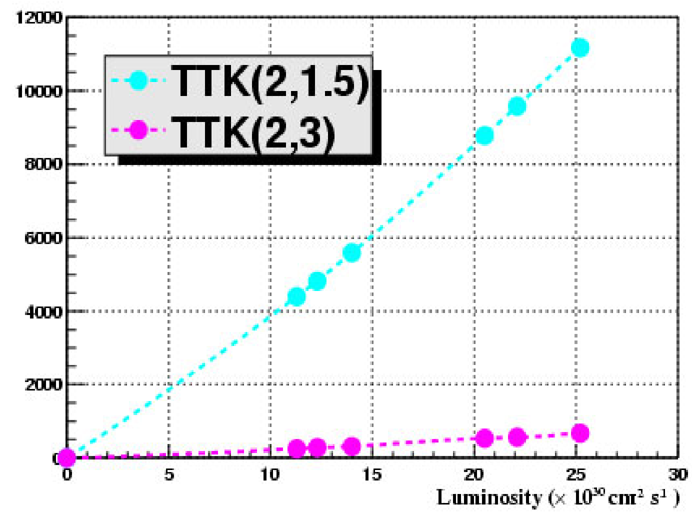


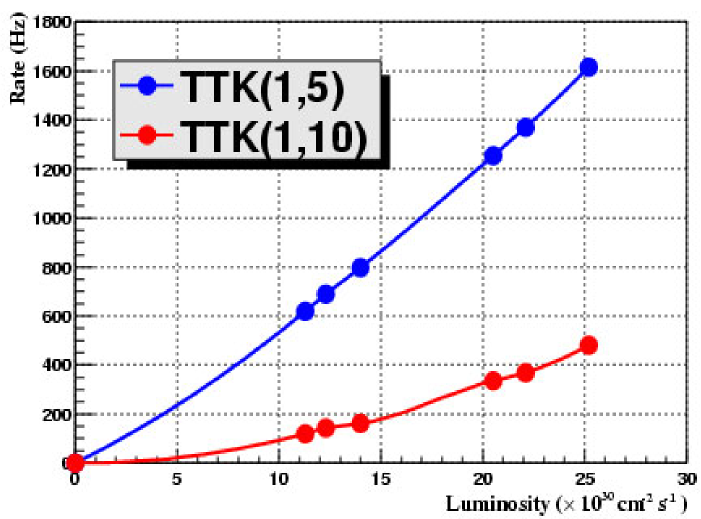
- Run 168664, Event 28548120
- Triggered by TTK(2,10)

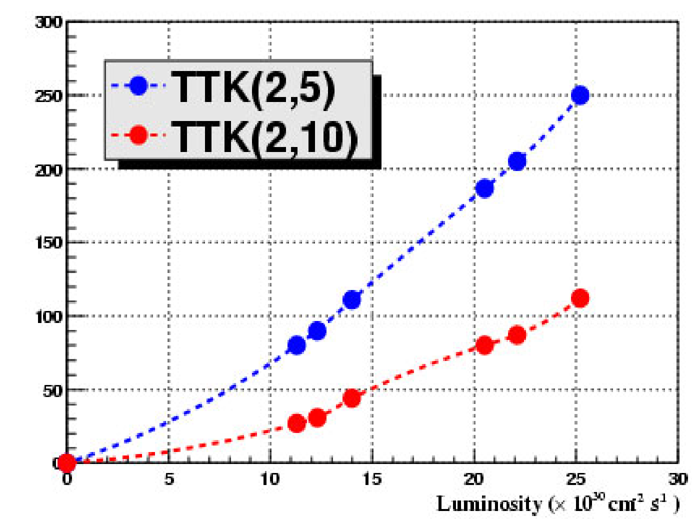


Luminosity Profiles of L1CTT Triggers

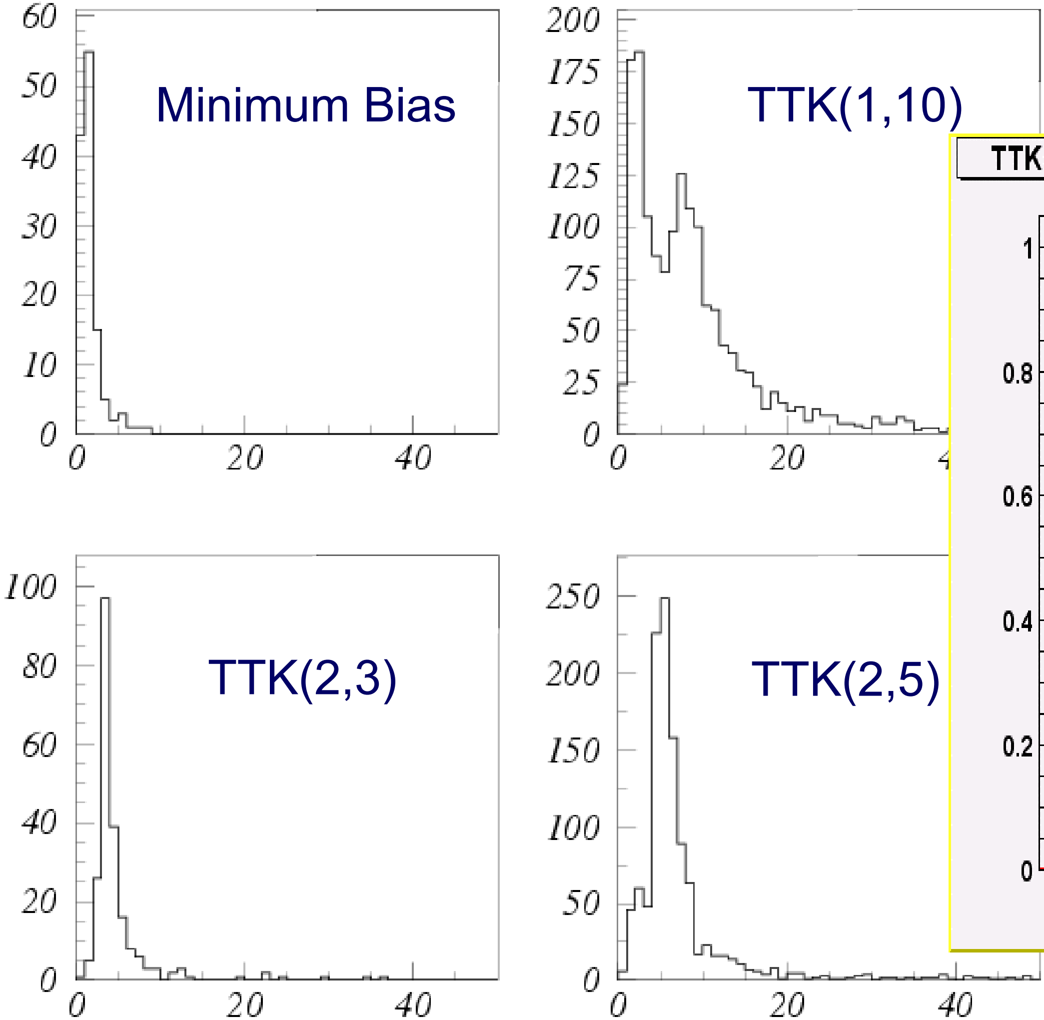




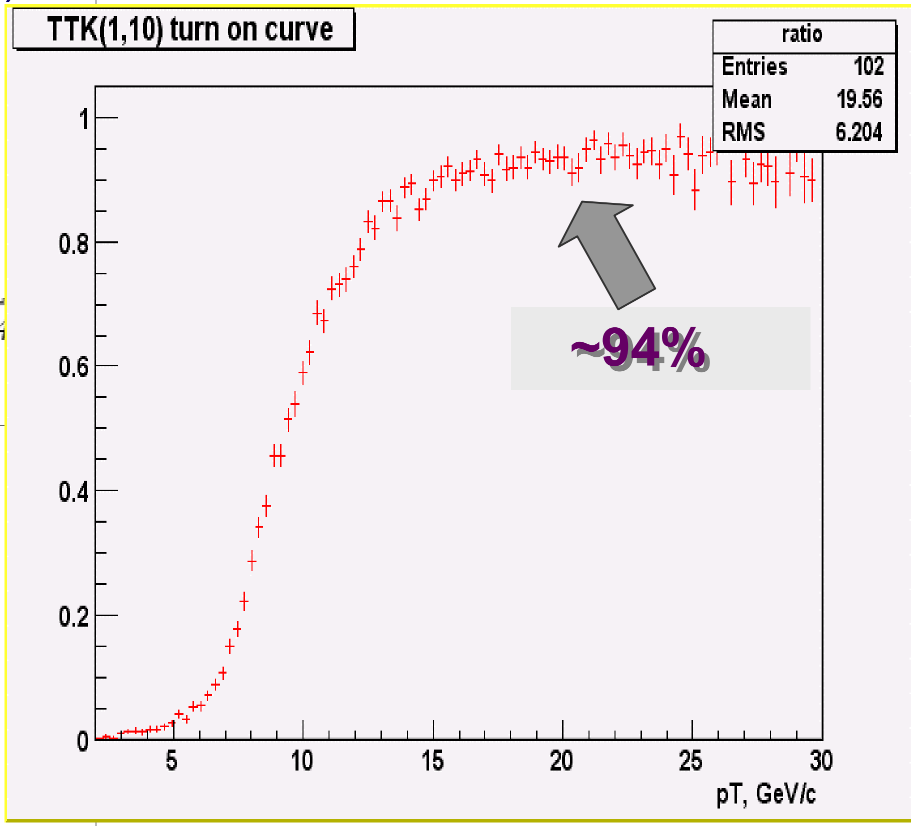




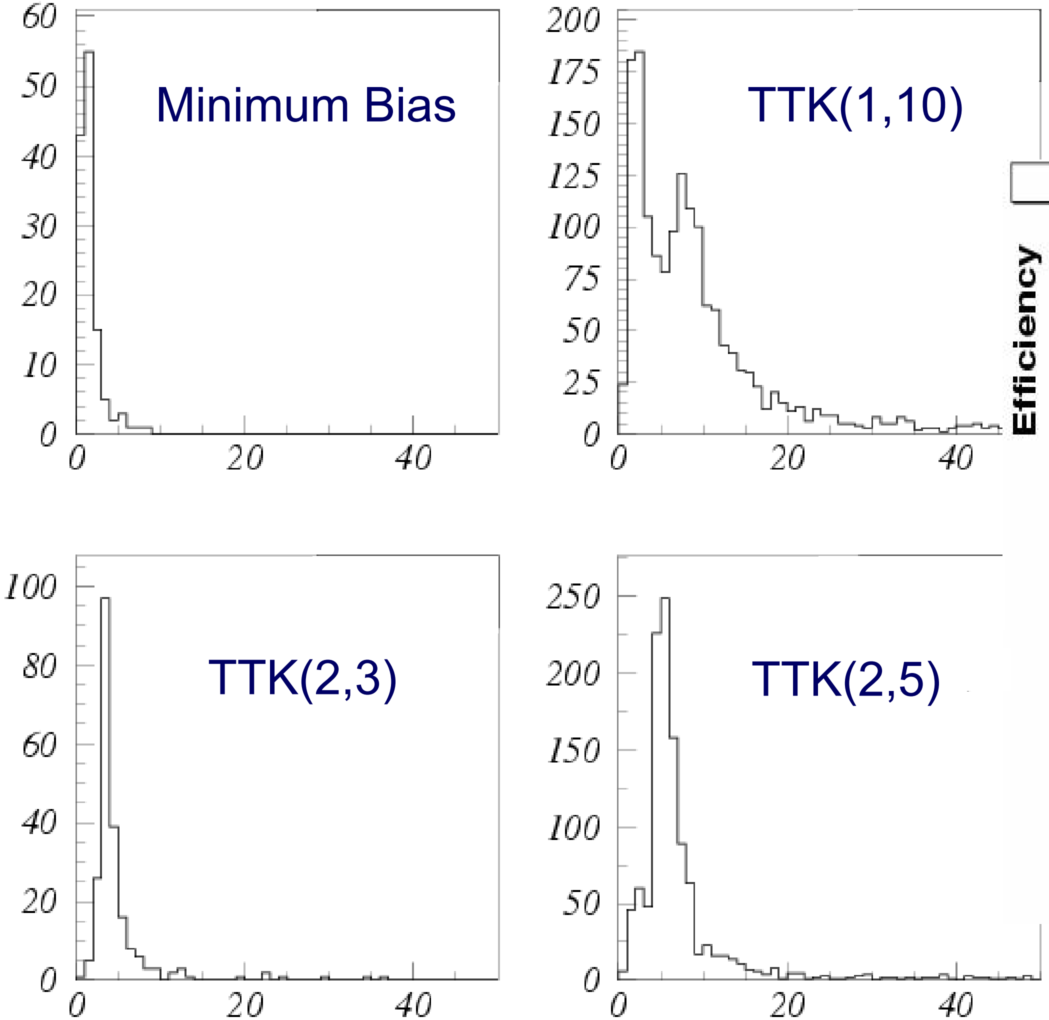
L1CTT at Work



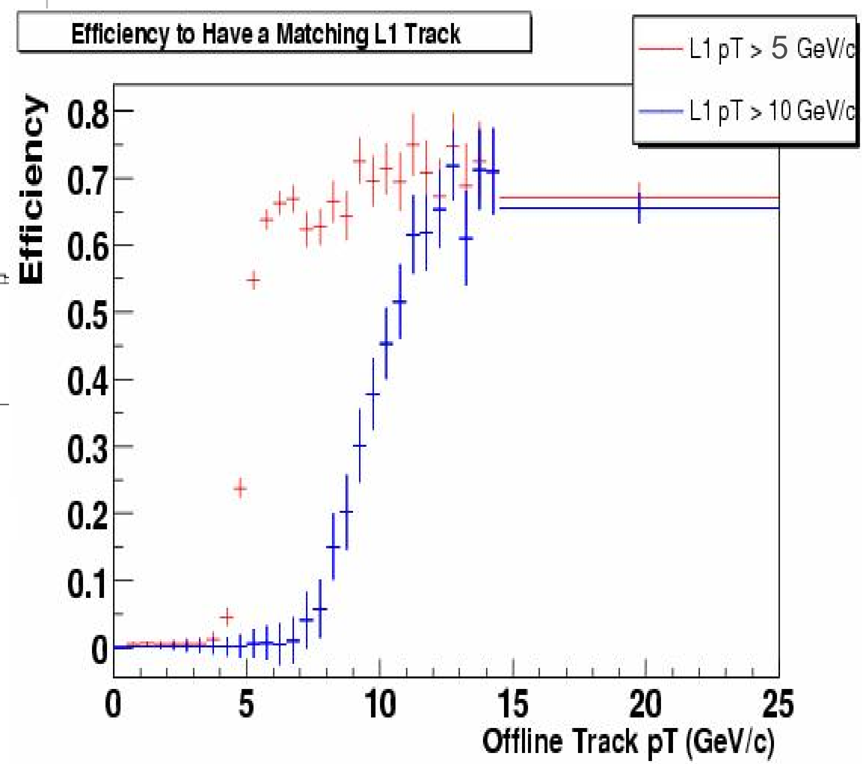
Offline track p_T (GeV)



L1CTT at Work

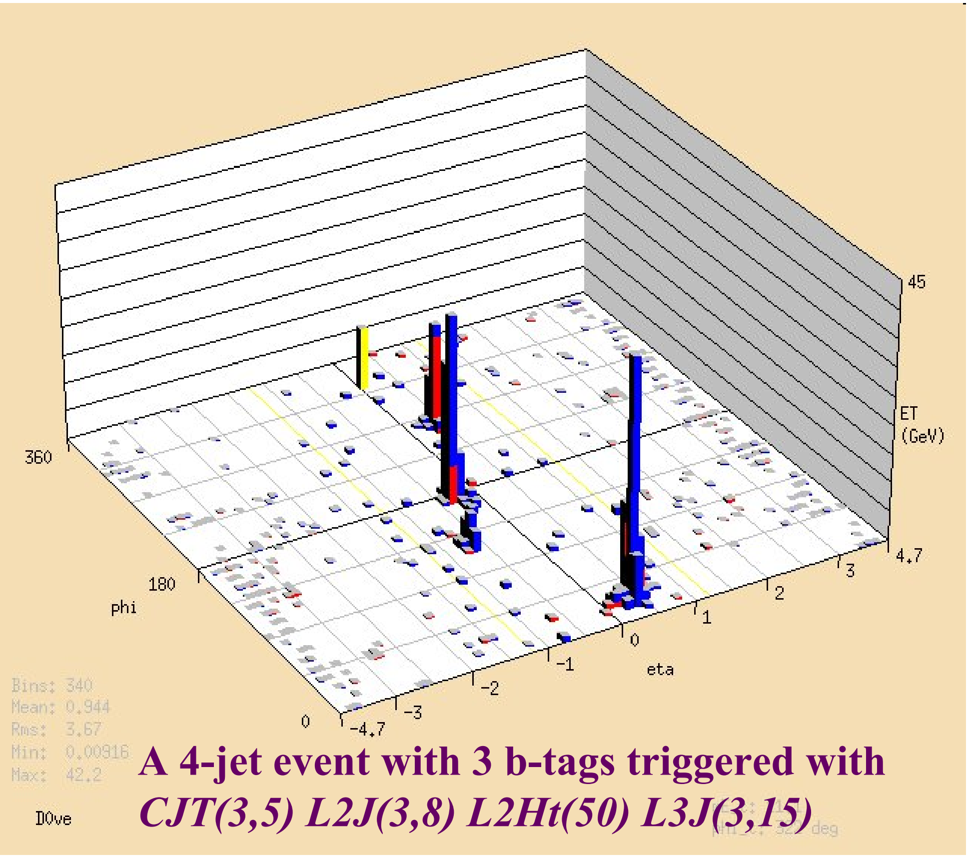


Offline track p_T (GeV)



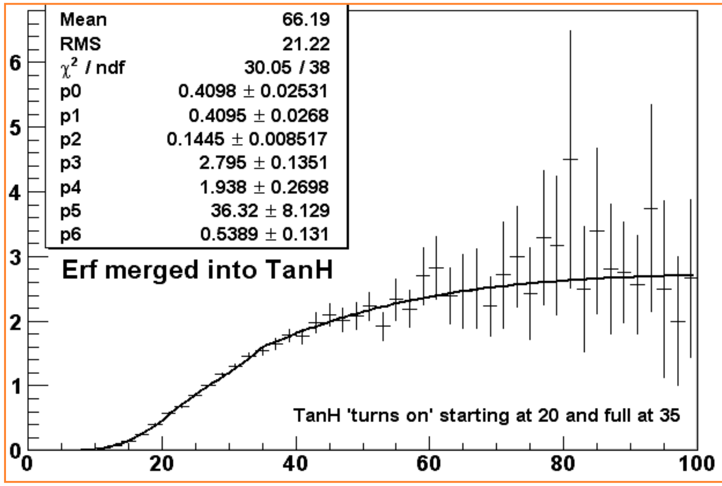
*bb*φ Trigger

- Until displaced vertex trigger in L2 or impact parameter in L3, have to rely on carefully designed mutlijet trigger
  - L1: require three calorimeter trigger towers (0.2×0.2 in $\eta\times\varphi$) to have E_T above 5 GeV
  - L2: require three (0.5×0.5 in $\eta\times\varphi$) jets to have $E_T > 8$ GeV, and also require $H_T > 50$ GeV
  - L3: require two leading jets to have $E_T > 25$ GeV and the 3^{rd} jet $E_T > 15$ GeV; also cut on Primary Vertex z-position
- A lot of detailed work in designing and understanding the trigger at all levels
- Very hard to design efficient trigger for low E_T jets, rate is constantly an issue



A 4-jet event with 3 b-tags triggered with *CJT(3,5) L2J(3,8) L2Ht(50) L3J(3,15)*

Measuring *bbφ* Trigger Efficiency (L1)



Jet 1
Et = 70 GeV
2.3 towers

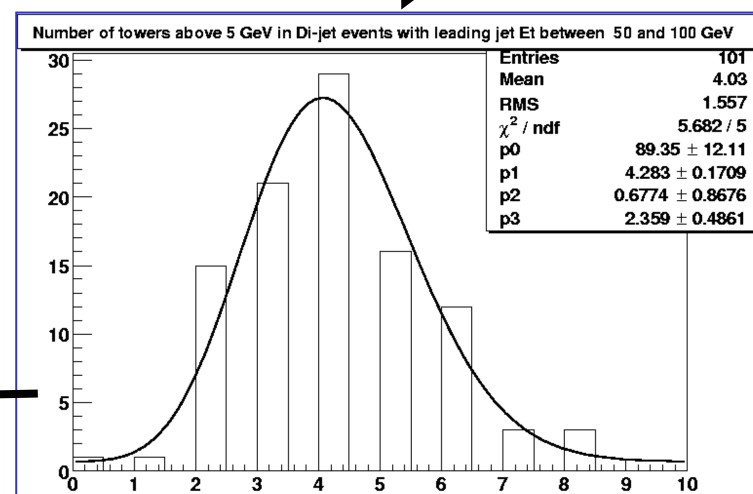
Jet 2
Et = 40 GeV
1.7 towers

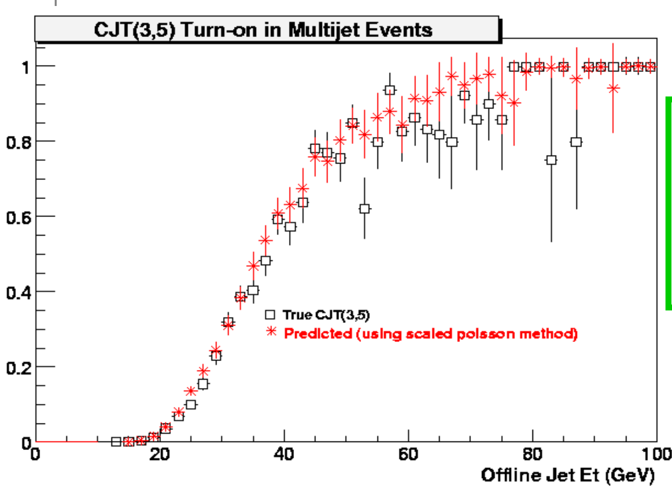
Jet 3
Et = 20 GeV
.65 towers

Total number of towers for event

4.65

- The distribution of the number of trigger towers above threshold is ‘sampled’ to predict the probability of any number of trigger towers to be above threshold





P(1,5) = 92%
P(2,5) = 87%
P(3,5) = 67%

General method, used e.g. in the *ννbb* trigger

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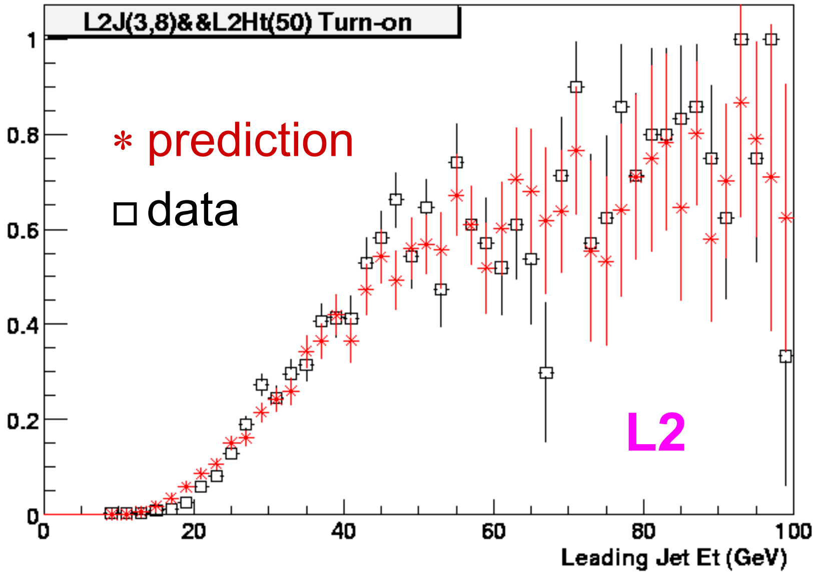
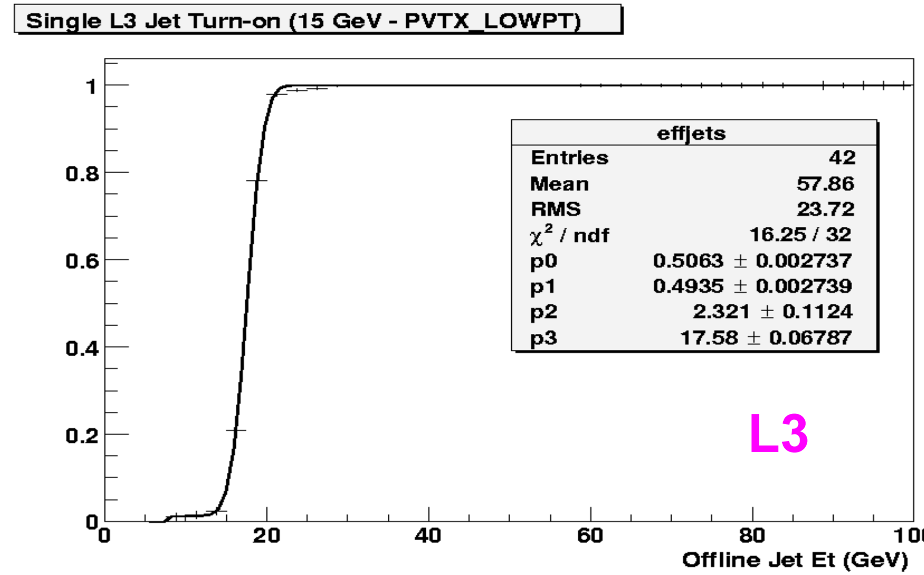
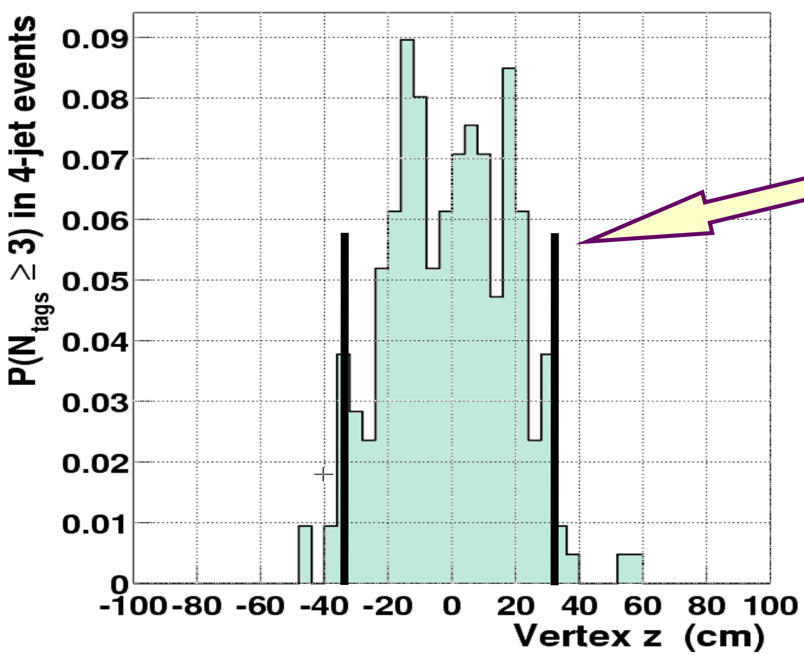
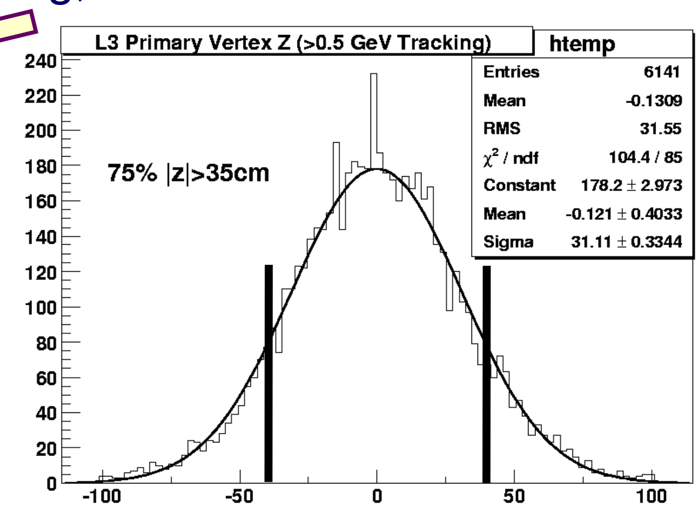
Measuring *bbφ* Trigger Efficiency (L2/L3)







- Studied L3 tracking (b-tagging eventually)
- L3 vertexing, cut outside SMT fiducial



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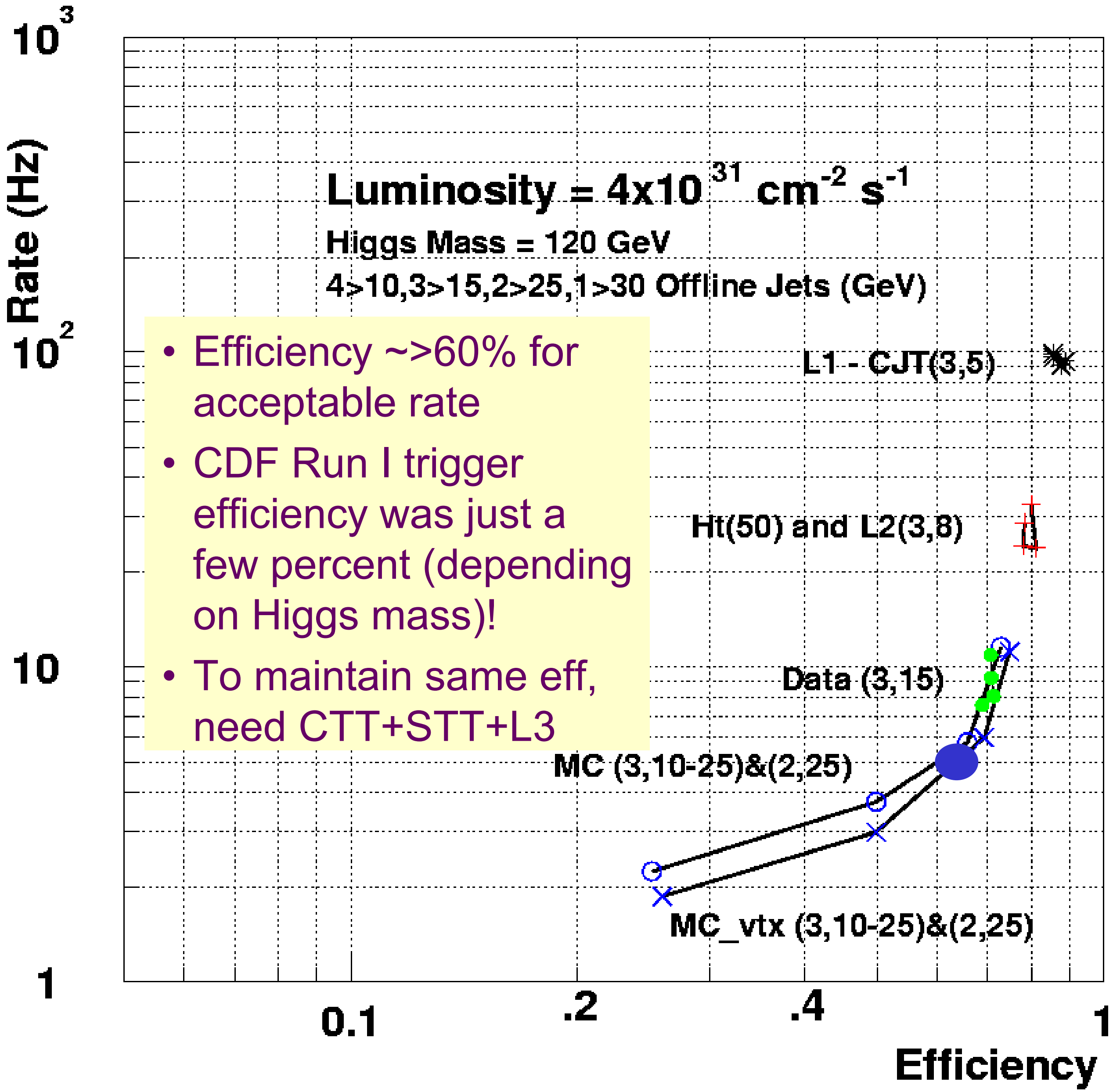
*bb*φ Trigger Efficiency



- Efficiency ~>60% for acceptable rate
- CDF Run I trigger efficiency was just a few percent (depending on Higgs mass)!
- To maintain same eff, need CTT+STT+L3

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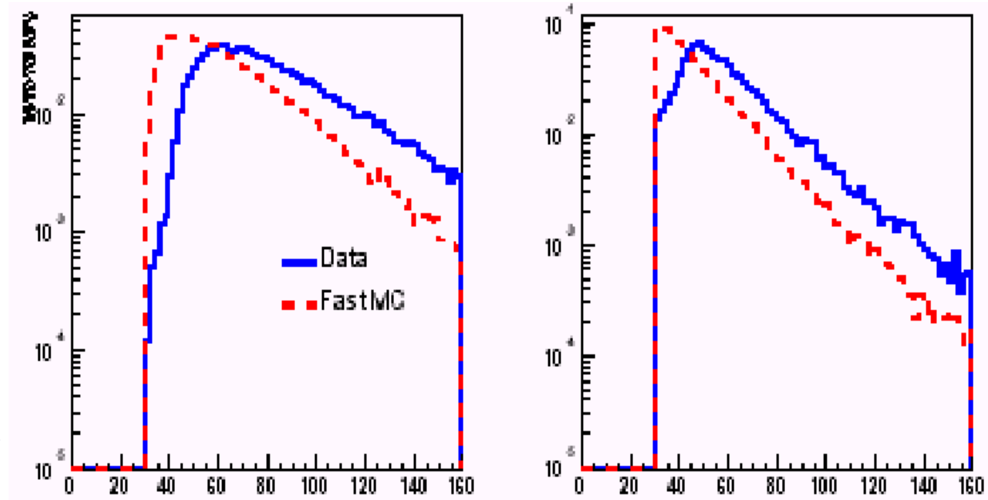
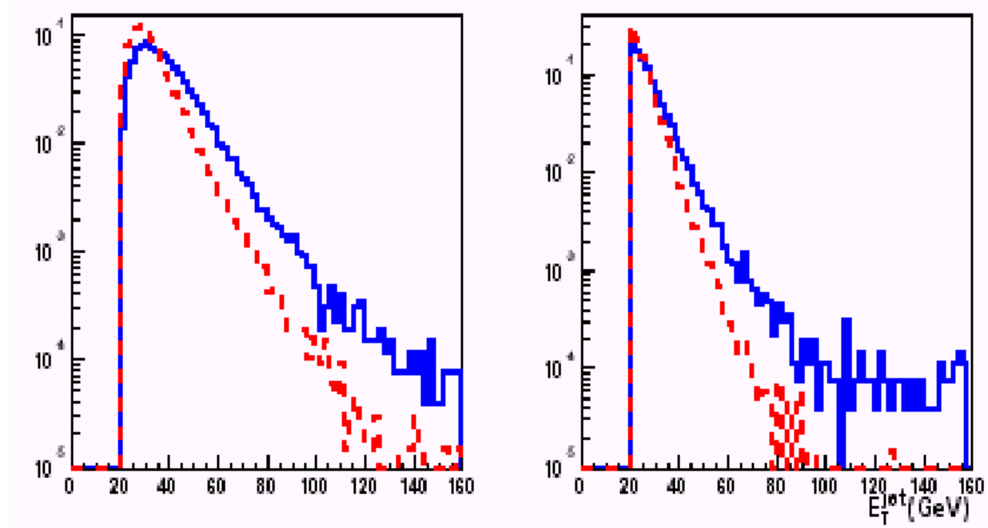
QCD Background (1)

- QCD multijet production with heavy quark content
  - dominant background to SUSY Higgs searches in *bb*h → *bbbb* final states
  - no way to simulate with general purpose event generators
- Di-jet processes
  - get extra jets from ISR+FSR
  - CompHEP/Pythia fail to describe data
- Three-jet processes, e.g. *bbg*
  - in Pythia, still di-jet production; get two *b*'s from flavor excitation or gluon splitting
  - can potentially tune to Tevatron data results on *b* production
- *bb+jj*/*cc*/*bb* four-jet processes
  - CompHEP slow or would bias kinem.
  - ALPGEN by M. Mangano et al.
- Eventually, data driven → require good understanding of *b*-tagging

1st, 2nd, 3rd, and 4th leading jet E_T spectra



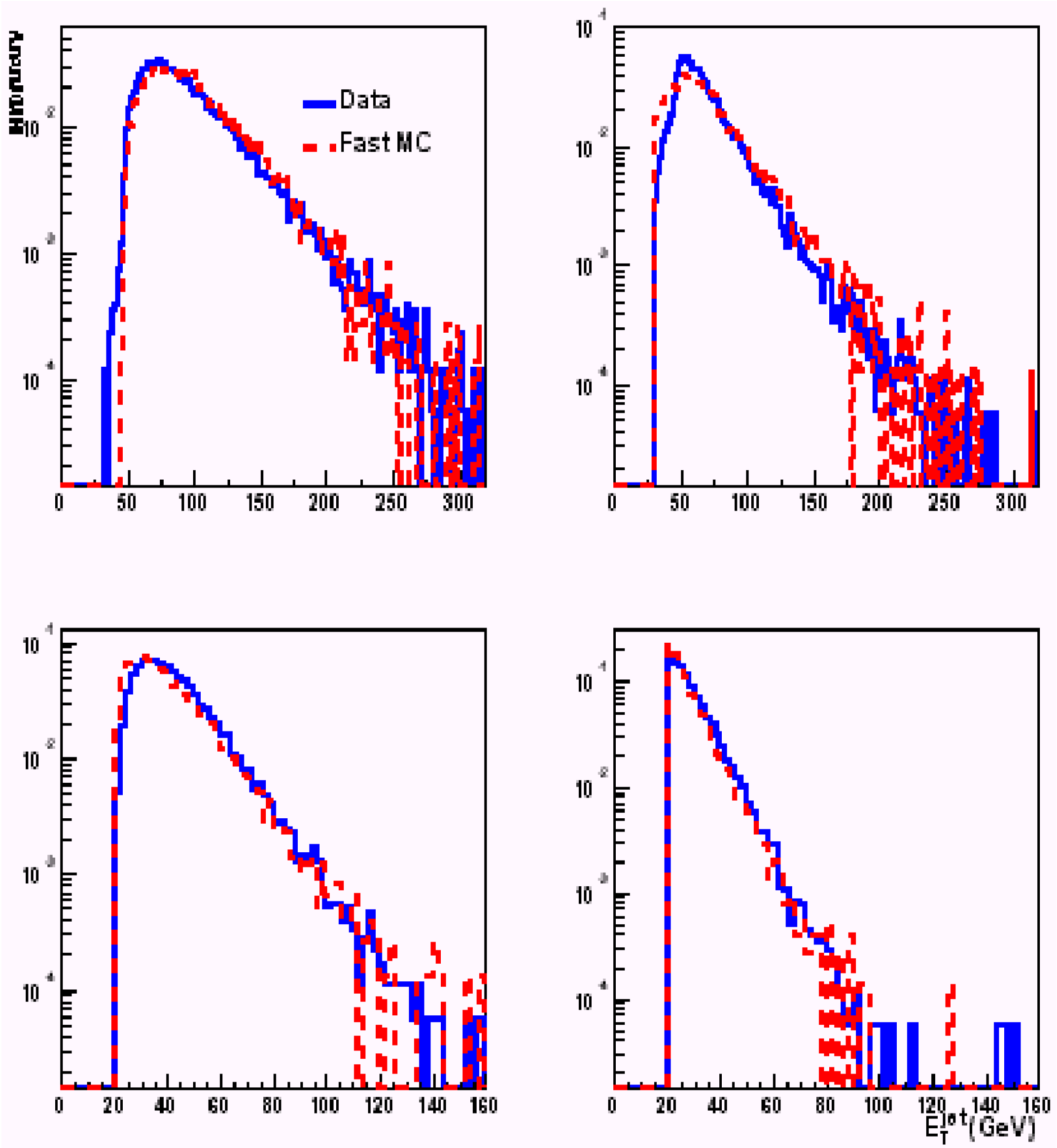
Apply JES correction in data, trigger mix



QCD Background (2)

- Select data with the dedicated *bb*φ trigger
- Apply trigger efficiency turn-on curves measured in data (previous transparencies)
- Fair agreement in jet E_T spectra, (except maybe 2nd jet…)
- Also good agreement in jet η
- Able to use fast MC having checked that it agrees with results from detailed detector simulations
- Also fair agreement in mass spectra of various dijet combinations (except 1st/2nd jet mass)
- Concentrating on *b*-tagging (both offline and in the trigger, L2 and L3) and on determination of QCD background from data

1st, 2nd, 3rd, and 4th leading jet E_T spectra



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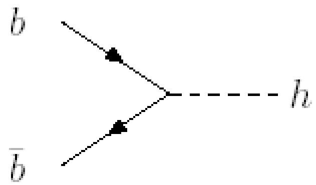
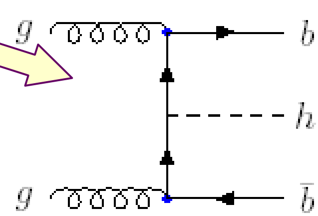
Two *b*'s or not two *b*'s

- Due to recent theoretical advances models with enhanced couplings of Higgs to Beauty even more attractive (see e.g. hep-ph/0204093, 0301033)
- Main production of Higgs in association with *b*'s at both Tevatron and LHC

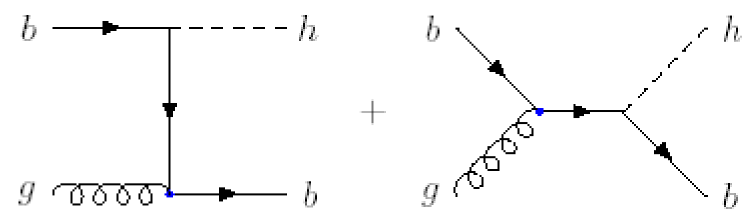


  - use *b*-quark distribution (*b*-quark sea from gluon splitting)
  - no high p_T *b*-quark
  - $h \to \tau\tau$ at Tevatron and LHC
  - $h \to \mu\mu$ at LHC
  - $h \to bb$ overwhelmed by $gg, qq \to bb$
- Should be same as having integrated out *b*'s



- Used to be x10 bigger!

- With a proper choice of $\mu_F = \mu_R \approx m_h/4$ (also motivated by NLO calculations) this problem has been resolved
- Ok to sum collinear logs to all orders via DGLAP equations into *b* distribution
- Require at least one high p_T *b*-quark
  - leading order subprocess $gb \to bh(\to bb)$



  - $h \to \tau\tau/\mu\mu$, *b*-tagged jet to reduce bckg
  - $h \to bb$ gives final states with 3 *b*-quark jets
- Good news is that XS for *bb*h is x3 higher and there also is $gb \to bh(\to bb)$, an order of magnitude higher than *bb*h (bckgs higher too, but S/sqrt(B) might be better – studying now)
- Improves prospects for Higgs discovery with enhanced couplings to Beauty

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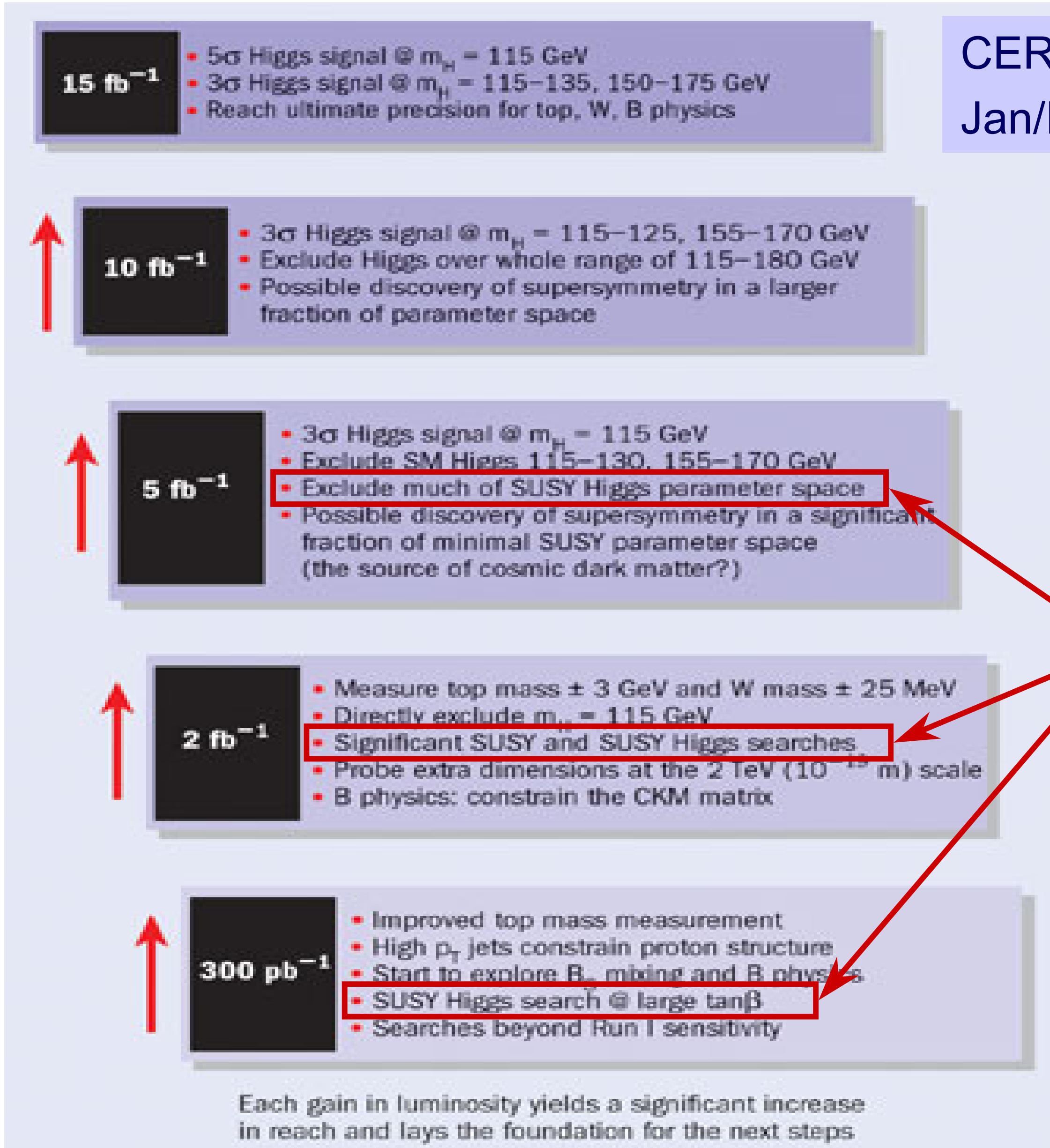
Where in the Bigger Picture?



CERN Currier
Jan/Feb 2003

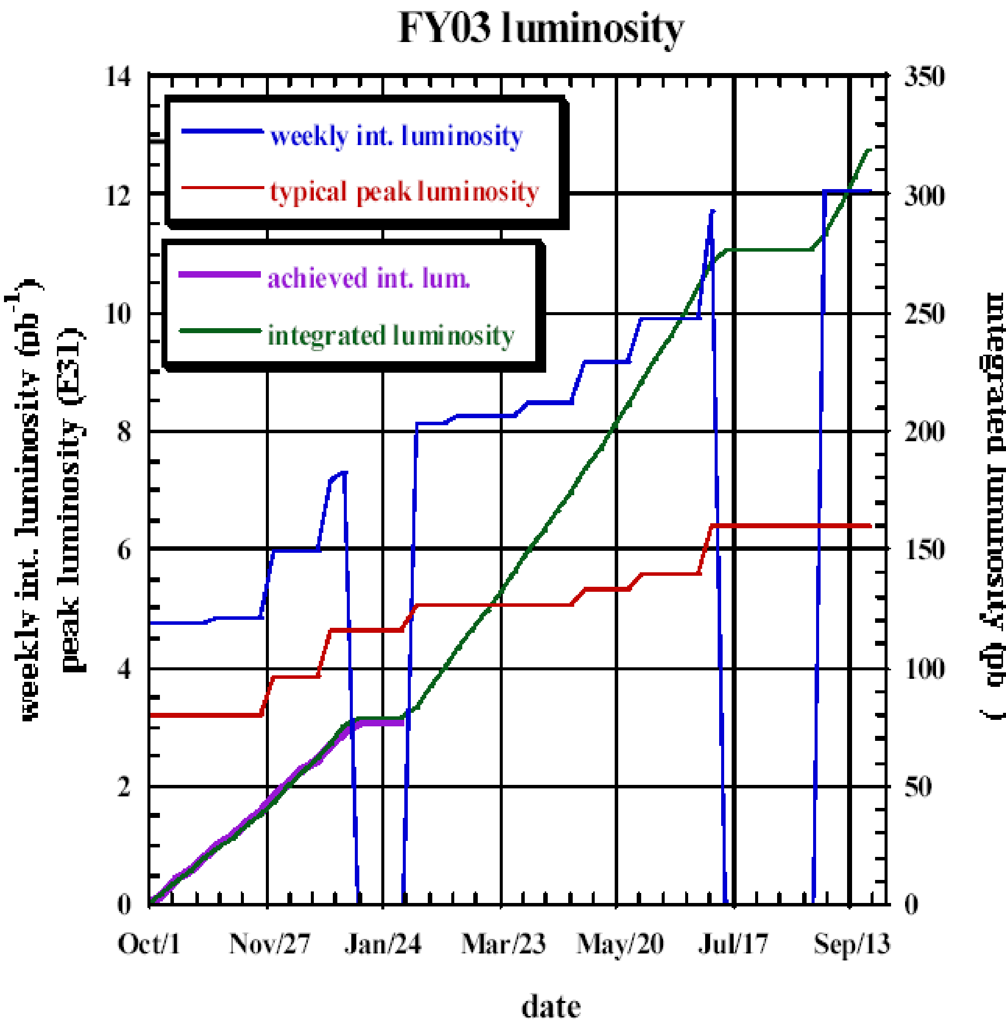
Right here!

Conclusions

- Higgs is the only remaining fundamental puzzle in the Standard Model and its discovery would complete it
- However, many reasons to believe that the SM Higgs is not the end of the story – rather the first window to new physics
  - In the SM, Higgs mass diverges, fine tuning, "scale hierarchy"
  - The SM Higgs potential is just an effective theory of something else
  - Hierarchy of masses indicative of deeper underlying principles
  - Origin of Mass, Mass without Mass, or Mass without Matter, or …?
- Searching for Higgs with enhanced coupling to Beauty at large tanβ particularly attractive at the Tevatron (and LHC)
- DØ is back, Run 2 detector performance is very encouraging, and the SM and beyond-the-SM Higgs searches are well underway
- First new Tevatron results on Higgs to come from the *(b)b*φ channel
- Stay tuned for summer conferences…

FY03 Luminosity Expectations

- Run February to late-July
- Continued running in Fall
- C0 Lambertson replacement
  10% in peak luminosity by 3/1/03
- Accumulator bands 2&3 equalizers
  5% in peak luminosity by 5/1/03
- AP3 beamline
  5% in peak luminosity by 6/1/03
- MI longitudinal dampers
  15% in peak luminosity by 7/1/03
- 6 week shutdown in July-August
  - Recycler vacuum
  - e-cooling civil construction
  - Tevatron collimators
  - NUMI installation work
- Reliability – 1.5%/month in <u>integrated luminosity</u> over 9 months
- Stacking upgrades – 1.5%/month in <u>integrated luminosity</u> over 9 months



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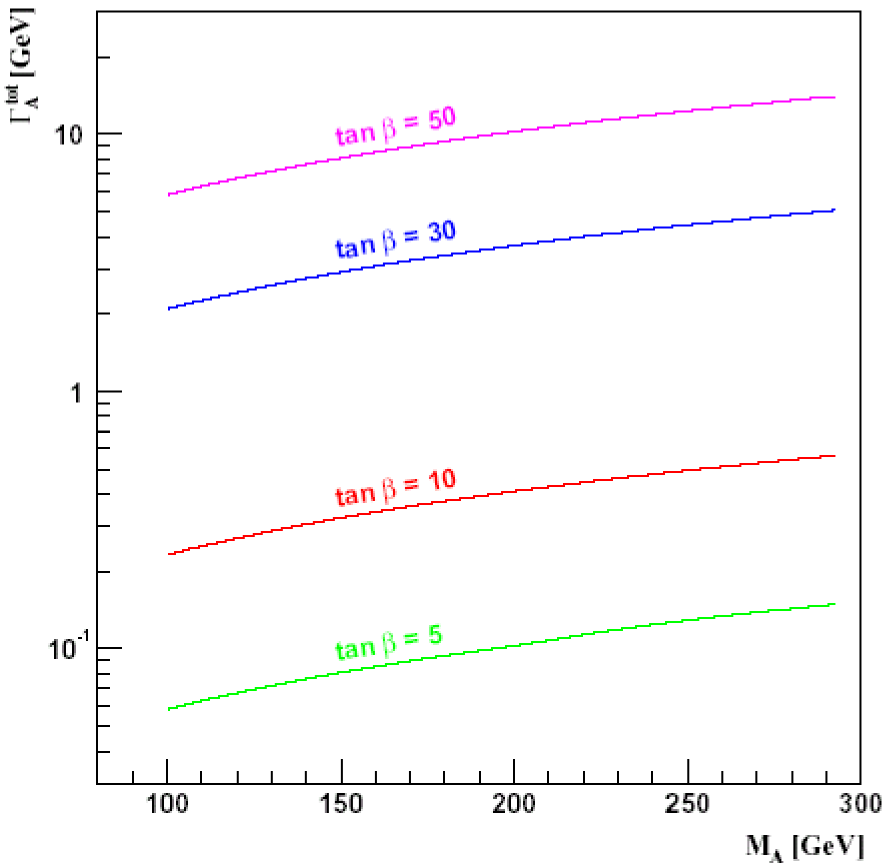
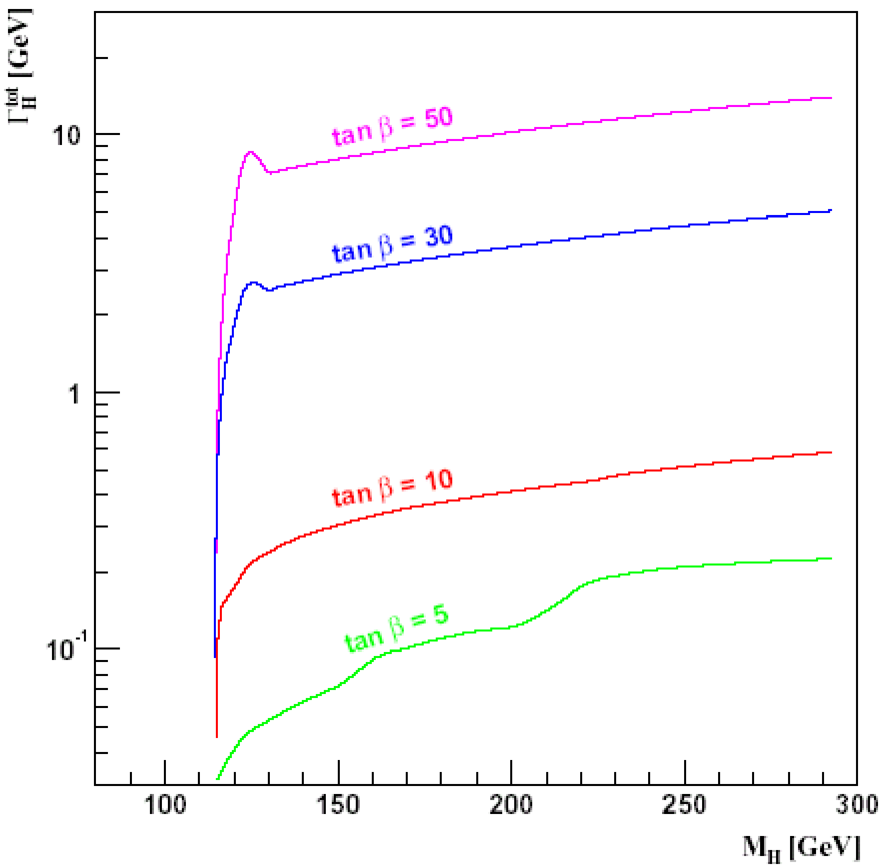
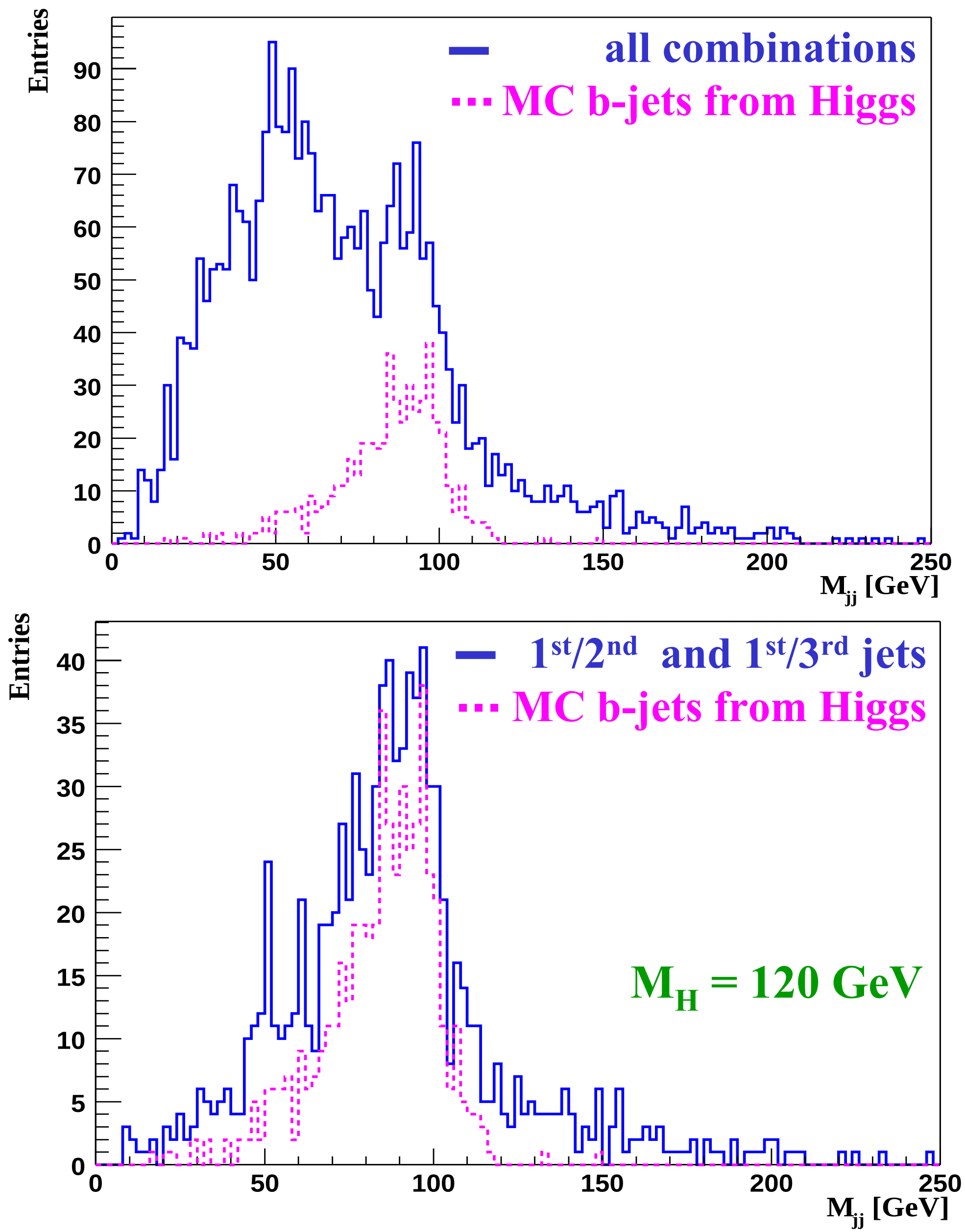
φ Width


Γ_A^{tot} [GeV]
10
1
10^{-1}
tan β = 50
tan β = 30
tan β = 10
tan β = 5
100
150
200
250
300
M_A [GeV]


Γ_H^{tot} [GeV]
10
1
10^{-1}
tan β = 50
tan β = 30
tan β = 10
tan β = 5
100
150
200
250
300
M_H [GeV]

Higgs Mass Reconstruction



Kinematic cuts:

- **1st & 2nd jets –**
  E_T > 30 GeV, $|\eta|$ < 2
- **3rd & 4th jets –**
  E_T > 15 GeV, $|\eta|$ < 2.5

1st/2nd and 1st/3rd hardest jets invariant mass selects 50-60% of the signal

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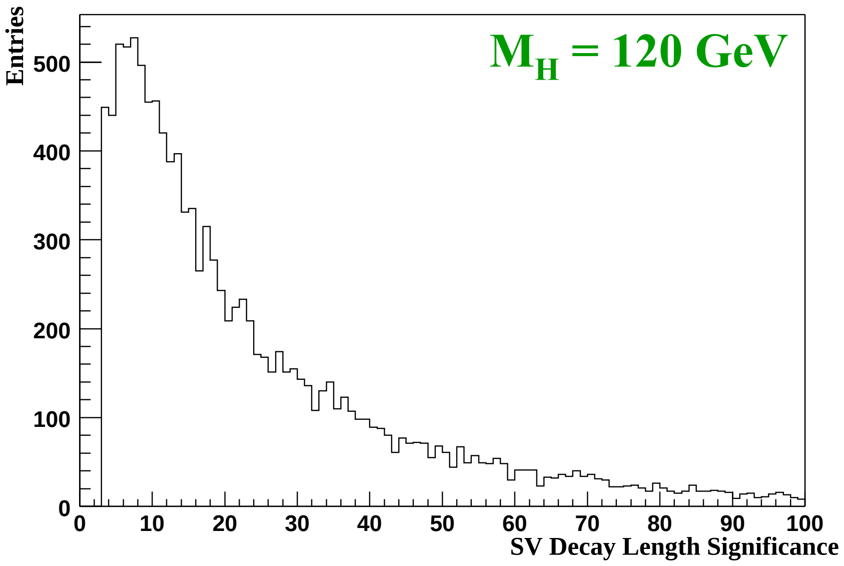
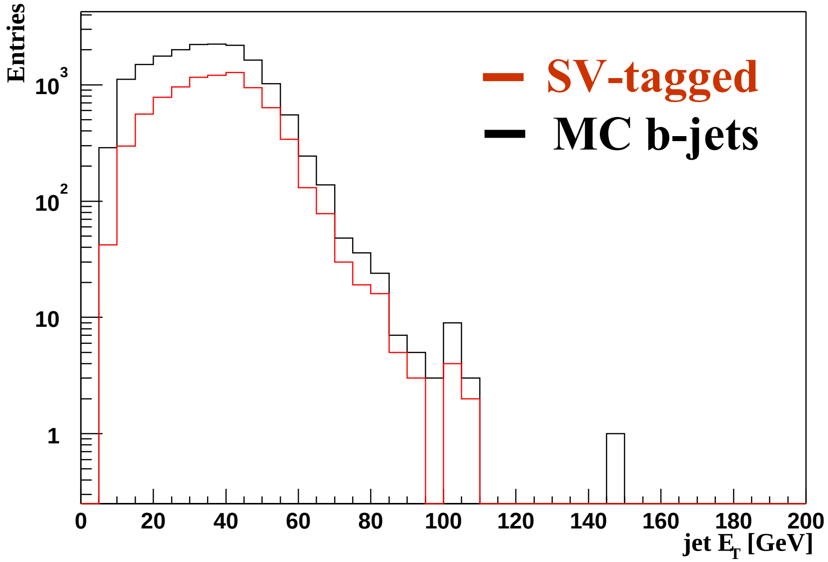
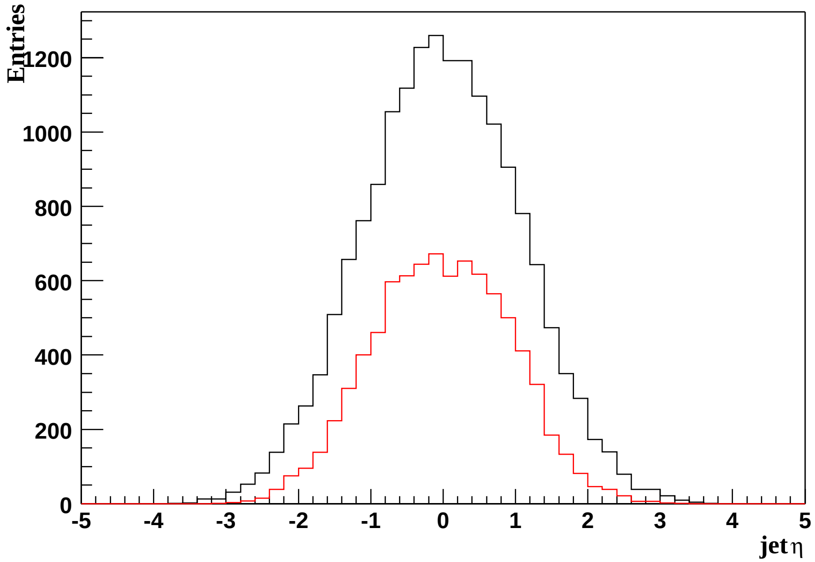
Secondary Vertex Tagging

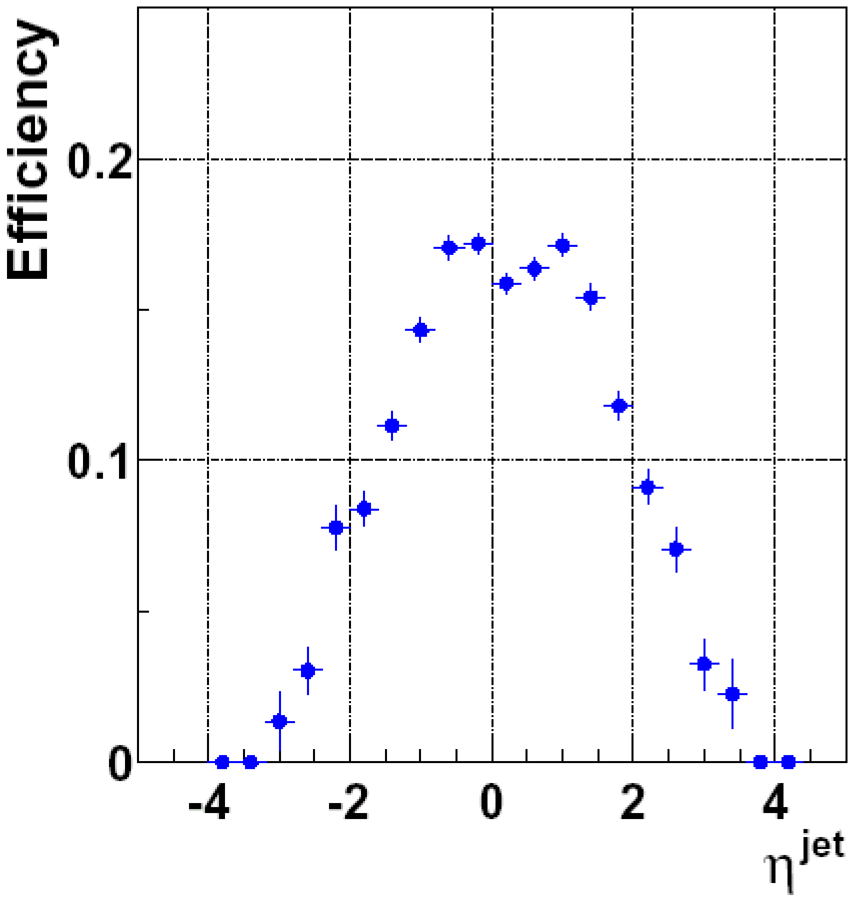
- Long *b* lifetime ($\tau_b \sim 1.6$ *ps*) and many decay products (several charged tracks) allow for *b*-quark tagging using detached vertex
- Secondary vertices (SV) found using Kalman filter algorithm, require Decay Length Significance $\equiv L/\sigma_L > 3$
- Tag jets within ΔR of 0.3 of SV's

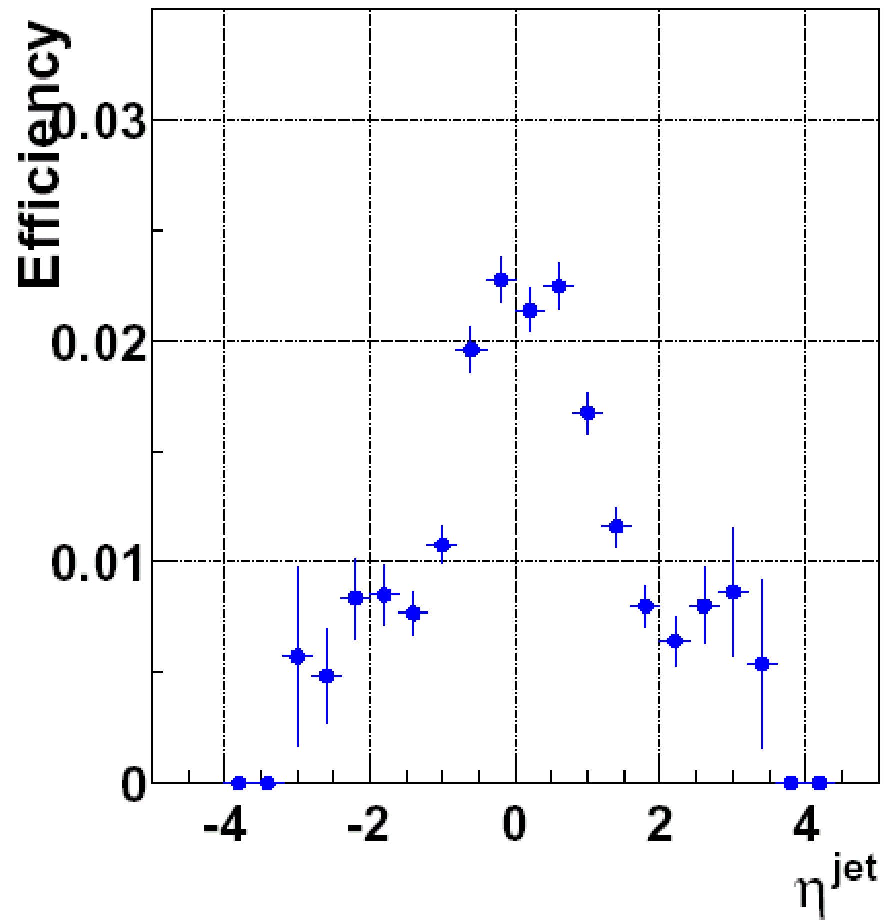






c/light-quark mis-tagging in eta





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QCD Background (3)

1st, 2nd, 3rd, and 4th leading jet η