RESULTS FROM THE TEVATRON AND THE LHC

(*EXCEPT FOR RESULTS THAT RELATE TO THE HIGGS*)

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CTEQ Summer School

OUTLINE

- The Accelerators
- The Detectors
- The Physics Programs
  - Today: Five Measurements
- Tomorrow:
  - Surprises
  - Searches
  - The Informed Scientific Citizen
    - How to possibly keep up with all of this?

THE ACCELERATORS
TEVATRON - LHC

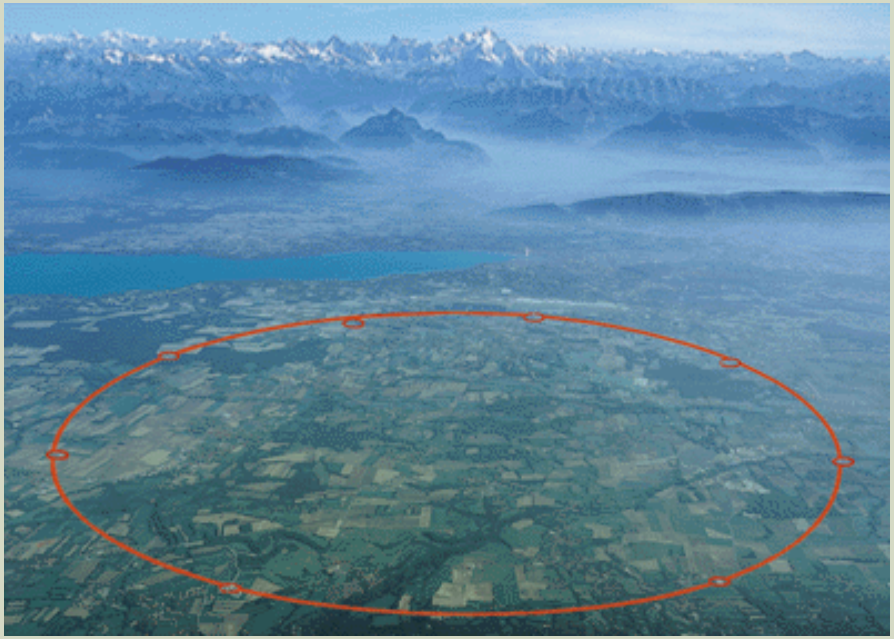
TeVatron

The LHC
(*Large Horrible Catastrophe*)

THE ACCELERATORS
TEVATRON - LHC

TeVatron

The LHC
(*Large Hadron Collider*)

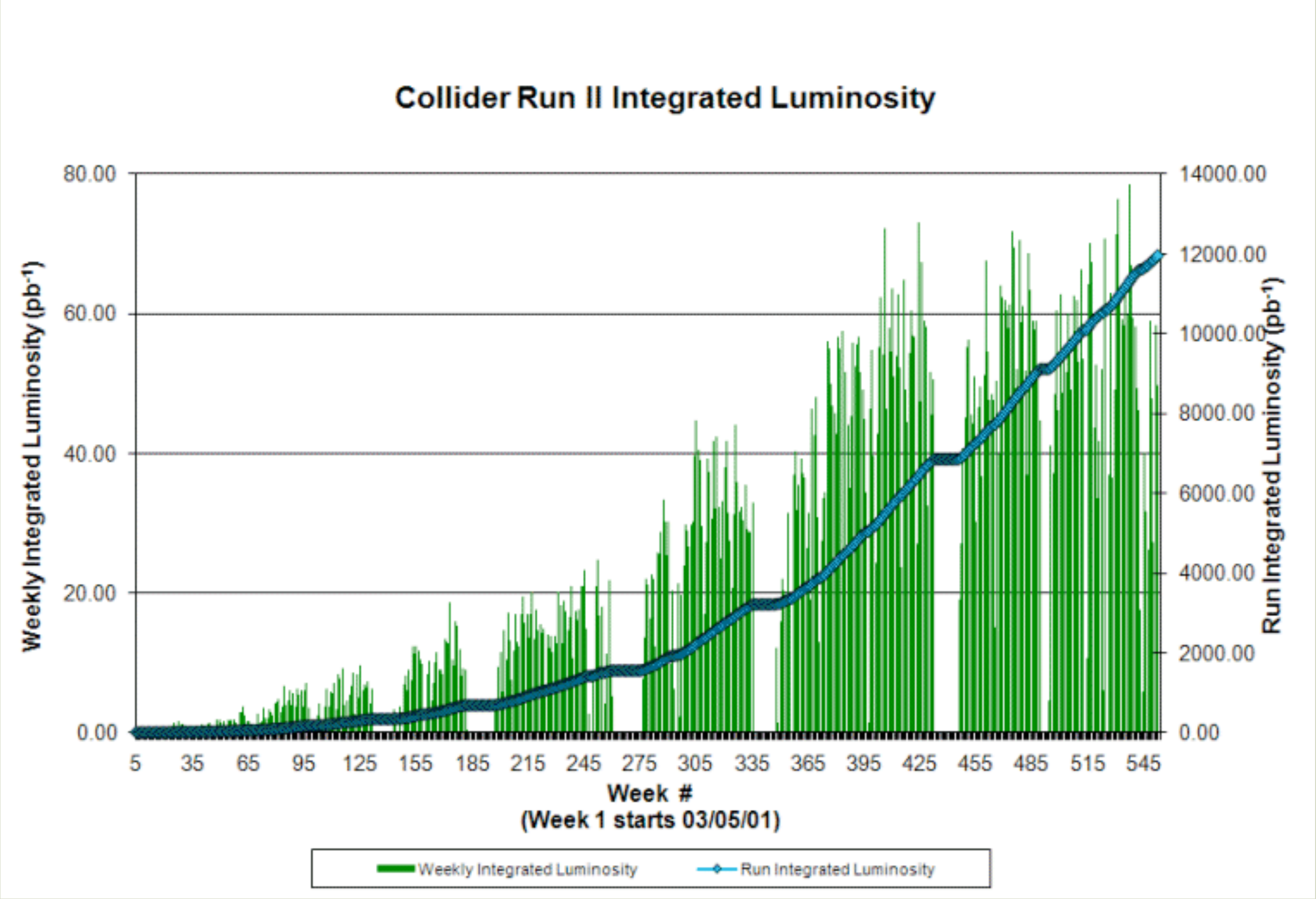


ACCELERATORS

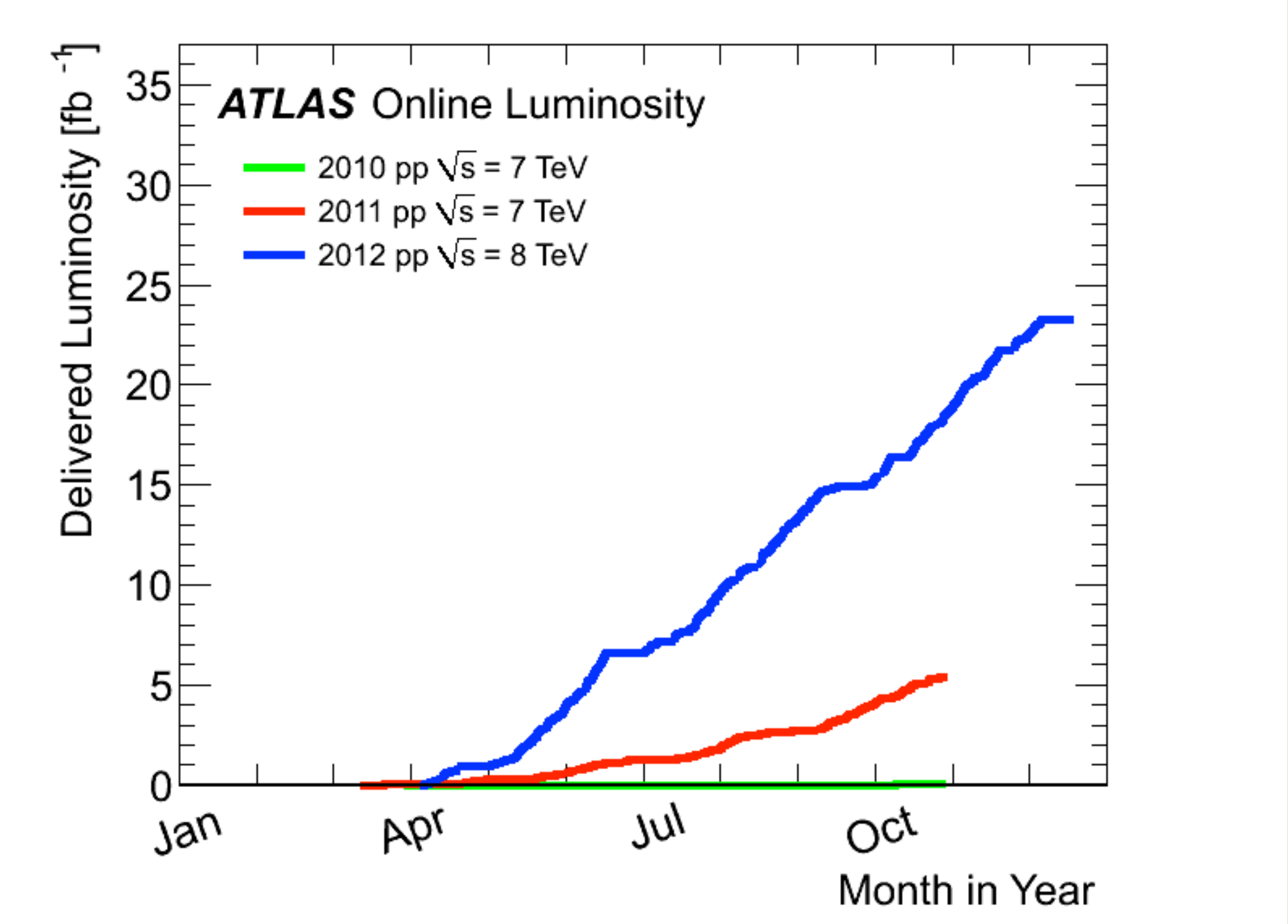
- proton beam: ~1 MJ
- diameter: 2π km
- Center of Mass Energy: 1.96 TeV
- proton, anti-proton collisions

- beam: ~350 MJ
- diameter: 27 km
- Center of Mass Energy: 7, 8 TeV (13?)
- proton-proton collisions

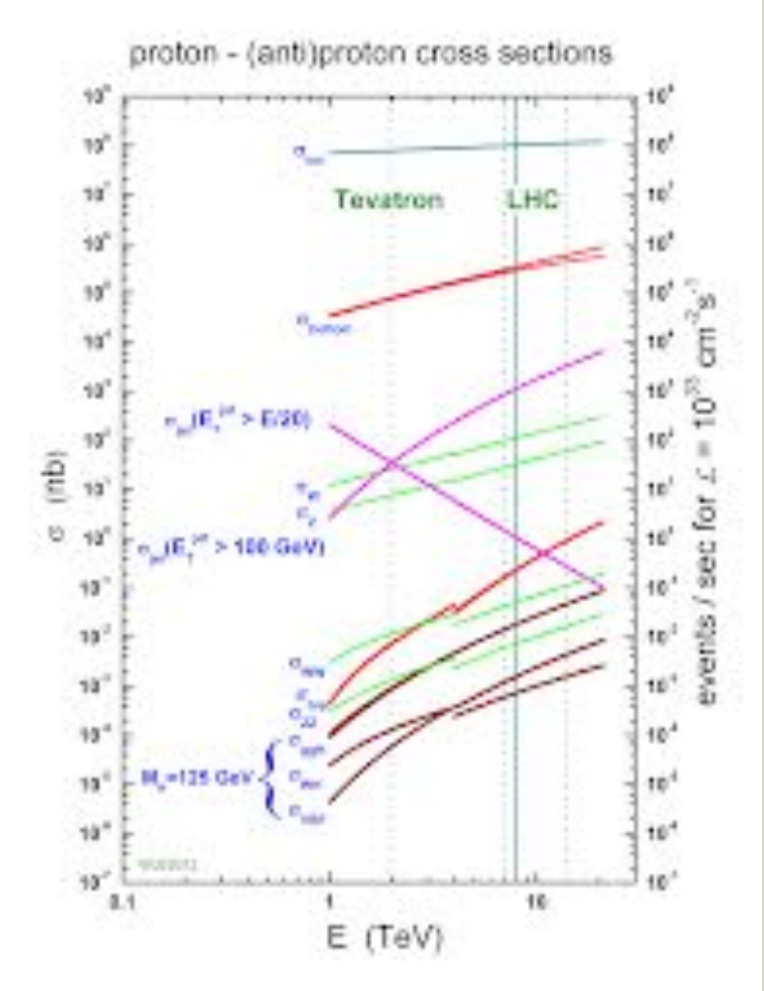
(A DECADE OF) TEVATRON PERFORMANCE



LHC PERFORMANCE (+ ATLAS)

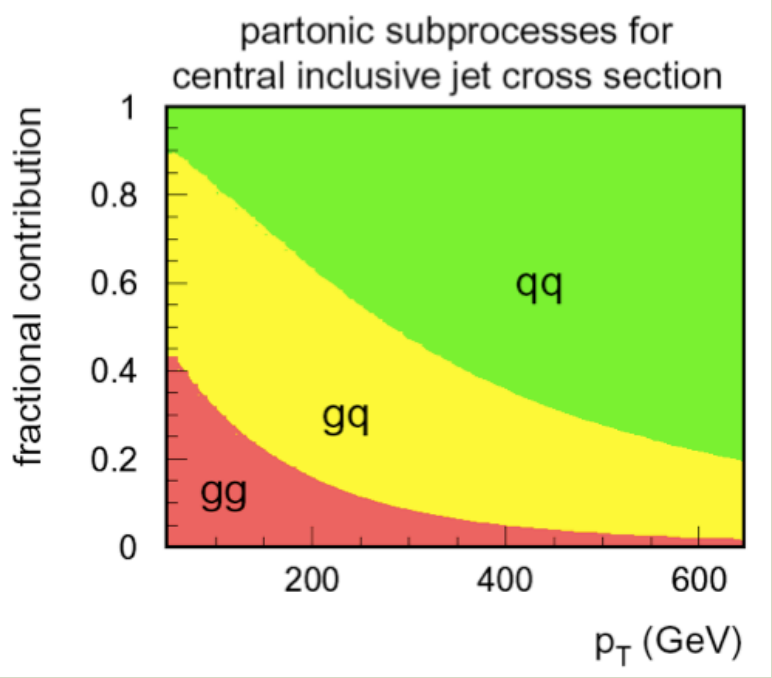


CROSS SECTIONS VS. ENERGY



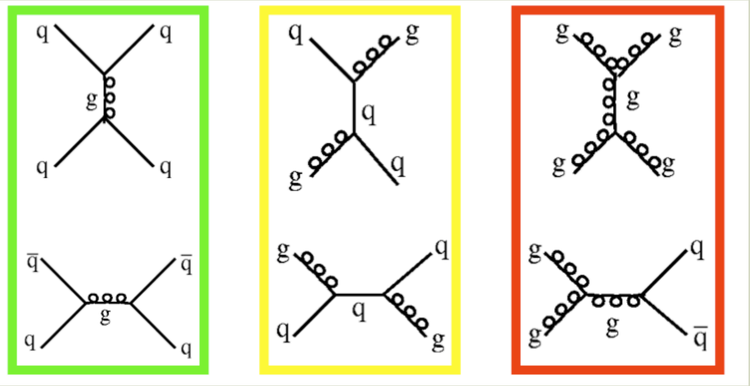
PARTONS CONTRIBUTING TO CROSS SECTION

TeVatron (*S. Bentvelsen*)

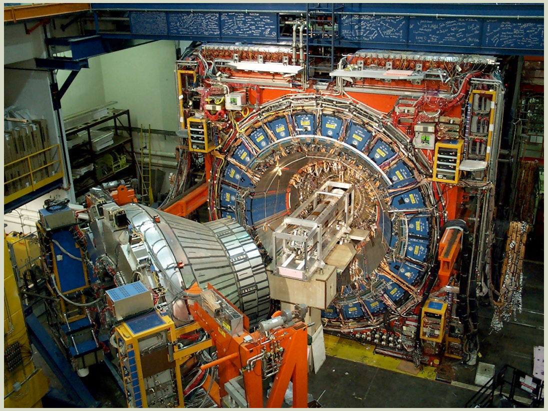


TeVatron physics
quark dominated

LHC physics
gluon dominated

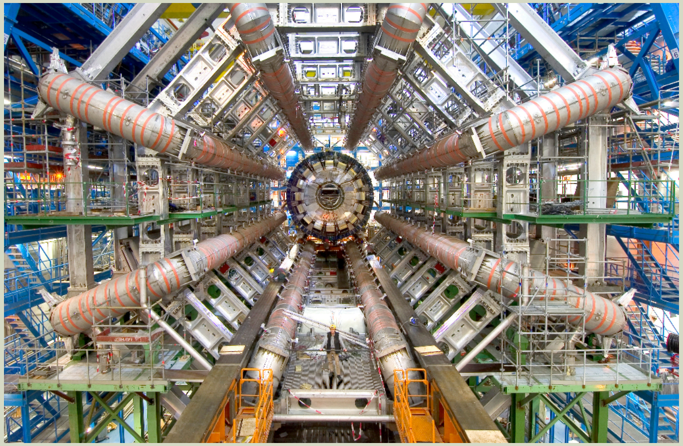


THE DETECTORS



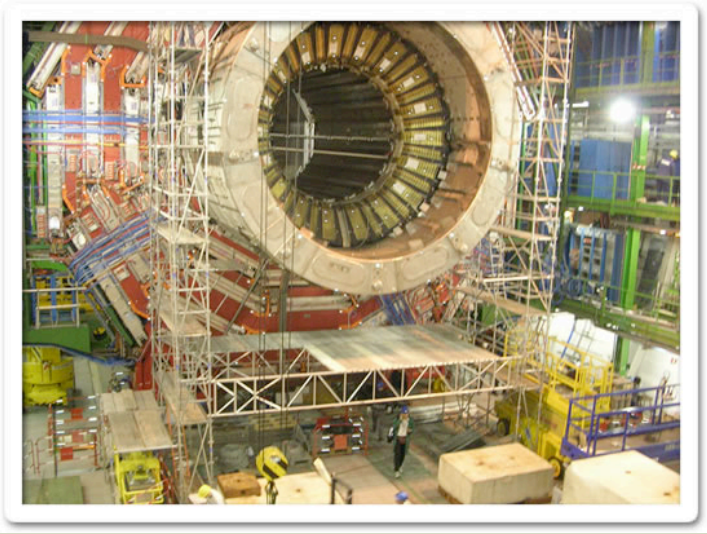
CDF

ATLAS

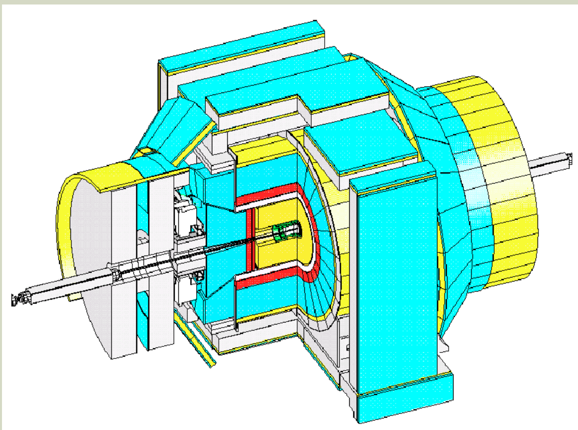


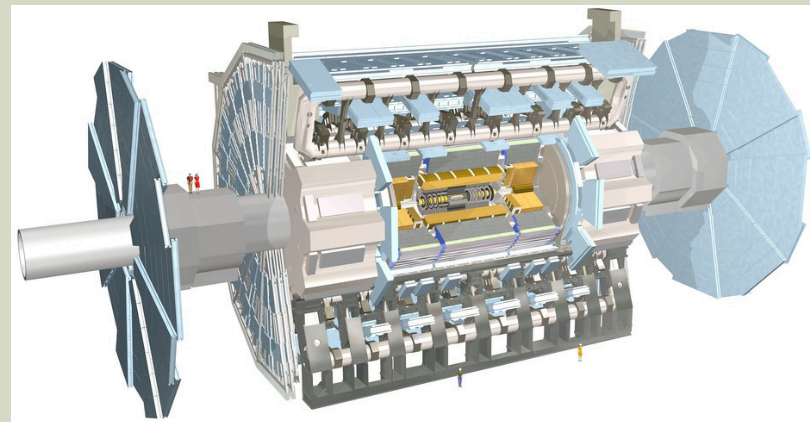
DO

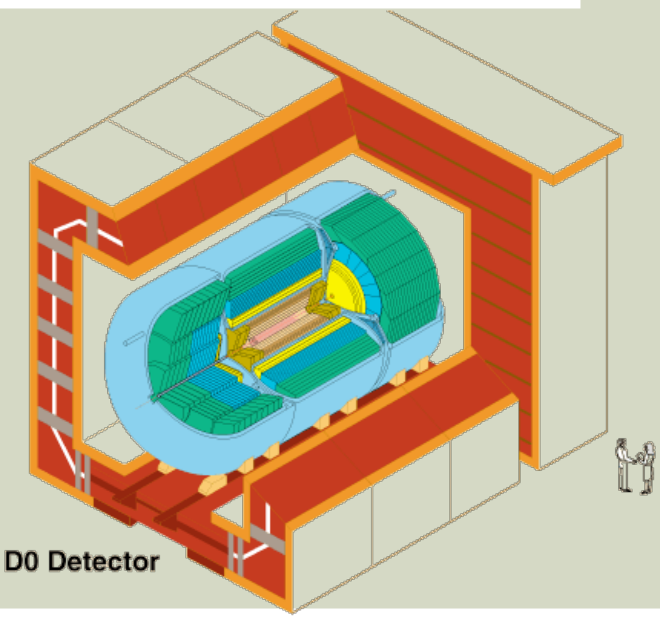
CMS

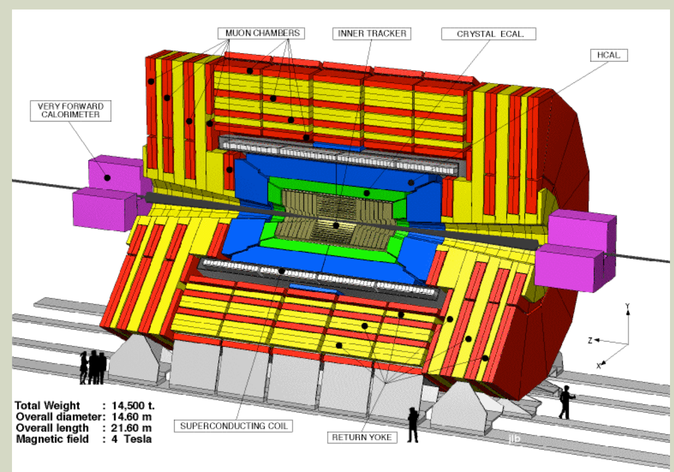


THE DETECTORS



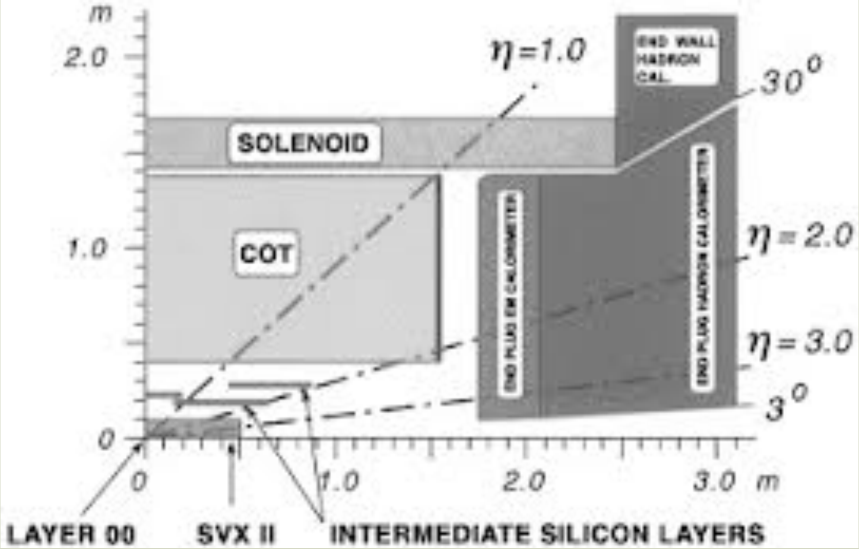




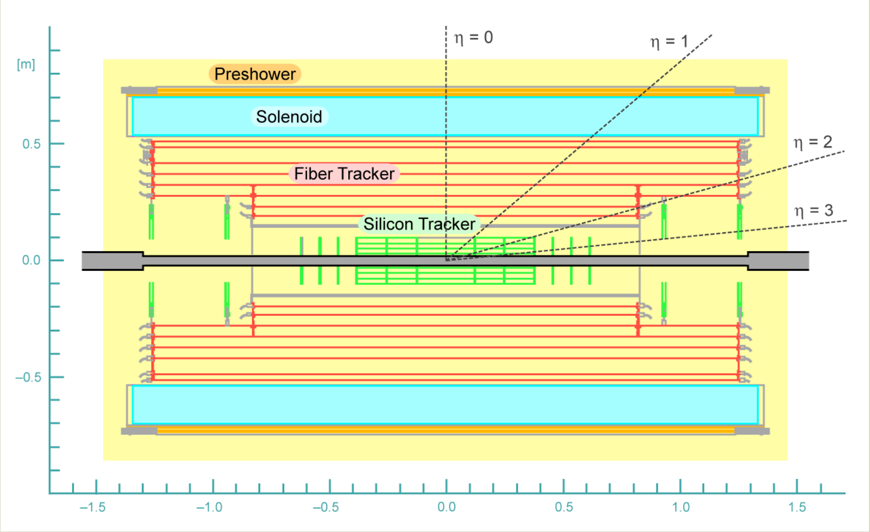


TEVATRON TRACKERS

CDF

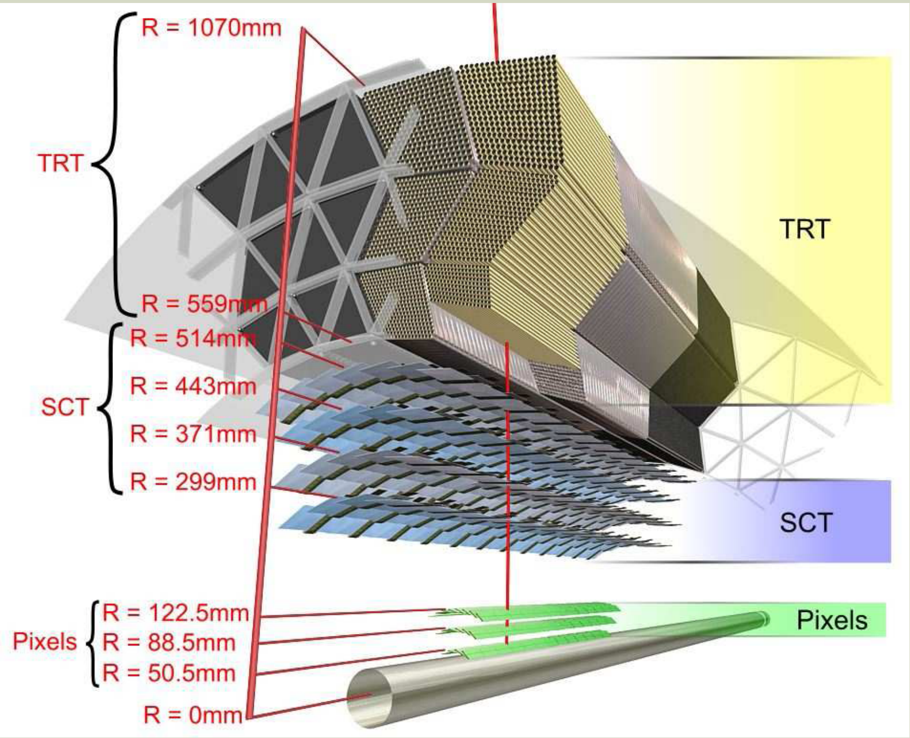


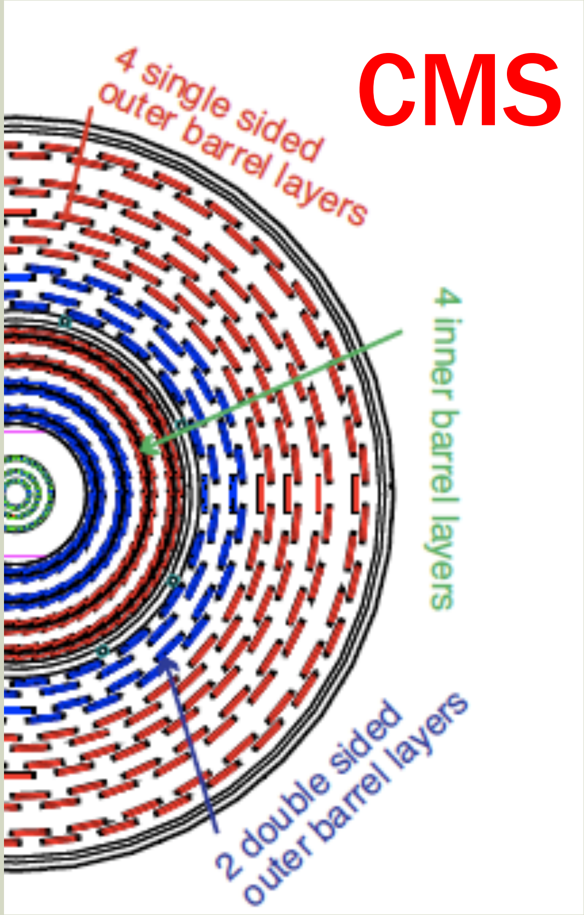
D0



TRACKING CHAMBERS

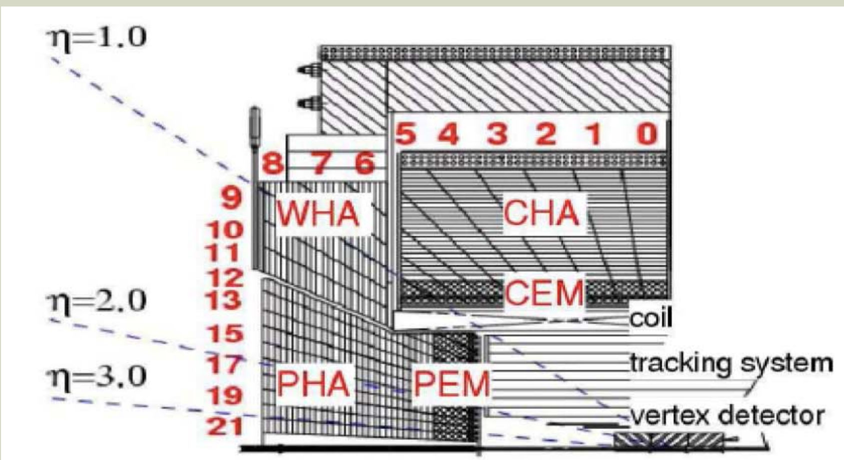
ATLAS





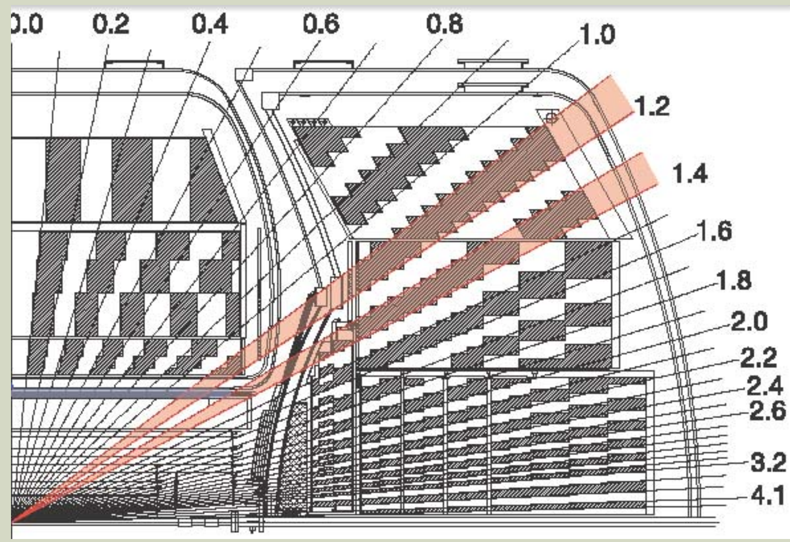
CALORIMETERS: TEVATRON

CDF Calorimeters



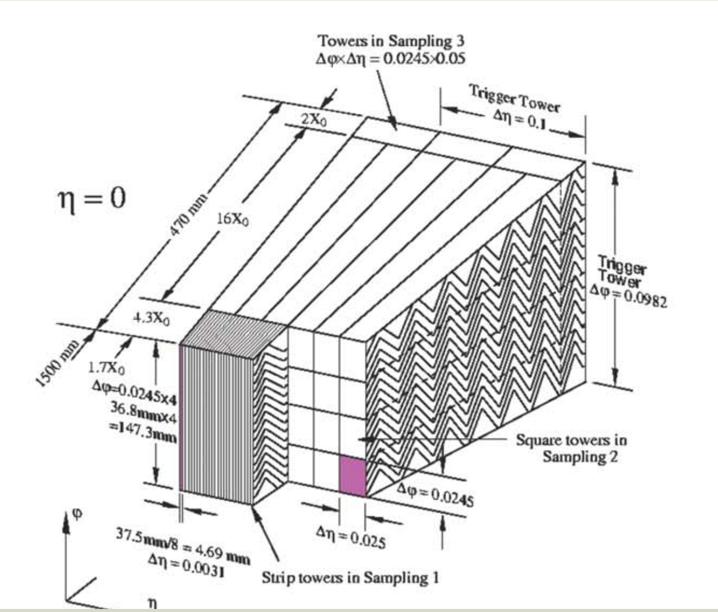
$\lvert\eta\rvert$ Range	$\Delta\phi$	$\Delta\eta$
0. - 1.1 (1.2 h)	15°	~ 0.1
1.1 (1.2 h) - 1.8	7.5°	~ 0.1
1.8 - 2.1	7.5°	~ 0.16
2.1 - 3.64	15°	0.2 - 0.6

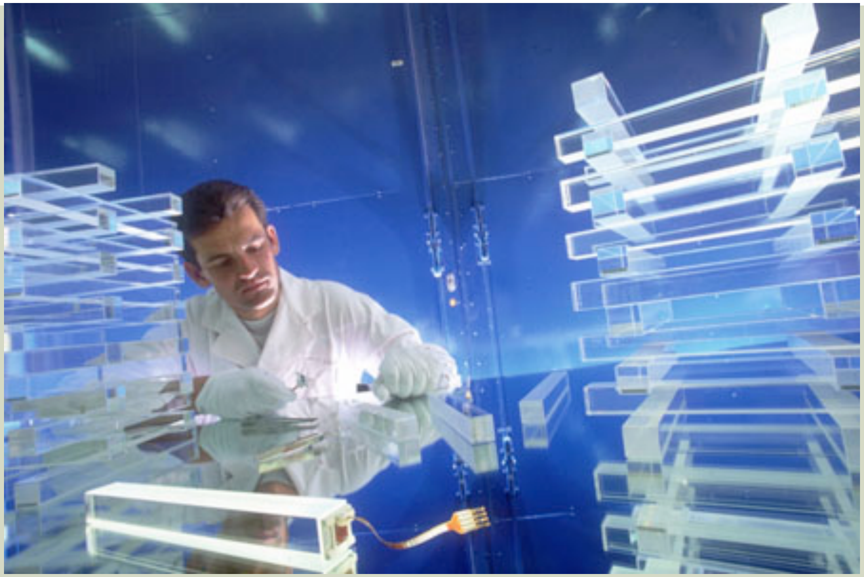
D0 Calorimeters

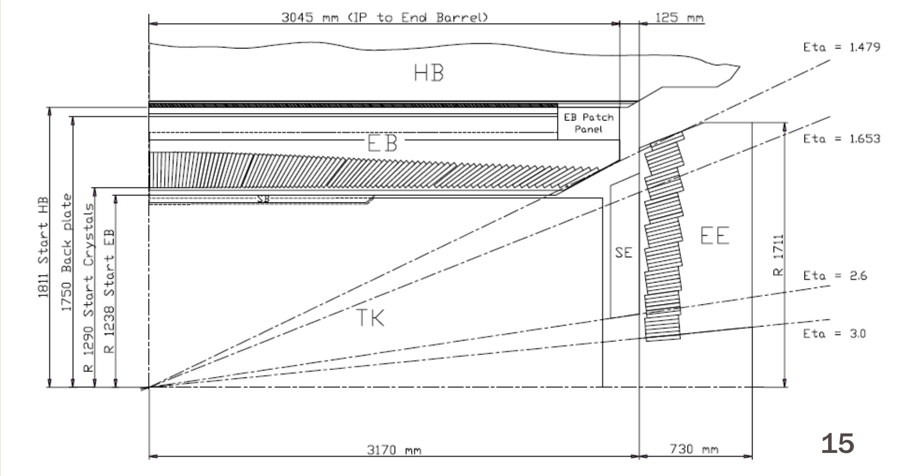


CALORIMETERS: LHC

ATLAS and CMS electromagnetic calorimeters







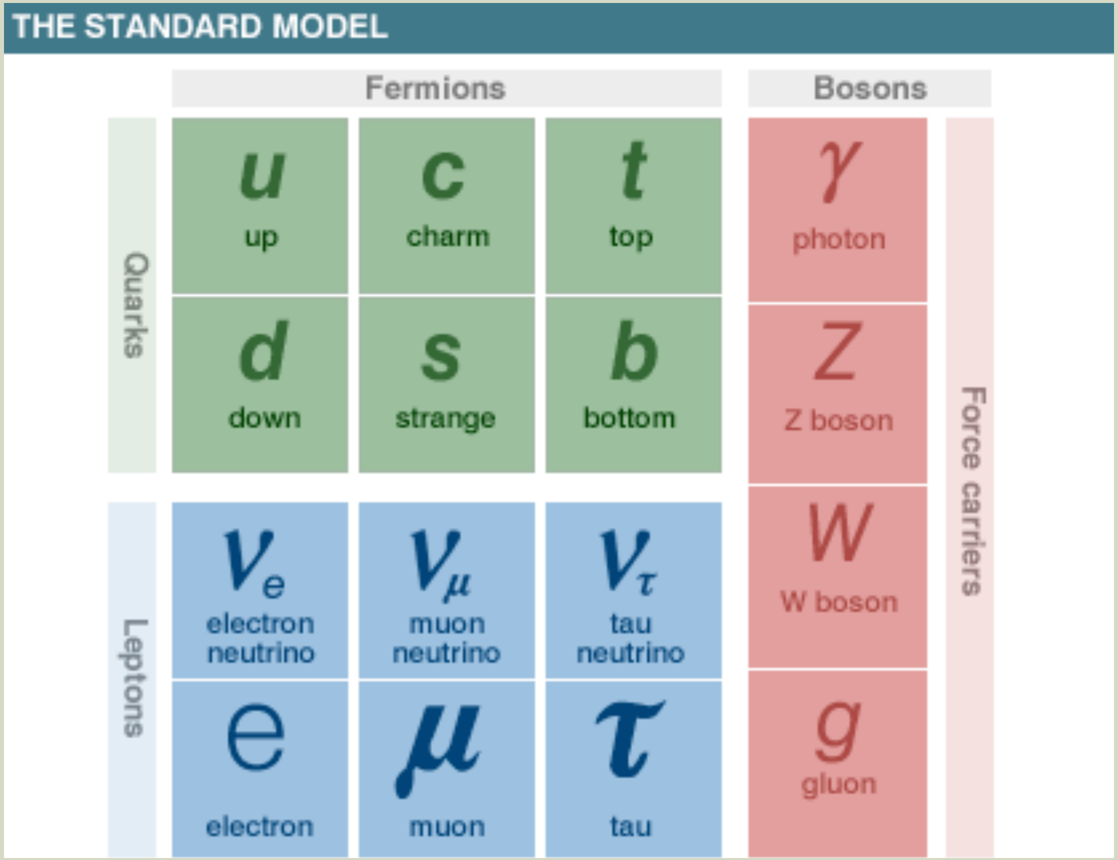
LHC CALORIMETER COMPARISON

(FROM C. TULLY CERN SUMMER SCHOOL LECTURE)

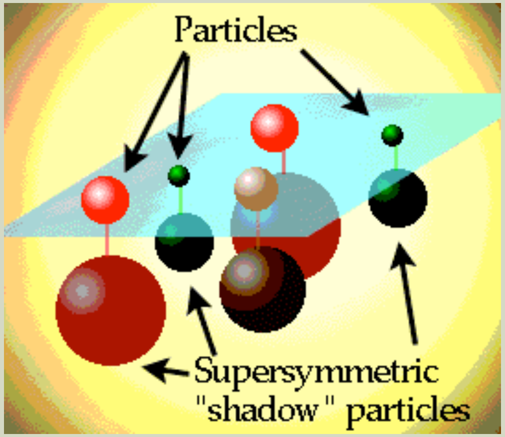
	ATLAS Lead/L. Ar ECAL		CMS PWO Crystal ECAL	
	Barrel	Endcaps	Barrel	Endcaps
# of Channels	110,208	83,744	61,200	14,648
Lateral Segmentation ($\Delta\eta \times \Delta\varphi$)				
Presampler	0.025 x 0.1			
Strip/Preshower	0.003 x 0.1	0.005 x 0.1		32 S /4 crystals
Main Body	0.025 x 0.025		0.0175 x 0.0175	Up to 0.05 x 0.05
Back	0.05 x 0.025			
Longitudinal Segmentation				
Presampler	10 mm L. Ar	2 x 2 mm L. Ar		
Strip/Preshower	~4.3 X_0	~4 X_0		3 X_0
Main Body	~16 X_0	~20 X_0	26 X_0	25 X_0
Back	~2 X_0	~2 X_0		
Designed Energy Resolution				
Stochastic: a	10%	10 - 12%	2.7%	5.7%
Constant: b	0.7%	0.7%	0.55%	0.55%
Noise: C	0.25 GeV	0.25 GeV	0.16 GeV	0.77 GeV

PHYSICS PROGRAM: MEASURE

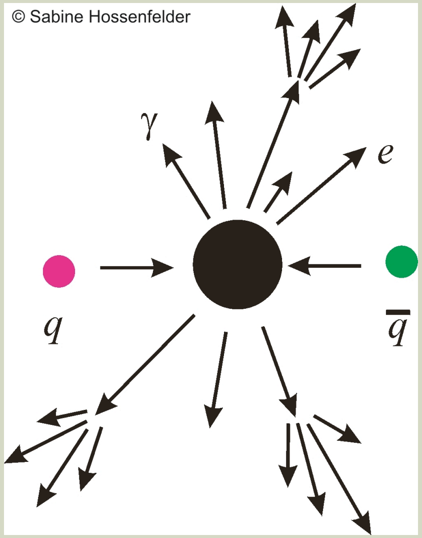
Constrain, over-constrain, test, probe:
mass, width, lifetime, charge, kinematics, polarization, spin, …

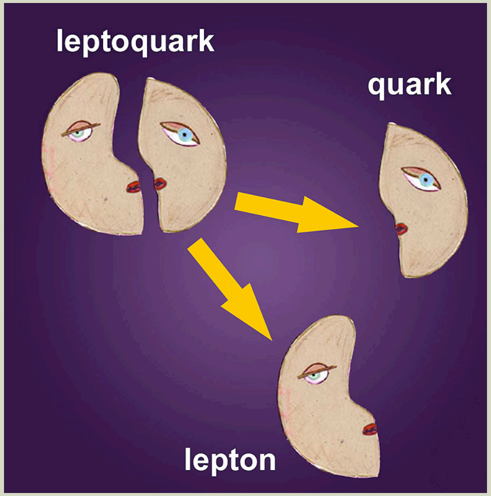


PHYSICS PROGRAM: SEARCH



Supersymmetry, extra dimensions, gravitons, mini black holes
leptoquarks, axions, dark matter, rare decays, CP violation, ...





USING THE STANDARD MODEL AS A GUIDE

Toolbox

TAG AND PROBE WITH Z BOSONS

Tag: passes trigger
tight identification cuts

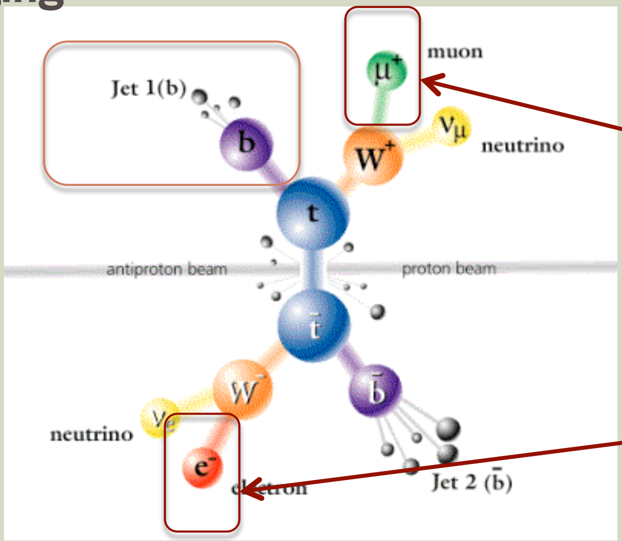
Probe: unbiased object
with known ID

$e/\mu \leftarrow Z \rightarrow e/\mu$

Require ee / $\mu\mu$ pair to
- have opposite charge
- give Z mass

TOP QUARKS AS GUIDES

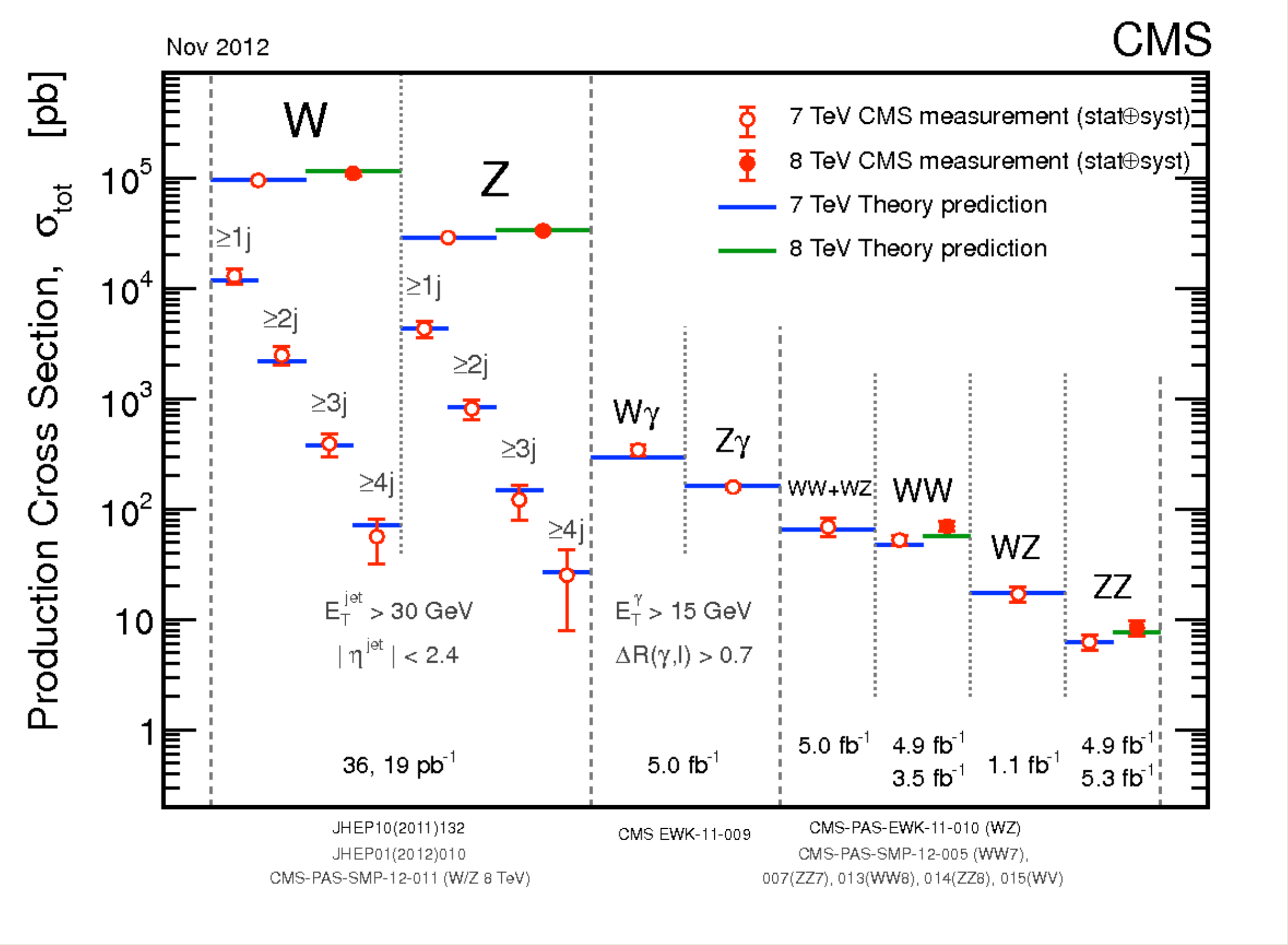
Measure b-tagging efficiencies



Measure lepton efficiencies in busy environment common in searches

$t\bar{t}$ is a primary background in many searches (we'll discuss some of these tomorrow!)

STANDARD MODEL BEHAVING TOO WELL

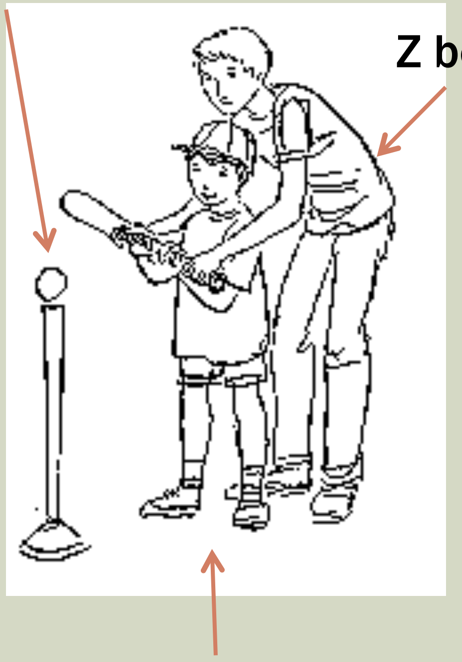


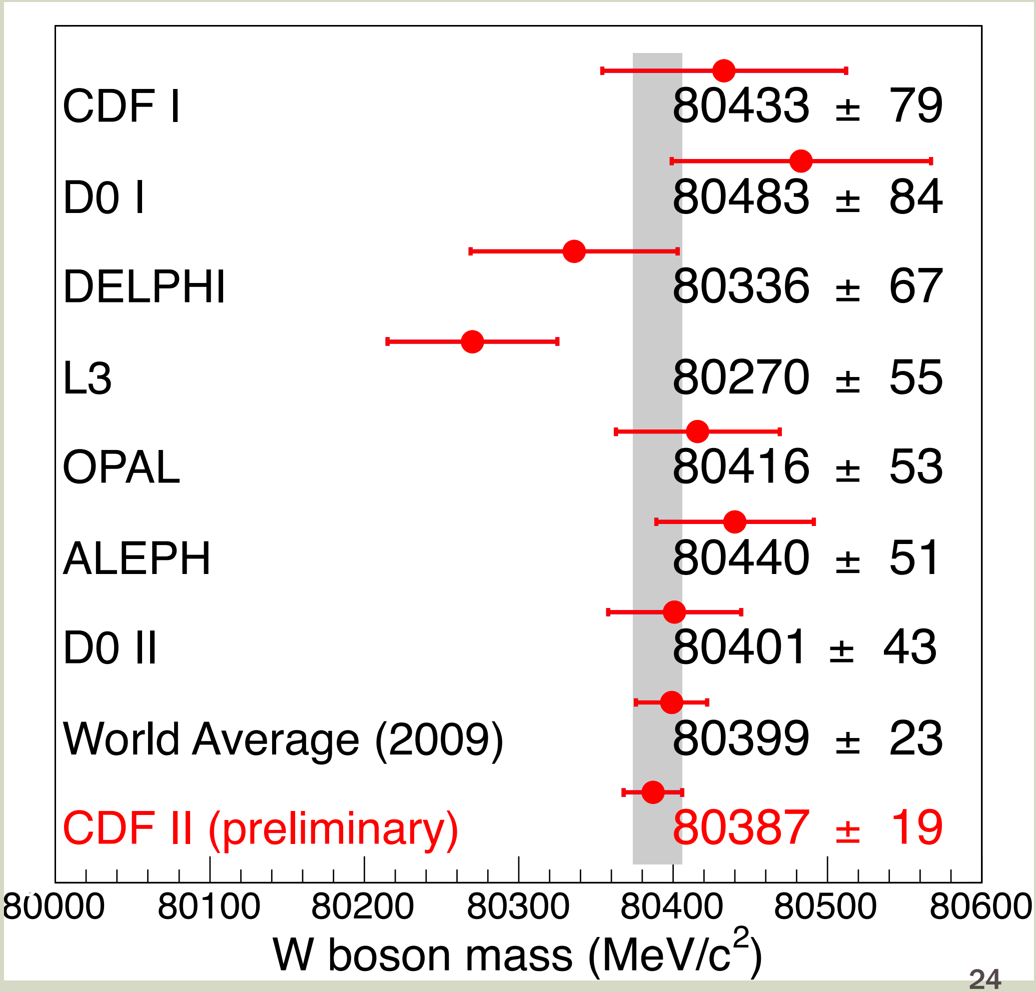
W MASS MEASUREMENT

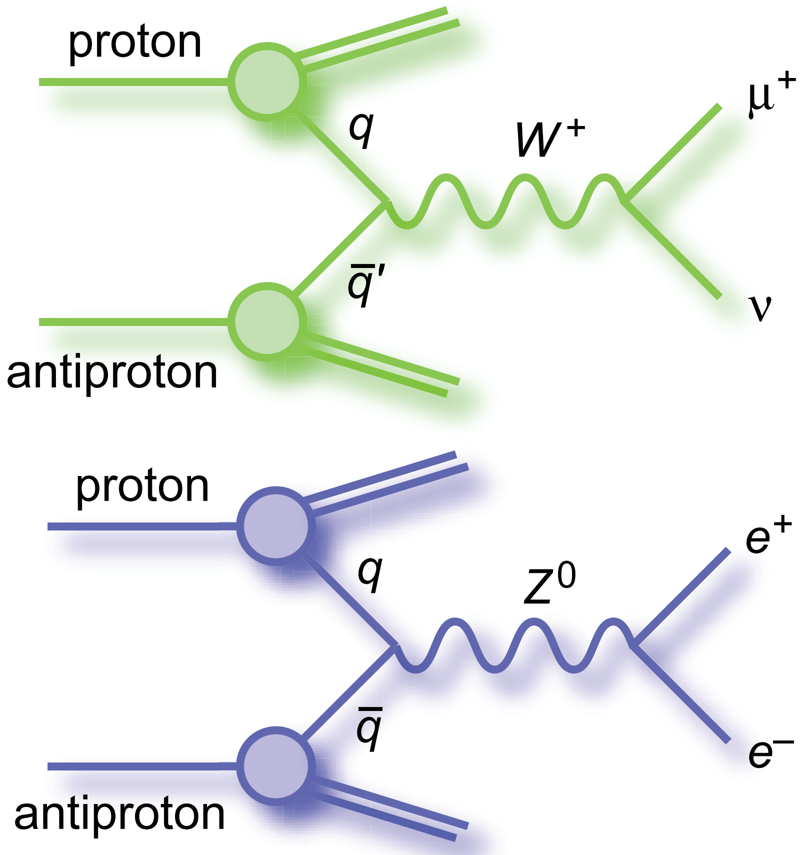
CDF

W MASS AT CDF

W boson mass measurement







W mass used 2.2 fb^{-1}

470126 W->$e\nu$ events

624708 W->$\mu\nu$ events

GOAL :

$$m_T = \sqrt{2\ (\ p_T^\ell\ p_T^\nu - \vec{p}_T^{\,\ell} \cdot \vec{p}_T^{\,\nu}\ )}$$

W AND Z PRODUCTION AT TEVATRON

SELECTION

- Electrons
  - Drift chamber track, $p_T > 18$ GeV
  - EM calo cluster > 30 GeV
  - track-cluster matching
  - $|\eta| < 1$
  - $E/p < 1.6$
  - $E_{HAD}/E_{EM} < 0.1$
  - transverse shower shape requirement
- Muons
  - Drift chamber track, $p_T > 30$ GeV
  - matching hits in muon chambers and minimum-ionizing in calorimeter

reject events with 2nd lepton
lepton pT between 30 and 55 GeV
neutrino pT between 30 and 55 GeV
hadronic recoil < 15 GeV (using calo towers – lepton deposits)
transverse mass between 60 and 100 GeV

BACKGROUNDS

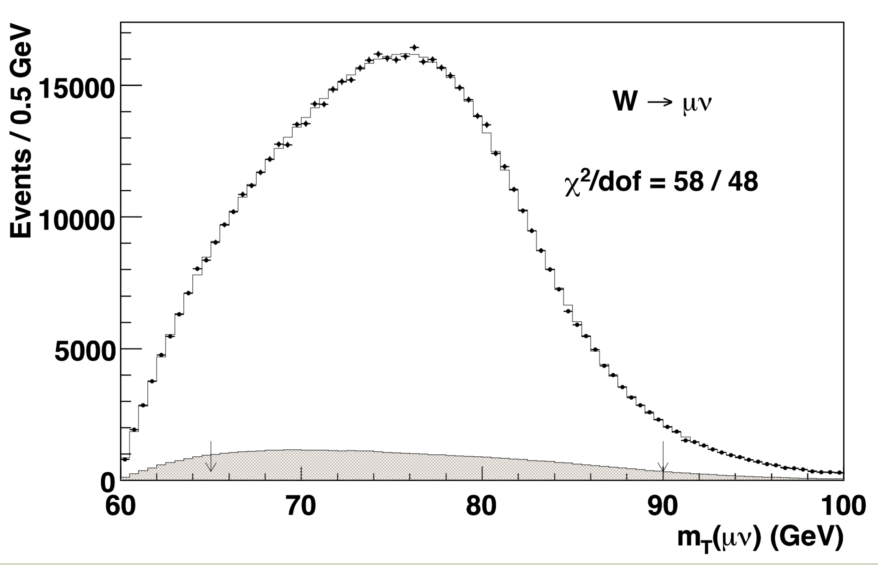
Background	% of $W \rightarrow \mu\nu$ data	δm_W (MeV) m_T fit	p_T^μ fit	p_T^ν fit
$Z \rightarrow \mu\mu$	7.35 ± 0.09	2	4	5
$W \rightarrow \tau\nu$	0.880 ± 0.004	0	0	0
QCD	0.035 ± 0.025	1	1	1
DIF	0.24 ± 0.08	1	3	1
Cosmic rays	0.02 ± 0.02	1	1	1
Total		3	5	6

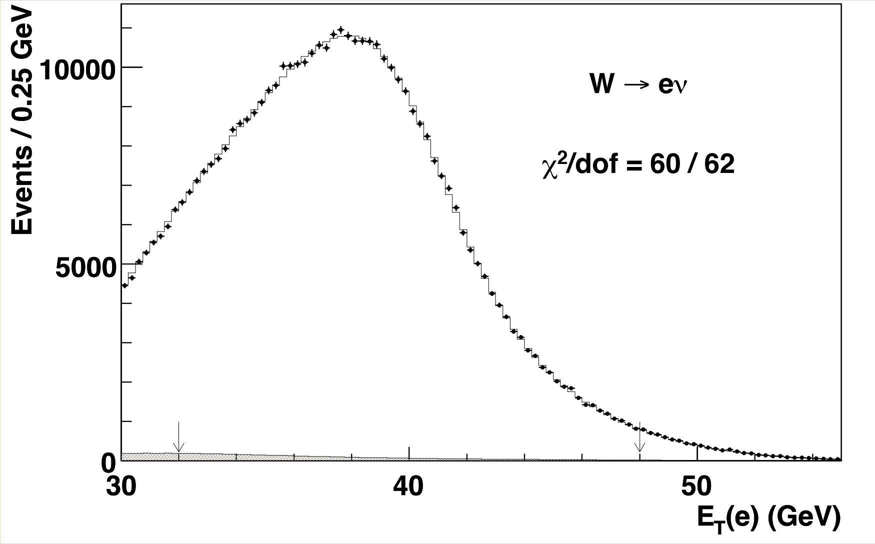
π and k decays in flight

Background	% of $W \rightarrow e\nu$ data	δm_W (MeV) m_T fit	p_T^e fit	p_T^ν fit
$Z \rightarrow ee$	0.139 ± 0.014	1	2	1
$W \rightarrow \tau\nu$	0.93 ± 0.01	1	1	1
QCD	0.39 ± 0.14	4	2	4
Total		4	3	4

MEASUREMENT

Fit data to three distributions made in templates as a function of W mass between 80 GeV and 81 GeV: transverse mass, lepton p_T, neutrino p_T





(*showing template comparison with best fit*)

RESULT

values are combined, taking into account the correlations

Distribution	W-boson mass (MeV)	χ^2/dof
$m_T(e,\nu)$	$80\ 408 \pm 19_{\text{stat}} \pm 18_{\text{syst}}$	$52/48$
$p_T^{\ell}(e)$	$80\ 393 \pm 21_{\text{stat}} \pm 19_{\text{syst}}$	$60/62$
$p_T^{\nu}(e)$	$80\ 431 \pm 25_{\text{stat}} \pm 22_{\text{syst}}$	$71/62$
$m_T(\mu,\nu)$	$80\ 379 \pm 16_{\text{stat}} \pm 16_{\text{syst}}$	$58/48$
$p_T^{\ell}(\mu)$	$80\ 348 \pm 18_{\text{stat}} \pm 18_{\text{syst}}$	$54/62$
$p_T^{\nu}(\mu)$	$80\ 406 \pm 22_{\text{stat}} \pm 20_{\text{syst}}$	$79/62$

fit results

Source	Uncertainty (MeV)
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12
Total	19

uncertainties

MEASUREMENT OF U AND D COUPLINGS

D0

DØ: U AND D QUARK COUPLINGS TO Z

Measurement of $\sin^2\theta^{\ell}_{\rm eff}$ and Z-light quark couplings using the forward-backward charge asymmetry in $p\bar{p} \to Z/\gamma^* \to e^+e^-$ events with $\mathcal{L} = 5.0\ \mathrm{fb}^{-1}$ at $\sqrt{s} = 1.96$ TeV

PRD 84, 012007 (2011)

Measurement of vector and axial-vector couplings of u, d to Z bosons

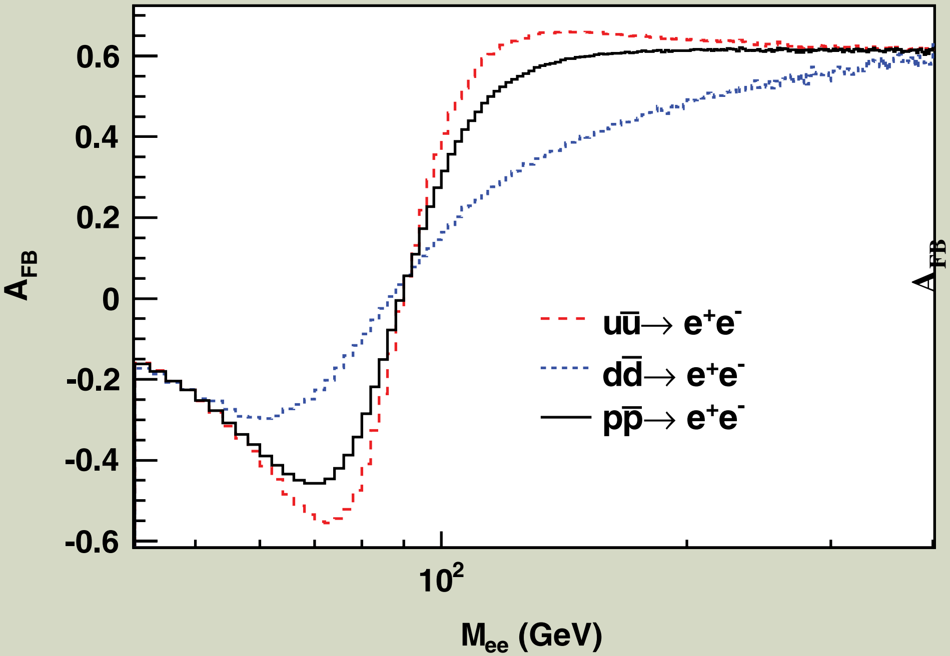
$$g_V^f = I_3^f - 2q_f \cdot \sin^2\theta_W$$

$$g_A^f = I_3^f$$

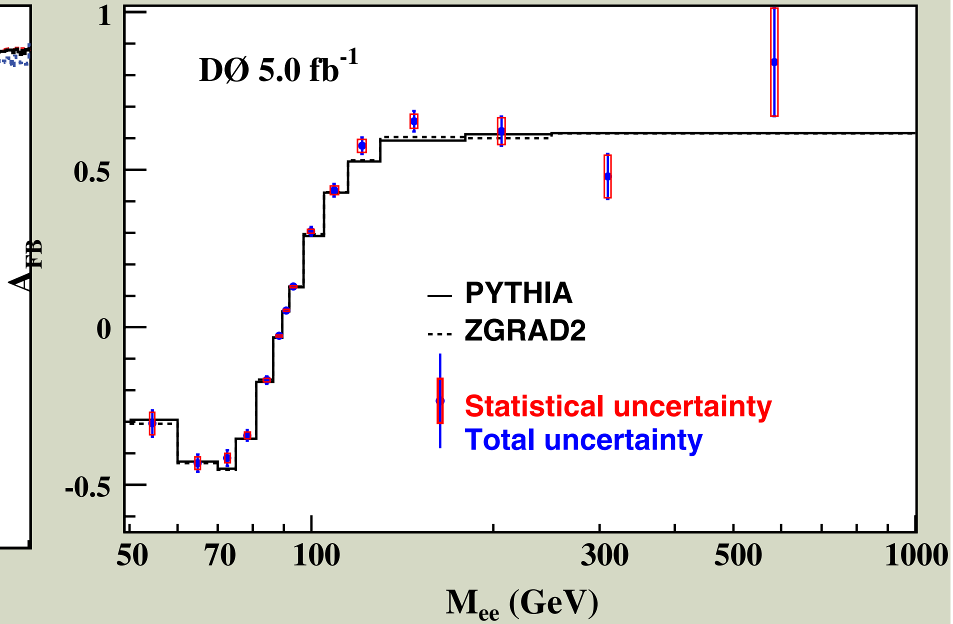
TABLE VIII. Measured $g_V^{u(d)}$ and $g_A^{u(d)}$ values from different experiments compared with the SM predictions. The D0 results are derived from best two-dimensional and four-dimensional χ^2 fit, given with their total uncertainty.

	g_A^u	g_V^u	g_A^d	g_V^d
D0 (2–D)	0.501 ± 0.061	0.202 ± 0.025	-0.477 ± 0.112	-0.377 ± 0.081
D0 (4–D)	0.501 ± 0.110	0.201 ± 0.112	-0.497 ± 0.165	-0.351 ± 0.251
CDF [21] (4–D)	$0.441^{+0.218}_{-0.186}$	$0.399^{+0.166}_{-0.199}$	$-0.016^{+0.358}_{-0.544}$	$-0.226^{+0.641}_{-0.304}$
H1 [22] (4–D)	0.56 ± 0.10	0.05 ± 0.19	-0.77 ± 0.37	-0.50 ± 0.37
LEP [15] (4–D)	$0.47^{+0.05}_{-0.33}$	$0.24^{+0.28}_{-0.11}$	$-0.52^{+0.05}_{-0.03}$	$-0.33^{+0.05}_{-0.07}$
SM [16]	0.501	0.192	-0.502	-0.347

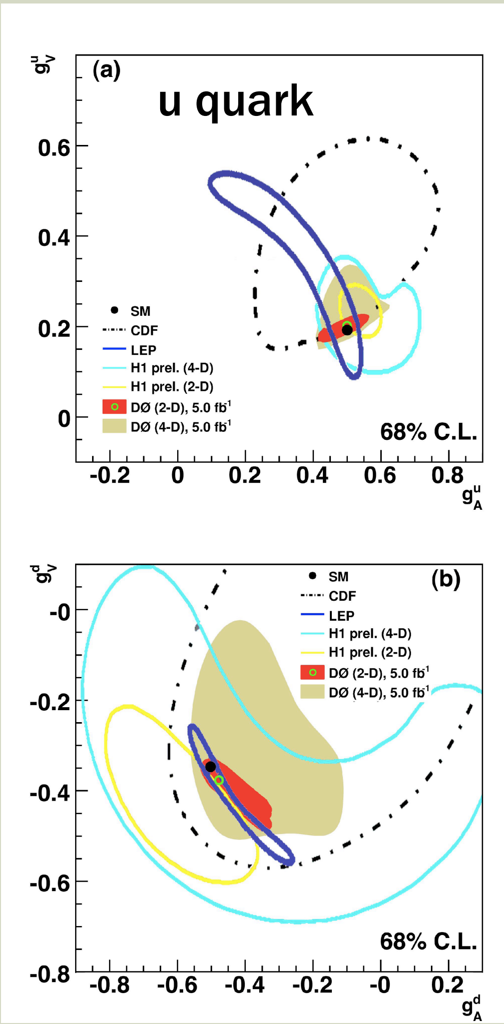
Theory



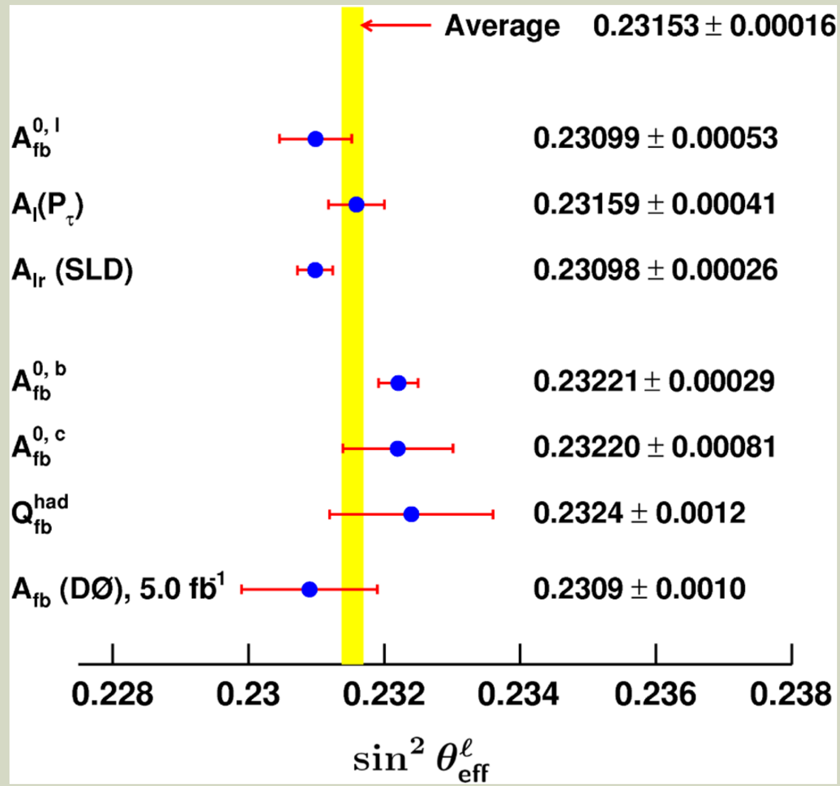
Measured



RESULTS



d
quark



TOP QUARK WIDTH

CDF

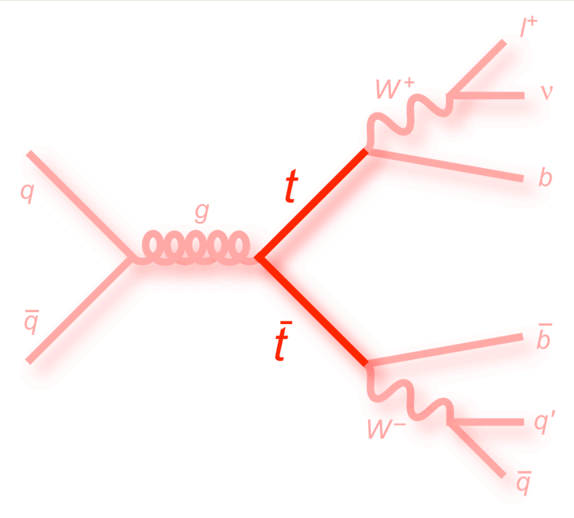
TOP QUARK WIDTH

$$\Gamma_{\text{top}} = \frac{G_F m_t^3}{8\pi\sqrt{2}} \left(1 - \frac{M_W^2}{m_t^2}\right)^2 \left(1 + 2\frac{M_W^2}{m_t^2}\right) \left[1 - \frac{2\alpha_s}{3\pi}\left(\frac{2\pi^2}{3} - \frac{5}{2}\right)\right]$$

$$\tau = \hbar/\Gamma$$

Channel:
ttbar lepton + jets

technique:
2-D template method with reconstructed mass and invariant mass of jets in hadronic W decay



Predicted width:
1.25 GeV

CDF Note 10936

DETERMINE MASS

chi squared created for each pairing of jet and leptons consistent with b-tagging

mass with minimum chi squared is used for each event

$$\chi^2 = \sum_{i=l,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_T^{UE,meas})^2}{\sigma_j^2}$$

$$+ \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jj} - M_W)^2}{\Gamma_W^2}$$

$$+ \frac{(M_{bl\nu} - m_t^{\mathrm{reco}})^2}{\Gamma_t^2} + \frac{(M_{bjj} - m_t^{\mathrm{reco}})^2}{\Gamma_t^2}$$

DETERMINE MASS

Constrain p_T of jets and leptons

constrain un-clustered energy

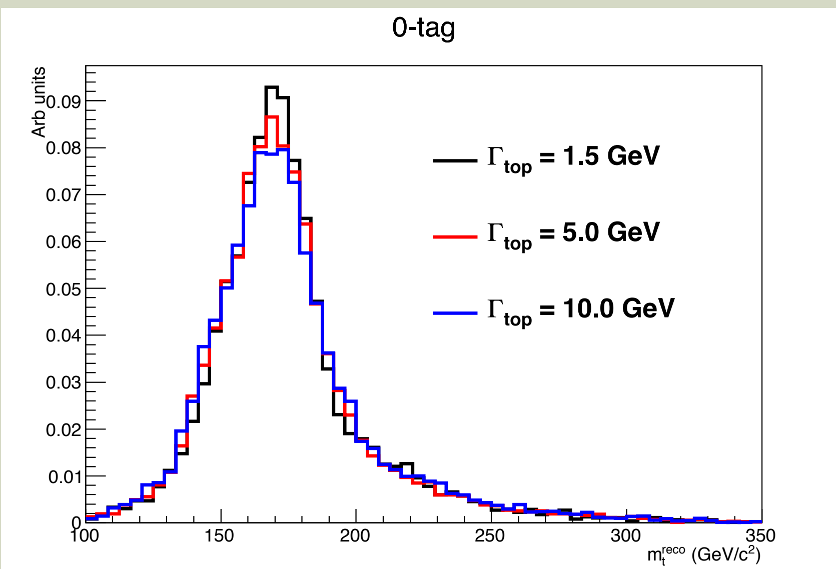
$$\chi^2 = \sum_{i=l,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_T^{UE,meas})^2}{\sigma_j^2}$$
$$+ \frac{(M_{l\nu} - M_W)^2}{\Gamma_W^2} + \frac{(m_{jj} - M_W)^2}{\Gamma_W^2}$$
$$+ \frac{(M_{bl\nu} - m_t^{\rm reco})^2}{\Gamma_t^2} + \frac{(M_{bjj} - m_t^{\rm reco})^2}{\Gamma_t^2}$$

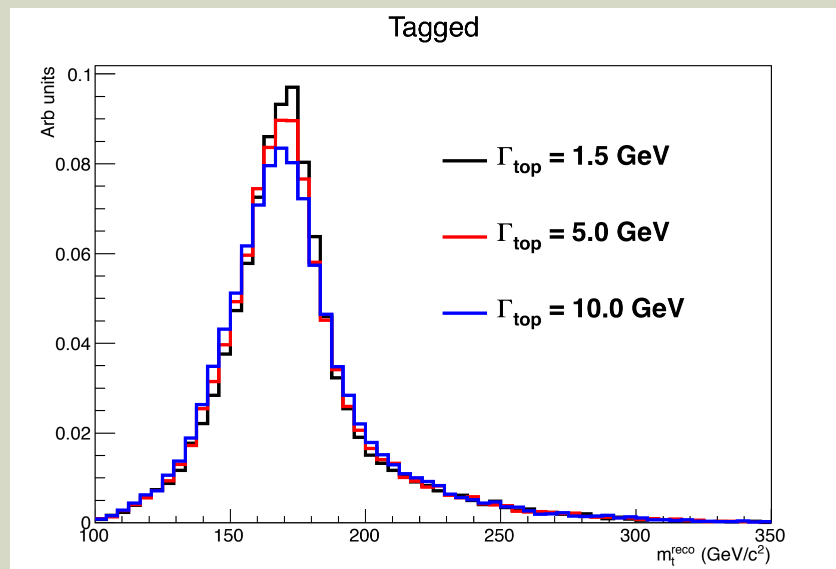
constrain with W mass
(most powerful constraint in fit)

two top quark masses constrained to be equal

TEMPLATES

Reconstructed mass templates without and with b-tags



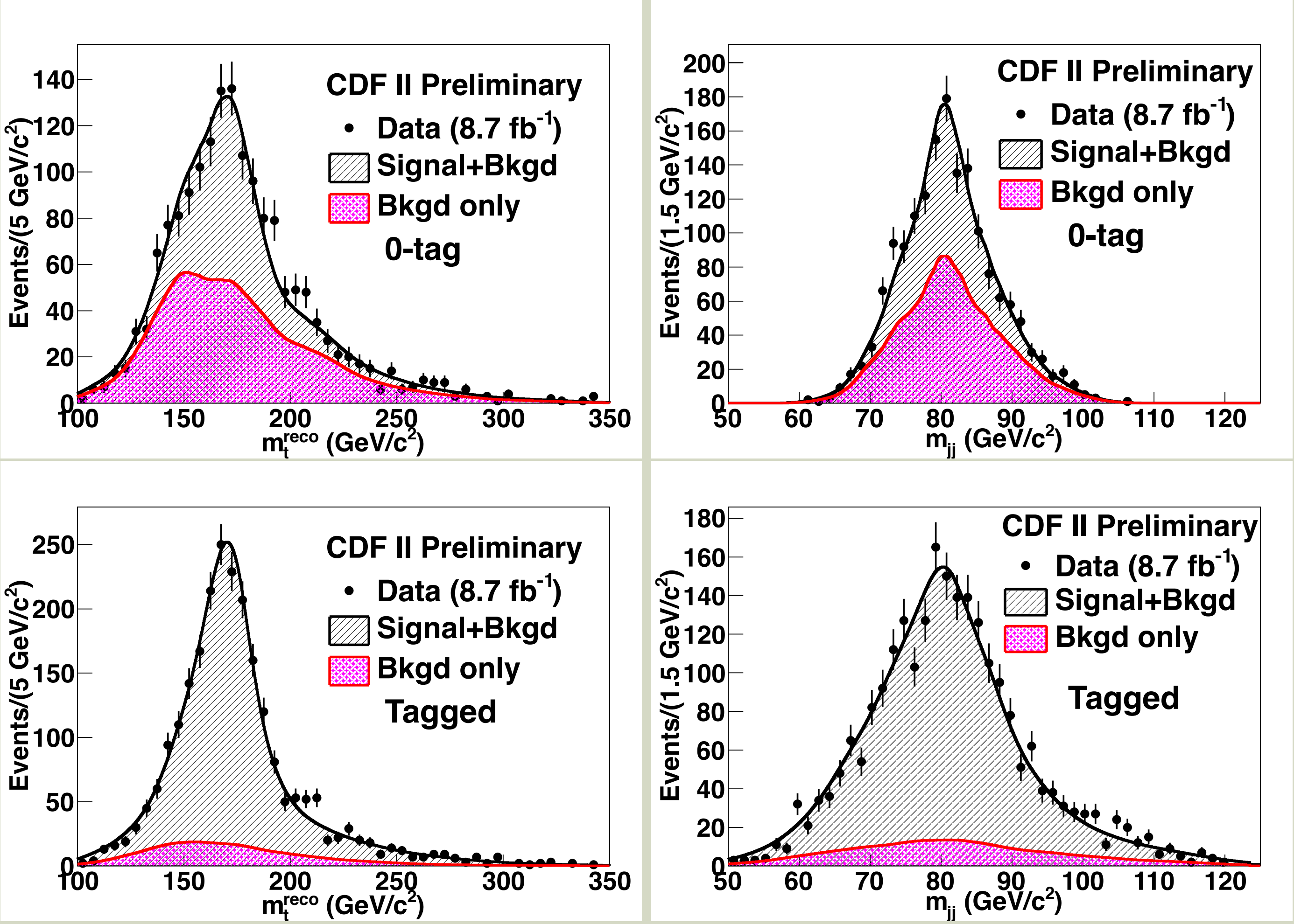


WIDTH: BACKGROUNDS

CDF II Preliminary 8.7 fb^{-1}

	0-tag	1-tagL	1-tagT	2-tagL	2-tagT
W+jets	703 ± 199	170 ± 60	102 ± 37	11.6 ± 4.9	8.4 ± 3.5
Z+jets	52.3 ± 4.4	8.9 ± 1.1	5.9 ± 0.7	0.8 ± 0.1	0.5 ± 0.1
Single top	4.8 ± 0.5	10.5 ± 0.9	6.8 ± 0.6	2.2 ± 0.3	1.7 ± 0.2
Diboson	60.3 ± 5.6	111 ± 1.4	8.5 ± 1.1	1.0 ± 0.2	0.8 ± 0.1
Multijets	143 ± 114	34.5 ± 12.6	20.7 ± 16.6	4.4 ± 2.5	2.5 ± 2.4
Background	963 ± 229	235 ± 61	144 ± 41	19.9 ± 5.5	13.8 ± 4.2
$t\bar{t}$ signal	645 ± 86	695 ± 87	867 ± 108	192 ± 30	304 ± 47
Expected	1608 ± 245	930 ± 106	1011 ± 115	212 ± 30	318 ± 47
Observed	1627	882	997	208	275

RESULTS



CDF II Preliminary
Data (8.7 fb^{-1})
Signal+Bkgd
Bkgd only
0-tag
Events/(5 GeV/c^2)
m_t^{reco} (GeV/c^2)
CDF II Preliminary
Data (8.7 fb^{-1})
Signal+Bkgd
Bkgd only
0-tag
Events/(1.5 GeV/c^2)
m_{jj} (GeV/c^2)
CDF II Preliminary
Data (8.7 fb^{-1})
Signal+Bkgd
Bkgd only
Tagged
Events/(5 GeV/c^2)
m_t^{reco} (GeV/c^2)
CDF II Preliminary
Data (8.7 fb^{-1})
Signal+Bkgd
Bkgd only
Tagged
Events/(1.5 GeV/c^2)
m_{jj} (GeV/c^2)

LIKELIHOOD FIT

# of signal and background events must obey Poisson stats

constrains # of background events to predicted value (n_{b0})

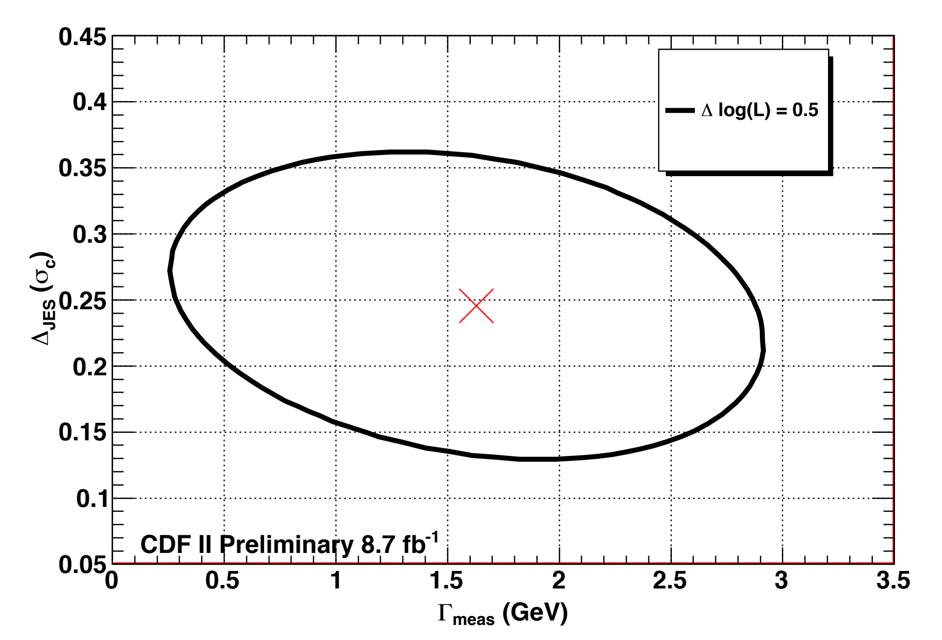
$$\mathcal{L}_{shape} = \frac{(n_s+n_b)^N e^{-(n_s+n_b)}}{N!} \times e^{-\frac{(n_{b0}-n_b)^2}{2\sigma^2_{n_{b0}}}}$$
$$\times \prod_{i=1}^{N} \frac{n_s P_s(m_t^{\mathrm{reco}}, m_{jj}; \Gamma_{\mathrm{top}}, \Delta_{\mathrm{JES}}) + n_b P_b(m_t^{\mathrm{reco}}, m_{jj}; \Delta_{\mathrm{JES}})}{n_s + n_b}$$

$P(m_t^{\mathrm{reco}}, m_{jj} | \Gamma_{\mathrm{top}}, \Delta_{\mathrm{JES}})$ **Probability functions from Kernel Density Estimation**

MEASUREMENT

$$\Gamma_{\mathrm{top}} = 2.21^{+1.46}_{-0.92}(\mathrm{stat})^{+1.12}_{-0.62}(\mathrm{syst})\mathrm{GeV} = 2.21^{+1.84}_{-1.11}\mathrm{GeV}$$

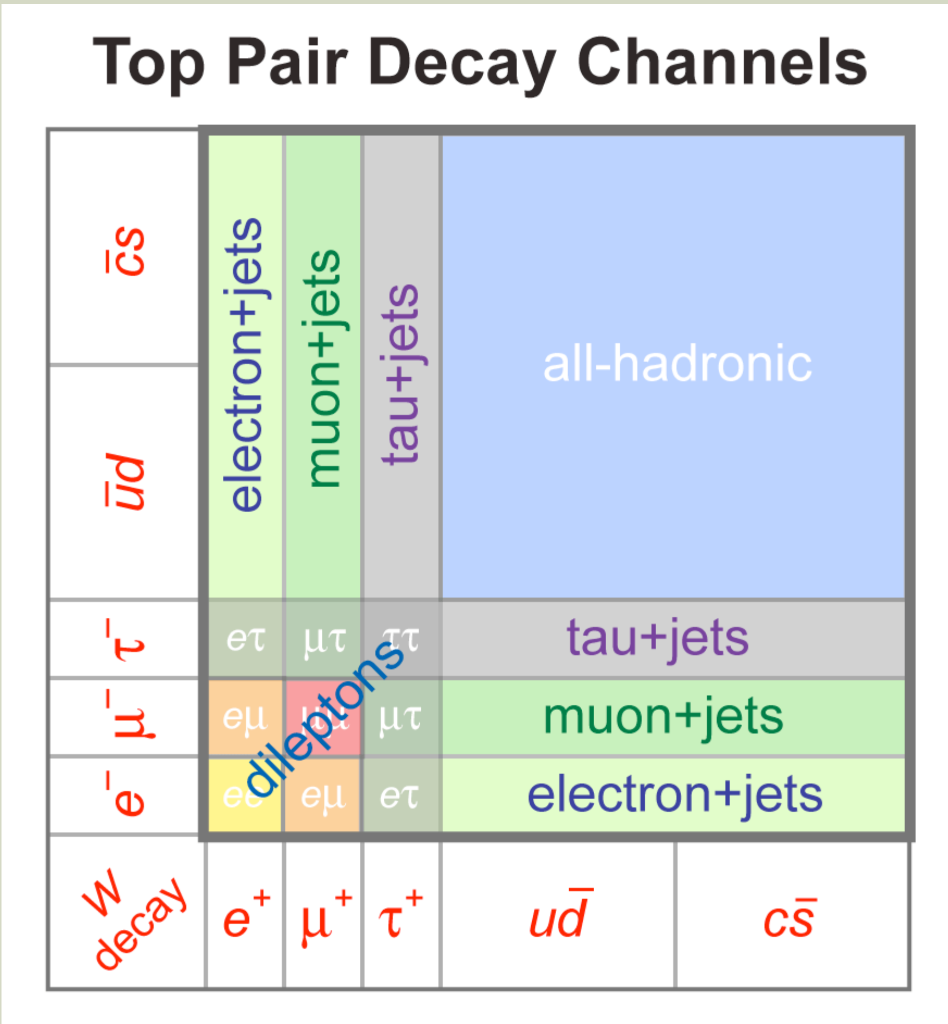
$$\tau_{\mathrm{top}} = 2.98^{+3.00}_{-1.35} \times 10^{-25}\mathrm{s}$$

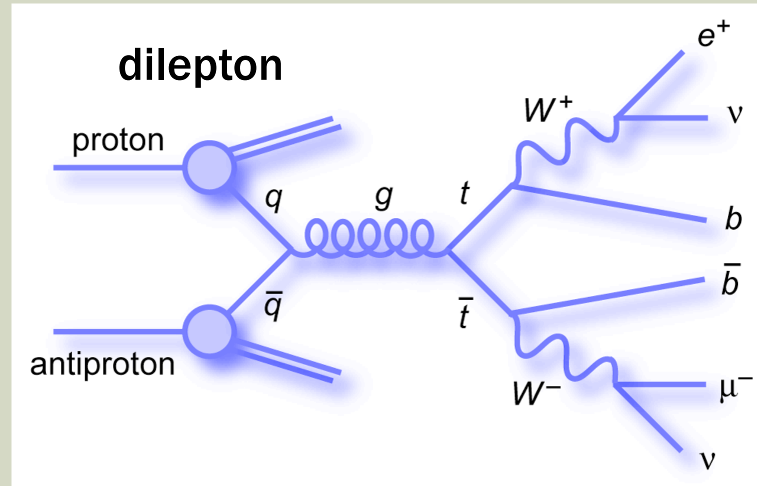


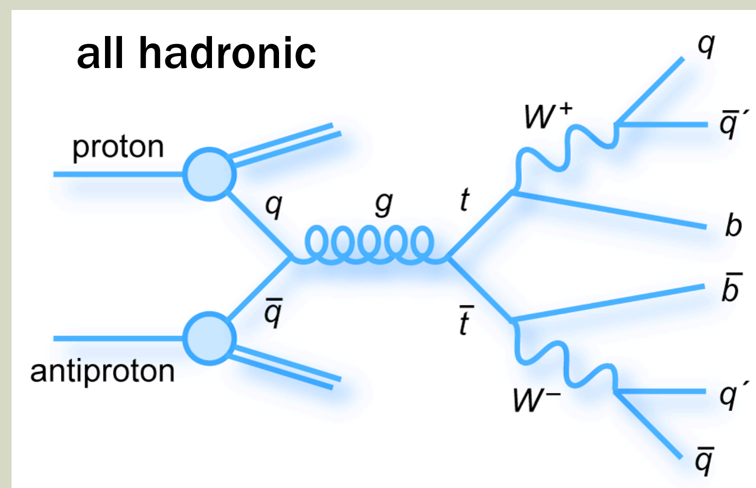
TOP QUARK MASS COMBINATION

TeVatron

CDF AND D0 TOP QUARK COMBINED MASS







TOP MASS: TWELVE CHANNELS USED

This table shows the twelve channels in the correlation matrix between channels, including both CDF and D0

	Run I published					Run II published						Run II preliminary
	CDF			DØ		CDF				DØ		CDF
	ℓ+jets	$\ell\ell$	alljets	ℓ+jets	$\ell\ell$	ℓ+jets	$\ell\ell$	alljets	L_{XY}	ℓ+jets	$\ell\ell$	MEt
CDF-I ℓ+jets	1.00	0.29	0.32	0.26	0.11	0.49	0.54	0.25	0.07	0.21	0.12	0.27
CDF-I $\ell\ell$	0.29	1.00	0.19	0.15	0.08	0.29	0.32	0.15	0.04	0.13	0.08	0.17
CDF-I alljets	0.32	0.19	1.00	0.14	0.07	0.30	0.38	0.15	0.04	0.09	0.06	0.16
DØ-I ℓ+jets	0.26	0.15	0.14	1.00	0.16	0.22	0.27	0.12	0.05	0.14	0.07	0.12
DØ-I $\ell\ell$	0.11	0.08	0.07	0.16	1.00	0.11	0.13	0.07	0.02	0.07	0.05	0.07
CDF-II ℓ+jets	0.49	0.29	0.30	0.22	0.11	1.00	0.48	0.29	0.08	0.30	0.18	0.33
CDF-II $\ell\ell$	0.54	0.32	0.38	0.27	0.13	0.48	1.00	0.25	0.06	0.11	0.07	0.26
CDF-II alljets	0.25	0.15	0.15	0.12	0.07	0.29	0.25	1.00	0.04	0.16	0.10	0.17
CDF-II L_{XY}	0.07	0.04	0.04	0.05	0.02	0.08	0.06	0.04	1.00	0.06	0.03	0.04
DØ-II ℓ+jets	0.21	0.13	0.09	0.14	0.07	0.30	0.11	0.16	0.06	1.00	0.39	0.18
DØ-II $\ell\ell$	0.12	0.08	0.06	0.07	0.05	0.18	0.07	0.10	0.03	0.39	1.00	0.11
CDF-II MEt	0.27	0.17	0.16	0.12	0.07	0.33	0.26	0.17	0.04	0.18	0.11	1.00

CDF AND D0 TOP QUARK COMBINED MASS

$$M_{\mathrm{t}} = 173.20 \pm 0.51\,(\mathrm{stat}) \pm 0.71\,(\mathrm{syst})\ \mathrm{GeV}/c^2$$

	Tevatron combined values (GeV/c^2)
M_{t}	173.20
In situ light-jet calibration (iJES)	0.36
Response to $b/q/g$ jets (aJES)	0.09
Model for b jets (bJES)	0.11
Out-of-cone correction (cJES)	0.01
Light-jet response (2) (dJES)	0.15
Light-jet response (1) (rJES)	0.16
Lepton modeling (LepPt)	0.05
Signal modeling (Signal)	0.52
Jet modeling (DetMod)	0.08
Offset (UN/MI)	0.00
Background from theory (BGMC)	0.06
Background based on data (BGData)	0.13
Calibration method (Method)	0.06
Multiple interactions model (MHI)	0.07
Systematic uncertainty (syst)	0.71
Statistical uncertainty (stat)	0.51
Total uncertainty	0.87

uranium noise in D0 calo (Run 1)

TAU POLARIZATION

ATLAS

TAU POLARIZATION

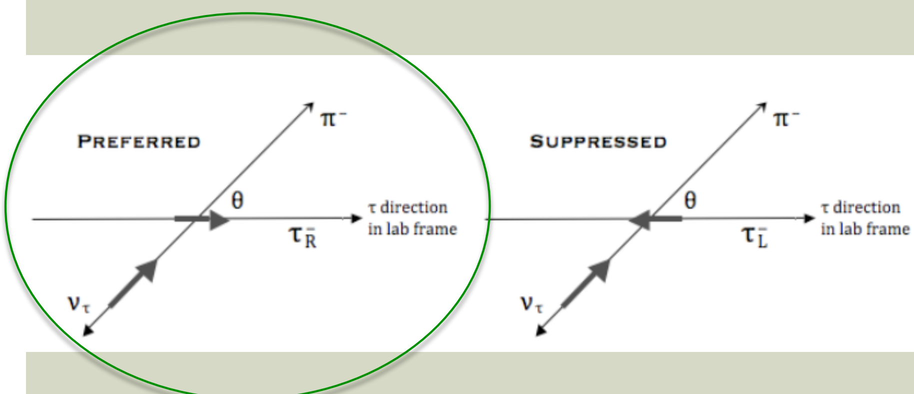
$$P_\tau = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L}$$

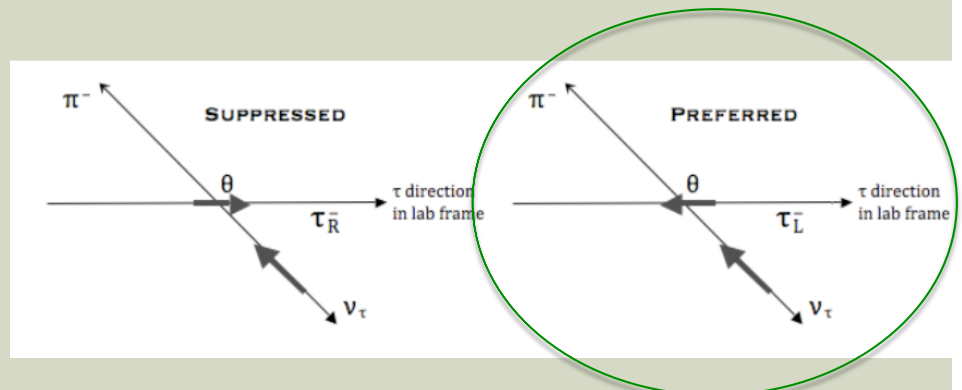
relative cross-section of left- and right-handed taus

Access to P_τ allows for

- tests of the SM
- searches for new physics
- discrimination between processes

Process	P_τ Prediction
$W^\pm \to \tau\nu$	-1
$H^\pm \to \tau\nu$	+1
$Z \to \tau\tau$	≈ -0.15
$H \to \tau\tau$	0





TAU DECAYS

tau decay channels and their branching ratios

Channel	Dominant Decay Mode	BR[%]
$e^-\bar{\nu}\nu$	$e^-\bar{\nu}_e\nu_\tau$	$17.82 \pm .04$
$\mu^-\bar{\nu}\nu$	$\mu^-\bar{\nu}_\mu\nu_\tau$	$17.39 \pm .04$
$h^-\nu$	$\pi^-\nu_\tau$	$11.61 \pm .06$
$h^-\pi^0\nu$	$\rho^-\nu_\tau \to \pi^-\pi^0\nu_\tau$	$25.94 \pm .09$
$h^-\pi^0\pi^0(\pi^0)\nu$	$a_1^-\nu_\tau \to \pi^-\pi^0\pi^0\nu_\tau$	$10.85 \pm .11$
$h^-h^-h^+(\pi^0)\nu$	$a_1^-\nu_\tau \to \pi^-\pi^-\pi^+\nu_\tau$	$14.56 \pm .07$

Unlike former experiments with electrons and positrons where the initial beam energy gave important constraints to the kinematics,
at a hadron collider, we do not know the initial energy of the interaction.
(not a one-to-one mapping of optimal observables!)

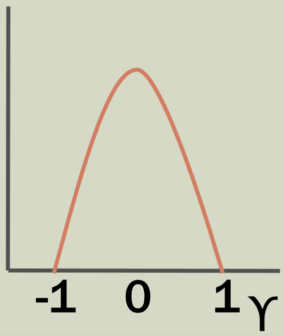
The ability to access the final state particles from the ρ decays is a way to regain sensitivity at the LHC.

POLARIZATION OBSERVABLE

Charged Asymmetry:

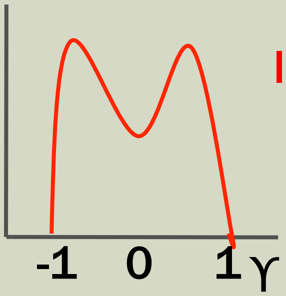
$$\Upsilon = \frac{2(track_{p_T})}{tau_{p_T}} - 1$$

When the energy is shared **evenly** between charged and neutral pions
ϒ will peak at zero



transversely polarized
ρ favored by τ_L

When the energy is shared **unevenly** between charged and neutral pions
ϒ will have peaks at +1 and -1



longitudinally polarized
ρ favored by τ_R

SAMPLE COMPOSITION

EW background from simulation, not dependent on tau Polarization

Sample	Number of Events
Data	1136
Electroweak Background	138 ± 4
Left-Handed Signal	
$W \rightarrow \tau_L \nu$	1002 ± 16
Multijet Background	69 ± 6
Right-Handed Signal	
$W \rightarrow \tau_R \nu$	1523 ± 22
Multijet Background	79 ± 4

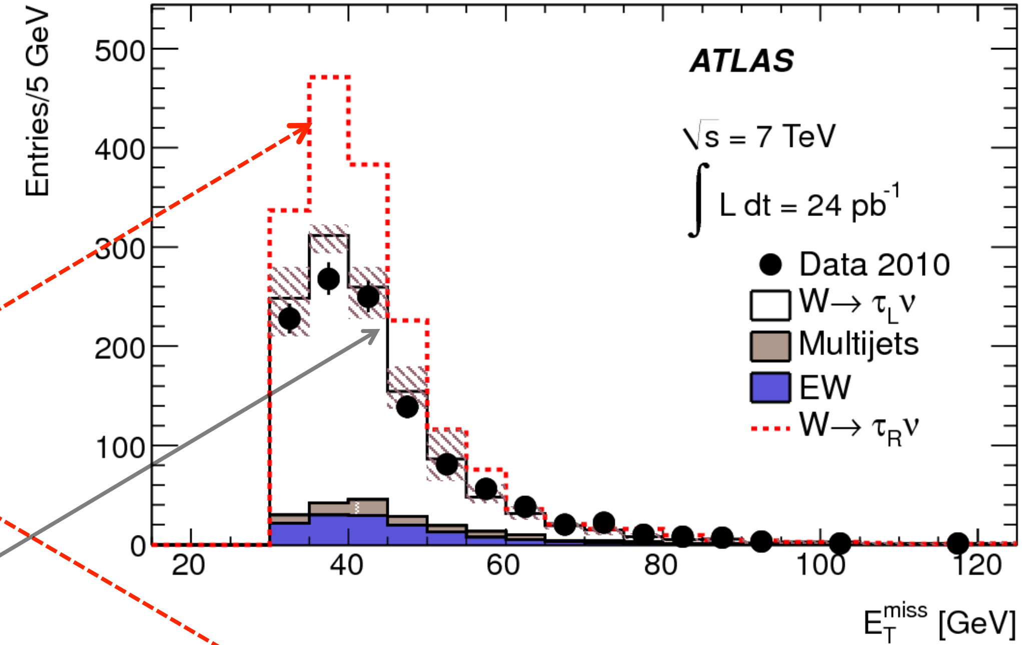
Multijet background from data, corrected for signal contribution (and therefore dependent on tau Polarization)

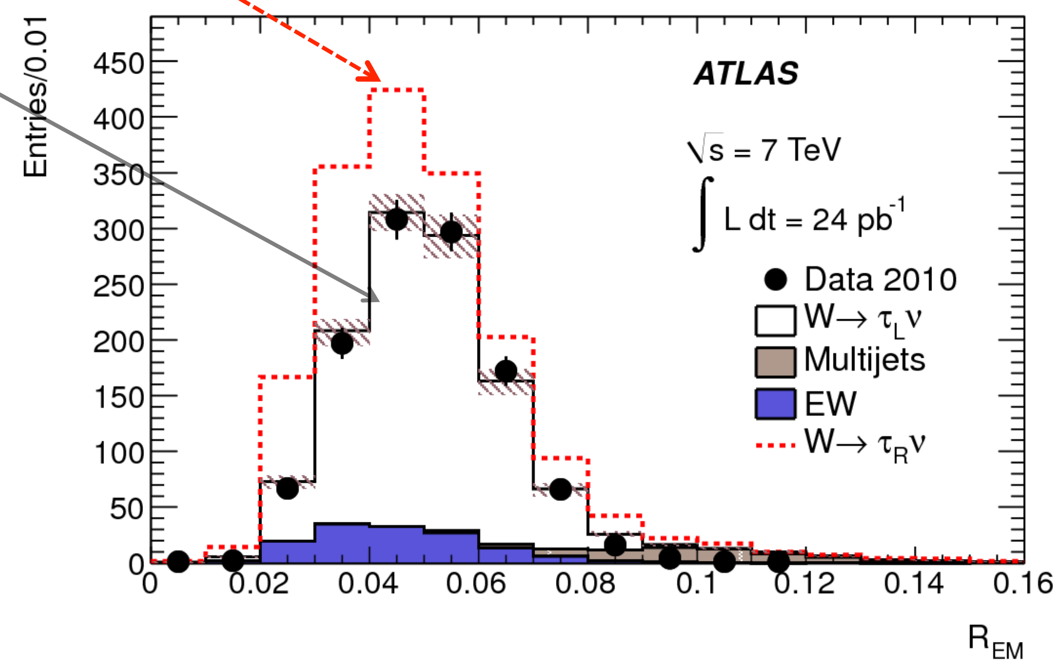
Signal to background ratio better than 5:1

Distributions

Expected Distributions for right-handed taus

Expected Distributions for left-handed taus





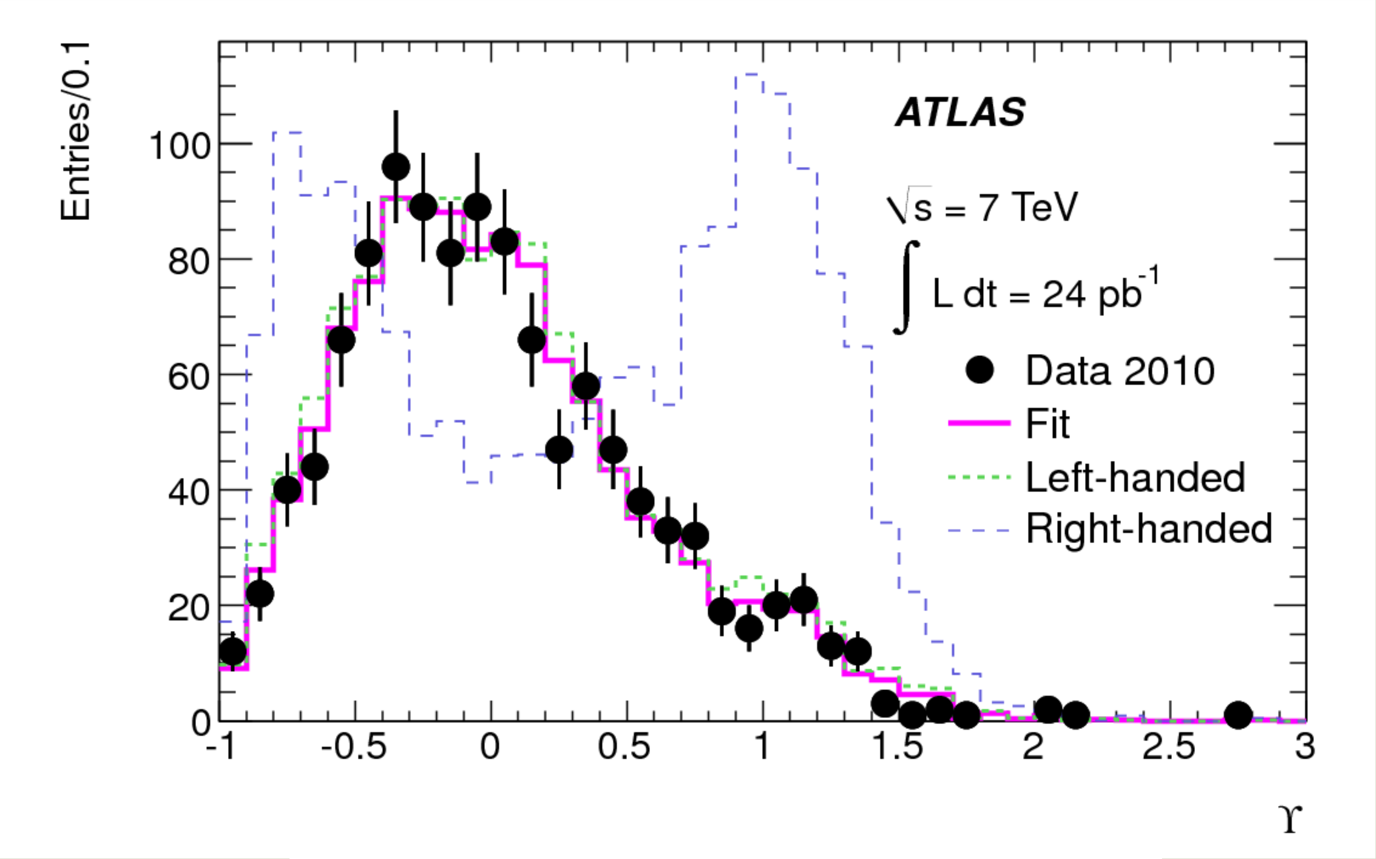
The handedness, given its impact on momentum, affects both the acceptance and the shape of distributions

SYSTEMATIC UNCERTAINTIES

Sources of Systematic Uncertainty

Source	$+\Delta P_\tau$	$-\Delta P_\tau$
Energy scale central	0.042	0.063
Energy scale forward	0.007	0.002
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	0.014	-
No FCal	0.003	-
τ identification	0.005	0.006
Trigger	0.007	0.006
MC model	0.020	0.020
W cross-section	0.005	0.005
Z cross-section	0.006	0.006
Combined	0.05	0.07

RESULTS



$$P_\tau = -1.06 \pm 0.04\ (stat)\ ^{+0.05}_{-0.07}\ (syst)$$

arXiv:1204.6720v1