International School Cargese 2012: Across the TeV Frontier with the LHC

August 20 – September 1st, 2012

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ICREA/IFAE, Barcelona

Opening Remarks

- In these lectures I won't attempt to give an overview of the many types of searches for new phenomena that have been pursued at the Tevatron over the last decade.

- Instead, I will be focusing on a few examples which I consider particularly interesting because either:
  - the Tevaton provides unique or complementary information and so remains competitive with the LHC, or
  - the Tevatron has been superseded in those areas, but the experimental techniques are interesting and/or pionered at the Tevatron and then adopted at the LHC, or
  - simply to better illustrate the breadth of the Tevatron program of new phenomena searches.

  Incidentally, in half of them the Tevatron results are "significant", although not reaching the discovery threshold of 5 standard deviations.

- Here I take a "loose definition" of new phenomena searches, involving particular precision measurements, in addition to direct searches.

- Please feel free to interrupt and ask questions at any point in time during the lectures!

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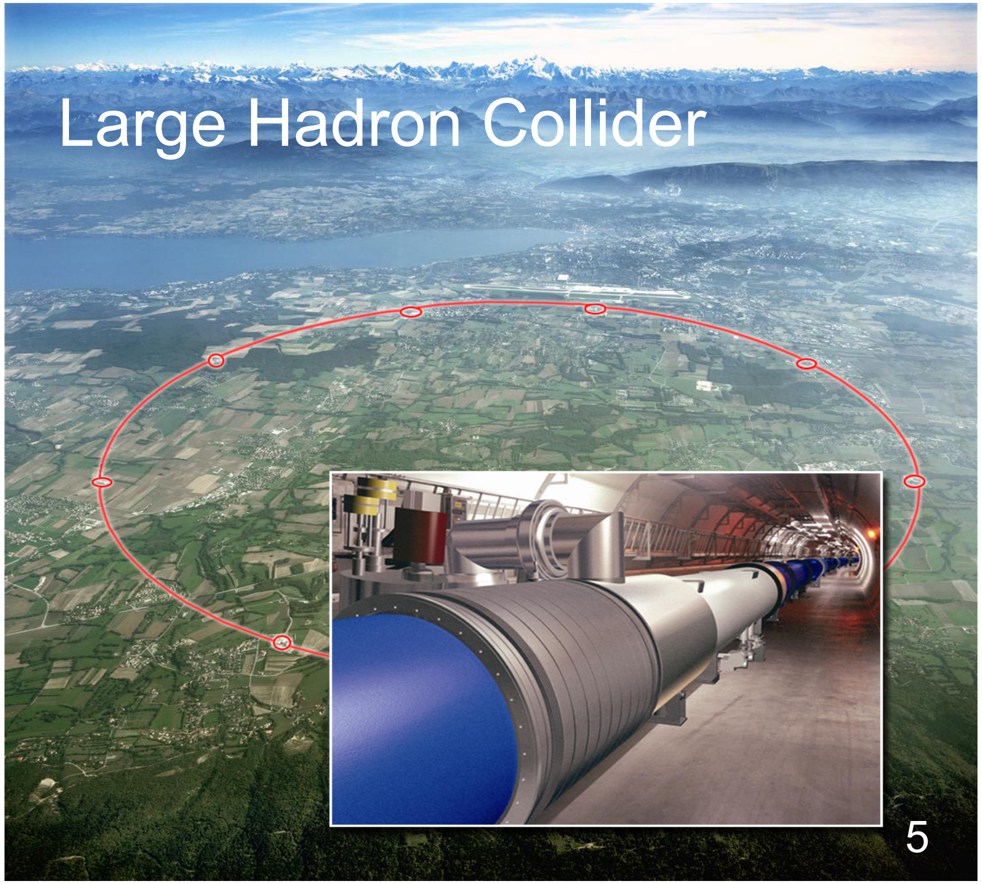
The Hadron Collider Era

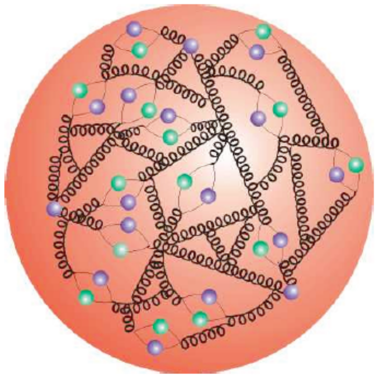
Lectures by: K. Jakobs

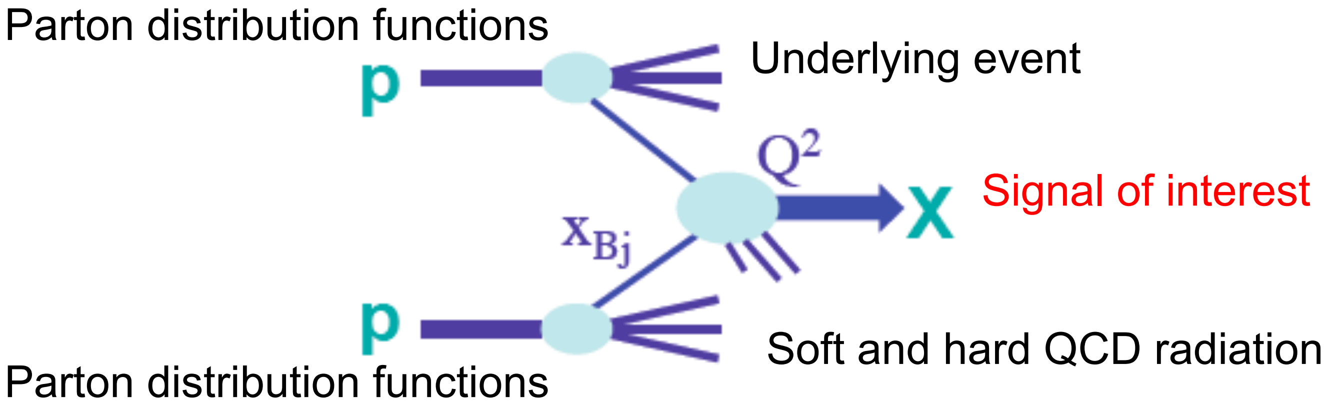
- CERN's Large Hadron Collider (LHC): only hadron collider in operation today.
  - proton-proton collisions at 7 TeV (2010-2011), 8 TeV (2012) and 14 TeV (2015).
- Fermilab's Tevatron Collider: 10-year long Run II ended Sept. 30th, 2011.
  - proton-antiproton collisions at 1.96 TeV.



Hadron Colliders as Discovery Machines

- Hadron colliders offer a brute-force approach to searches for New Physics:
  - Reach higher energies in a cheaper way than lepton colliders
  - Broad-band spectrum of collision energies and colliding particles ($u\bar{u}$, $d\bar{d}$, $u\bar{d}$, ug, gg, $b\bar{b}$,….).





- However, there is price to pay:
  - We don't know
    - which partons hit each other
    - what their momentum is
    - what the other partons do
  - We have limited knowledge of the proton/antiproton structure (PDFs).
  - The final state can be experimentally challenging (many jets, underlying event,..)
  - Precise theoretical calculations are more challenging.

Lectures by:
M. Perelstein's, A. Bafi

Tevatron vs LHC: Kinematic Reach

- LHC advantage #1:
  - the Tevatron cannot probe Q^2>(1.96 TeV)^2
- LHC advantage #2:
  - at a given Q^2 within reach, the Tevatron probes higher x values than the LHC
  - But parton distribution function rise dramatically towards low x

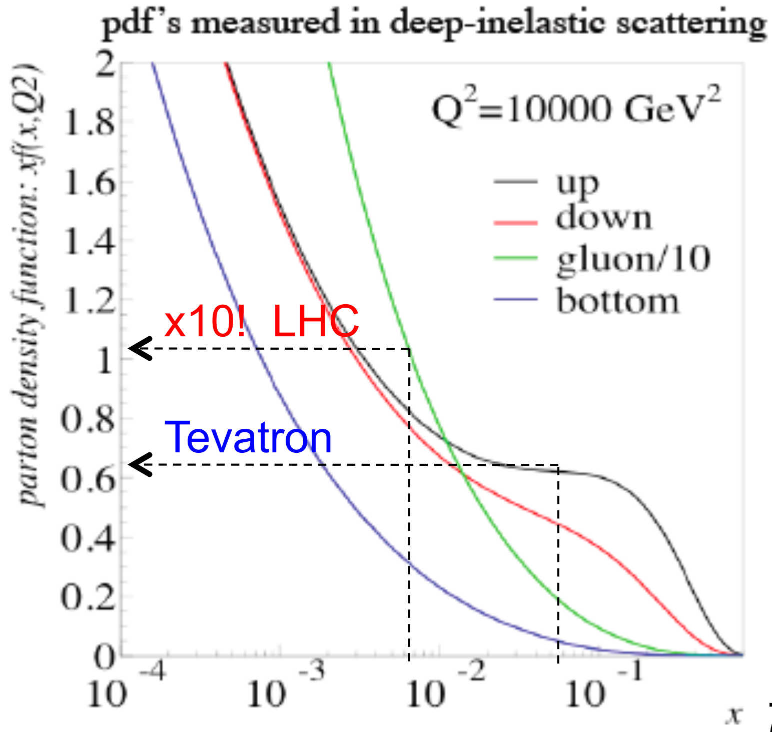
    ➔ larger cross sections at the LHC

Higgs: M~100 GeV
- LHC: <x>=100/14000≈0.007
- TeV: <x>=100/2000≈0.05

Gluino: M~1000 GeV
- LHC: <x>=1000/14000≈0.07
- TeV: <x>=1000/2000≈0.5

Cross Sections of Physics Processes (pb)

	Tevatron	LHC 14 TeV	Ratio
$W^\pm$ (80 GeV)	2600	20000	10
$t\bar{t}$ (2x172 GeV)	7	800	100
gg→H (120 GeV)	1	40	40
$\tilde{\chi}^+_1\tilde{\chi}^2_0$ (2x150 GeV)	0.1	1	10
$\tilde{q}\tilde{q}$ (2x400 GeV)	0.05	60	1000
$\tilde{g}\tilde{g}$ (2x400 GeV)	0.005	100	20000
Z' (1 TeV)	0.1	30	300



Tevatron vs LHC: Parton Luminosities

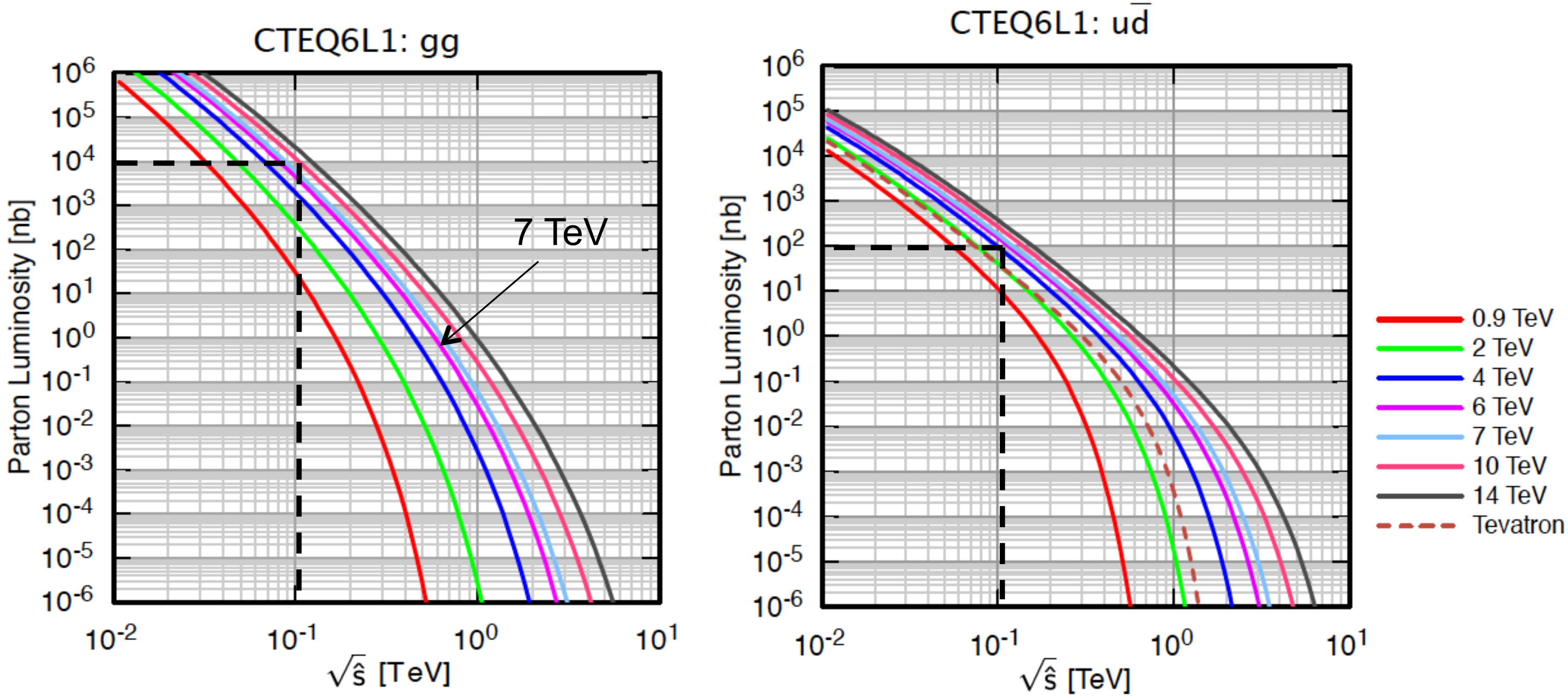
- Cross section for a hadronic reaction: $a + b \to \alpha + \text{anything}$

$$\sigma(s) = \sum_{\{ij\}} \int_{\tau_0}^{1} \frac{d\tau}{\tau} \cdot \frac{\tau}{\hat{s}} \frac{d\mathcal{L}_{ij}}{d\tau} \cdot [\hat{s}\hat{\sigma}_{ij\to\alpha}(\hat{s})] \qquad \tau = \hat{s}/s$$

C. Quigg, arXiv:0908.3660

Parton luminosity

$$\frac{\tau}{\hat{s}} \frac{d\mathcal{L}_{ij}}{d\tau} \equiv \frac{\tau/\hat{s}}{1+\delta_{ij}} \int_{\tau}^{1} dx [f_i^{(a)}(x) f_j^{(b)}(\tau/x) + f_j^{(a)}(x) f_i^{(b)}(\tau/x)]/x$$



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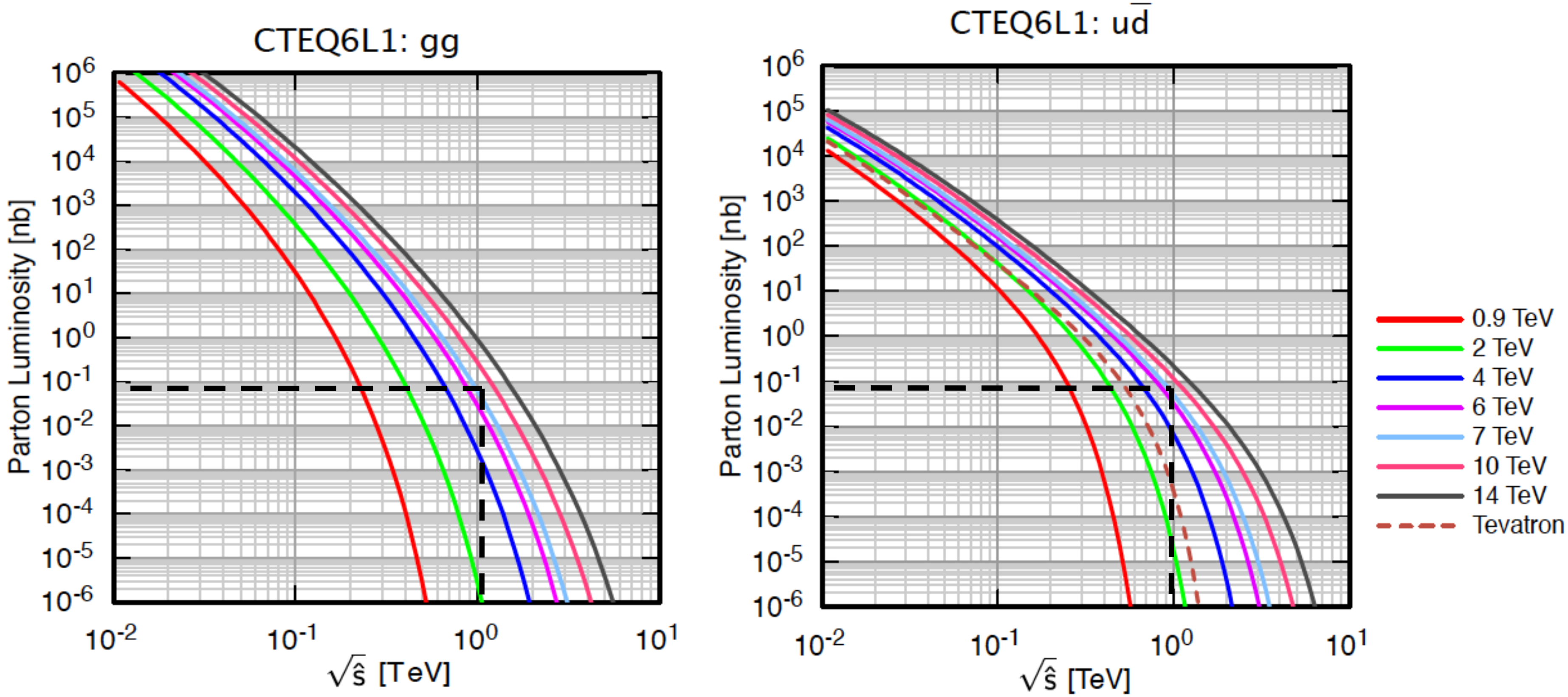
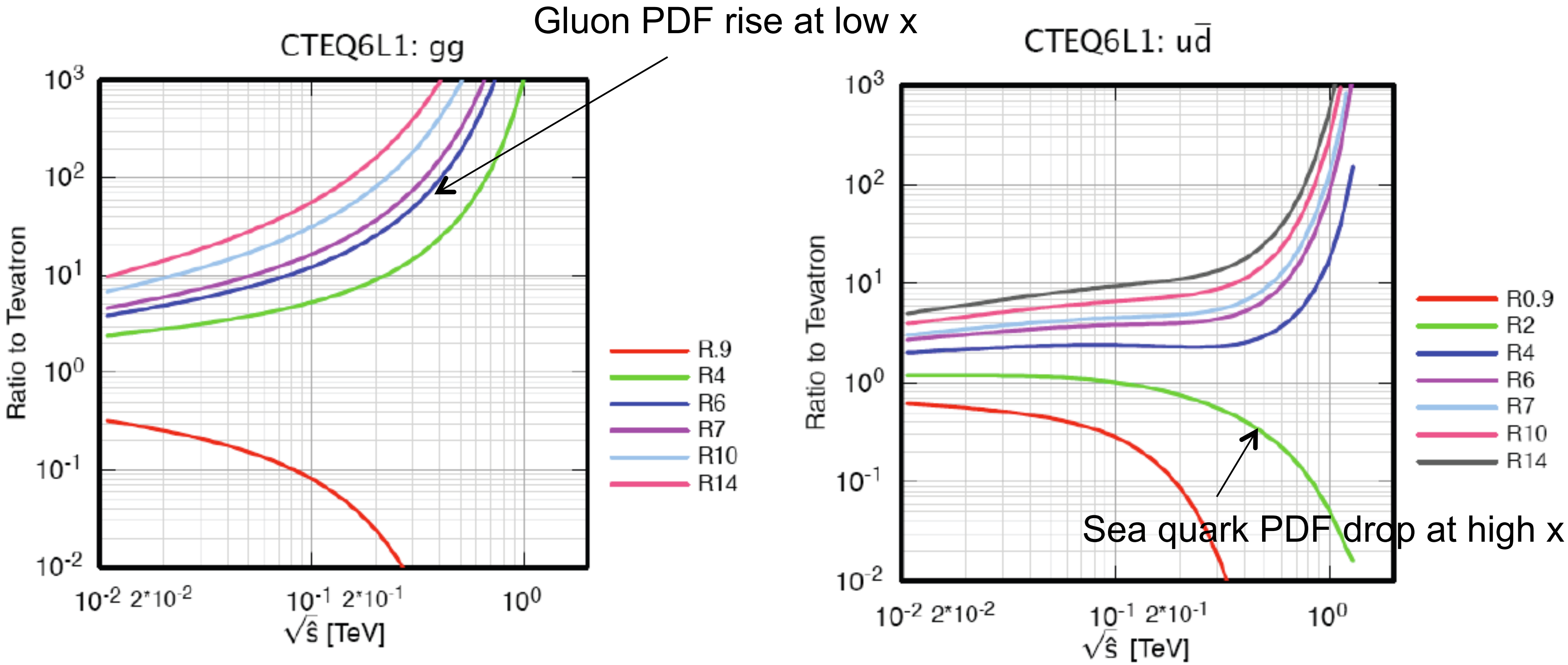


Tevatron vs LHC: Parton Luminosity Ratios

- To first order, power of collider can be characterized by the ratio of parton luminosities
  ➔Gives an idea of how much luminosity is needed by the LHC to supersede the Tevatron in a given process:
  e.g. ratio=10 means 1 fb^{-1} at LHC is comparable to 10 fb^{-1} at the Tevatron….



➔ The LHC is already operating at 8 TeV and delivered >12 fb^{-1} in 2012…
So what's the relevance of the Tevatron?

The Relevance of the Tevatron in the LHC Era

- The Tevatron can still compete with the LHC in a number of areas:

1) When not only the increase in signal cross section matters but the increase in the background can also have a significant impact. Examples:
    - One is interested primarily in $q\bar{q}$ but gg has similar signature ➔ large background
      E.g. $t\bar{t}$ charge asymmetry
    - Sometimes physics backgrounds increase faster than signal of interest and S/B at Tevatron is better.
      E.g. search for low mass Higgs, $H \rightarrow b\bar{b}$

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3) Searches exploiting unique features of a Tevatron experiment (e.g. low p_T lepton triggers, regular reversal of magnetic fields, etc).
   E.g. CP violation in B system

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4) Precision measurements not driven by overall statistics or kinematic reach, but rather by good understanding of environmental effects (e.g. pileup) or systematics in general.
   E.g. W mass, top mass

Won't be talking about these

Outline

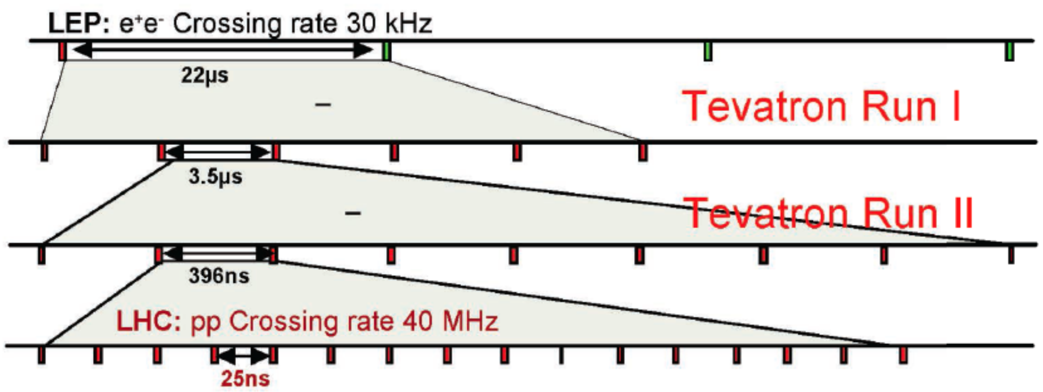
- Lecture 1
  - Preliminaries
    - The Tevatron, CDF and D0
    - Trigger and object reconstruction
  - Probing the electroweak sector
    - Forward-backward asymmetry in $Z/\gamma^* \rightarrow l^+l^-$
  - Probing the top quark sector
    - Forward-backward asymmetry in $t\bar{t}$

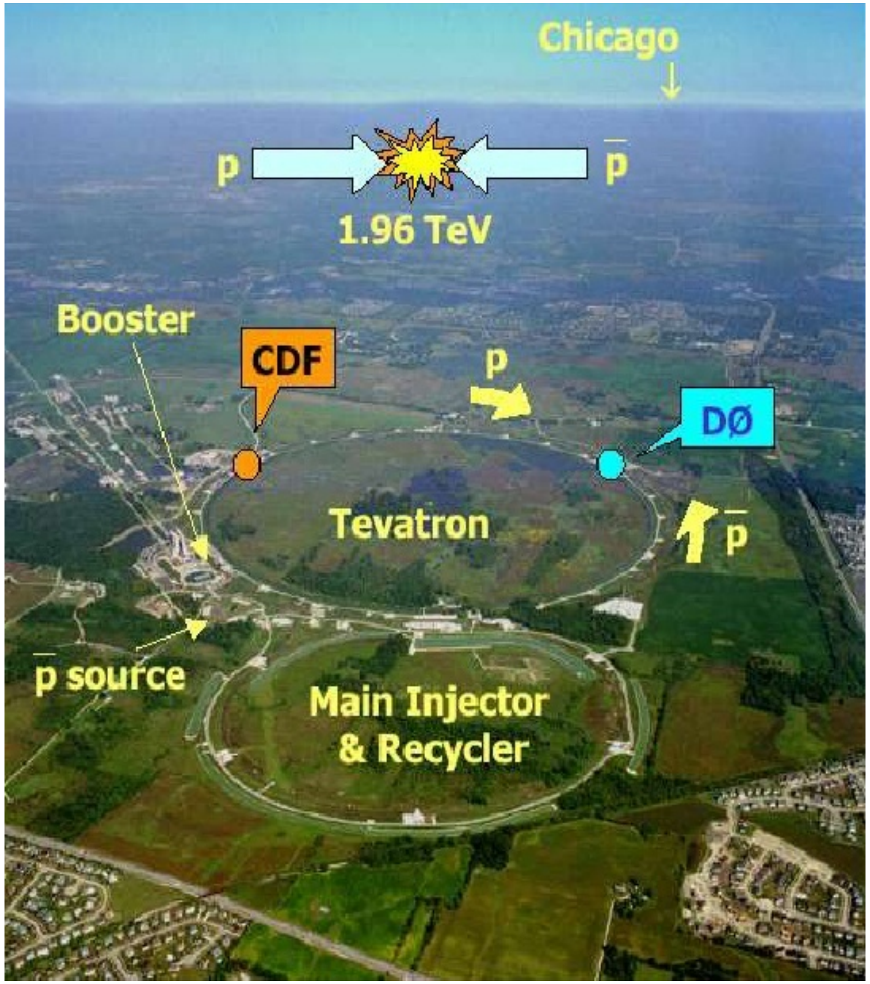
- Lecture 2
  - Probing the dark sector
    - Searches for dark matter
  - Probing the b-quark sector
    - Measurement of the dimuon charge asymmetry
  - Probing the EWSB sector
    - Searches for the SM Higgs boson

Tevatron Accelerator

- 6.3 km circumference $p\bar{p}$ collider
- Run 2:
    - Started March 2001
    - Ended September 2011
- Beam energy: 980 GeV ➔ $\sqrt{s}$=1.96 TeV

- 36 x 36 bunches
- Bunches cross every 396ns
    - ~2.5 M crossings/sec
- ~3 x 10^{11} protons/bunch
- ~3 x 10^{10} antiprotons/bunch
    - Making/storing so many antiprotons is a real challenge!





Tevatron Accelerator

- 6.3 km circumference $p\bar{p}$ collider
- Run 1: 1987-1996, $\sqrt{s}$=1.8 TeV, ~120 pb^{-1}
- Run 2: Mar 2001 - Sept 2011

  Beam energy: 980 GeV ➔ $\sqrt{s}$=1.96 TeV

- 36 x 36 bunches
- Bunches cross every 396ns
  - ~2.5 M crossings/sec
- ~3 x 10^{11} protons/bunch
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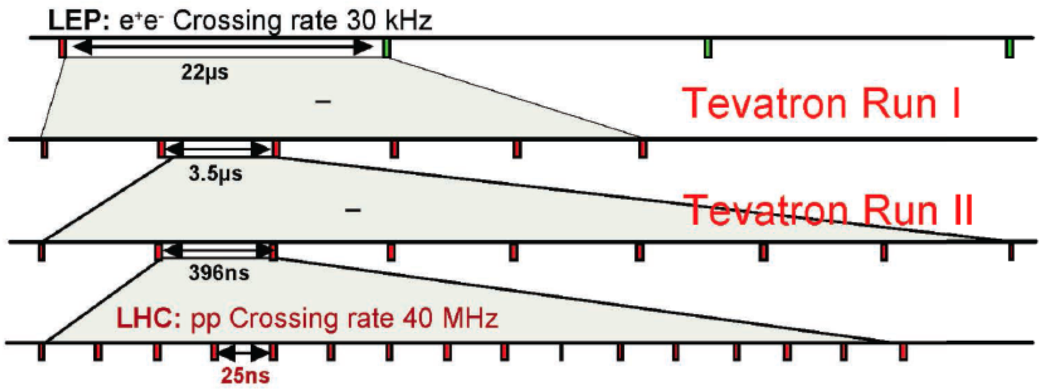
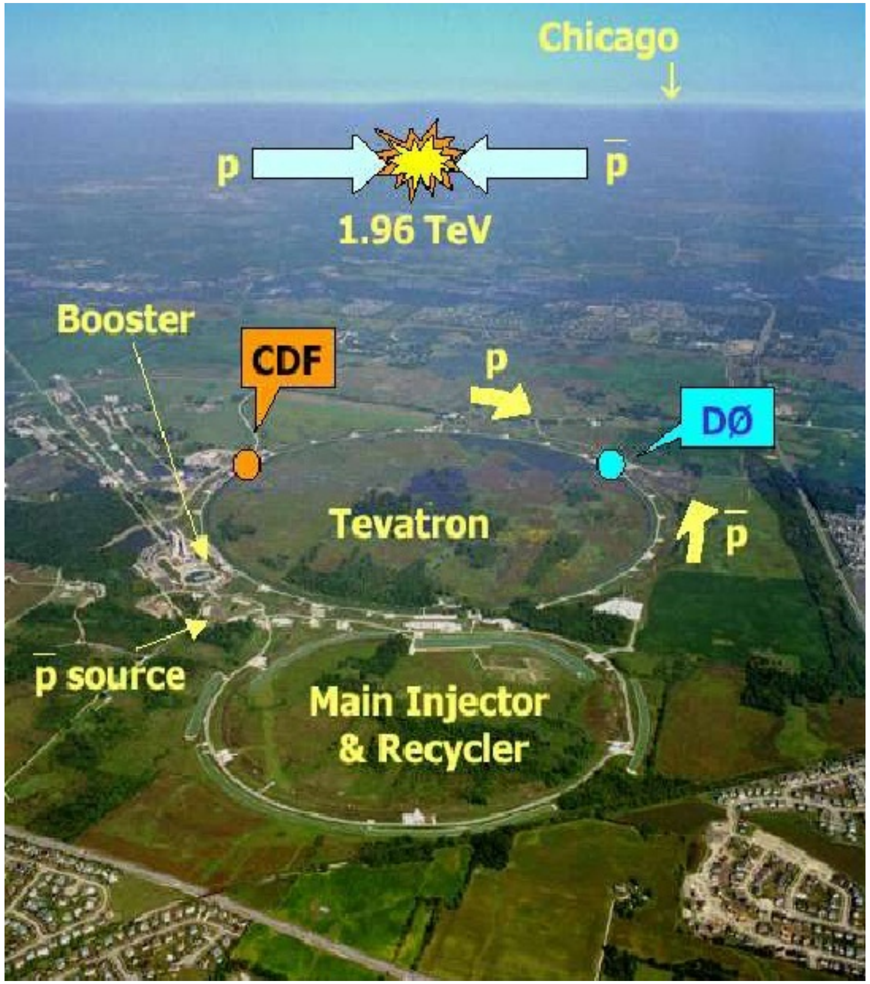
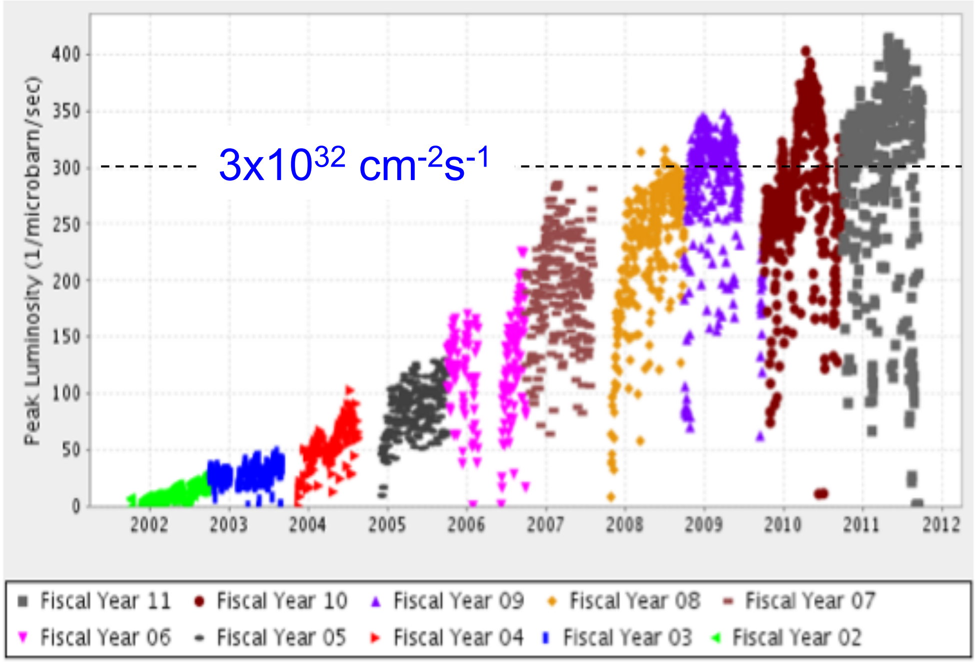
  ➔ ~x100 higher inst lum. than in Run 1!



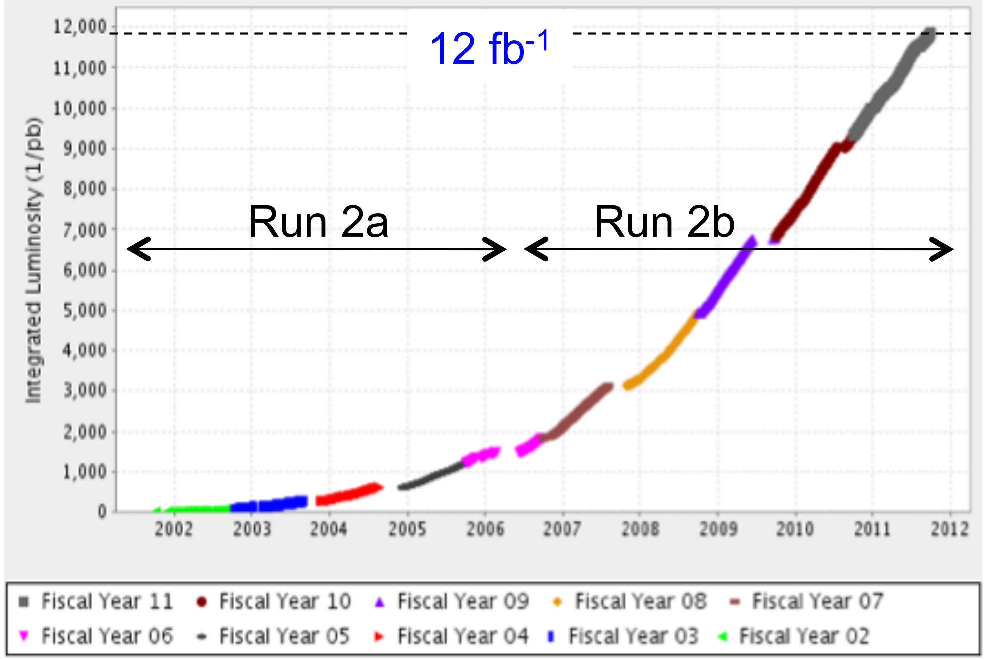


Tevatron Performance

Instantaneous luminosity vs time



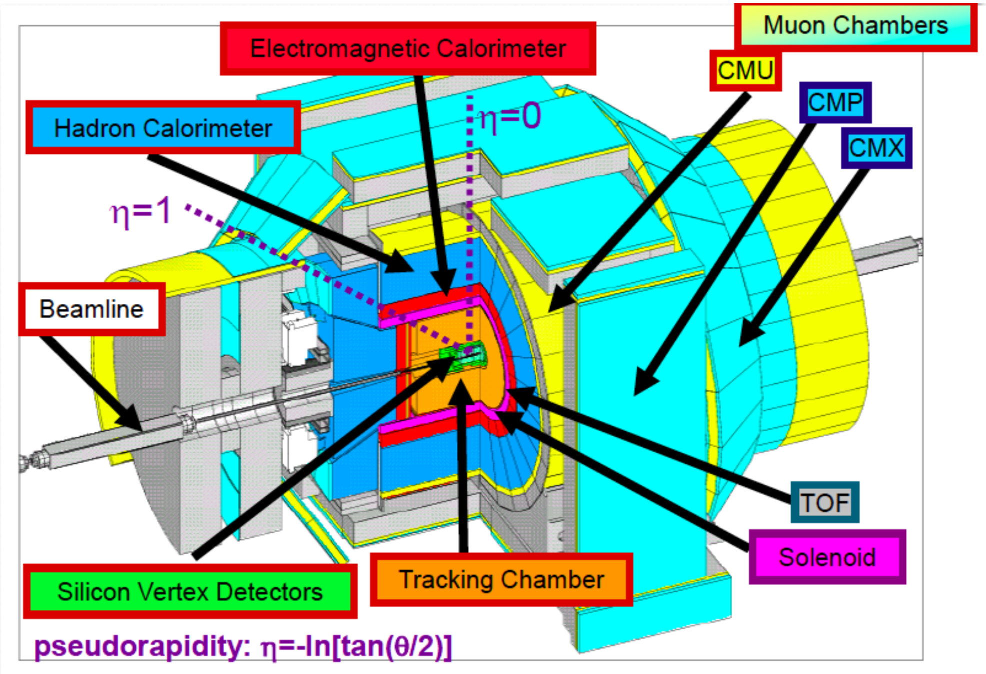
Integrated luminosity vs time

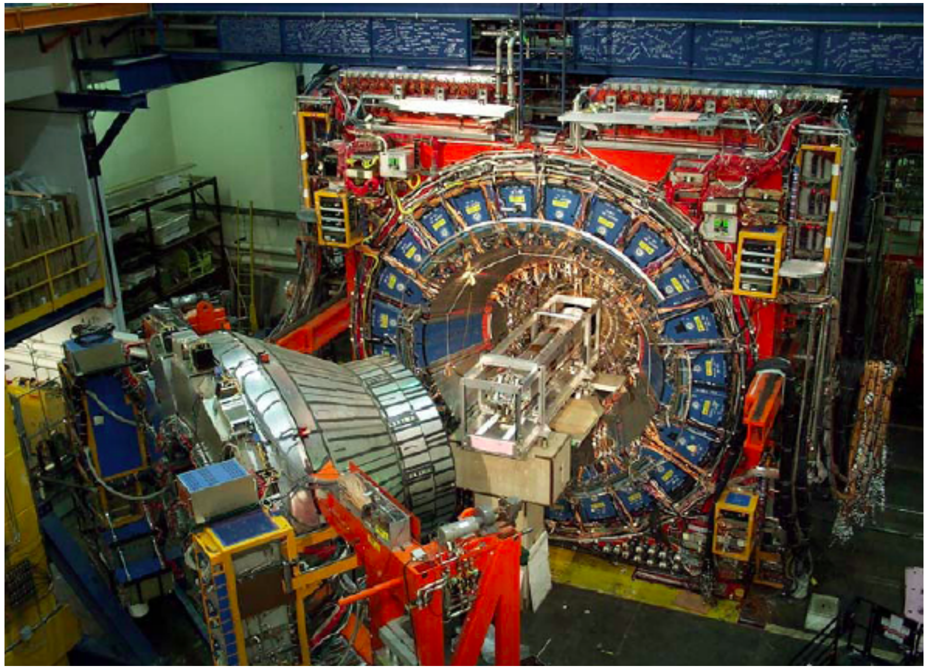


After many years of hard-work by the Accelerator Division, achieved impressive performance:

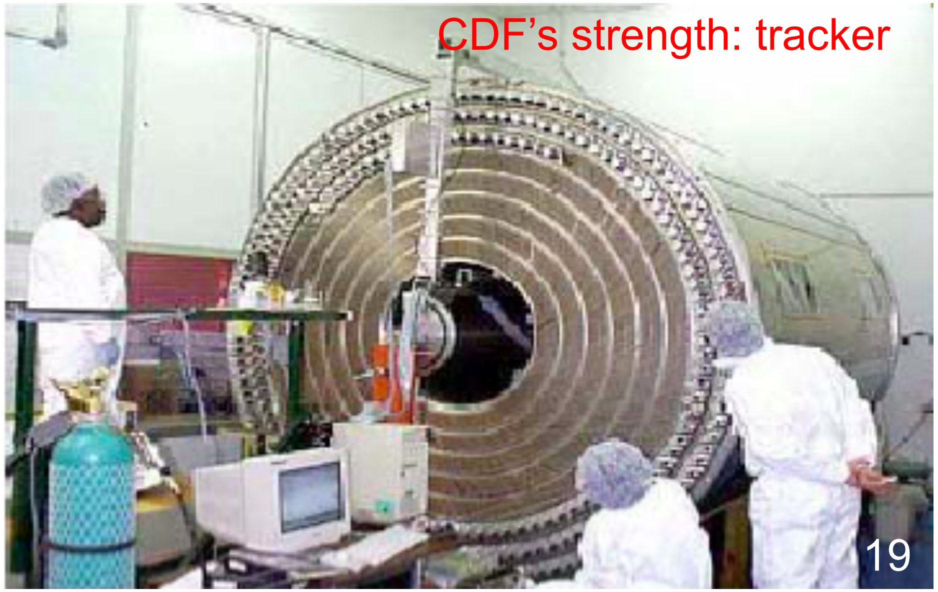
- Typical instantaneous luminosity: >$3x10^{32}$ cm^{-2}s^{-1}
- Typical integrated lum./week: ~60 pb^{-1}
  ➔ equiv. Run I dataset every 2 weeks!
- ~2.5 fb^{-1}/year in 2010 and 2011
- **11.9 fb^{-1}** delivered in Run 2

CDF Detector

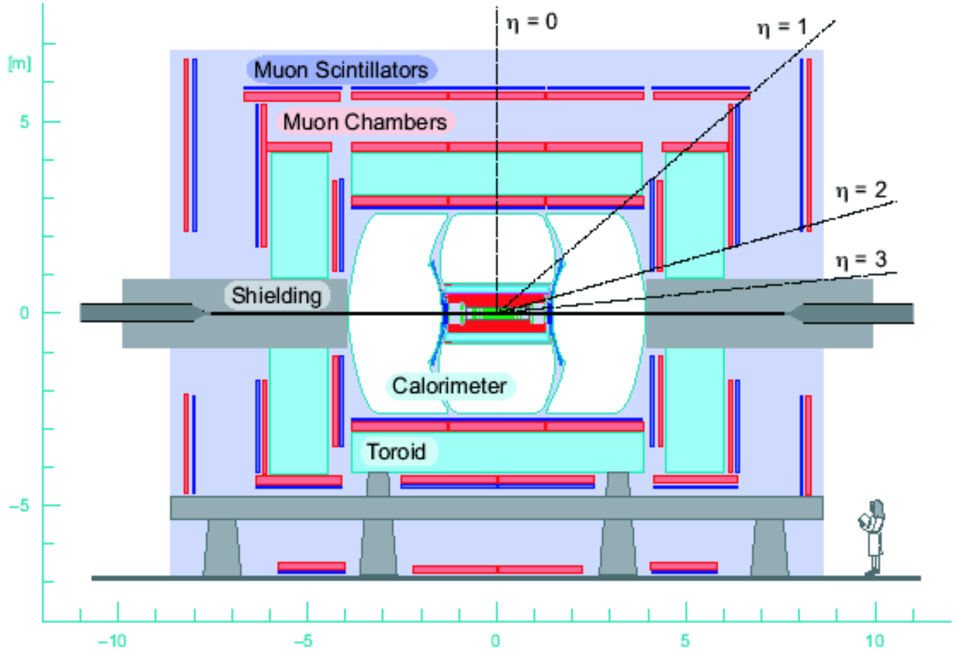




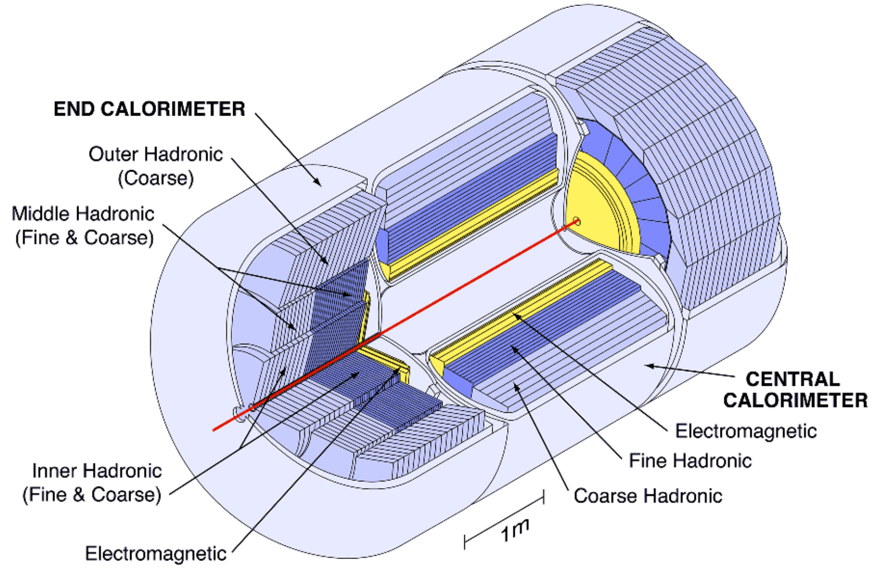
- All purpose detector composed of:
  - Silicon tracker (L00+SVX+ISL): 7 silicon layers
  - Central tracker (COT): $|\eta|<1.1$
  - Central solenoid: B=1.4 T
  - Time of flight
  - Preshower
  - EM calorimeters: $|\eta|<2.0$
  - Hadronic calorimeters
  - Muon system: $|\eta|<1.5$



D0 Detector

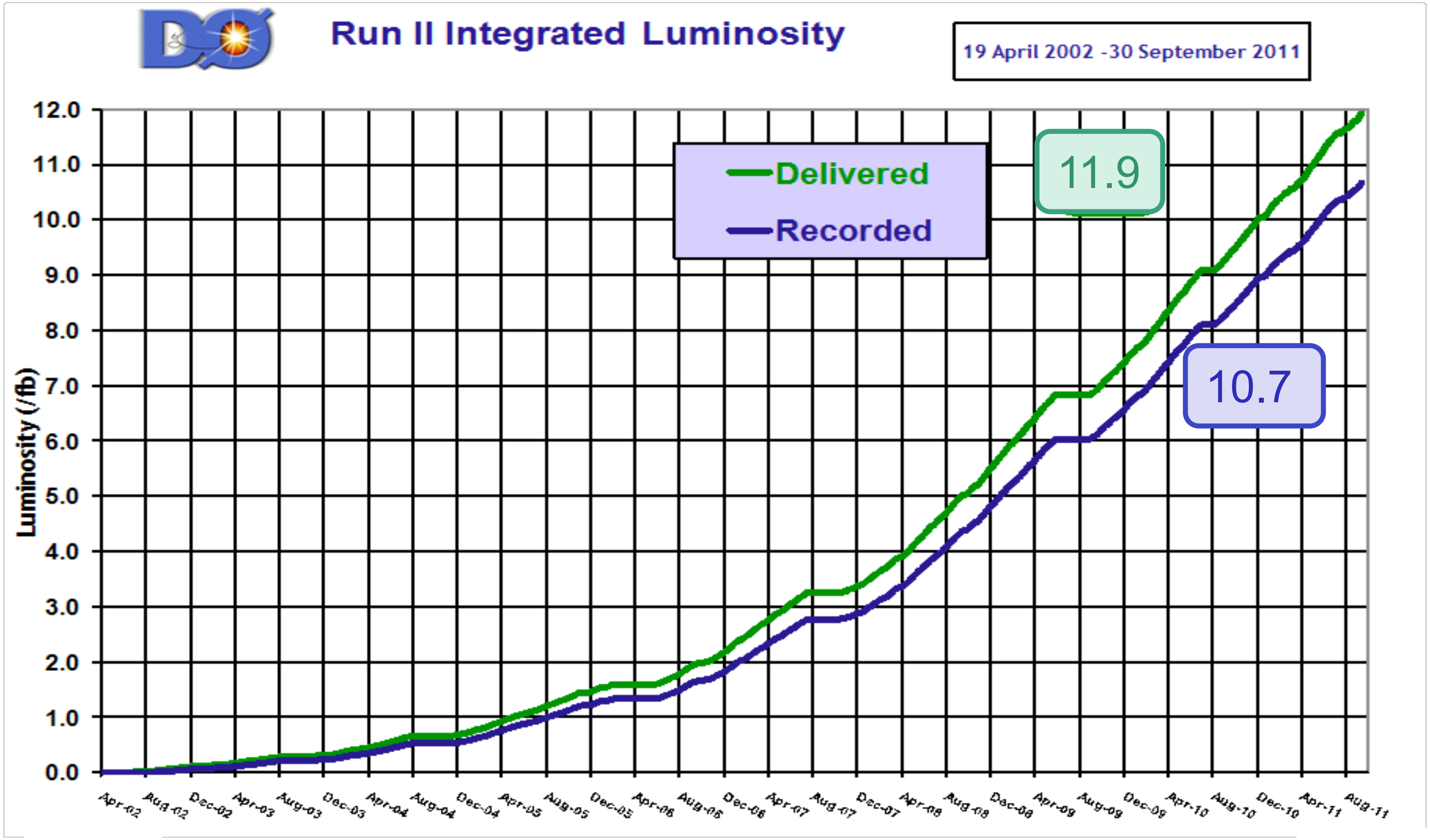


D0's strengths: calorimeter and muon system



- Different detector, same concepts:
  - Silicon tracker (L0+SMT): 5 silicon layers
  - Central fiber tracker (CFT): $|\eta|<1.5$
  - Central solenoid: B=2.0 T
  - Preshower
  - EM calorimeters: $|\eta|<2.5$
  - Hadronic calorimeters
  - Muon system: $|\eta|<2.0$

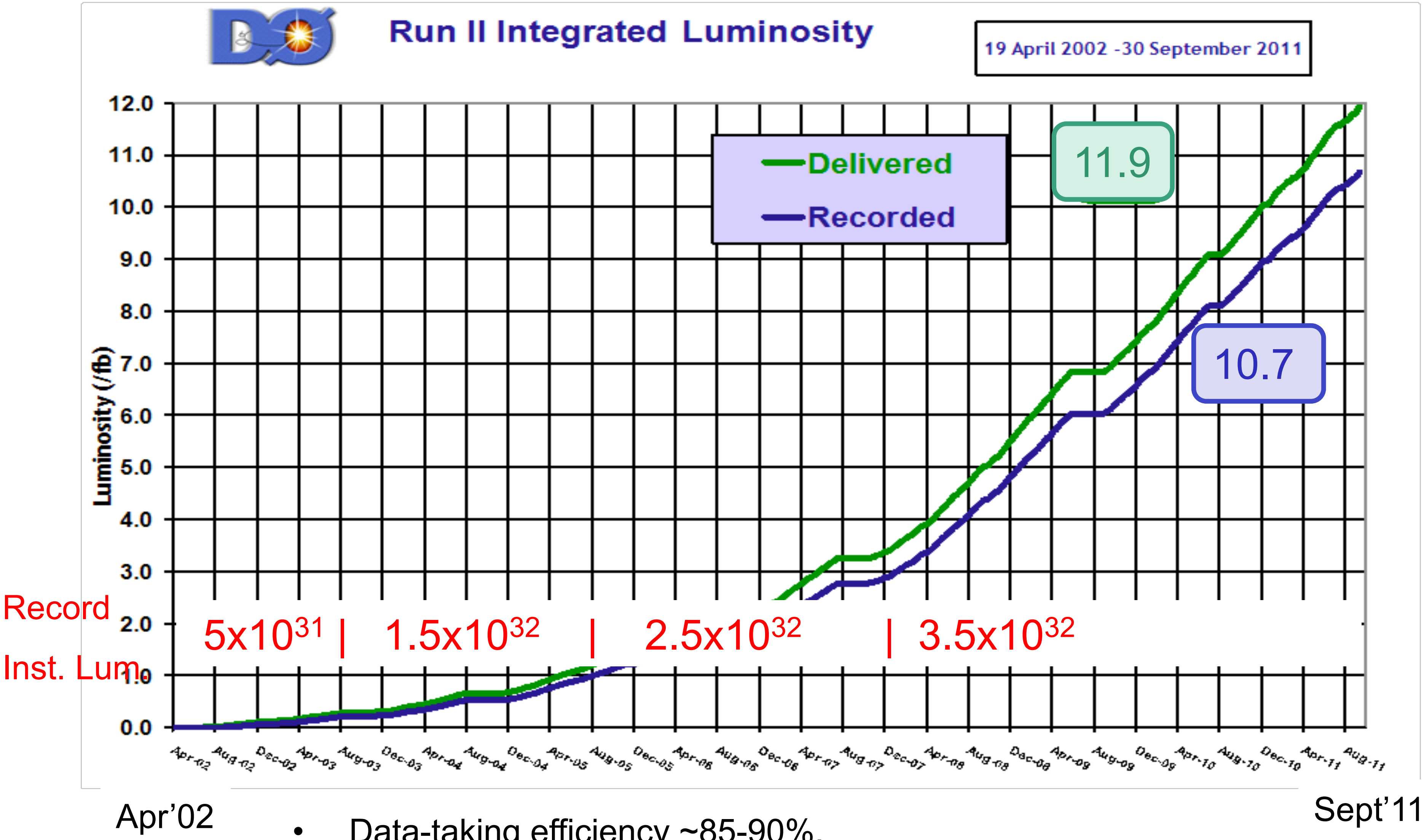
Detector Operation



Apr’02 Sept’11

- Data-taking efficiency ~85-90%.
- Up to 10 fb^{-1} in analysis (after data quality requirements)

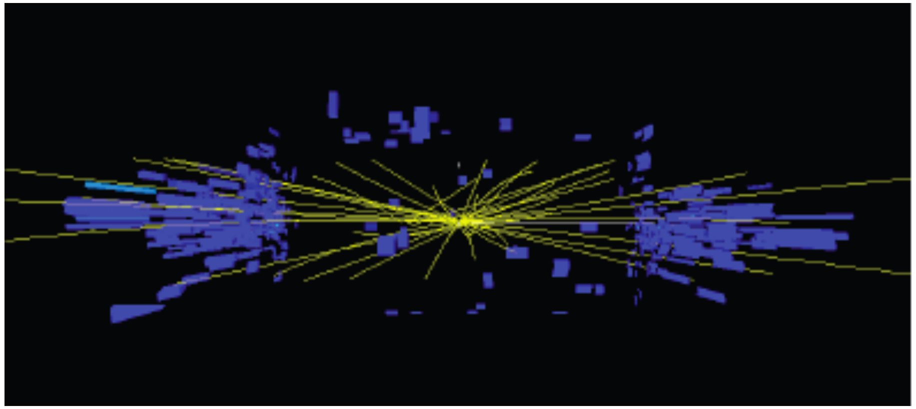
Detector Operation

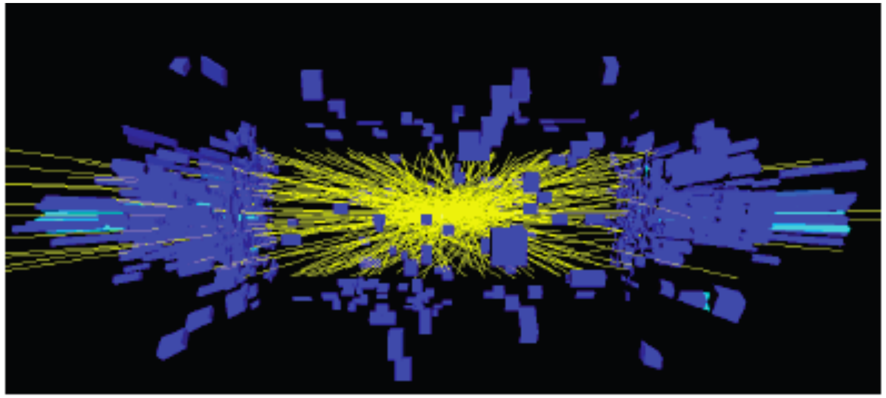


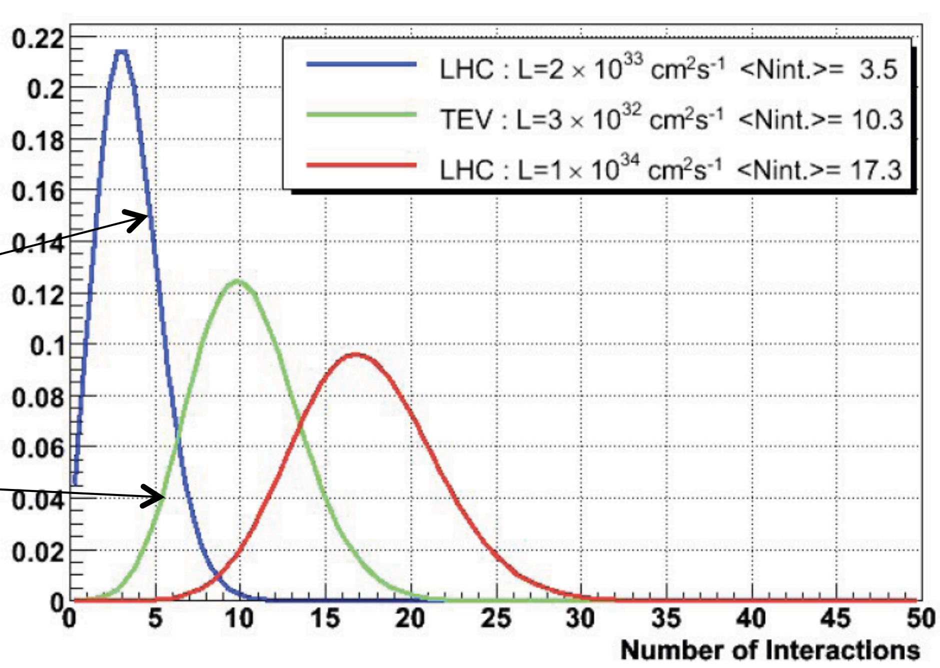
- Data-taking efficiency ~85-90%.
- Up to 10 fb^{-1} in analysis (after data quality requirements)
- Despite the steady increase in instantaneous luminosity!

The Challenges of Higher Luminosity

A random crossing event at @ $6x10^{31}$ cm^2s^{-1} …and at @ $2.4x10^{32}$ cm^2s^{-1}







Average number of interactions:

LHC: initial “low” lumi run
(L= $2x10^{33}$ cm^2s^{-1}): <N>=3.5

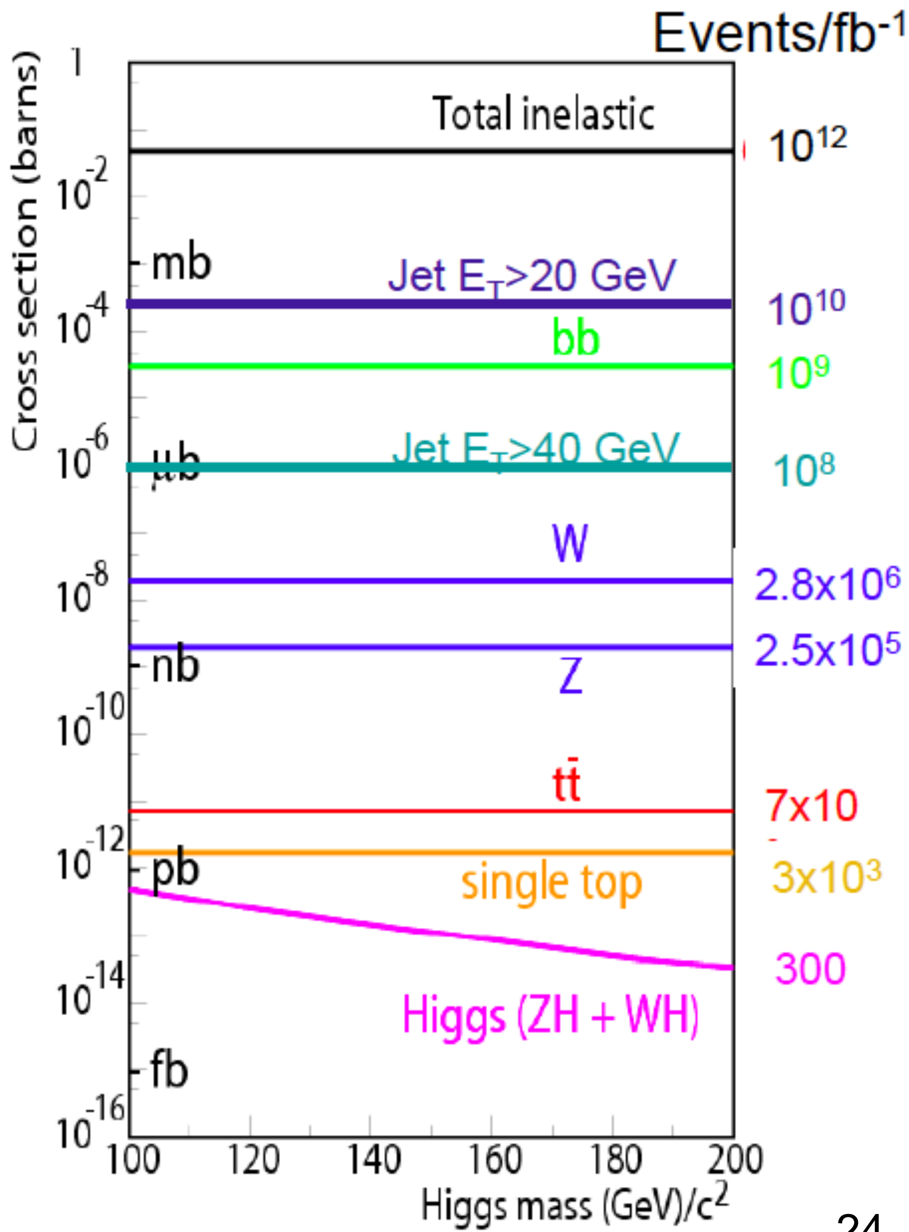
TeV: (L=$3x10^{32}$ cm^2s^{-1}): <N>=10

Tevatron Physics & Event Rates

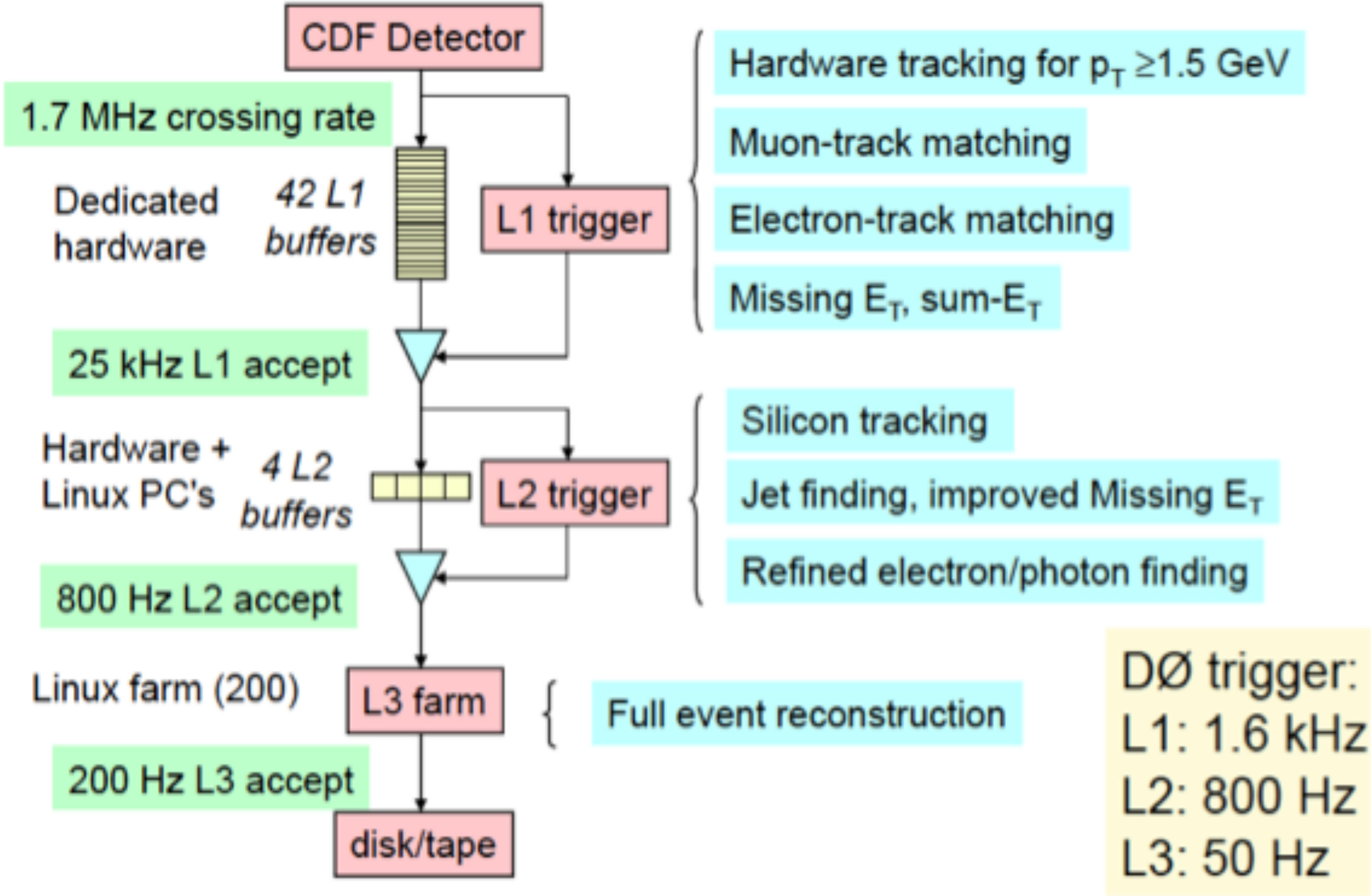
- Total inelastic cross section is huge:
  - Used to measure the luminosity

- Rates at e.g. 10^{32} $cm^{-2}s^{-1}$:
  - Total inelastic: 70 MHz
  - $b\bar{b}$: ~40 kHz
  - Jets with p_T>40 GeV: 300 Hz
  - W: 3 Hz
  - $t\bar{t}$: 25/hour

- Available bandwidth for writing to tape is ~50-200 Hz so need a carefully designed trigger strategy to make sure the interesting events are recorded!

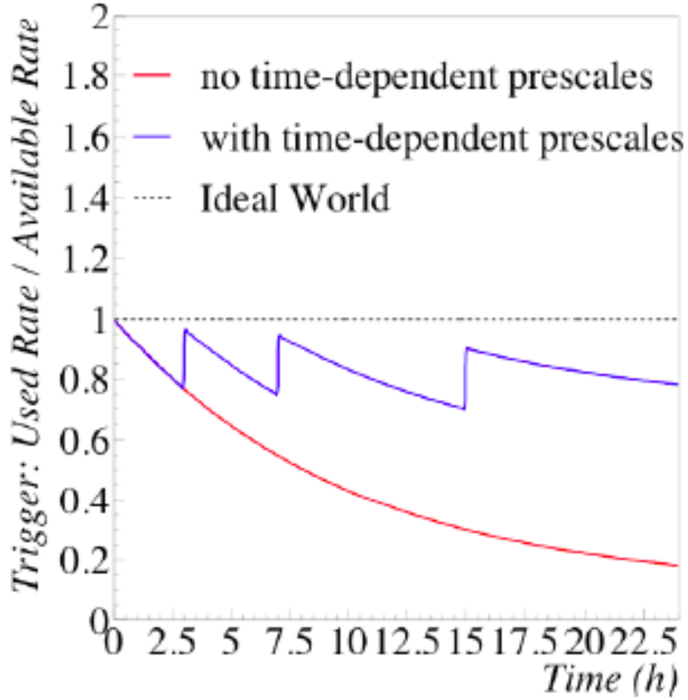


Typical Trigger System



Trigger Operation

- Goal is to maximize physics at trigger level:
  - Trigger cross section: N_{events}/nb^{-1}
  - Trigger rate: cross section x luminosity
- Luminosity falls within the store:
  - Trigger rate also falls within store
  - 75% of data are taken at <2/3 of peak luminosity
- Use sophisticated prescale system to optimize bandwidth usage: trigger more physics!
- As bandwidth at L1 and L2 becomes available, change prescales or bring in higher efficiency triggers (lower p_T, looser quality cuts, etc) which have higher trigger rates.



	CDF	DØ
L1 bits	64	128
L2 bits	125	>128
L3 bits	173	418

Typical Triggers and their Usage

- Unprescaled triggers:
  - Used for primary physics goals.

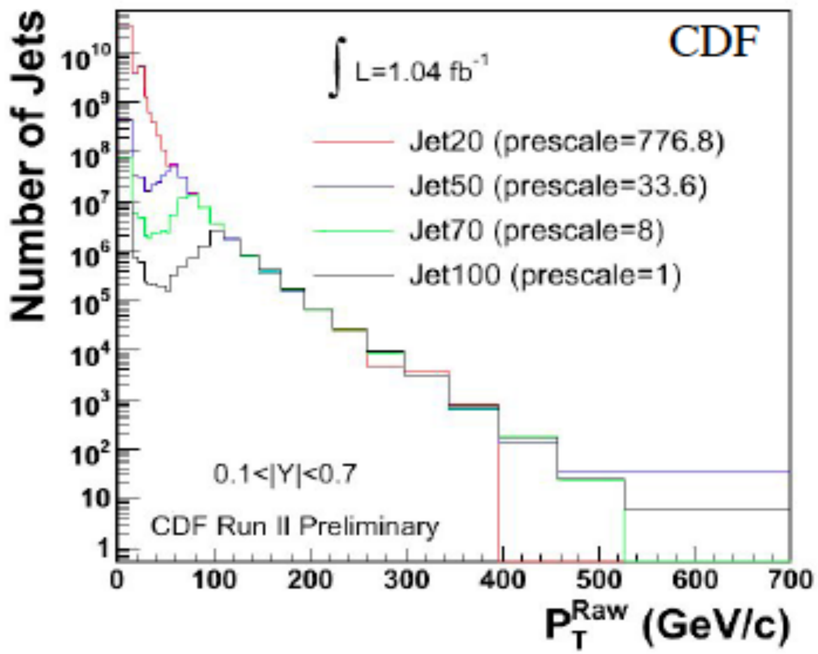
Examples:

- Inclusive electron, muon, p_T>20 GeV
  W, Z, top, WH, single top, SUSY, Z'
- Dilepton, p_T>4 GeV
  SUSY
- Photons, p_T>25 GeV
  Photon cross section, searches (monophoton)
  Jet energy scale (γ+jet)
- Inclusive jets, p_T>100 GeV
  Jet cross section, monojet
  Lepton and b-jet fake rates
- MET, MET>30 GeV
  SUSY, ZH→$\nu\nu$bb

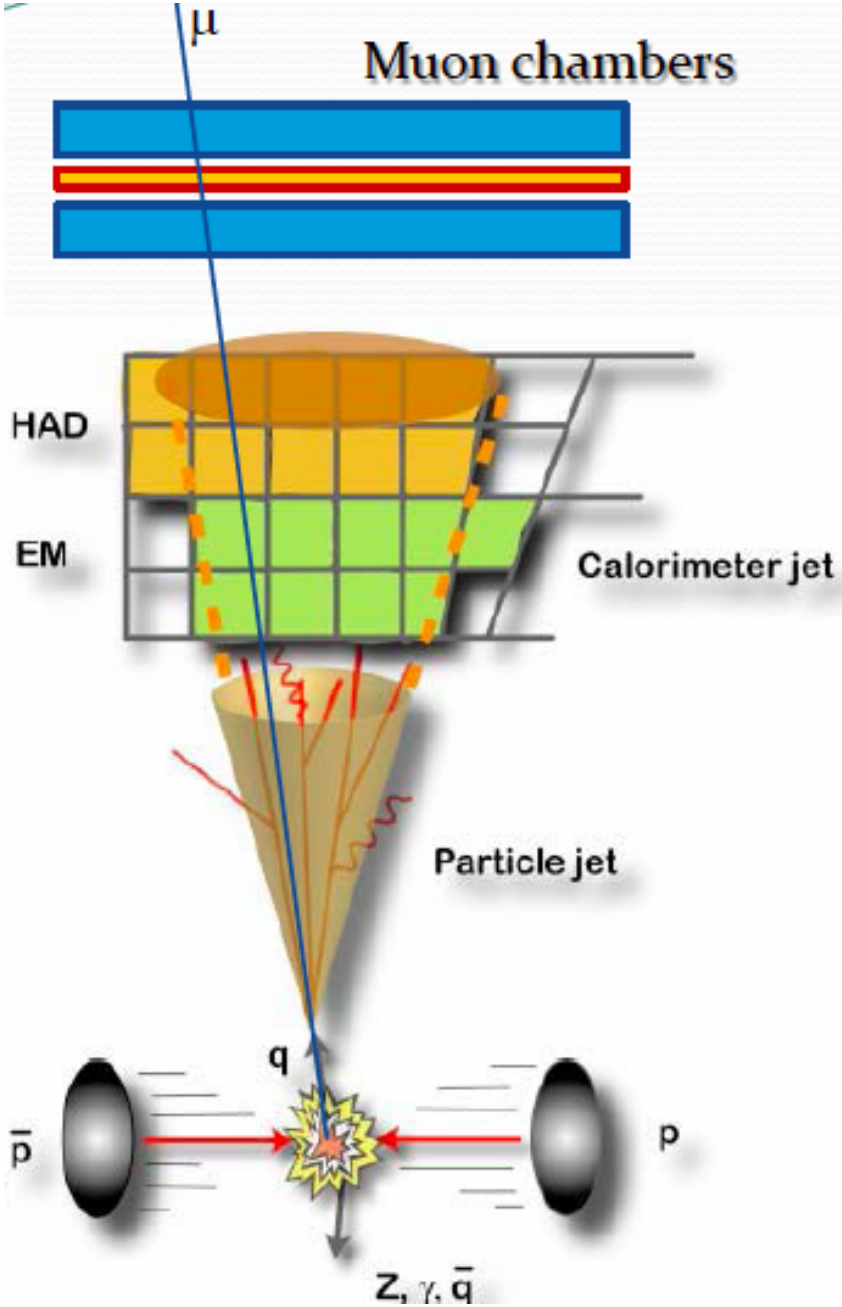
- Prescaled triggers:
  - Need to be turned off at higher lumi
  - Needed for monitoring
  - Prescales depend often on lumi

Examples:

- Inclusive jets, p_T>20, 50, 70 GeV
- Inclusive electron, muon, p_T>8 GeV
- B-physics triggers
- Backup triggers for any threshold



Particle Identification Basics



- Electrons:
  - EM clusters with e-like shower shape and with matching isolated track
- Photons:
  - Similar requirements as for electrons but with NO track pointing to them
- Muons:
  - Central track matched to muon chamber tracks and mip-like energy deposit in calorimeter
- Jets:
  - Result of a jet algorithm running on EM and hadronic calorimeter clusters

Lectures by: M. Schwartz

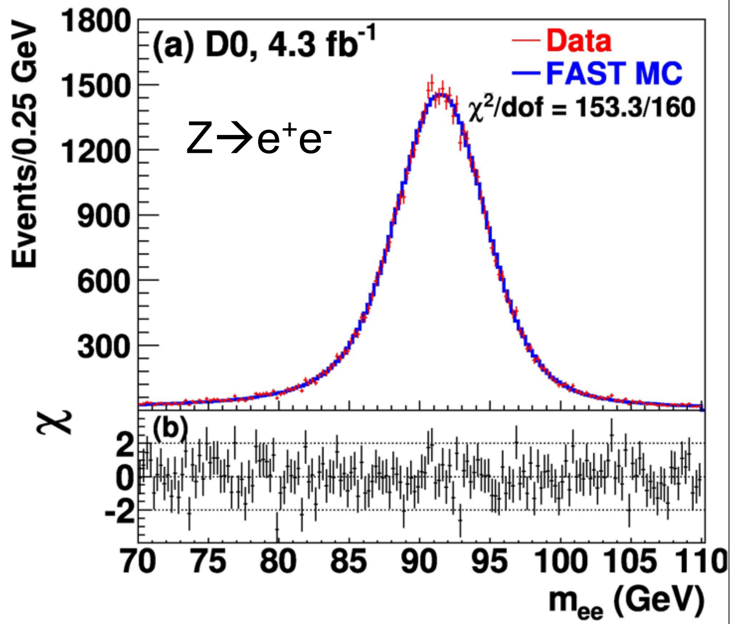
- Neutrinos:
  - Escape undetected; vector p_T inferred from p_T balance of all calorimeter deposits, corrected by identified muons

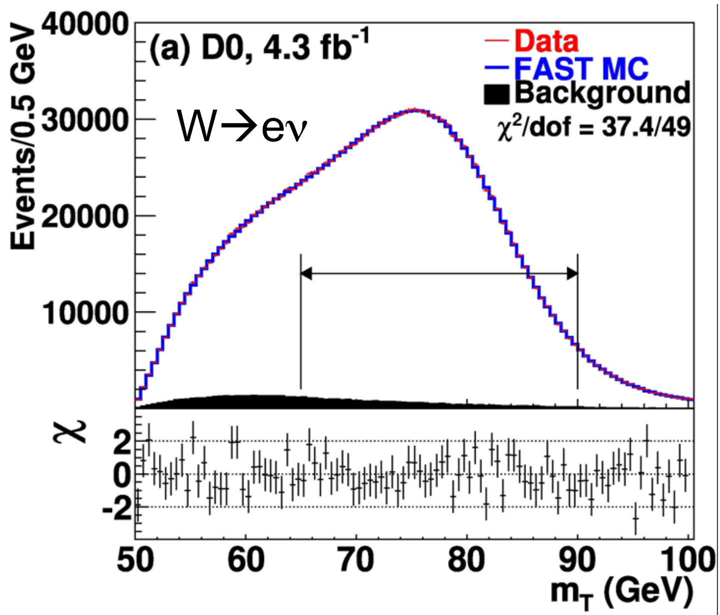
W and Z Candles

- Single $W(\rightarrow l\nu)/Z(\rightarrow l^+l^-)$ production occurs at high rate: O(100k/10k)/week!!
- Provide “standard candles”:
  - lepton identification/trigger efficiencies vs. time,
  - integrated luminosity verification,
  - electron energy scale, etc.

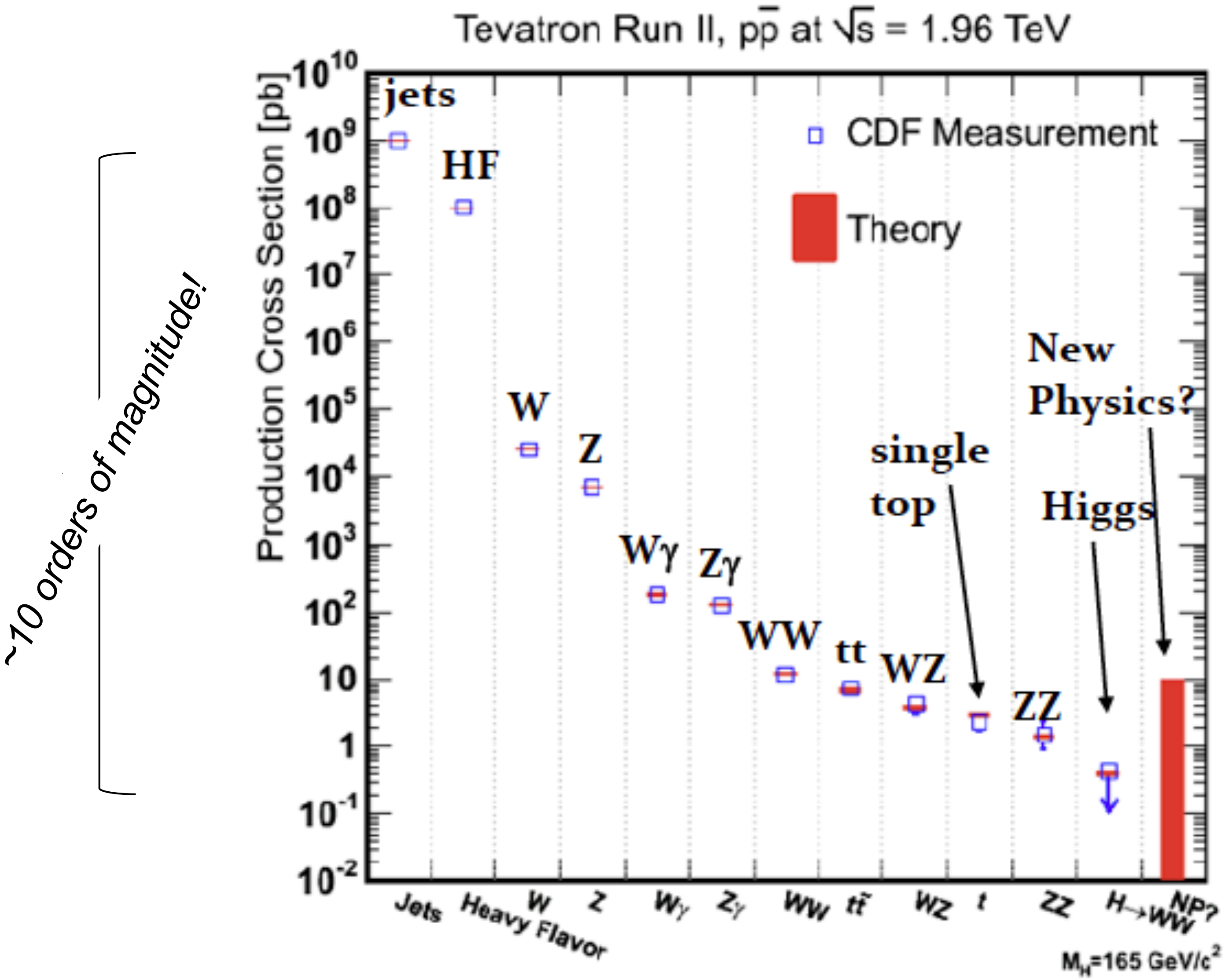
Extensive and competitive physics program:

- W/Z production cross sections and differential distributions
- Precision measurements: M_W, Γ_W, $\sin^2\theta_w$,…
- Diboson physics





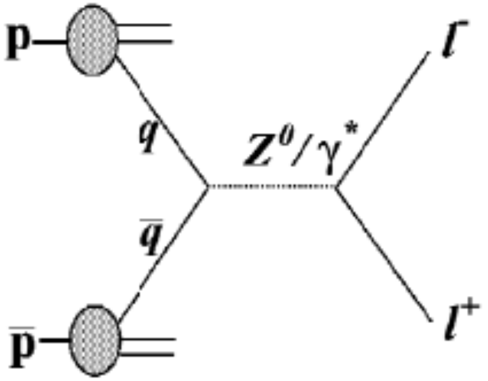
The SM as a Stepping Stone



Tevatron experiments have established a solid foundation to search for new phenomena through precise measurements of SM processes

Forward-Backward Asymmetry

A_{FB}



- Annihilation process uniquely specified by the helicities of the initial fermion and final l⁻. Corresponding amplitudes:

$$A_{ij} \equiv A(f_i \bar{f} \to e_j^- e^+)$$

$$C_L^Z(f) = g_Z\left[-I_3(f) + Q(f)\sin^2\theta_W\right]$$

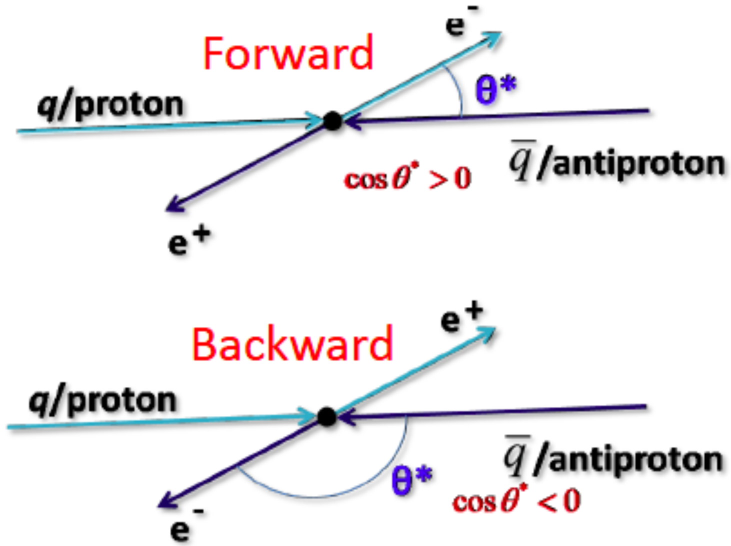
$$C_R^Z(f) = g_Z Q(f)\sin^2\theta_W$$

$$= -Qe^2 + \frac{\hat{s}}{\hat{s} - m_Z^2 + iM_Z\Gamma_Z} C_i^Z(f) C_j^Z(e)$$

- Differential cross section:

$$\frac{d\sigma(f\bar{f} \to e^- e^+)}{d\cos\theta^*} = (1/128\pi\hat{s})[(|A_{LL}|^2 + |A_{RR}|^2)(1+\cos\theta^*)^2$$

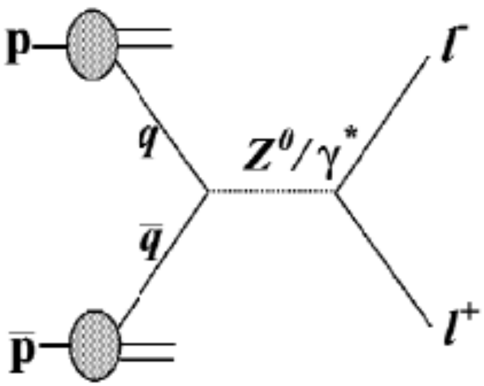
$$+ (|A_{LR}|^2 + |A_{RL}|^2)(1-\cos\theta^*)^2]$$



- Forward-backward asymmetry (A_{FB}):

$$A_{\rm FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B} = \frac{3}{4}\,\frac{|A_{LL}|^2 + |A_{RR}|^2 - |A_{LR}|^2 - |A_{RL}|^2}{|A_{LL}|^2 + |A_{RR}|^2 + |A_{LR}|^2 + |A_{RL}|^2}$$

A_{FB}



- Annihilation process uniquely specified by the helicities of the initial fermion and final l^-. Corresponding amplitudes:

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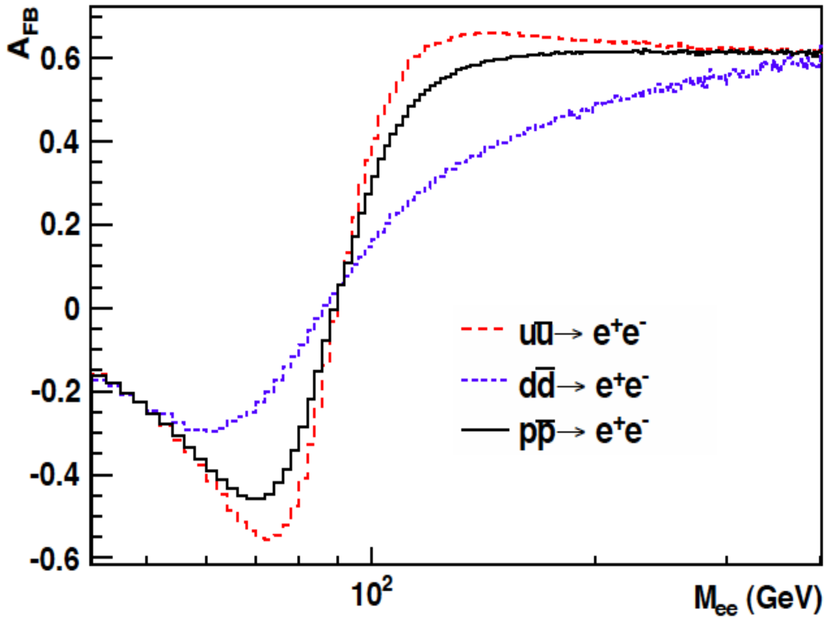
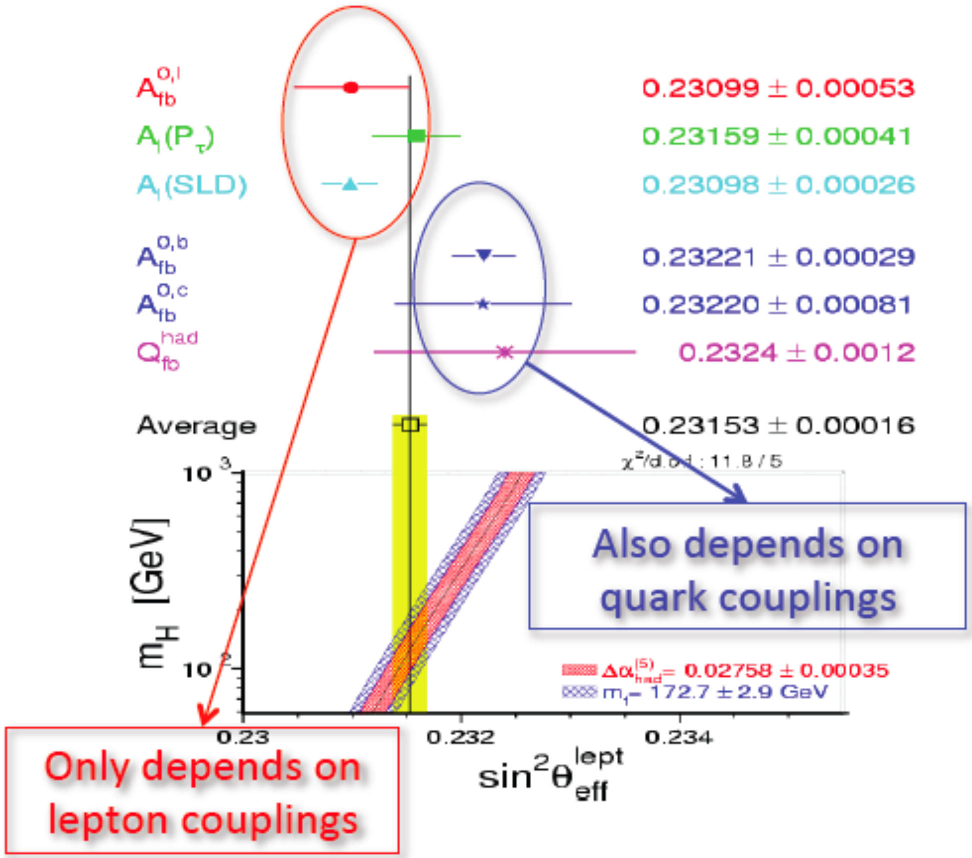
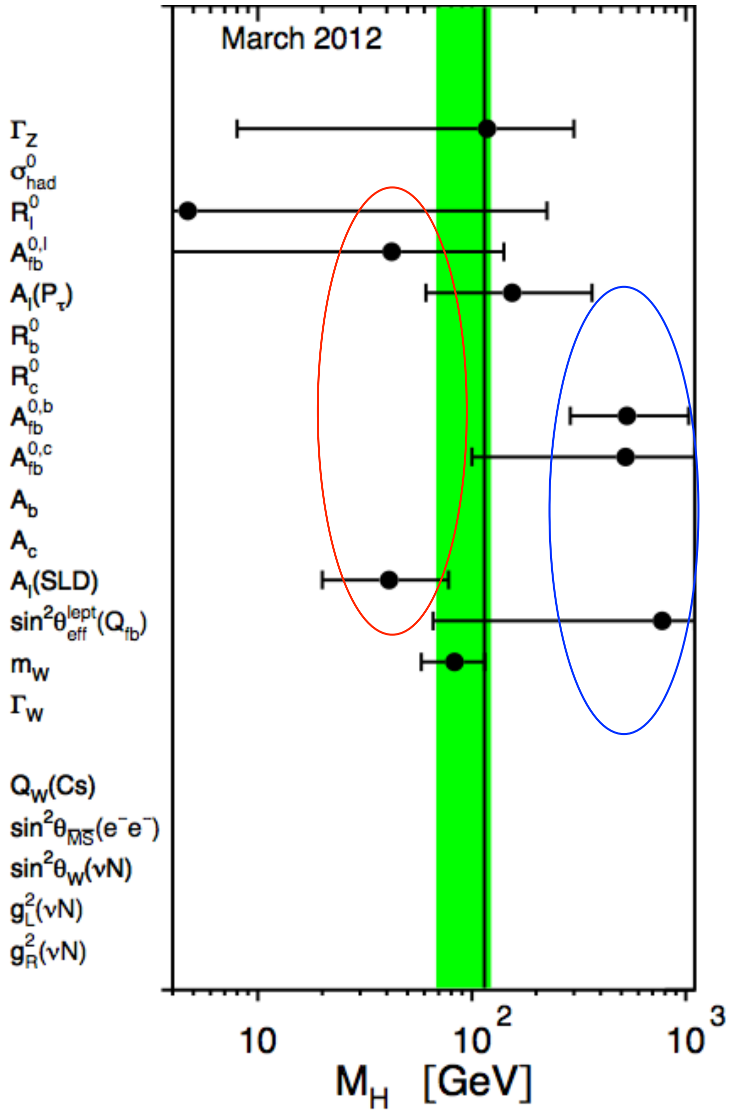
Not trivial mass dependence!!



Motivation

- A_{FB} is sensitive to $\sin^2\theta_W^{eff}$.
  - $\sin^2\theta_W^{eff}$ is an important precision EW parameter, logarithmically sensitive to M_H.
- Direct measurement of Z-to-light quark couplings.
  - There is “some tension” between measurements depending only on lepton couplings and those also sensitive to quark couplings.





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- Direct measurement of Z-to-light quark couplings.
  - There is “some tension” between measurements depending only on lepton couplings and those also sensitive to quark couplings.
- Probe for new physics affecting A_{FB} at energy scales beyond those probed at LEP (>200 GeV).
  - A_{FB} would be particularly useful to unravel nature of a resonance found!

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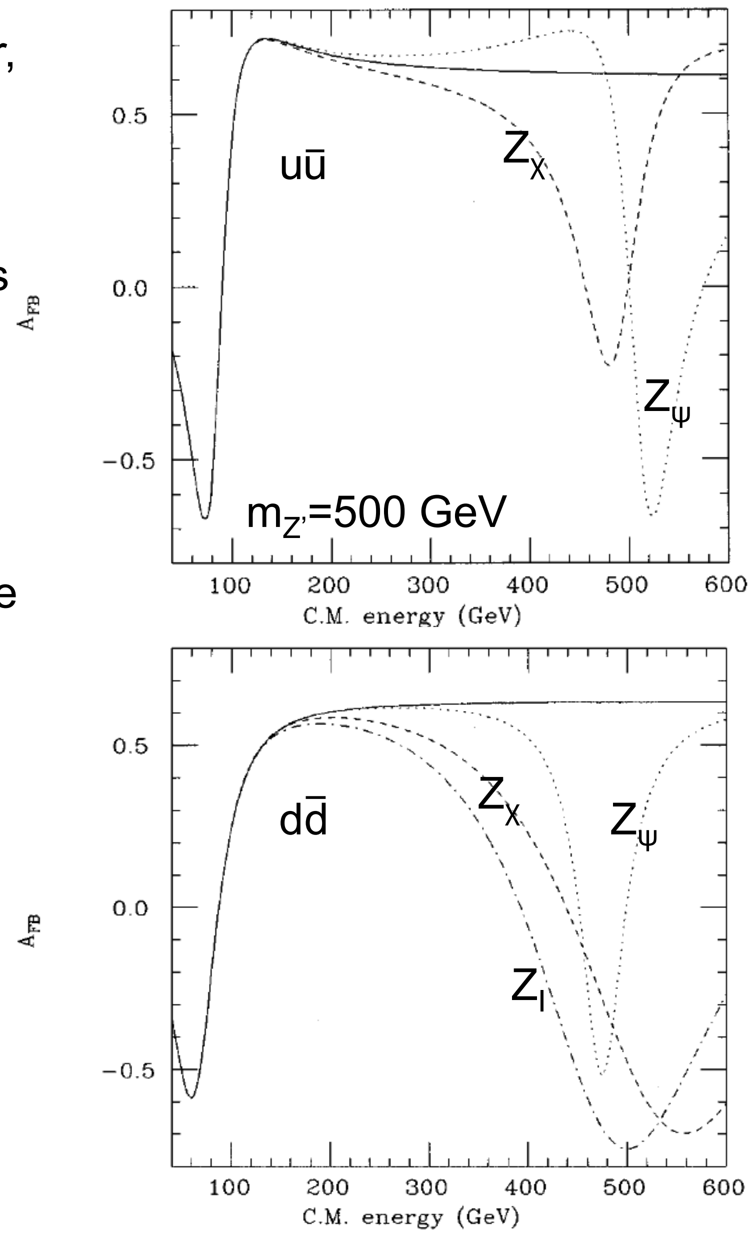
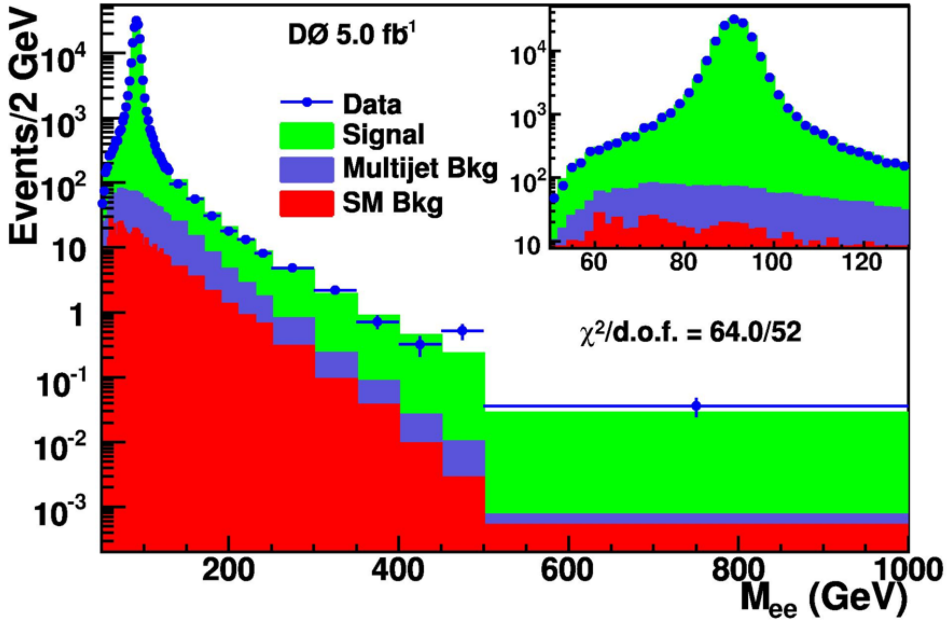


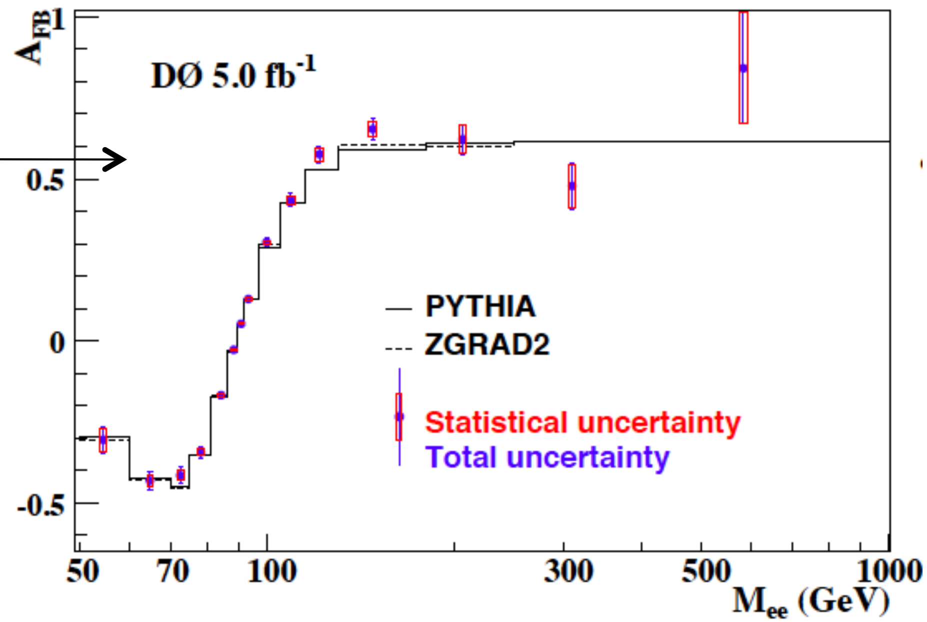
Measurement of A_{FB}

- Event selection:
  - 2 isolated electrons with p_T>25 GeV with shower shape consistent with that of an electron.
  - If both electrons in the central calorimeter, require them to be track-matched and of opposite charge.
  - If only one electron in the central calorimeter, require it to be track-matched and use its charge to determine forward/backward.



- Small backgrounds, dominated by QCD multijet, measured directly in data.

- Measured A_{FB} corrected for effects of detector acceptance and resolution, and charge misidentification rate.
  - Statistically-limited!



Measurement of Z-to-Light Quark Couplings

- Simultaneous measurement of Z-to-light quark vector and axial couplings

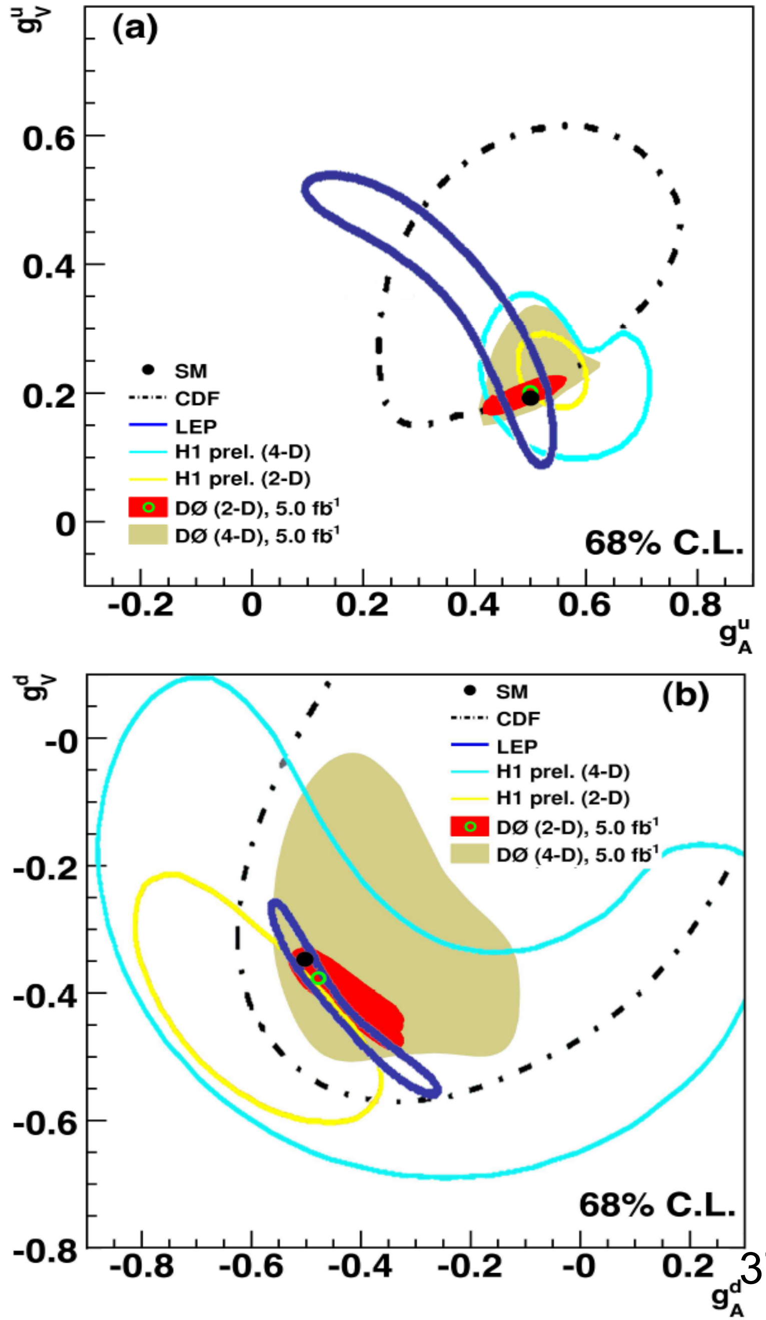
$$g_V^f = I_3^f - 2q_f \cdot \sin^2\theta_W\,,$$
$$g_A^f = I_3^f\,,$$

by comparing the unfolded A_{FB} distribution to templates generated with RESBOS for different values of the couplings.

  - Electron couplings fixed to the SM prediction and $\sin^2\theta_{eff}^l$ to the world-average value.

- Perform two types of fits:
  - 2D: fixing u(d) quark couplings and fitting d(u) quarlk couplings
  - 4D: fitting all quark couplings simultaneously

- Most precise direct measurement!



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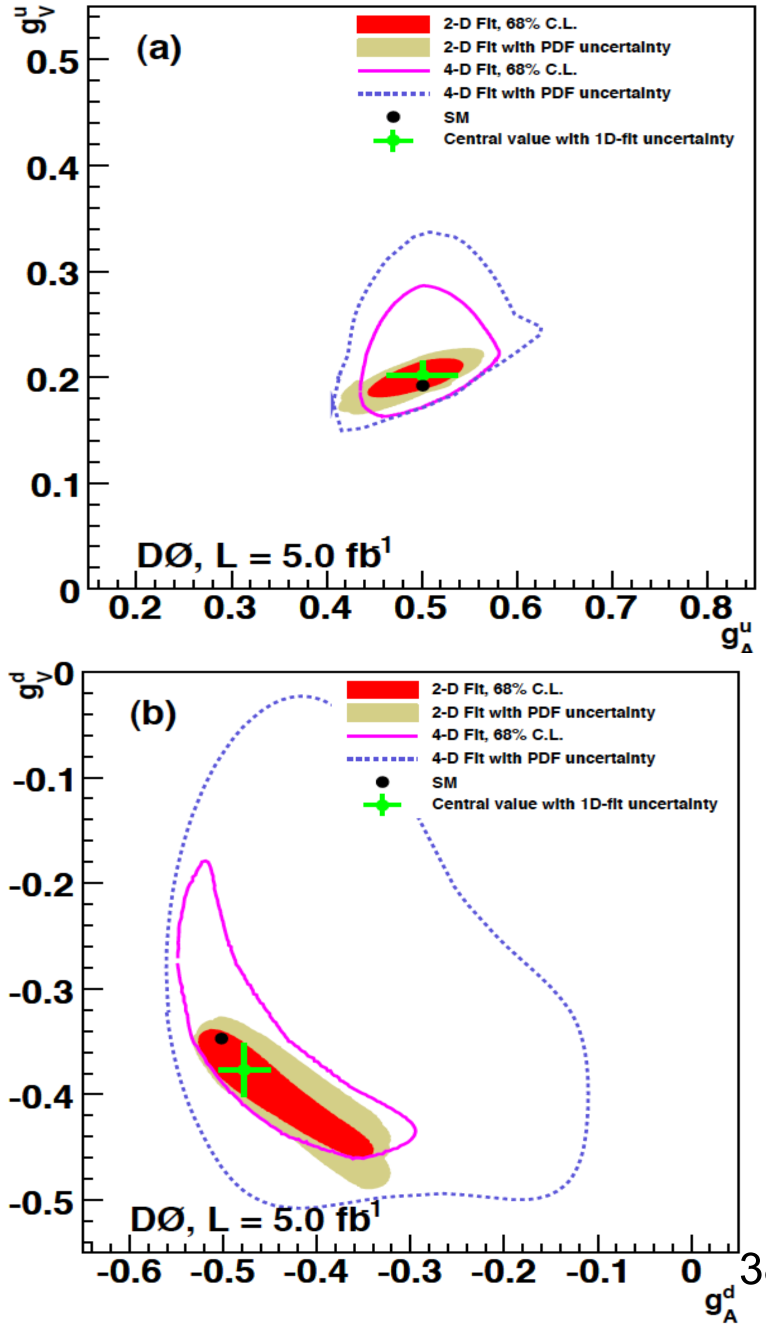
  Further improvement expected from combination of channels (and CDF+D0), as well as reduced PDF uncertainties!



Measurement of $\sin^2\theta_{eff}^l$

- Compare measured raw A_{FB} (not unfolded) with predicted one from MC samples with different values of $\sin^2\theta_{eff}^l$.
  ➔ Avoid systematic uncertainty from unfolding!

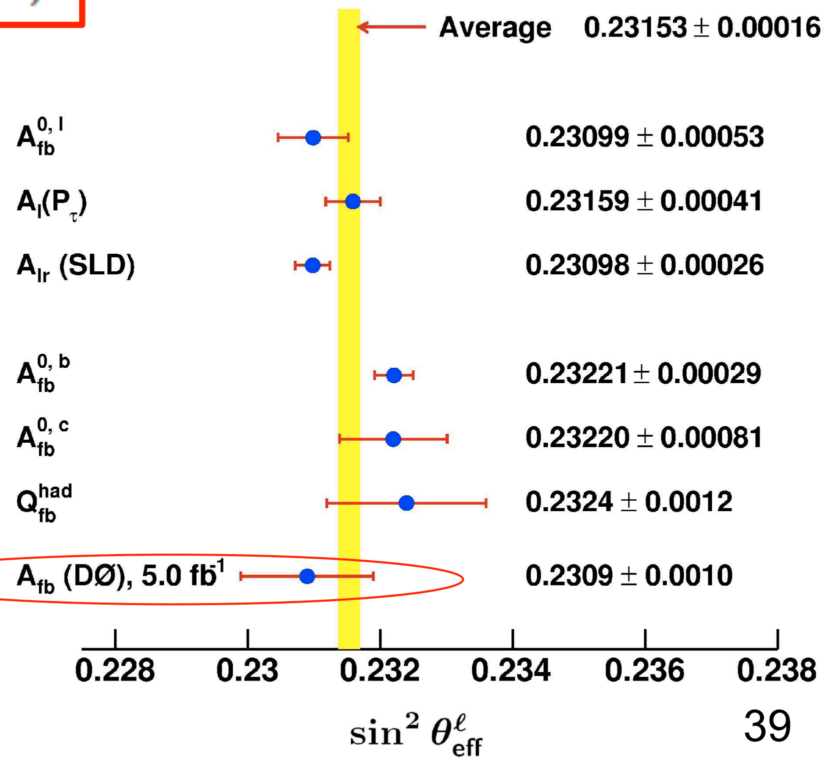
- Measurement corrected by higher-order corrections from ZGrad:

$$\boxed{\sin^2\theta^\ell_{\rm eff} = 0.2309 \pm 0.0008\,(\text{stat.}) \pm 0.0006\,(\text{syst.})}$$

- Statistics-limited measurement.
  Largest systematic uncertainty from PDFs.

- With improvements in PDF uncertainties, anticipate combined measurement from CDF and D0 using both ee and $\mu\mu$ channels can achieve a combined uncertainty competitive to the single best available measurements (A_{LR} and A_{FB}^b).

Uncertainty source	$\Delta \sin^2\theta^\ell_{\rm eff}$
Statistical	0.00080
Systematics	0.00061
PDFs	0.00048
EM scale/resolution	0.00029
MC stat.	0.00020
EMID	0.00008
Bkg. modeling	0.00008
Charge misID	0.00004
Higher order	0.00008
Total uncertainty	0.00102



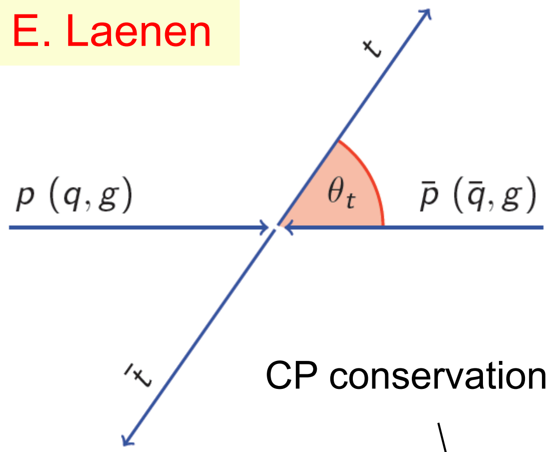
$t\bar{t}$ Charge Asymmetry

Introduction

Lectures by: E. Laenen

- The top quark may serve as a window to New Physics strongly coupled to it because of its large mass.
  ➔ precision measurements of top quark properties may yield first hints.

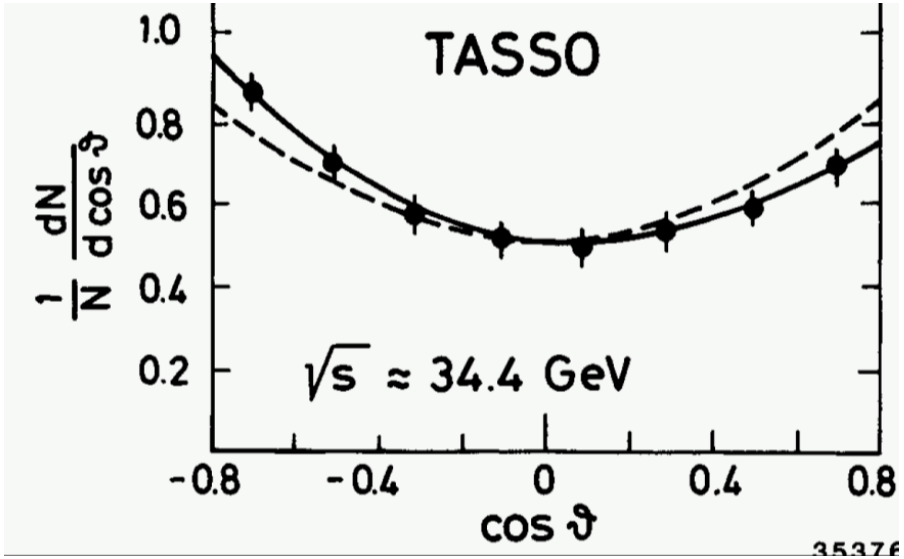
- Wisdom from the past:
  - Indications of Z boson in measured A_{FB} in $e^+e^- \rightarrow \mu^+\mu^-$ at $\sqrt{s} << M_Z$



CP conservation

$$A_C^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)} \equiv A_{FB}^{t\bar{t}}$$

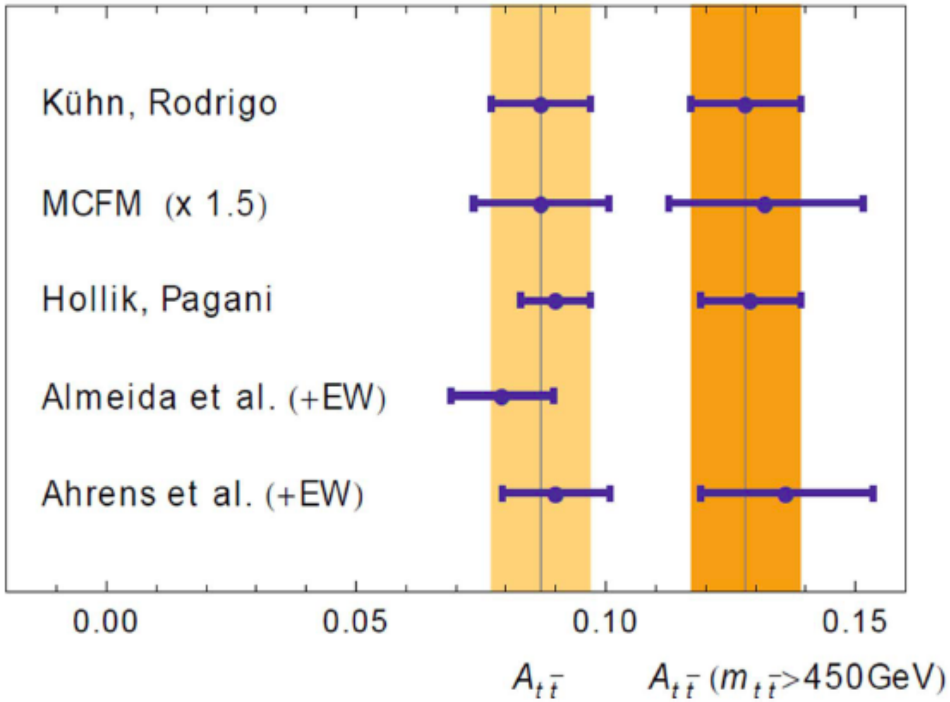
$$\Delta y = y_t - y_{\bar{t}}$$

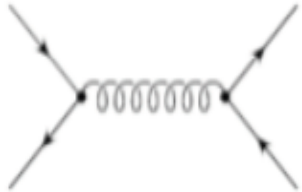


- At the Tevatron, a forward-backward and a charge asymmetry are equivalent.
- Tevatron is uniquely positioned to perform this measurement:
  - $q\bar{q}$-dominated initial state (85%)
  - $p\bar{p}$ collisions give direction for incoming quark and antiquark

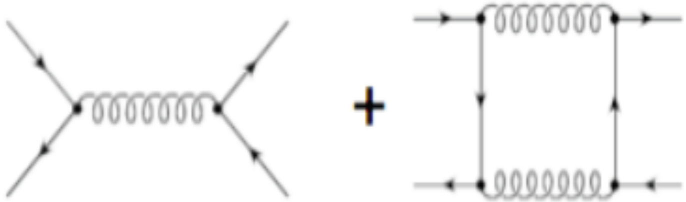
Standard Model Prediction

- LO ($O(\alpha_s^2)$): no asymmetry
- NLO ($O(\alpha_s^3)$): small positive asymmetry from interference effects ➔ LO prediction for A_{FB}!
  - State of art: includes NLL resummation and mixed QCD/EW effects.

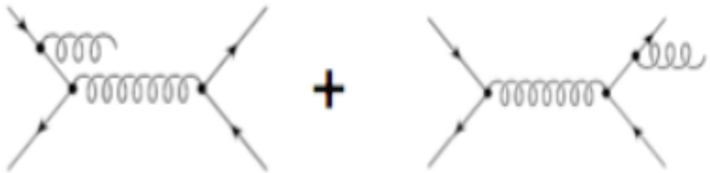




Born + Box Interference
Positive Contribution to A_{FB}



ISR/FSR Interference
Negative Contribution to A_{FB}



- Progress ongoing towards first complete NLO calculation of A_{FB}.

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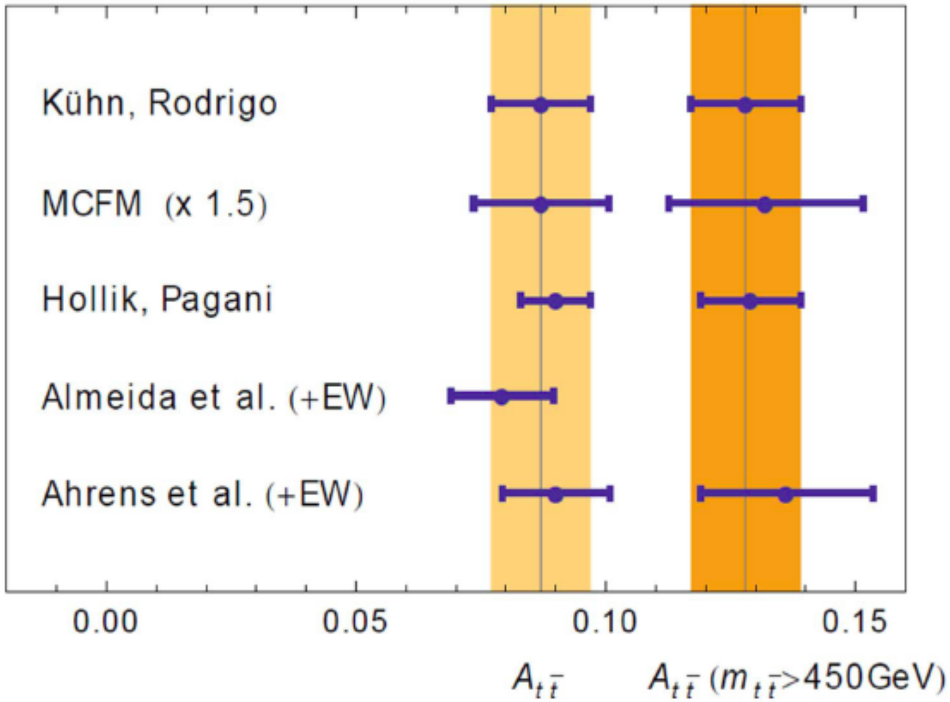
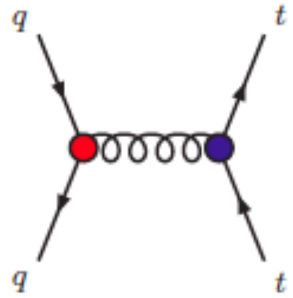


- Progress ongoing towards first complete NLO calculation of A_{FB}.

- Also available NLO calculations interfaced to parton shower MC (e.g. MC@NLO, POWHEG).
  ➔ typically used by experimentalists to get predicted asymmetry. Often scale by x1.26 to account for EW effects.

Disclaimer:
➔ these “MC-based” predictions are ~30-40% lower than “state-of-art” predictions. Should be careful when comparing measured and predicted asymmetries!

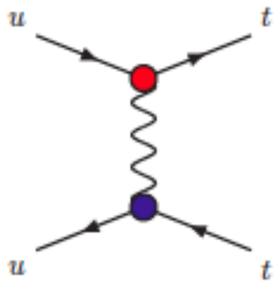
Examples of New Physics Contributions



s channel: Color-octet vectors (e.g. axigluon)

$\mathcal{G}_\mu \sim (8,1)_0$

t channel: Color-singlet vector/scalar (FCNC interactions)

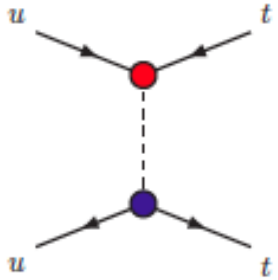


$Z' \sim (1,1)_0$

$W' \sim (1,1)_1$

$\phi \sim (1,2)_{-\frac{1}{2}}$

u channel: Colored scalars

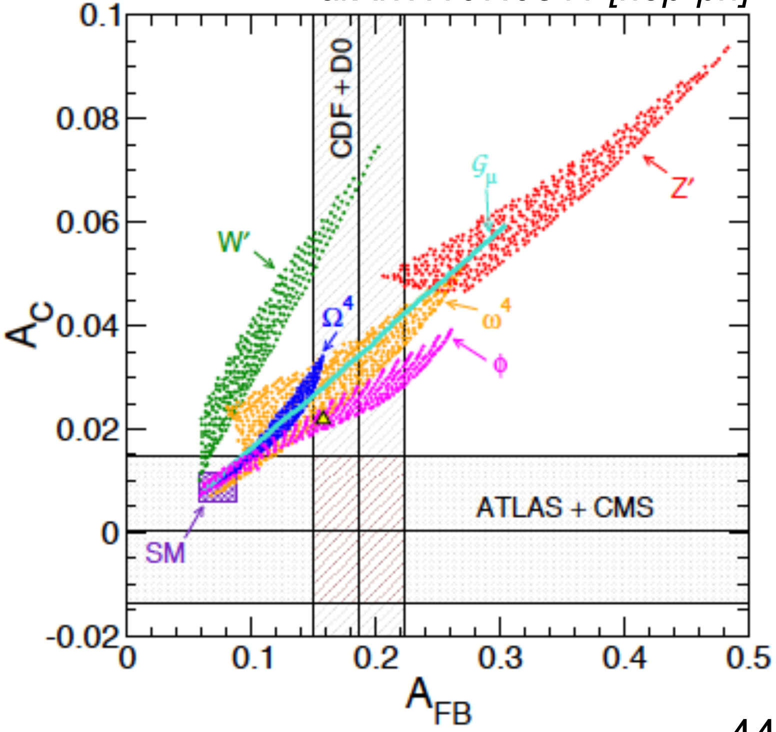


$\omega^4 \sim (3,1)_{-\frac{4}{3}}$

$\Omega^4 \sim (\bar{6},1)_{-\frac{4}{3}}$

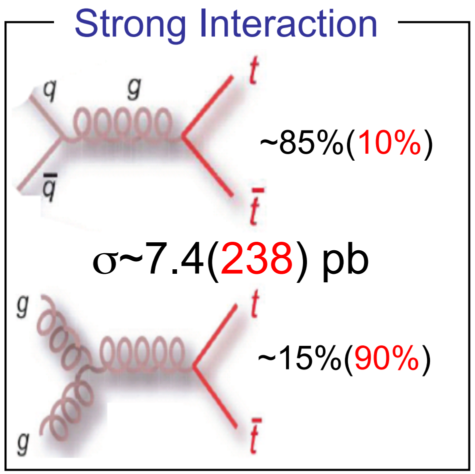
- Possible New Physics contributions must satisfy constraints from:
  - σ_{tt} at the Tevatron & LHC
  - $d\sigma_{tt}/dm_{tt}$ at the Tevatron & LHC
  - Absence of other direct indications of New Physics (e.g. like-sign tops @ LHC)

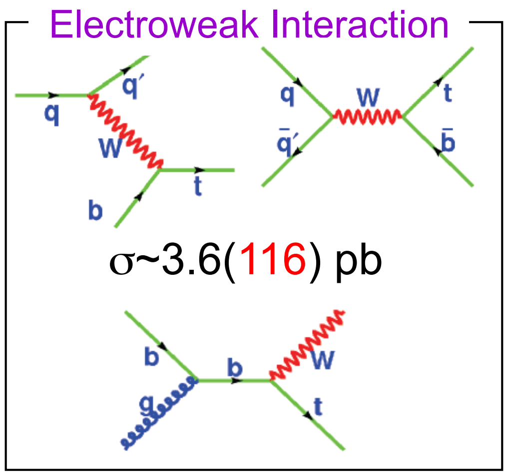
arXiv:1107.0841 [hep-ph]



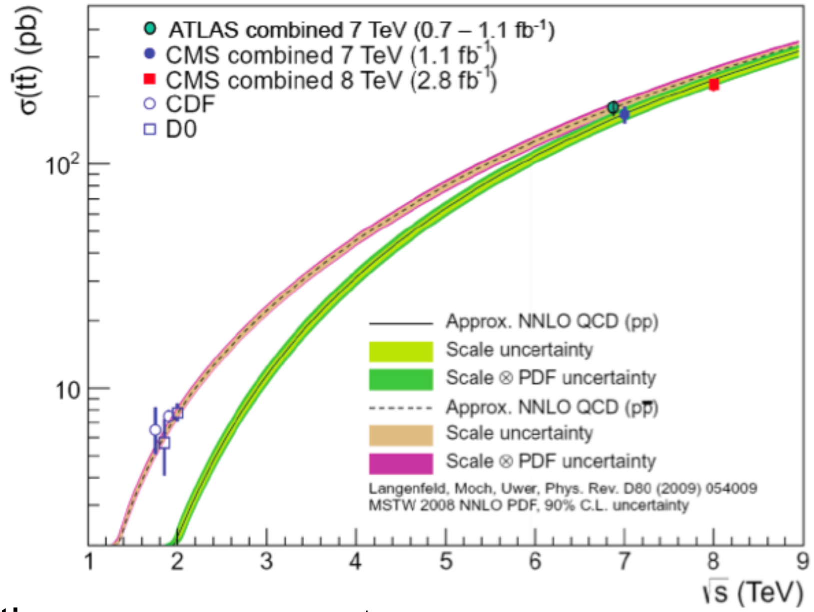
Top Production and Decay

Tevatron (LHC 8 TeV)



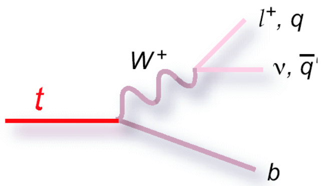


m_t=172.5 GeV



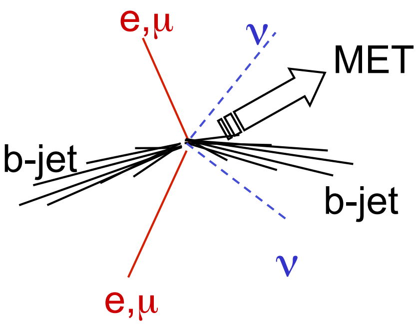
- Production: dominantly in pairs via strong interaction.
- Decay: t→Wb with ~100% BR

  ➔ final state signatures driven by W decay modes

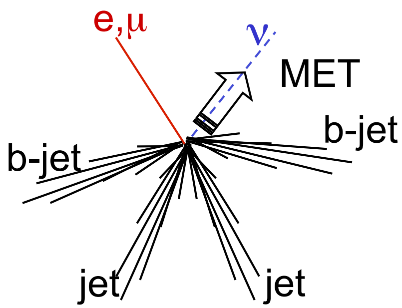


BR($W \rightarrow q\bar{q}'$) ~ 67%

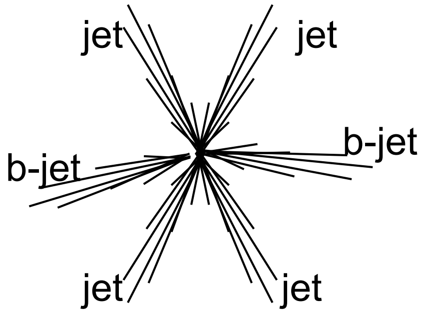
BR($W \rightarrow l\nu$) ~ 11%, l=e,μ,τ



Dilepton
(BR~5%, low bckg)

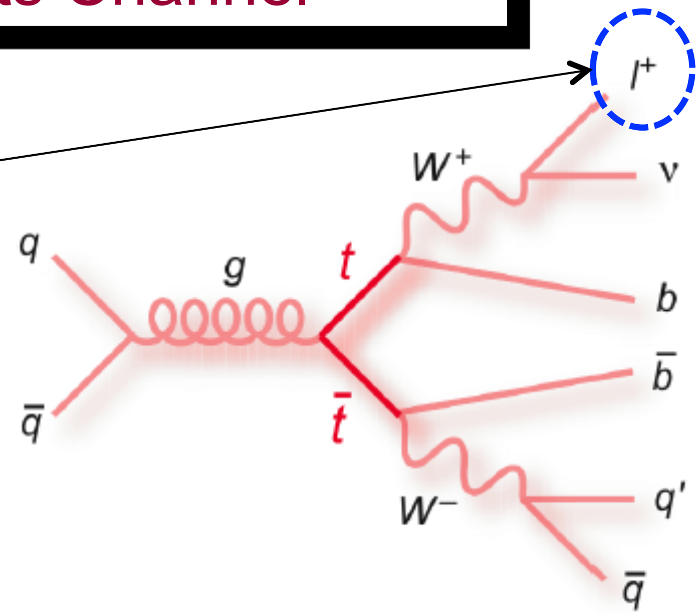


Lepton+jets
(BR~30%, moderate bckg)



All-hadronic
(BR~46%, huge bckg)

Measuring A_{FB}: Lepton+Jets Channel

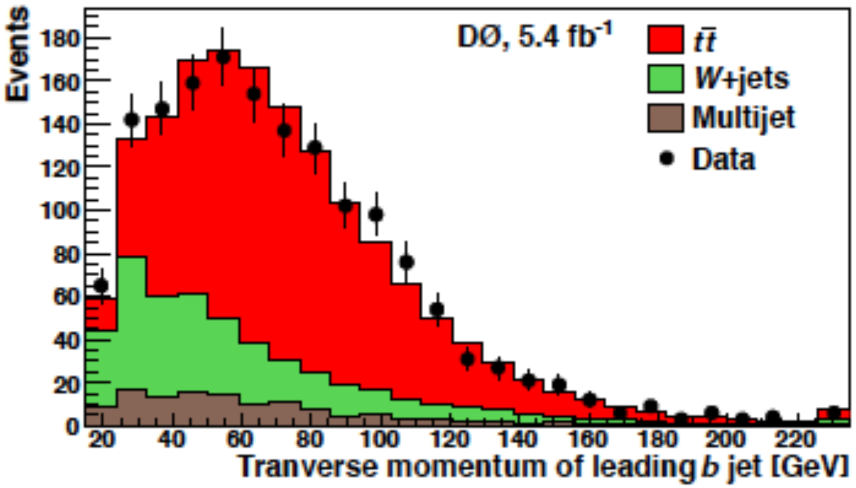


- Pros: High statistics. Can reconstruct $t\bar{t}$ kinematics.
  Lepton charge tags top or anti-top.
  Cons: Non-negligible charge-asymmetric W+jets
  background.

- Typical event selection:
  - 1 e or μ, p_T>20 GeV
  - E_T^{miss}>20 GeV
  - ≥4 jets, p_T>20 GeV
  - ≥1 b-tagged jet

  ~2k $t\bar{t}$ events expected

- Background dominated by W+jets and QCD multijet (S:B~4:1)

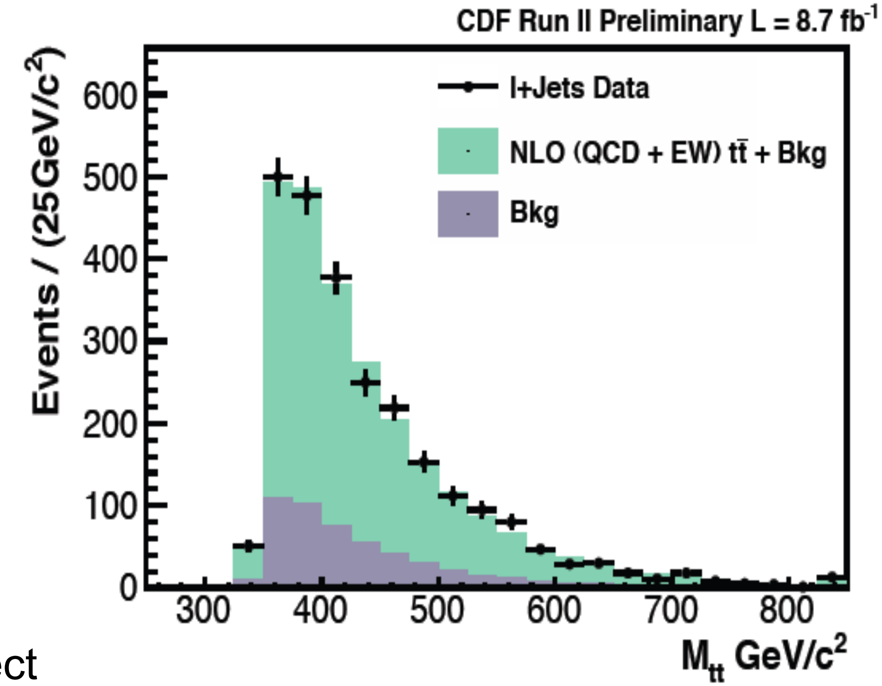


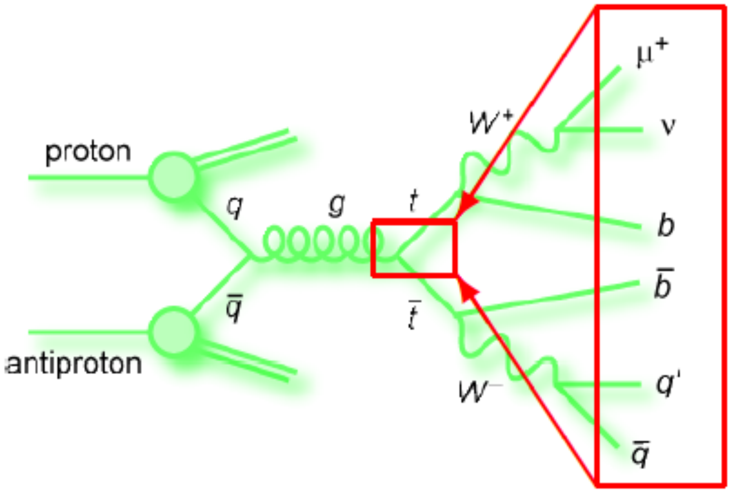
Source	Predicted Event Count, 8.7 fb^{-1}
W + Heavy Flavor	241 ± 78
Non-W (QCD)	98 ± 51
W + Light Flavor	96 ± 29
Single Top	33 ± 2
Diboson	19 ± 3
Z + Jets	18 ± 2
Total Background	505 ± 123
Top Pairs (7.4 pb)	2037 ± 277
Total Prediction	2542 ± 303
Data	2498

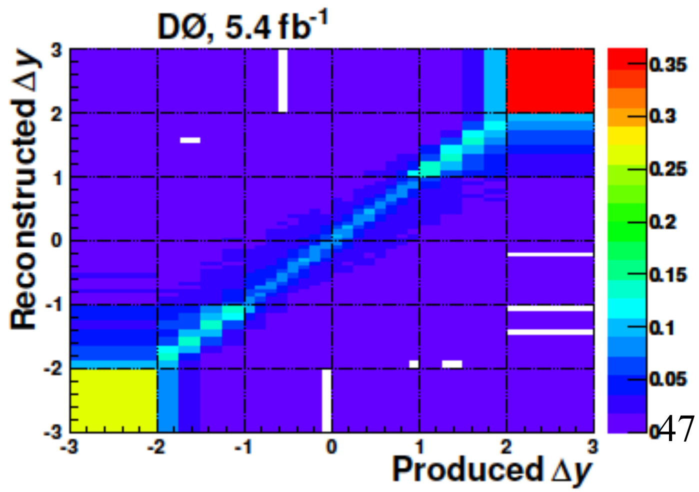
Measuring A_{FB}: Lepton+Jets Channel

- Kinematic reconstruction:
  - Jet energies fitted and assigned to partons based on χ^2 test-statistic including basic constrains (p_T balancing, W and top resonances, jet energy resolution).
  - Define: $\boxed{\Delta y = q_\ell (y_{t,lep} - y_{t,had})}$
  - Fraction of right sign(Δy) ~70%

    ➔ Measured asymmetry ~x2 smaller than true one.
- Unfolding:
  - After background subtraction, need to correct for acceptance as well as resolution effects.
  - Both CDF and D0 use regularized unfolding.

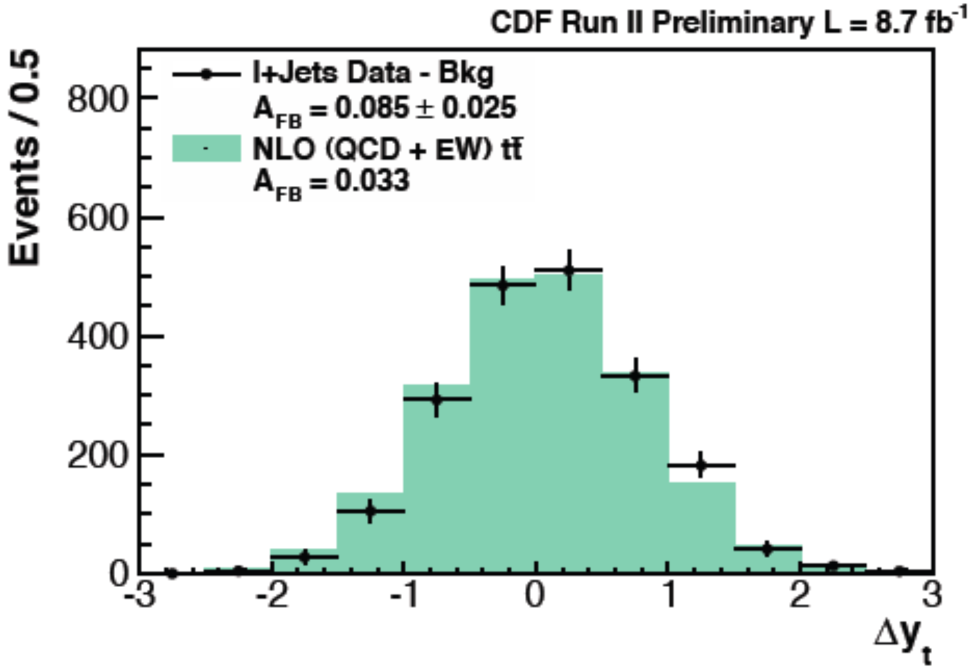


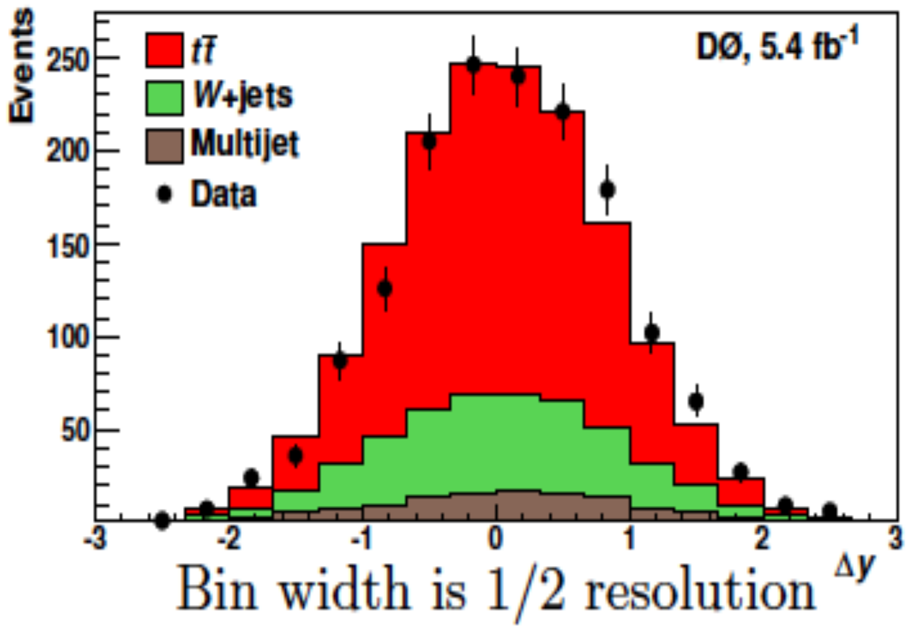




Inclusive A_{FB}: Background-Subtracted Level

Measured asymmetry after background subtraction:





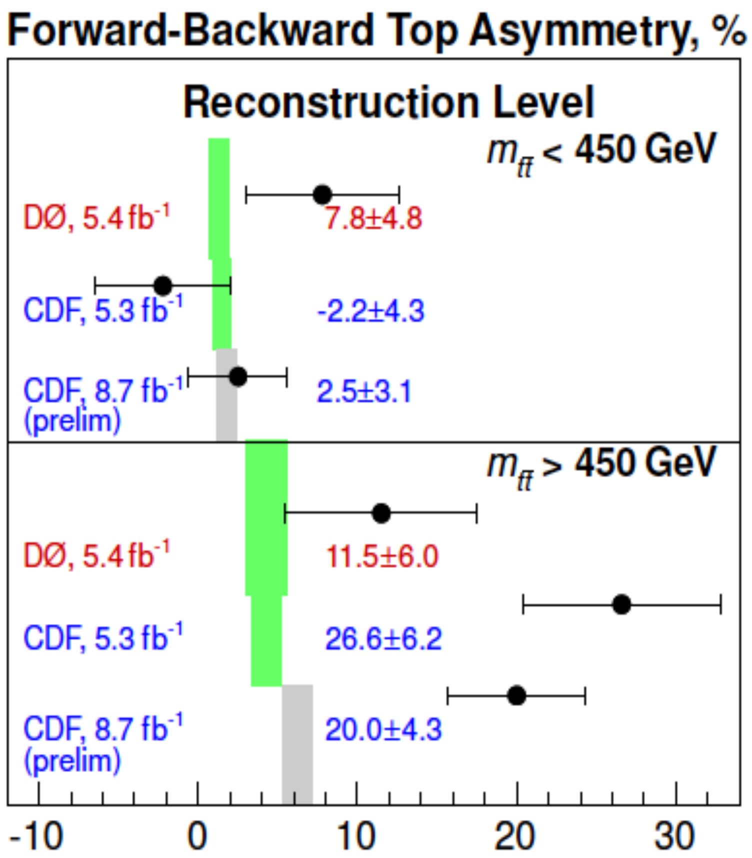
- Background-subtracted level:
  A_{FB} = (8.5 ± 2.5)%

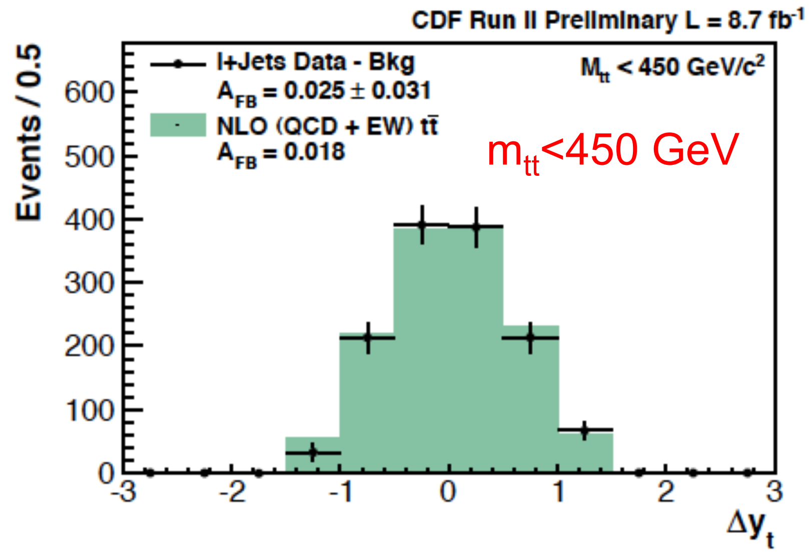
- NLO POWHEG+PYTHIA MC:
  A_{FB} = 3.3% (includes x1.26 for EW effects)

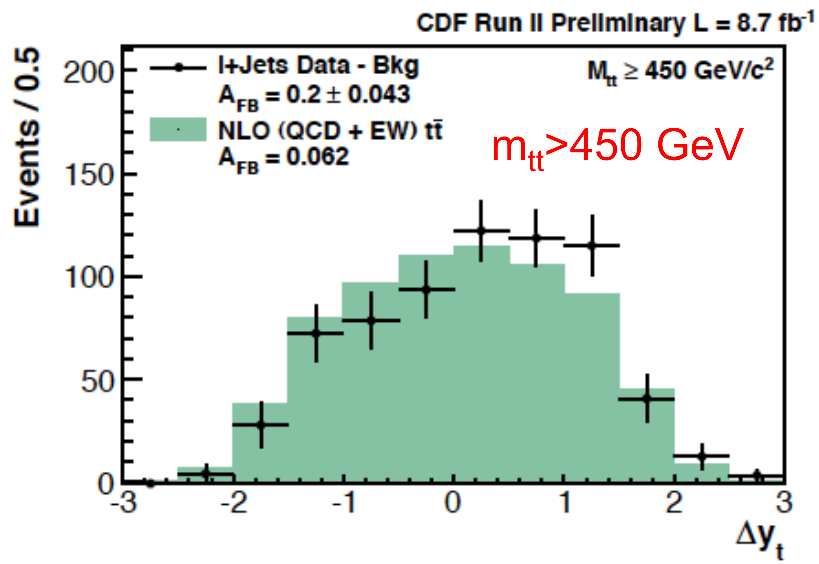
	$l+\geq 4$ jets	$l+4$ jets	$l+\geq 5$ jets
A_{FB}(%)	9.2±3.7	12.2±4.3	-3.0±7.9
MC@NLO A_{FB} (%)	2.4±0.7	3.9±0.8	-2.9±1.1

A_{FB} vs m_{tt}: Background-Subtracted Level

- New Physics contributions to A_{FB} will affect the dependence vs m_{tt}, mostly through interference with the SM.
- Define two regions m_{tt}<450 GeV and m_{tt}>450 GeV. Cut optimized in MC.







➔ Most significant mass dependence observed by CDF.

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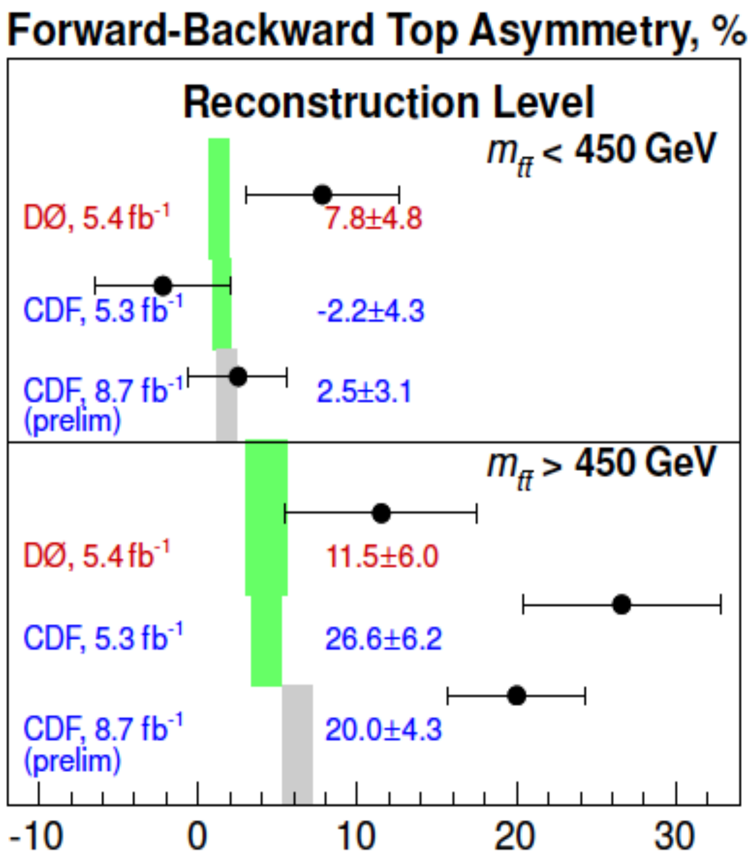
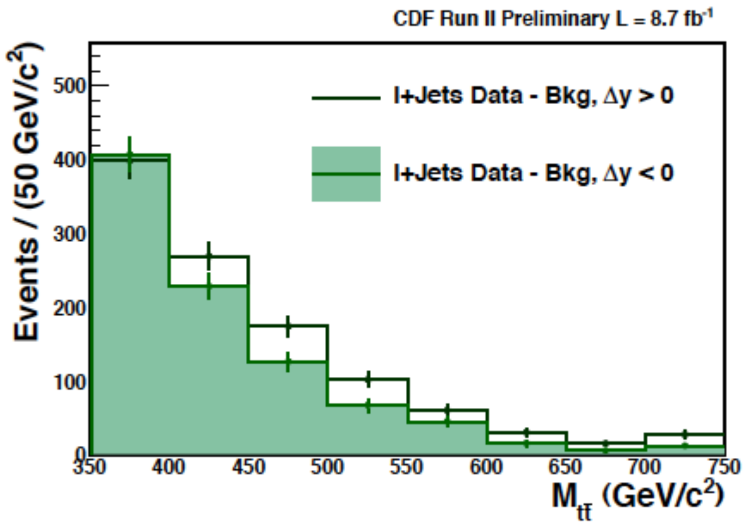
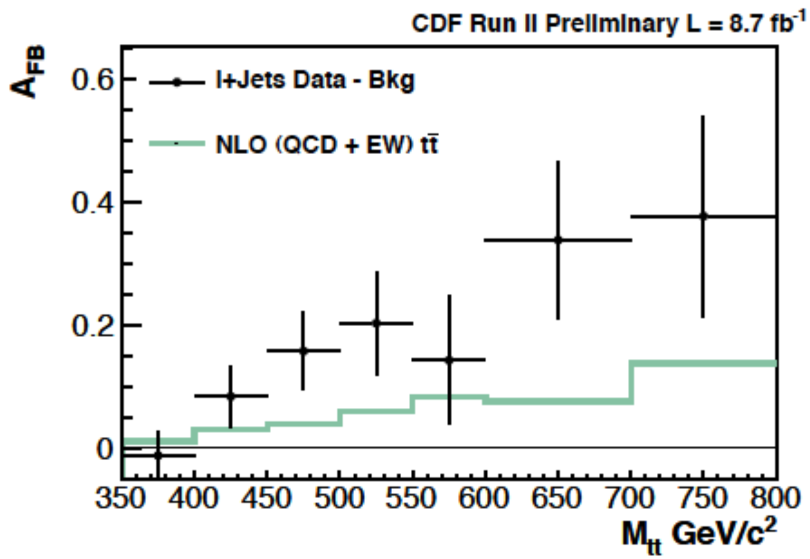
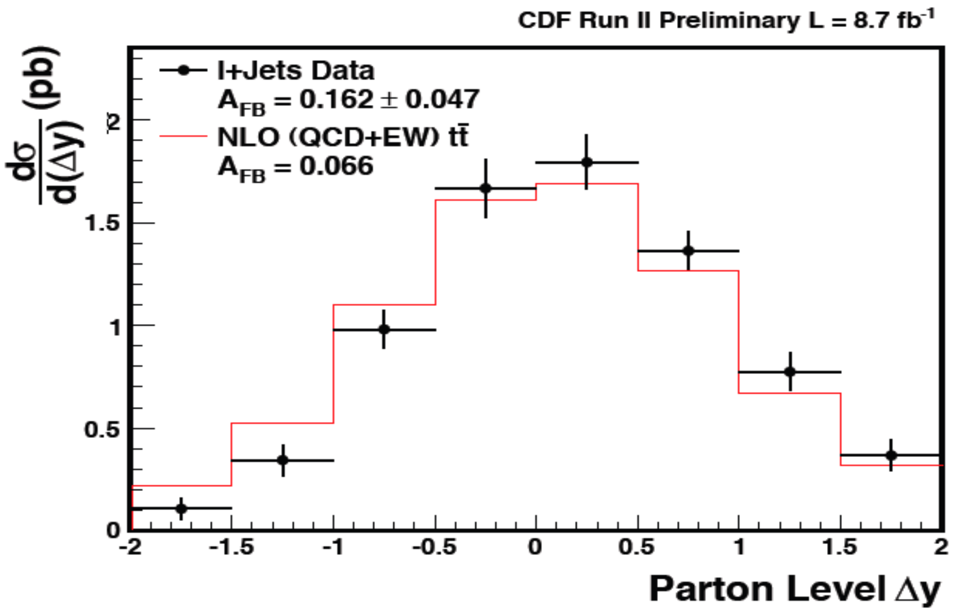


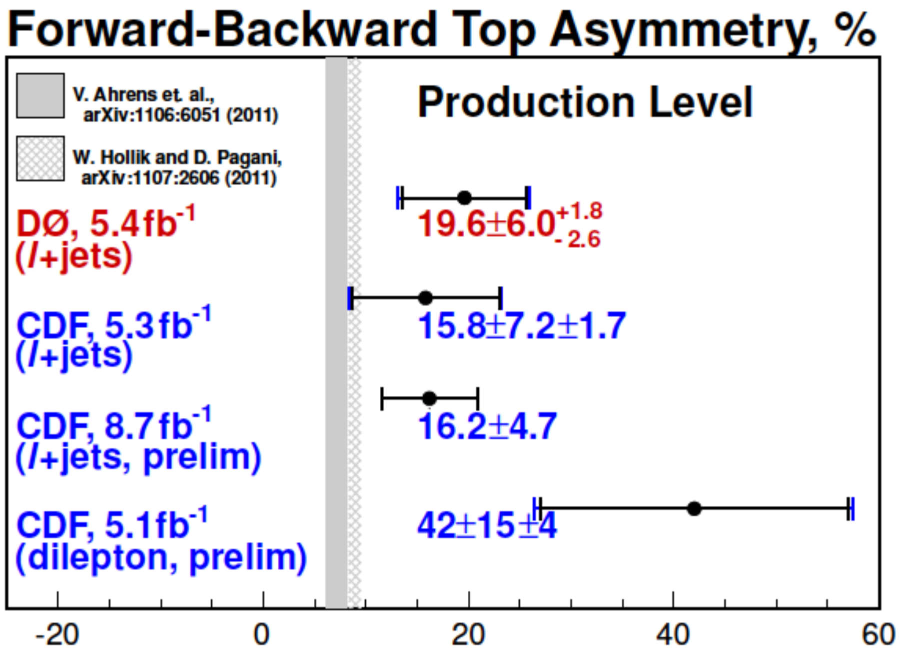




➔ Most significant mass dependence observed by CDF.

Inclusive A_{FB}: Production Level





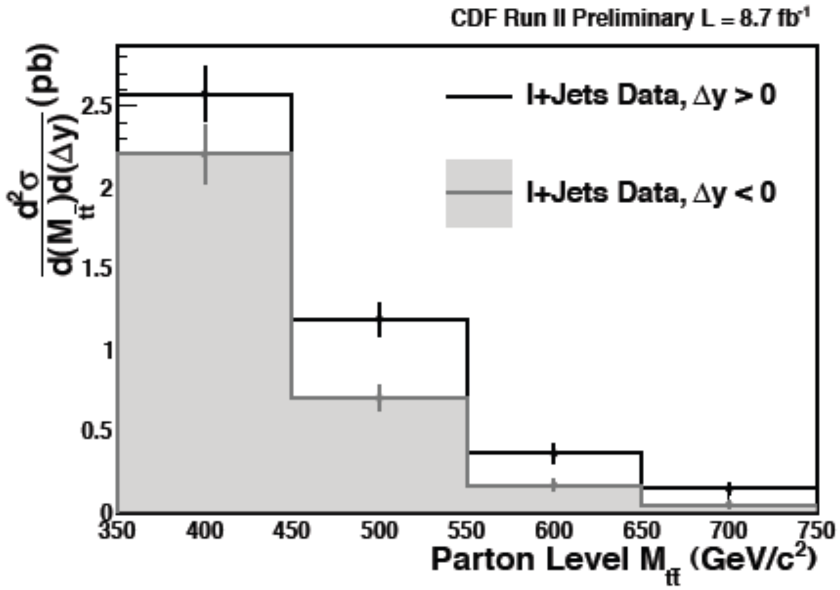
Source	Uncertainty (%)
Background Shape	1.4
Background Normalization	1.1
Parton Showering	1.0
Jet Energy Scale	0.5
Initial/Final State Radiation	0.5
Color Reconnection	0.1
Parton Distribution Functions	0.1
Correction Procedure	0.3
Total Systematic Uncertainty	2.2
Statistical Uncertainty	4.1
Total Uncertainty	4.7

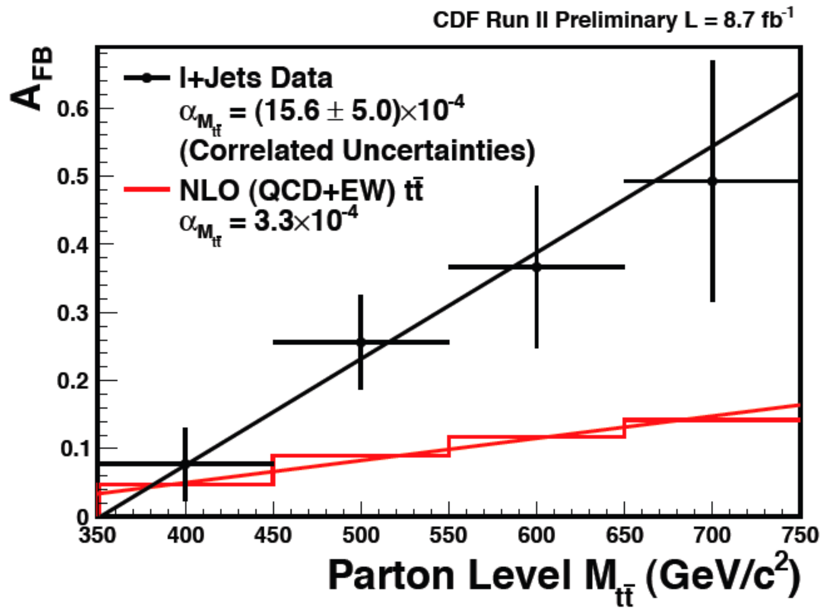
- Statistics-limited measurement.
- Dominant systematic uncertainties are background shape followed by signal modeling.
- Naïve average (*): $A_{FB} = (18.8 \pm 3.7)\%$

3.3σ from expectation (A_{FB} = 6.6%)

(*) Correlations in syst. uncertainties neglected

A_{FB} vs m_{tt}: Production Level





Selection	Prediction	CDF, 5.3 fb^{-1}	D0, 5.4 fb^{-1}	CDF, 8.7 fb-1
Inclusive	6.6	15.8 ± 7.4	19.6 ± 6.5	16.2 ± 4.7
$M_{tt} < 450$ GeV/c^2	4.7	−11.6 ± 15.3	7.8 ± 4.8 (Bkg. Subtracted)	7.8 ± 5.4
$M_{tt} \geq 450$ GeV/c^2	10.0	47.5 ± 11.2	11.5 ± 6.0 (Bkg. Subtracted)	29.6 ± 6.7

Measuring A_{FB}: Dilepton Channel

- Pros: Clean final state signature.
  Cons: Small rate. More difficult kinematic reconstruction.

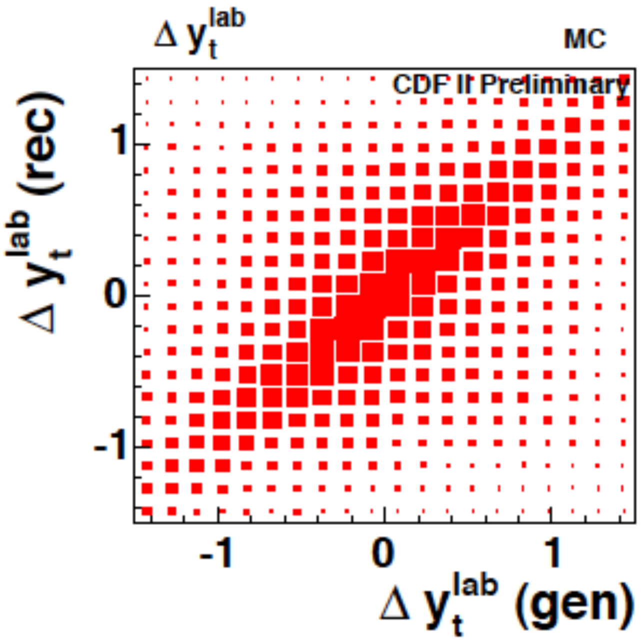
- Event selection:
  - 2 OS dileptons (ee, μμ, eμ), p_T>20 GeV
  - E_t^{miss}>25 GeV
  - ≥2 jets, p_T>15 GeV, |η|<2.5
  - H_T>200 GeV

  ➔ S:B~3:1

- Kinematic reconstruction:
  - Under-constrained kinematics.
  - Maximum likelihood fit with additional constraints.

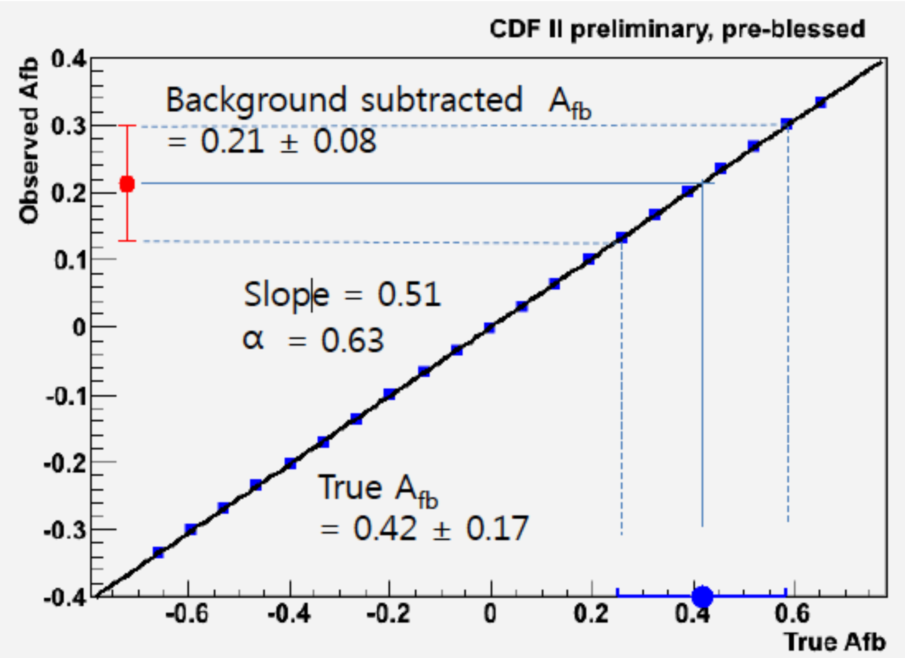
$$\mathcal{L}(\vec{p}_\nu, \vec{p}_{\bar{\nu}}, E_b, E_{\bar{b}}) = P\left(p_z^{t\bar{t}}\right) P\left(p_T^{t\bar{t}}\right) P\left(M_{t\bar{t}}\right) \times$$
$$\frac{1}{\sigma_{\text{jet1}}} \exp\left[-\frac{1}{2}\left\{\frac{E_{\text{jet1}}^{\text{meas}} - E_{\text{jet1}}^{\text{guess}}}{\sigma_{\text{jet1}}}\right\}^2\right] \times \frac{1}{\sigma_{\text{jet2}}} \exp\left[-\frac{1}{2}\left\{\frac{E_{\text{jet2}}^{\text{meas}} - E_{\text{jet2}}^{\text{guess}}}{\sigma_{\text{jet2}}}\right\}^2\right] \times$$
$$\frac{1}{\sigma_x^{\text{MET}}} \exp\left[-\frac{1}{2}\left\{\frac{\not{E}_x^{\text{meas}} - \not{E}_x^{\text{guess}}}{\sigma_x^{\text{MET}}}\right\}^2\right] \times \frac{1}{\sigma_y^{\text{MET}}} \exp\left[-\frac{1}{2}\left\{\frac{\not{E}_y^{\text{meas}} - \not{E}_y^{\text{guess}}}{\sigma_y^{\text{MET}}}\right\}^2\right],$$

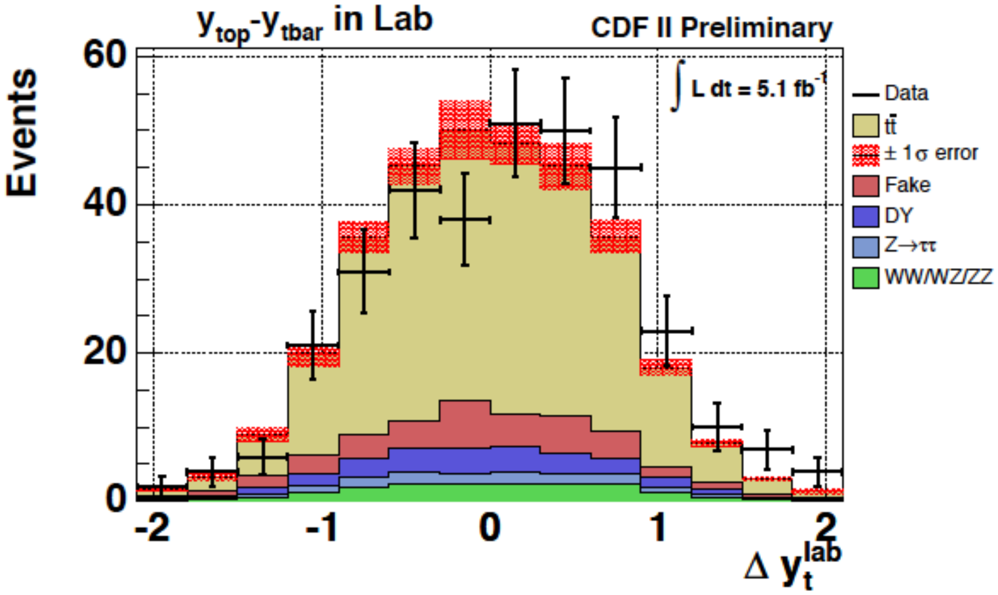
Process	Events
WW	11.7 ± 2.4
WZ	3.5 ± 0.6
ZZ	2.3 ± 1.8
$W\gamma$	0.4 ± 0.4
DY$\to \tau\tau$	12.3 ± 2.2
DY$\to ee + \mu\mu$	22.4 ± 3.2
Fakes	34.3 ± 14.7
$t\bar{t}$	237.1 ± 11.3
Total	324.0 ± 28.3
Data	334



Inclusive A_{FB}: Production Level

- Production-level asymmetry "unfolded" using calibration curve between background-subtracted asymmetry and true asymmetry.
  - Derived using PYTHIA MC applying a per-event weight of $(1+\alpha\Delta y)$





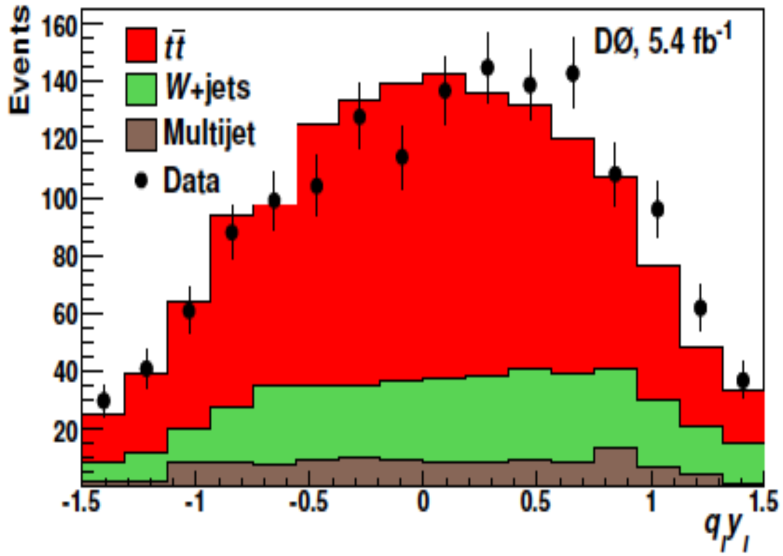
- Raw asymmetry: (14 ± 5 (stat))%
- Bkg-subtracted: (21 ± 7 (stat))%
- Production-level:
  A_{FB} = (42 ± 15 (stat) ± 5 (syst))%

2.3σ from expectation (A_{FB} = 6.6%)

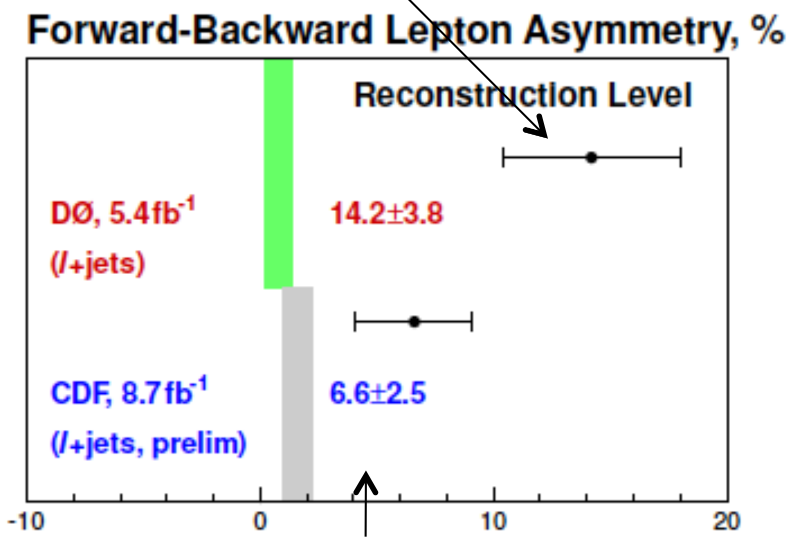
Lepton-Based Asymmetries: Lepton+Jets

$$A_{FB}^{\ell} = \frac{N(q_\ell y_\ell > 0) - N(q_\ell y_\ell < 0)}{N(q_\ell y_\ell > 0) + N(q_\ell y_\ell < 0)}$$

- Sensitive to the top pair A_{FB} and top polarization.
- Pros:
  - Simpler observable, not involving explicit event reconstruction.
  - Good resolution. No unfolding necessary.
- Cons:
  - Less sensitivity to cosθ*
  - Stronger asymmetry from W+jets



~3.4σ from expectation



Inclusive A^l_{FB}

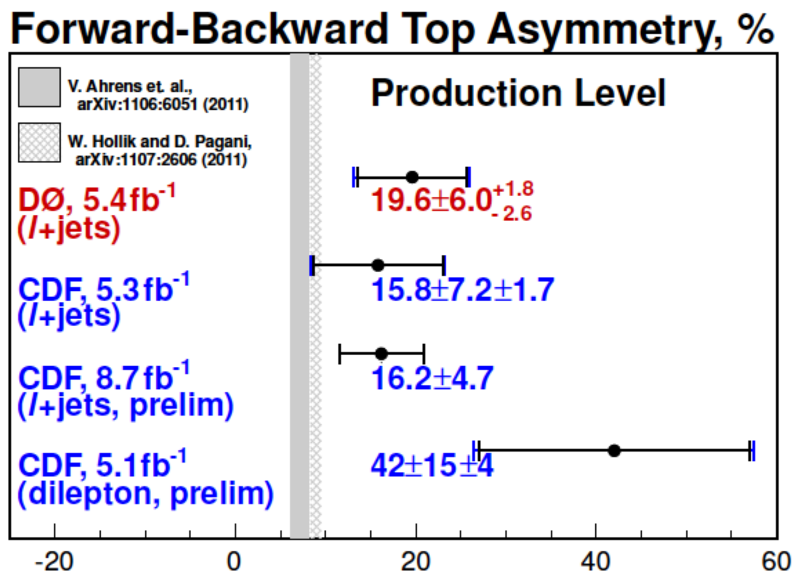
CDF (8.7 fb^{-1})

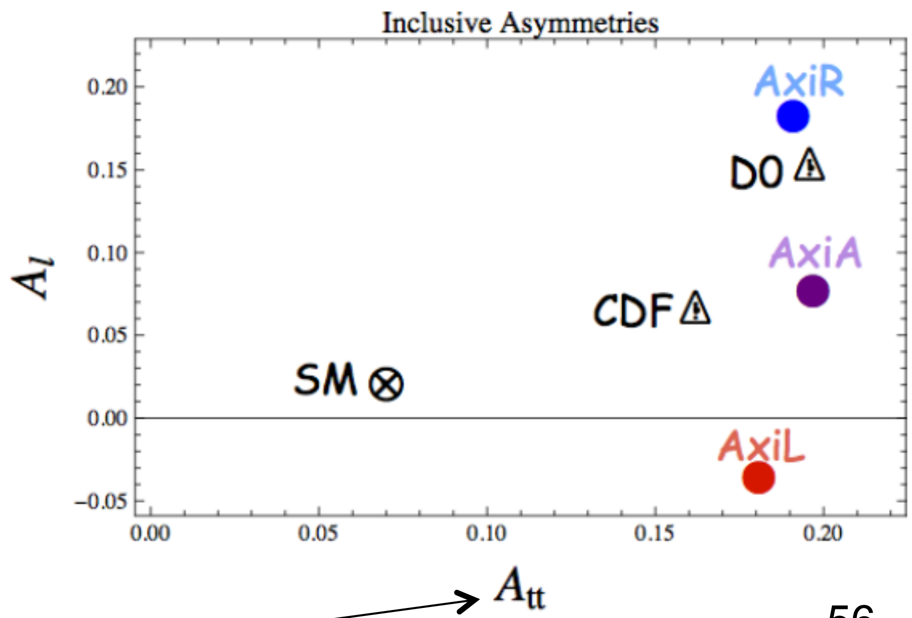
Sample	Predicted A_{FB} (%)	Observed A_{FB} (%)
Inclusive	1.6	6.6 ± 2.5
M_{tt} < 450 GeV/c²	0.7	3.7 ± 3.1
M_{tt} ≥ 450 GeV/c²	3.2	11.6 ± 4.2

m_{tt}-dependent A^l_{FB}

Summary and Prospects

- Up until now measurements at the Tevatron offer a relatively consistent picture above current theoretical predictions.
- All options are open and expect new critical information in the very near future:
  - Improved measurements upcoming with the full dataset, as well as considering additional observables (e.g. lepton asymmetries)





These are complementary observables!

Summary and Prospects

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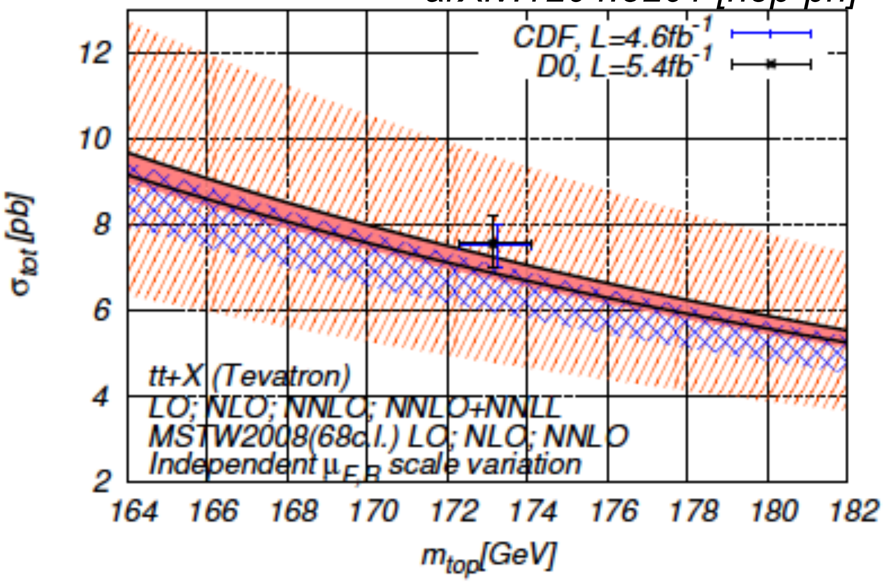
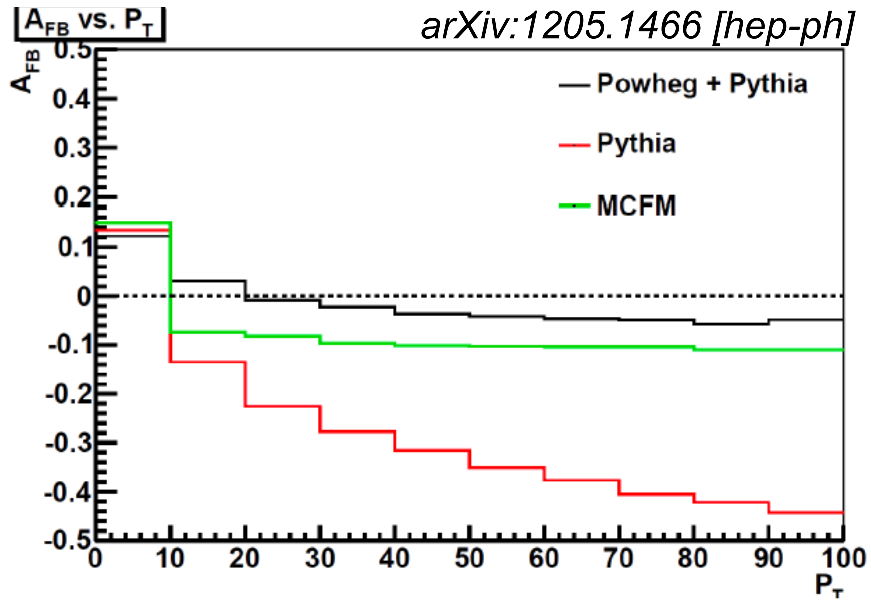
  - Improved theoretical tools on the way. Progress towards NLO A_{FB} as well as understanding physics effects related to color coherence in parton shower MCs.

arXiv:1204.5201 [hep-ph]



arXiv:1205.1466 [hep-ph]



Summary and Prospects

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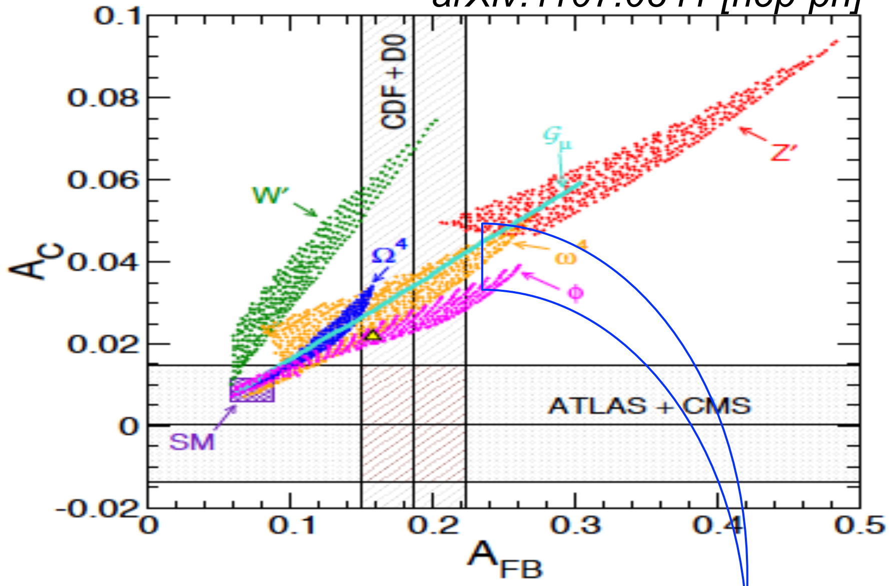
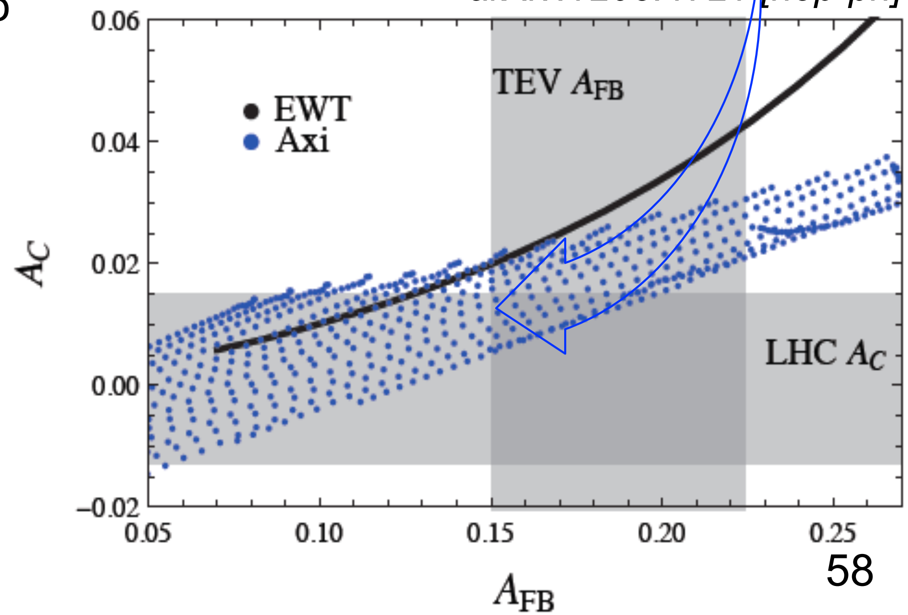
  - Improved theoretical tools on the way. Progress towards NLO A_{FB} as well as understanding physics effects related to color coherence in parton shower MCs.
  - Learning how to extend New Physics models to reconcile measurements at Tevatron and LHC.

arXiv:1107.0841 [hep-ph]

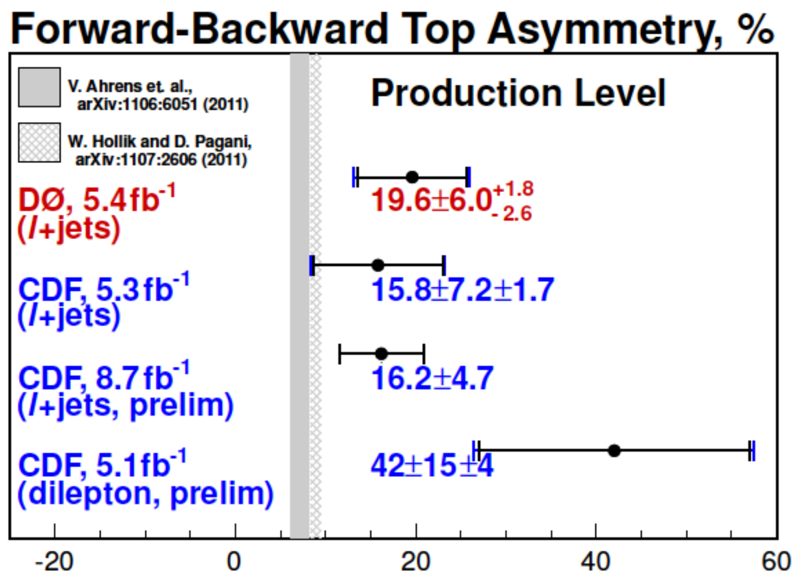


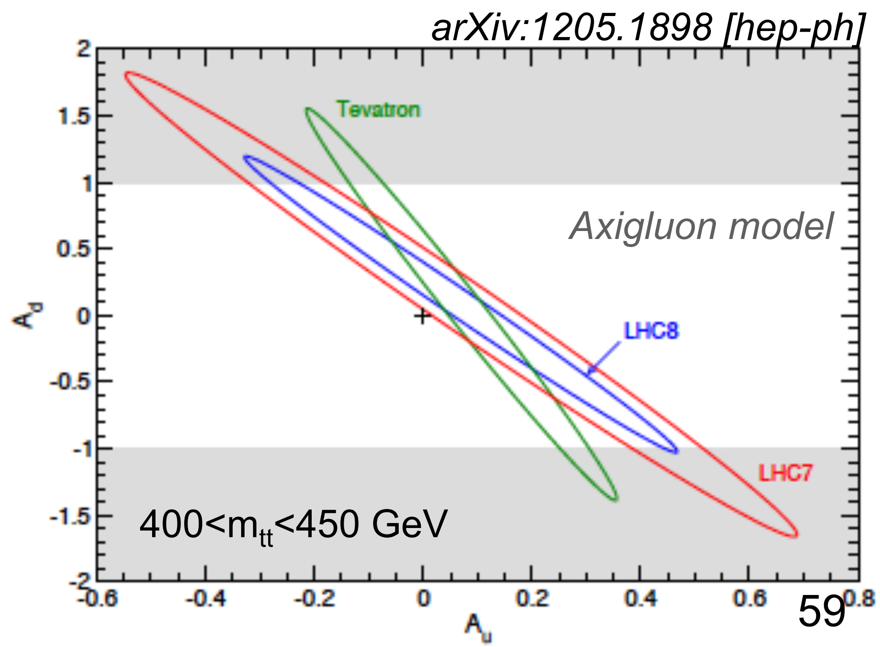
arXiv:1205.4721 [hep-ph]



Summary and Prospects

- Up until now measurements at the Tevatron offer a relatively consistent picture above current theoretical predictions.
- All options are open and expect new critical information in the very near future:
  - Improved measurements upcoming with the full dataset, as well as considering additional observables (e.g. lepton asymmetries)
  - Improved theoretical tools on the way. Progress towards NLO A_{FB} as well as understanding physics effects related to color coherence in parton shower MCs.
  - Learning how to extend New Physics models to reconcile measurements at Tevatron and LHC.
  - And even how to define "collider-independent" asymmetry variables that will eventually allow to combine measurements at the Tevatron and the LHC.

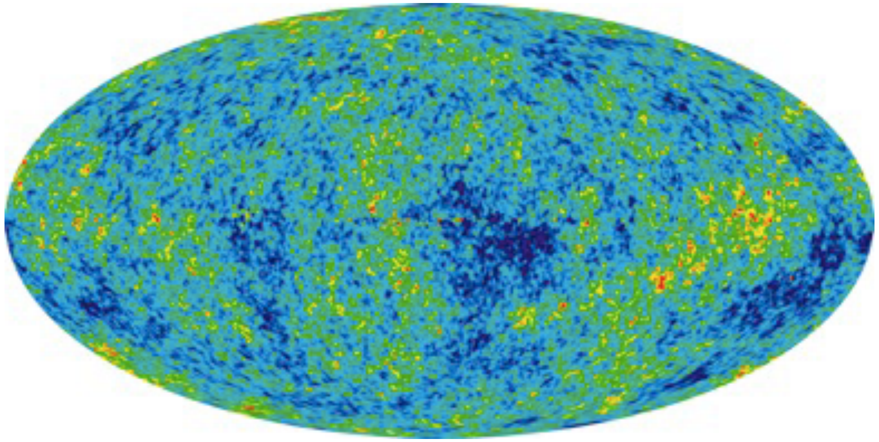


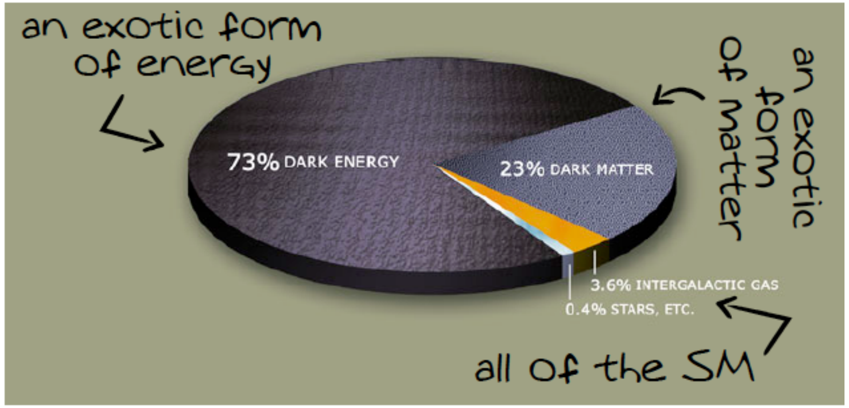


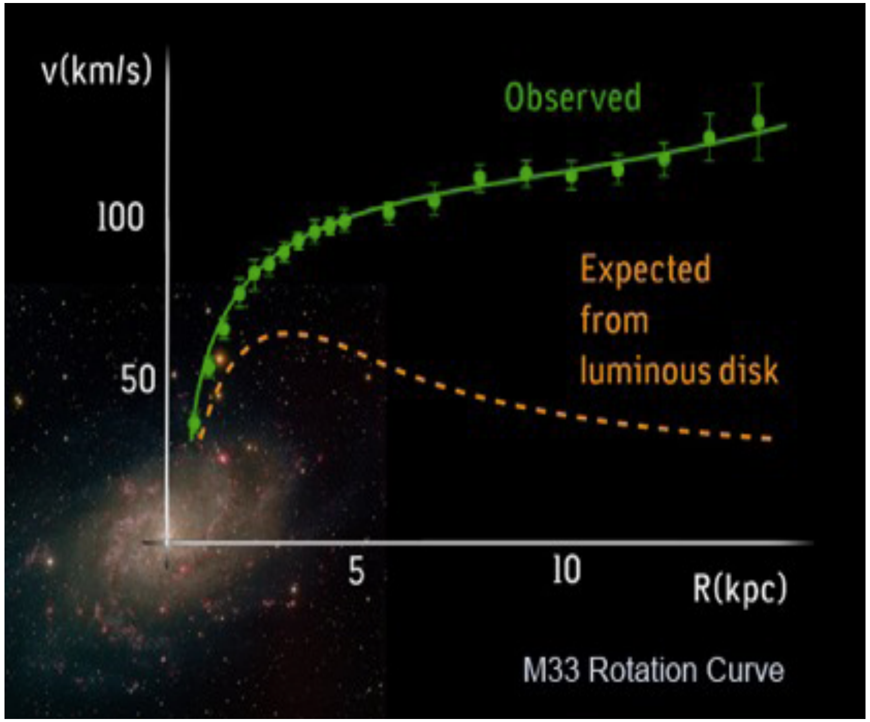
Searching for Dark Matter

Dark Matter Abundance and Distribution

- Compelling cosmological evidence for the existence of dark matter:
  - Combination of CMB data with Hubble expansion data from SNIa







  - Deviations from ~$1/\sqrt{r}$ expectation in galaxy rotation curves.
  - Estimated galactic abundance: ρ_{DM}~0.3 GeV/cm^3 (± a factor of 2)

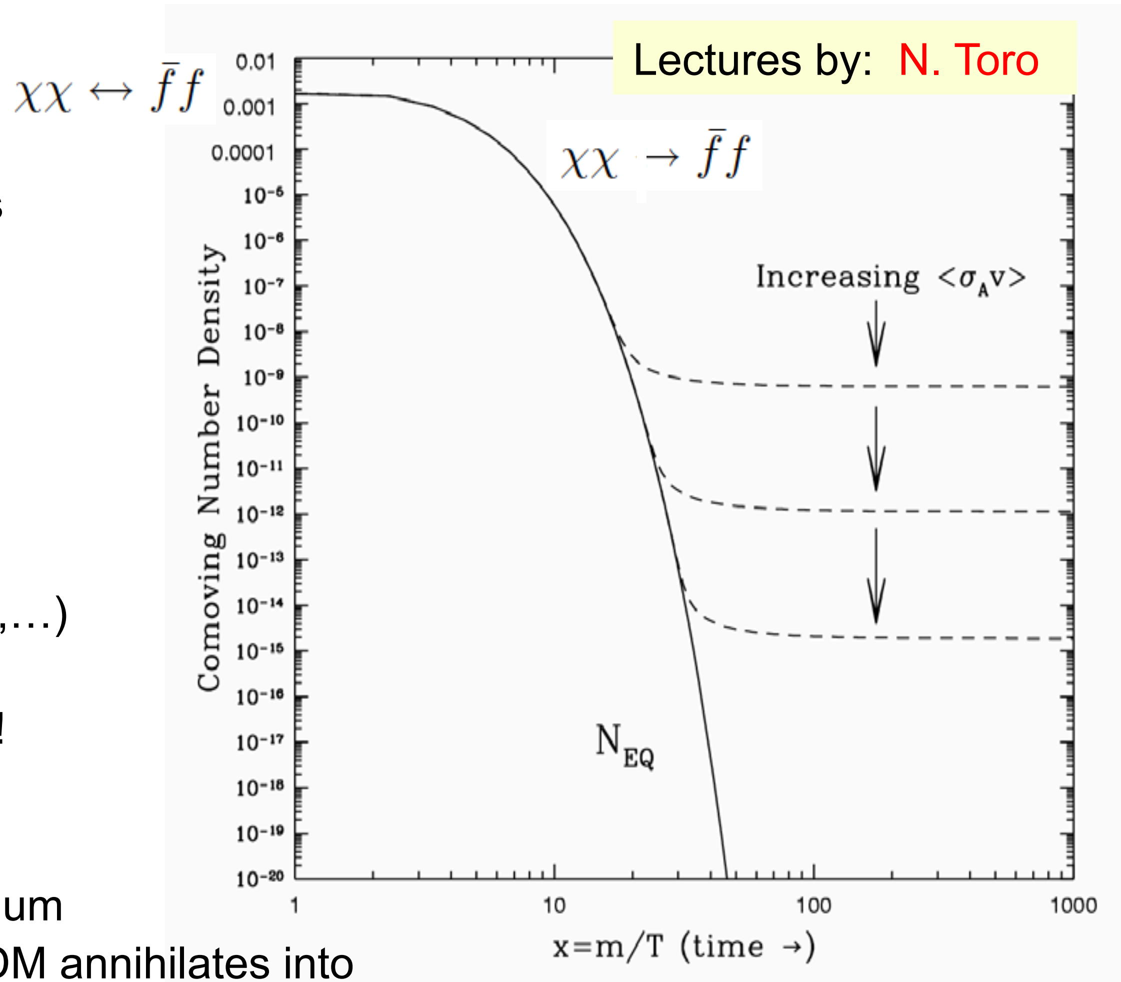
Dark Matter Properties

- "Cold" (i.e. non-relativistic)
- Non-baryonic
- Stable on cosmological time scales
- "Dark", i.e. neutral under SM

- Possible candidates:
  - Axions
  - Gravitinos
  - Primordial black holes
  - WIMPs (e.g. SUSY neutralino,…)
  - …

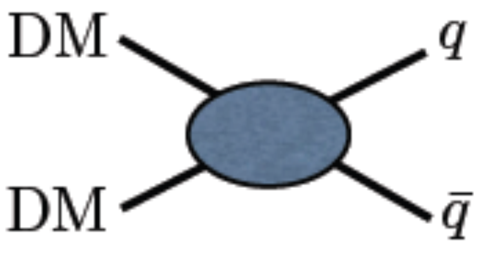
  Not all of them "weakly interacting"!

- The "WIMP miracle":
  - Initially DM in thermal equilibrium
  - As T drops below DM mass, DM annihilates into SM particles and abundance begins to drop
  - At some point, DM particles won't find each other to annihilate: abundance is set (freeze-out)
  - A weak-scale particle freezes out to give the correct relic abundance!

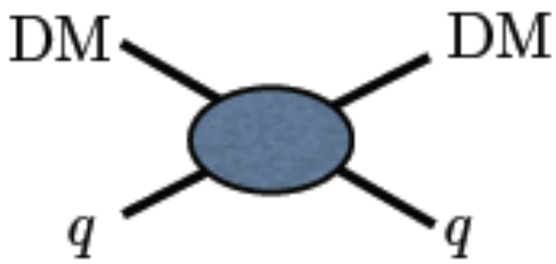


$$\langle \sigma v \rangle \sim \frac{\alpha_W^2}{M_W^2} \sim 1\,\mathrm{pb} \sim 3 \times 10^{-26} \mathrm{cm}^2 \mathrm{s}^{-1}$$

Searching for Dark Matter



Indirect detection



Direct detection

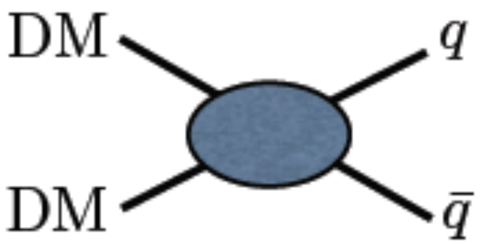
Look up

Annihilation in our galaxy
Antimatter excesses in
cosmic rays, photons
from centre of galaxy

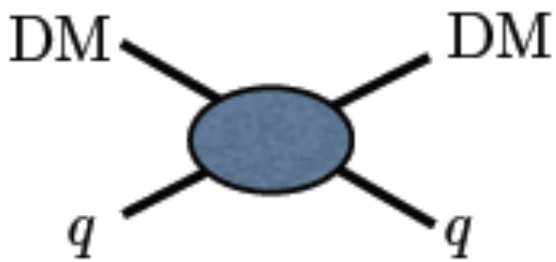
Look down

Scattering off a nucleus
Low rate, low energy
recoil events in
underground labs

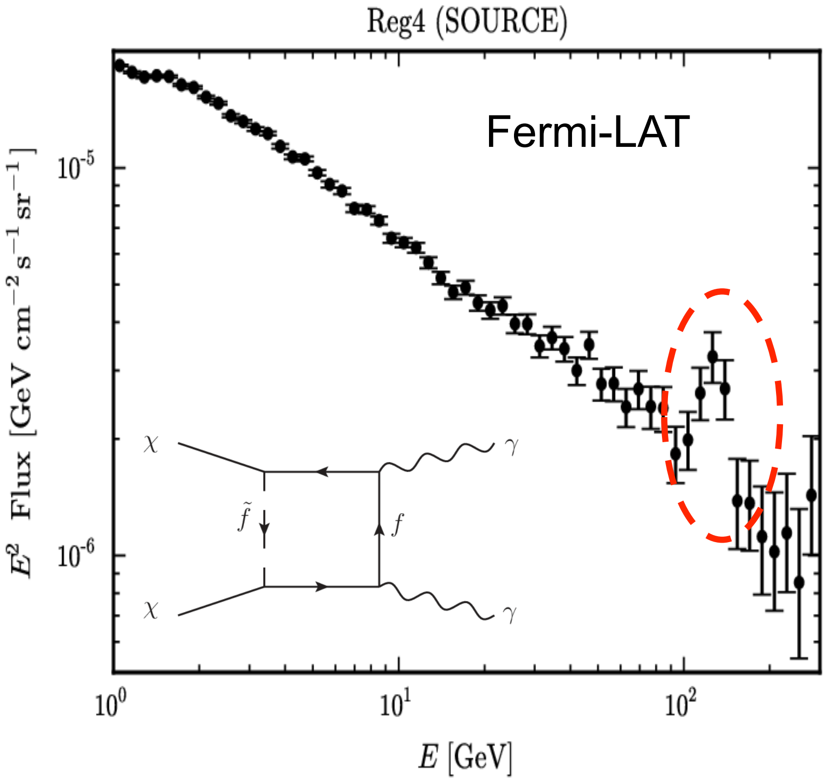
Searching for Dark Matter

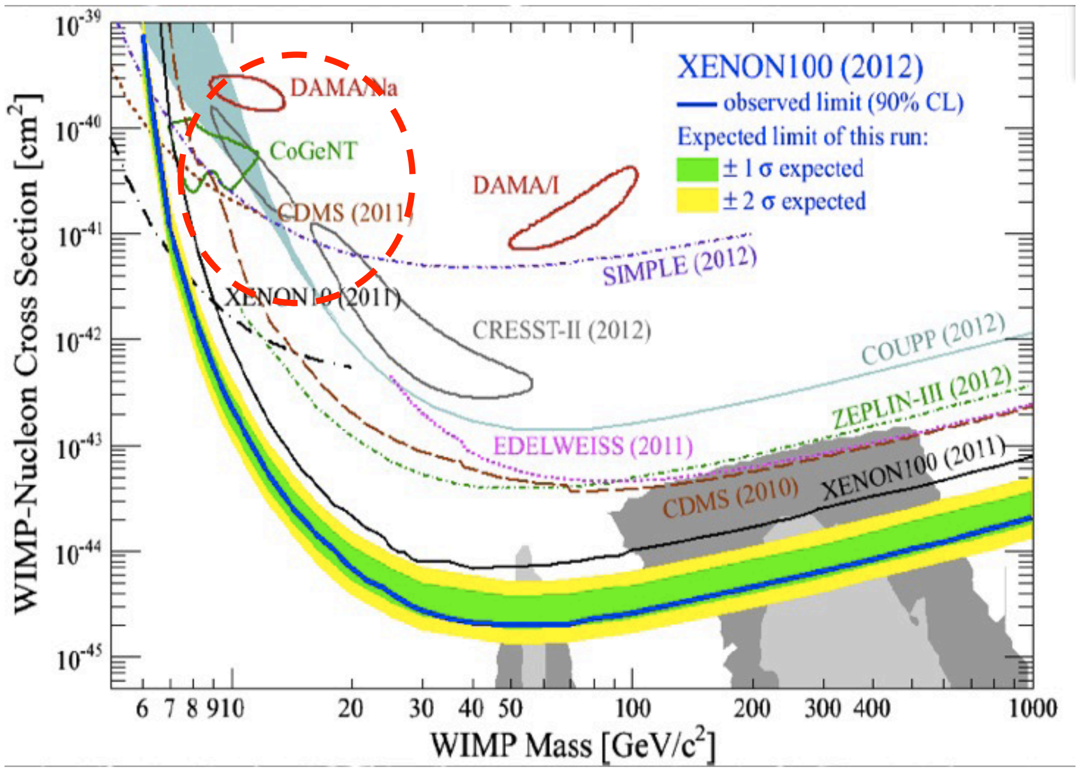


Indirect detection



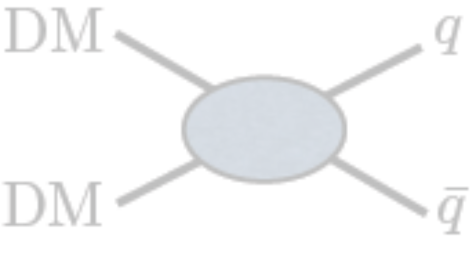
Direct detection

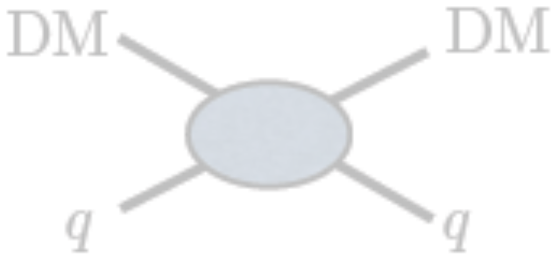


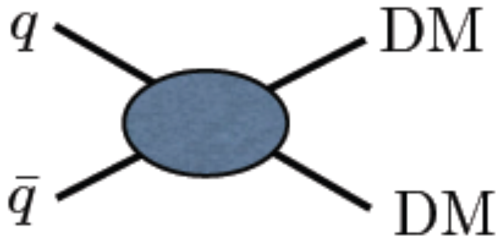


Excesses in several experiments. Strong limits from others. Open question!

Searching for Dark Matter







Indirect detection

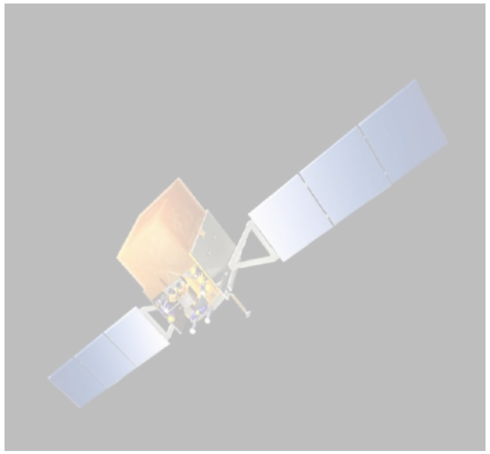
Direct detection

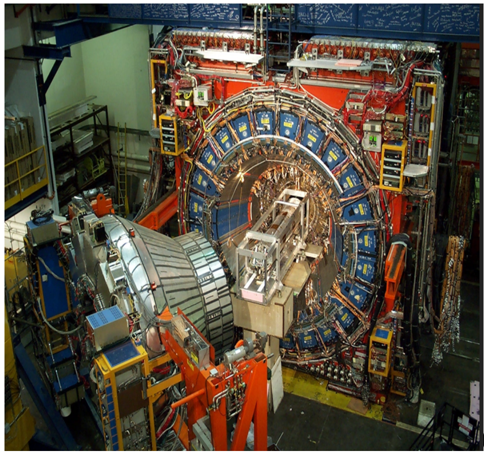
Collider searches

Look up
Annihilation in our galaxy
Antimatter excesses in cosmic rays, photons from centre of galaxy

Look down
Scattering off a nucleus
Low rate, low energy recoil events in underground labs

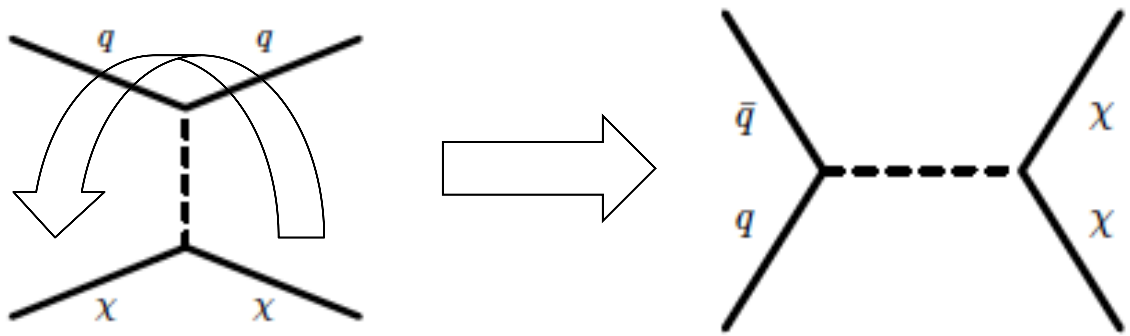
Look small
Missing energy events at a collider experiment





Collider Production

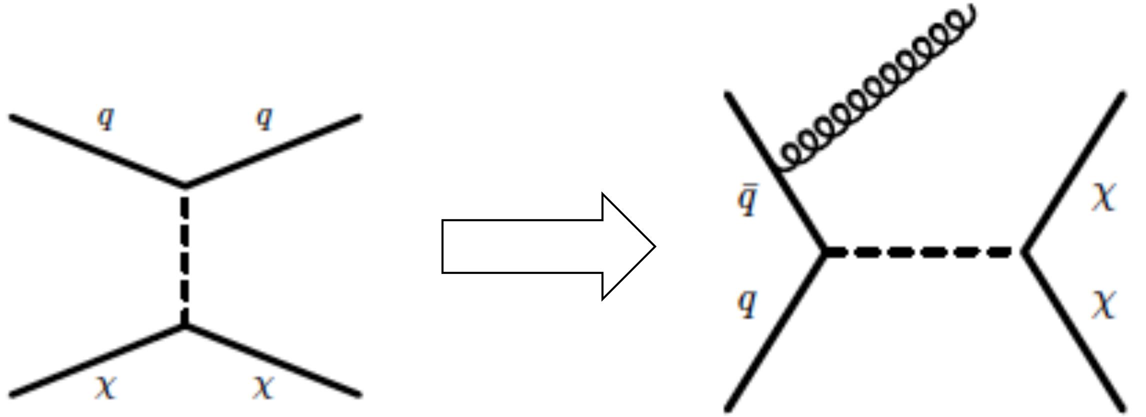
- Assuming dark matter couples to the SM (quarks and gluons), we can relate direct detection experiments to production of dark matter at hadron colliders:



- Problem: in collider production, dark matter leaves no trace in the detector!

Collider Production

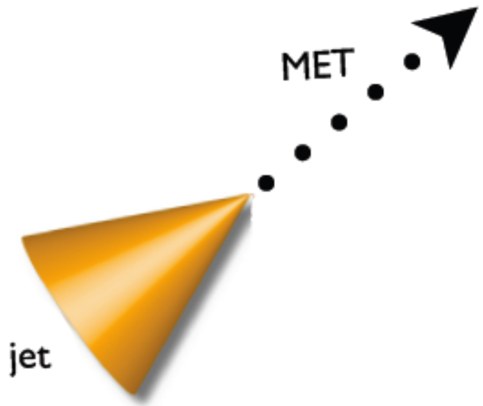
- Assuming dark matter couples to the SM (quarks and gluons), we can relate direct detection experiments to production of dark matter at hadron colliders:



- When produced in association with a ISR jet it is possible to detect and analyze these events

  ➔ signature of mono-jet plus MET

- Could also consider a mono-photon plus MET search! (hasn't been done yet).



Back-of-the Envelope Calculation

Consider massive mediator:

$(p_T \sim 100\,\mathrm{GeV})$ $\qquad$ $(\mu \sim 1\,\mathrm{GeV})$

$$\sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{p_T^2}{M^4} \qquad \sigma_{\mathrm{DD}} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4}$$

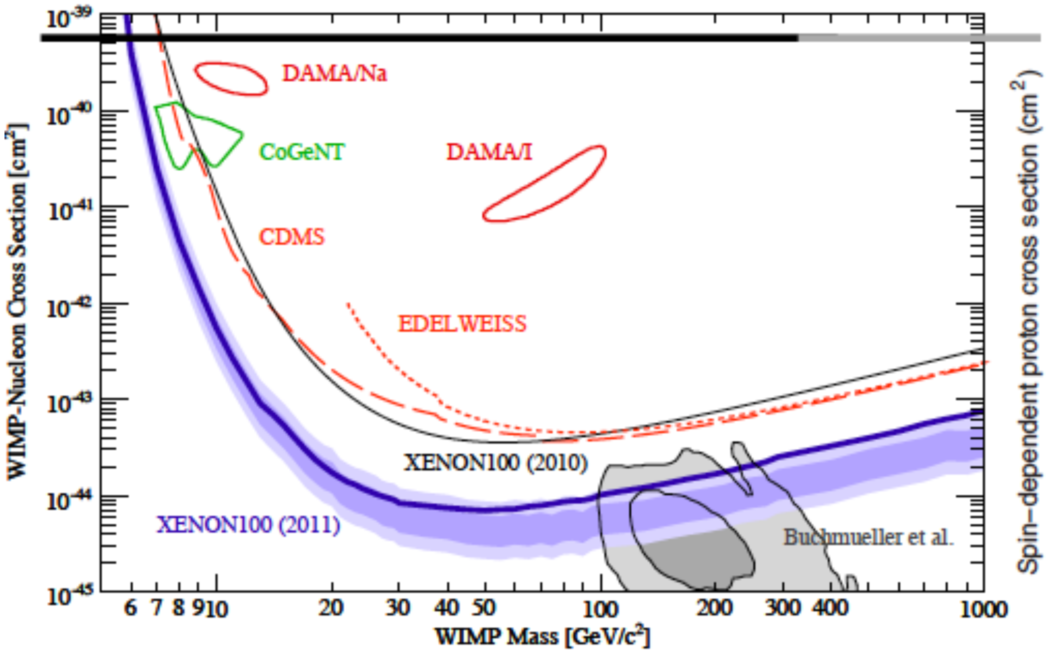
$$\frac{\sigma_{1j}}{\sigma_{DD}} \sim \mathcal{O}(1000)$$

In 1 invfb CDF saw 8449 mono-jet events, expected 8663 $\pm$ 332 $\quad \Rightarrow \quad \sigma_{1j} \lesssim 500\,\mathrm{fb}$

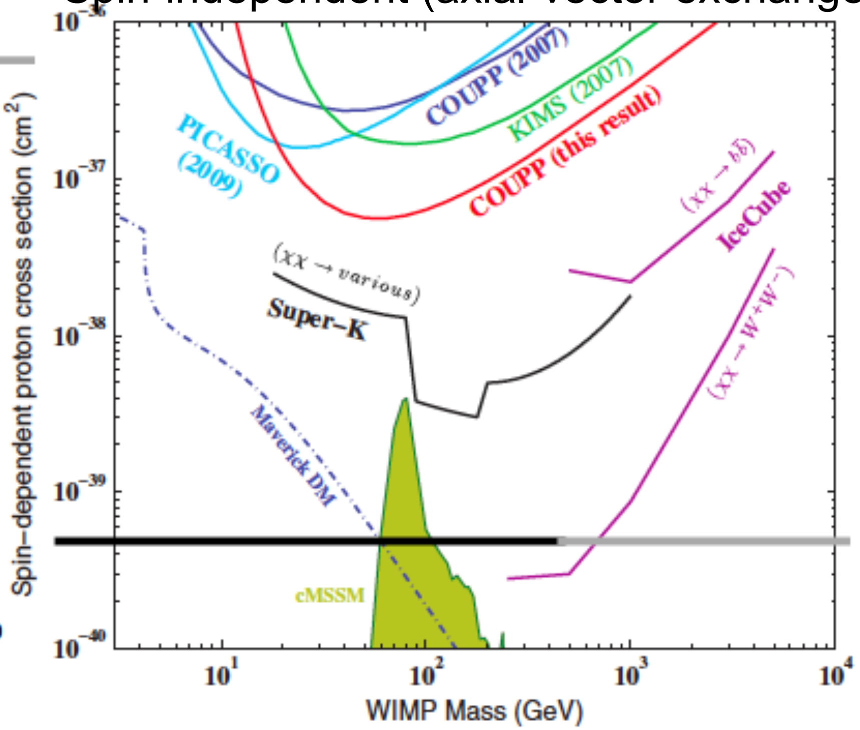
$$\sigma_{DD} \lesssim 0.5\,\mathrm{fb} = 5 \times 10^{-40}\mathrm{cm}^2$$

Collider Advantages

Spin-independent (scalar/vector exchange)



Spin-independent (axial-vector exchange)



- Advantage #1: No detection threshold. In contrast, ~1 GeV DM-recoil can fail below detection threshold in DD search experiments.
- Advantage #2: "model independent" (no spin-indep vs spin-dep interaction) and astrophysics independent (DD results assume local abundance is ρ_{DM}~0.3 GeV/cm^3).

➔ Expect competitive bounds at low mass for spin-independent interactions and over all masses for spin-dependent interactions.

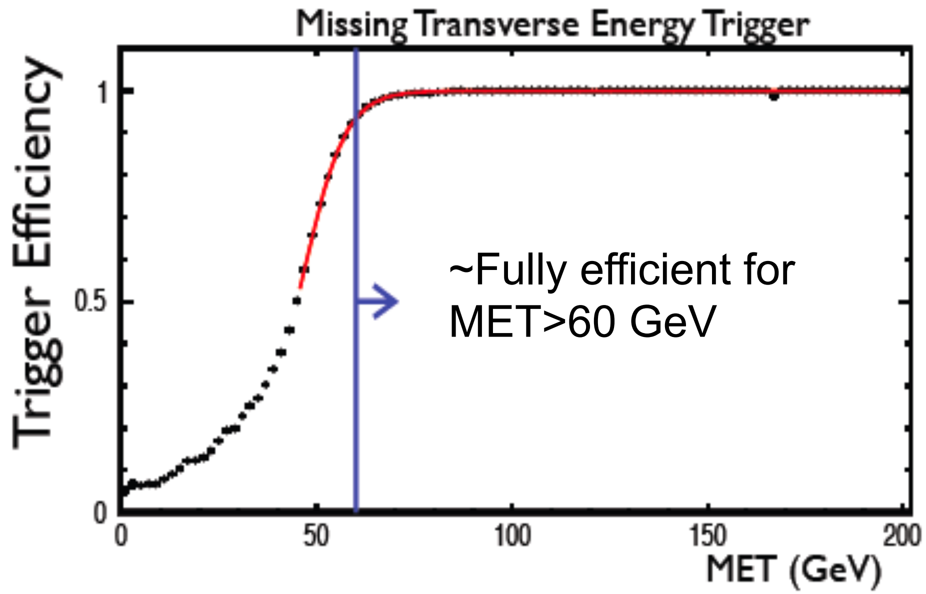
➔ For light mediators (M<<100 GeV) expect DD searches to win (except at low m_χ):

$$\sigma_{\rm DD} \sim g_\chi^2\, g_q^2\, \frac{\mu^2}{M^4} \qquad \text{vs} \qquad \sigma_{1j} \sim \alpha_s g_\chi^2 g_q^2 \frac{1}{p_T^2}$$

Event Selection

- 6.7 fb-1 of data selected with MET triggers (MET>40 GeV).

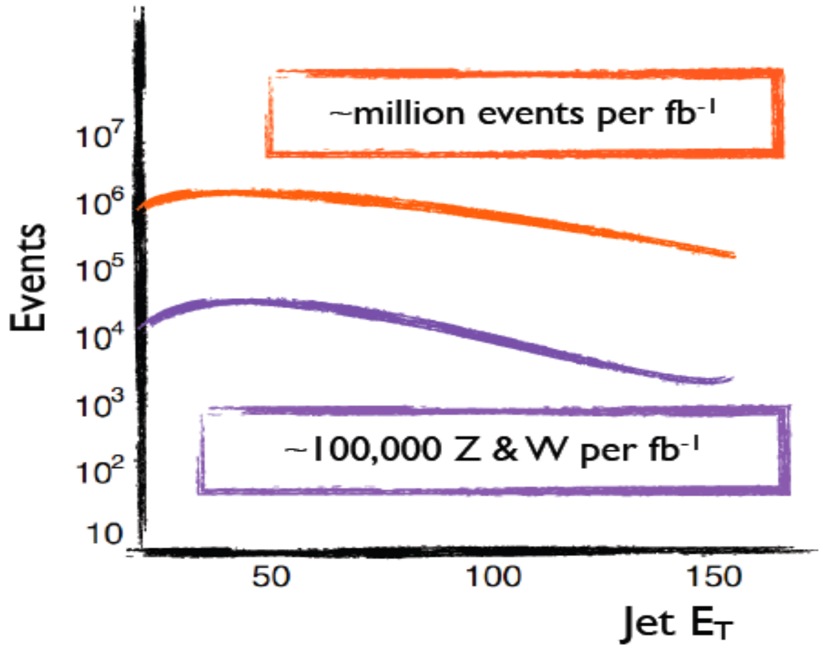
- Offline selection cuts:
  - =1 jet with p_T>60 GeV
  - ≤1 additional jets with p_T<30 GeV
  - MET>60 GeV



- Easy on the paper, but real life is a bit more complicated..
  ➔ background is HUGE!

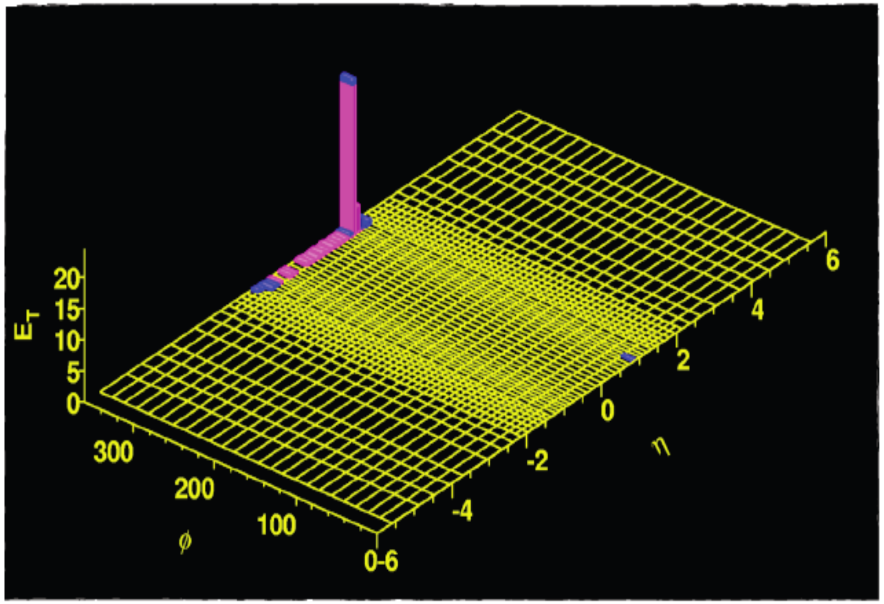
  - W/Z+jets
  - QCD multijets
  - Non-Collision backgrounds

  Total data ~ QCD multijet+non-collision



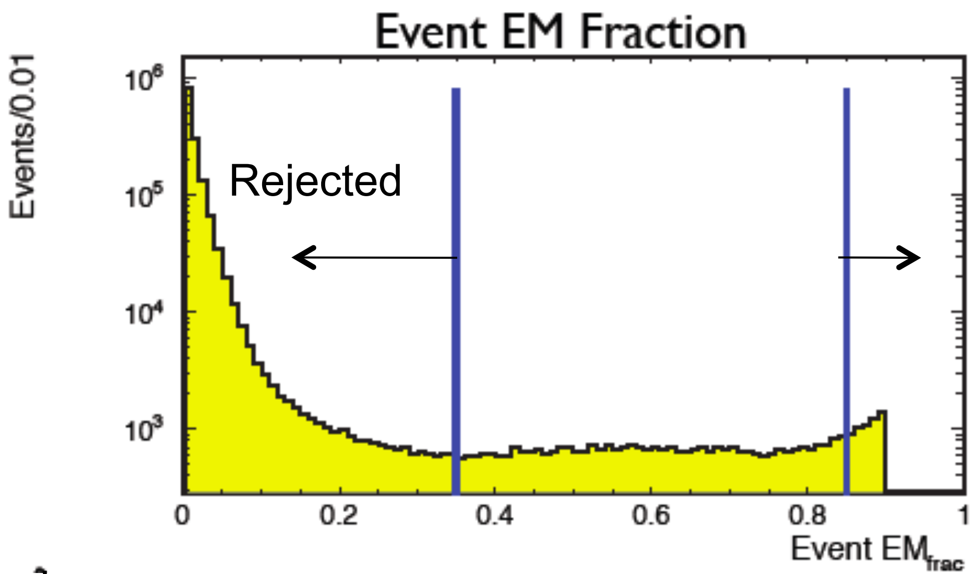
Non-Collision Backgrounds

- Consists mainly of cosmics and beam-halo (dominant contribution).
- Comics:
  - Mostly rejected by vetoing evens with cosmic track candidate in muon system or out-of-time calorimeter deposits wrt the bunch crossing.
- Beam-halo:
  - Detector-gas interactions can produce muons that travel through the calorimeter parallel to the beam



- Typically have low fraction of energy deposited in the electromagnetic calorimeter:

$$\text{Event } EM_{frac} = \frac{\sum_{jets} E_T * EM_{frac}^{jet}}{\sum_{jets} E_T}$$

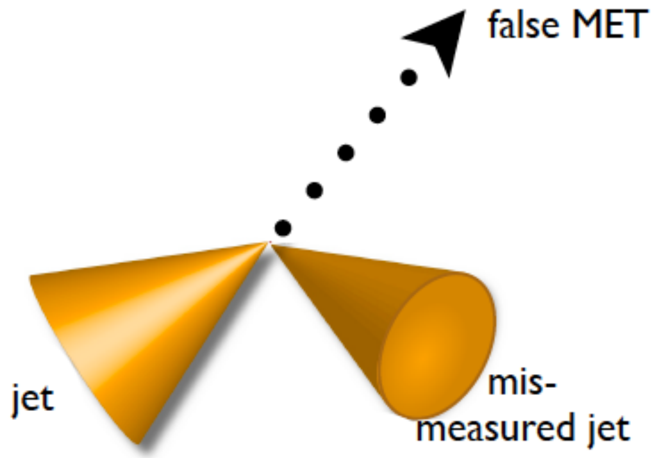


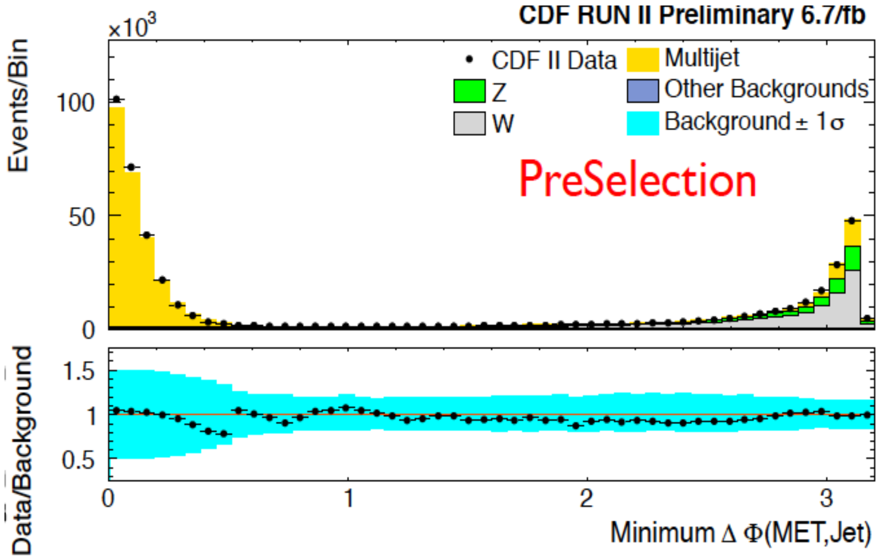
➔ rejects 99% of non-collision background

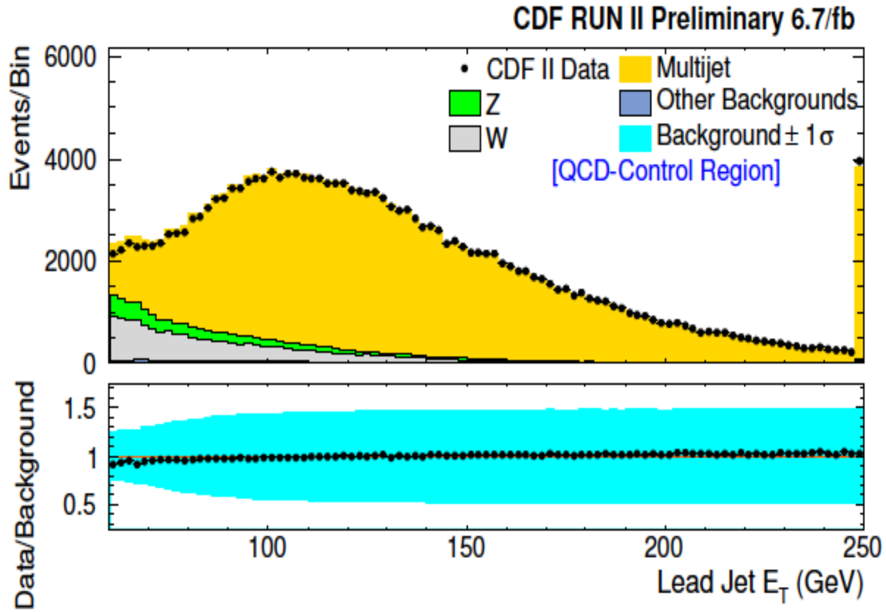
QCD Multijet Background

- QCD multijet events enter mono-jet selection due to misreconstruction or mismeasurement of jets in 2- or 3-jet events.

  Key characteristics:
  - Imbalance in ratio of p_T(jet 1)/MET
  - MET aligned with a jet in transverse plane







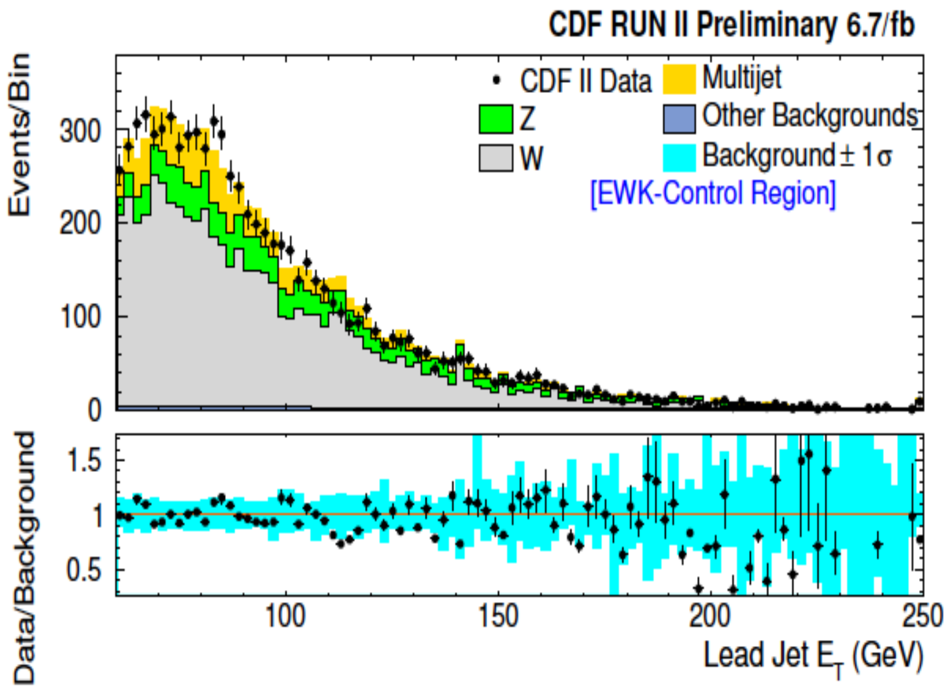
- Use this a other kinematic distributions to train a NN to discriminate between QCD multijet background from W/Z+jet events.

  A cut on this NN has 90% signal efficiency and rejects 80% of the multijet background.

Data-driven modeling validated in QCD-enriched control region

EW Background

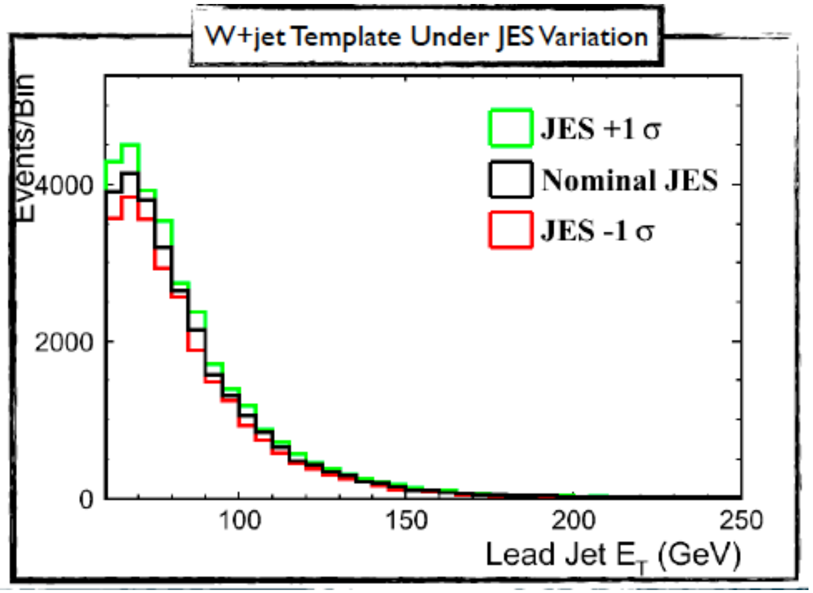
- Dominant background after non-collision and QCD multijet background rejection cuts.
  Main contributions from:
  - Z(→νν)+jets: real MET; irreducible
  - W(→lν)+jets: real MET: reducible by vetoing events with at least one isolated track with p_T>10 GeV.
- Modeled via the MC simulation (ALPGEN - matrix element+parton shower – in the case of W/Z+jets).
- Define control region with same analysis cuts except for requiring at least one isolated track with p_T>10 GeV.

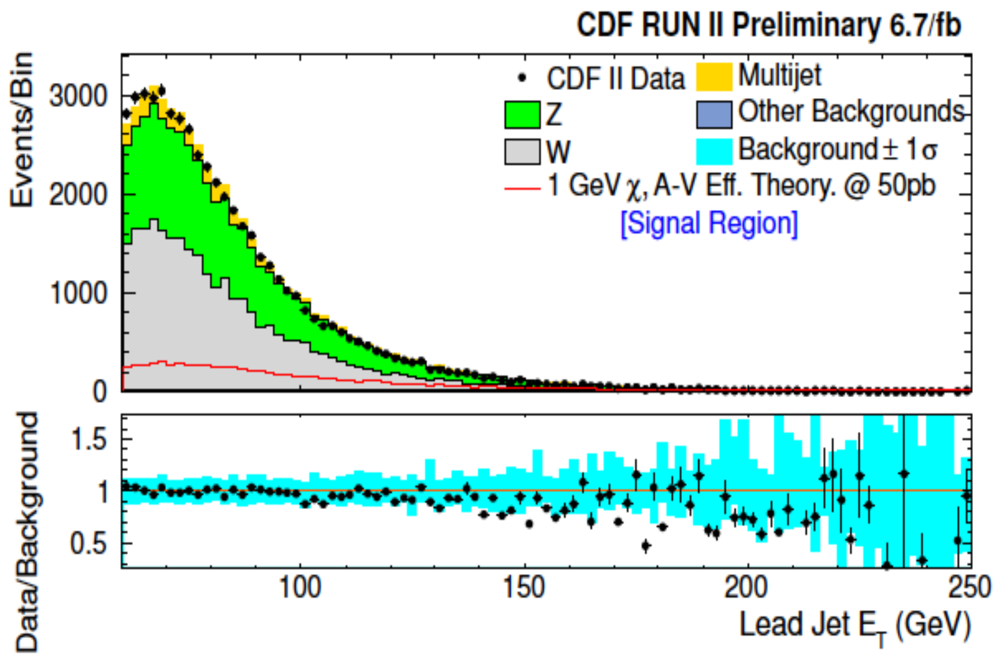


Signal Region

- Good agreement between data and total background prediction (90% W/Z+jets).
- Will use leading jet p_T distribution as main observable to perform the search.
- Main W/Z+jets background systematic uncertainties:
  - Cross section: ~10%
  - JES uncertainty: both normalization and shape.

Contribution	Signal Region
non-collision	6 ± 6
Z	22191 ± 2681
W	27892 ± 3735
diboson	412 ± 36
$t\bar{t}$	23 ± 4
single-top	104 ± 14
multijet	3278 ± 1639
total model	53904 ± 6022
A-V$[\mathcal{M}_{10\,\mathrm{TeV}}, \chi_{1\,\mathrm{GeV}}]$@ 50 pb	151 ± 11
data	52633



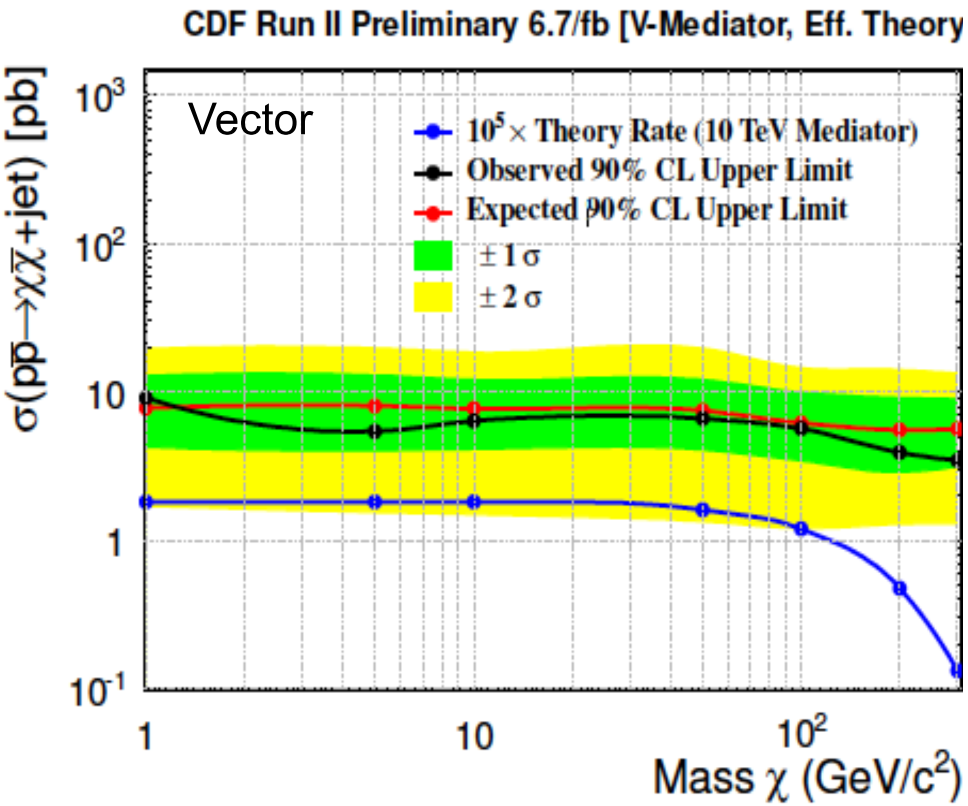


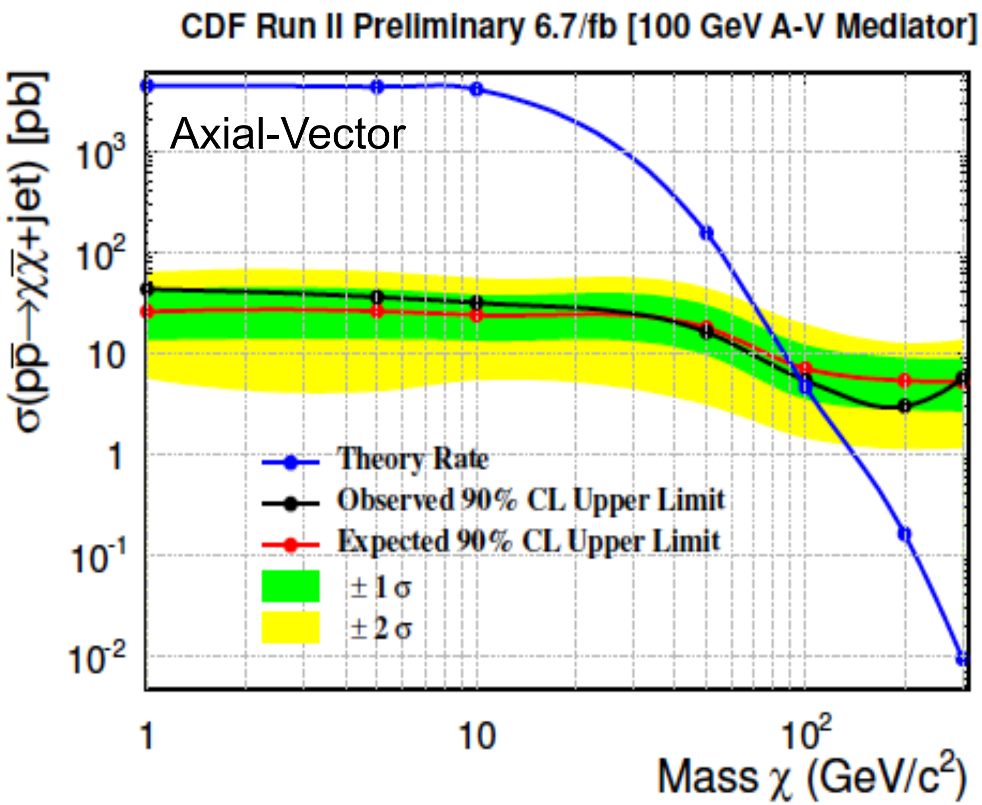
Cross Section Limits

- Set 90% upper limits on $\sigma(p\bar{p} \to \chi\chi+\text{jet})$ as a function of m_χ for different production modes (axial-vector mediated, vector mediated, t-channel mediated) and different values of the mediator mass.

  Examples:

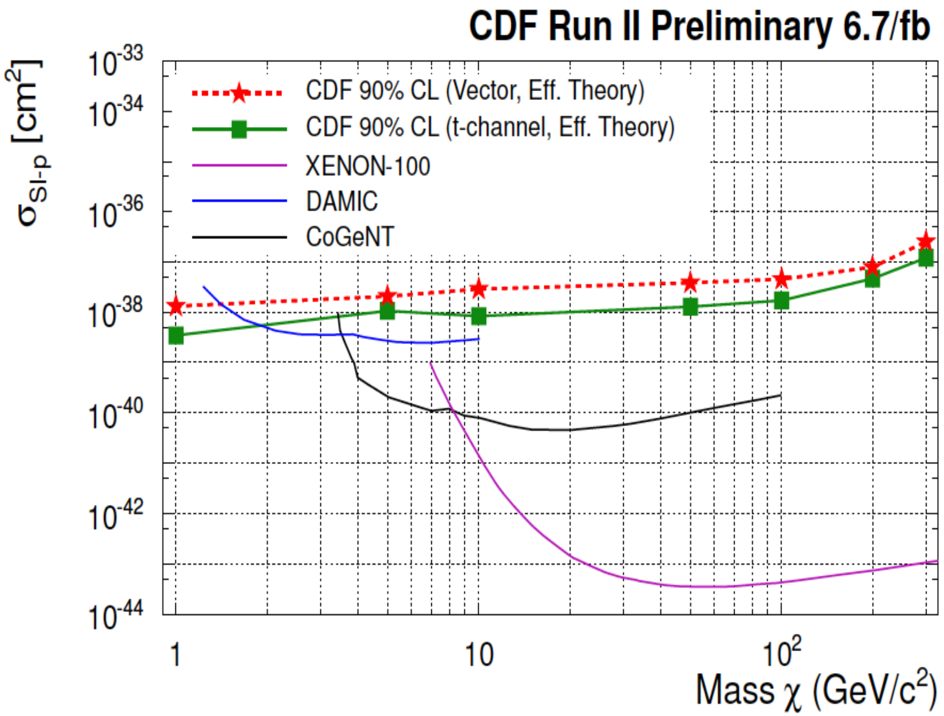
Lectures by: G. Cowan

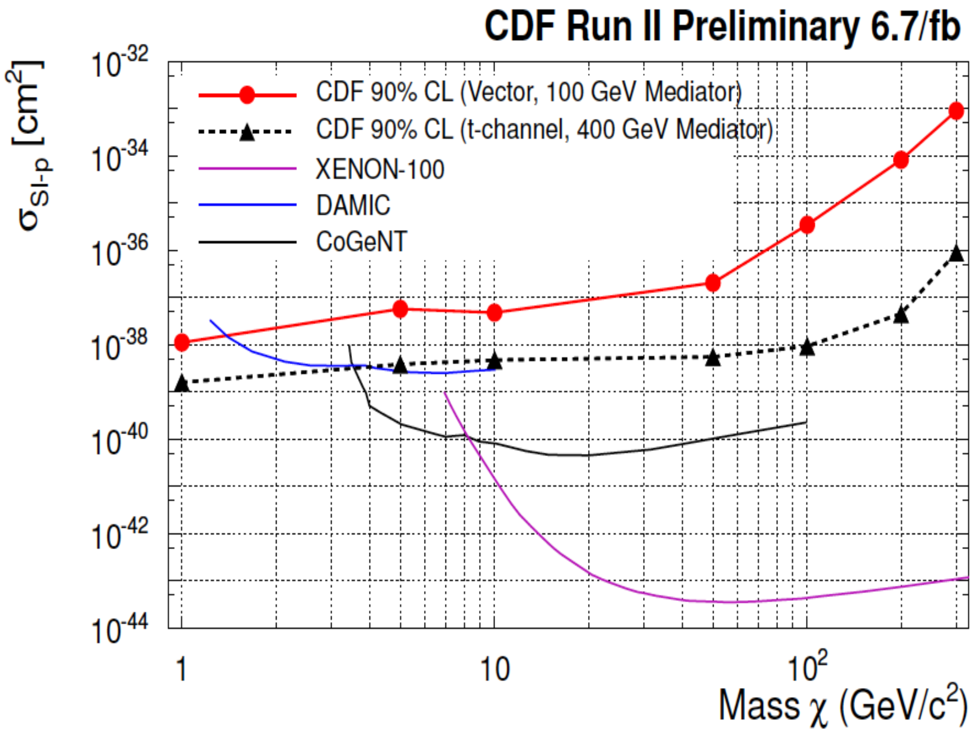




Comparison to Direct Detection

- Translation to spin-independent bounds on DM-nucleon scattering cross section:

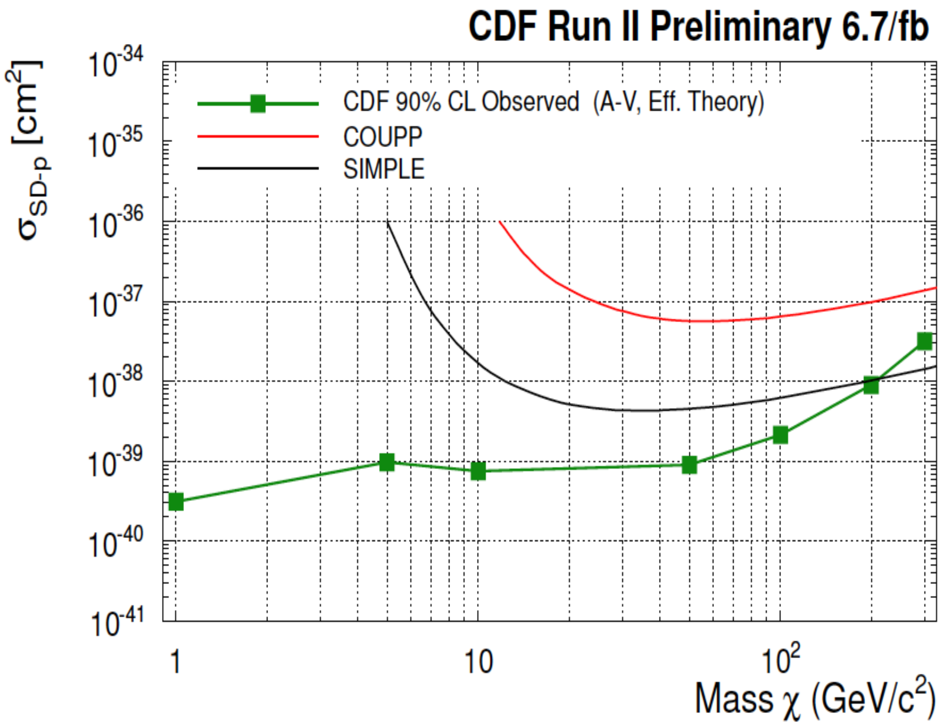


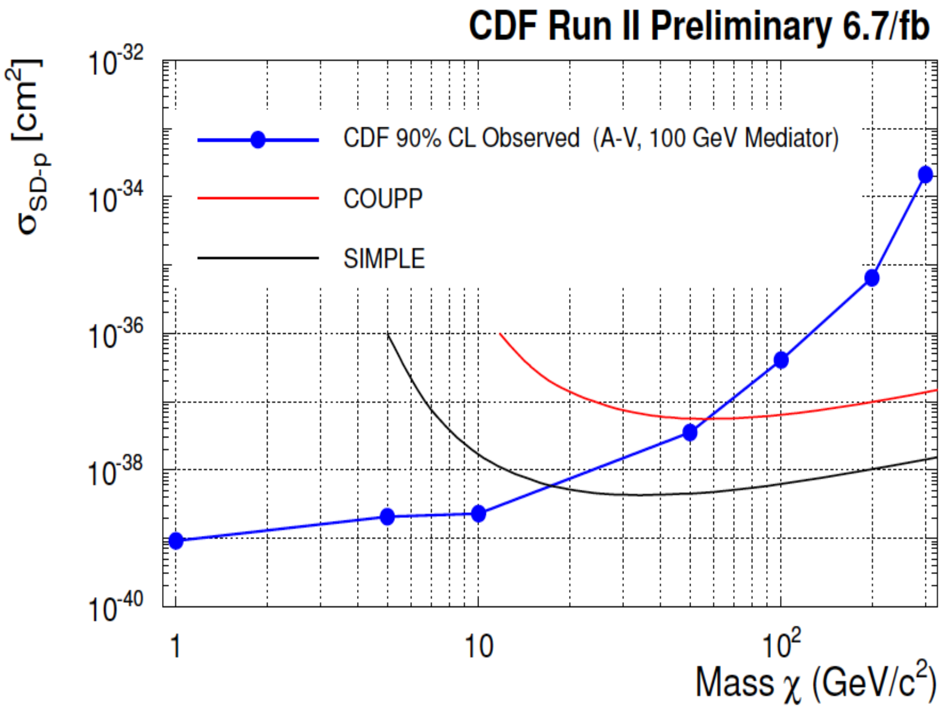


(CoGeNT), Phys. Rev. Lett. 106, 131301 (2011), astro-ph.CO/1002.4703
(DAMIC) 2011, astro-ph.IM/1105.5191
(XENON100), Phys. Rev. Lett. 105, 131302 (2010), astro-ph.CO/1005.0380

Comparison to Direct Detection

- Translation to spin-dependent bounds on DM-nucleon scattering cross section:



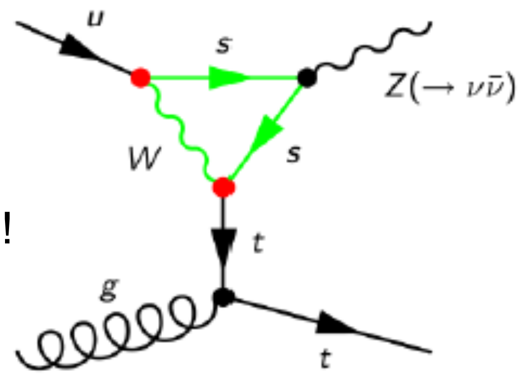


(SIMPLE) 2011, astro-ph.CO/1106.3014
(COUPP) Phys. Rev. Lett. 106, 021303 (2011), astro-ph.CO/1008.3518

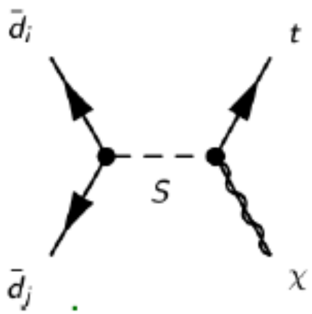
A novel signature: monotop+MET

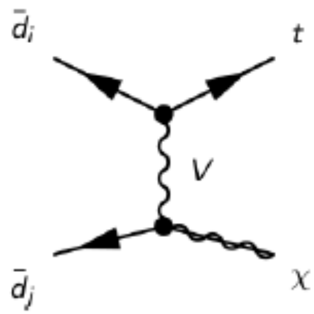
- Monotop production in the SM:
  - Loop-suppressed
  - CKM-suppressed

➔ sounds like a promising signature to search for New Physics!



- Monotop production beyond the SM. A bottom-up approach:
  Two broad classes of models:
  - Fermionic missing energy state: baryon number violating interaction

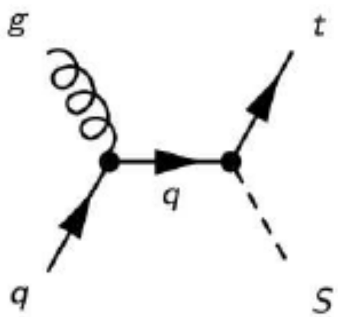


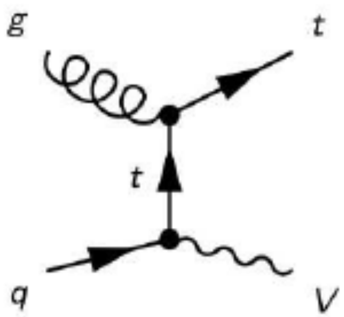


arXiv:1106.6199

s-, t-, and u-channel exchange of a new state (scalar or vector)

  - Bosonic missing energy state: flavor-changing interaction





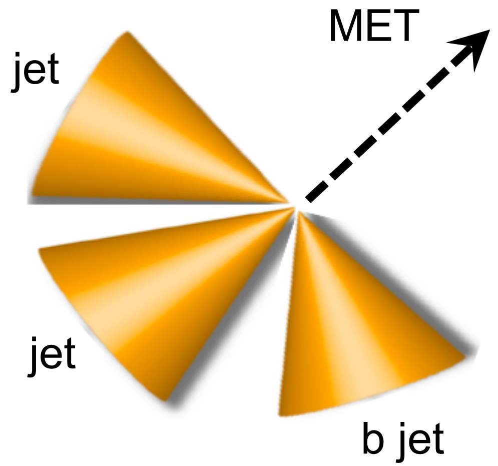
with a new neutral scalar, vector or tensor field either long-lived or decaying invisibly

Event Selection and Backgrounds

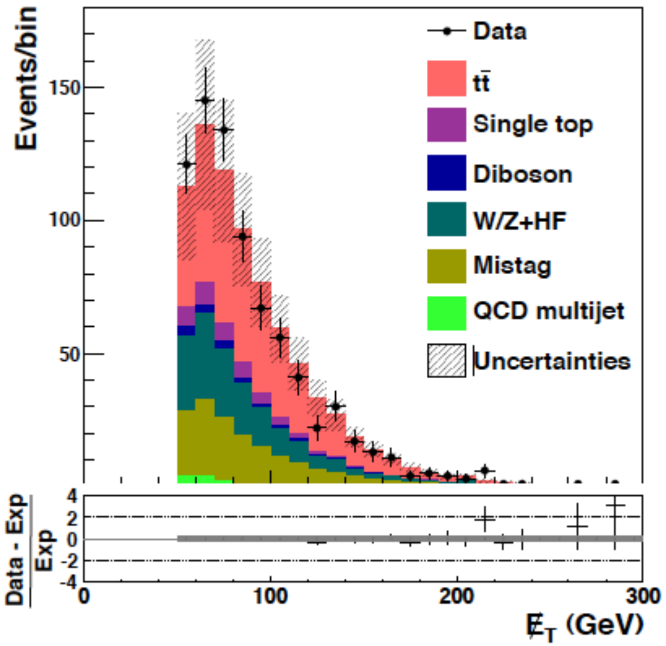
- Strategy: focus on hadronic top quark decay mode
  - Largest BR
  - Full reconstruction of top quark candidate
  - MET uniquely assigned to invisible particle
    ➔ main observable

- Event selection:
  - Jets+MET trigger (MET>30 GeV requirement)
  - 3 jets with p_T>35/25/15 GeV, =1 b-tagged jet
  - MET>50 GeV, $\Delta\phi$(jet2, MET)>0.7
    MET significance>3.5
  - Hadronic top quark candidate:110<m_{jjj}<200 GeV
  - Veto events with electron or muon

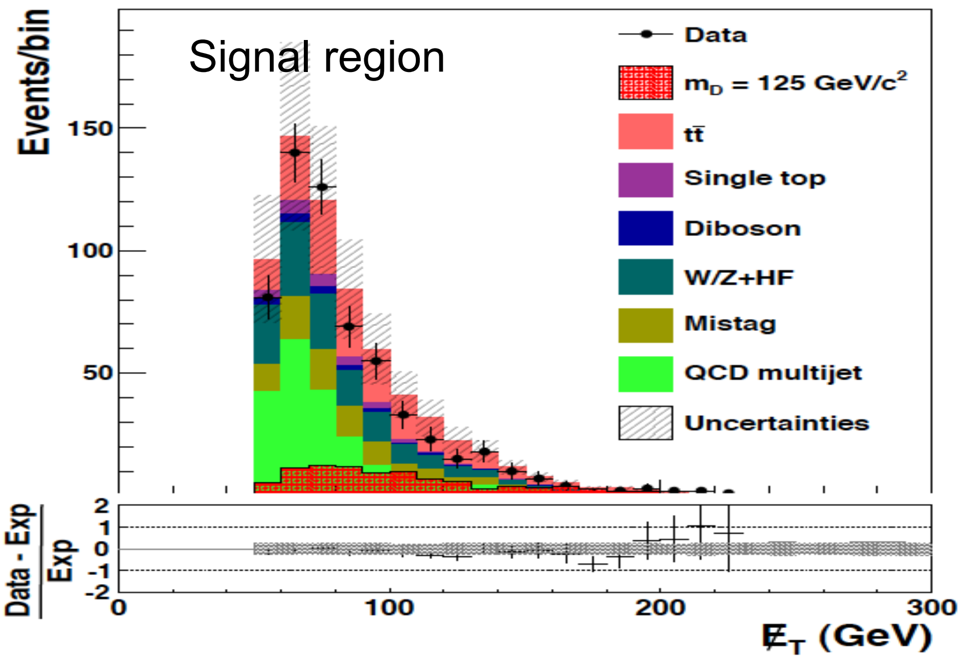
- Main backgrounds:
  - $t\bar{t}$: real hadronic top, MET from leptonic W with non-reconstructed lepton
  - W/Z+jets: fake hadronic top (combinatorial bkg), MET from leptonic W with non-reconstructed lepton
  - QCD multijet: fake hadronic top, MET from jet p_T mismeasurement



Control region requiring identified electron or muon

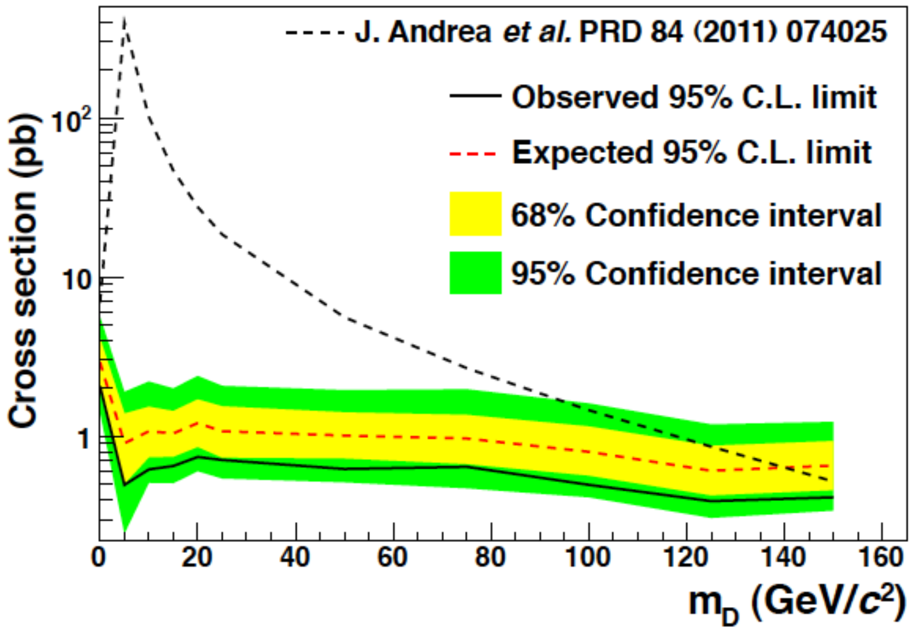


Result



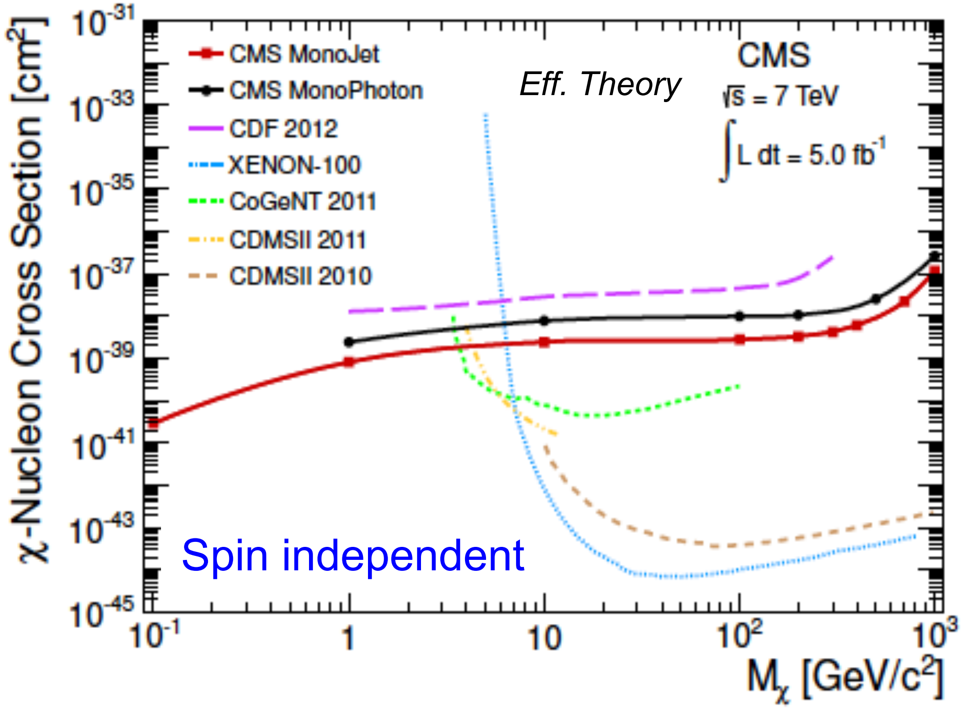
Processes	Events
$p\bar{p} \to t + D$	
$m_D = 20$ GeV$/c^2$	2116.9 ± 121.4
$m_D = 75$ GeV$/c^2$	232.3 ± 22.9
$m_D = 100$ GeV$/c^2$	129.8 ± 12.5
$m_D = 125$ GeV$/c^2$	94.5 ± 9.3
$t\bar{t}$	182.8 ± 20.2
Single top	24.3 ± 4.5
Diboson	15.7 ± 2.7
W/Z+HF	130.5 ± 33.8
Mistag	96.9 ± 39.4
QCD multijet	210.2 ± 54.5
Total background	660.2 ± 78.1
Data	592

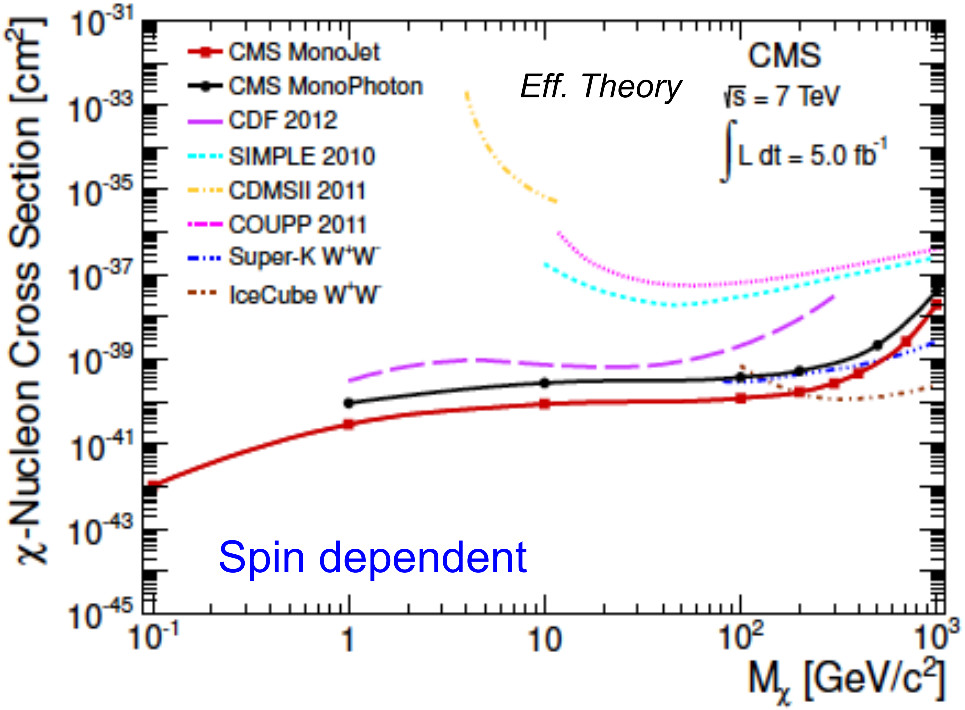
- Data found in good agreement with SM expectations.
- Signal modeled as a flavor-violating process ug→tD with Madgraph.
- Set limits 95% CL upper limits of σ(ug→tD)<0.4-2.0 pb as a function of m_D.
- Exclude m_D<150 GeV in the highest-cross section model.



Summary and Prospects

- Recent LHC results on mono-jet/photon+MET supersede the Tevatron:





And still great potential for improvement!

- Limits demonstrate that hadron-collider experiments can contribute an important piece of information to solve the dark-matter puzzle.
- However, we need to keep in mind that there are many dark-matter-unrelated BSM theories that can predict similar signatures (e.g. extra-dimensions)

It'd be very hard to disentangle the various possibilities!

Plan for Lecture 2

- Lecture 1
  - Preliminaries
    - The Tevatron, CDF and D0
    - Trigger and object reconstruction
  - Probing the electroweak sector
    - Forward-backward asymmetry in $Z/\gamma^* \rightarrow l^+l^-$
  - Probing the top quark sector
    - Forward-backward asymmetry in $t\bar{t}$

- Lecture 2
  - Probing the dark sector
    - Searches for dark matter
  - Probing the b-quark sector
    - Measurement of the dimuon charge asymmetry
  - Probing the EWSB sector
    - Searches for the SM Higgs boson