The physics of top, W and Z

from LHC, Tevatron, HERA

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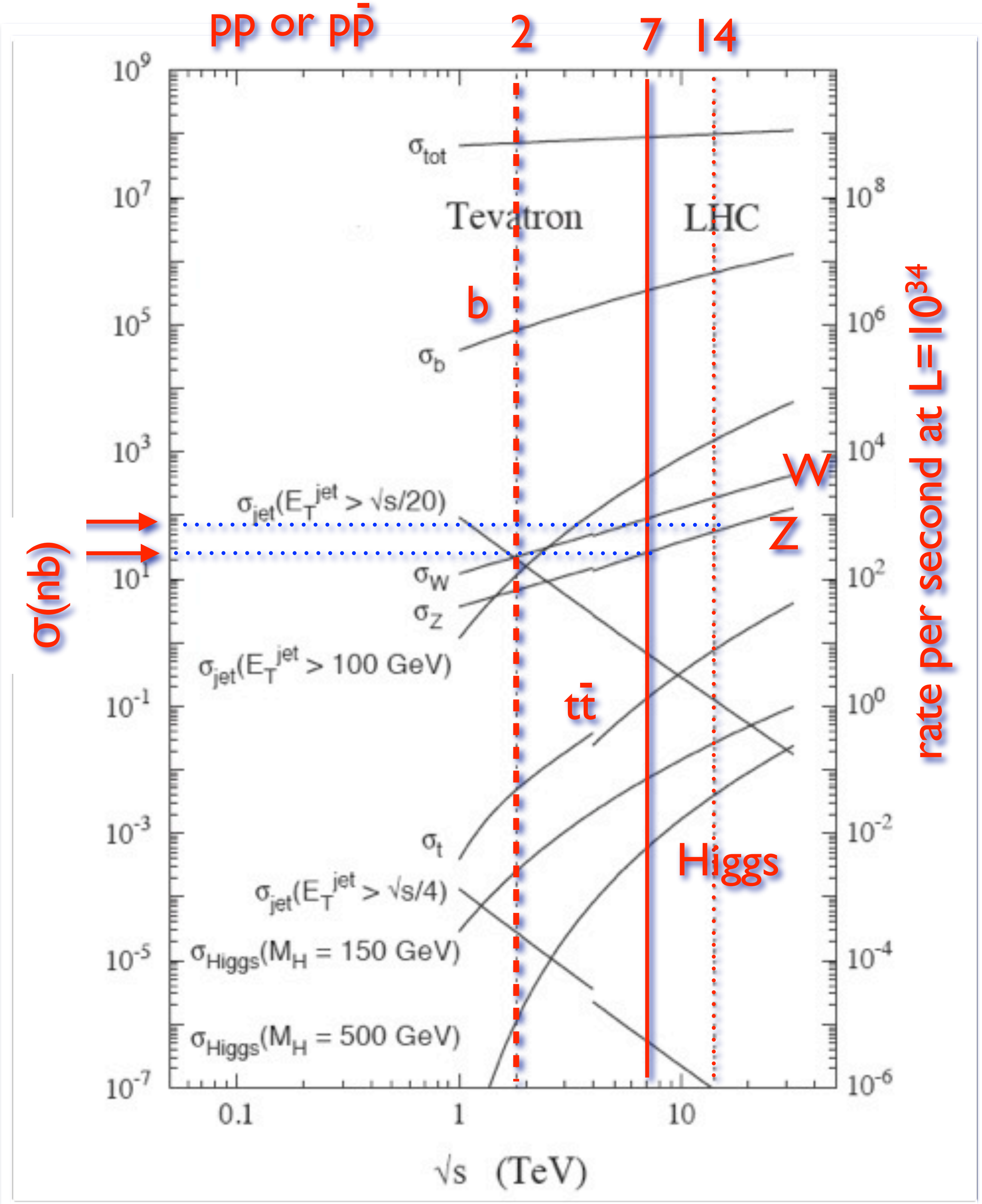
FSP 101 ATLAS

PHYSICS AT THE TERA SCALE
Helmholtz-Alliance

W, Z and top quark



- backgrounds for Higgs and new physics searches
- have to be well understood
- for each 1fb^{-1} @ 14 TeV
  - 10,000,000 W→lν
  - 1,000,000 Z→ll
  - 300,000 $t\bar{t} \to \ell\nu jj$
- useful to calibrate the detector and tune event generators
- ~2,000,000 reconstructed Z→ll at Tevatron
- top events at LHC will be used for detector calibration

> - compliment direct searches for new physics
> - explore higher mass scales through virtual effects

W and Z production

Dibosons

W mass and width

The top quark

Top quark production
top quark pairs
electroweak single top quark

Top quark properties
mass
width
forward-backward asymmetry
spin correlations

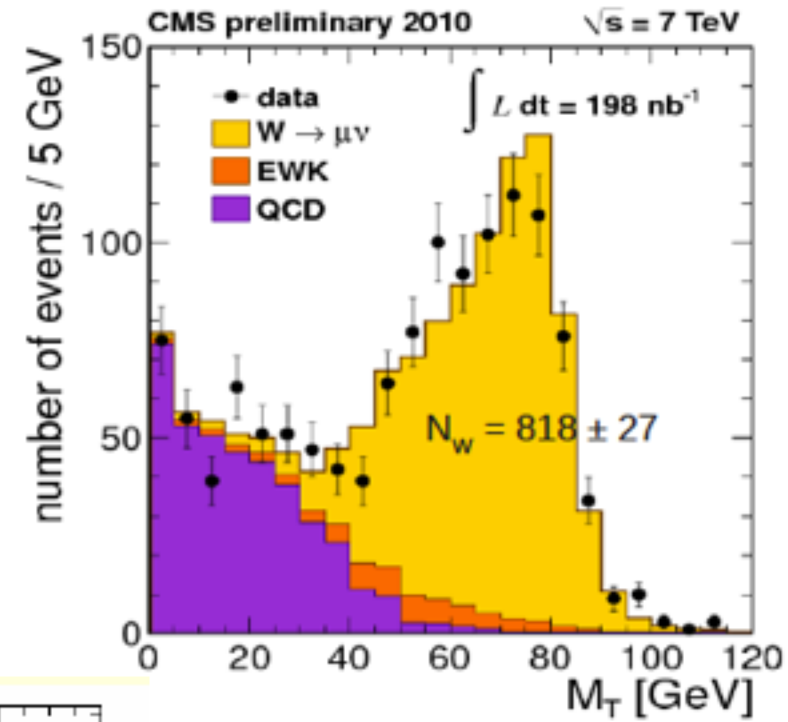
Searches in top quark sector

Electroweak fit

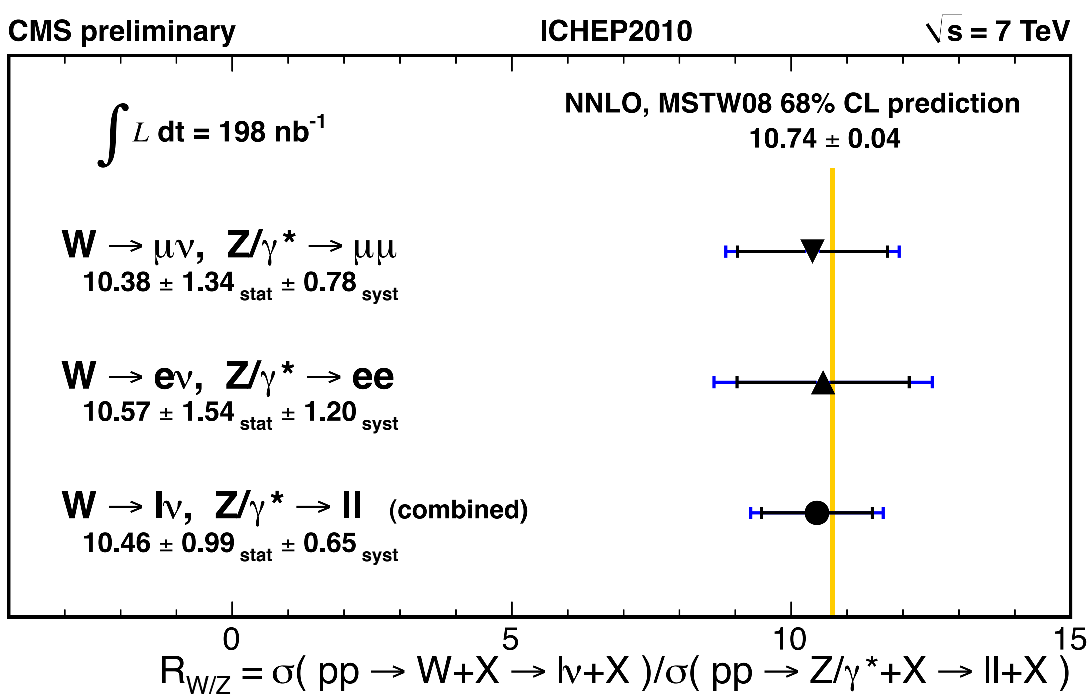
Many more exciting results were presented. This is just a short summary...

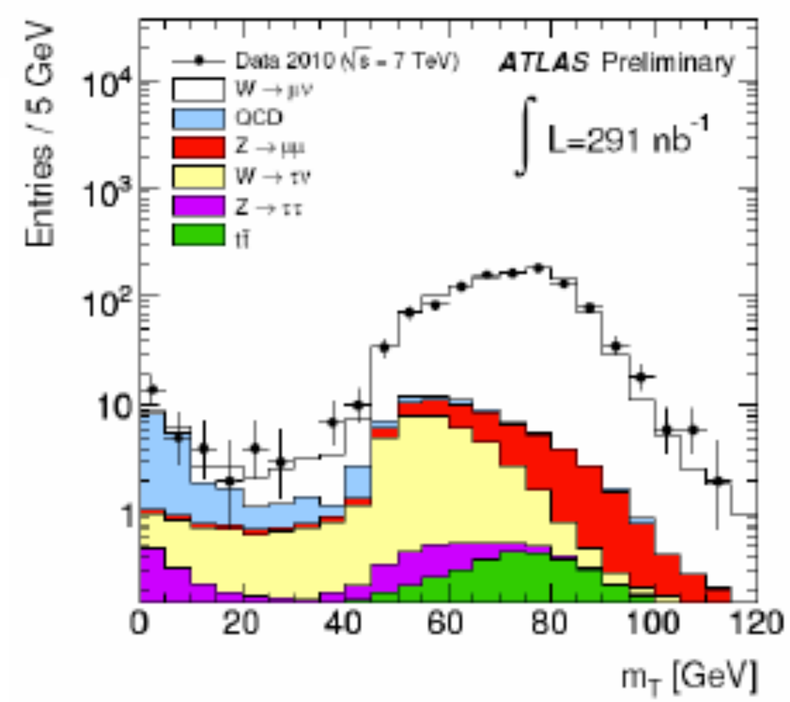
W and Z observation at LHC

- W inclusive cross section
  - CMS: L=196 nb^{-1}, Atlas: 17 nb^{-1}
- Z inclusive cross section
  - CMS: L=196 nb^{-1}, Atlas: ~225 nb^{-1}
- W/Z ratios (CMS)



W to Z ratios





Transverse W mass $W \rightarrow \mu\nu$

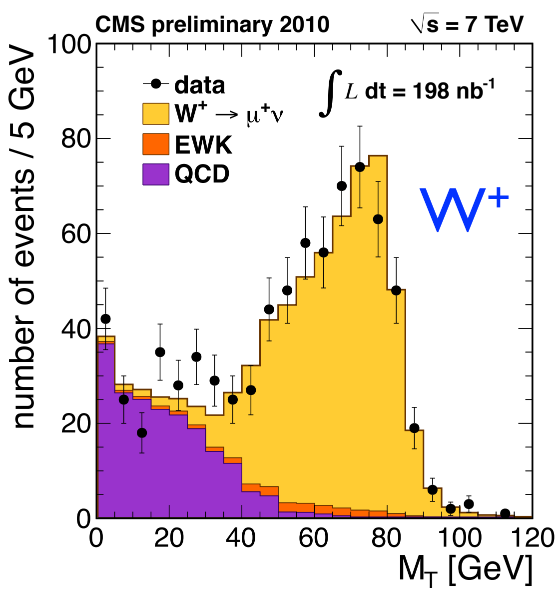
← candidates in 291 nb^{-1} of data

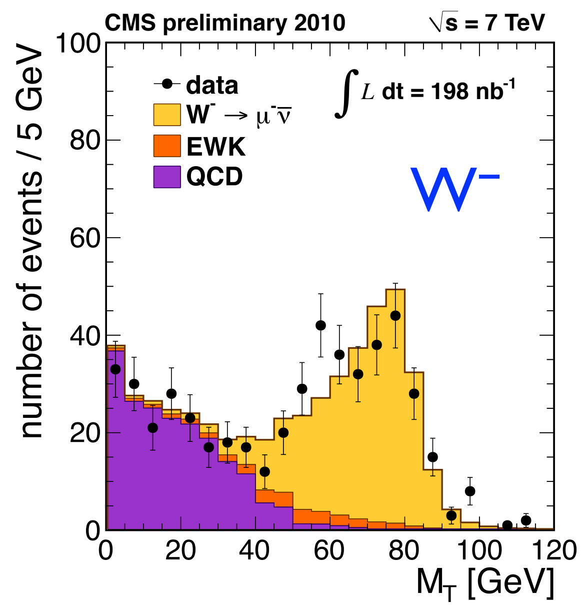
Measurements agree between electron and muon channels and with the NNLO calculation

W distributions at LHC

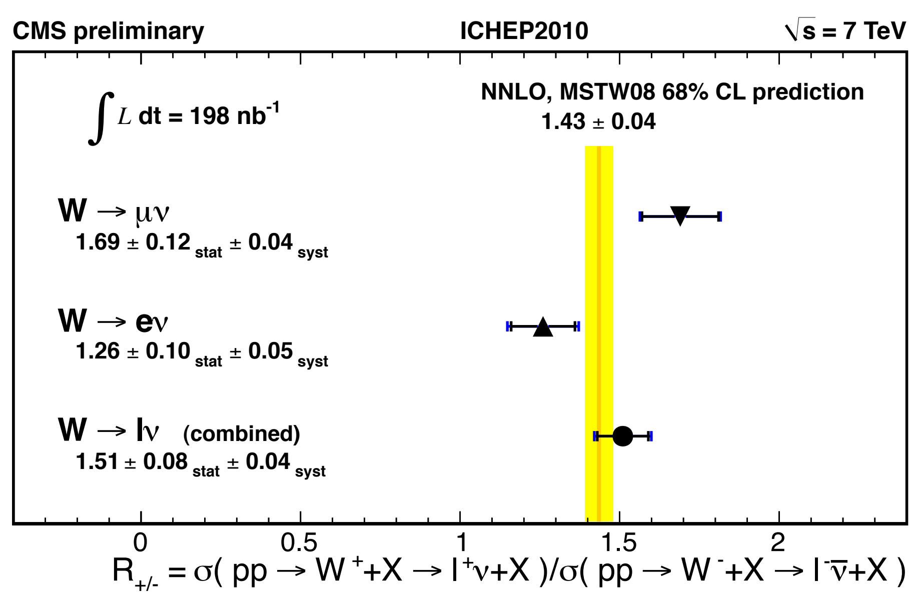
Splitting by charge

At LHC $\sigma(W^+) > \sigma(W^-)$

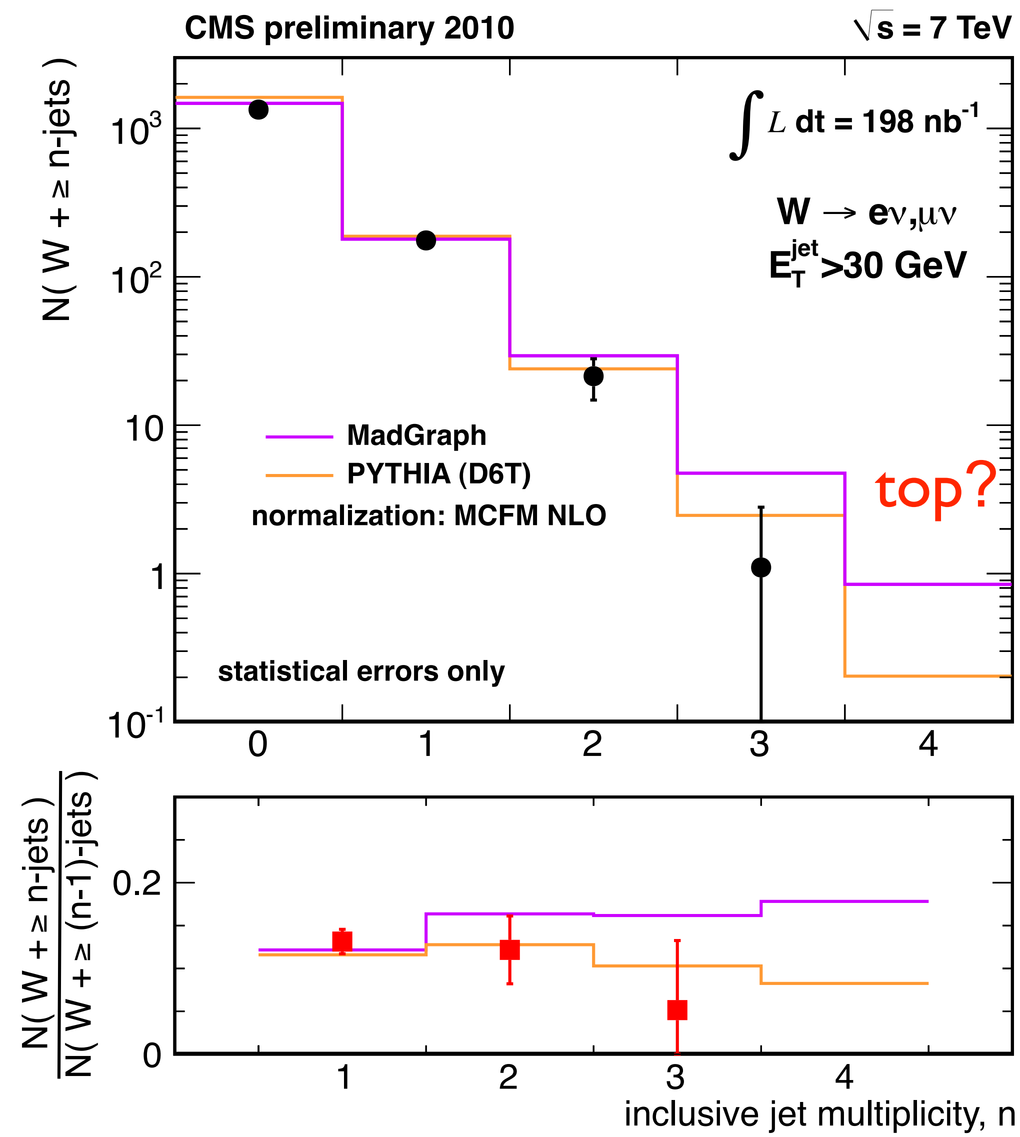




$\sigma(W^+)/\sigma(W^-)$



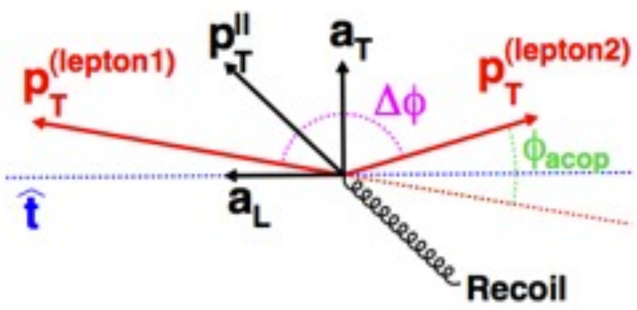
W+jets



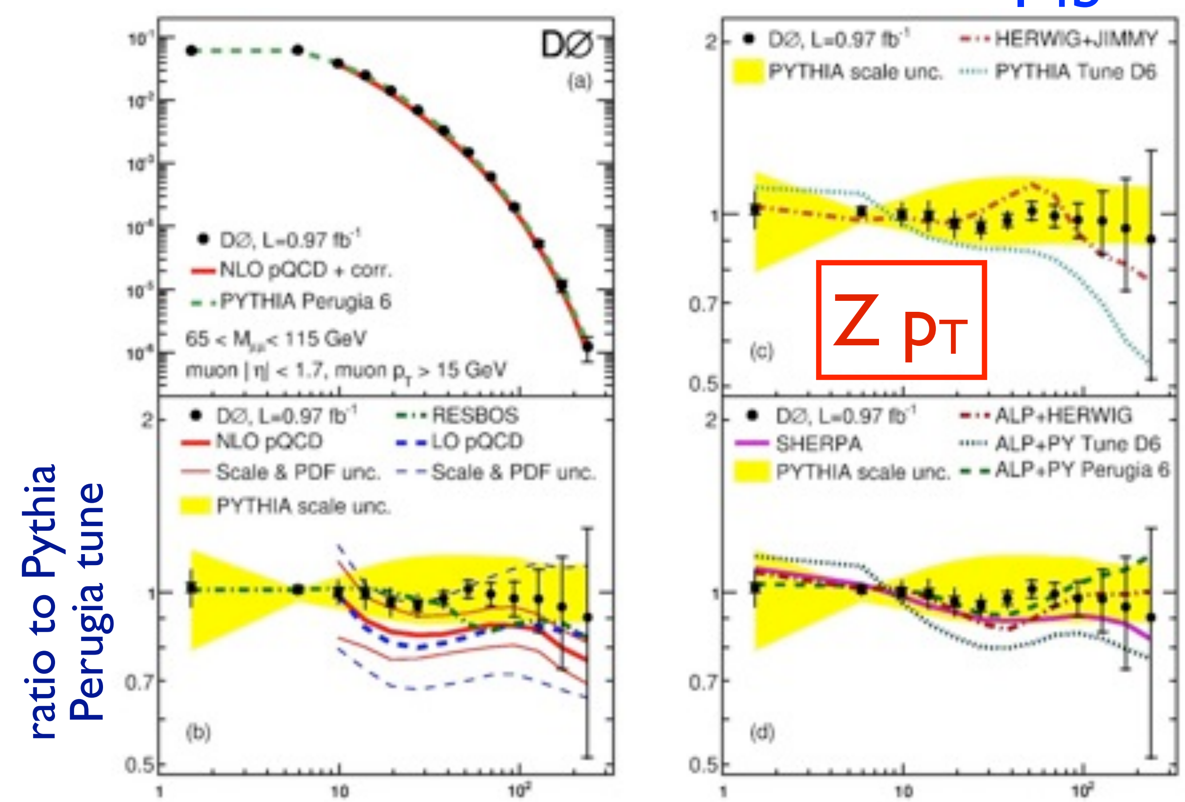
- W+jets - main background for top pair production in l+jets channel
- Its understanding is a key to top physics analyses

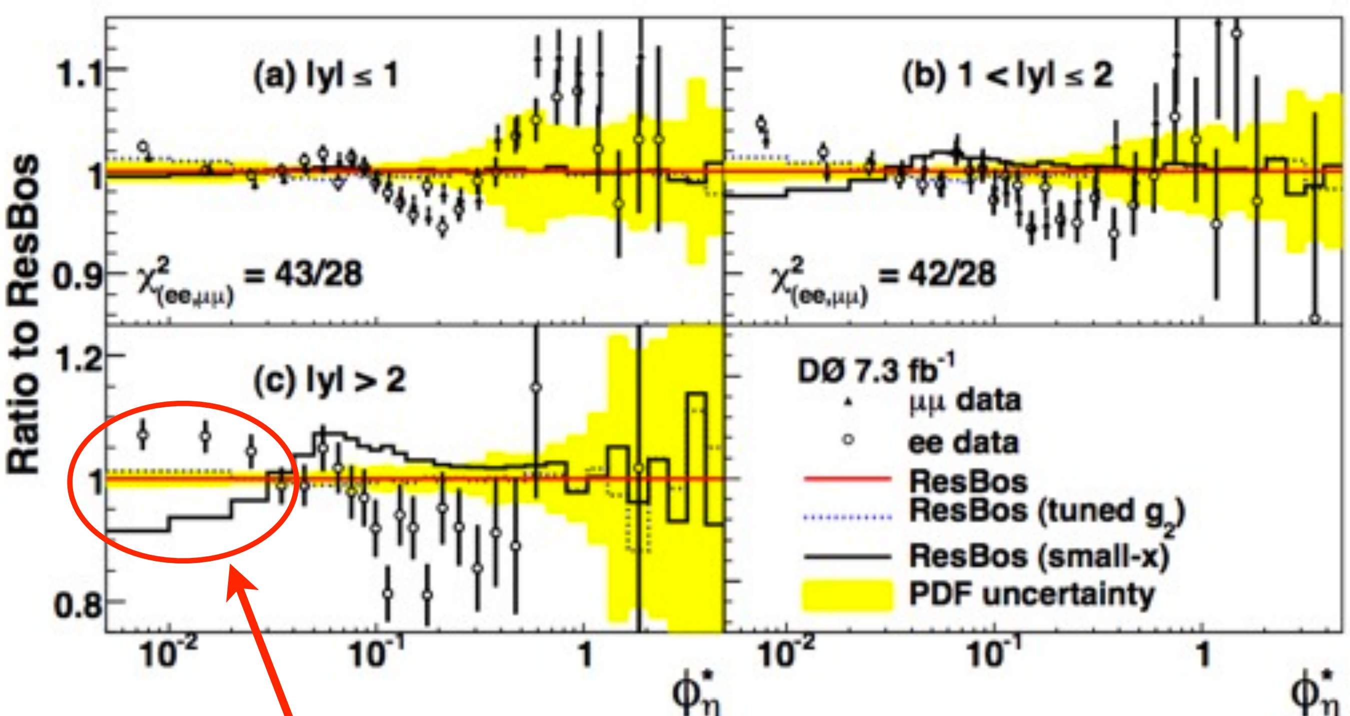
Z/γ* differential distributions

- excellent ground for testing QCD
- colorless and low background state
- background for many processes: important to model correctly



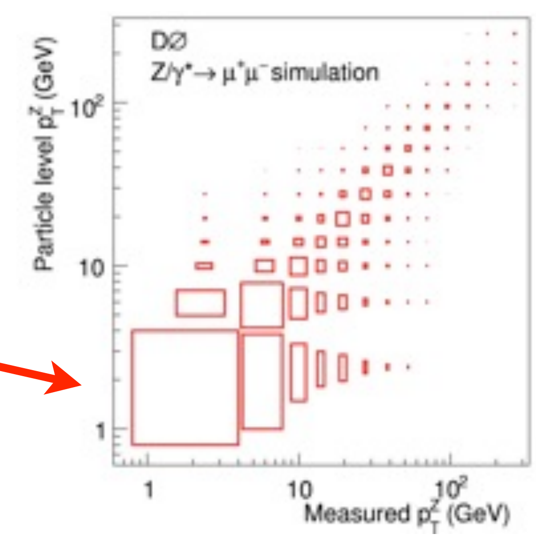
1 fb^{-1}





Data does NOT support "small-x broadening"

Limited by large unfolding systematics at low pT

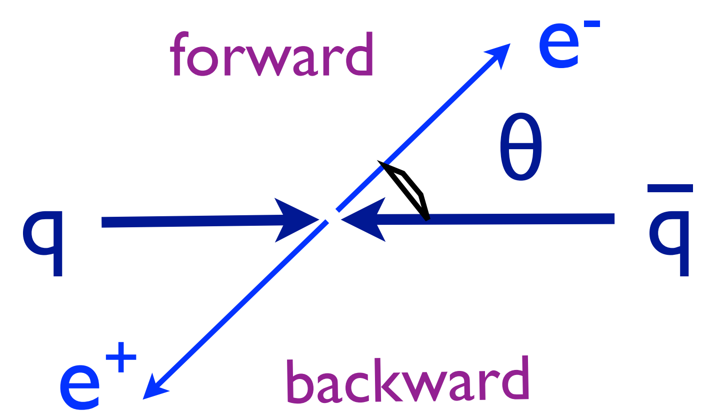


- new variable: depends only on directions of two leptons
- sensitive to same physics effects as Z p_T

Forward-backward charge asymmetry

- Presence of both vector and axial-vector couplings of W and Z bosons to quarks
- A_{FB} - relative strengths of couplings
- Sensitive to
  - Z-quark couplings: a_u, v_u, a_d, v_d
  - Z-electron couplings: a_e, v_e
  - weak mixing angle $\sin^2\theta_W$

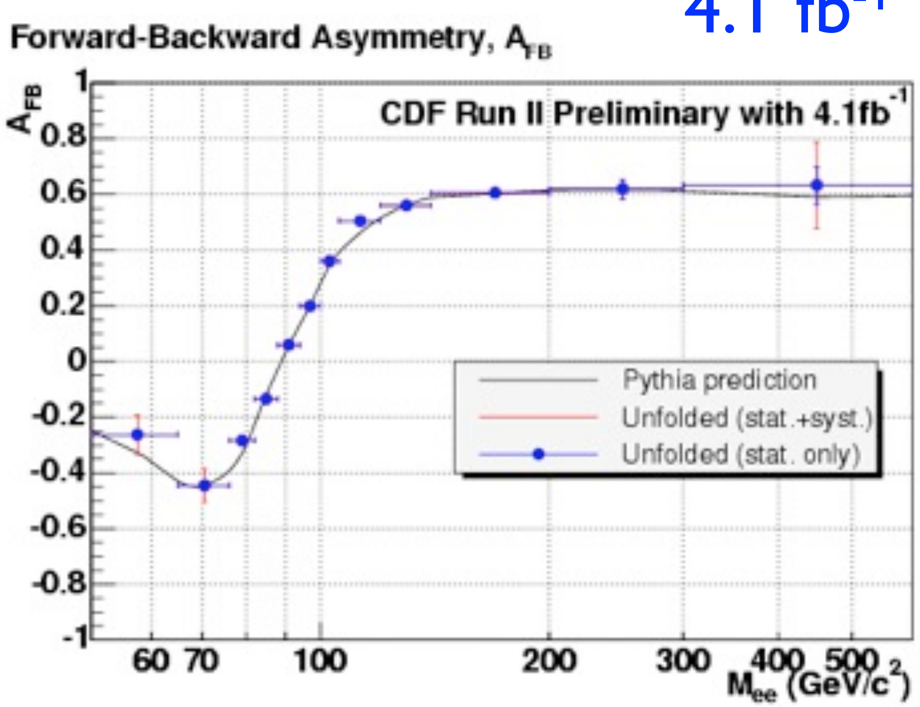
rest frame of e^+e^- pair



$$A_{FB} = \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$

$$\frac{d\sigma}{dcos\theta} = A(1 + cos^2\theta) + Bcos\theta$$

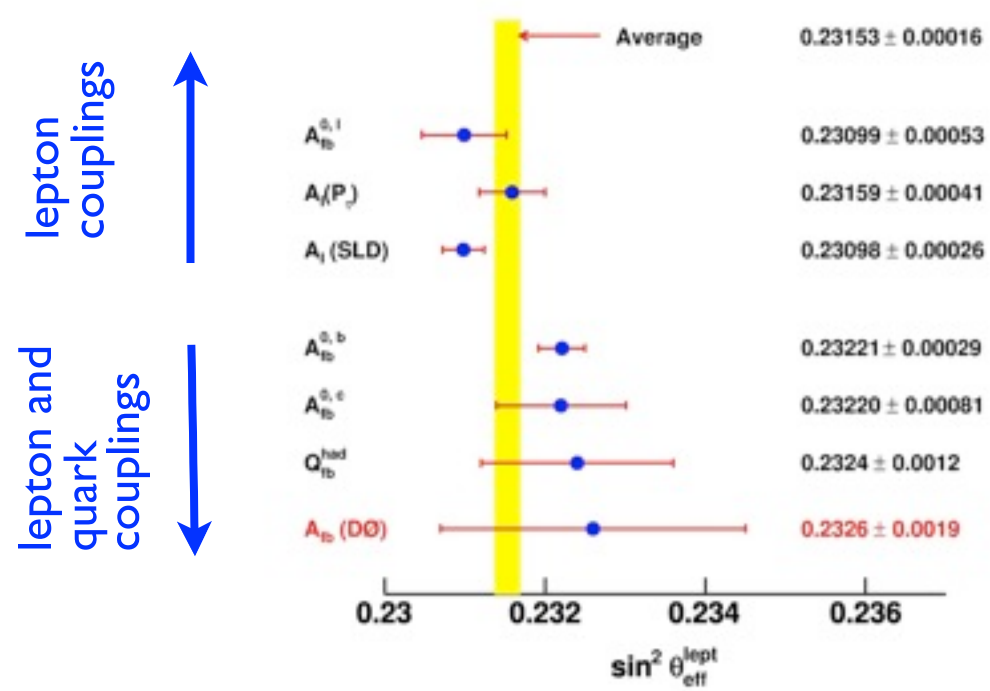
4.1 fb^{-1}



invariant mass of e^+e^- pair

1.1 fb^{-1}

$$\sin^2\theta_W^{\text{eff}} = 0.2326 \pm 0.0018(\text{stat}) \pm 0.0006(\text{syst})$$



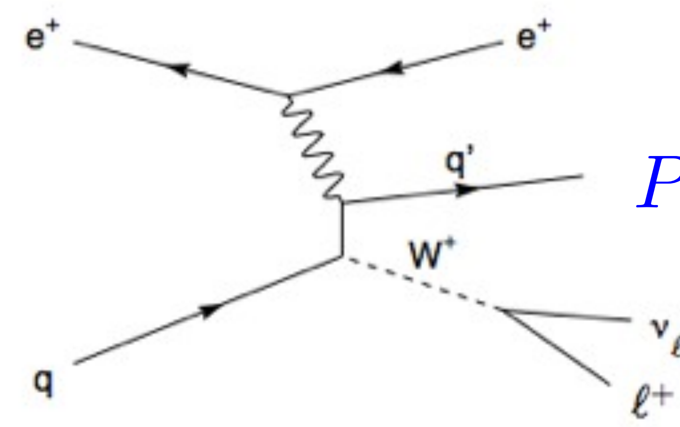
W production at HERA

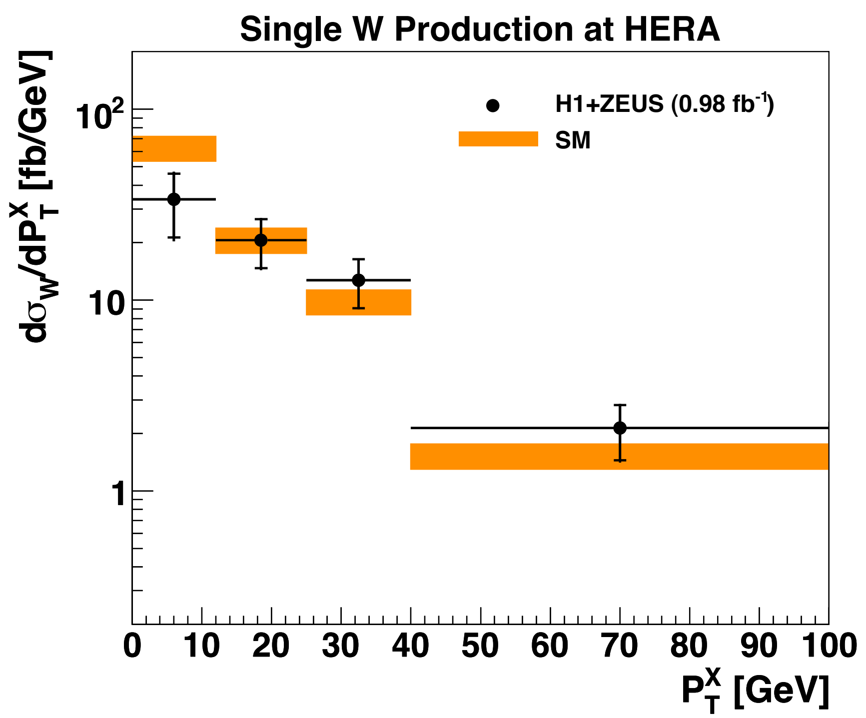
- Events with isolated lepton and high P_T^{miss}
- dominated by SM single W production
- excess in earlier H1 data at high P_T^X

Combined H1+ZEUS, 0.98 fb^{-1}

σ_W=1.06±0.16(stat)±0.07(syst) pb

SM theory: σ_W=1.27±0.19 pb





$P_T^X > 25\mathrm{GeV}$

29 observed

24.0±3.2 SM

no excess in combined H1+ZEUS data

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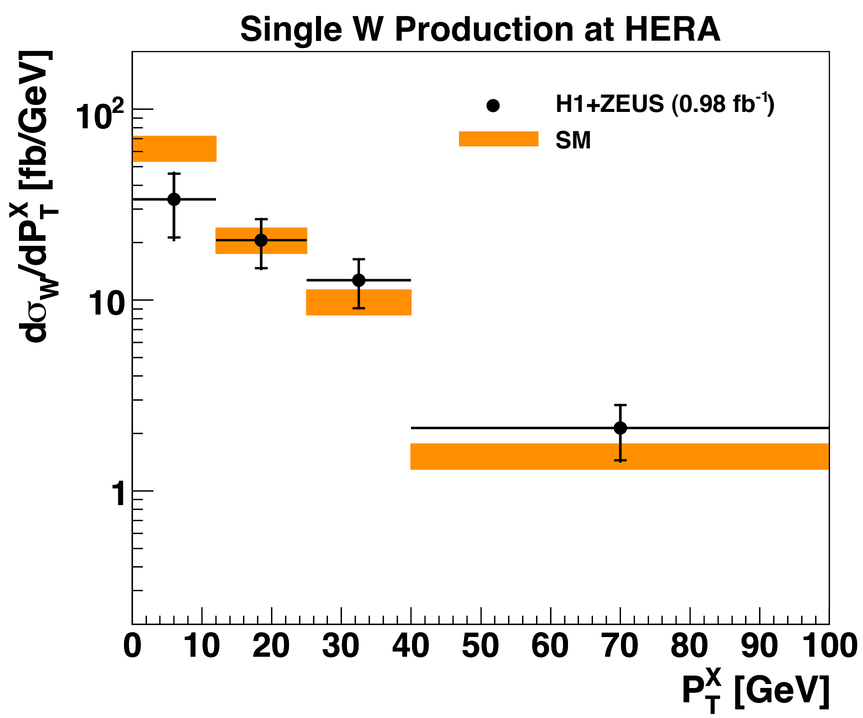

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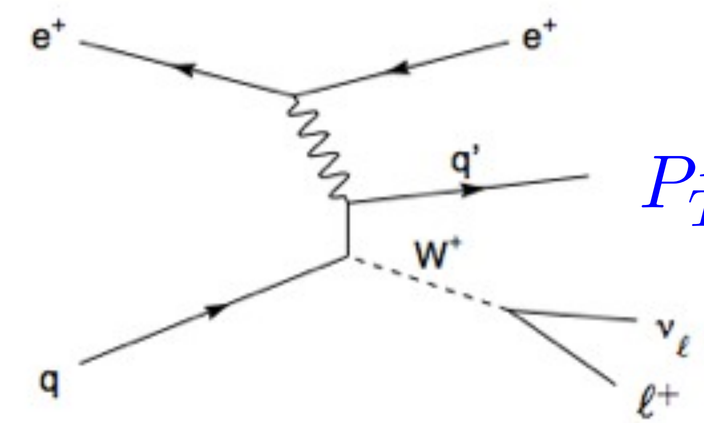
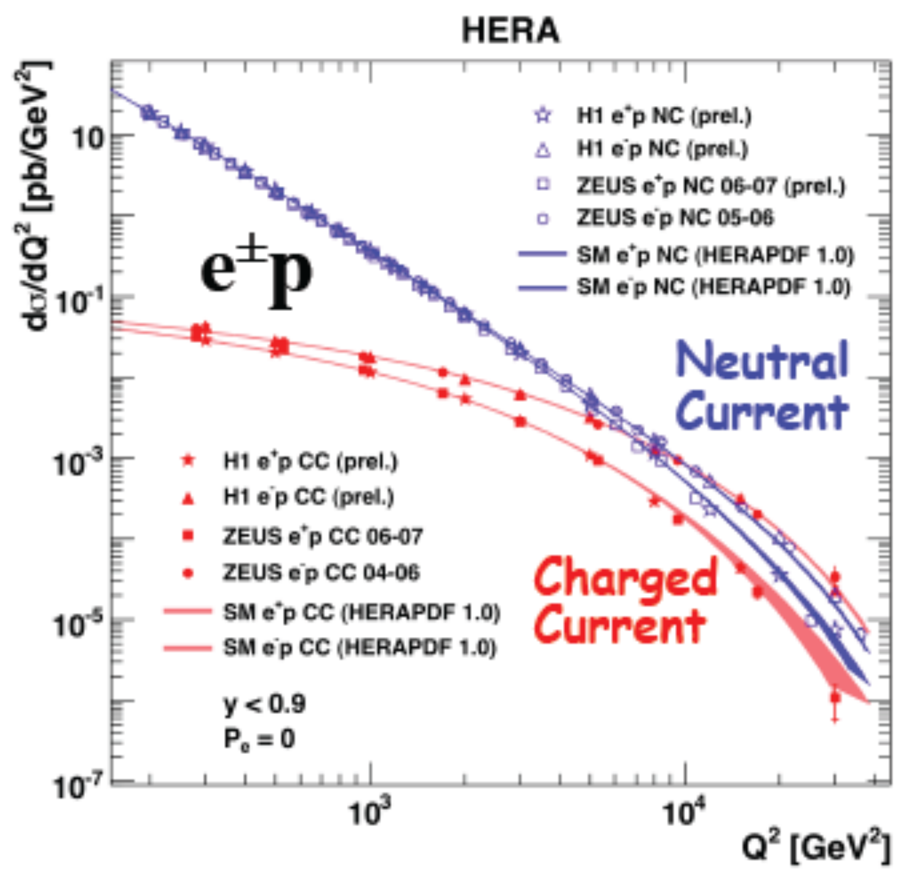


P_T^X hadronic system

P_T^{miss} lepton



Electroweak unification:

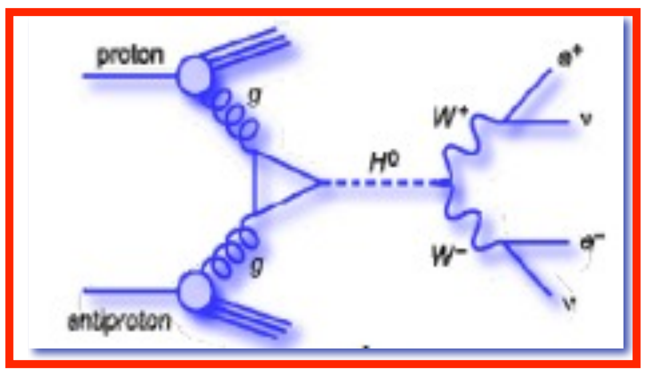
$\sigma_{NC} \approx \sigma_{CC}$ for $Q^2 > M^2_Z, M^2_W$

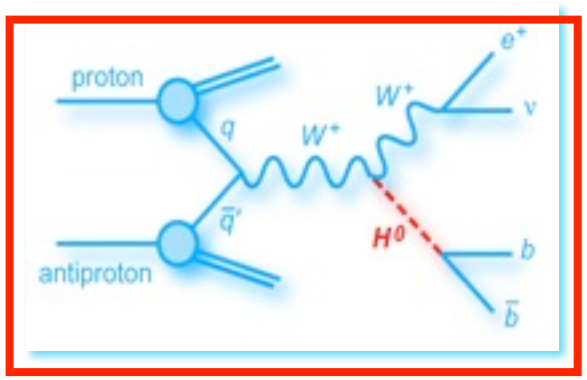
final ZEUS CC measurement and HERAPDF 1.0

Dibosons

Diboson physics

- Probe of electroweak sector of the standard model
  - cross sections
  - gauge boson couplings
- Background for Higgs searches
  - high mass Higgs (M_H>135 GeV) H→WW
  - low mass Higgs (M_H<135 GeV) WH→ lνbb





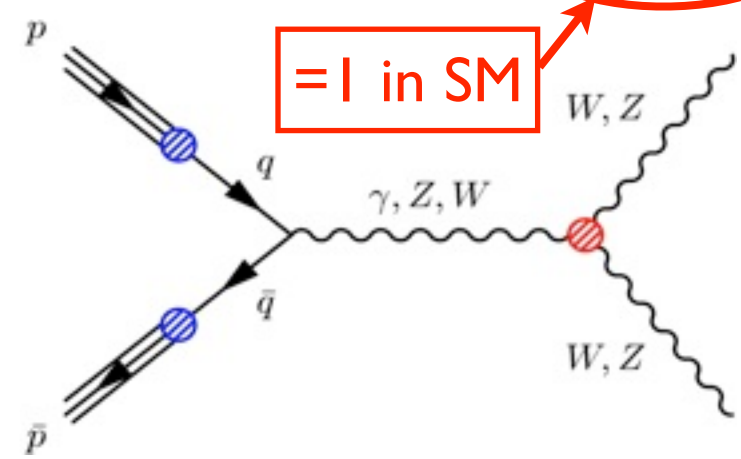
- Exercise multivariate analysis techniques used for Higgs searches

- Charged Triple Gauge Couplings
  - probed by WW, WZ, Wγ
  - general Lagrangian: 14 parameters
  - EM gauge invariance and CP conservation

5 TGC parameters: g_1^Z, κ_γ, κ_Z, λ_γ, λ_Z

=1 in SM

=0 in SM



$SU(2)_L \otimes U(1)_Y$, 3 parameters:

$\Delta\kappa_Z = \Delta g_1^Z - \Delta\kappa_\gamma \tan^2\theta_W$, $\lambda = \lambda_\gamma = \lambda_Z$

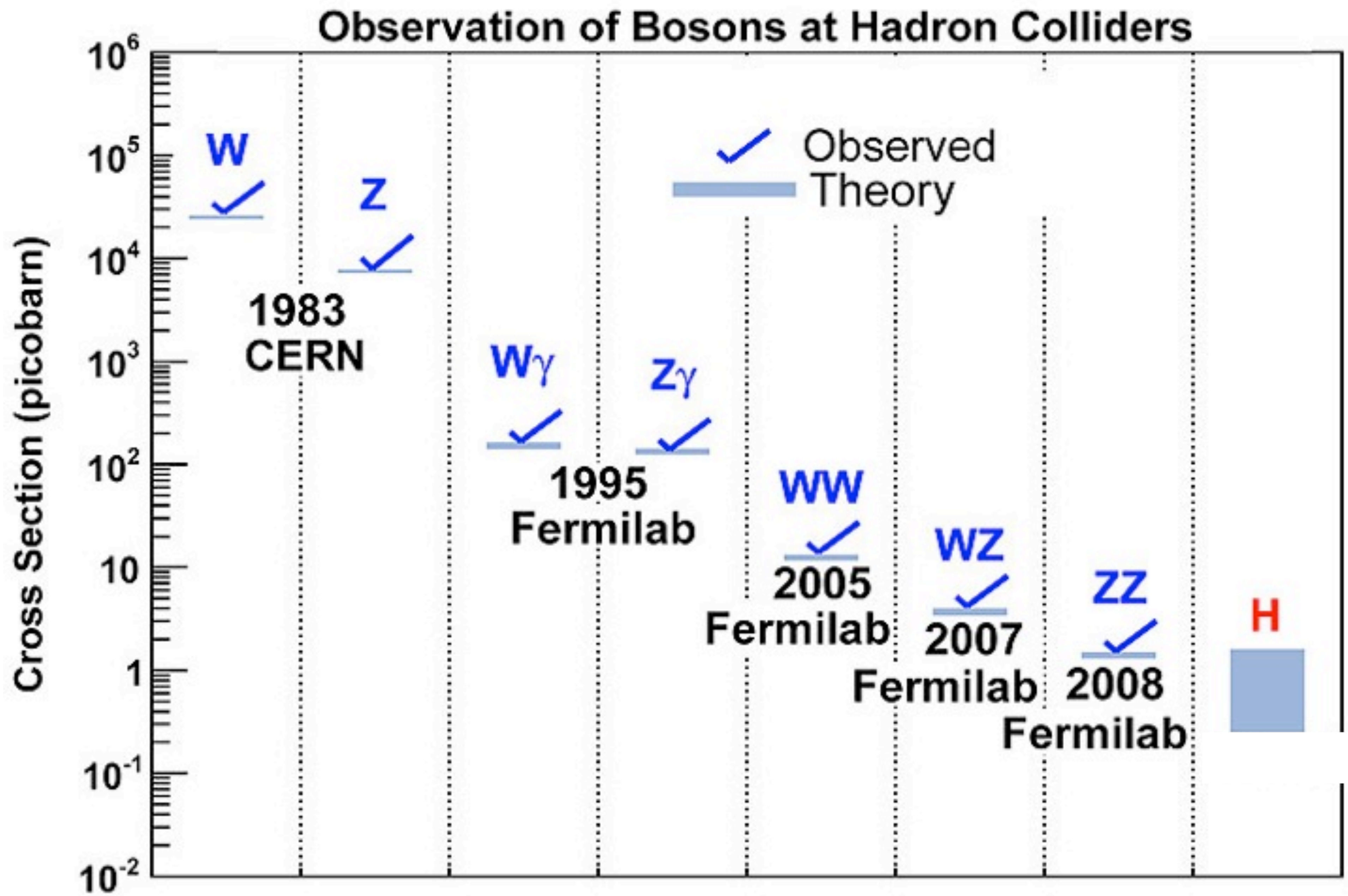
- Neutral Triple Gauge Couplings
  - probed by ZZ, Zγ
  - general Lagrangian: 8 parameters
  - CP conservation

4 TGC parameters: h_3^γ, h_3^Z, h_4^γ, h_4^Z

all zero in SM

Tuesday, July 27, 2010

Observation of diboson signals

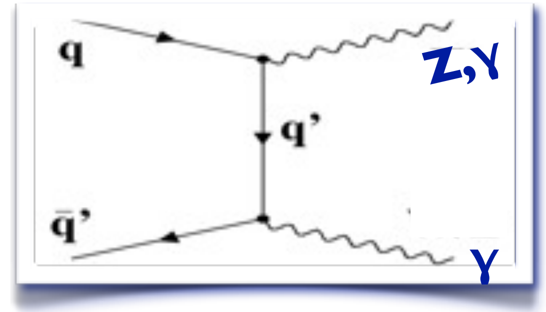


All diboson signals observed at Fermilab by both CDF and D0 in many different final states

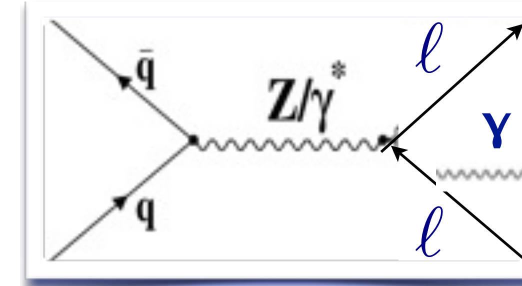
Zγ production

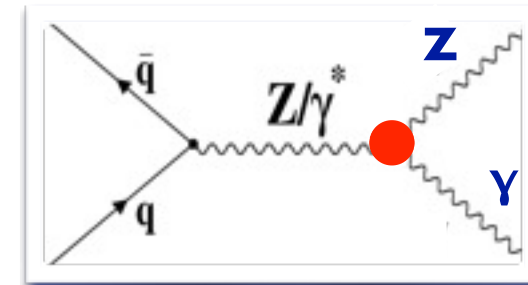
- SM production through ISR and FSR
- $Z \to ee\gamma, \mu\mu\gamma, \nu\nu\gamma$ ($5\ fb^{-1}$)
- Cross sections in good agreement with standard model
- Photon E_T spectra used to set limits on TGC

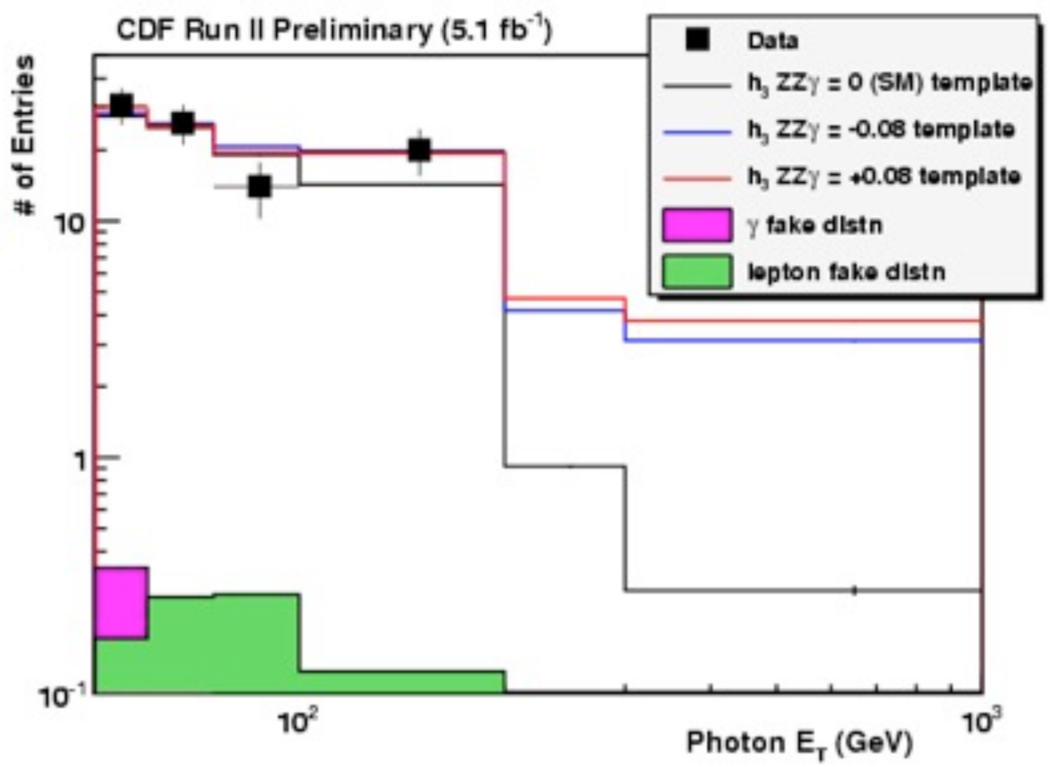
ISR



FSR







new

The most stringent limits

Λ=1.2 TeV

	h_3^γ	h_3^Z	h_4^γ	h_4^Z
CDF	-0.022,0.021	-0.018, 0.020	-0.0009, 0.0010	<0.0009

WZ production

- Triple lepton final state (lllν)
- Two different techniques

new

CDF: 6.0 fb^{-1} $\sigma_{WZ} = 4.1 \pm 0.7$ pb — reduced uncertainty

5.9 fb^{-1} $\sigma_{WZ} = 3.7 \pm 0.8$ pb

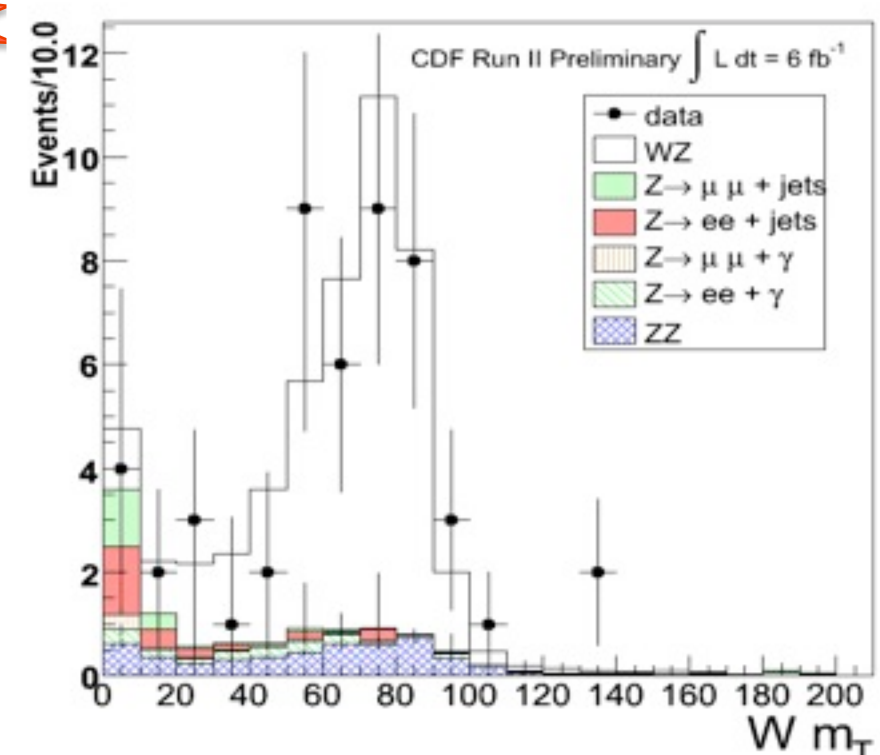
DØ: $\sigma_{WZ} = 3.9^{+1.1}_{-0.9}$ pb 4.1 fb^{-1}

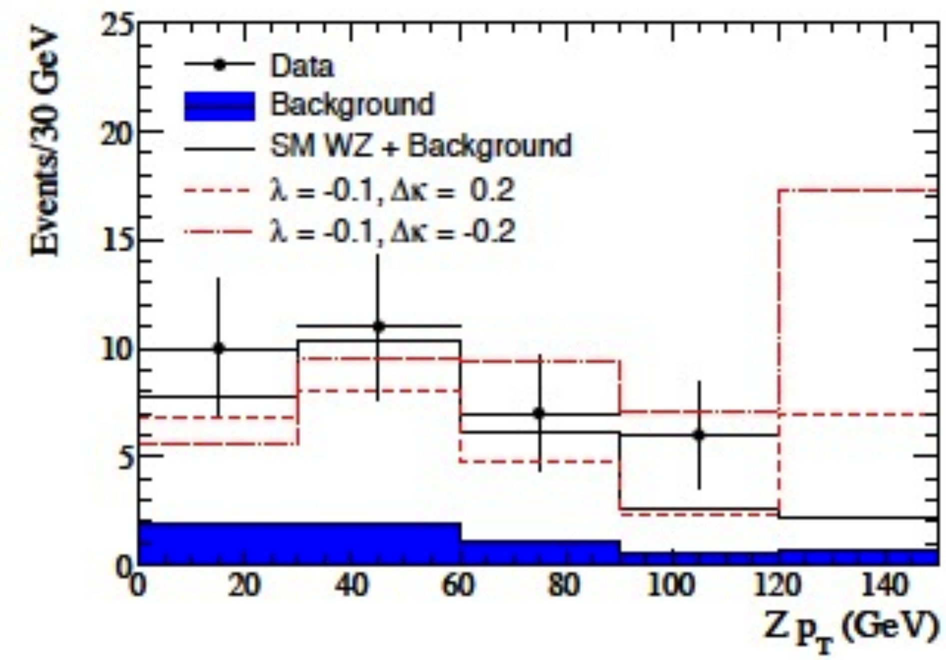
- Extract limit on WWZ couplings from Z p_T distribution

λ_Z	Δg_1^Z	$\Delta\kappa_Z$
-0.075, 0.093	0	0
0	-0.053, 0.156	0
0	0	-0.376, 0.686

Most stringent limits from direct study of WZ production

NLO: σ_{WZ}=3.46±0.21 pb

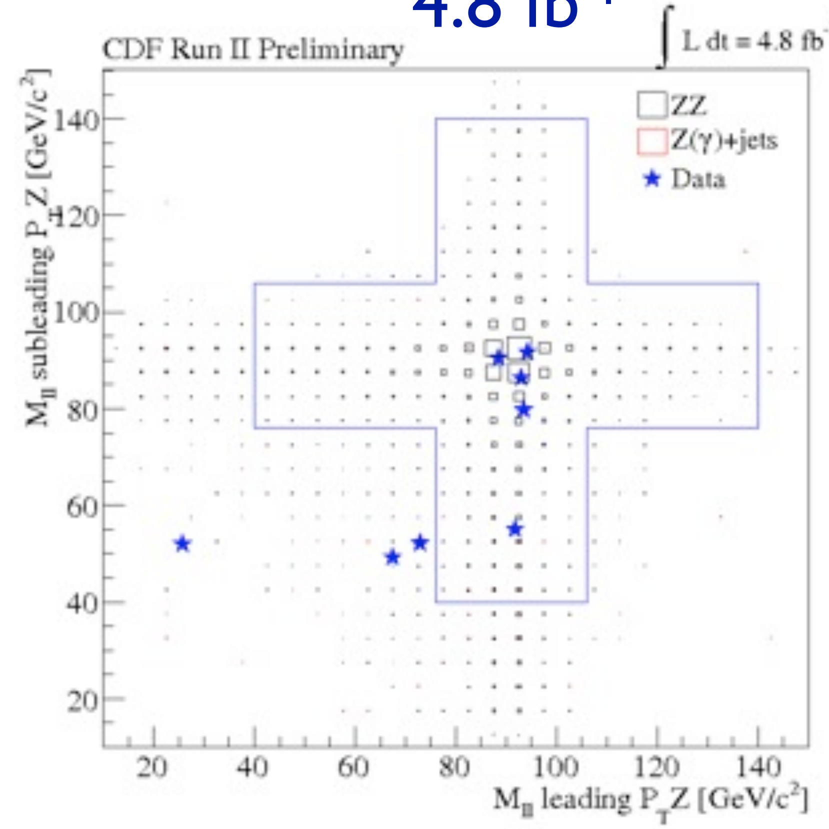




ZZ production

- ZZ→ lll'l'
  - clean but very small signal (σ·Br ~1%)
- NLO theory: σ_{ZZ} =1.4±0.1pb

4.8 fb^{-1}

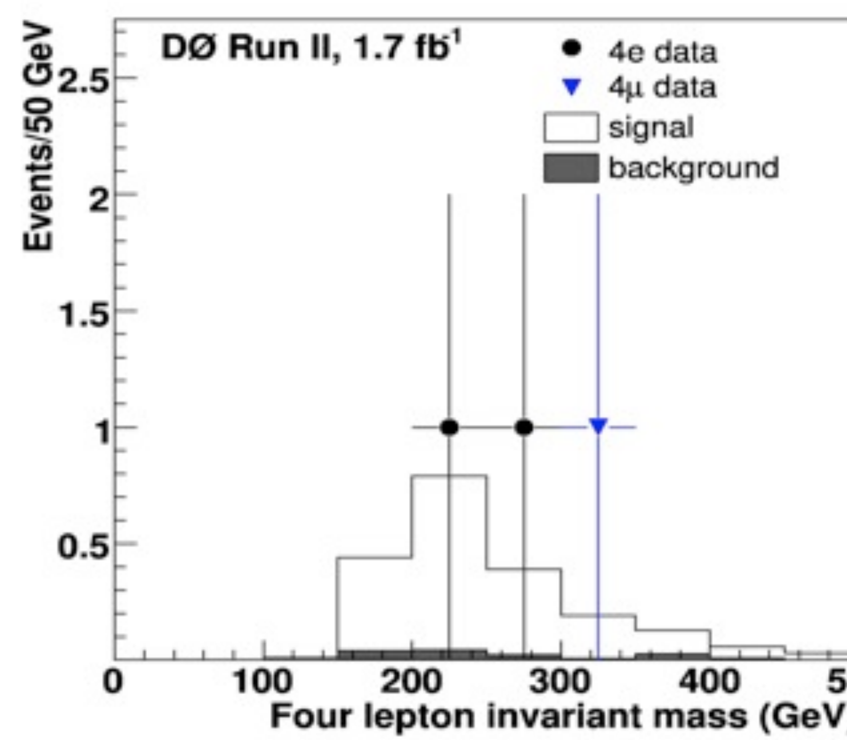


Events in $\mathcal{L}$ = 4.8 fb^{-1}	
Signal	4.68 ± 0.02(stat.) ± 0.76(syst.)
Z(γ)+jets	0.041 ± 0.016(stat.) ± 0.029(syst.)
Total expected	4.72 ± 0.03(stat.) ± 0.76(syst.)
Observed	5

$\sigma_{ZZ} = 1.56^{+0.80}_{-0.63}(\text{stat}) \pm 0.25(\text{syst})$ pb   5.7σ significance

- Combination of ZZ→ lll'l' and ZZ→ llνν
  - first measurement in llνν final state at hadron colliders
  - large Z+jets background

2.7 fb^{-1}



$\sigma_{ZZ} = 2.01 \pm 0.97(\text{total})\text{pb}$ 2.6σ significance

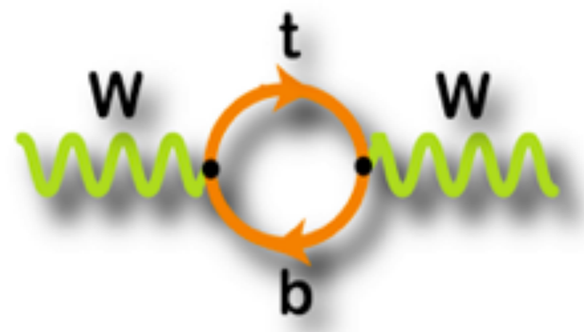
$\sigma_{ZZ} = 1.60 \pm 0.65(\text{total})\text{pb}$ 5.7σ significance

W mass and width

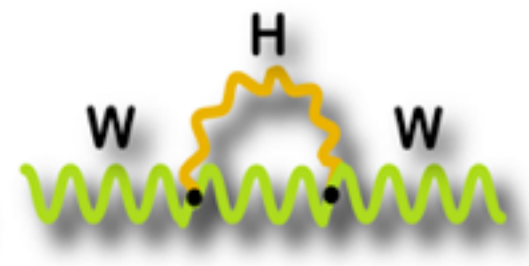
Top, W and Higgs masses

$$M_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \frac{1}{\sin\theta_W \sqrt{1-\Delta r}}$$

$$\cos\theta_W = \frac{M_W}{M_Z}$$



$\Delta r_t \sim m_t^2$



$\Delta r_{Higgs} \sim \ln(m_H^2)$

- W mass has quadratic dependence on top mass and logarithmic on Higgs mass through radiative corrections
- Precise measurements of W mass and top quark mass are essential for
  - testing consistency of the standard model
  - predicting Higgs mass
  - further testing standard model if Higgs is found

W mass and width

- ~499,830 $W \rightarrow e\nu$ candidates

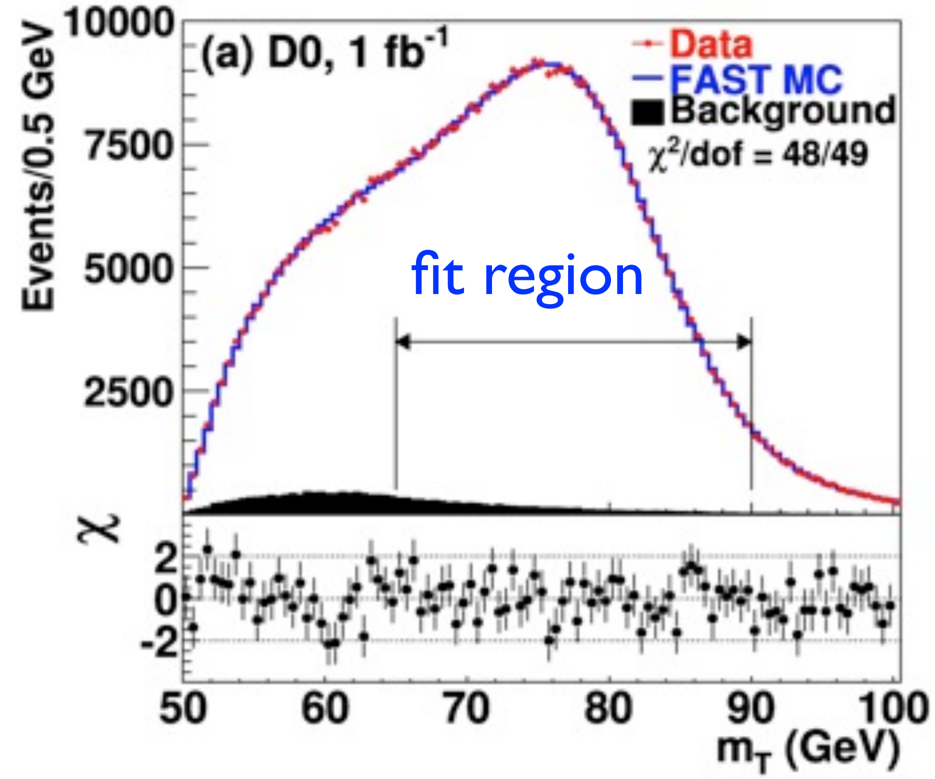
1 fb^{-1}

- Many systematic uncertainties are due to limited statistics of calibration data samples

M_W=80.401±0.043 GeV

Single most precise measurement

World average M_W=80.399±0.023 GeV

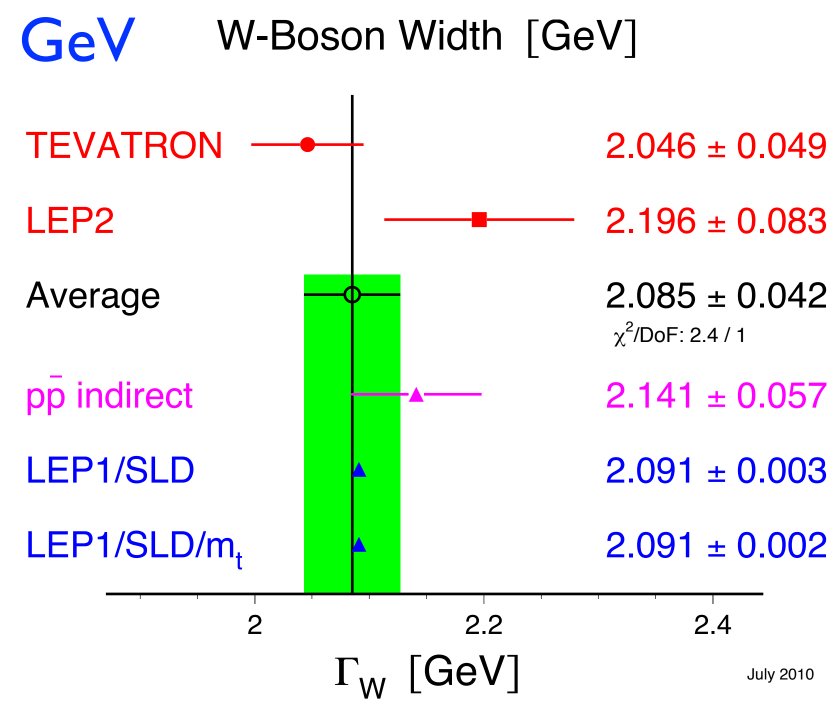


- Measure W width from the shape of transverse mass distribution

Γ_W=2.028±0.072 GeV

World average Γ_W=2.085±0.042 GeV

SM: Γ_W=2.093±0.002 GeV



- study of $W \rightarrow \pi\gamma$

4.3 fb^{-1}

SM: $BR(W \rightarrow \pi\gamma)/BR(W \rightarrow e\nu) = 10^{-6}\text{-}10^{-8}$

$BR(W \rightarrow \pi\gamma)/BR(W \rightarrow e\nu) < 6.4 \times 10^{-5}$ at 95% CL

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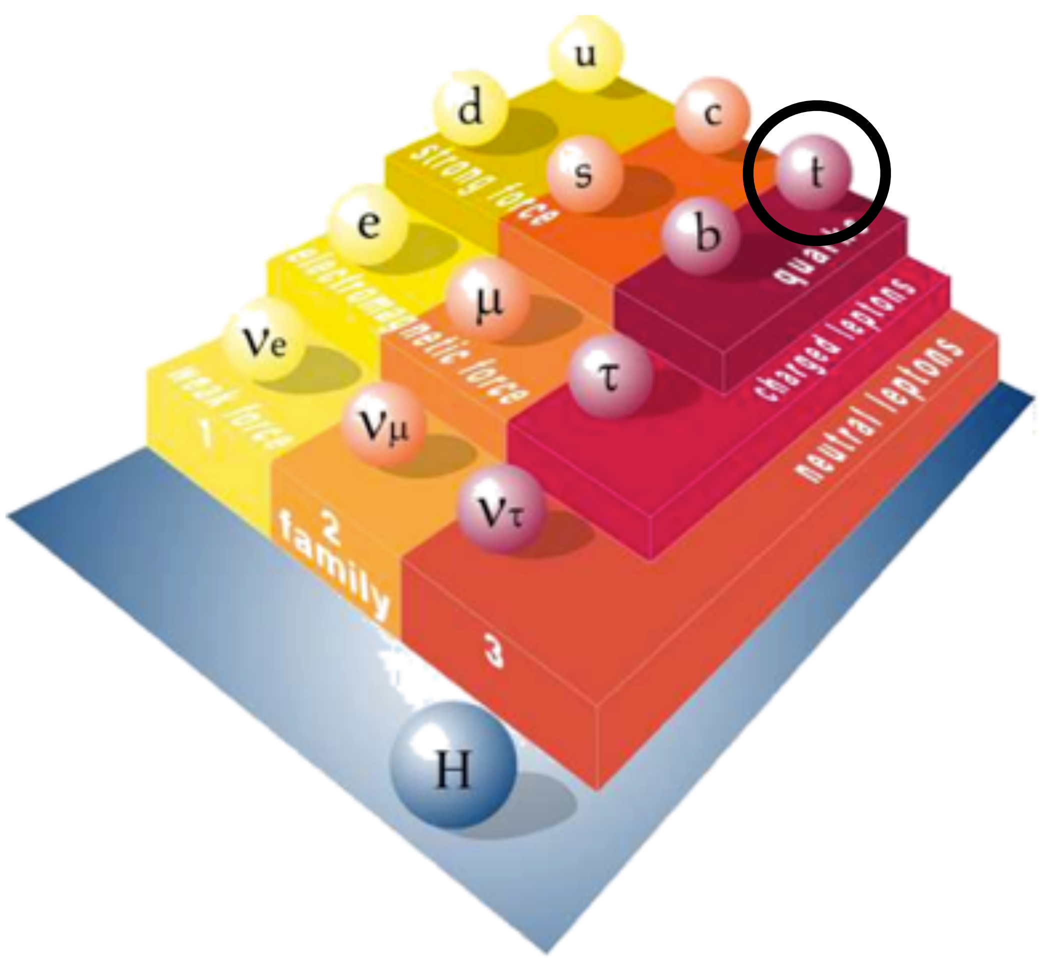
The top quark

The top quark

- Needed in theory as isospin partner of b-quark
- Properties well defined by SM
- Unknown - top quark mass



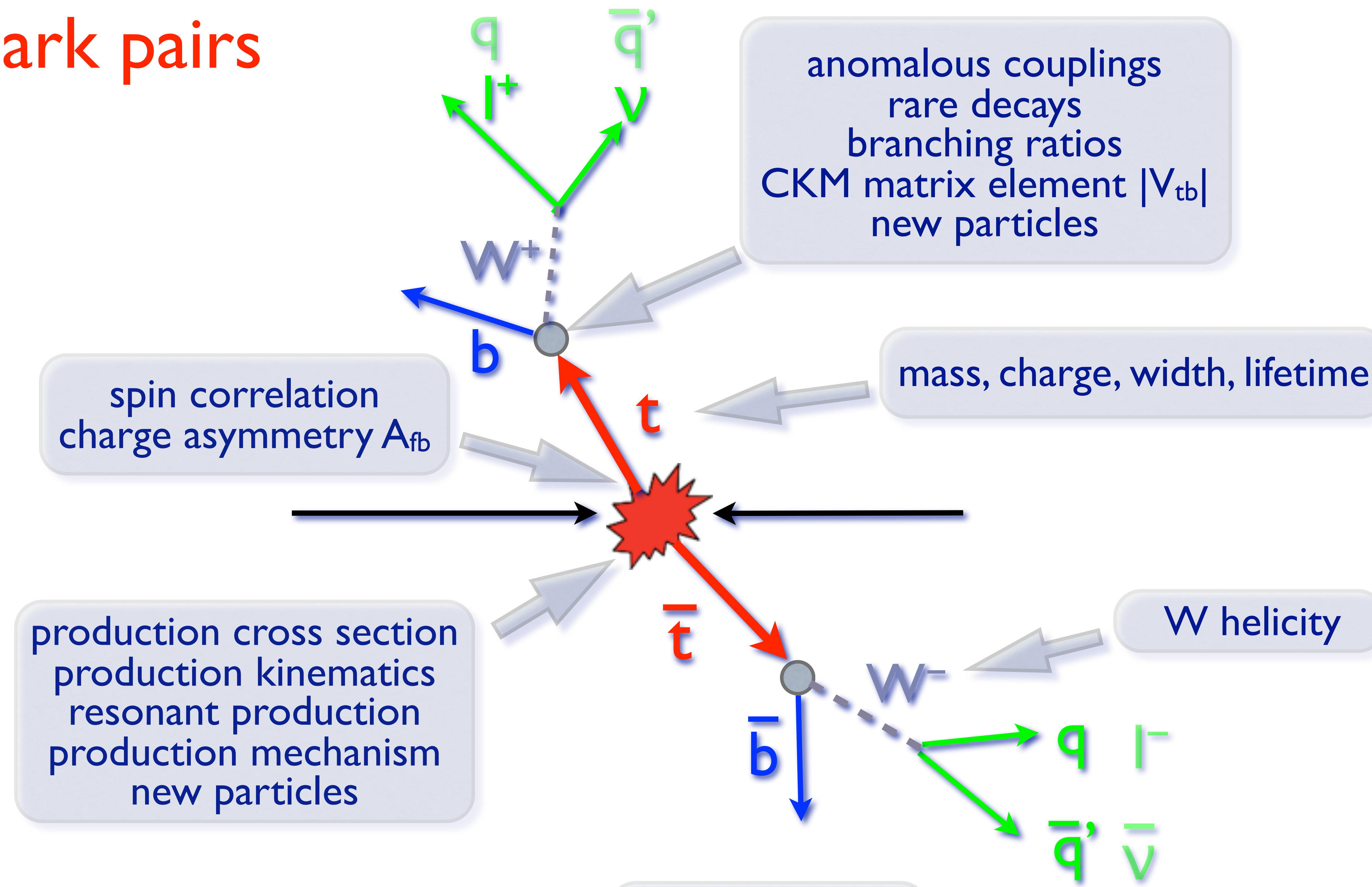
- The heaviest fundamental particle with unique properties
  - Large coupling to Higgs boson (~1)
  - important role in electroweak symmetry breaking?
  - short lifetime: decays before fragmenting

$$\tau \approx 5 \times 10^{-25} s << \Lambda_{QCD}^{-1}$$

The most probable place for new physics to show up?

What do we know about top?

top quark pairs

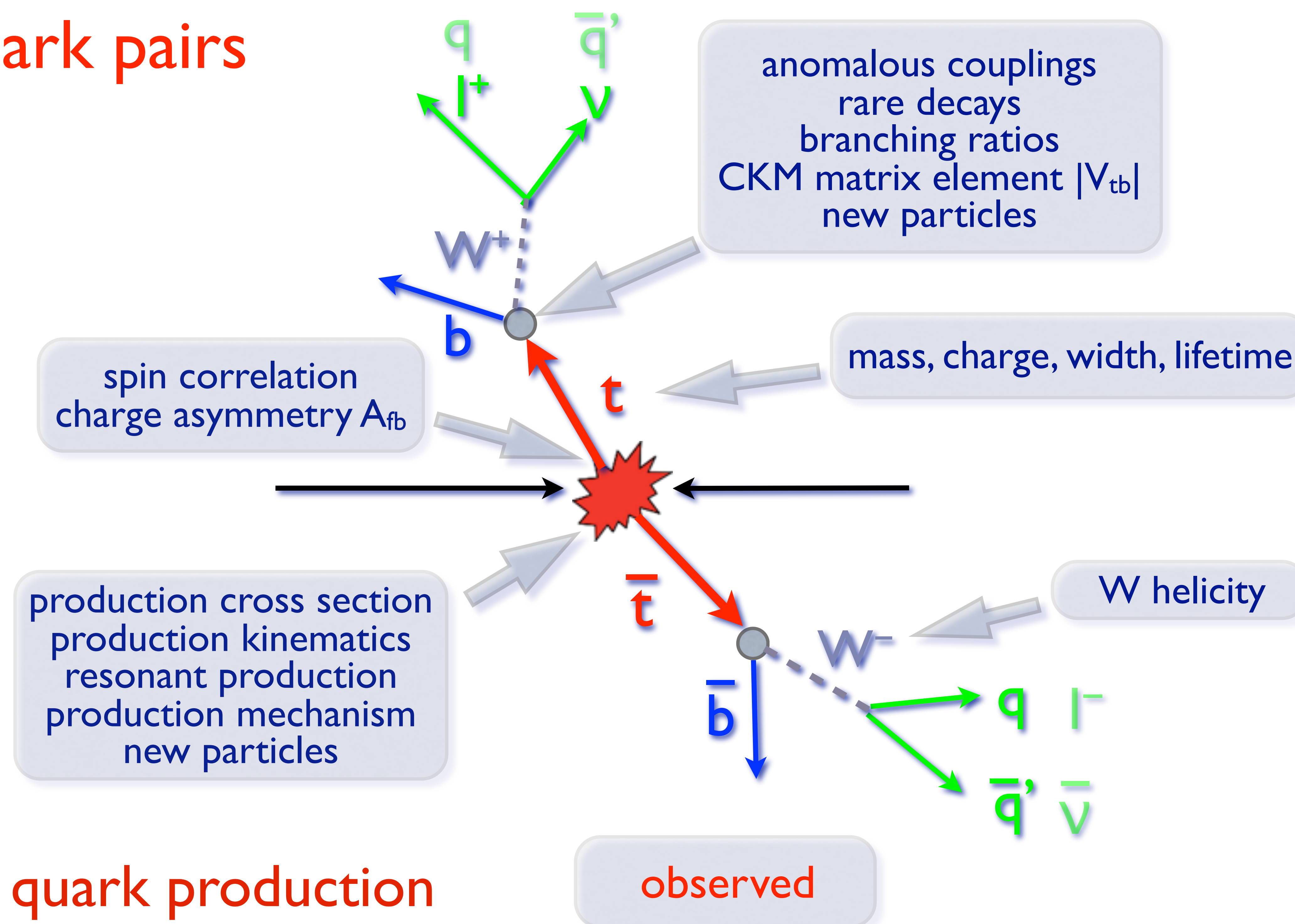


EW top quark production

observed

What do we know about top?

top quark pairs



EW top quark production

Is it the standard model top? Deviation can be a sign of new physics

Top quark production

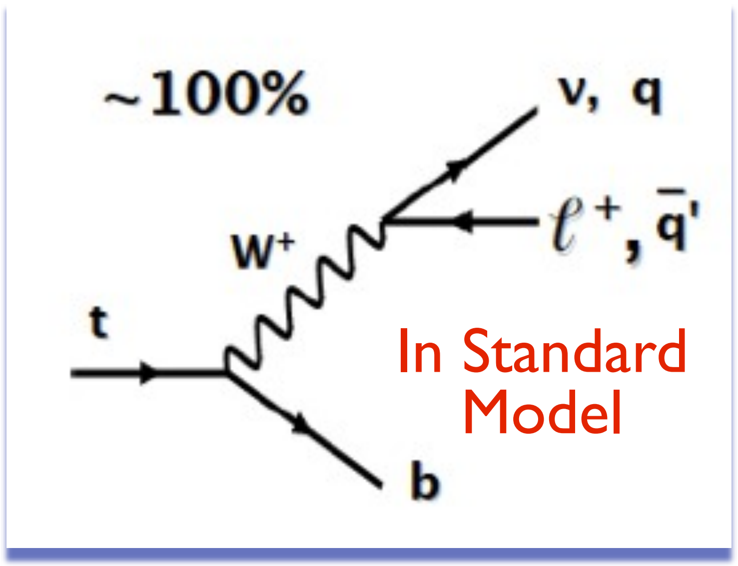
top quark pairs

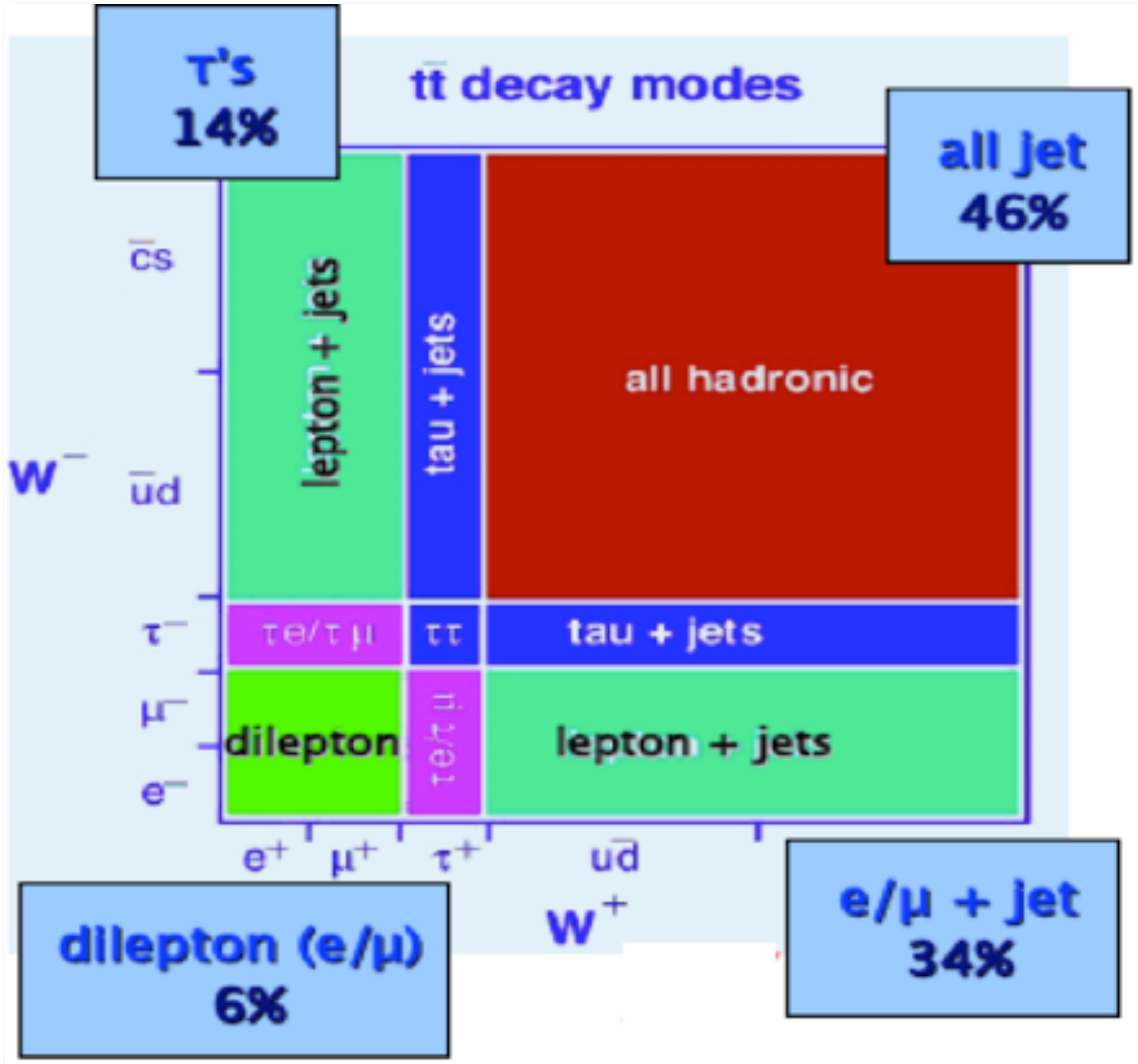
electroweak single top quark

Top quark production and decay

- Main mechanism: pair production via strong interaction
  - Tevatron: $q\bar{q}$ (85%), σ=7.46 pb
  - LHC@7 TeV: gg (~90%), σ=160.8 pb
  - theoretical uncertainty ~9%

NNLO$_{approx}$ for m_t = 172.5 GeV
PRD 80, 054009 (2009)





W decay mode defines top pair final state

>5 fb^{-1} of data, ~3,000 b-tagged top candidates per Tevatron experiment

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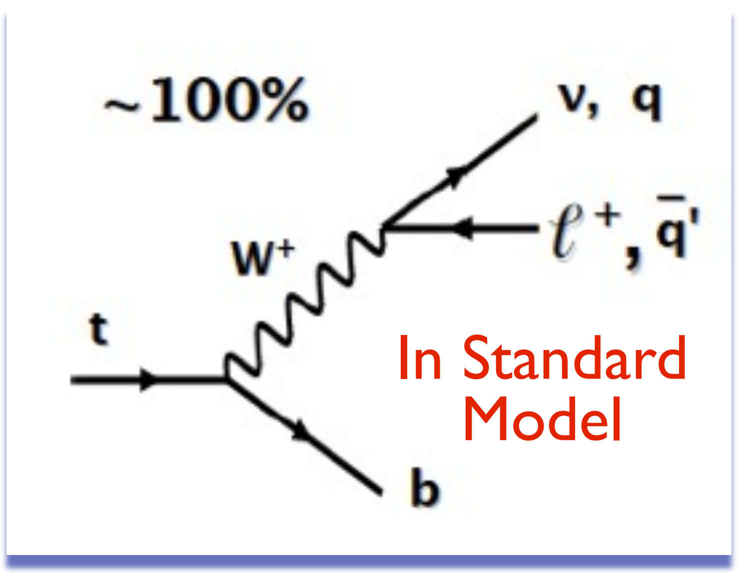
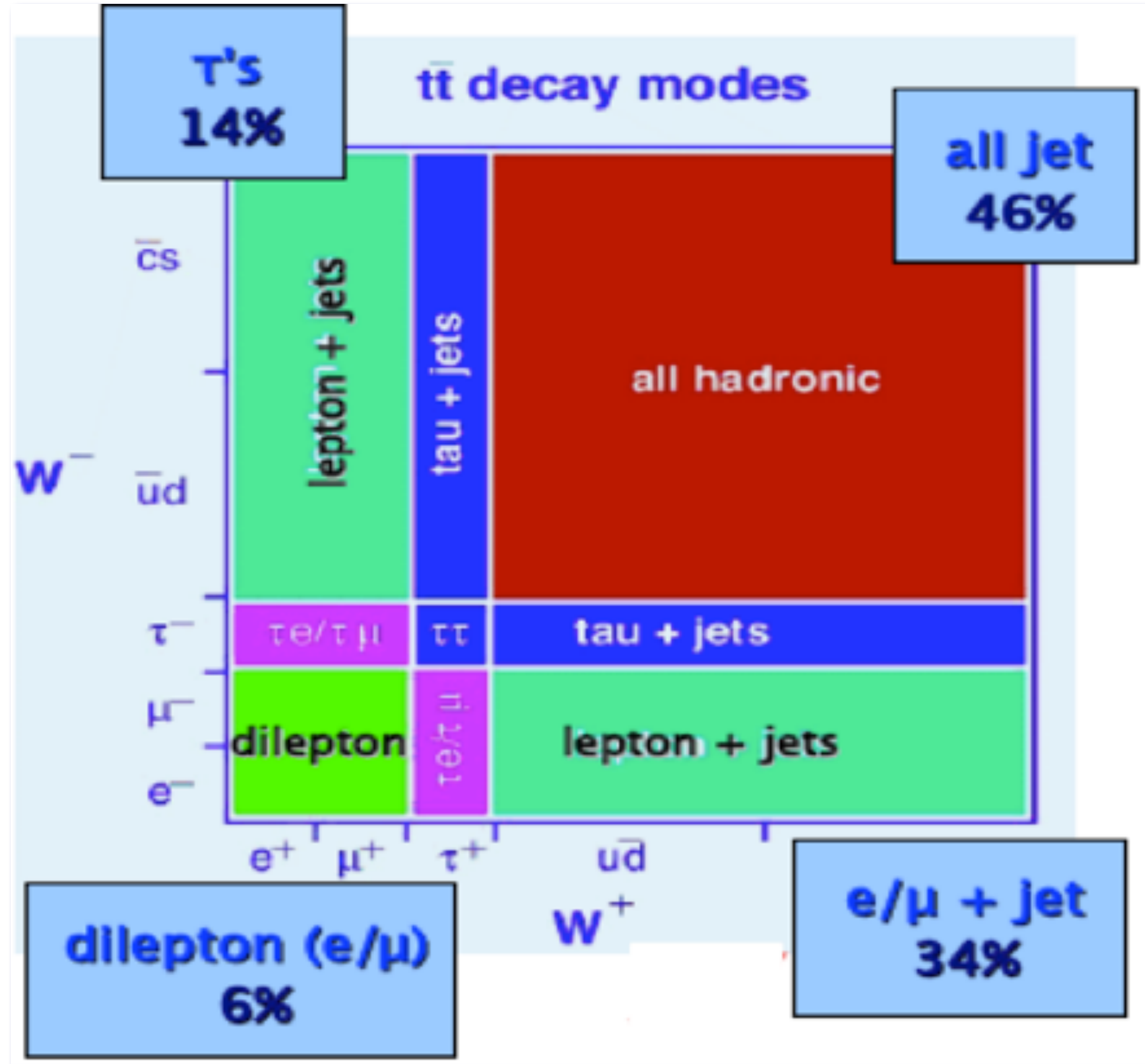


W decay mode defines top pair final state

small rate, high background
backgrounds: multijet, W+jets

high rate, high background
main background: multijet

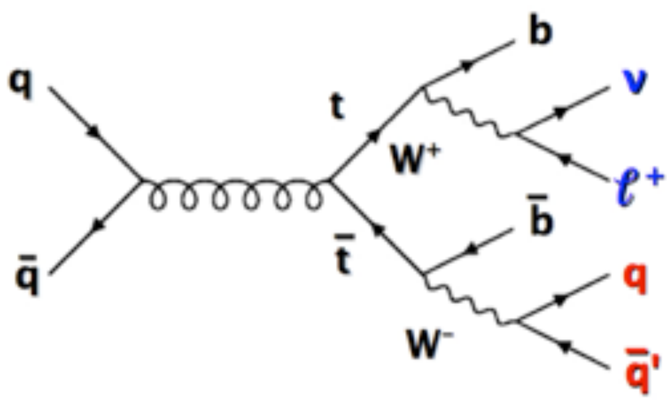


small rate, small background
main background: Drell-Yan

good rate, manageable background
main background: W+jets

>5 fb^{-1} of data, ~3,000 b-tagged top candidates per Tevatron experiment

Top pair cross section

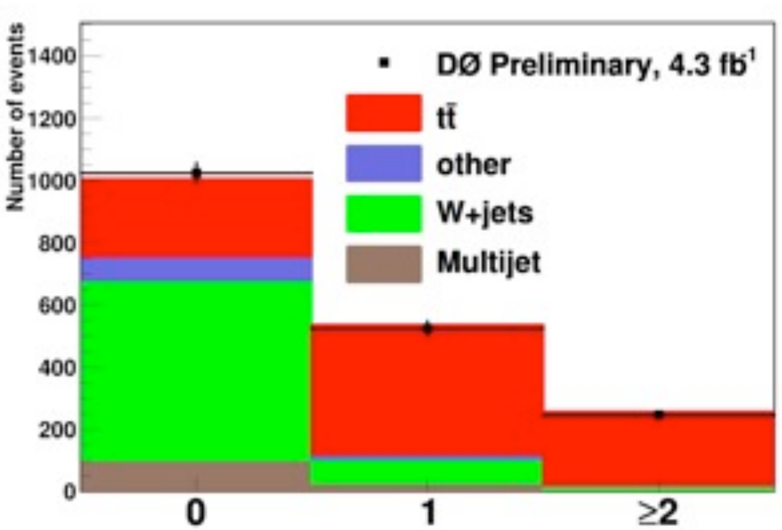


- First step in understanding selected top quark sample
- Test of theoretical QCD calculations

l+jets channel

Methods:

- kinematical information
- b-jet identification

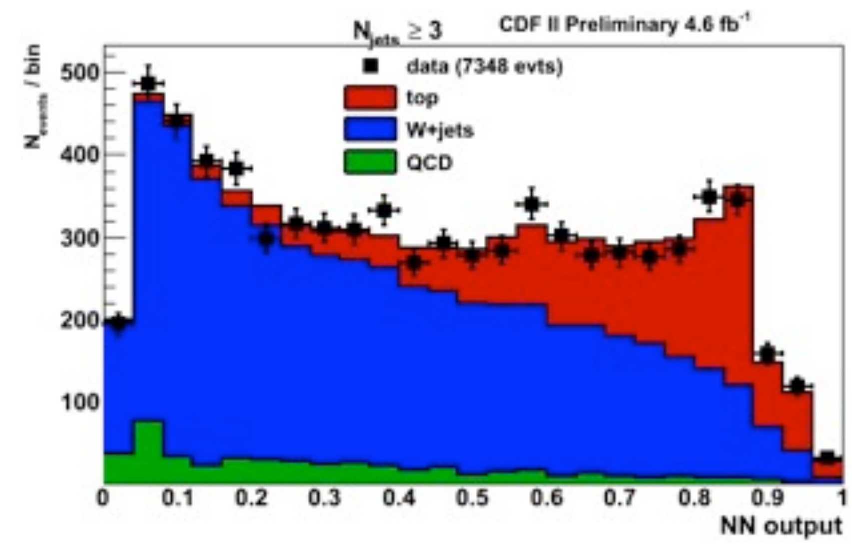


$\sigma_{t\bar{t}} = 7.70^{+0.79}_{-0.70}\text{(total)pb}$

Total uncertainty ~10-12%

- Limited by systematics, luminosity dominates at ~6%.
- Take ratio to Z cross section: trade for Z theory uncertainty

4.6 fb^{-1} PRL 105:012001,2010



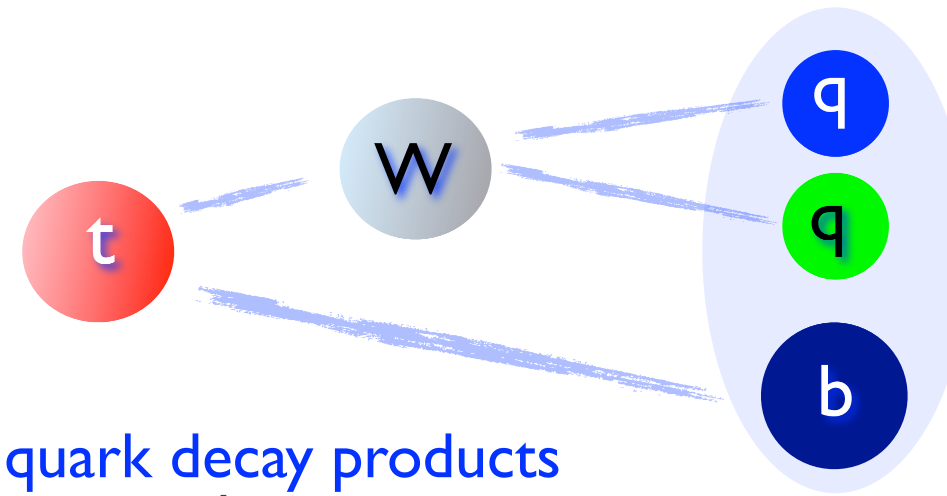
Combined topological and b-tagged

$\sigma_{t\bar{t}} = 7.70 \pm 0.52\text{(total) pb}$

7% relative precision, 9% with luminosity uncertainty

Boosted top quarks

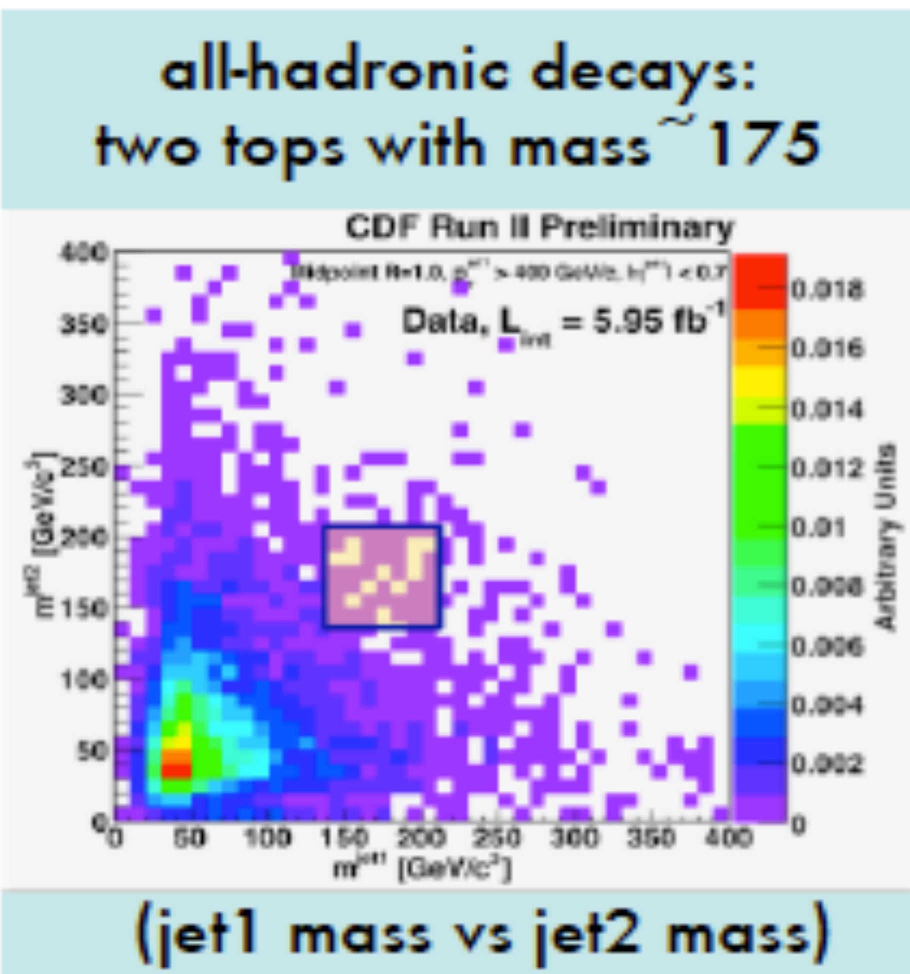
- First measurement of this kind at Tevatron
- Important for LHC
- High p_T top quarks can originate from decay of heavy objects



All top quark decay products are contained in one jet

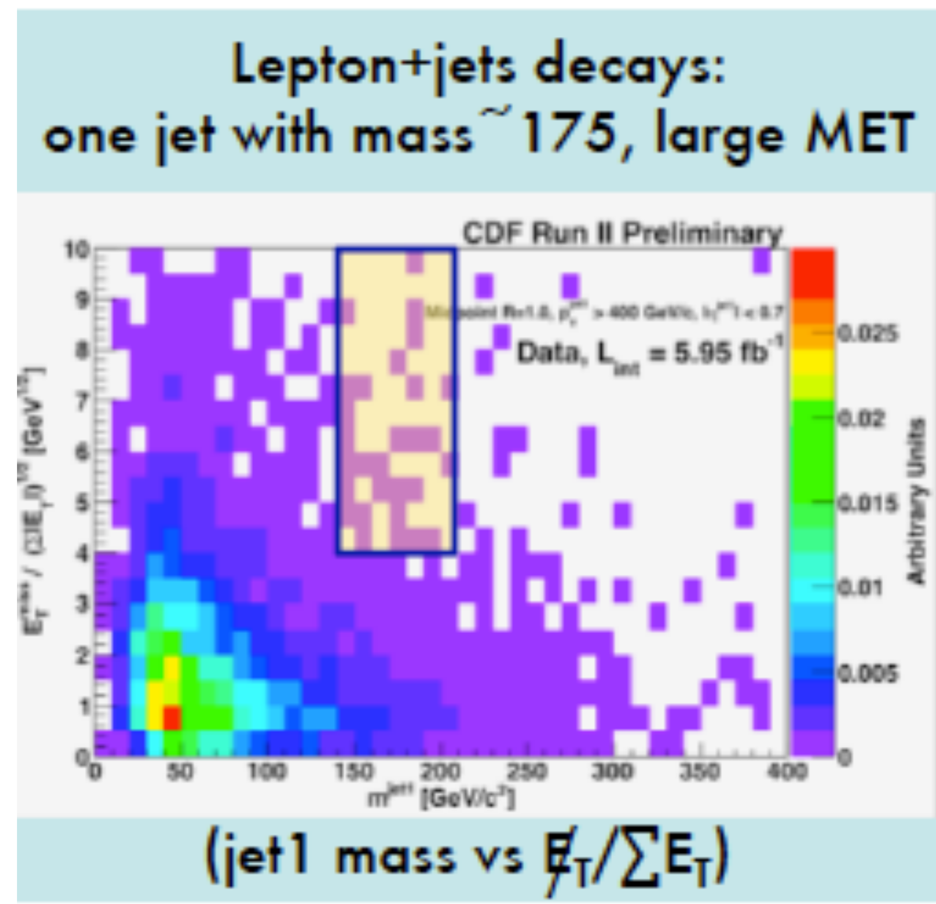
$m_{jet} \sim m_{top}$

Events with leading jet p_T>400 GeV



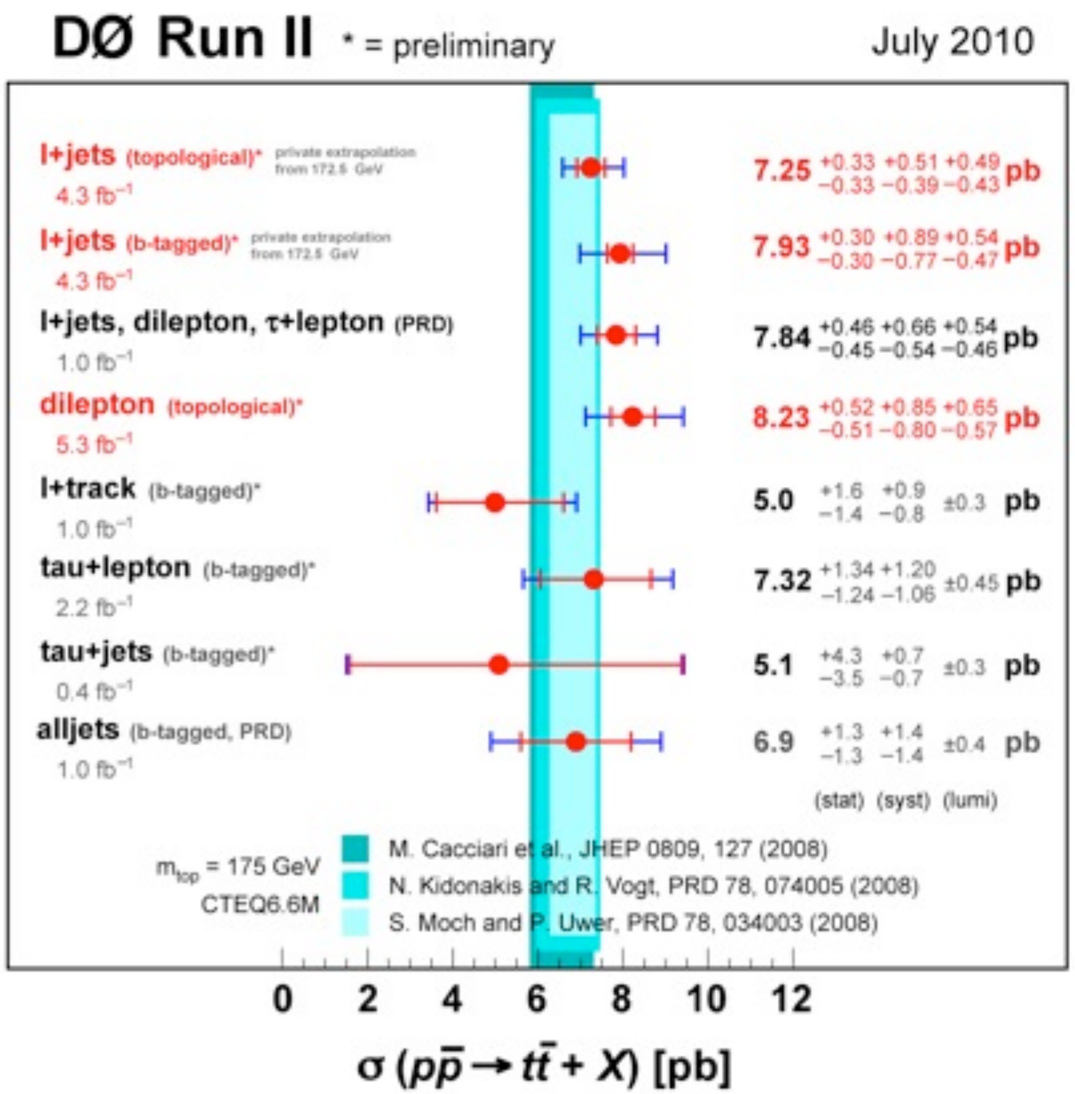
6 fb^{-1}

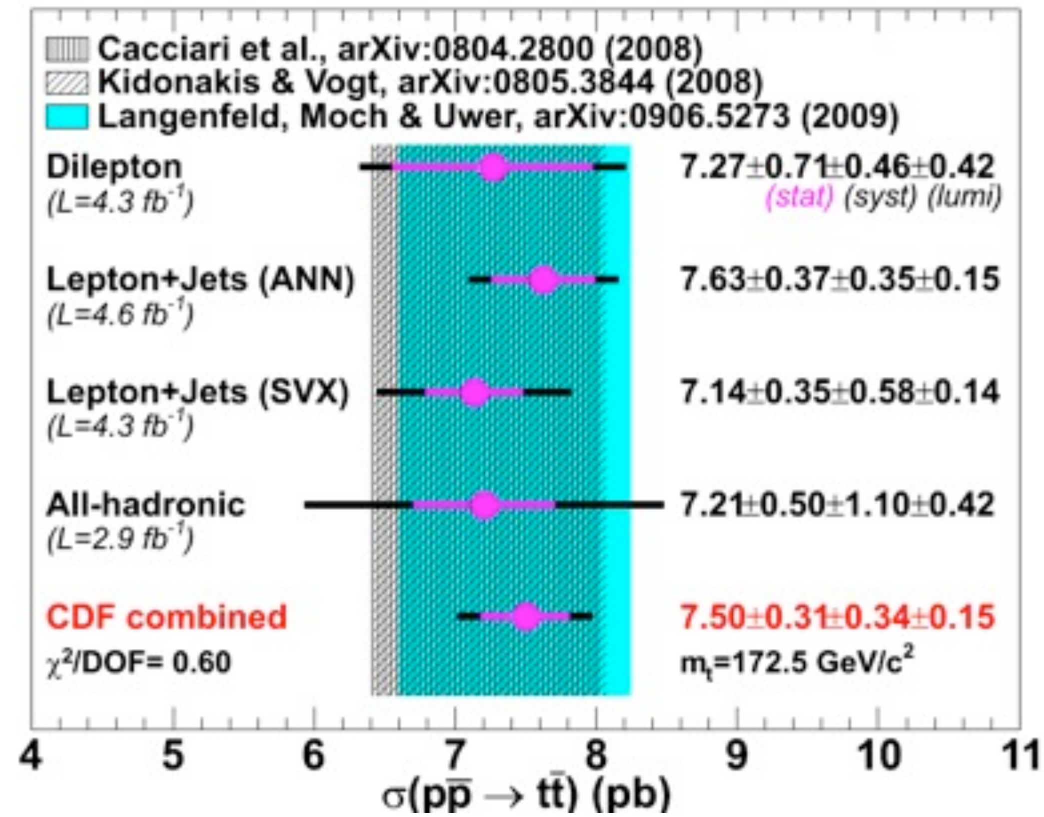
new



$\sigma_{t\bar{t}}$ < 54 fb for top quark p_T>400 GeV

Cross sections summary





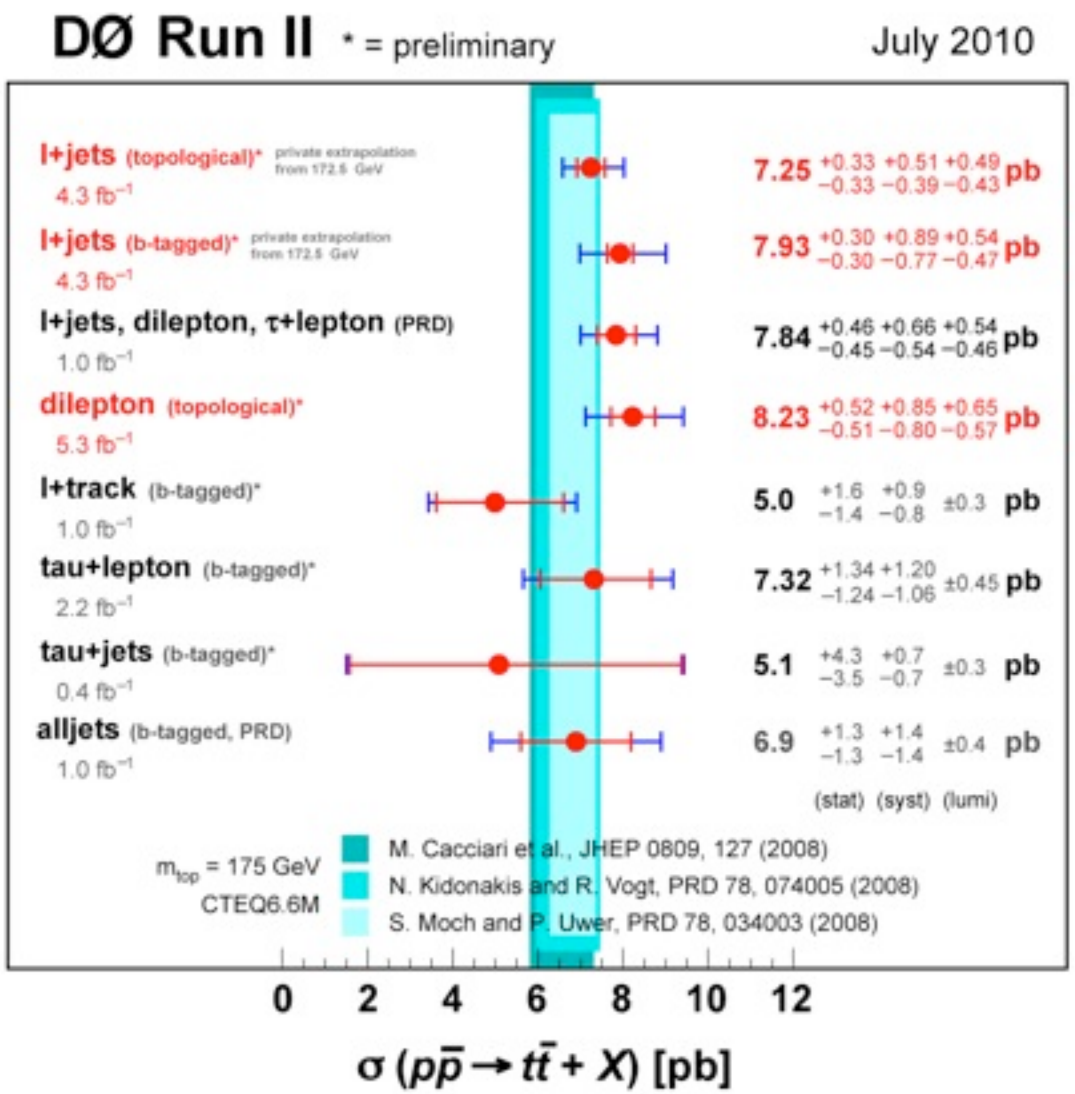
CDF combination: 6% precision!

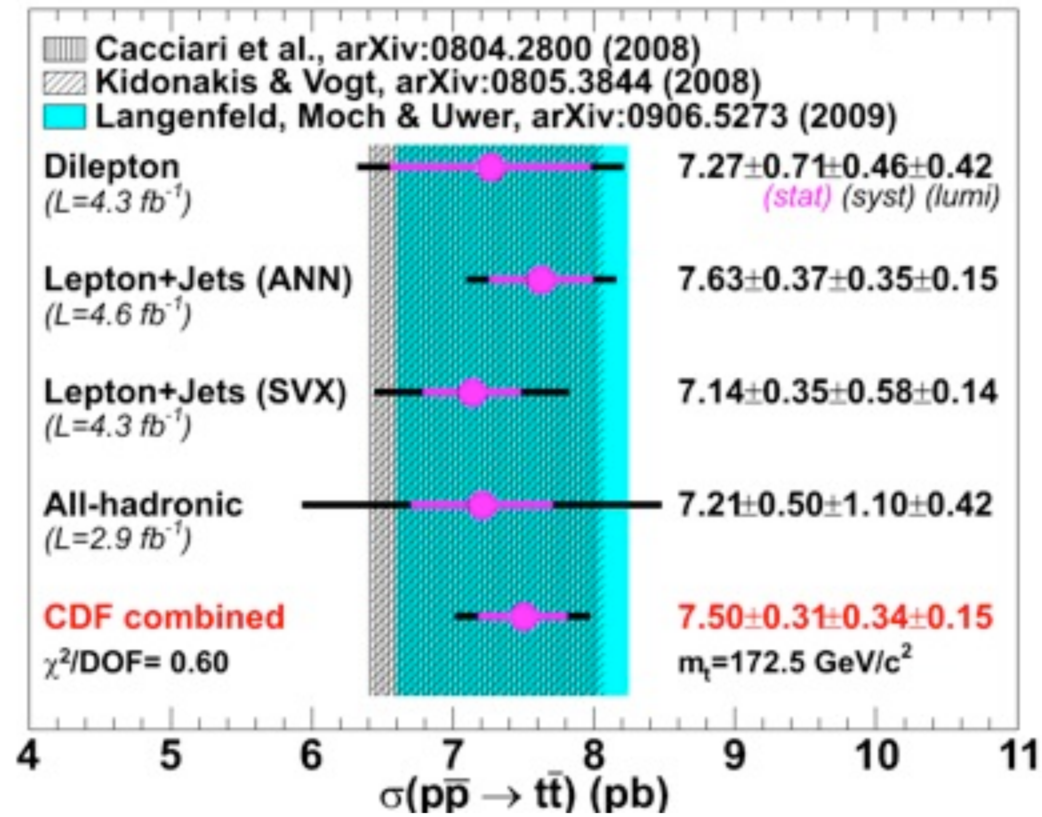
...exceeds Tevatron goal of 10%

- Measured in all channels but $\tau_{had}\tau_{had}$
- Agree between channels and methods

Consistent with theory prediction
Challenges its precision

Cross sections summary





CDF combination: 6% precision!

...exceeds Tevatron goal of 10%

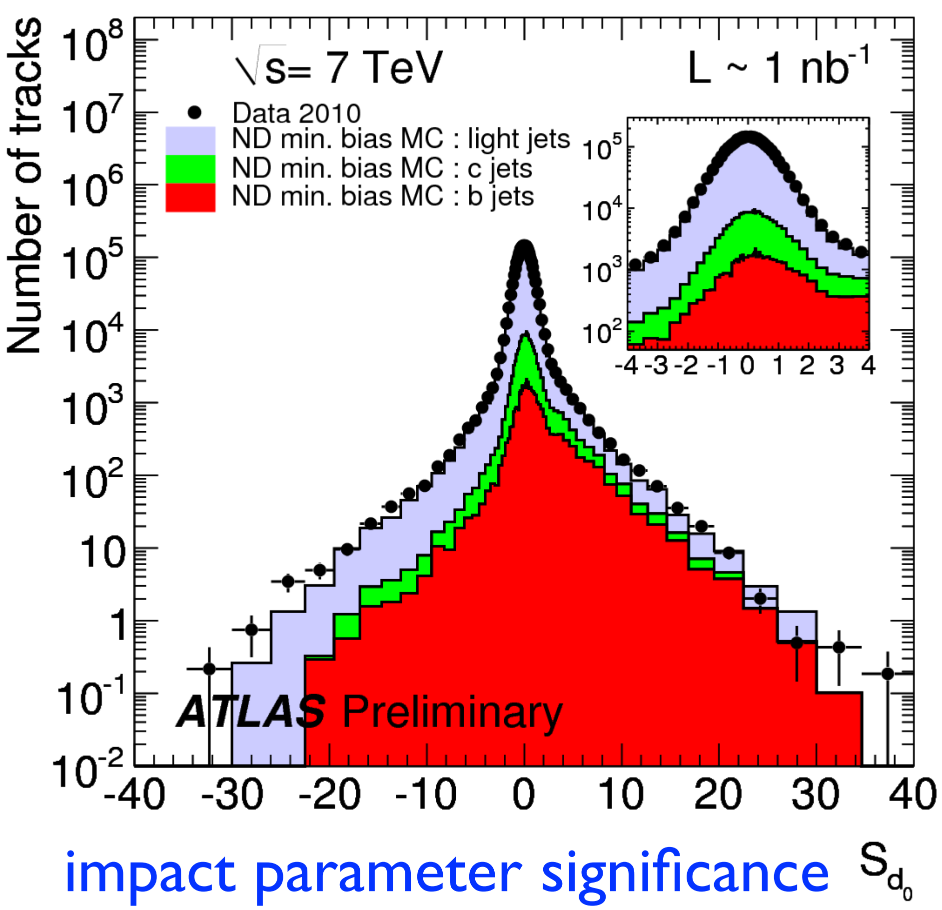
- Measured in all channels but $\tau_{had}\tau_{had}$
- Agree between channels and methods

Consistent with theory prediction
Challenges its precision

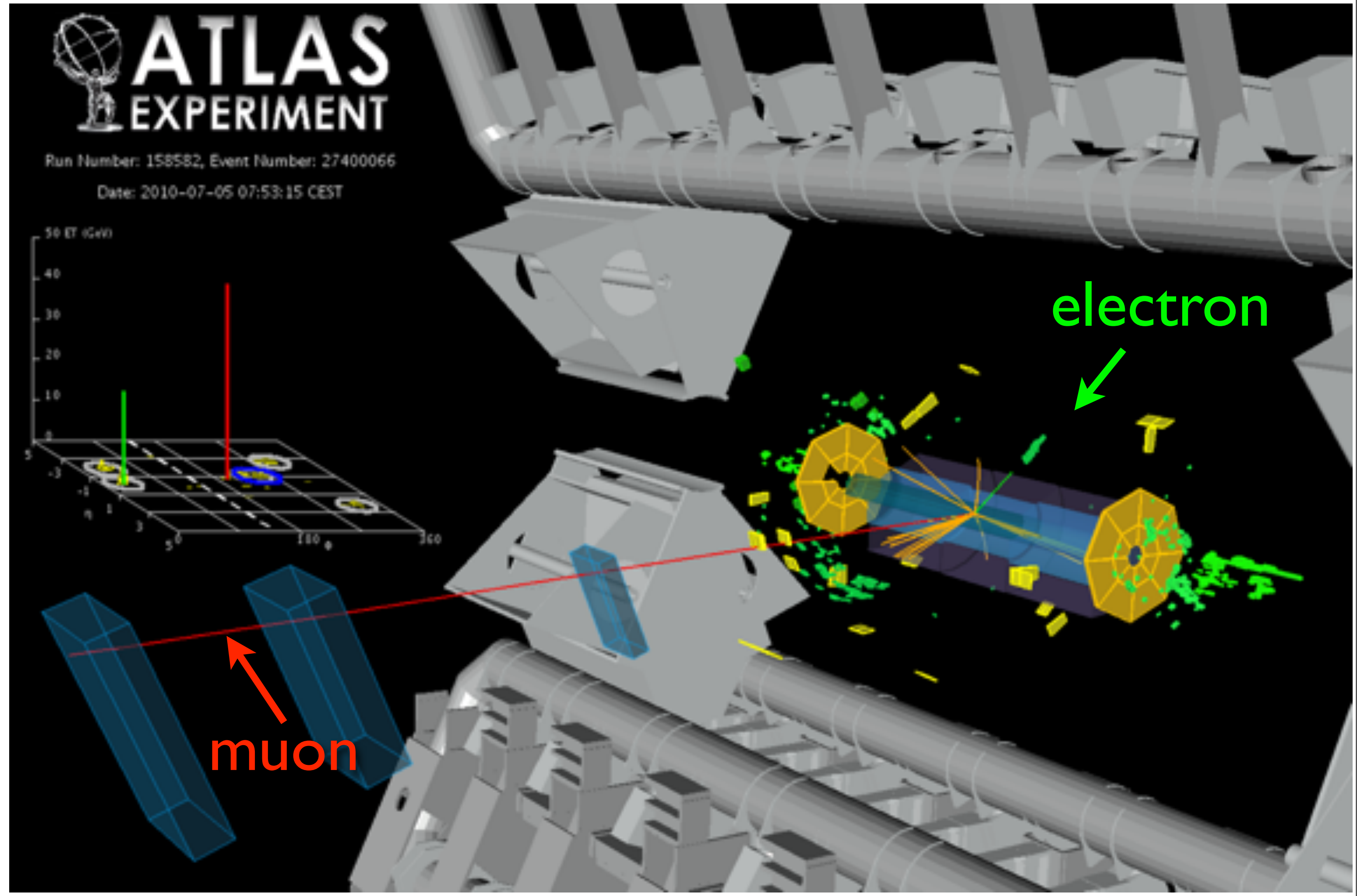
Theoretical contributions:
P.Uwer, N.Kidonakis, M.Neubert, P.Ruiz-Femenia

Top pair candidates at LHC

- Top physics requires excellent performance of all components
  - demonstrated by Atlas and CMS
- Impressive agreement between data and simulation



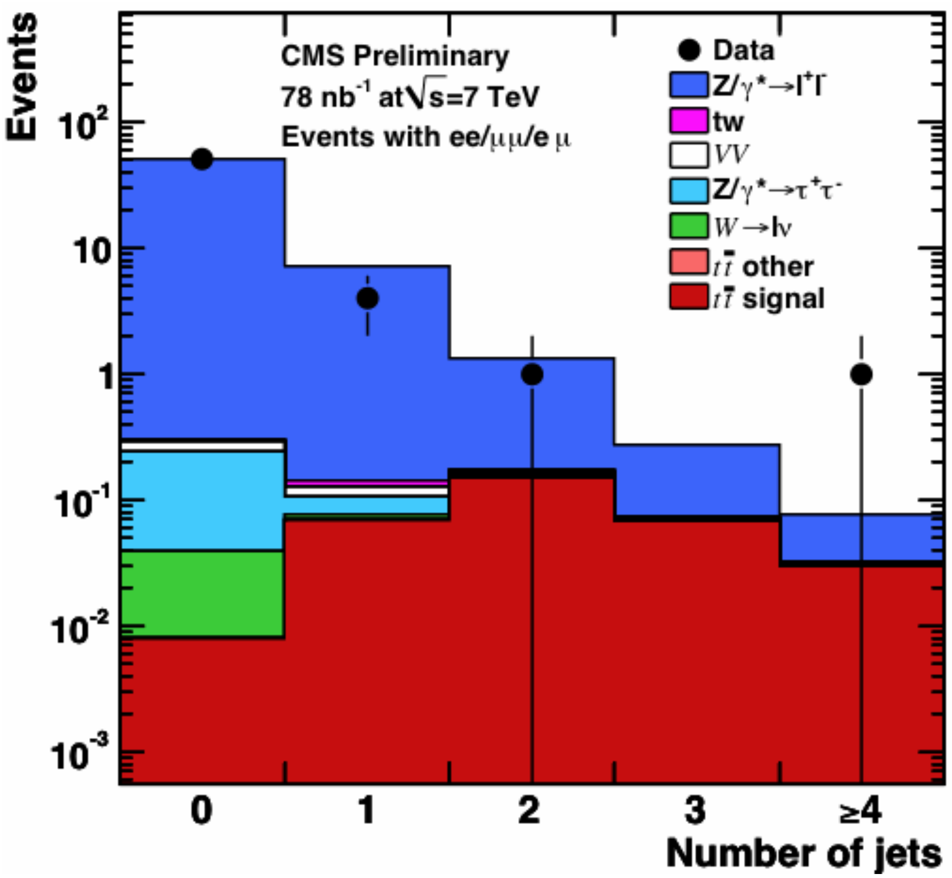
critical for b-jet identification!



- Several top pair candidate events
- example: eμ event
  - 3 jets with p_T>20 GeV, H_T=196 GeV, E_T^{mis} = 77 GeV
  - one identified as b-jet

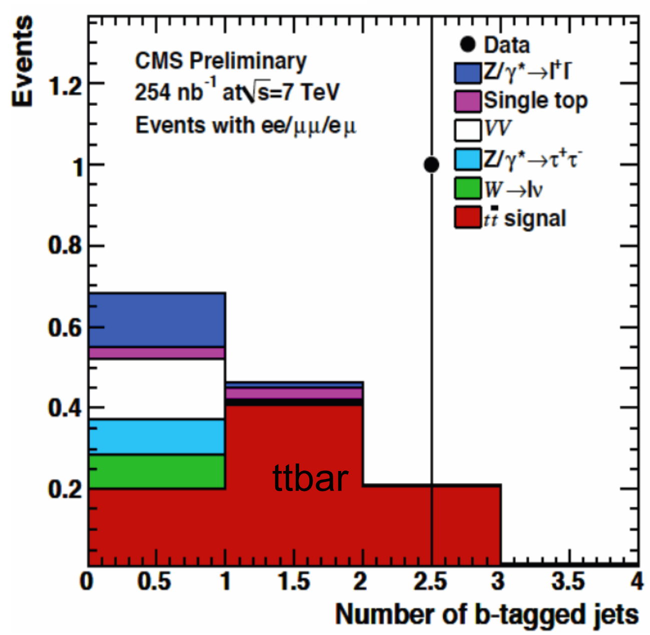
Top pair candidates at LHC

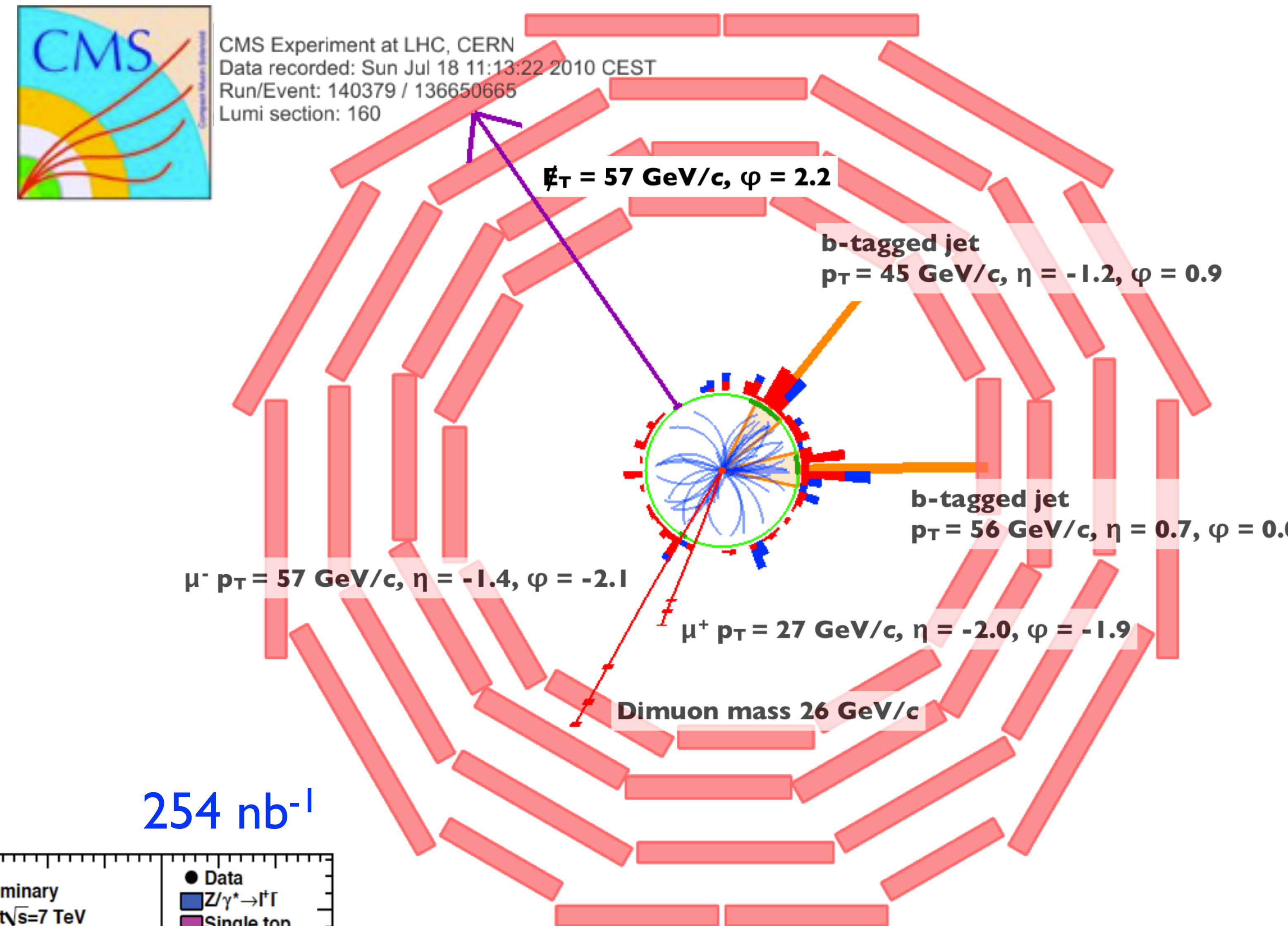
$78\ nb^{-1}$



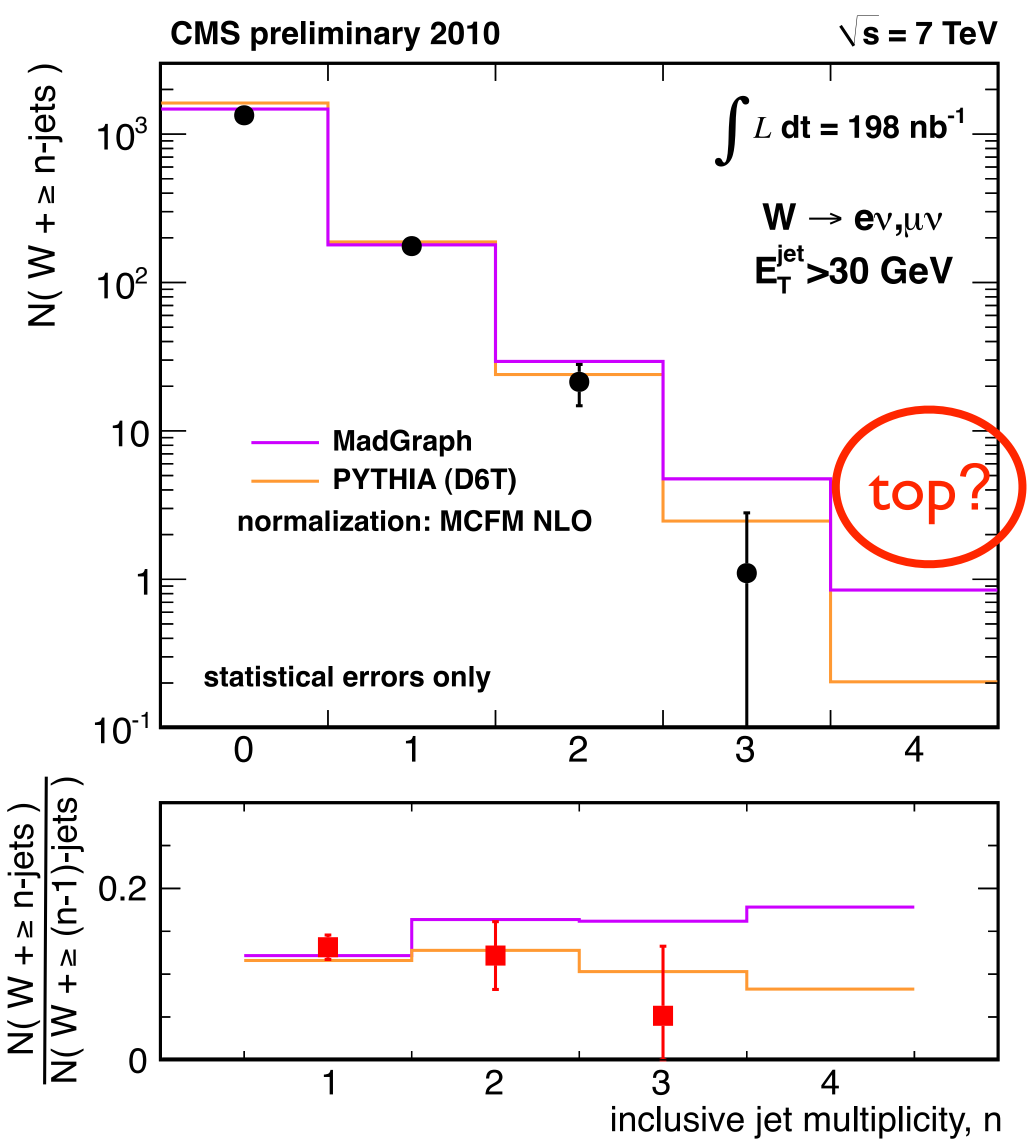
- Small luminosity
  - not enough signal yet
- But... ready to do the measurement

$254\ nb^{-1}$

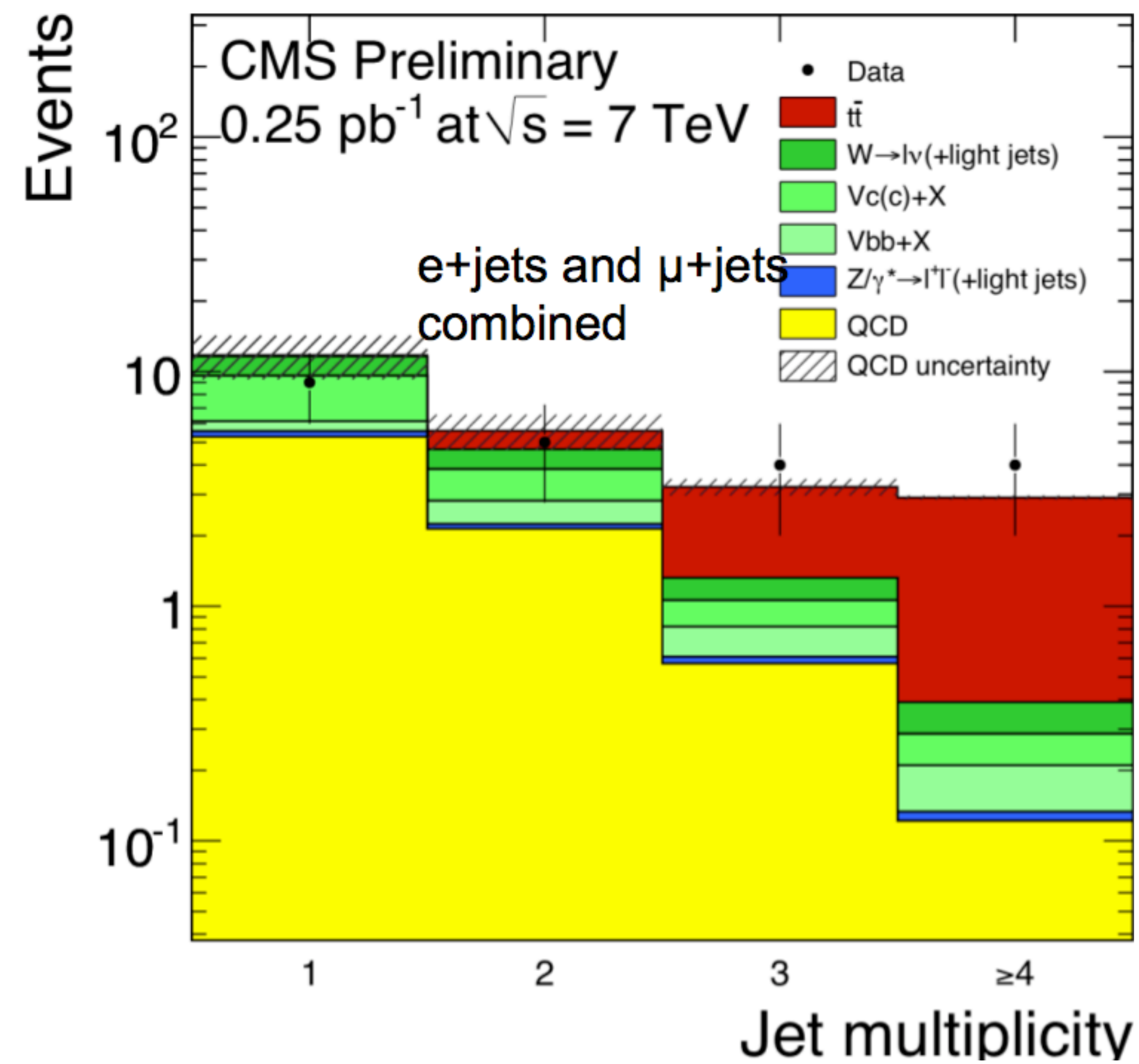




- Dimuon event
  - two identified b-jets
  - dimuon mass 26 GeV
  - preliminary reconstructed mass consistent with m_{top}


CMS preliminary 2010
√s = 7 TeV
∫L dt = 198 nb^-1
W → eν,μν
E_T^jet>30 GeV
MadGraph
PYTHIA (D6T)
normalization: MCFM NLO
statistical errors only
top?
N(W + ≥ n-jets)
N(W + ≥ n-jets) / N(W + ≥ (n-1)-jets)
inclusive jet multiplicity, n

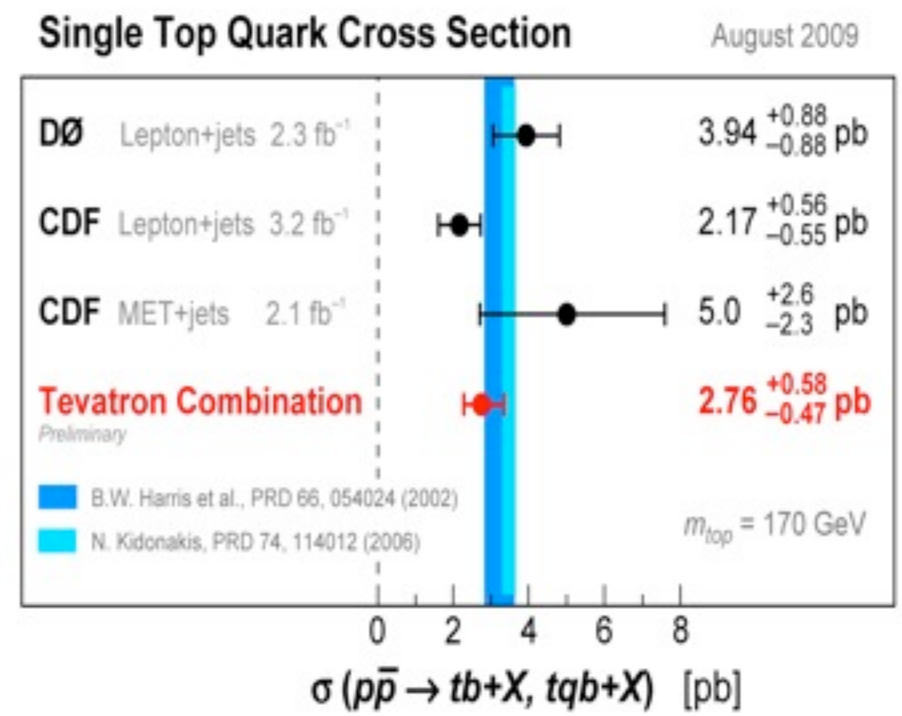
top!


CMS Preliminary
0.25 pb^-1 at √s = 7 TeV
e+jets and μ+jets
combined
Data
tt̄
W→lν(+light jets)
Vc(c)+X
Vbb+X
Z/γ*→l+l-(+light jets)
QCD
QCD uncertainty
Events
Jet multiplicity

Electroweak top production

- Predicted 10 years before top discovery
  - s- and t-channels
- Observed by CDF and D0 in 2009, 14 years after top discovery
  - small cross section
  - large background with large uncertainties
  - multivariate techniques necessary

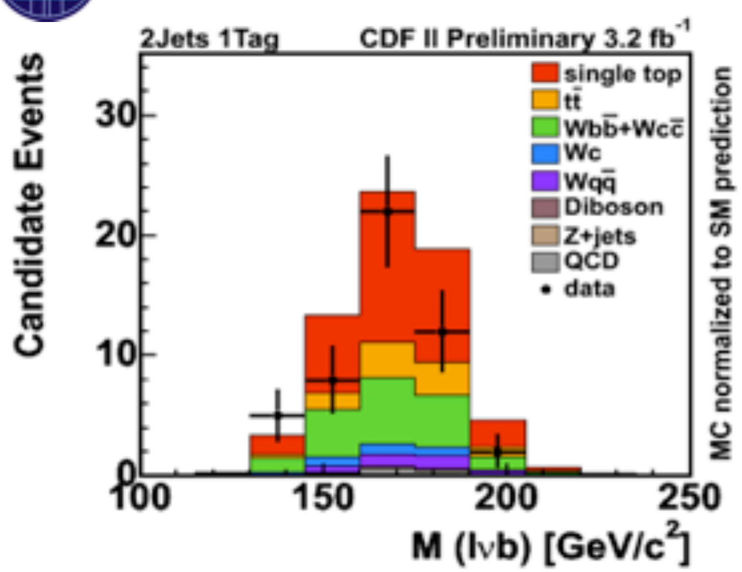
S.Willenbrock, D. Dicus, Phys. Rev. D34, 155 (1986); S Cortese and R Petronzio, PLB 253, 494 (1991)

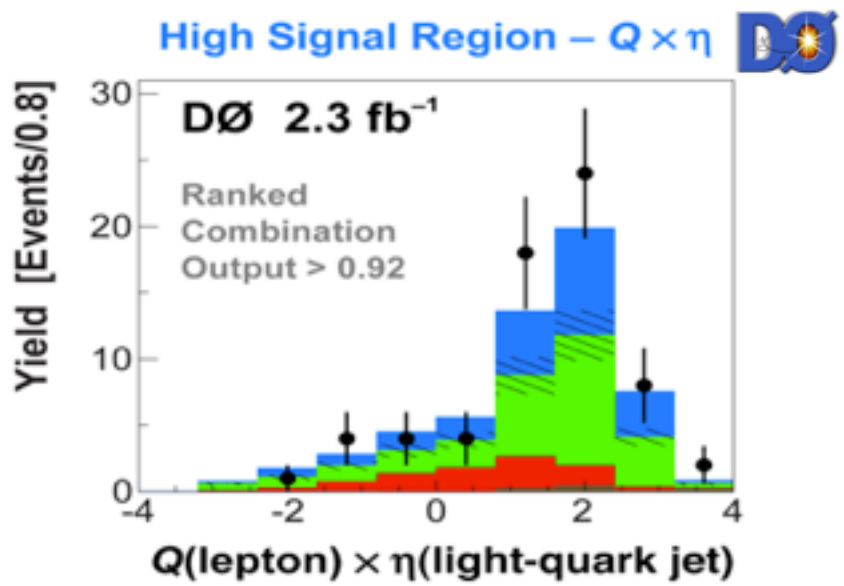


$$\sigma = 2.76^{+0.58}_{-0.47}(\mathrm{stat+syst})\mathrm{pb}$$

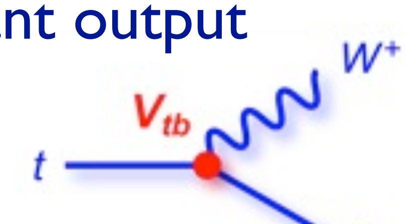
$|V_{tb}|$=0.91±0.08 (stat+syst)

arXiv:0908.2171v1 [hep-ex]





Events with high discriminant output



- Allows to measure $|V_{tb}|^2$
- Sensitive to new physics

$\sigma \sim |V_{tb}|^2$

- 4.8 σ evidence for t-channel production

PLB 683 363 (2010)

Top quark properties

mass

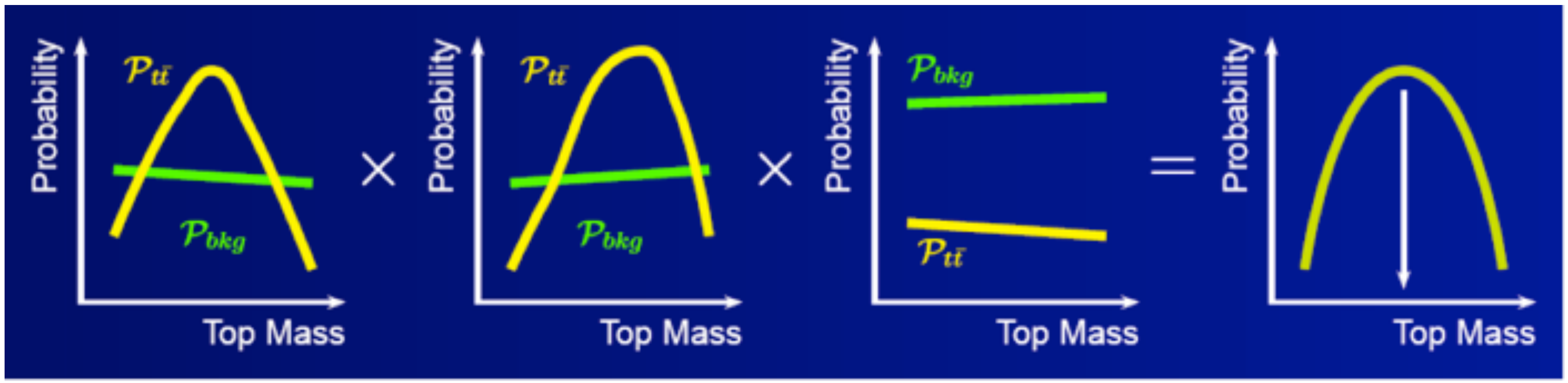
width

forward-backward asymmetry

spin correlations

Top quark mass measurement

- The most powerful method: matrix element method
  - Calculate probability for event to be signal or background as a function of top mass
  - Multiply event probabilities to extract the most likely mass

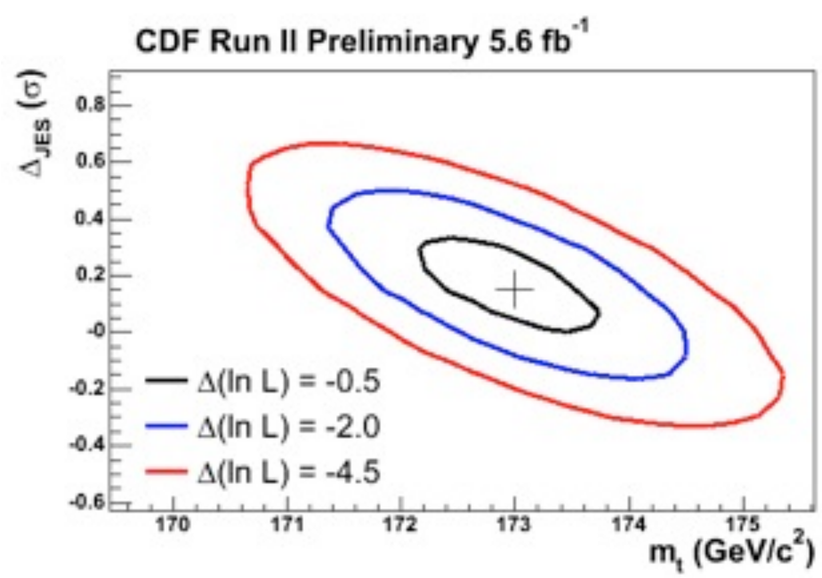


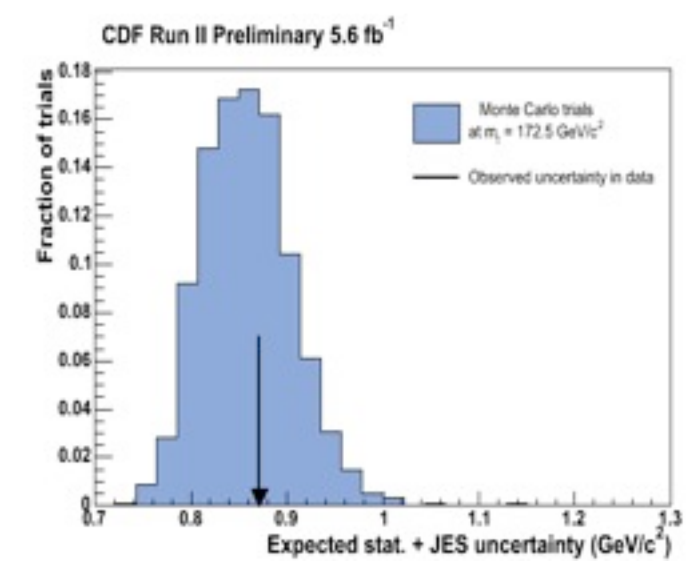
Maximizes statistical power by using full event information

l+jets channel

Top mass and jet energy scale extracted simultaneously from maximum likelihood fit to data

$\Delta_{JES} = 0.15 \pm 0.18\ \sigma$ 5.6 fb^{-1}

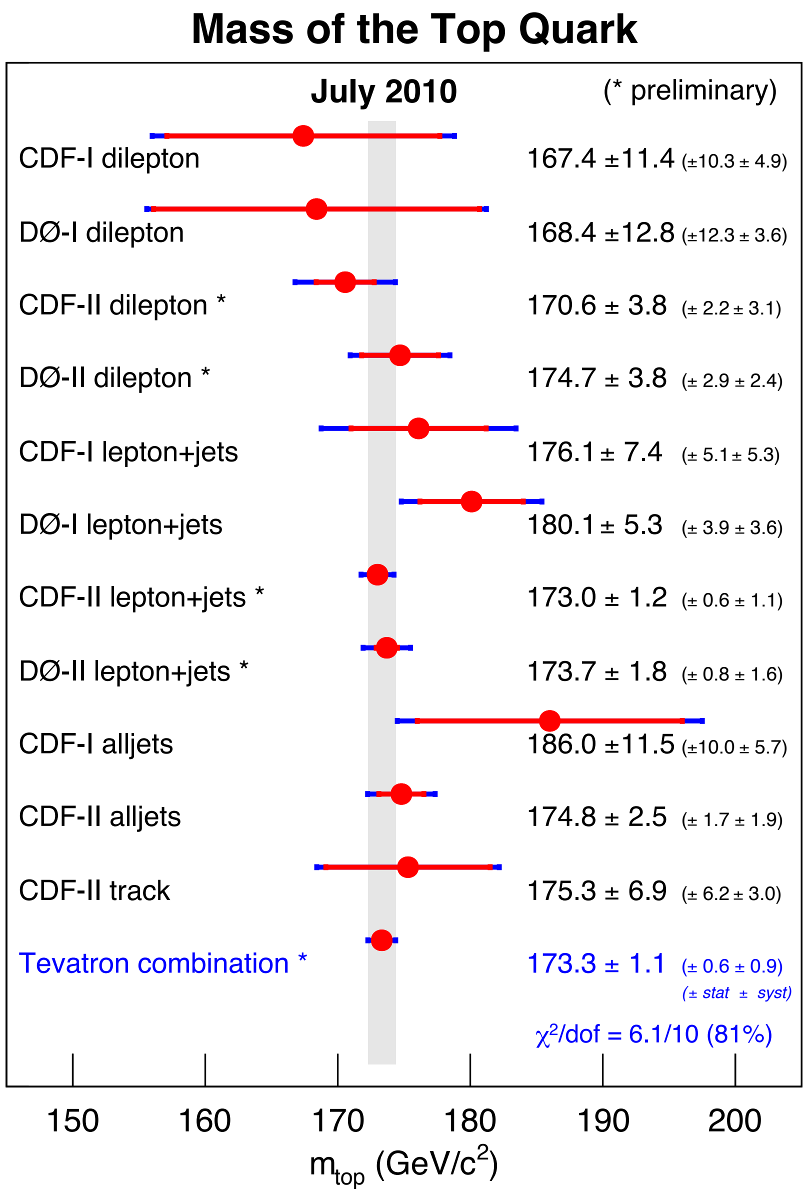




m_{top}=173.0±0.7(stat)±1.1(syst) GeV
±1.2(total) GeV

the most precise single measurement: ±0.7%

Tevatron mass combination



new

0.6% relative uncertainty

m_{top}=173.3±1.1(total) GeV

- Measurement in different channels consistent with each other
- Different methods produce consistent results

statistical component of JES

b-jet response

b-jet energy scale

modeling uncertainties

residual JES

detector response

ISR/FSR, PDF, NLO

showering model

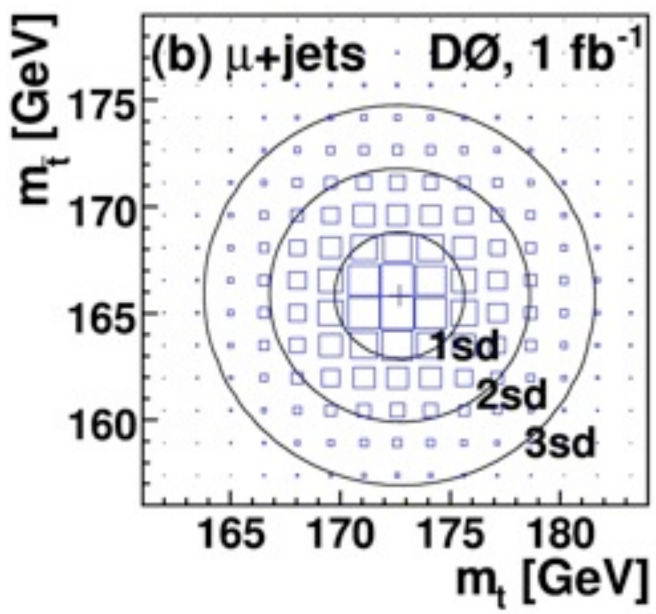
Systematic source	δm_{top} (GeV)
iJES	0.46
aJES	0.21
bJES	0.20
cJES	0.13
dJES	0.19
rJES	0.15
Lepton p_T	0.10
Signal model	0.19
Background	0.23
Fit	0.11
MC generator	0.40
Color reconnection	0.39
Multiple interactions	0.08
Total	1.06

Probing CPT

Is top quark mass equal to anti-top quark mass?

Drop assumption $m_t = m_{\bar{t}}$ in top mass measurement

- Extension of ME mass analysis
- m_t, JES → m_t, $m_{\bar{t}}$

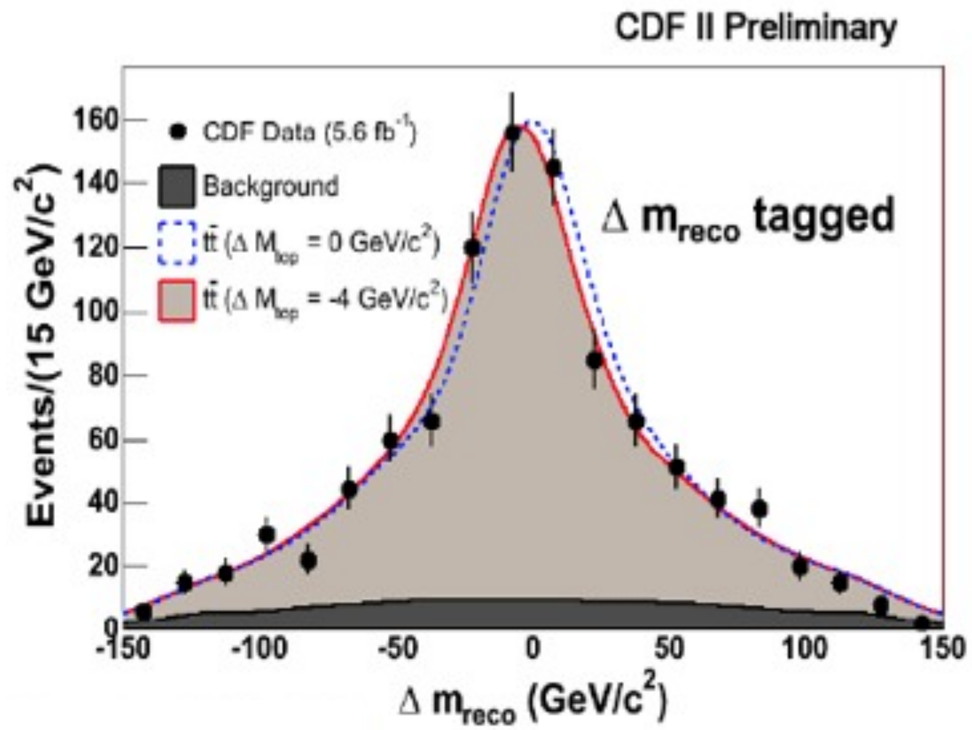


ΔM_{top} = 3.8 +/- 3.7 GeV/c^2

PRL 103, 132001 (2009)

First measurements of mass difference of bare quarks

- Template method
- variables: Δm_{reco} and $\Delta m_{reco(2)}$



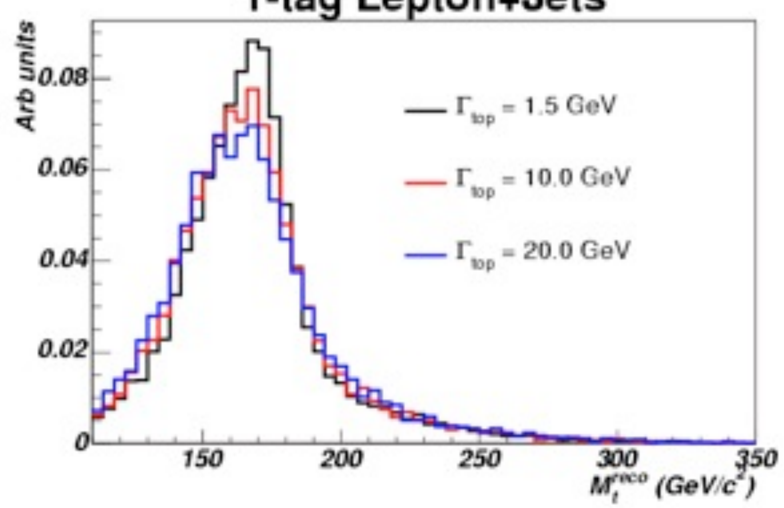
ΔM_{top} = -3.3 +/- 1.4(stat.) +/- 1.0 (syst.) GeV/c^2 5.6 fb^{-1}

Top quark width

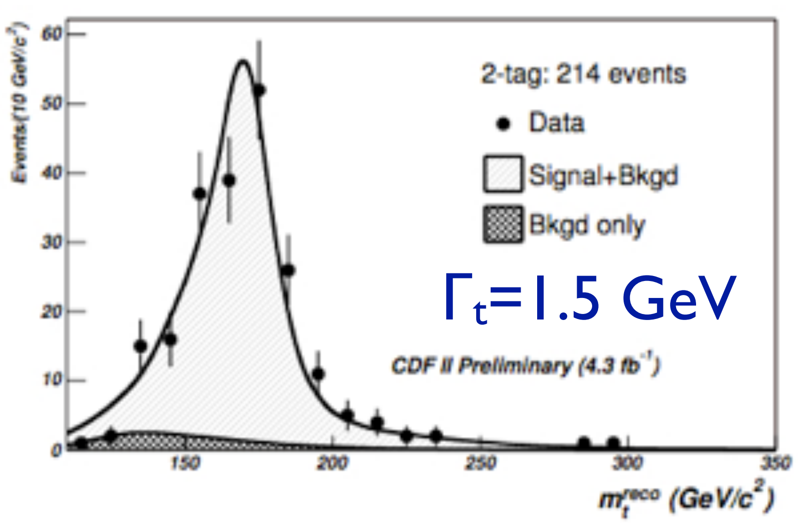
Standard Model: Γ_t~1.5 GeV at NLO for m_t=172.5 GeV

Additional decay modes: $t \rightarrow H^+b$, $t \rightarrow dW^+$, $t \rightarrow sW^+$?

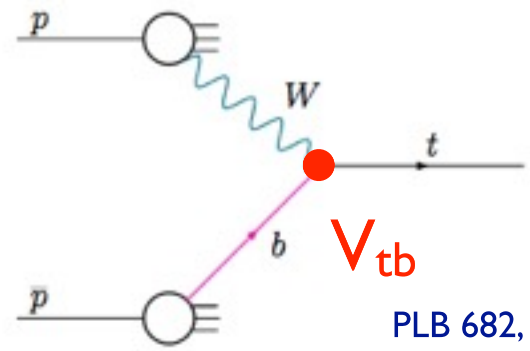
- Direct measurement
- use dependence of the reconstructed m_{top} on Γ_t

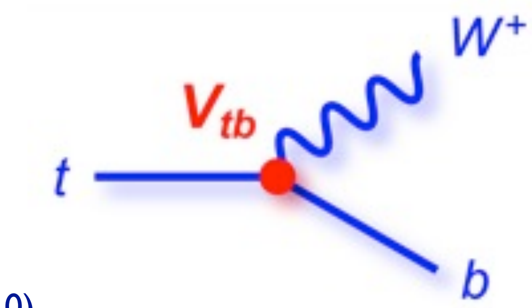


$\Gamma_t < 7.5$ GeV at 95% CL



- Indirect measurement
- use single top t-channel cross section
- combine with measured branching ratio
- assumption: coupling in top production and decay is the same





PLB 682, 363 (2010)

$$\Gamma_t = \frac{\sigma(t-ch)}{\mathcal{B}(t \rightarrow bW)} \times \frac{\Gamma(t \rightarrow bW)_{SM}}{\sigma(t-ch)_{SM}}$$

PRL 100, 192003 (2008)

$$\Gamma_t = (2.05^{+0.57}_{-0.52})\mathrm{GeV}$$
$$\tau_t = (3.2^{+1.1}_{-0.7}) \times 10^{-25} s$$

Consistent with the standard model

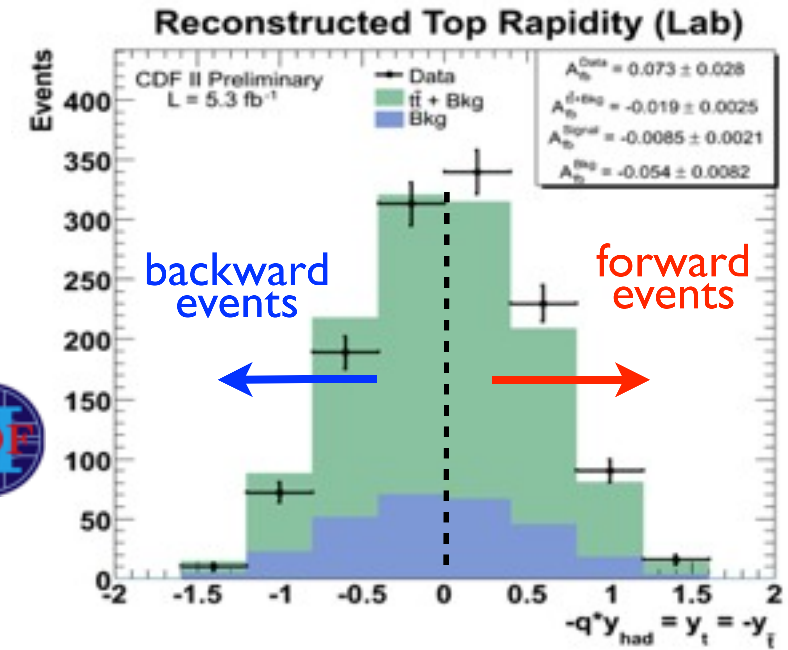
Forward-backward asymmetry

- LO: top quark production angle is symmetric with respect to beam direction
- NLO: asymmetry due to interference effects

l+jets events, $p\bar{p}$ rest frame

$$A_{fb} = \frac{N(-Q \times Y_{had} > 0) - N(-Q \times Y_{had} < 0)}{N(-Q \times Y_{had} > 0) + N(-Q \times Y_{had} < 0)}$$

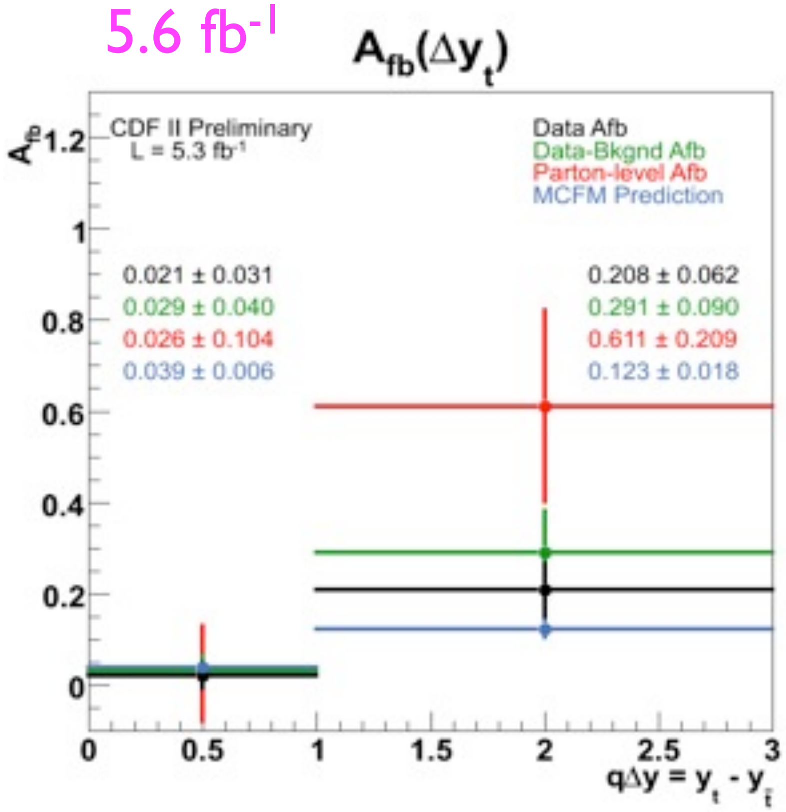
Q - lepton charge, Y_{had} - rapidity of hadronic top



unfolded: A_{fb} ($p\bar{p}$) = 15.0 ± 5.0 (stat) ± 2.4 (syst) %

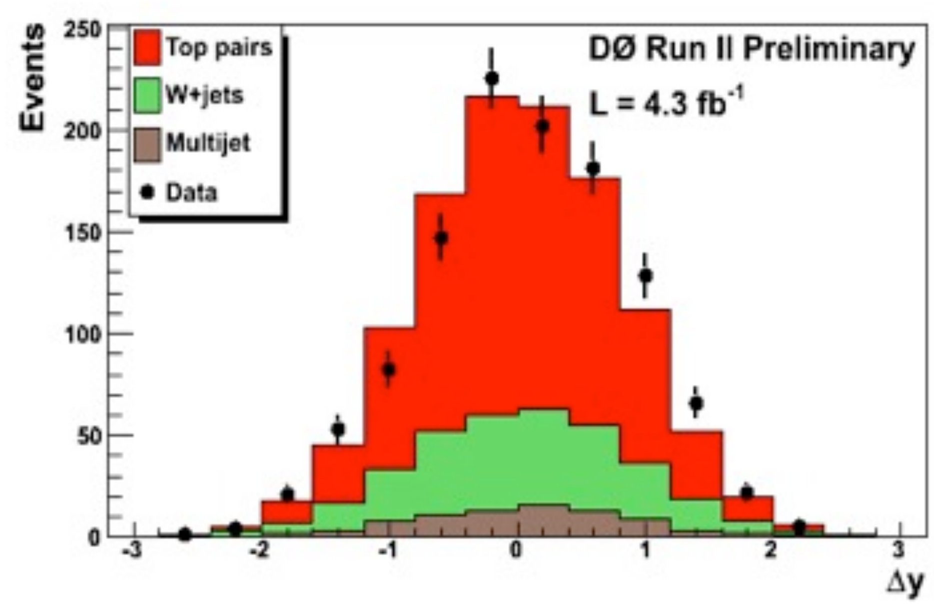
2.7σ deviation from 0

5.6 fb^{-1}



new

2.4 σ deviation from 0



4.3 fb^{-1}

predicted MC@NLO: $A_{fb} = 1^{+2}_{-1}$ %

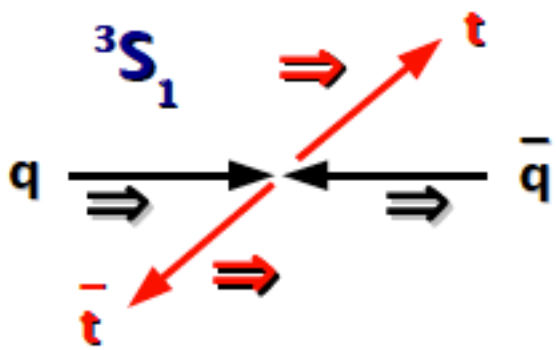
A_{fb} (|Δy|<1.0)= 2.6 ± 10.4(stat) ± 5.5(syst) %

A_{fb} (|Δy|>1.0)= 61.1 ± 21.0(stat) ± 14.1(syst) %

A_{fb}^{raw}(Δy)=8±4(stat)±1(syst) %

~30 theory papers in last 2 years!

Spin correlations



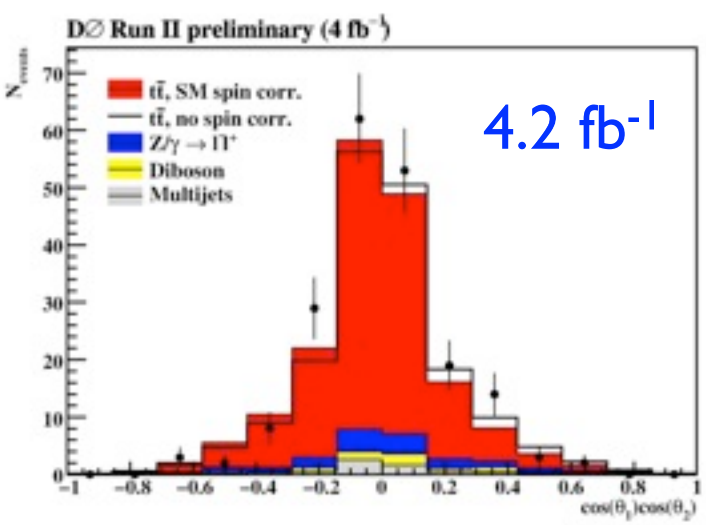
- Short lifetime
- Flight directions of top decay products carry information about top polarization at production

$$\kappa = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\downarrow\uparrow} - N_{\uparrow\downarrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\downarrow\uparrow} + N_{\uparrow\downarrow}}$$

Strength depends on spin quantization axis:

beam line, off-diagonal

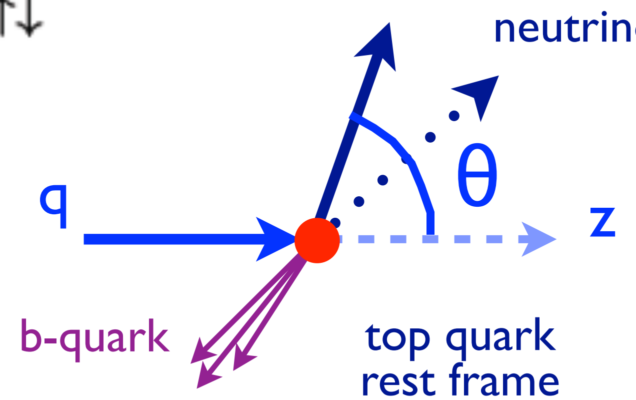
Dilepton channel



4.2 fb^{-1}

$\kappa = -0.17^{+0.64}_{-0.53}$

beam basis, NLO: κ=0.777



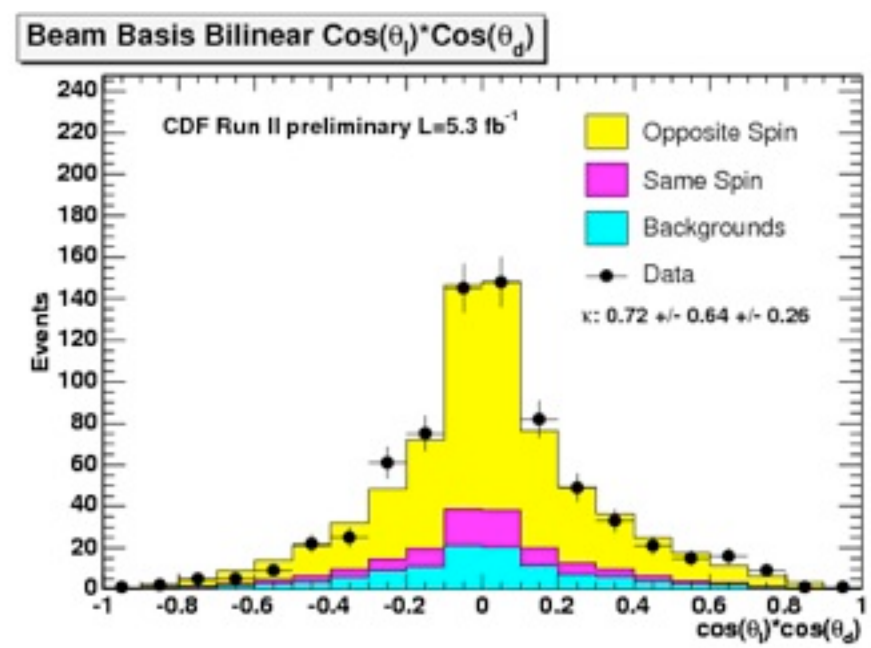
2.8 fb^{-1}

$\kappa = 0.32^{+0.55}_{-0.78}$

off-diagonal basis

NLO: κ=0.782

Lepton+jets channel



5.3 fb^{-1}

new

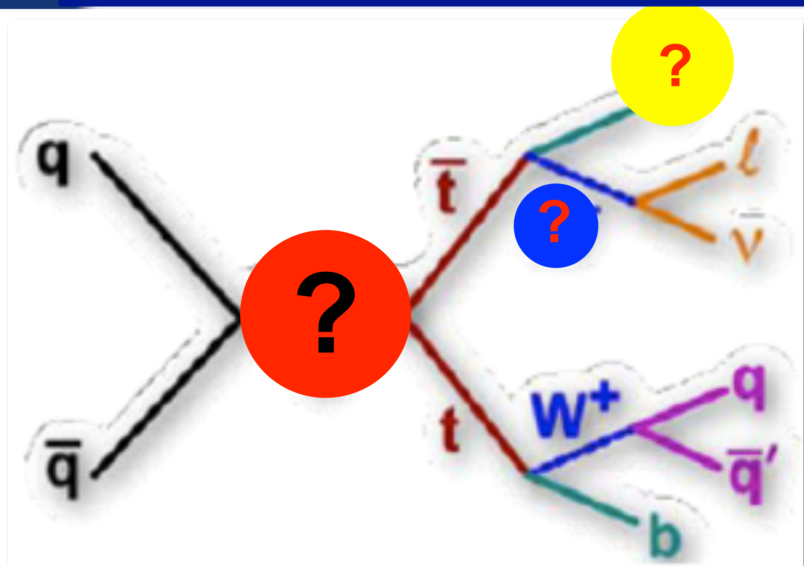
$\kappa = 0.72 \pm 0.64_{stat} \pm 0.26_{syst}$

beam basis

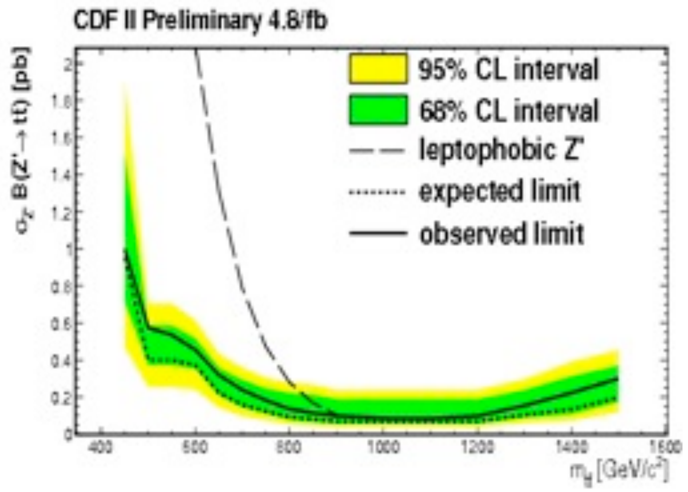
Three measurements in last year!

Searches in top quark sector

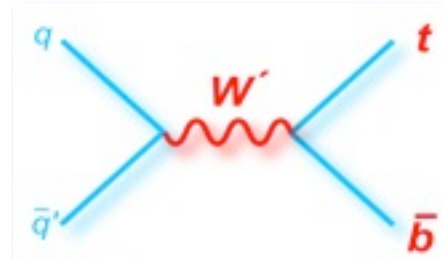
Selected searches in top sector

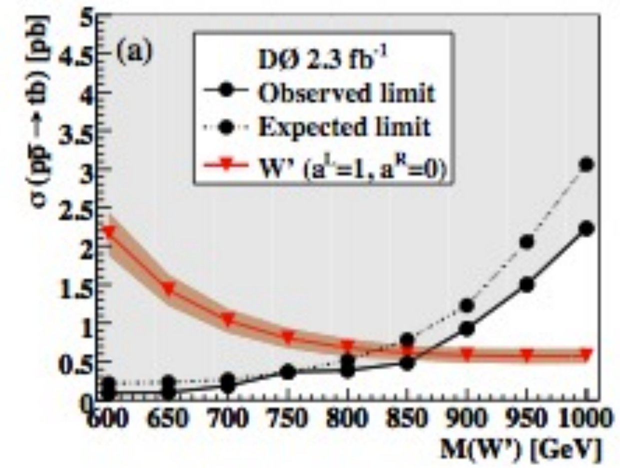


$t\bar{t}$ resonances

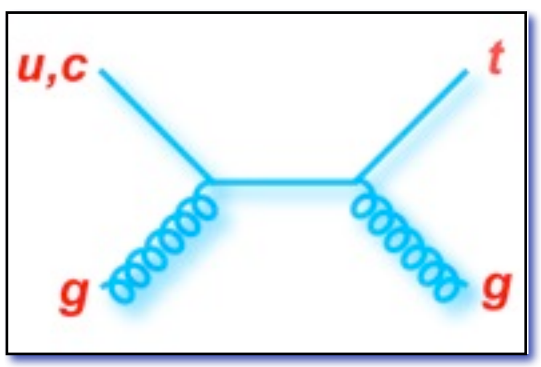


Single top s-channel





Single top t-channel

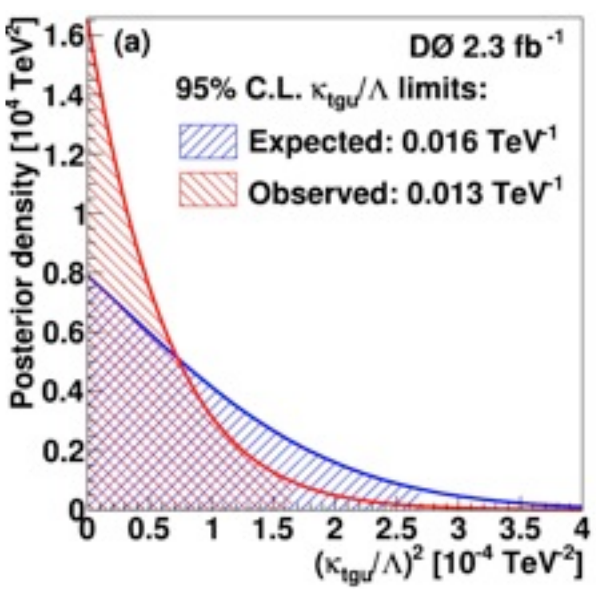


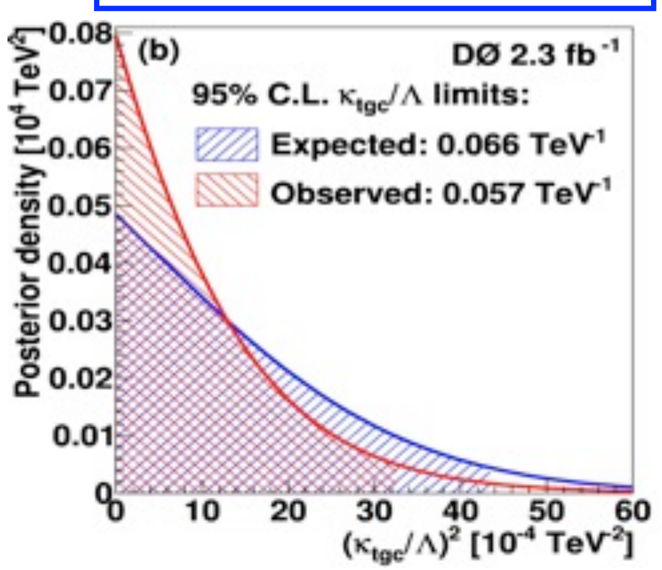
- Complimentary to FCNC search in top pair production: t→Zc, t→γc
- FCNC: t →gu, gc

new

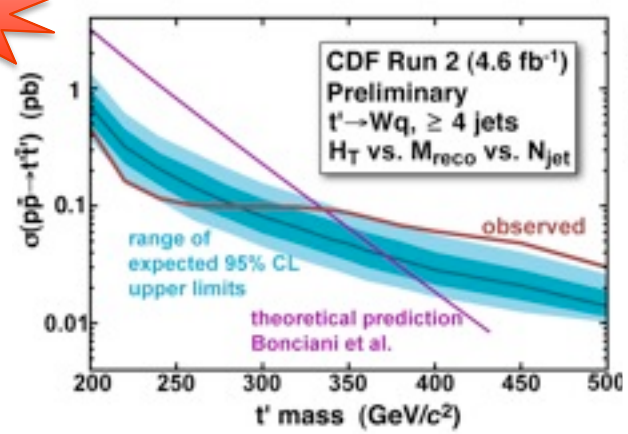
Br(t →gu)<2.0·10^{-4}

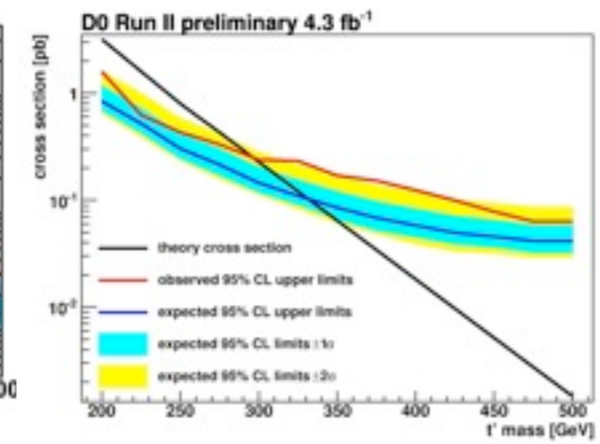
Br(t →gc)<3.9·10^{-3}





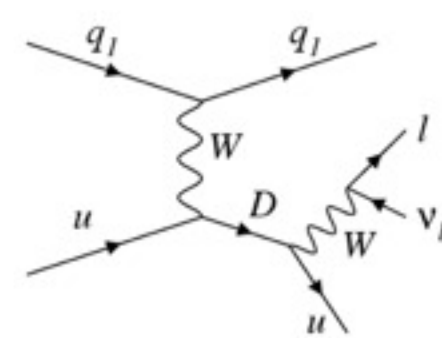
4th generation t' quark





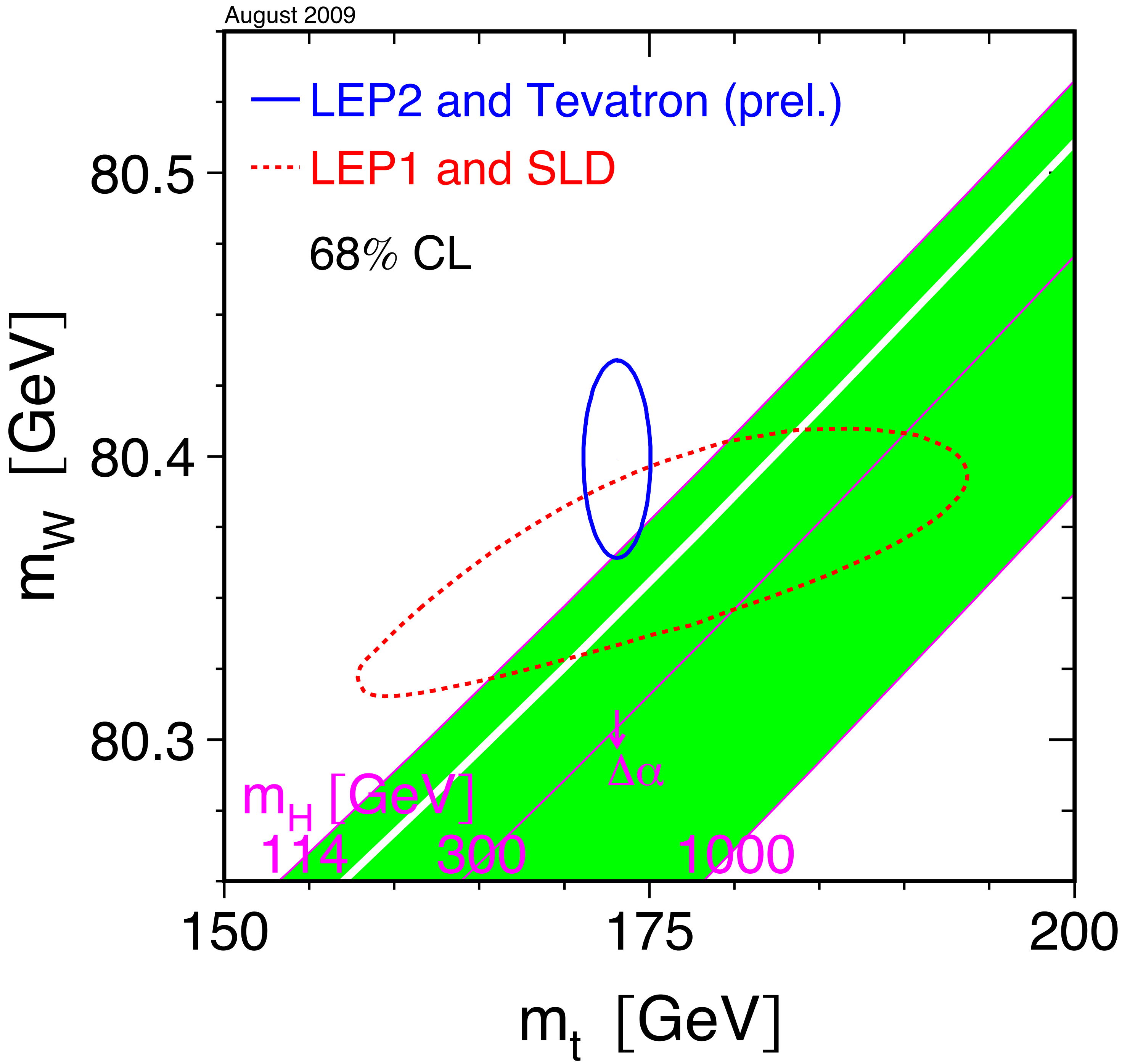
singly produced new heavy quarks

new results on t', W', $t\bar{t}$ resonances and singly produced heavy quarks in the talk by P. Murat

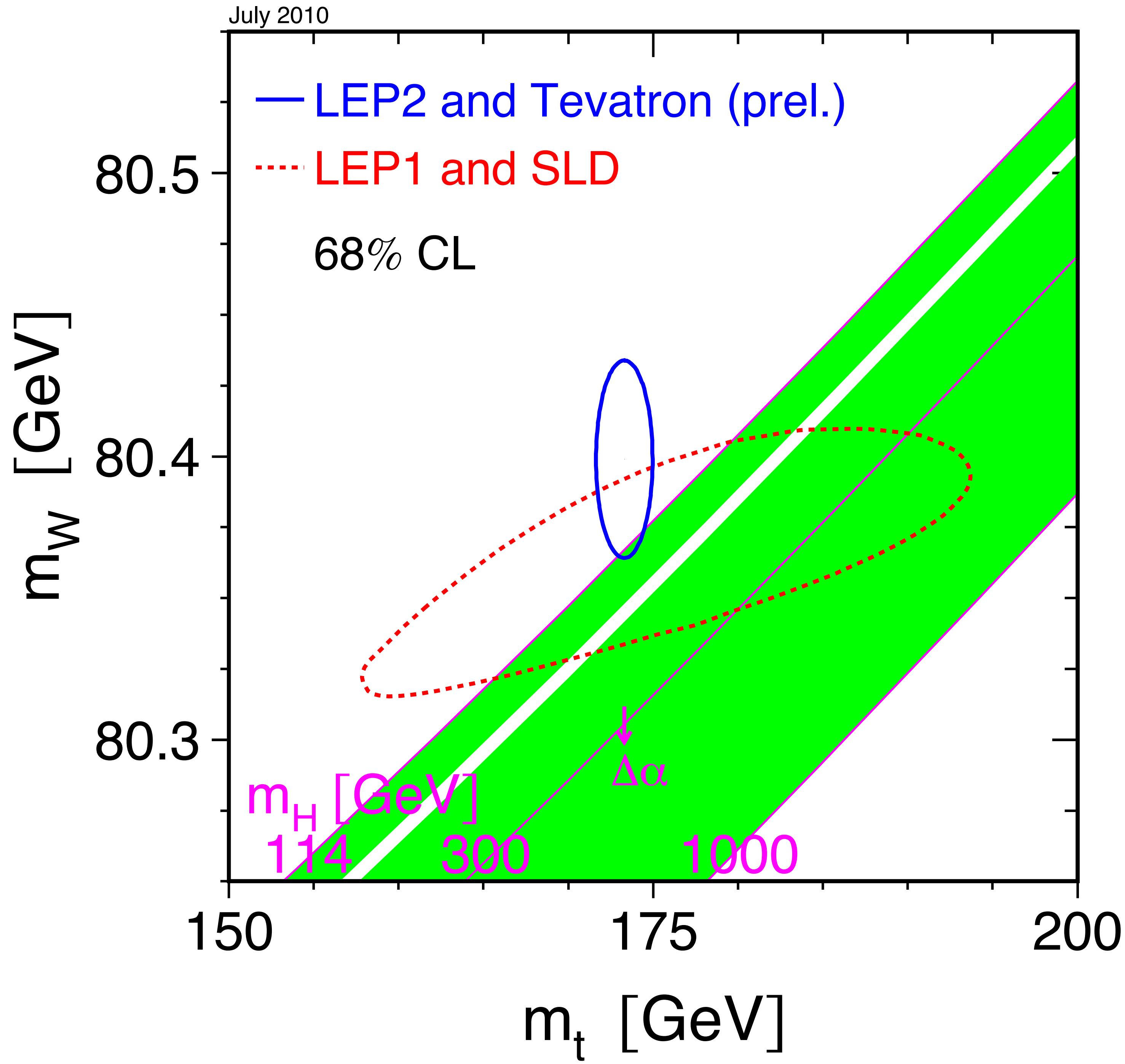


Electroweak fit

EW fit constraints



EW fit constraints



Updated inputs: m_{top}, W width

M_H<158 GeV

ignoring direct limit

M_H<185 GeV

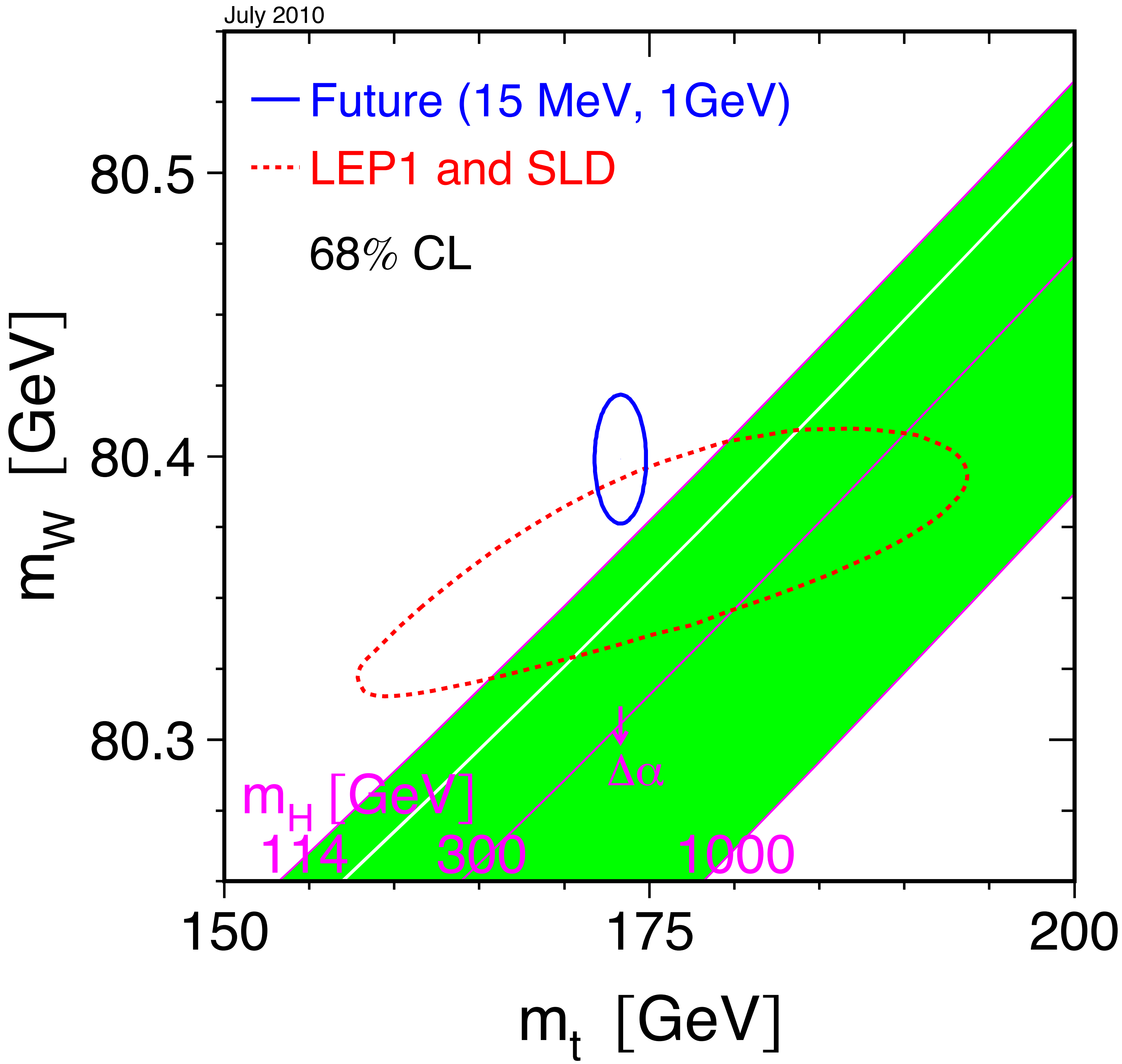
including 114 GeV LEP limit

$M_H = 89^{+35}_{-26}$ GeV

EW fits alone without theory uncertainties

Small change compared to August 2009

EW fit: future



Note: new direct Higgs exclusion limit was not propagated to this plot!

Improved W mass measurement is critical

Conclusions and outlook

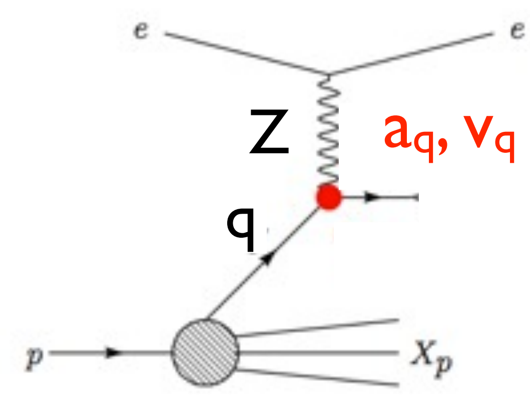
- Precision measurements in top quark sector at Tevatron
  - top pair production cross section uncertainty smaller than theoretical one
  - top mass uncertainty is approaching 1 GeV
  - precision of Mw measurement of 15 MeV is desirable
- Measurements of new top quark properties (forward-backward asymmetry, spin correlations) are now available and become to be sensitive
- Diboson signatures are well established at Tevatron
- First EW gauge boson measurements from LHC
  - CMS and Atlas demonstrated their readiness for exciting W, Z and top quark physics

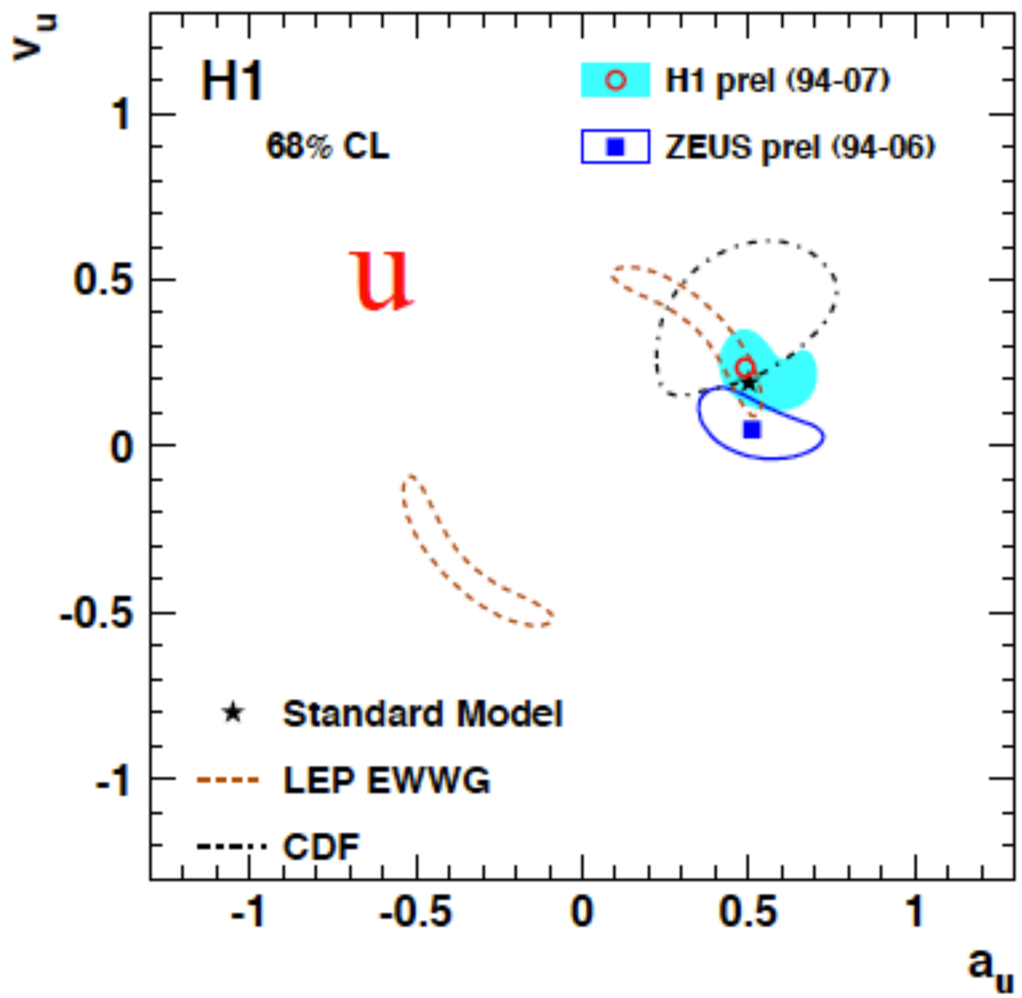
Tevatron and LHC are collecting data:
more exciting physics is ahead of us

Backup

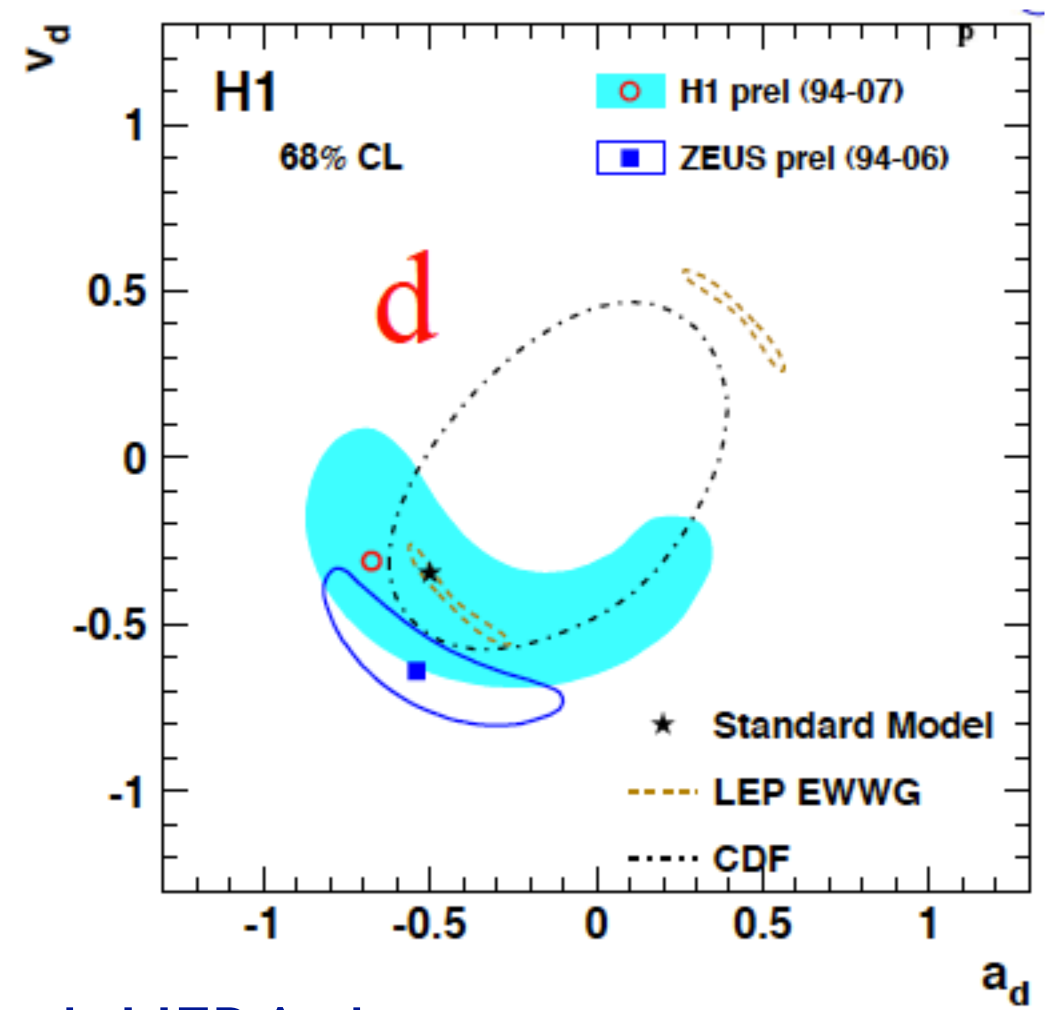
Couplings at HERA

- Extend NLO QCD fits of NC/CC HERA data to fit also the u- and d-quark couplings to Z





- CDF: $Z/\gamma \to ee$ (AFB)
- LEP/SLD: $ee \to qq$ at Z

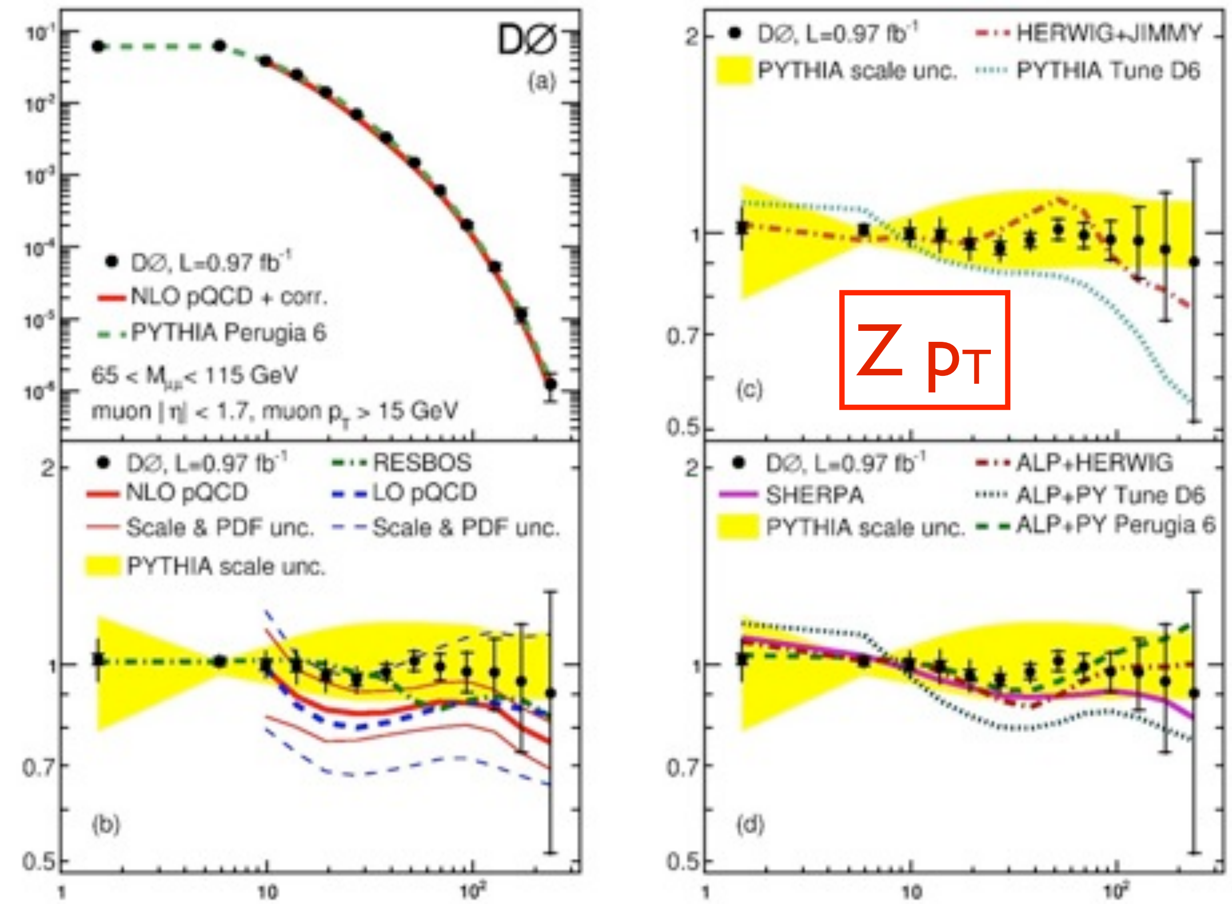


- much improved precision due to polarized HERA data
- will further improve with H1 & ZEUS combination

Z/γ* differential distributions

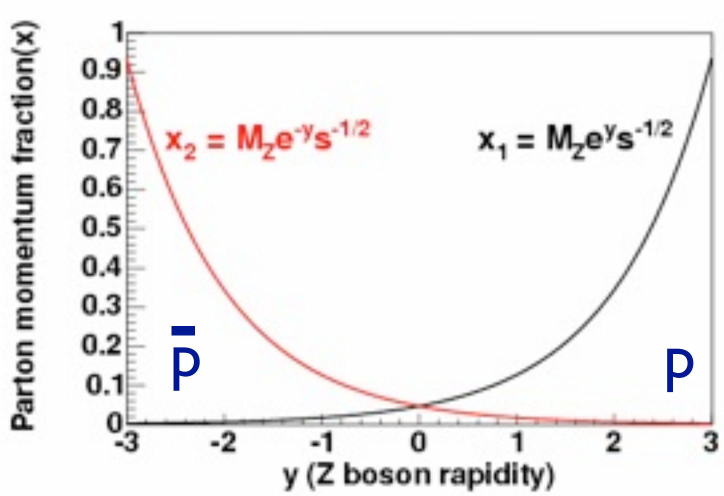
- colorless and low background state
- excellent ground for testing QCD
- important background for many processes: important to model

$1\ fb^{-1}$

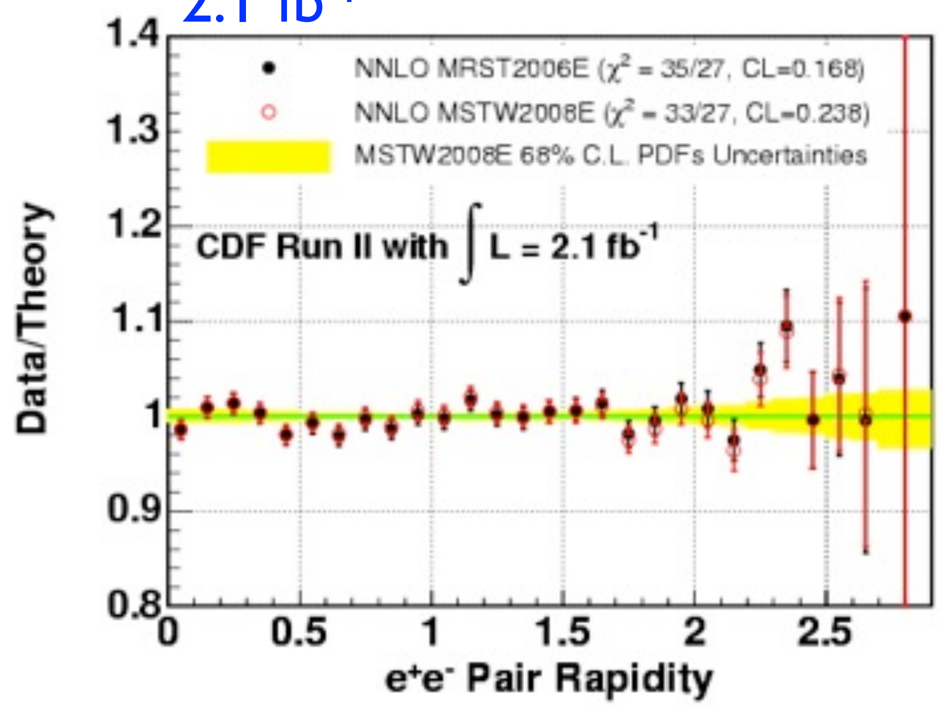


Z/γ* rapidity distribution sensitive to PDF

momentum fraction carried by partons



$2.1\ fb^{-1}$



- Theory prediction scaled to σ from data
- Yellow error band: MSTW2008 PDFs uncertainty at 68 % CL

$\sigma = 256.6 \pm 0.7(stat) \pm 2.0(syst)$ pb
$\sigma(y>0) = 256.4 \pm 1.0(stat)$ pb
$\sigma(y<0) = 256.9 \pm 0.9(stat.)$ pb

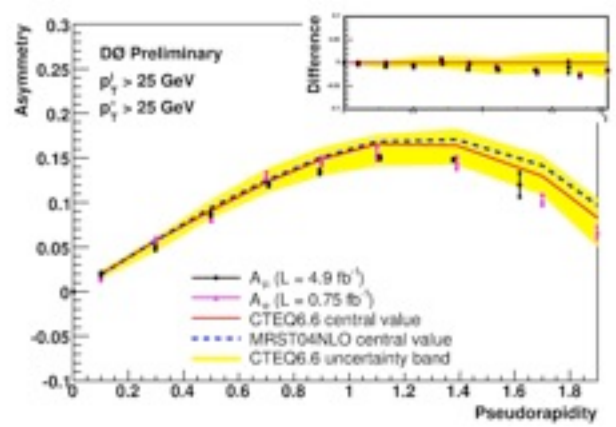
Charge asymmetry

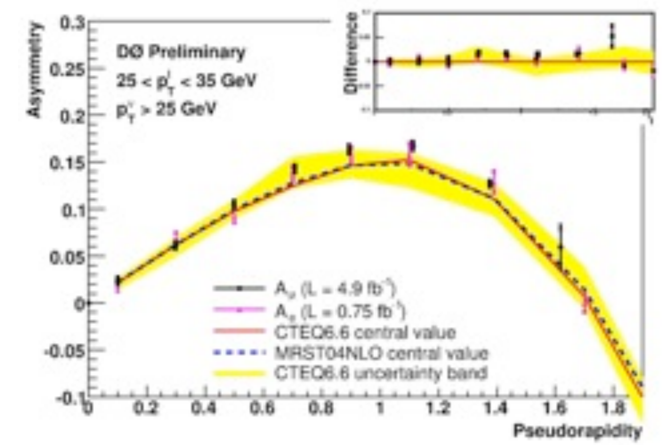
- $W^{\pm}$ produced through valence quarks ($\bar{u}d$ or $u\bar{d}$)
- u-quark tends to carry higher proton momentum fraction than d
- $W^+(W^-)$ produced preferably in the direction of proton(antiproton) beam

measure the asymmetry of W decay products

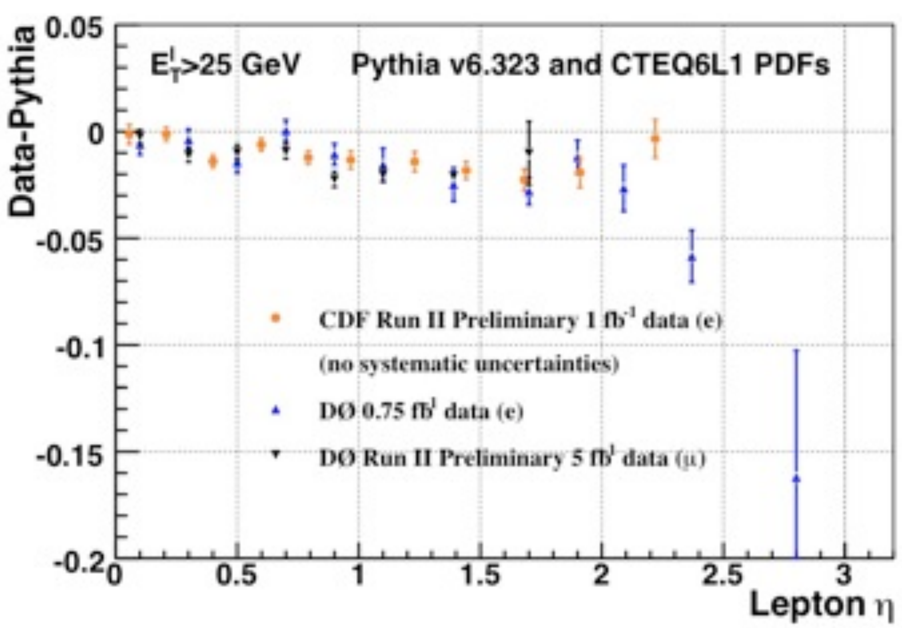
$$A(y_W) \rightarrow A(\eta_\mu): \quad A(\eta_\mu) = \frac{N_{\mu^+}(\eta) - N_{\mu^-}(\eta)}{N_{\mu^+}(\eta) + N_{\mu^-}(\eta)}$$

- high η and low muon p_T: dominated by V-A asymmetry of W decay
- high muon p_T: dominated by W production asymmetry

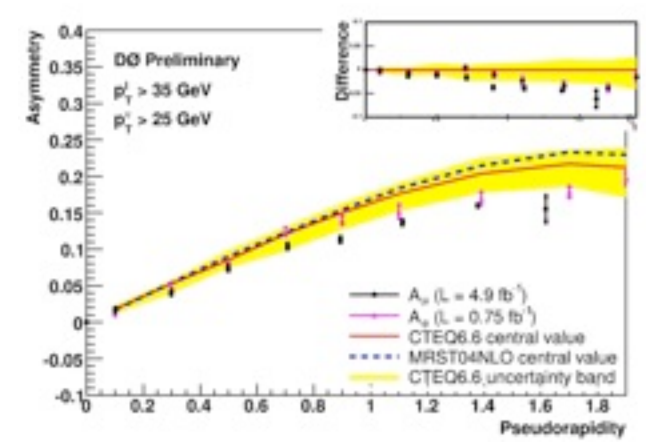




consistent results between electron and muon channels and with CDF



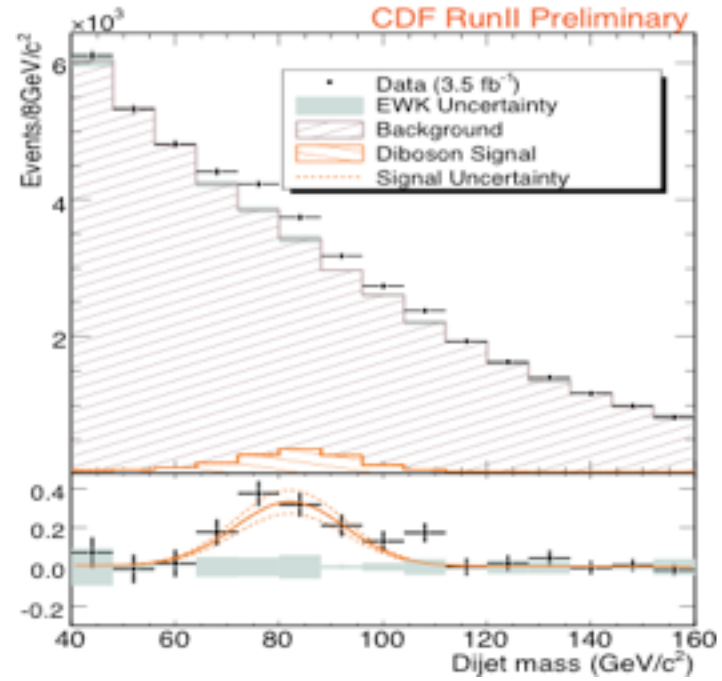
experimental uncertainties smaller than PDF uncertainties in most η bins



VV production

- WW+WZ+ZZ
- no explicit requirement on charged lepton
  - large missing E_T+jets

3.5 fb^{-1}



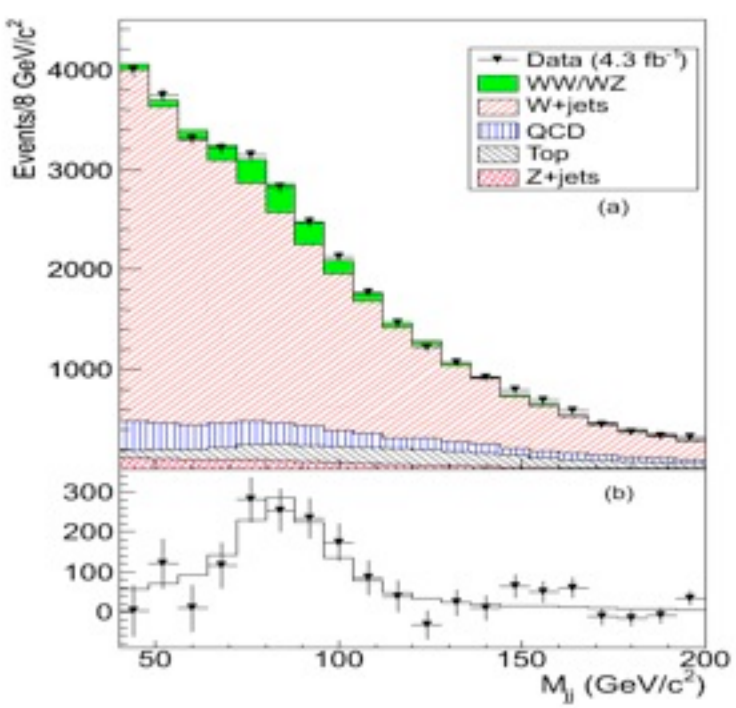
$\sigma_{VV} = 18.0 \pm 3.7(\text{stat}+\text{syst}) \pm 1.1(\text{lumi})\text{pb}$

NLO: σ_{VV}=16.8±0.5 pb   5.3σ significance

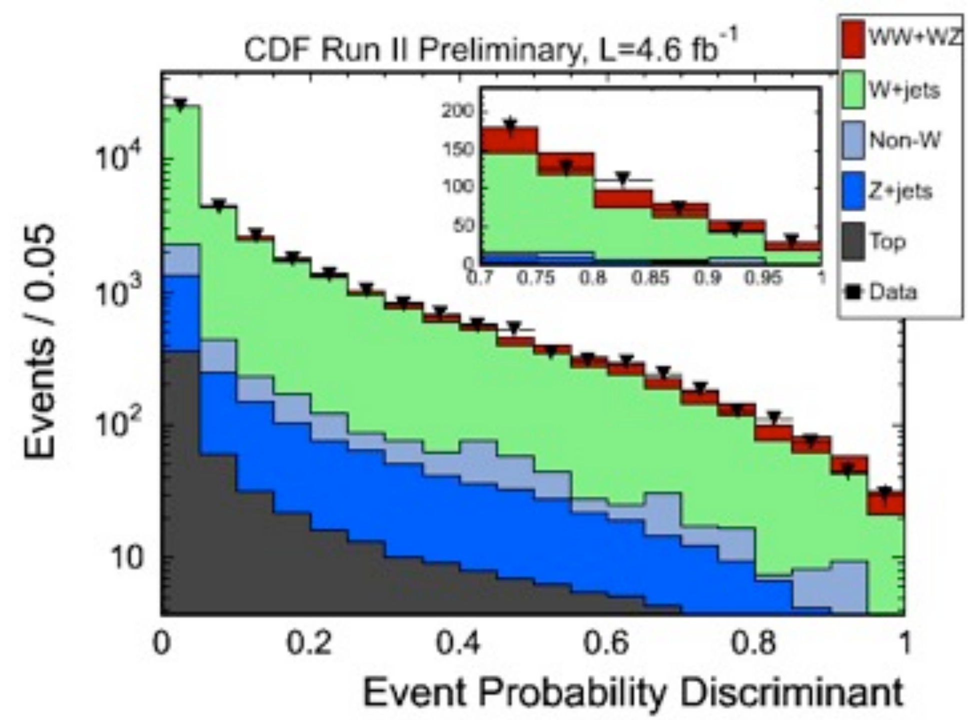
- WW+WZ →lνjj
  - dijet mass fit (4.3 fb^{-1})

NLO: σ_{WW+WZ}=16.1±0.9 pb

- matrix element (4.6 fb^{-1})



Challenging final states!



$\sigma_{WW+WZ} = 18.1 \pm 4.1(\text{stat}+\text{syst})\text{pb}$

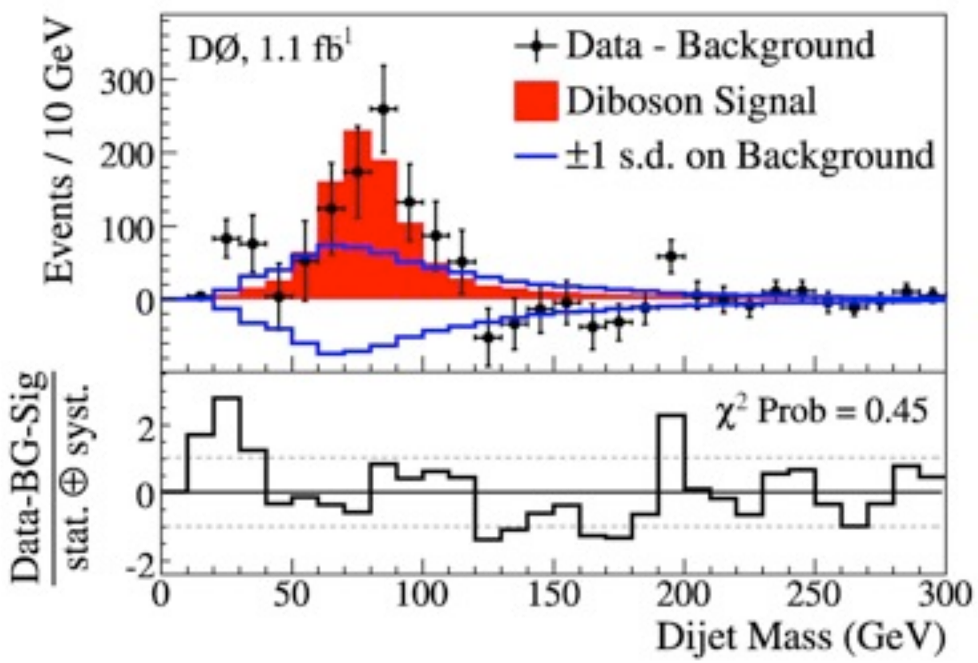
5.2σ significance

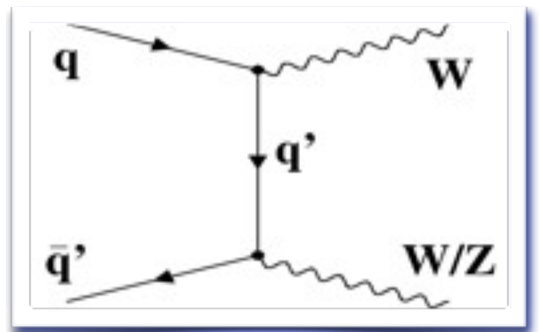
$\sigma_{WW+WZ} = 16.5^{+3.3}_{-3.0}(\text{stat}+\text{syst})\text{pb}$

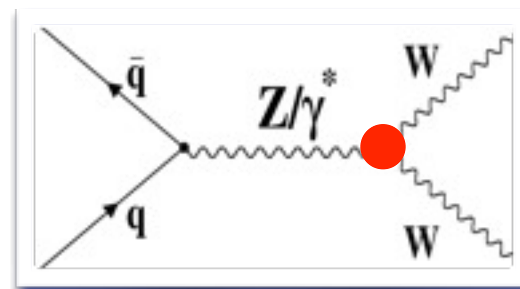
5.4σ significance

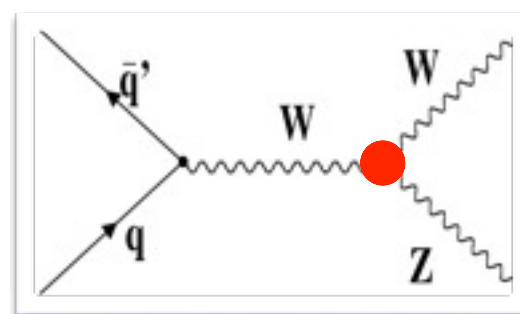
WW+WZ and TGC

- WW+WZ →lνjj
  - decision tree (1.1 fb^{-1})

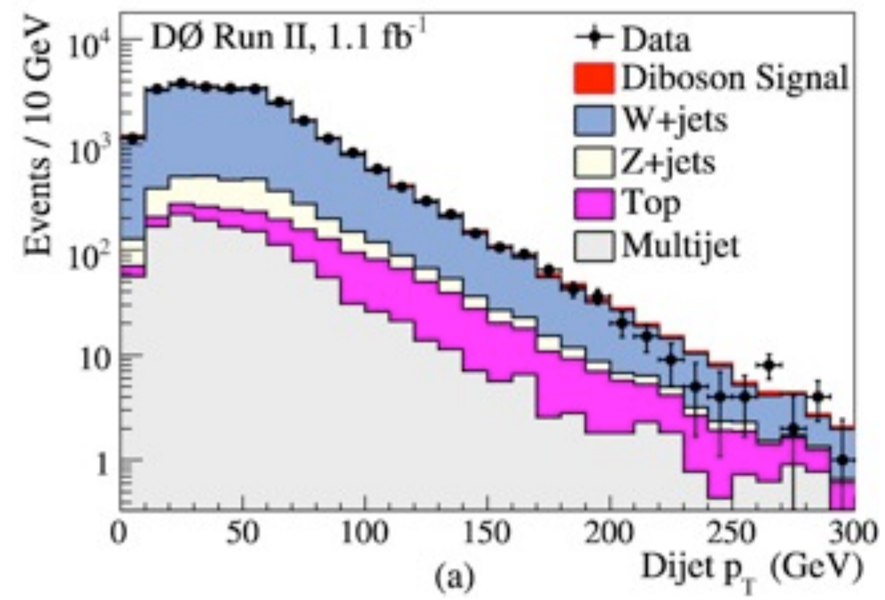


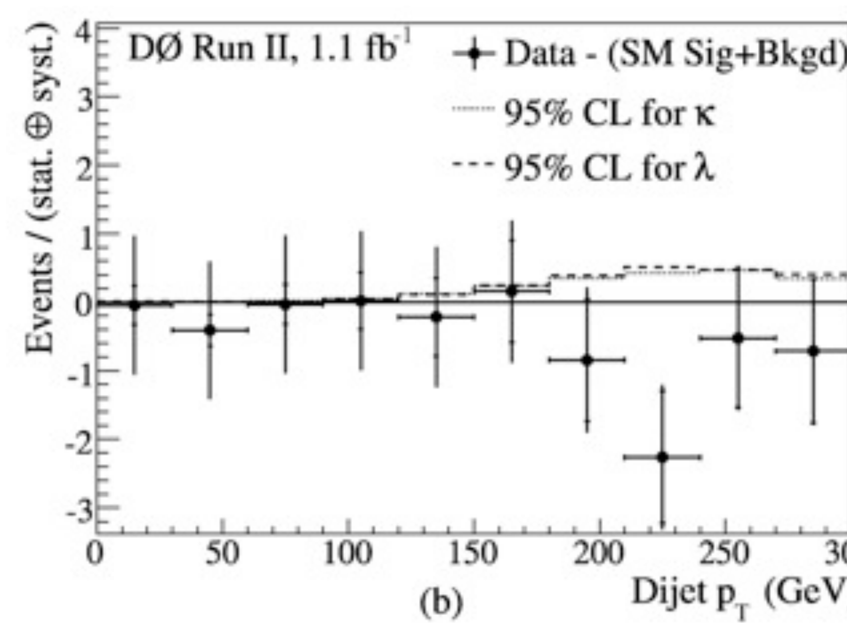






- Extension to coupling measurement
- sensitive variable: p_T of dijet system





	$\Delta\kappa_\gamma$	λ_γ	Δg_1^Z
SU(2)xU(1)	-0.44, 0.55	-0.10, 0.11	-0.12, 0.20
γWW=ZWW	-0.16, 0.23	-0.11, 0.11	-

Tightest limits on $\kappa_\gamma, \lambda_\gamma, \Delta g_1^Z$ in a single final state at the hadron collider