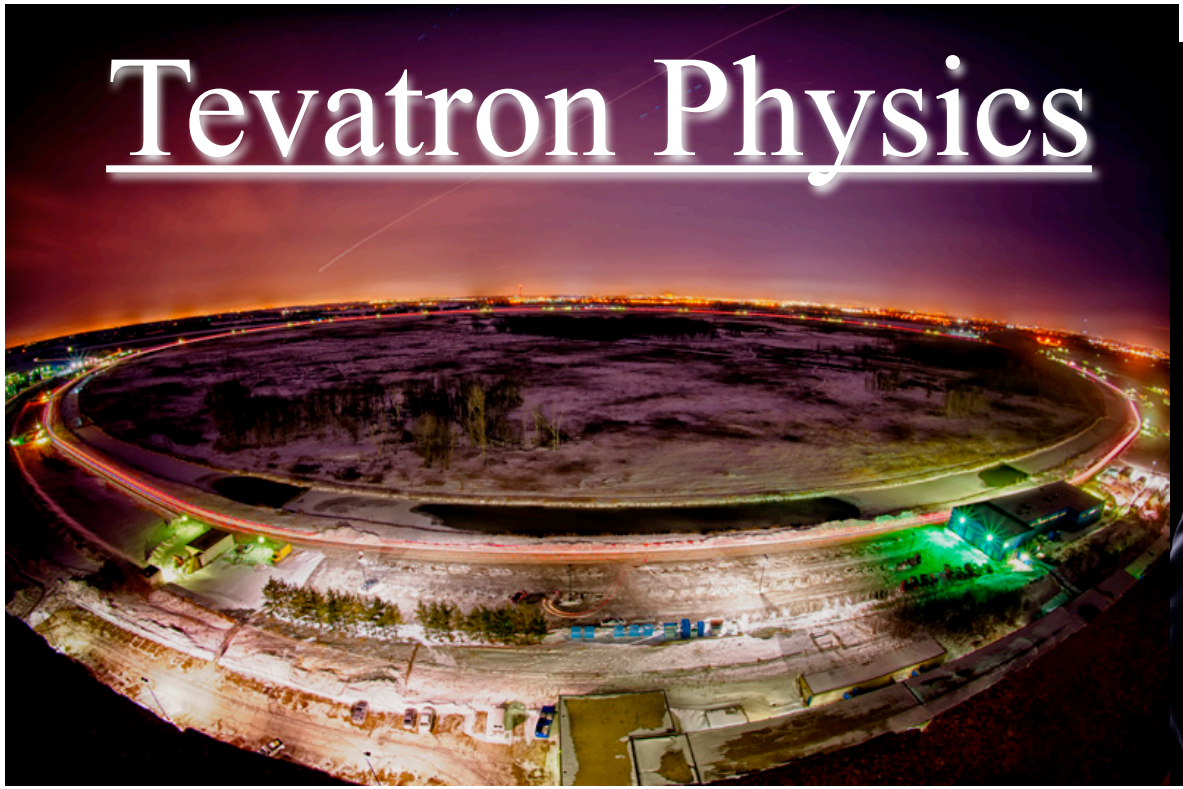
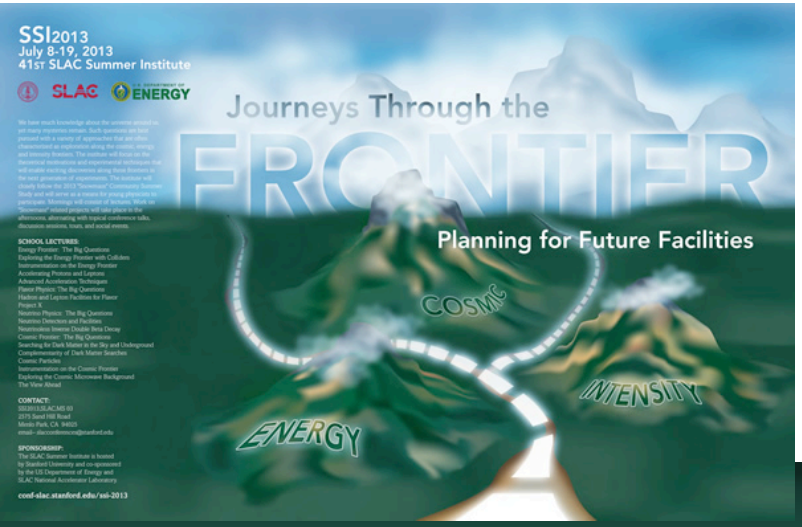
Tevatron Physics



Welcome new Fermilab director Nigel Lockyer

Reinhard Schwienhorst



MICHIGAN STATE UNIVERSITY

Outline

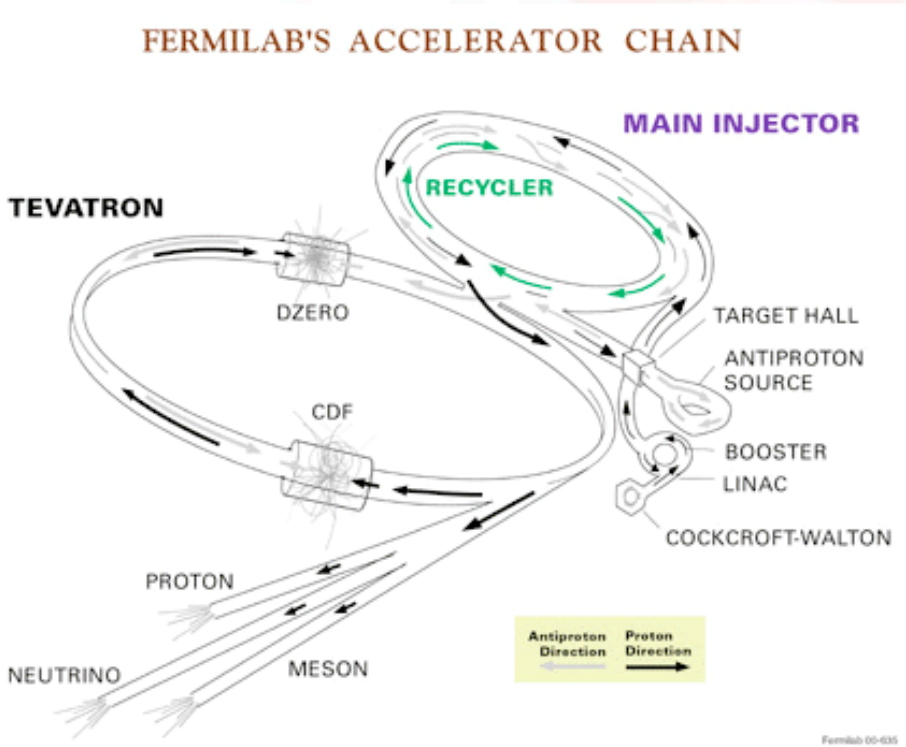
- Tevatron proton-antiproton collider
- Heavy flavor production
- QCD events
- Electroweak results
- Top quark measurements
- Higgs boson coupling to fermions
- Conclusions

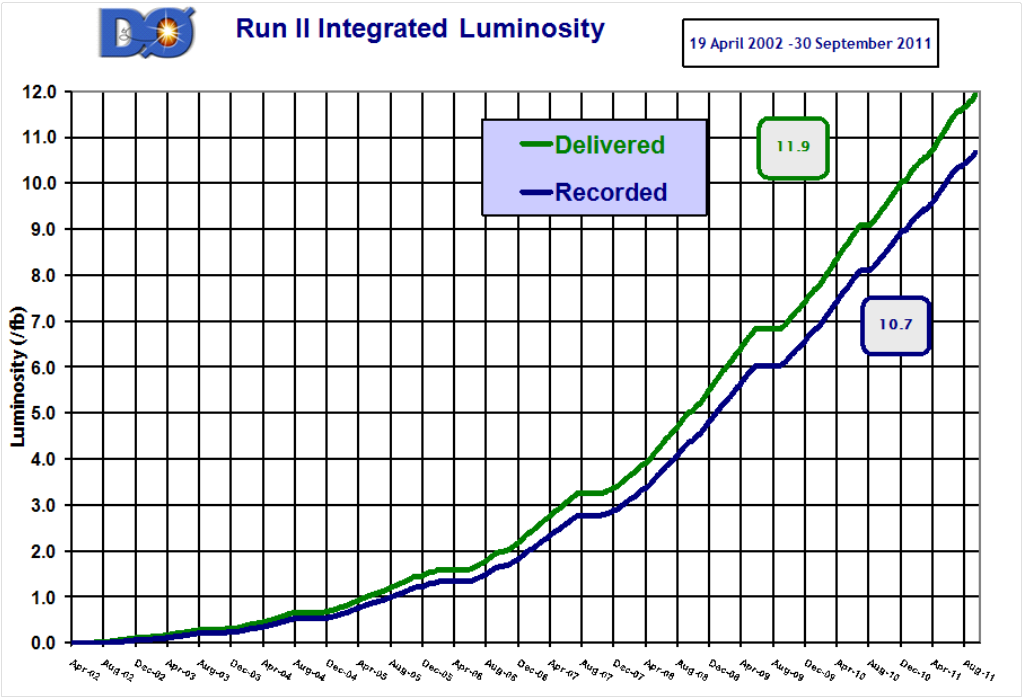
Tevatron at Fermilab

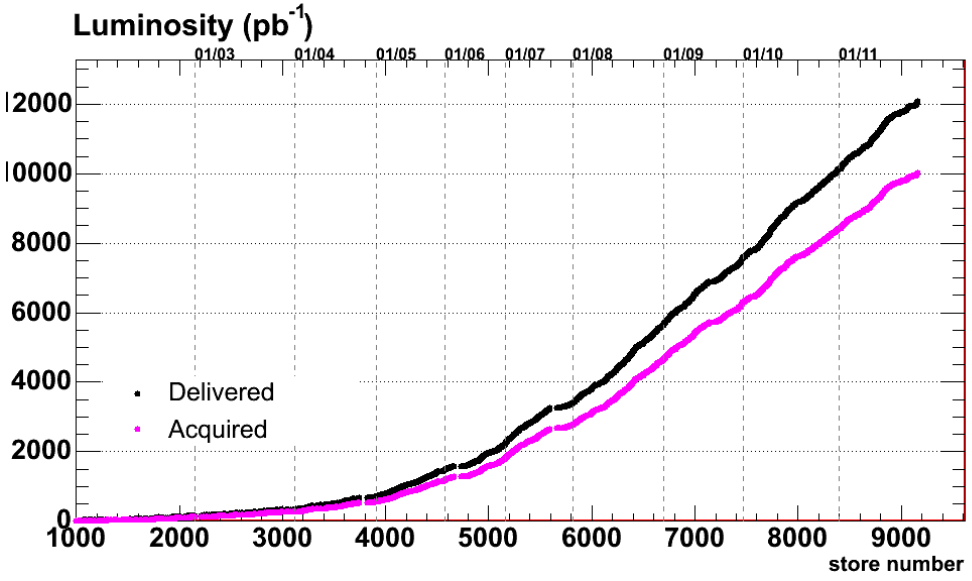
- Run II from 2002 to 2011
- CDF and D0: 400 + 400 members from 60 + 70 institutions

Tevatron collider in Run II

- proton-antiproton collider
- 1.96 TeV
- 12 fb^{-1} delivered
- 10 fb^{-1} recorded per experiment
- 10 pByte dataset (incl. MC) per experiment







Unique Tevatron physics

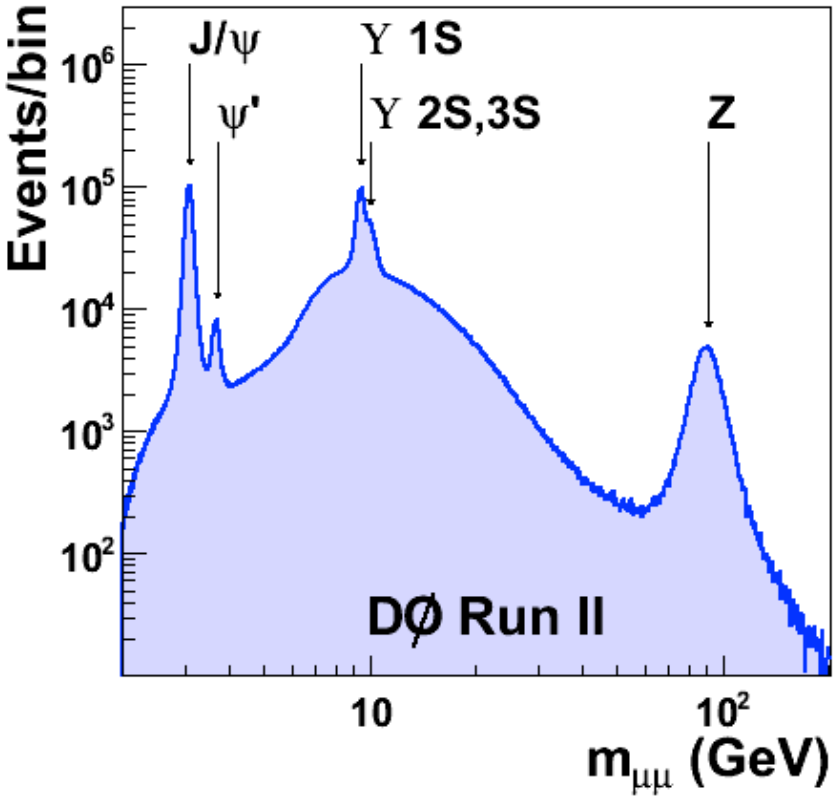
- proton-antiproton collider
  - quark-antiquark interactions
  - top pairs
  - forward-backward asymmetries
  - single top in the s-channel

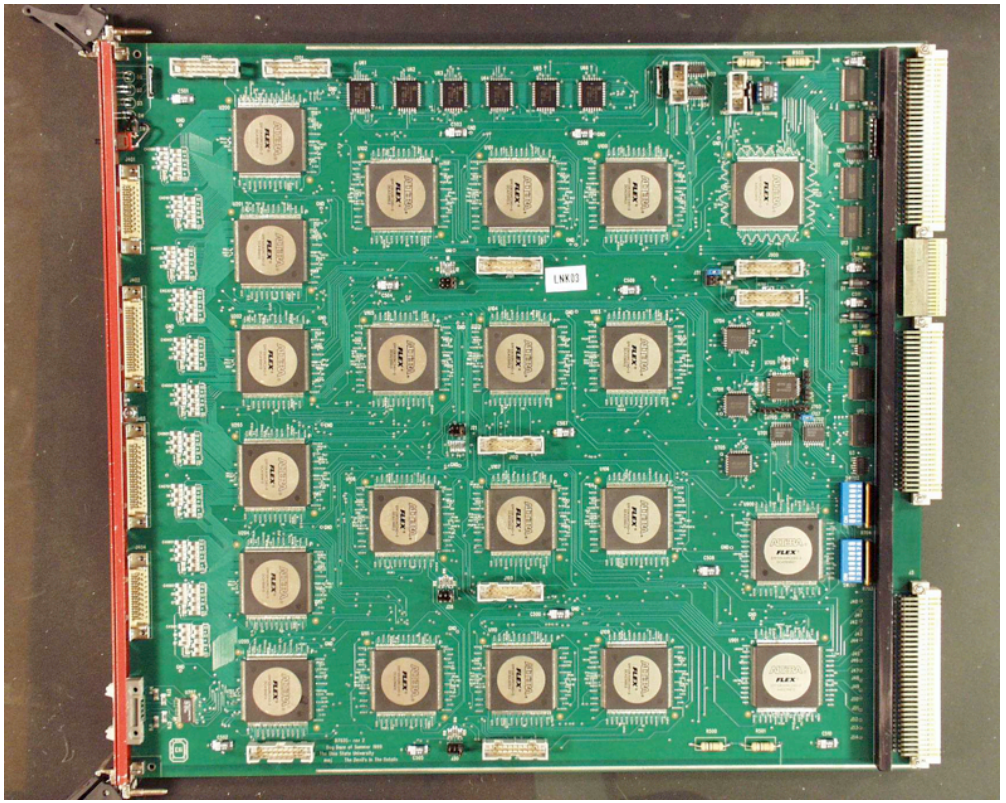
- lower CM energy
  - Higgs to bb in associated production
  - lower QCD background
  - coupling to fermions

- Much less pileup than LHC
  - clean events, low trigger thresholds
  - precision top quark mass
  - precision W boson mass

Heavy flavor physics

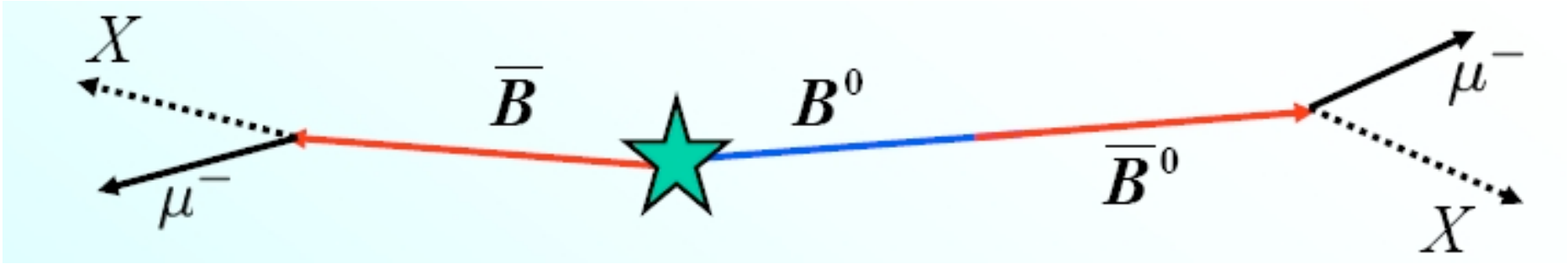
- Trigger and detector systems for heavy flavor
  - low-pT di-muons and regular reversal of B field (DØ)
  - track trigger and high-precision tracking (CDF)





CP Asymmetries

- Tevatron Proton-Antiproton initial state
  - CP conserving
- Look for neutral meson mixing
- Look for asymmetries in heavy flavor decay rates
- Sensitive to new physics
  - in weak and strong interactions



Like-sign di-muon asymmetry

- DØ di-muon asymmetry in semi-leptonic B decays
  - Significance 3.9 s.d.

PRD 84, 052007 (2011)

$$A_{\rm sl}^b = C_d a_{\rm sl}^d + C_s a_{\rm sl}^s$$

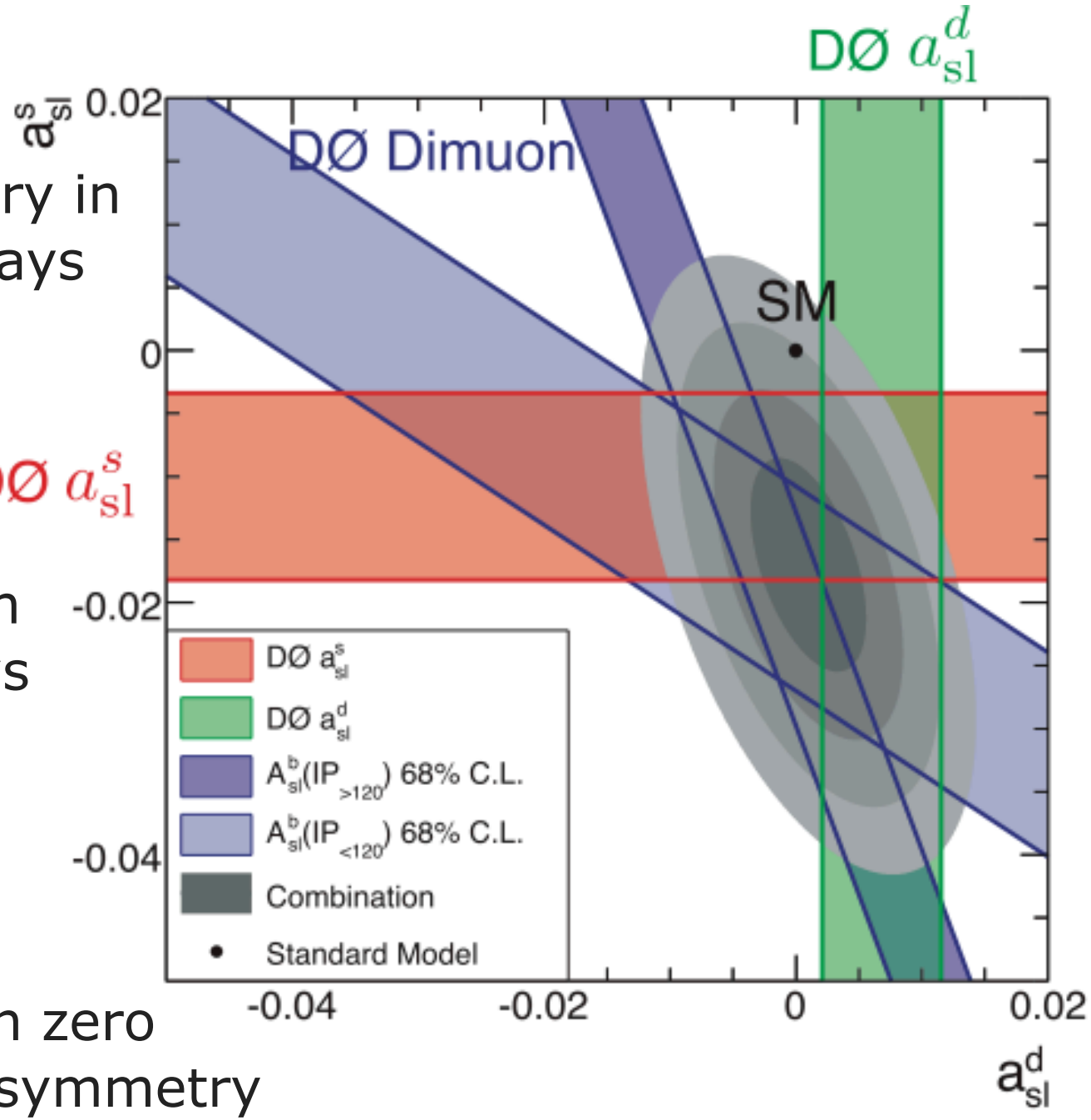
- Measure asymmetry in semi-leptonic decays
- a^s_{sl} in $B_s^0 \rightarrow \mu D_s X$

PRL 110, 011801 (2013)

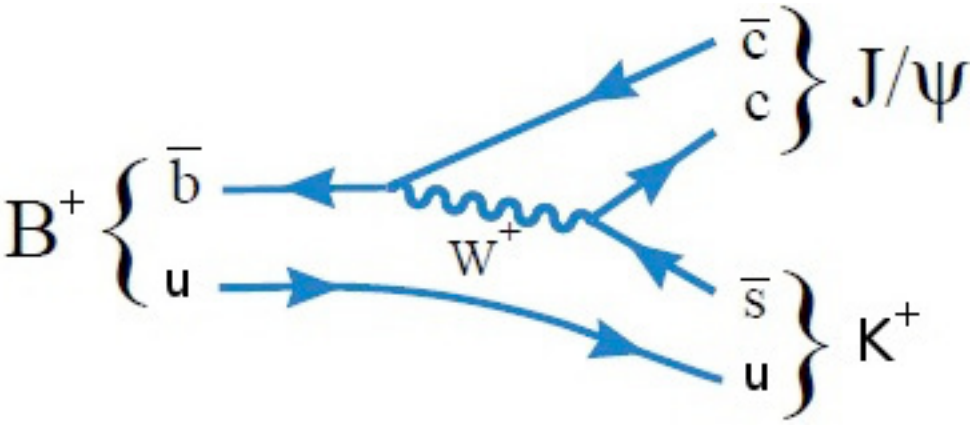
- a^d_{sl} in $B_d^0 \rightarrow \mu\, D^{(*)}X$

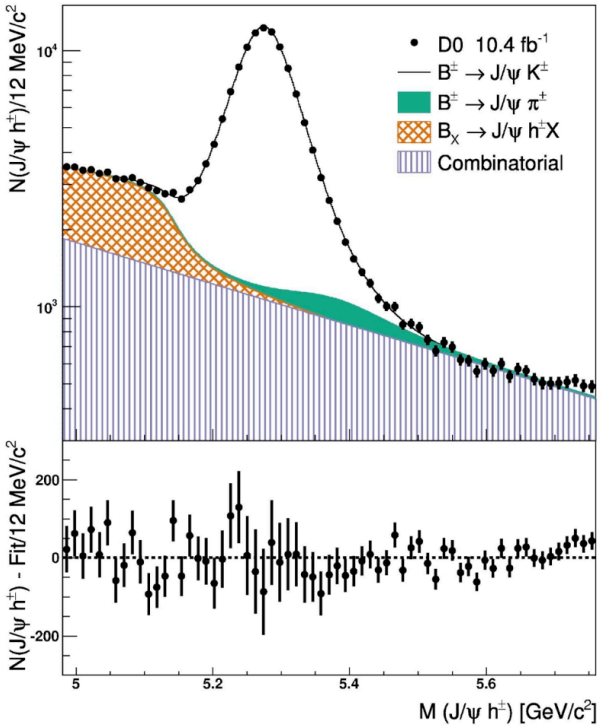
PRD 86, 072009 (2012)

- Results consistent with zero and with di-muon asymmetry



CP Asymmetry for $B^{\pm}$



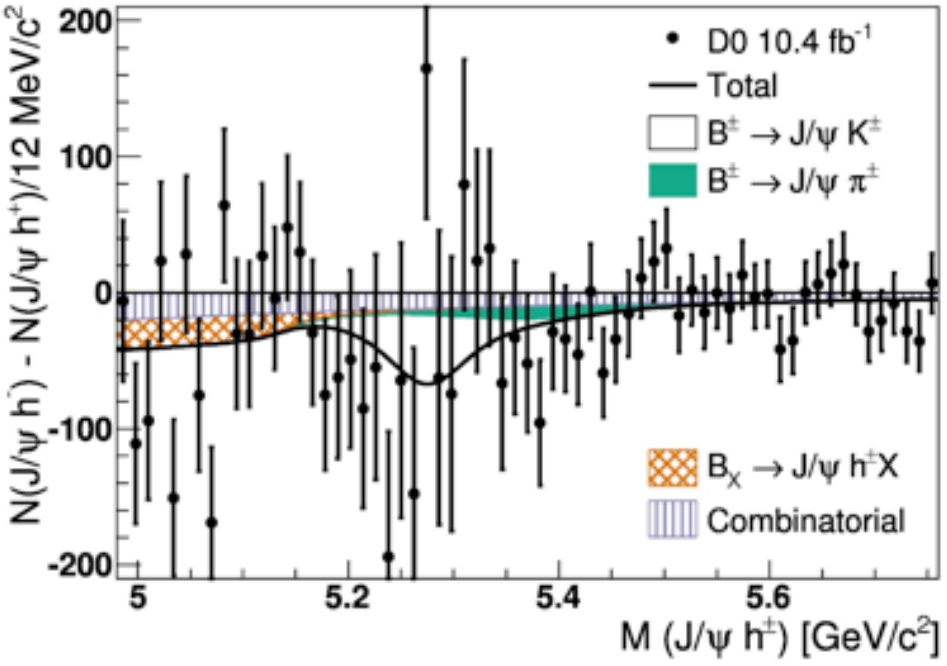


- Asymmetry A: Difference in decay rate for B^+ and B^-
  - CP violation in weak decay
- Small (<0.3%) in SM
- Result:

$$A^{J/\psi K} = [0.59 \pm 0.36\,(\text{stat}) \pm 0.07\,(\text{syst})]\,\%,$$

$$A^{J/\psi \pi} = [-4.2 \pm 4.4\,(\text{stat}) \pm 0.9\,(\text{syst})]\,\%.$$

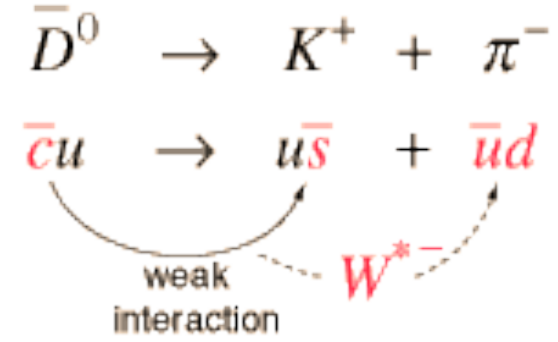
  - Consistent with zero
- Most precise measurement

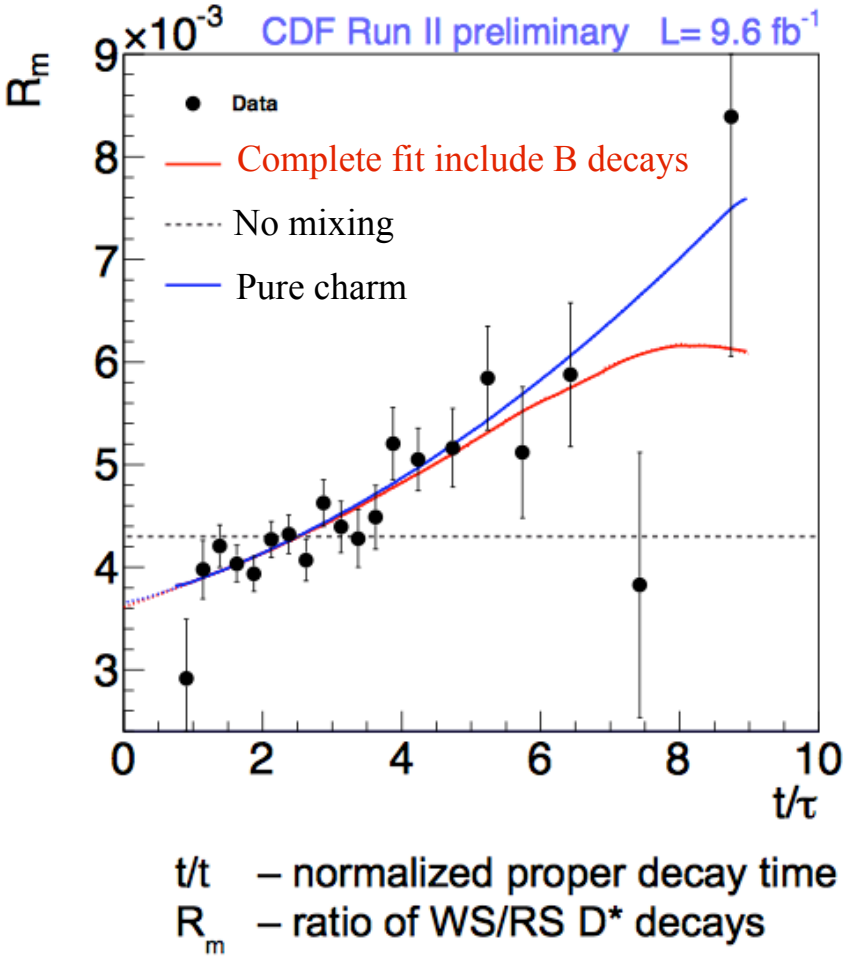


PRL 110, 241801 (2013)

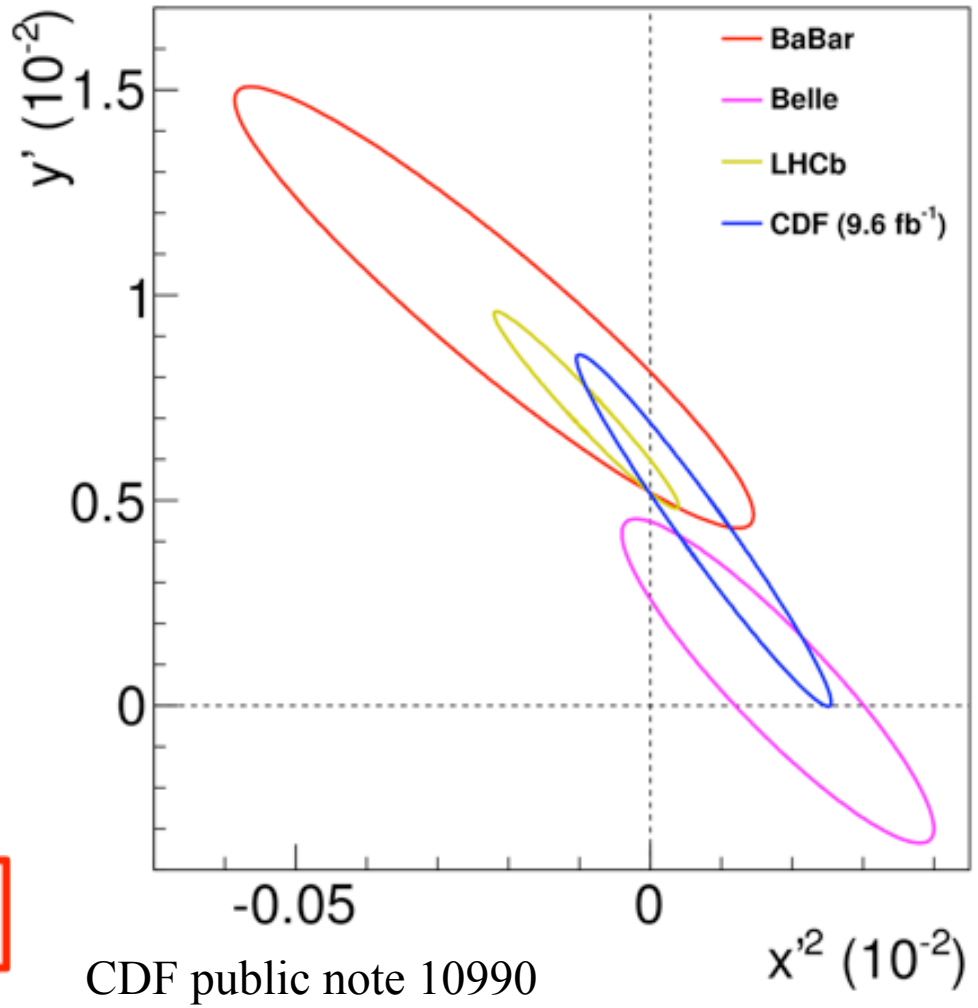
neutral D meson mixing

$$D^* \to D^0\pi^+ \begin{cases} \nearrow (K^-\pi^+)\pi^+ & \text{Right-sign} \\ \searrow (K^+\pi^-)\pi^+ & \text{Wrong-sign} \end{cases}$$





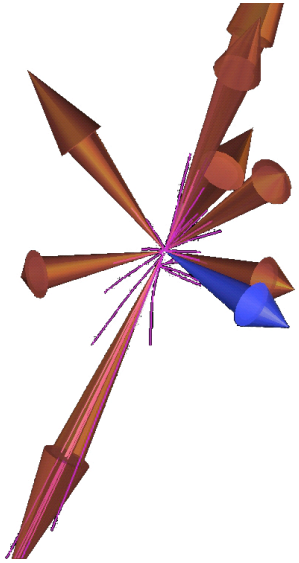
t/t – normalized proper decay time
R_m – ratio of WS/RS D* decays



CDF public note 10990

Observe $D^0 - \bar{D}^0$ mixing at 6.1 s.d.

QCD physics

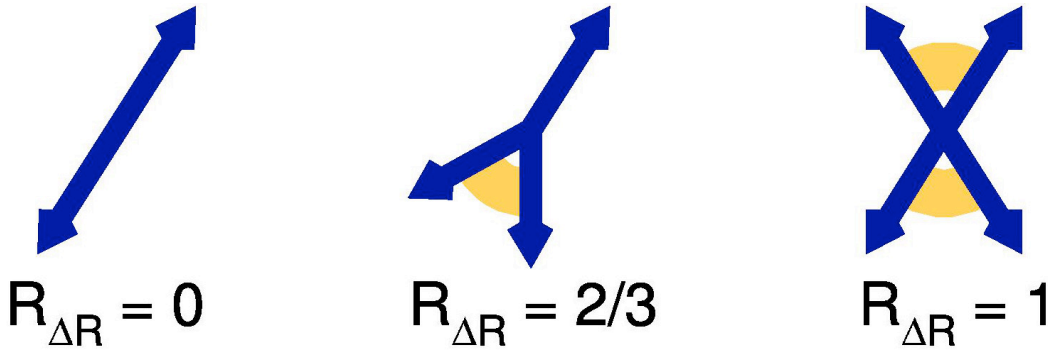


- Strong interaction studies ↔ Parton distribution functions (PDF)

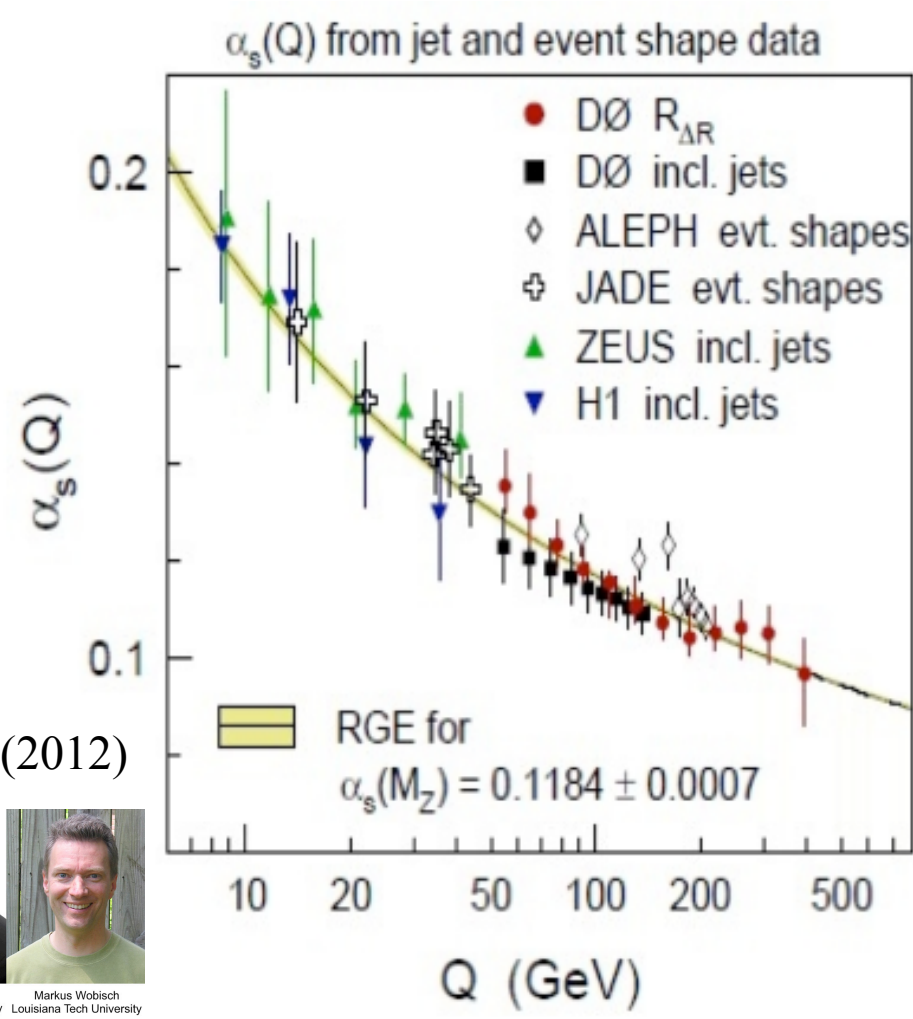
- Background to most Higgs, top, new physics analyses

QCD jet observables

$$R_{\Delta R}(p_T, p_{T\,\min}^{number}) = \frac{\#\text{ of neighboring jets}}{\#\text{ of inclusive jets}}$$



- Study strong interaction in jet formation
- Minimal dependence on PDFs
  - Extend energy reach beyond Lep



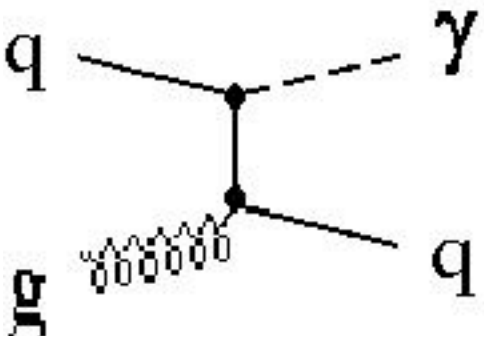
PLB 718, 56 (2012)

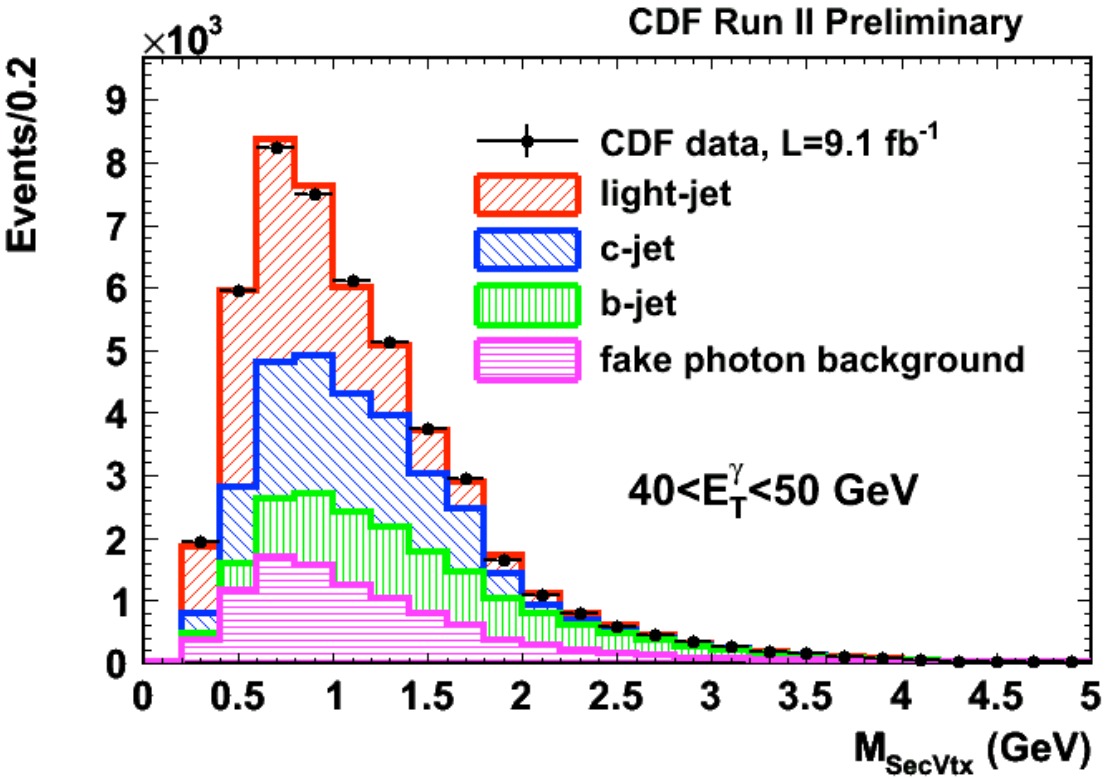
Using $R_{\Delta R}$ and NLO+MSTW2008NNLO PDFs

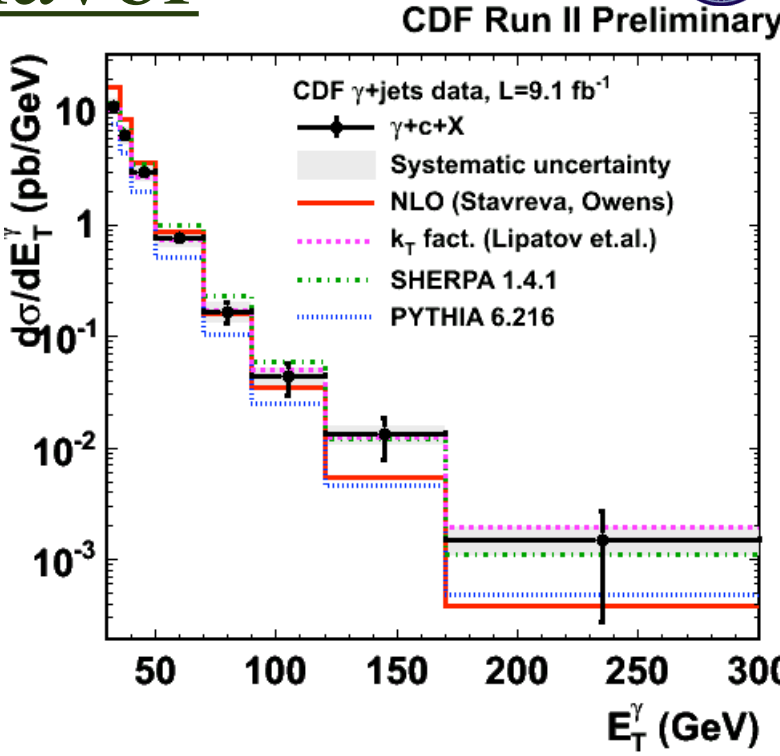
$$\alpha_s(M_z) = 0.1191\ ^{+0.0048}_{-0.0071}$$

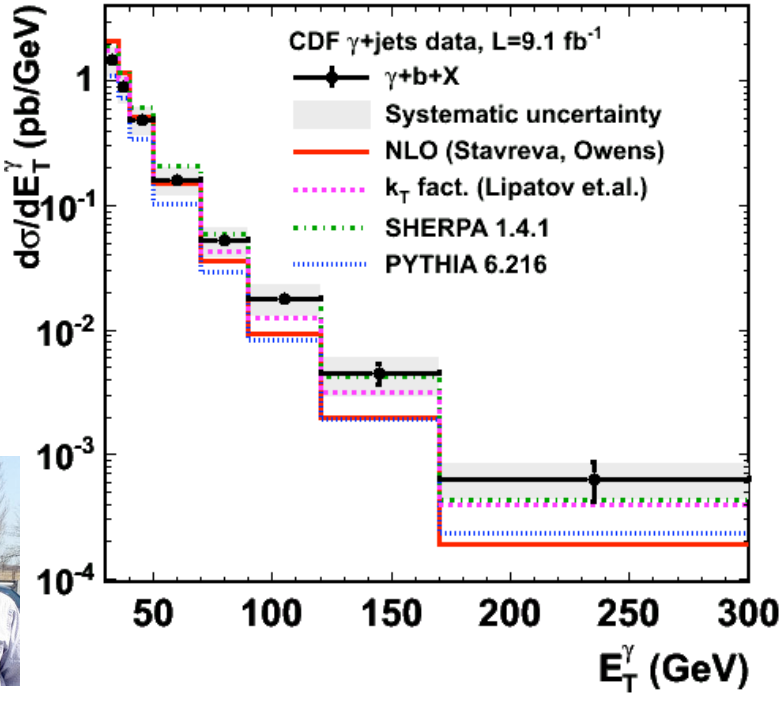
Scott Atkins, Louisiana Tech University
Lee Sawyer, Louisiana Tech University
Markus Wobisch, Louisiana Tech University

Photon + heavy flavor







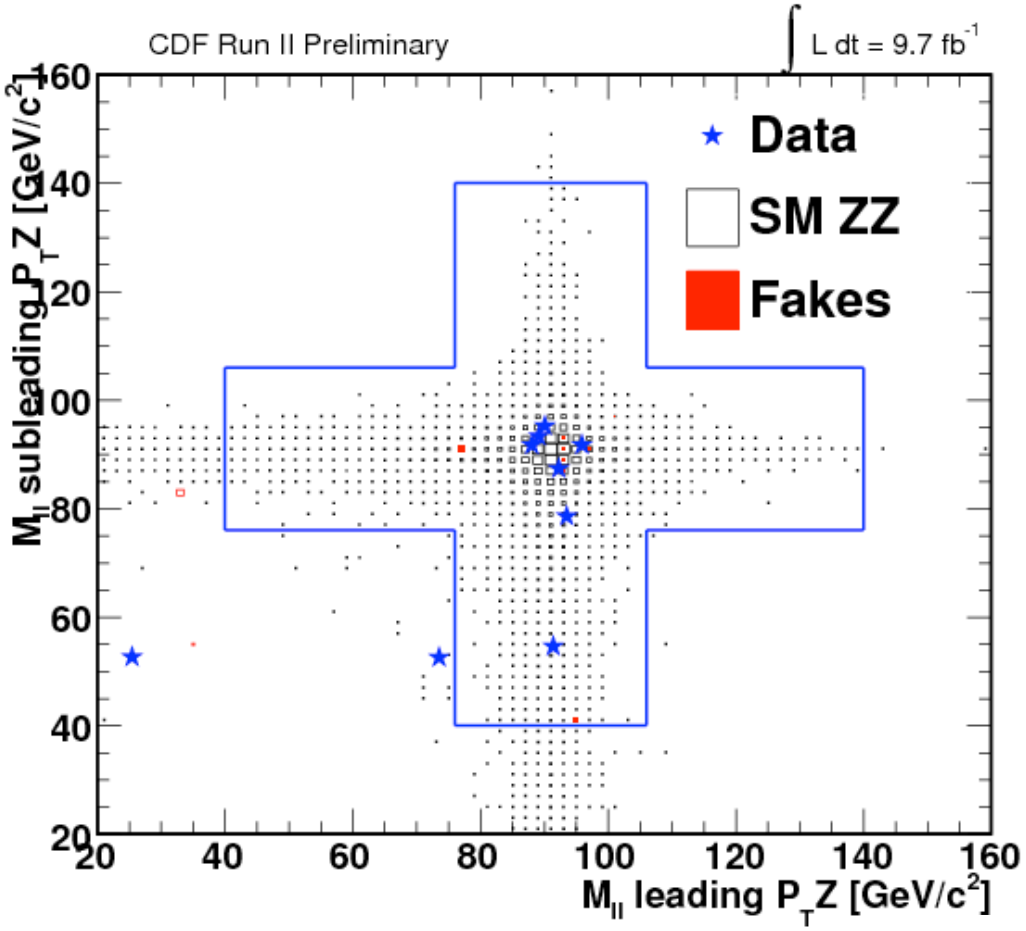


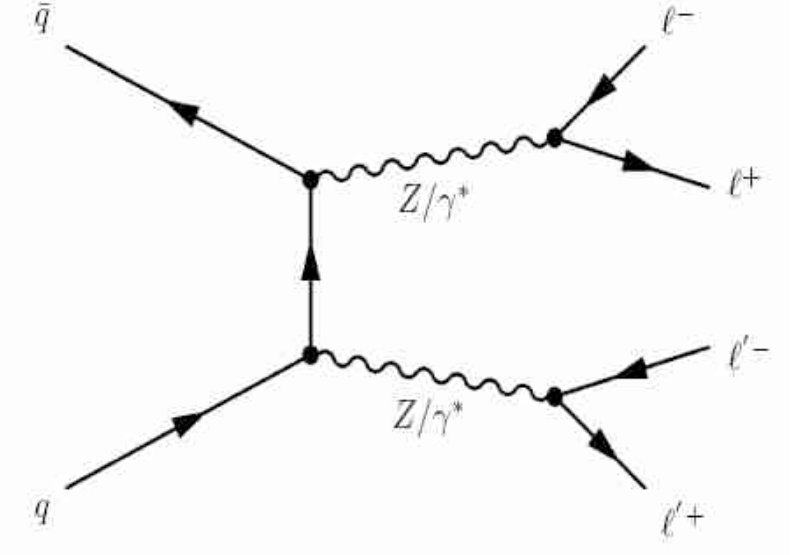
CDF note 10818

- Sensitive to b-quark and charm quark PDF

Electroweak results

ZZ cross section

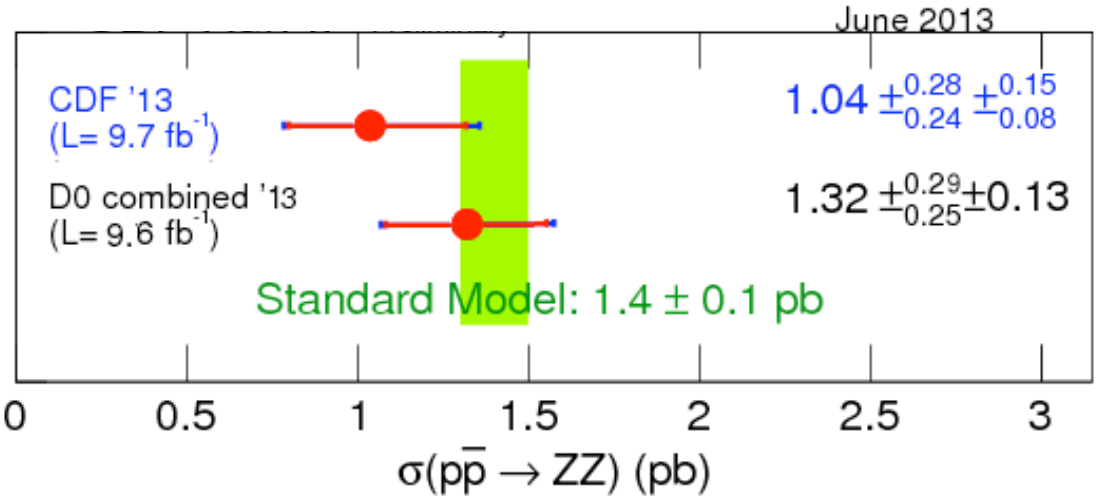




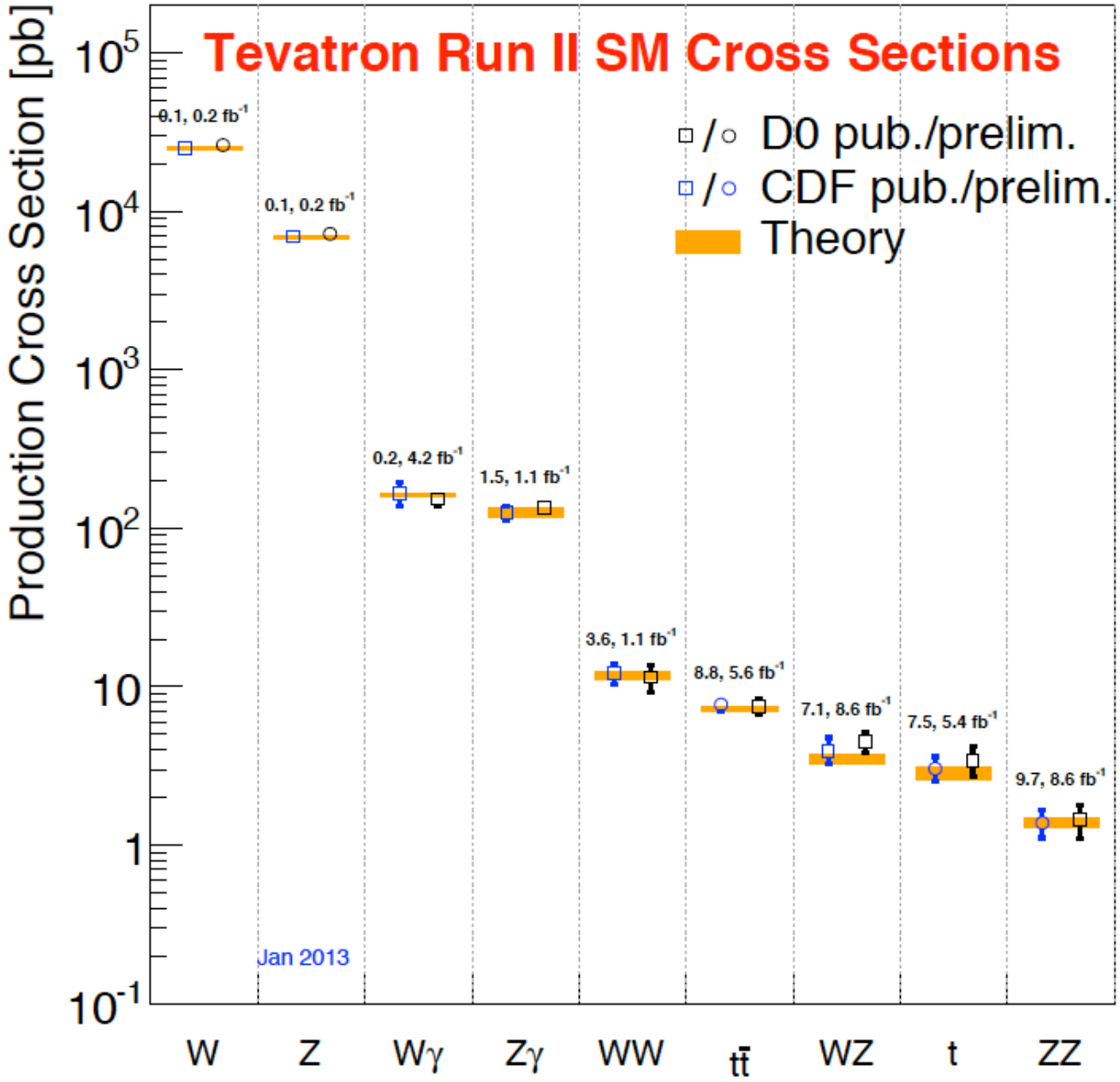
- llll and llνν final states
- Background to Higgs and new physics searches

CDF public note 10957

accepted by PRD, arXiv:1304.5422

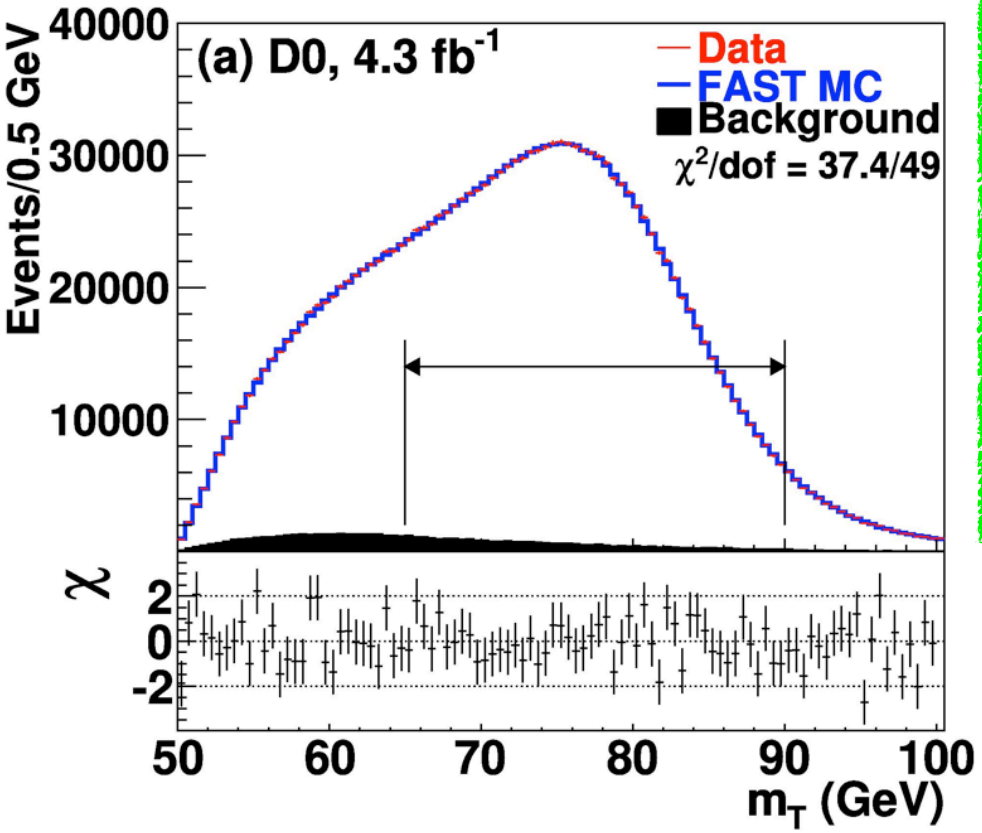


Electroweak measurements

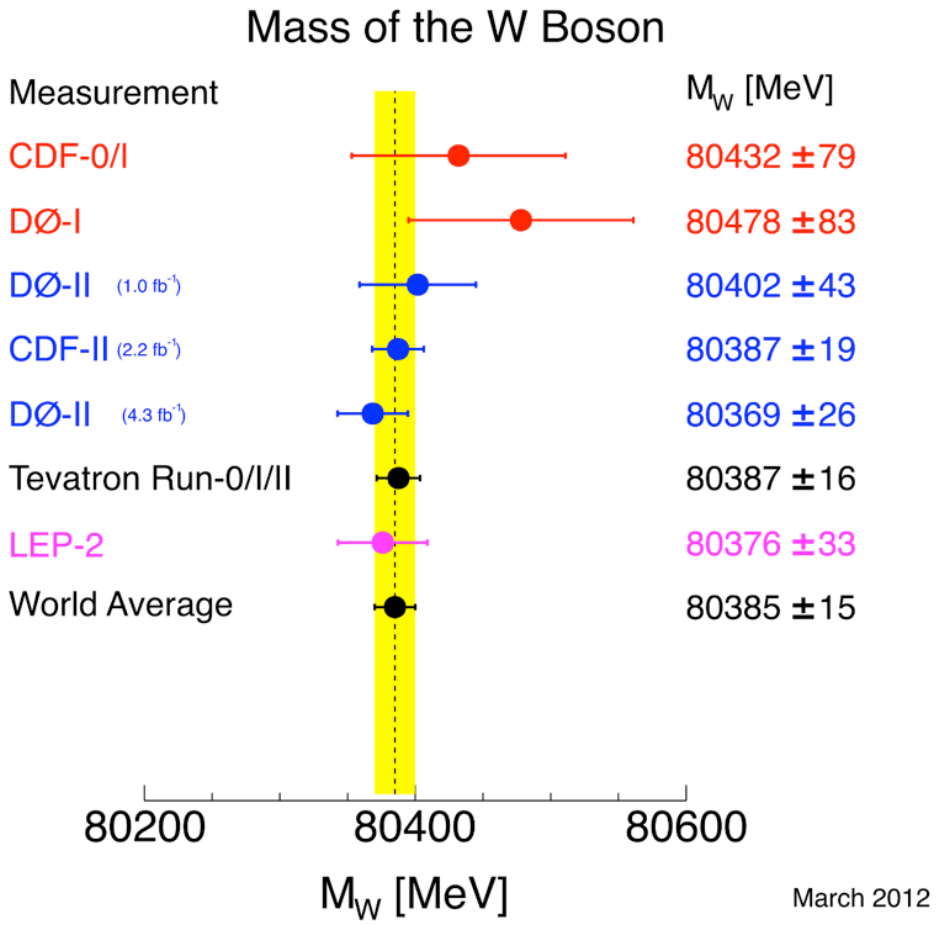


- All single and di-boson processes measured
- Also look for anomalous boson couplings in di-bosons

W boson mass

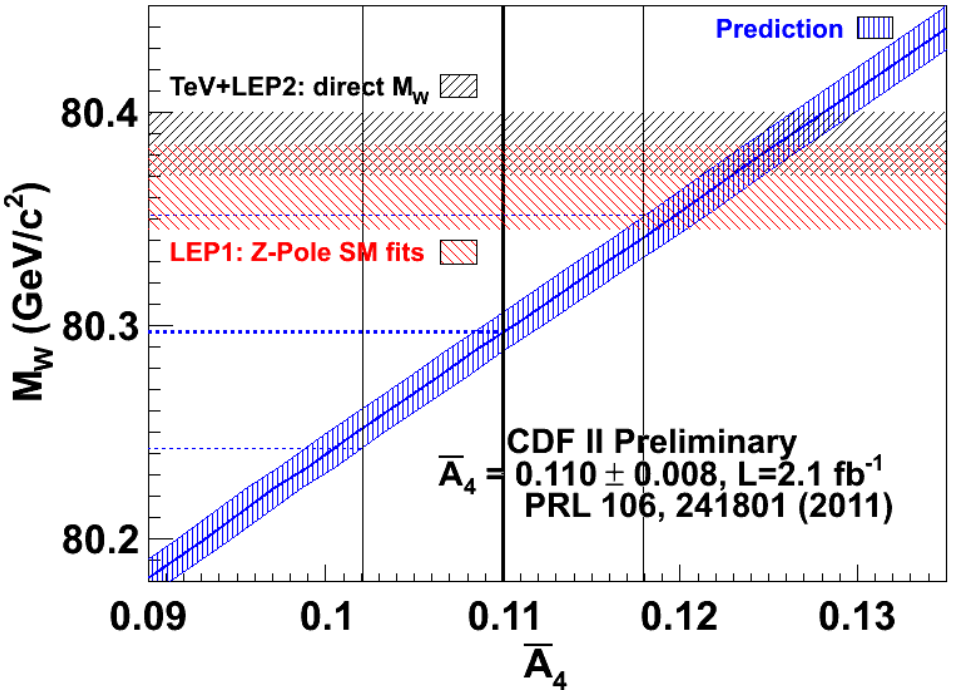


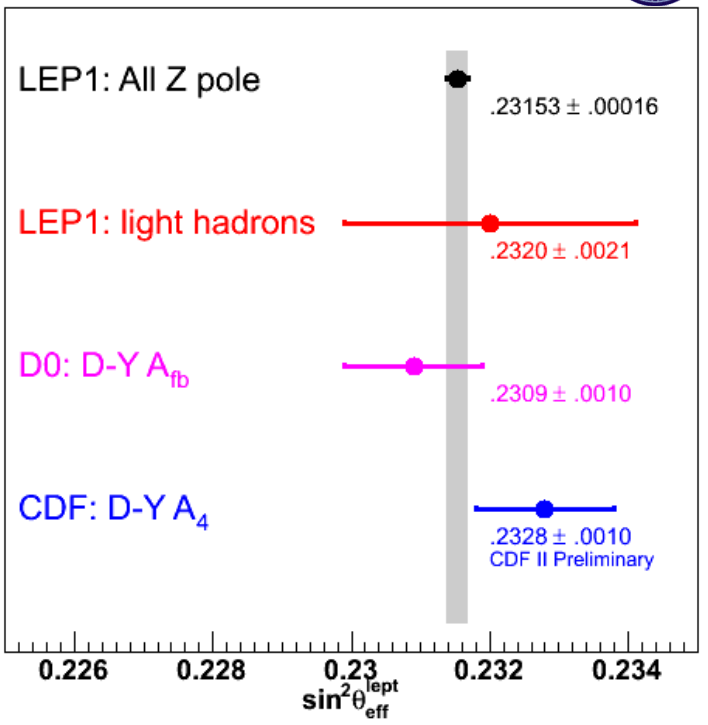
CDF Uncertainties	
Lepton energy scale and resolution	7
Recoil energy scale and resolution	6
Lepton removal	2
Backgrounds	3
$p_T(W)$ model	5
Parton distributions	10
QED radiation	4
W-boson statistics	12

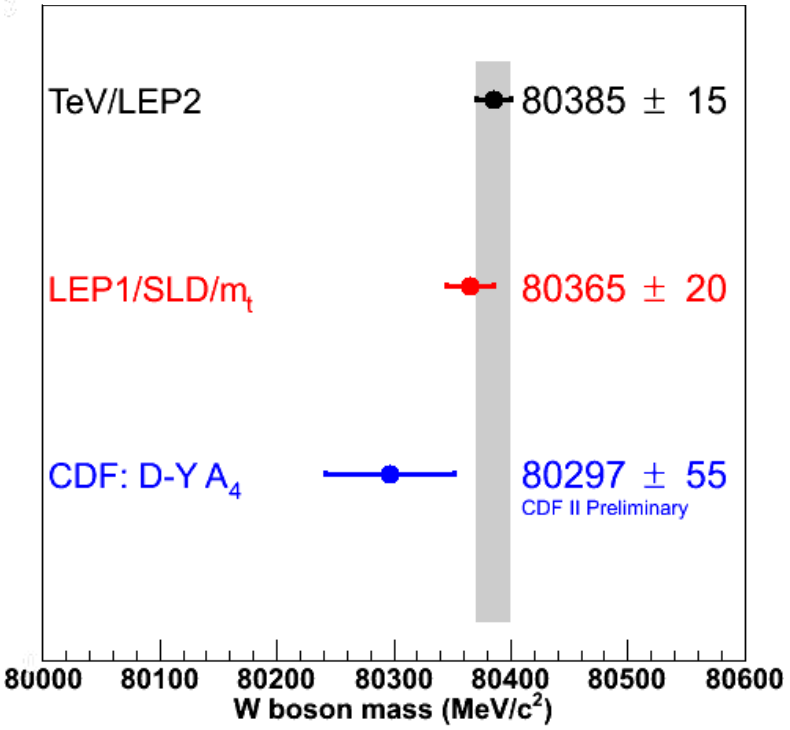


- Well understood detectors
- Well understood theory errors
- Clean event environment
- Expect final Tevatron measurement with <10 MeV uncertainty

$\sin\theta_W$ from Z→ee



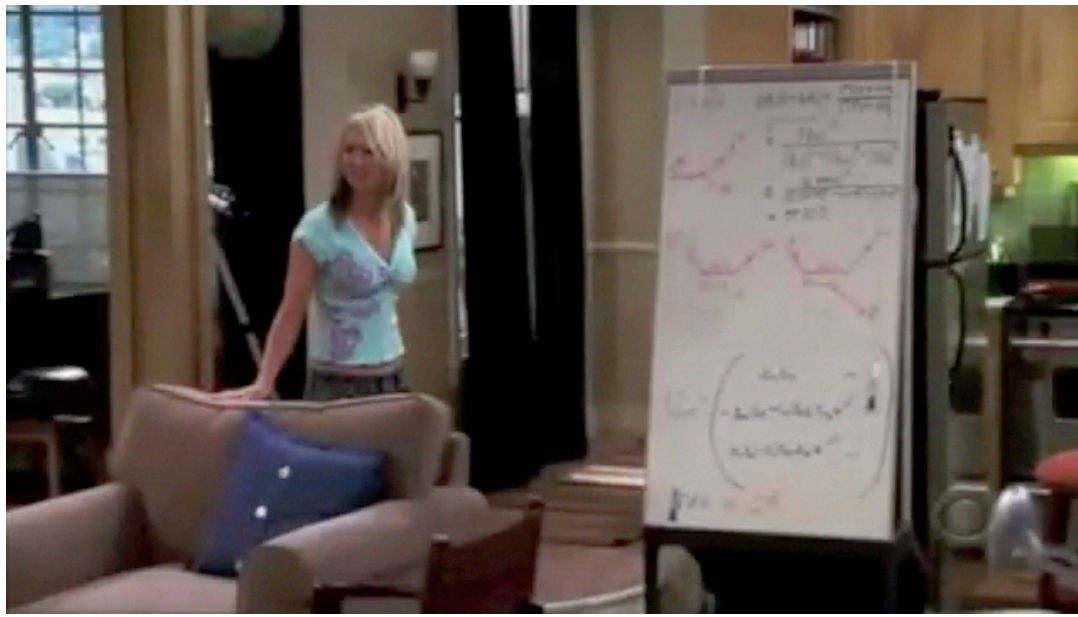




- Measured A_4 (V-A interference) from cosθ term of the angular distribution of e+e− pairs with M_{ee} in [66,116] GeV/c^2
- Derived $\sin\theta_{eff}^{lep}$ and M_W from A_4 and ResBos prediction

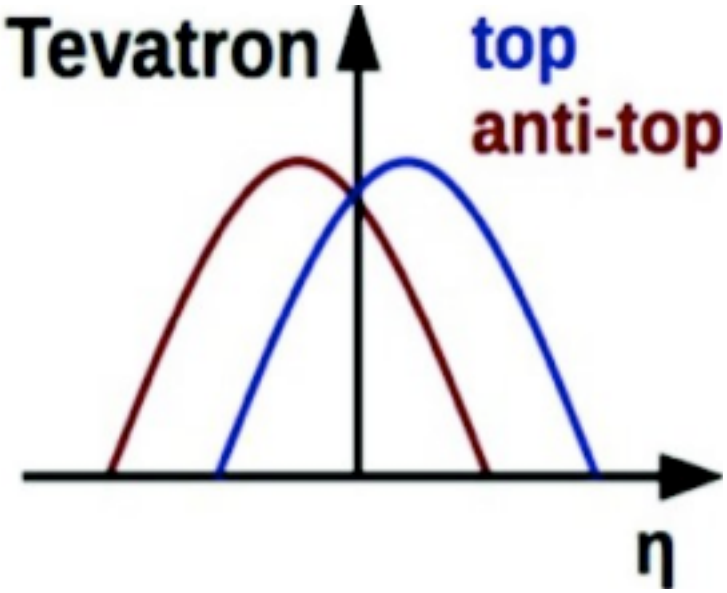
PRL 106, 241801 (2011)
arXiv:1307.0770, PRD
CDF public note 10952

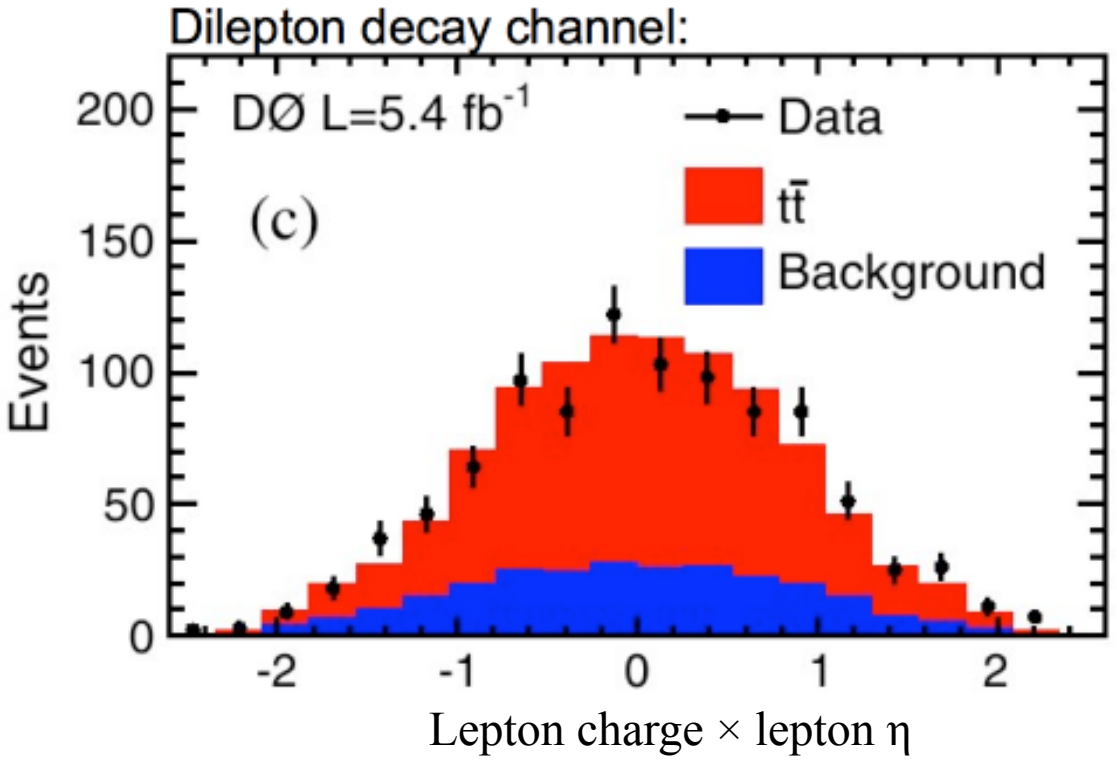
Top quark



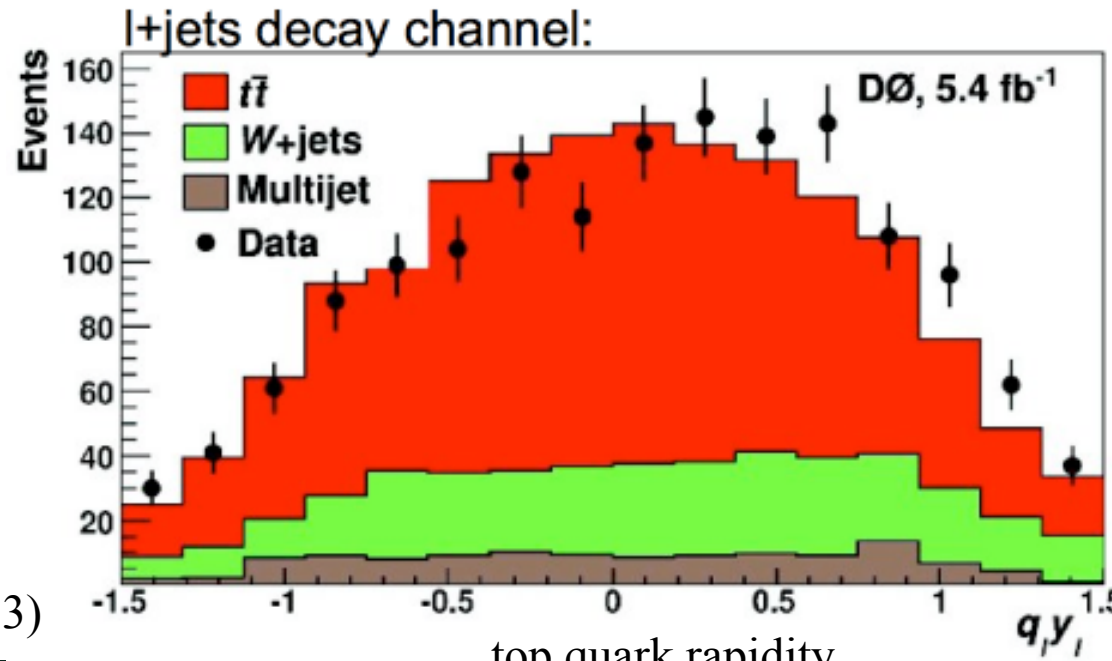
Top forward-backward asymmetry

antiproton direction | proton direction



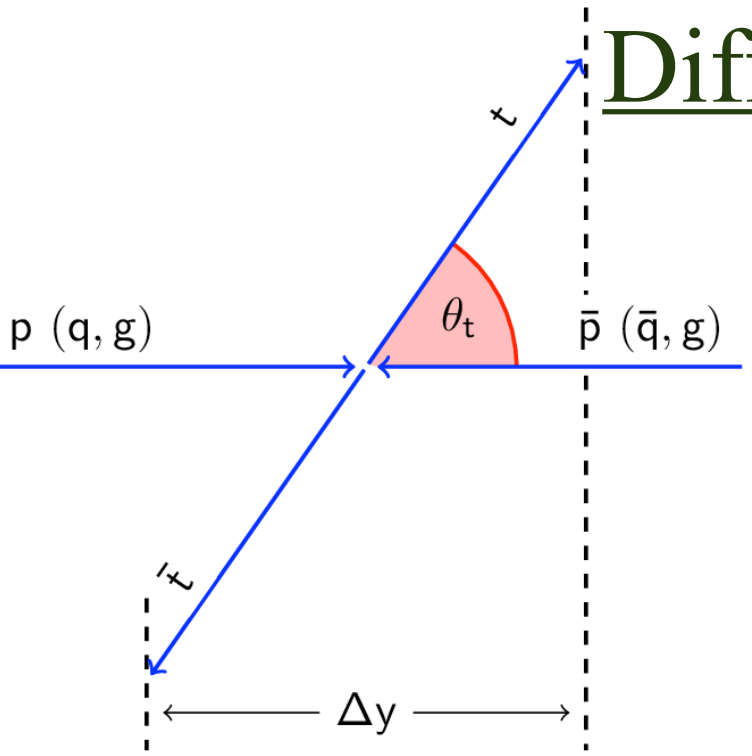


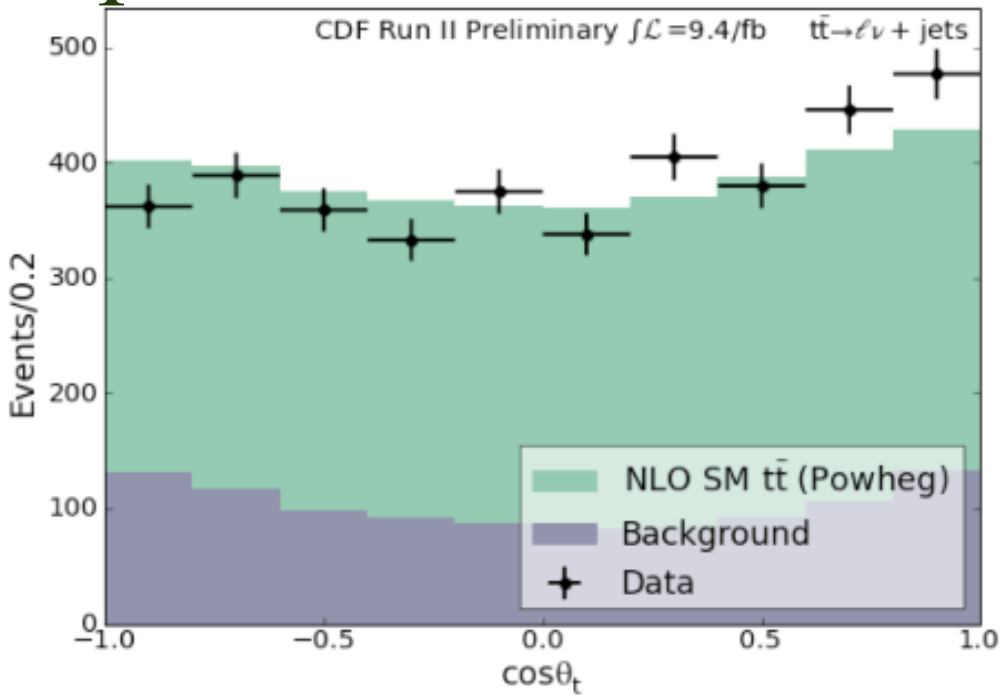
- SM prediction at NLO (QCD+EWK):
  A_{fb} = (6.6 ± 2.0)%
- Combined DØ result:
  A_{fb}^{l} = (11.8 ± 3.2)%
  → 2.2 s.d. above SM



PRD 87, 011103 (2013)

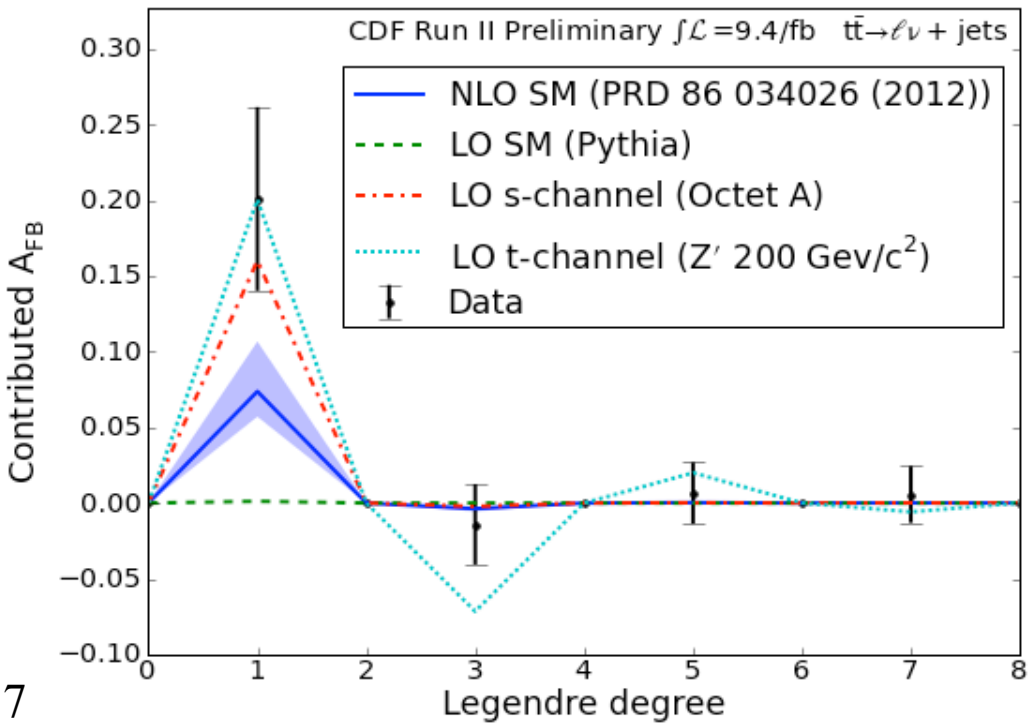
Differential top cross section





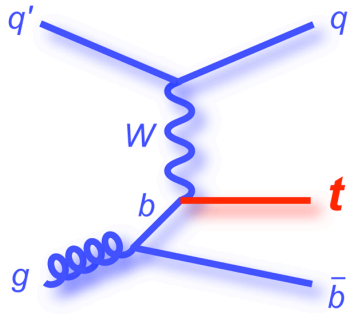
- CDF: A_{fb}^{lep} = (9.4 ± 4.3)%
- SM@NLO: A_{fb}^{lep} = 3.6%

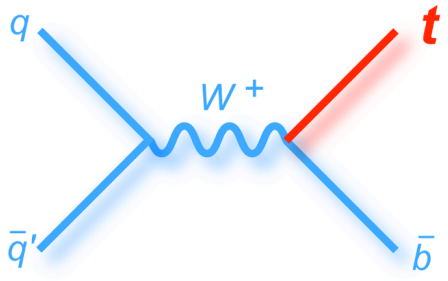
- Legendre moment to characterize shape
- Supports s-channel type model
  - Favors s-channel axi-gluon
  - Disfavors t-channel Z'

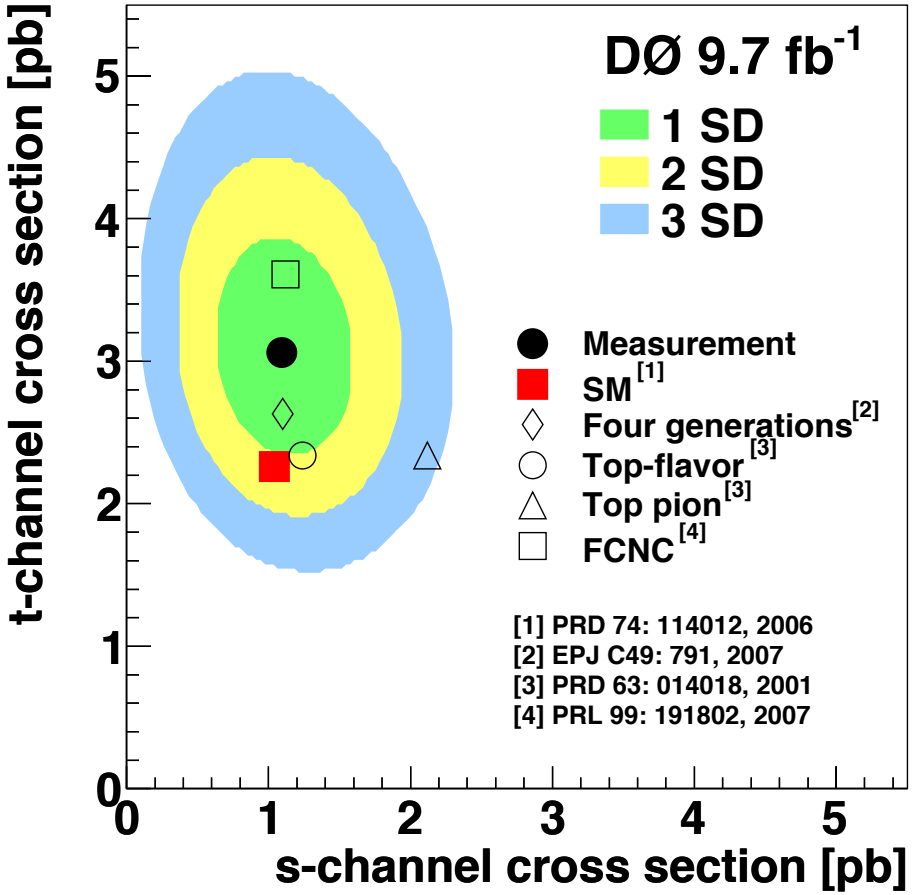


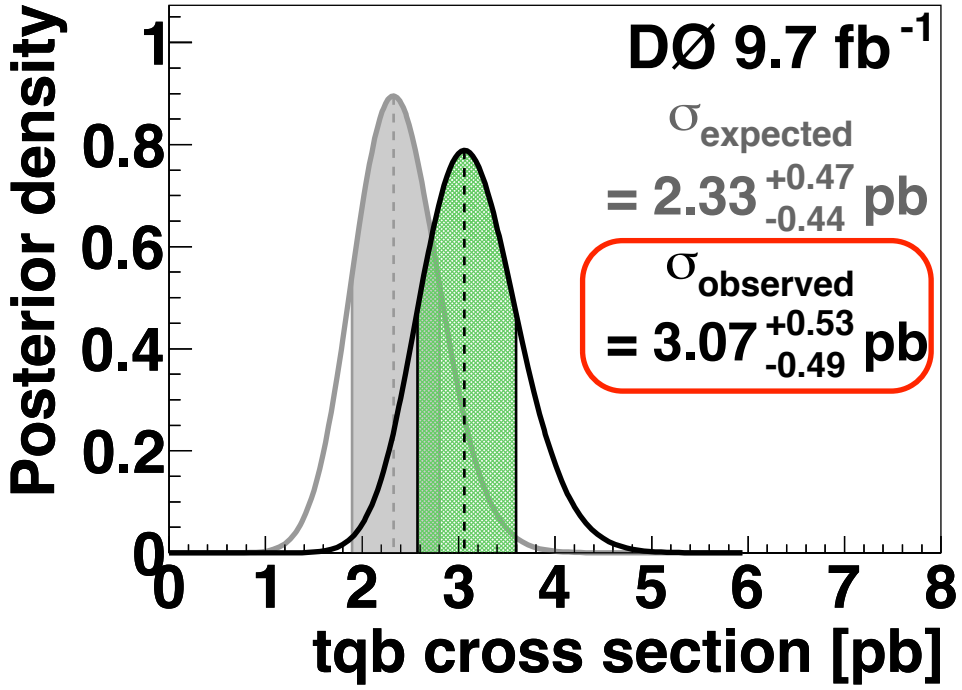
CDF public notes 10974, 10975,
submitted to PRL, arXiv:1306.2357

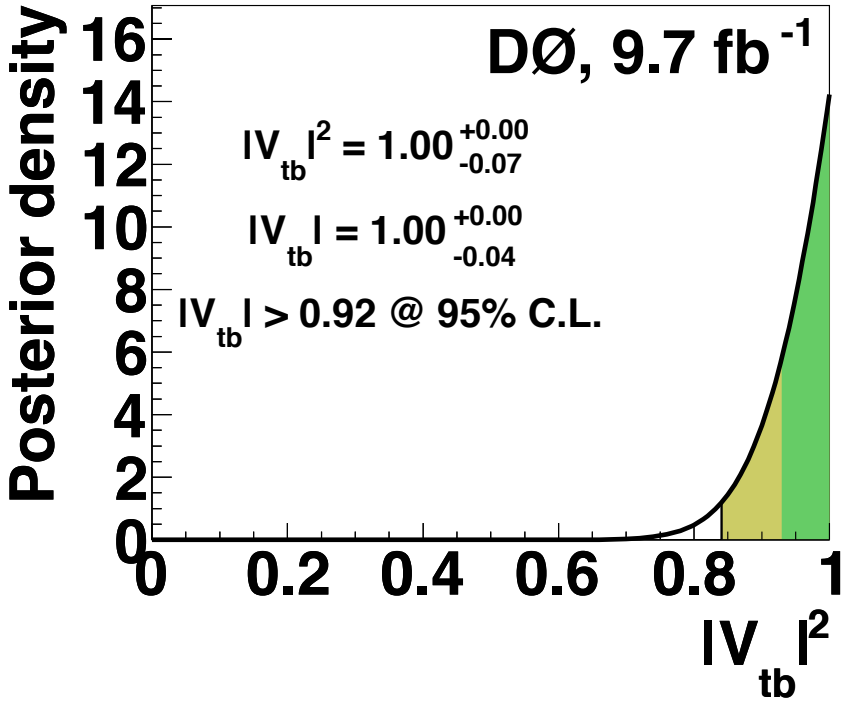
Single top quark production





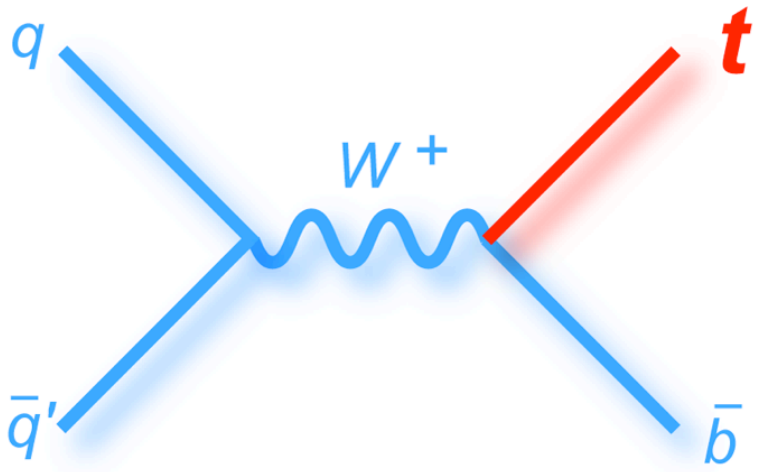


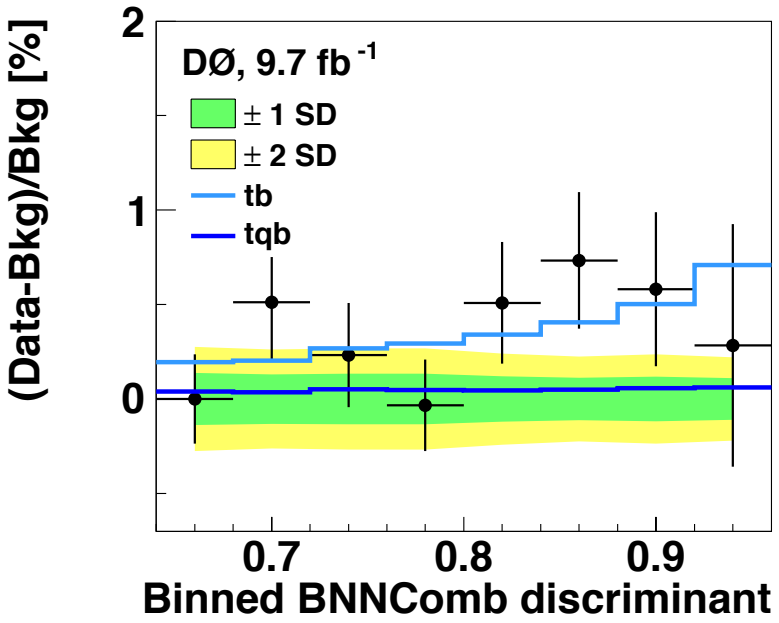


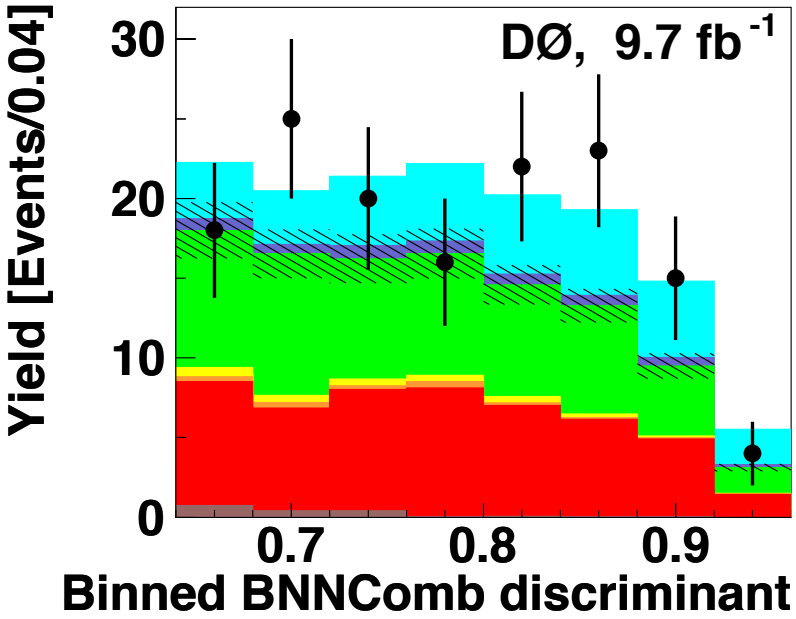


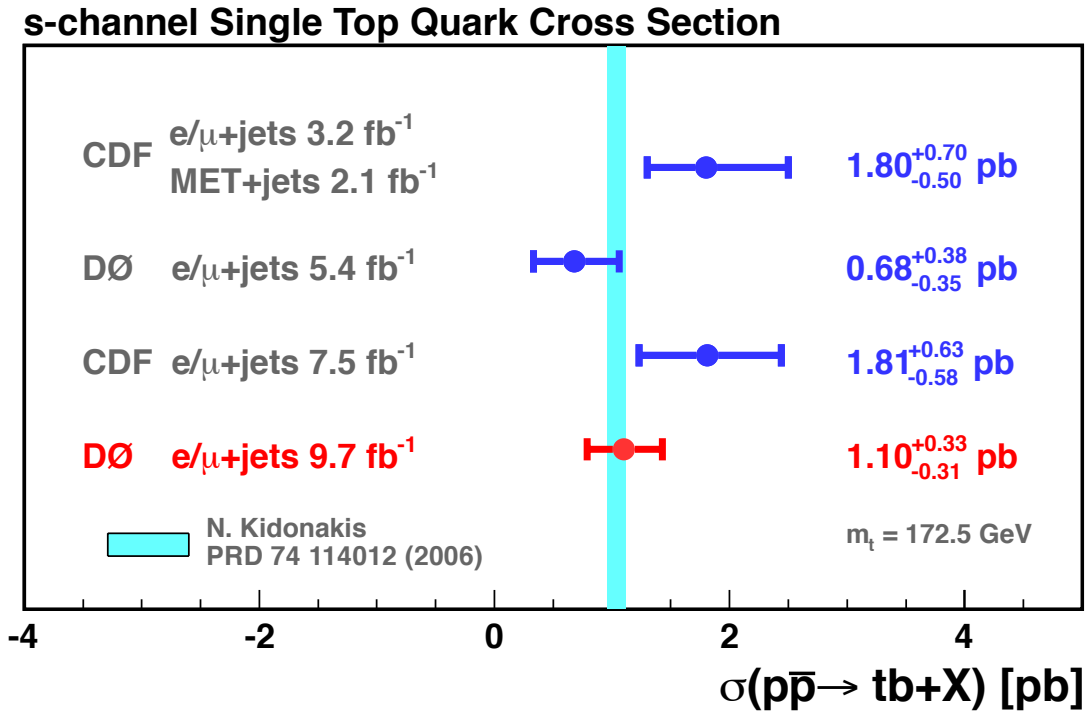
- CDF result and Tevatron combination this summer
- World's best |Vtb| measurement

s-channel signal



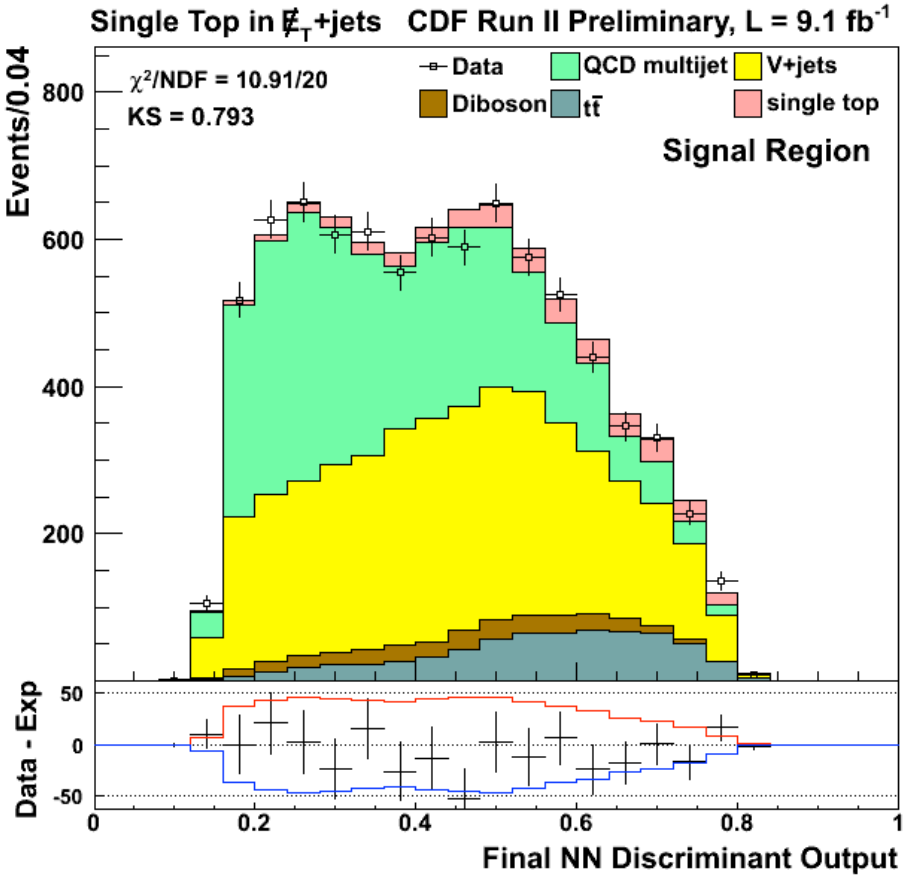




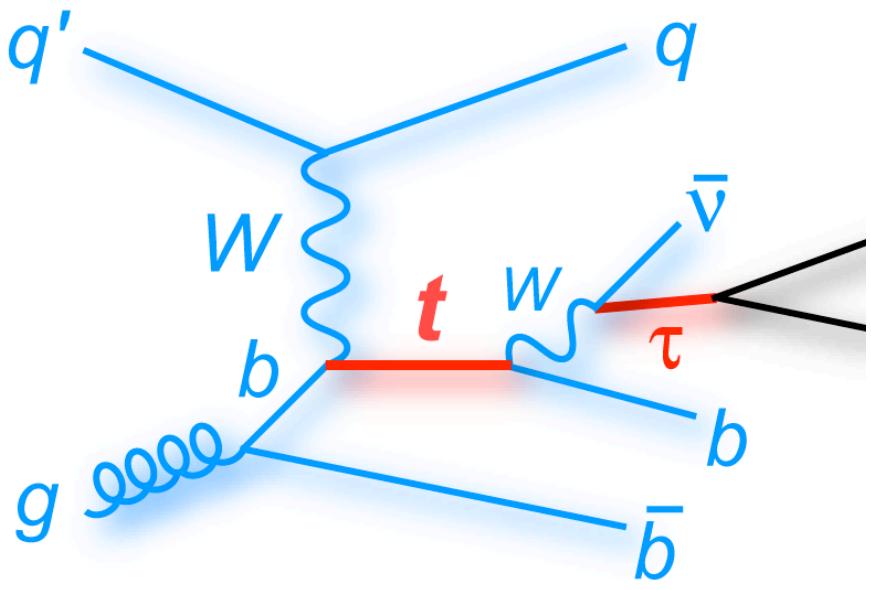


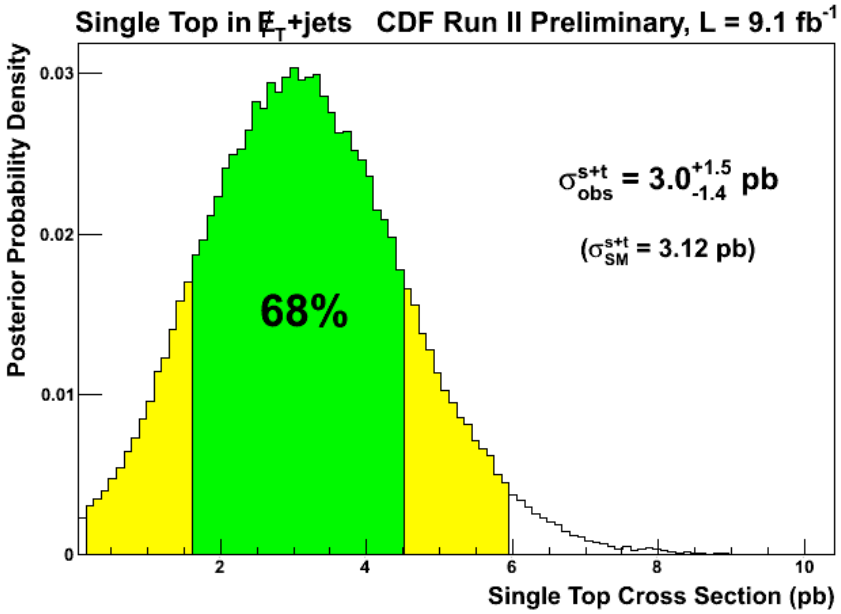
- 3.7 s.d. significance
- very difficult at LHC

Single top without leptons

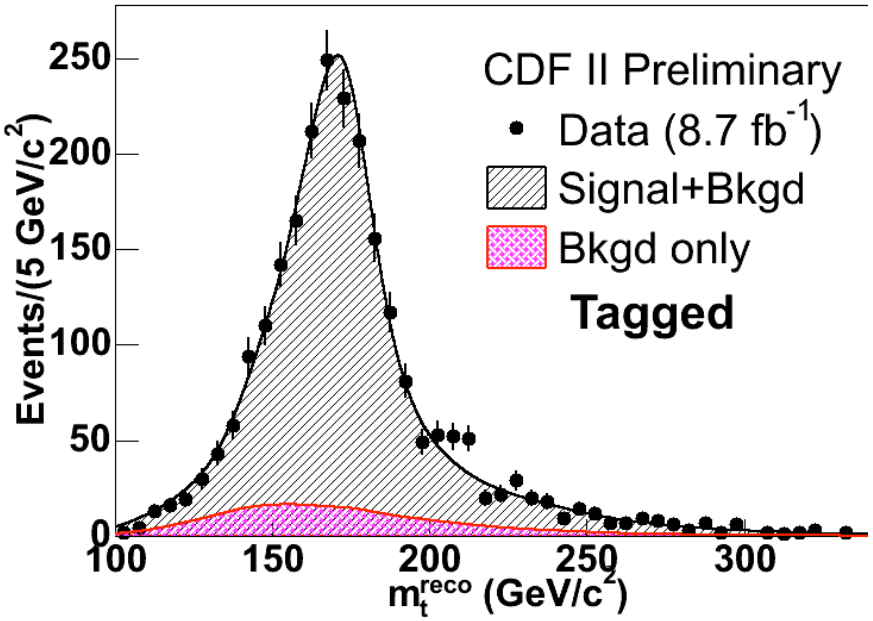


CDF public note 10979

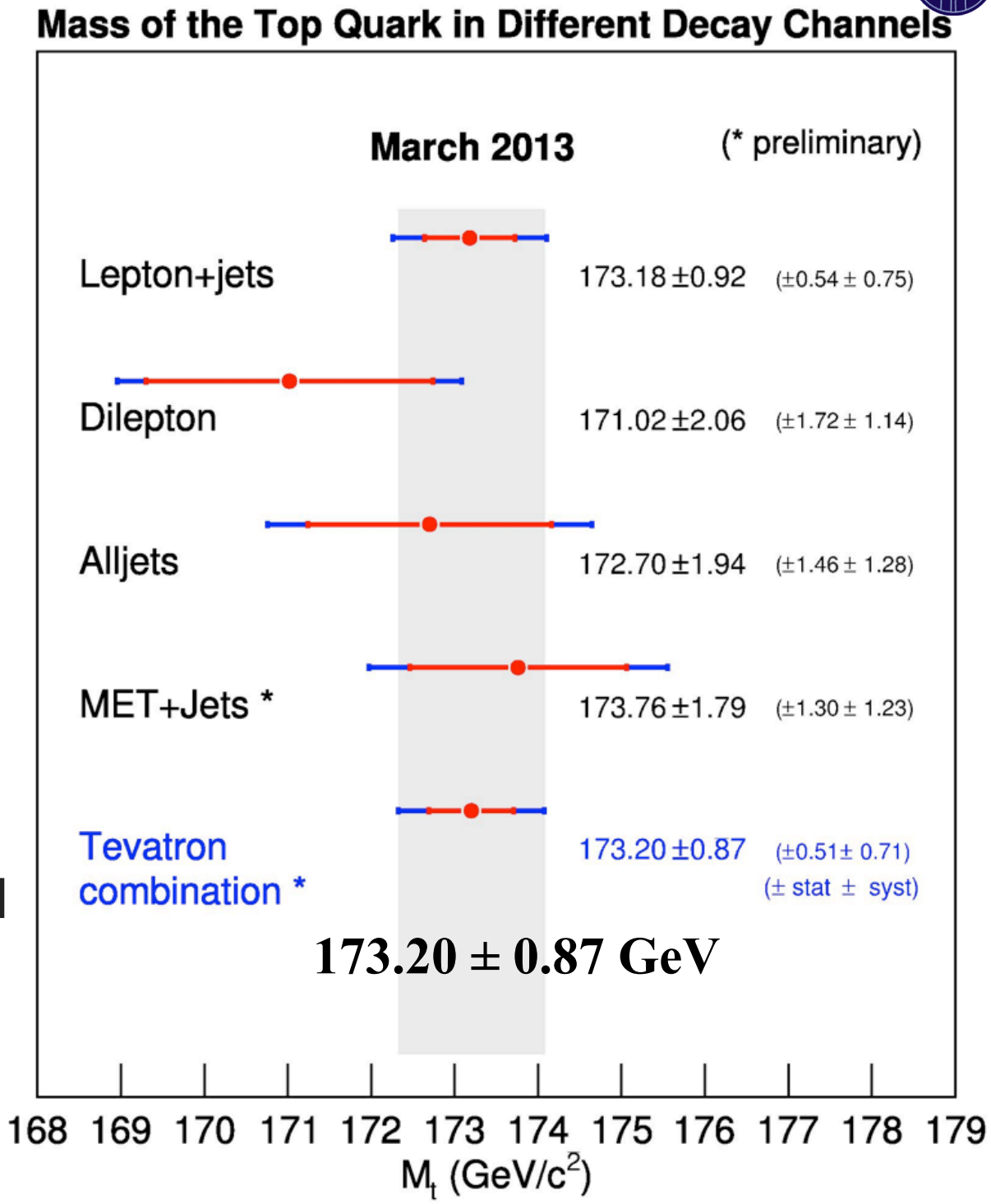




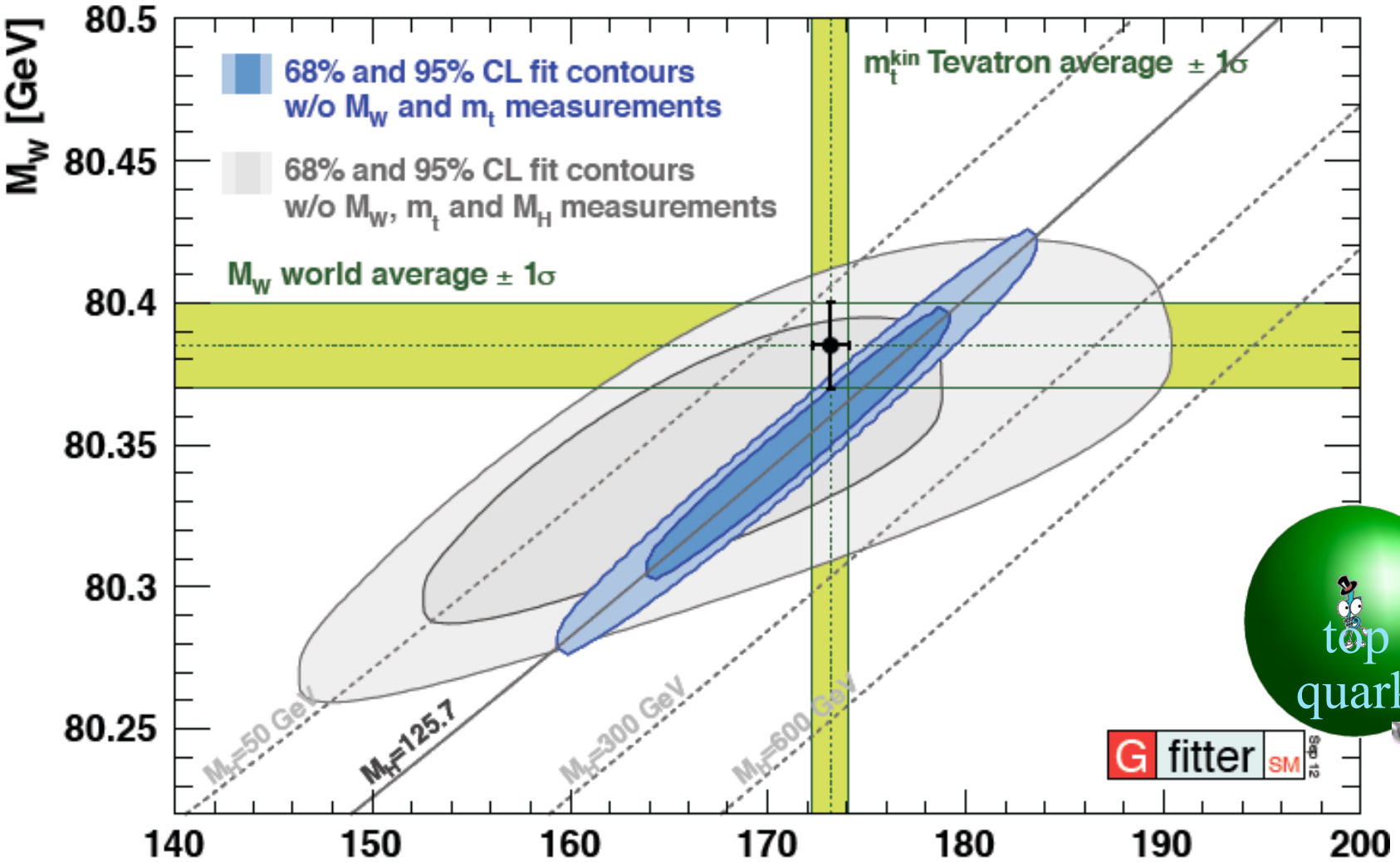
- Same technique as Zh→ννbb
- Select τ decays
  - And events lepton analysis missed

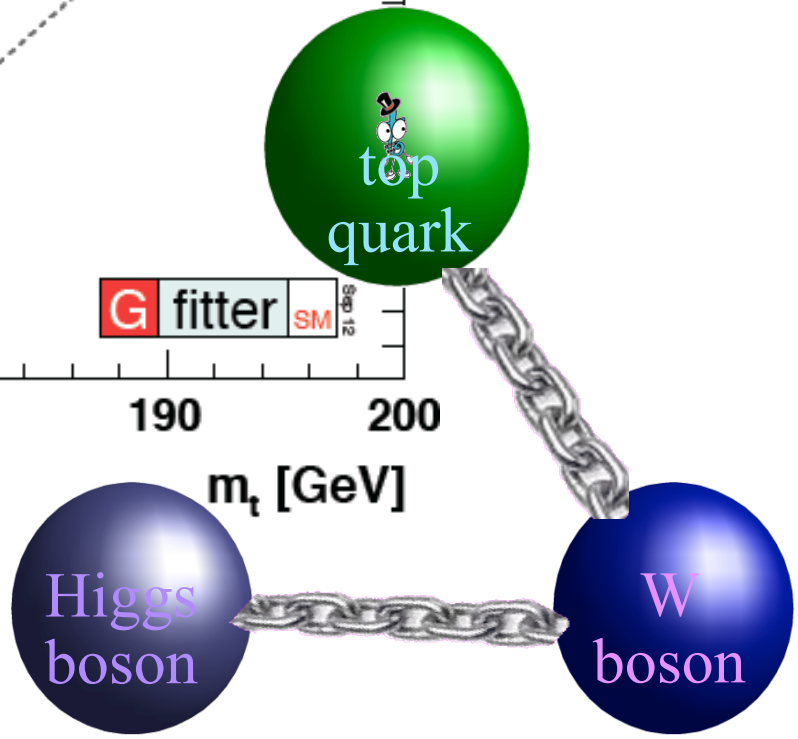


- Top mass reconstructed from top pair decay products
- lepton+jets, di-lepton and all-jet final states
- Dominant uncertainties
  - Signal modeling
  - Jet energy scale

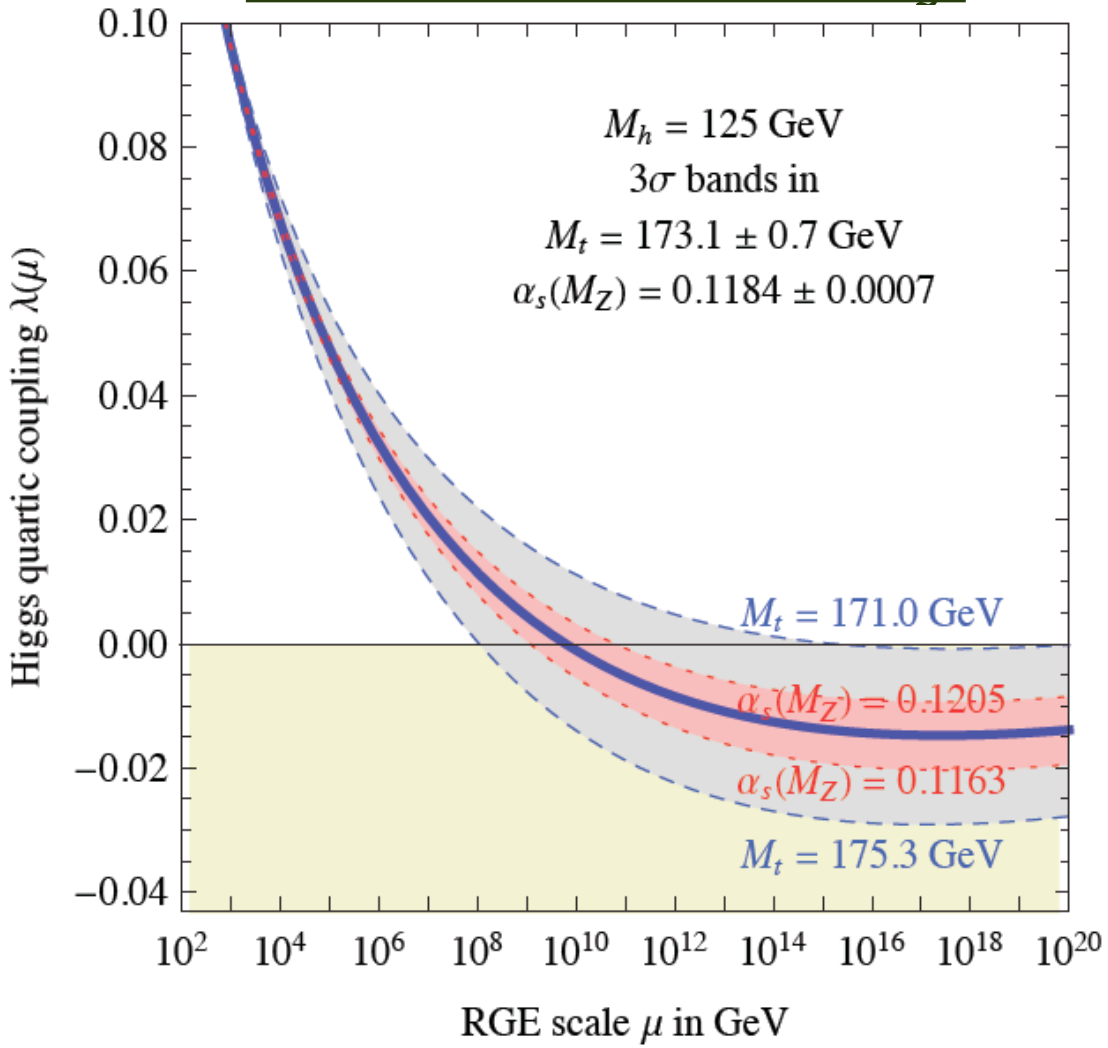


Top and W and Higgs boson masses

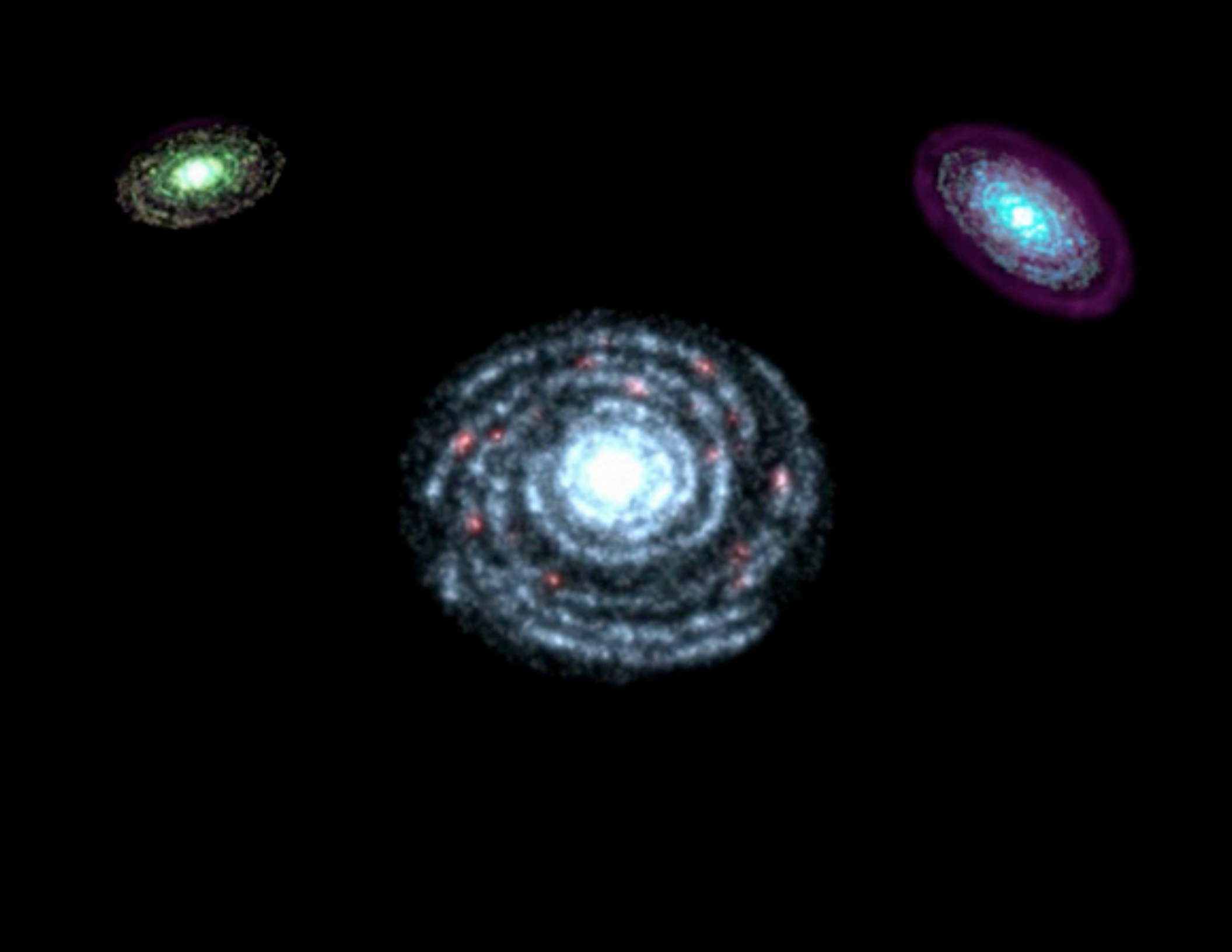




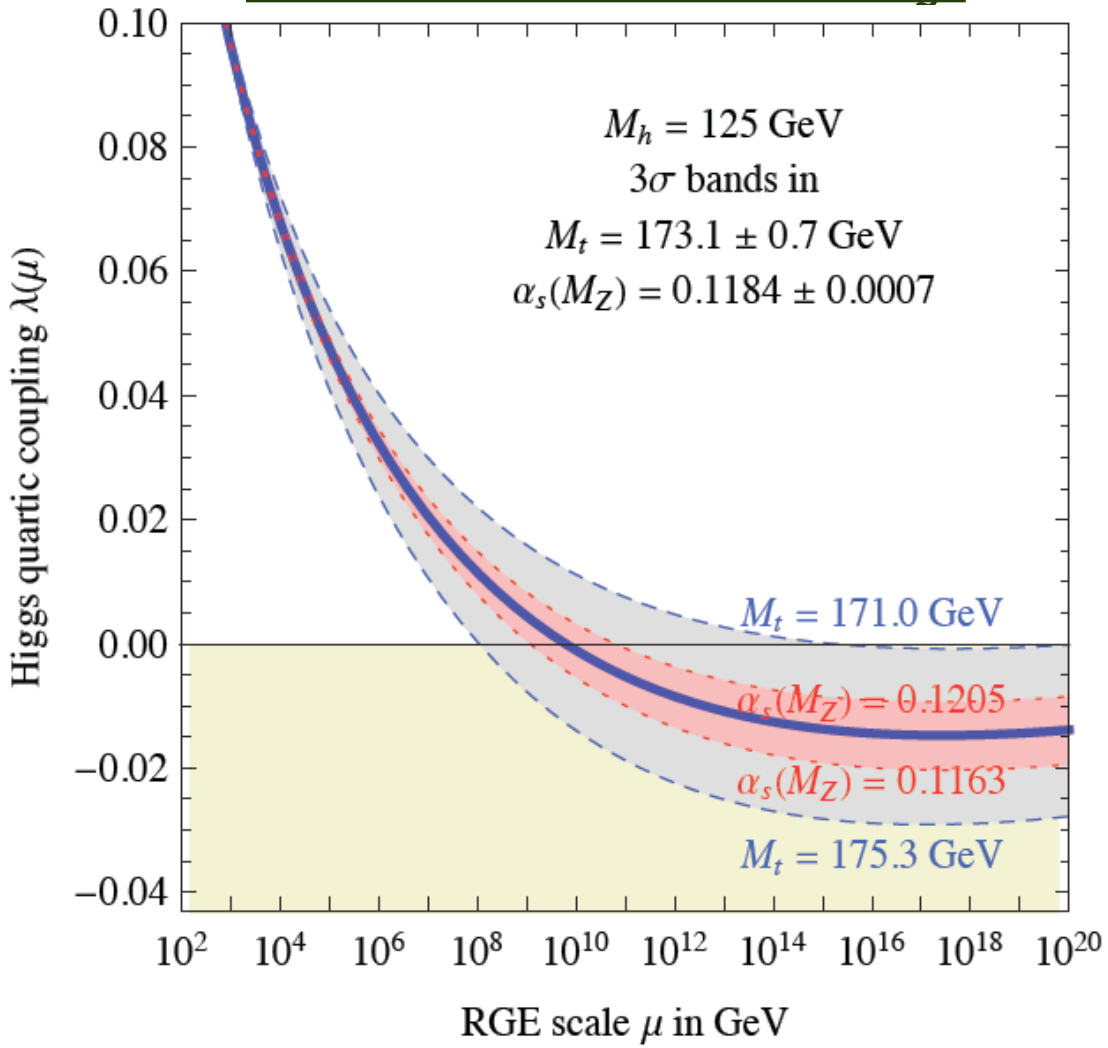
Vacuum stability



- Extrapolate Higgs coupling to Planck Scale (10^{19} GeV)
- Depends on top mass
  - Current value → Higgs quartic coupling negative at 10^{10} GeV



Vacuum stability

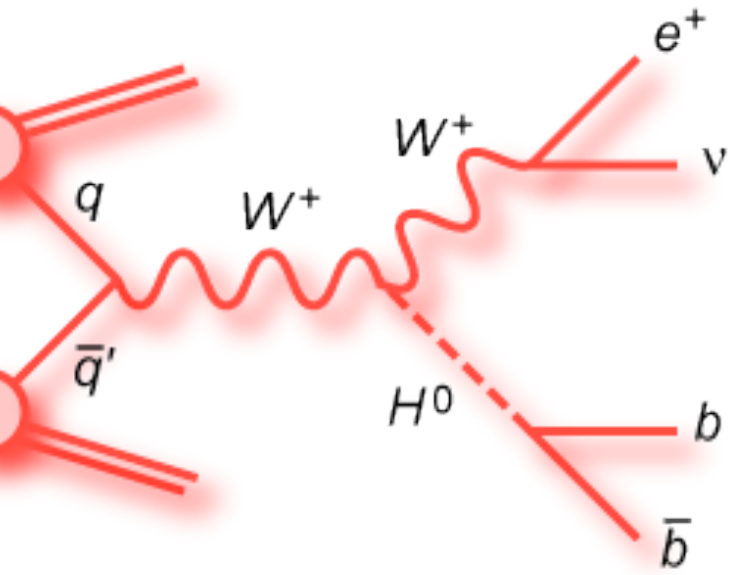


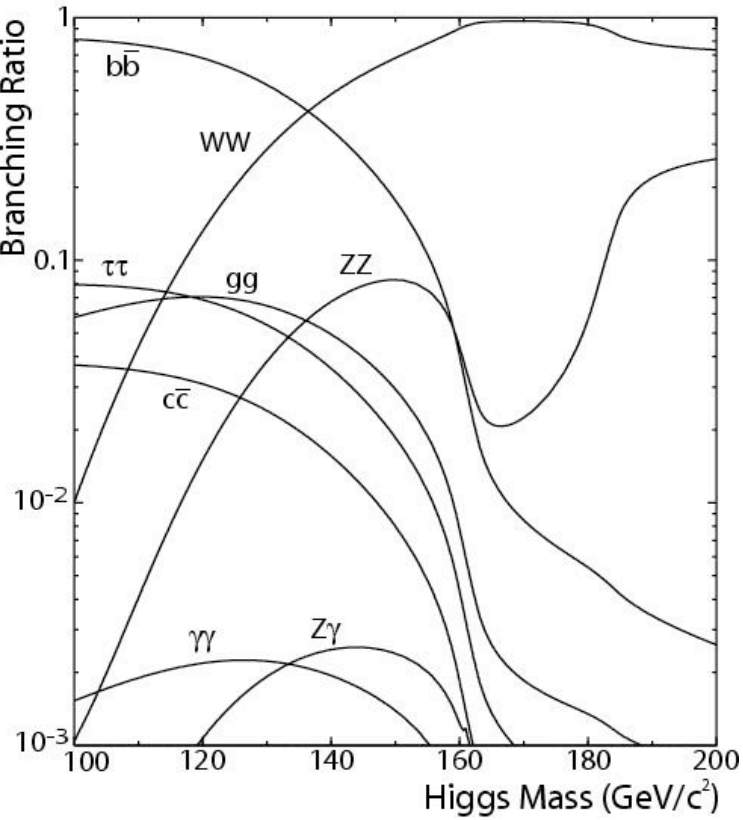
- Extrapolate Higgs coupling to Planck Scale (10^{19} GeV)
- Depends on top mass
  - Current value → Higgs quartic coupling negative at 10^{10} GeV
- Indication of new physics!

Higgs at the Tevatron

- Measure Higgs coupling to Fermions
  - So far only place in the world to do so

Higgs: fermion coupling in associated production

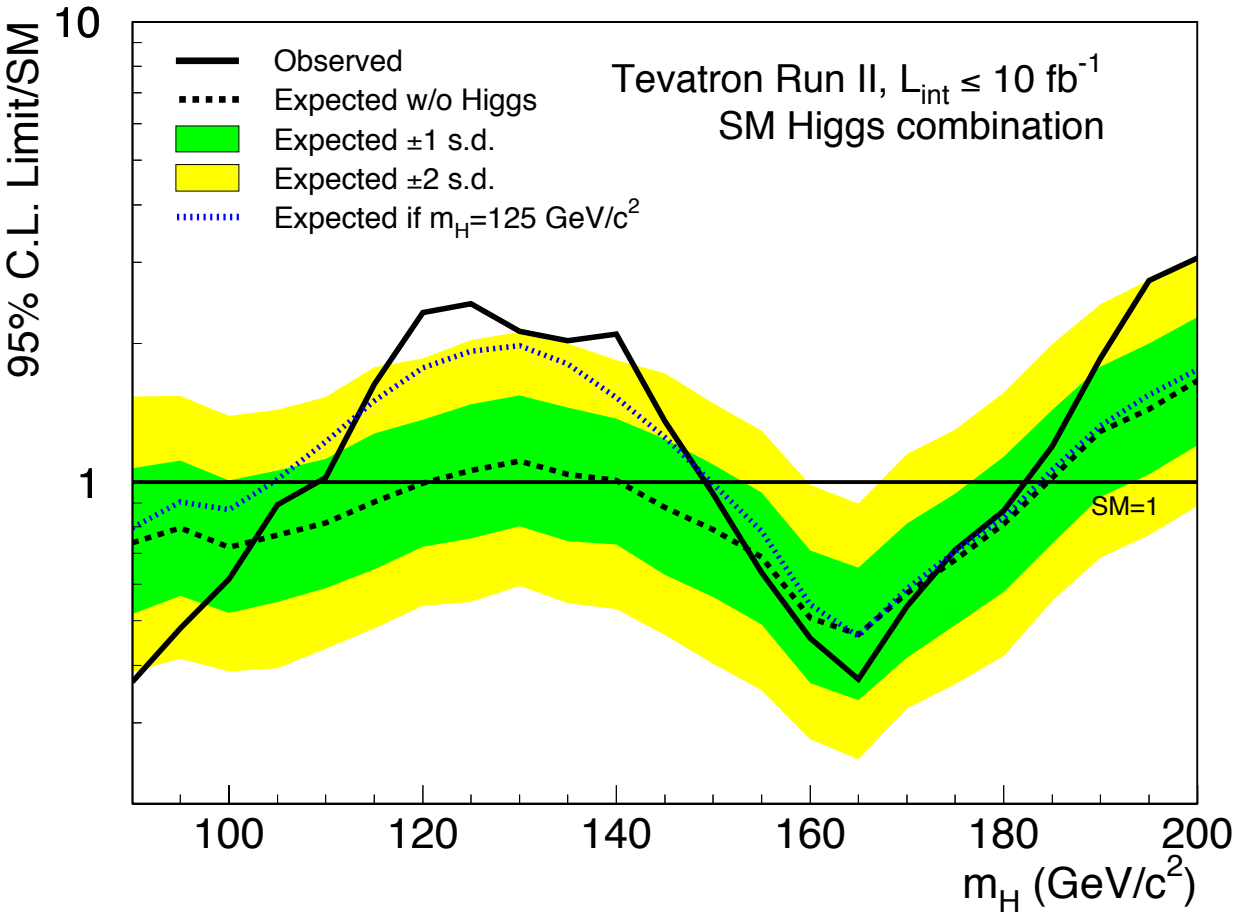


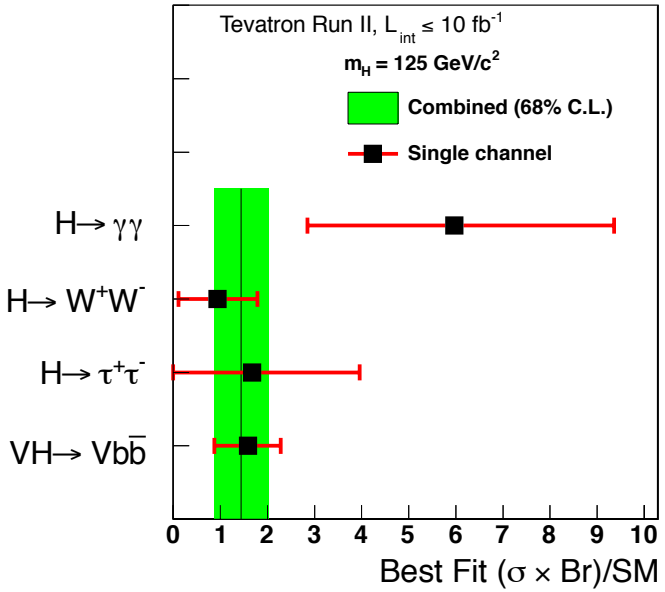


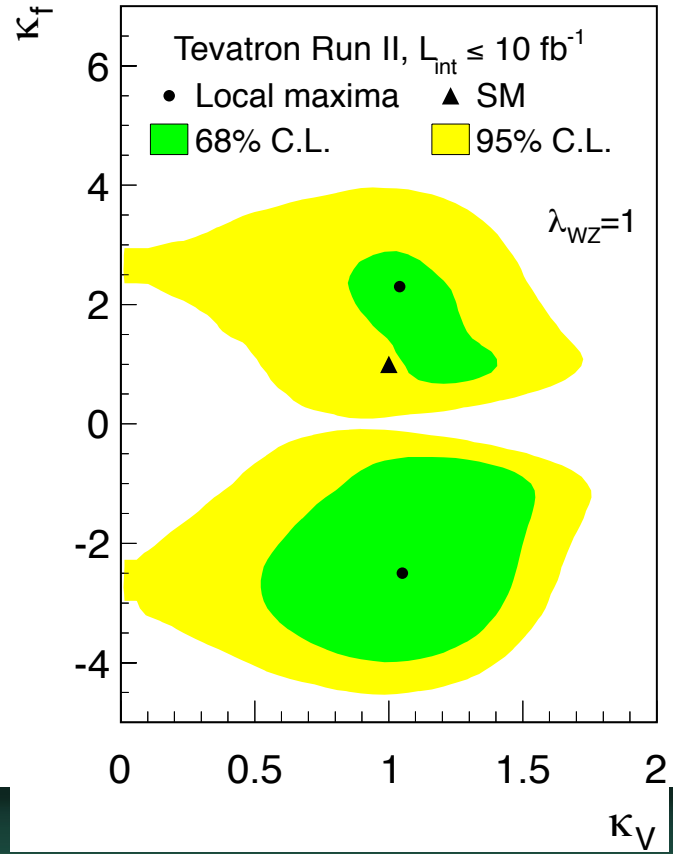
Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(5 b-tag categories)	$H \to b\bar{b}$	9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(2 b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2×(4 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 3-jet channels 2×(4 b-tag categories)		9.45	90–150
$WH + ZH \to jjb\bar{b}$ (2 b-tag categories)		9.45	100–150
$t\bar{t}H \to W^+bW^-\bar{b}b\bar{b}$ (4 jets,5 jets,≥6 jets)×(5 b-tag categories)		9.45	100-150
$H \to W^+W^-$ 2×(0 jets)+2×(1 jet)+1×(≥2 jets)+1×(low-$m_{\ell\ell}$)	$H \to W^+W^-$	9.7	110–200
$H \to W^+W^-$ (e-τ_{had})+(μ-τ_{had})		9.7	130–200
$WH \to WW^+W^-$ (same-sign leptons)+(tri-leptons)		9.7	110–200
$WH \to WW^+W^-$ (tri-leptons with 1 τ_{had})		9.7	130–200
$ZH \to ZW^+W^-$ (tri-leptons with 1 jet,≥2 jets)		9.7	110–200
$H \to \tau^+\tau^-$ (1 jet)+(≥2 jets)	$H \to \tau^+\tau^-$	6.0	100–150
$H \to \gamma\gamma$ 1×(0 jet)+1×(≥1 jet)+3×(all jets)	$H \to \gamma\gamma$	10.0	100–150
$H \to ZZ$ (four leptons)	$H \to ZZ$	9.7	120–200

Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ (4 b-tag categories)×(2 jets, 3 jets)	$H \to b\bar{b}$	9.7	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)		9.5	100–150
$ZH \to \ell^+\ell^- b\bar{b}$ (2 b-tag categories)×(4 lepton categories)		9.7	90–150
$H \to W^+W^- \to \ell^\pm\nu\ell^\mp\nu$ (0 jets,1 jet,≥2 jets)	$H \to W^+W^-$	9.7	115–200
$H + X \to W^+W^- \to \mu^\mp\nu\tau^\pm_{had}\nu$		7.3	115–200
$H \to W^+W^- \to \ell\bar{\nu}jj$ (2 b-tag categories)×(2 jets, 3 jets)		9.7	100–200
$VH \to e^\pm\mu^\pm + X$		9.7	100–200
$VH \to \ell\ell\ell + X$		9.7	100–200
$VH \to \ell\bar{\nu}jjjj$ (≥4 jets)		9.7	100-200
$VH \to \tau_{had}\tau_{had}\mu + X$	$H \to \tau^+\tau^-$	8.6	100-150
$H+X \to \ell^\pm\tau^\mp_{had}jj$		9.7	105–150
$H \to \gamma\gamma$		9.6	100-150

final Tevatron Higgs combination



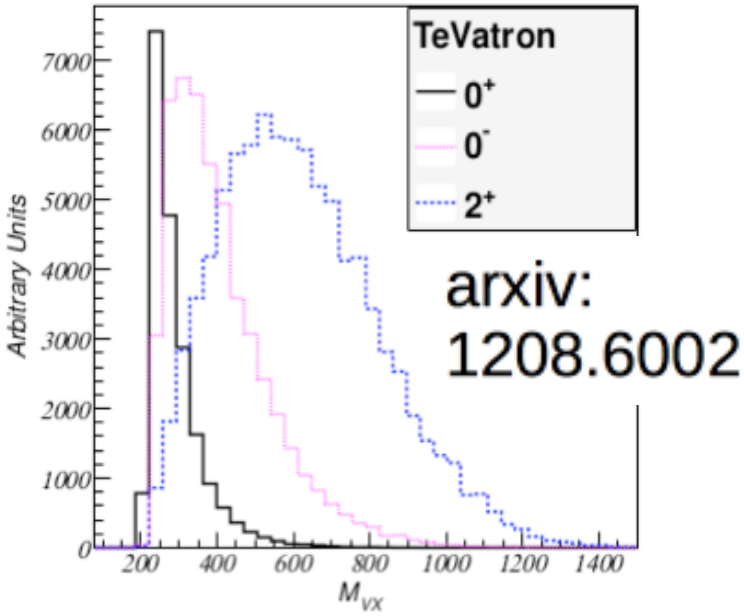


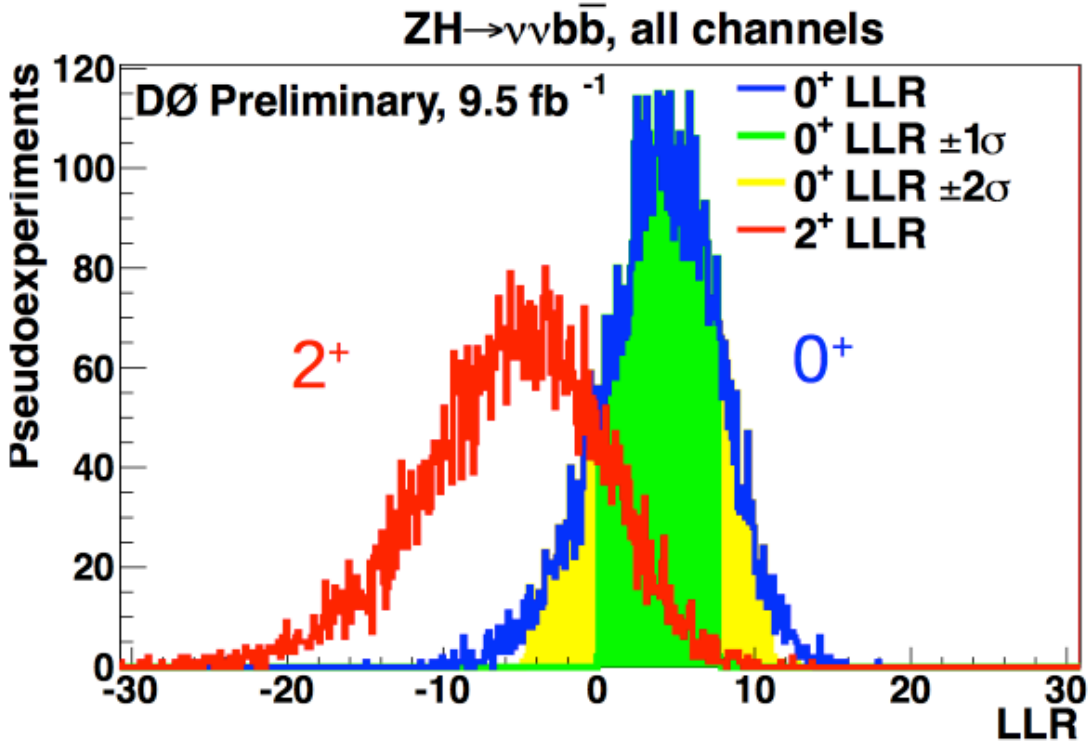


- Observed significance 3.0 s.d. at mH = 125 GeV/c^2
- Coupling measurements consistent with SM

Testing Higgs boson spin/parity

- Spin/parity of Higgs affects
  - Angles of decay products
  - cross-section behavior at threshold
    - s-wave for 0+: $\sigma \sim \beta$ (SM)
    - p-wave for 0-: $\sigma \sim \beta^3$
    - d-wave for 2+:$\sigma \sim \beta^5$
- pp → VH sensitive "threshold" effects
- Differential cross sections depend strongly on JPC of new particle
- Re-use published VH → Vbb analyses
- results later this summer





Conclusions/Outlook

- Tevatron physics impact
  - Top quark discovery, top and W boson mass measurements
  - First measurement of many cross sections and resonances
  - Higgs coupling to fermions
  - Limits on numerous new physics particles and interactions
  - Established hadron collider methods and analysis techniques
- Tevatron data analysis still providing important results
  - Expect ~100 more papers
- Unique collider provided precious dataset
  - CP symmetric collider at the highest energies
  - Well understood detectors
  - Higgs spin/parity tests
  - Follow up on anomalies
- Tevatron legacy measurements
  - Cross section measurements
  - Precision measurements of m_W and m_{top}
  - CP asymmetries

Thanks!

- DØ and CDF collaborations
- Physics coordinators
  - Bob Hirosky, Rick van Kooten, Jon Wilson,
- Previous Tevatron speakers
  - Costas Vellidis, Andreas Jung, Bob Hirosky

- Fermilab Result of the week
  - Tevatron physics for the informed public

- CDF physics results:
  http://www-cdf.fnal.gov/physics/physics.html
- DØ physics results:
  http://www-d0.fnal.gov/Run2Physics/WWW/results.htm