Recent results from the Tevatron

Costas Vellidis
Fermilab

DIS 2013, Marseille, April 22

Outline

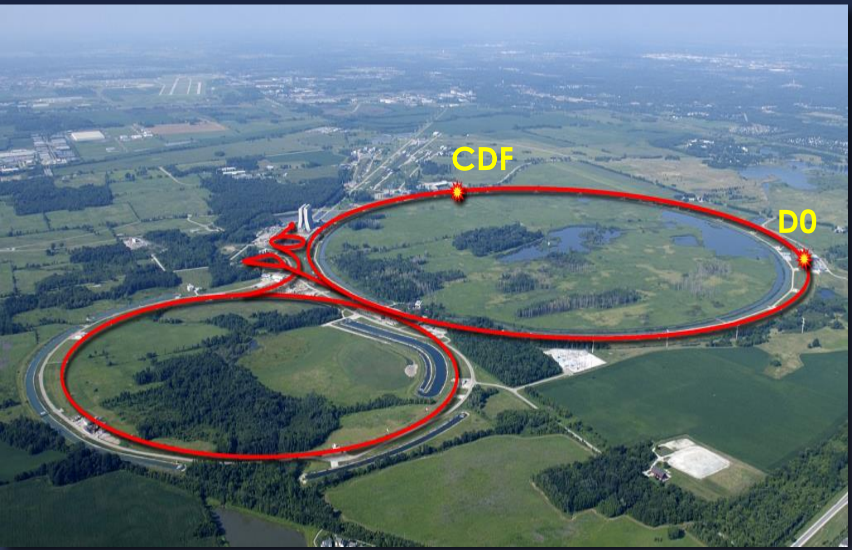
Introduction: The Tevatron, the sample, the physics potential

Results: Higgs, BSM, Top, EWK, QCD, Flavor

Plans: What is still expected

Conclusions: The Tevatron legacy

Tevatron

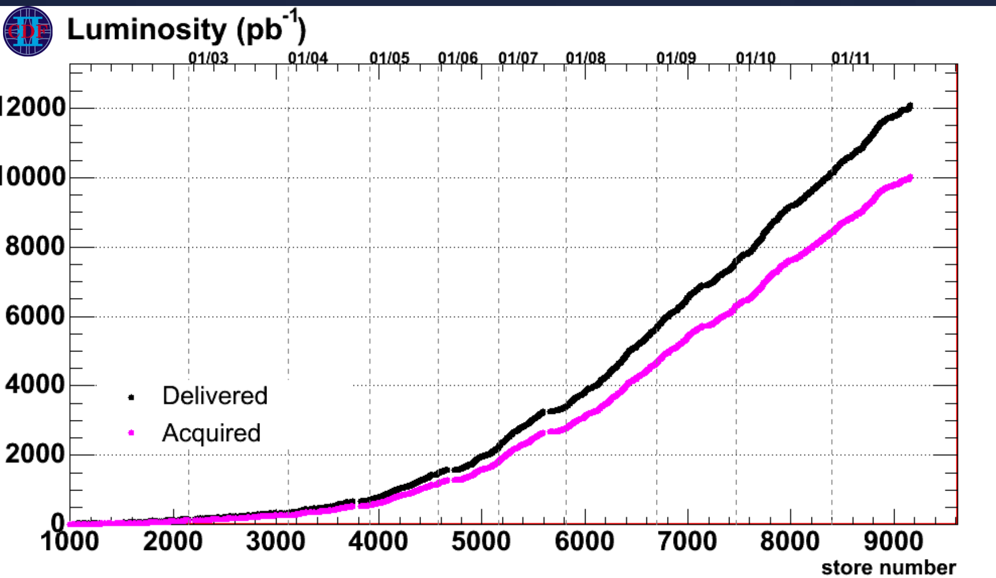


Proton-antiproton collider
operating at $\sqrt{s}$ = 1.96 TeV
from 2/2002 to 10/2011 (Run II)

+ $\sqrt{s}$ = 300, 900 GeV in 9/2011

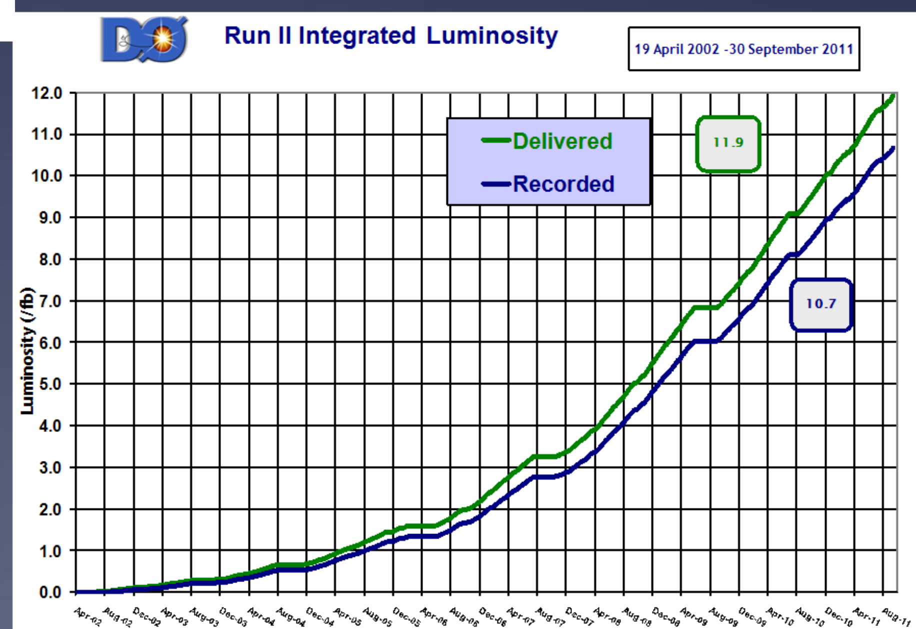
Currently
400 + 400 members
from 60 + 70 institutions

Sample

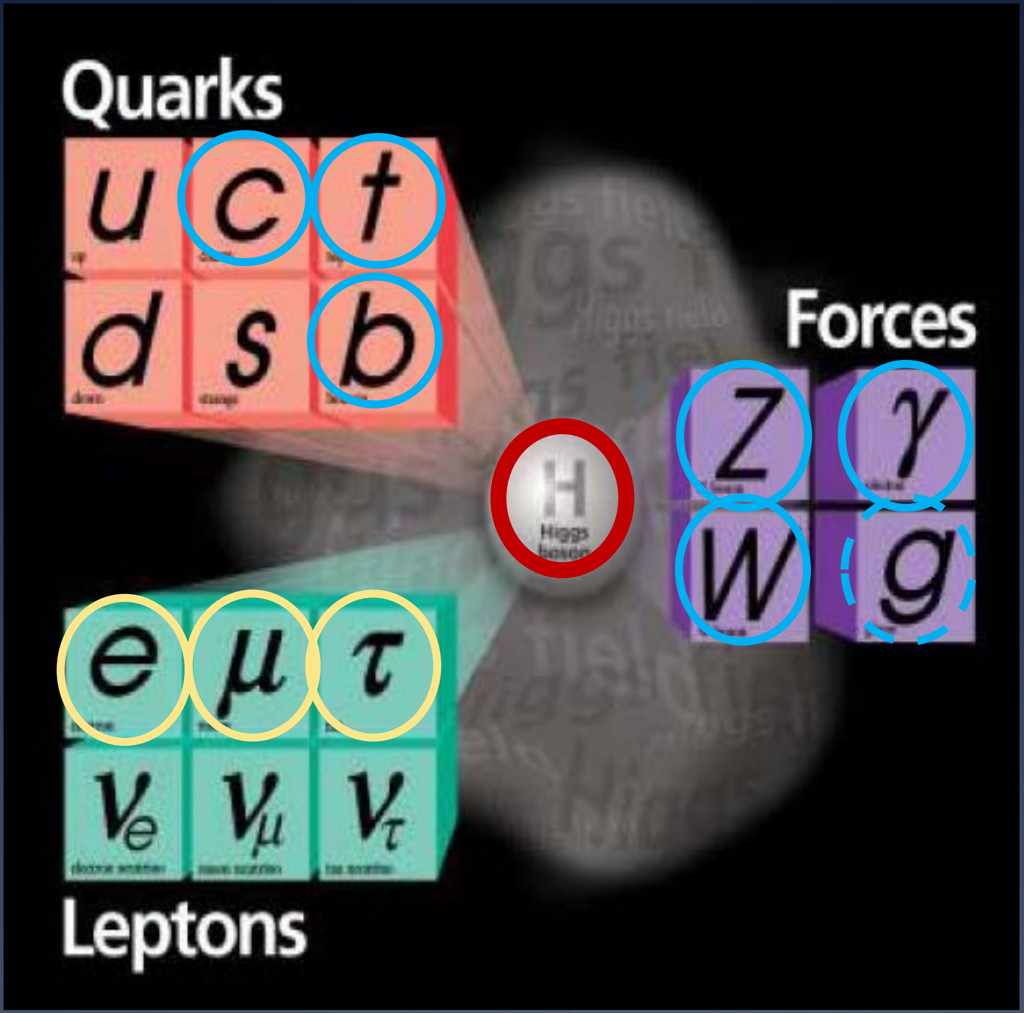


Delivered 12 fb^{-1}
Acquired 10 fb^{-1}/experiment

- ✧ 15B + 9B events total in Run II
- ✧ Total dataset 10 + 9 PB (including Monte Carlo)



Physics potential



All about the Standard Model – and beyond:

www-cdf.fnal.gov/physics/physics.html

www-d0.fnal.gov/Run2Physics/WWW/results.htm

Higgs

Final results from the Tevatron

Final Higgs combination from Tevatron

Combination: arXiv:hep-ex/1303.63416 ; submitted to Phys. Rev. D

All SM channels searched

Full luminosity used in almost all channels

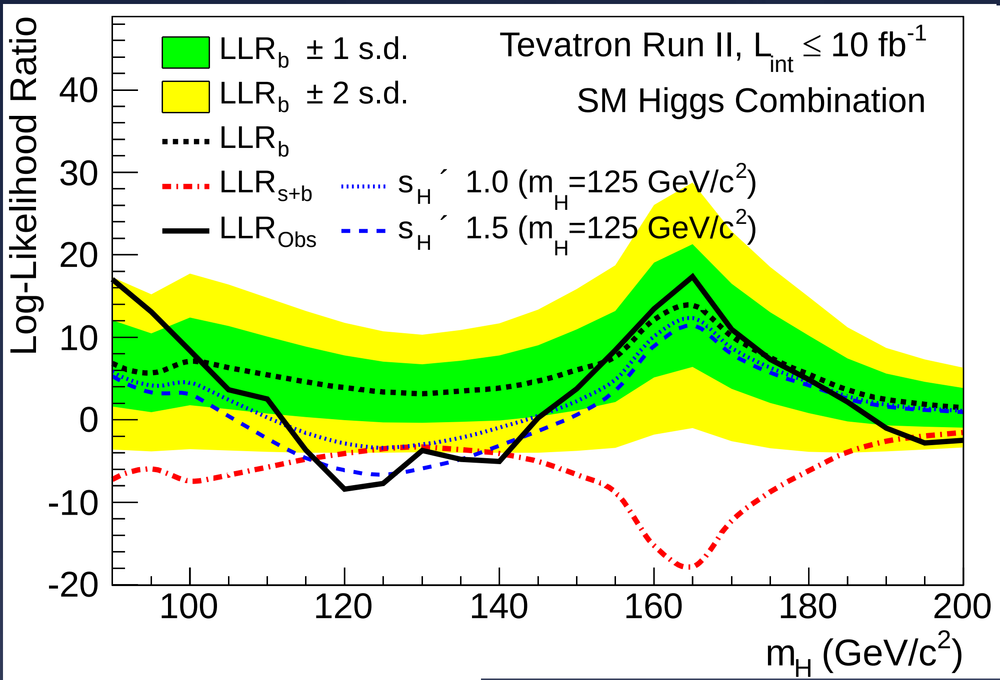
CDF

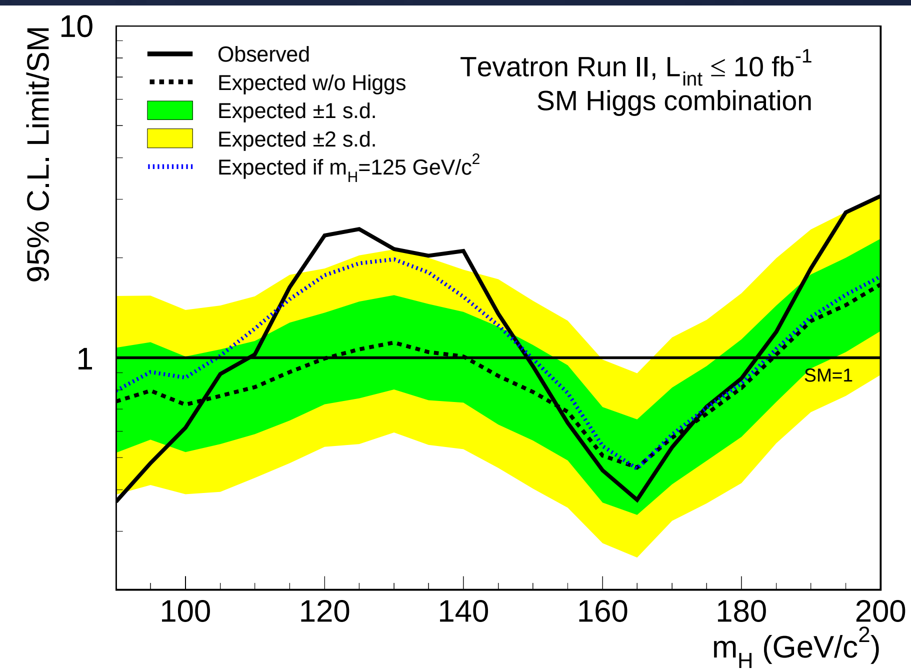
Channel		Luminosity (fb^{-1})	m_H range (GeV/c^2)
$WH \to \ell\nu b\bar{b}$ 2-jet channels 4×(5 b-tag categories)		9.45	90–150
$WH \to \ell\nu b\bar{b}$ 3-jet channels 3×(2 b-tag categories)		9.45	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (3 b-tag categories)		9.45	90–150
$ZH \to \ell^+\ell^- b\bar{b}$ 2-jet channels 2×(4 b-tag categories)	$H \to b\bar{b}$	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-$m_{\ell\ell}$)		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)	$H \to W^+W^-$	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

DØ

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)		9.7	90–150
$ZH \to \nu\bar{\nu}b\bar{b}$ (2 b-tag categories)	$H \to b\bar{b}$	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)		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)	$H \to W^+W^-$	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

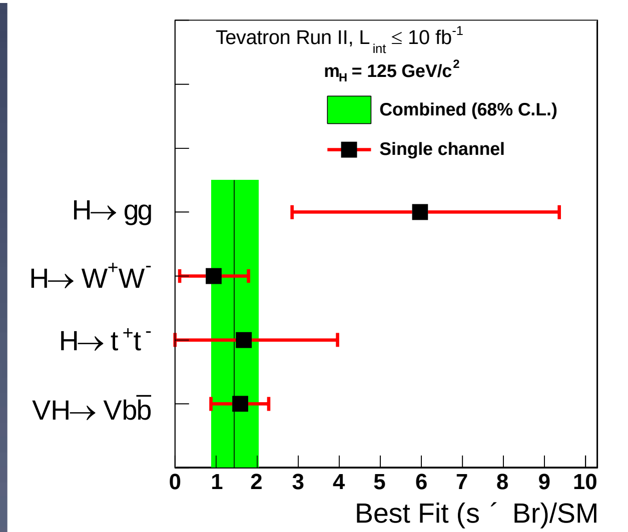
Final Higgs combination from Tevatron



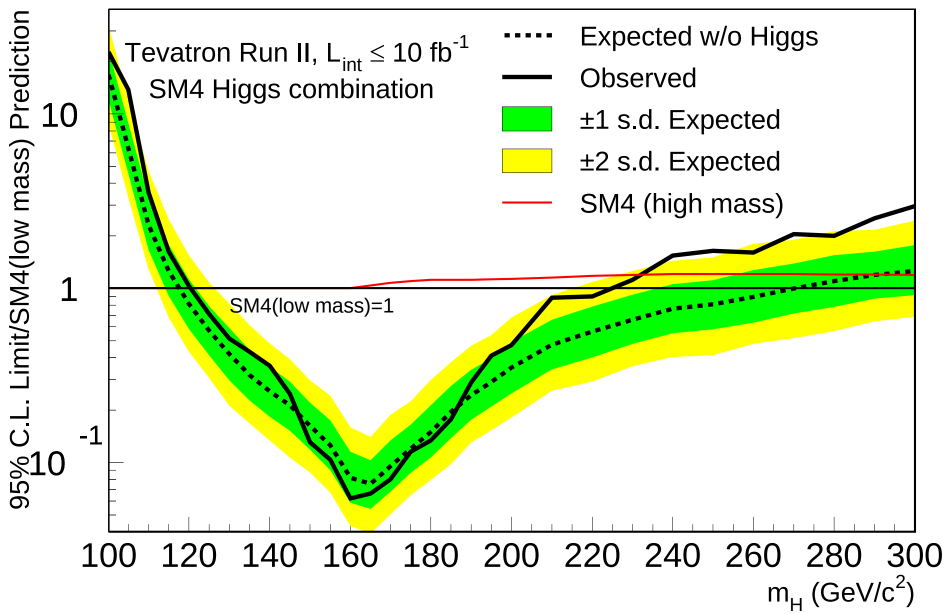


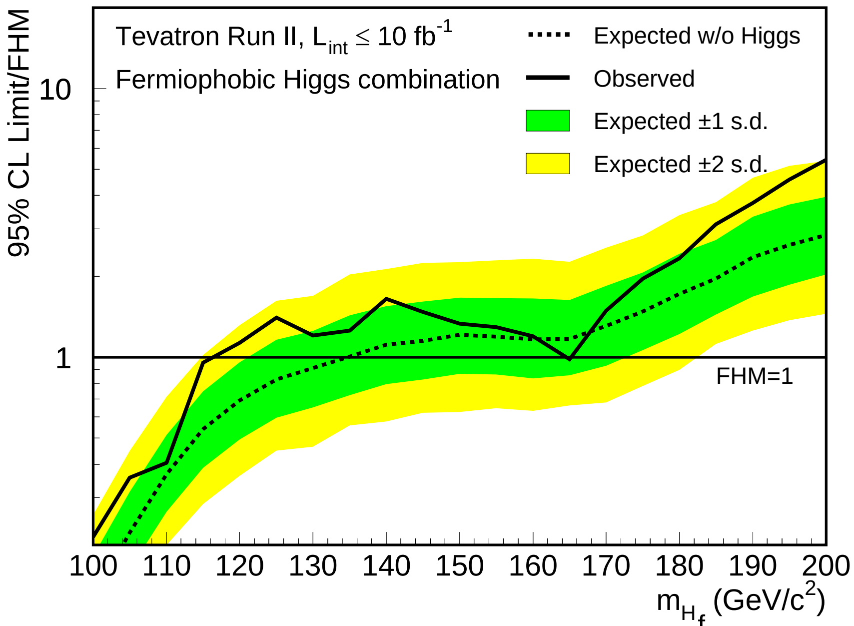
$$-2\ln Q \equiv LLR \equiv -2\ln\left(\frac{L(\text{data}\,|\,H_1,\hat{\theta})}{L(\text{data}\,|\,H_0,\hat{\hat{\theta}})}\right)$$

Observed significance 3.1σ
at m_H = 125 GeV/c^2



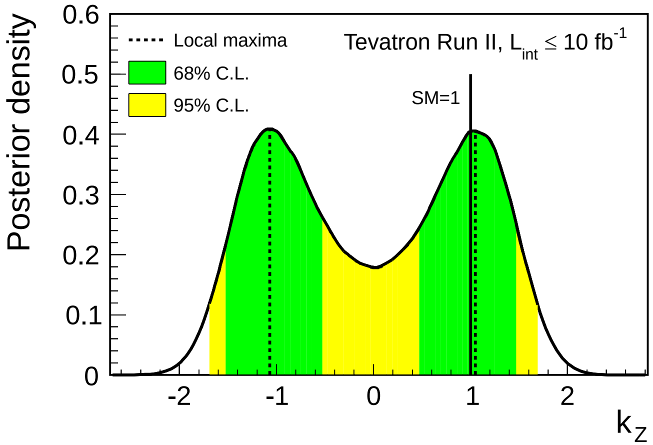
Tests of SM4 & FP Higgs

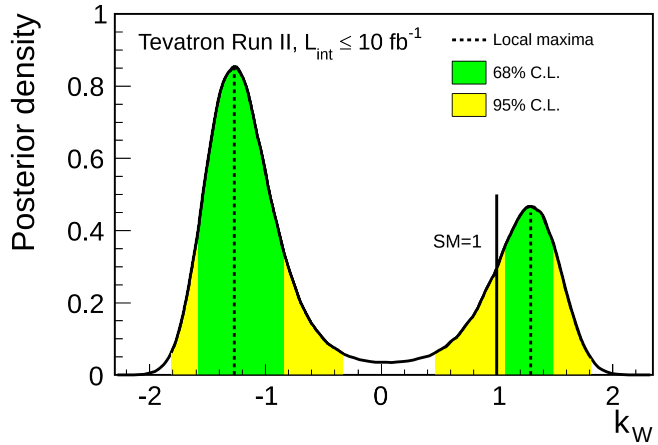


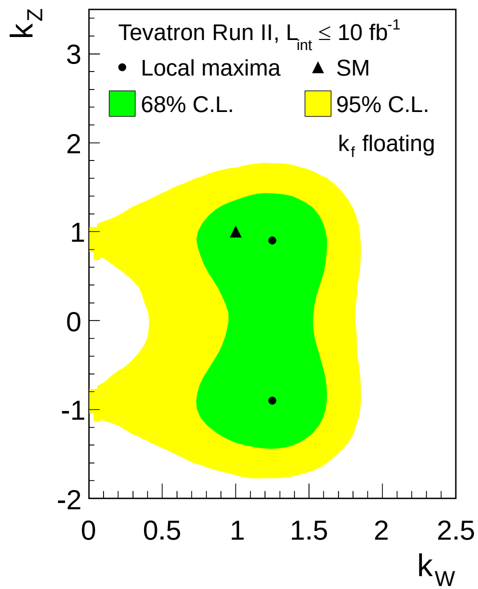


- ✧ Search for gg→H→WW with a 4^{th} fermion generation
  exp. exclusion [118,270] GeV/c^2; obs. [121,225] GeV/c^2
- ✧ Search for "fermiophobic" Higgs in H→γγ, H→WW, H→ZZ
  exp. exclusion [100,116] GeV/c^2; obs. [100,135] GeV/c^2

Constraints on couplings







$$\Gamma(H \to gg) = \Gamma_{SM}(H \to gg)(0.95k_f^2 + 0.05k_f k_V)$$

$$\Gamma(H \to W^+W^-) = \Gamma_{SM}(H \to W^+W^-)k_V^2$$

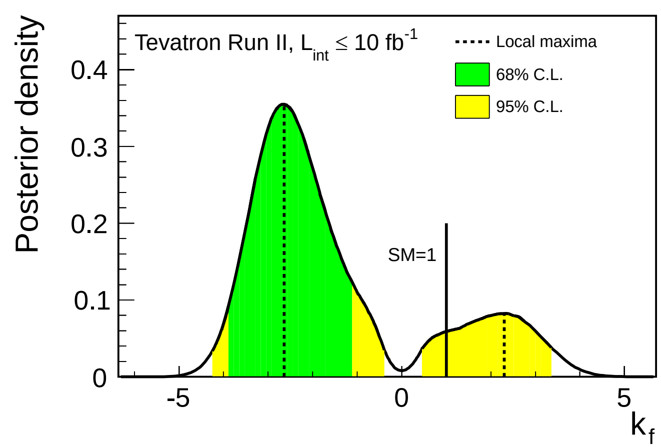
$$\Gamma(H \to b\bar{b}) = \Gamma_{SM}(H \to b\bar{b})k_f^2$$

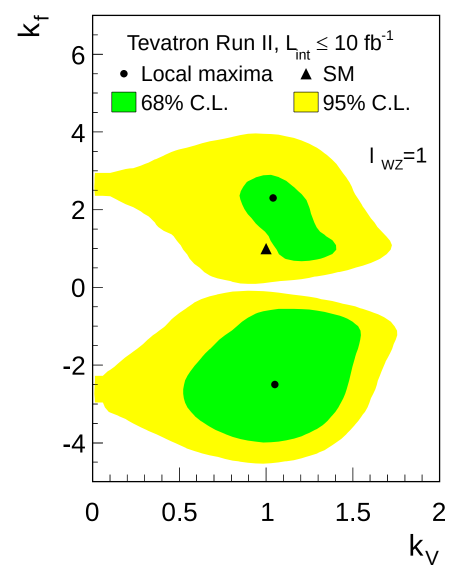
$$\Gamma(H \to t^+t^-) = \Gamma_{SM}(H \to t^+t^-)k_f^2$$

$$\Gamma(H \to c\bar{c}) = \Gamma_{SM}(H \to c\bar{c})k_f^2$$

$$\Gamma(H \to ZZ) = \Gamma_{SM}(H \to ZZ)k_V^2$$

$$\Gamma(H \to \gamma\gamma) = \Gamma_{SM}(H \to \gamma\gamma)\left|a k_V + b k_f\right|^2$$





$\alpha = 1.28$, $\beta = -0.21$, from Spira et al., arXiv:hep-ph/9504378

Consistent with SM

$$\sigma(gg \to H) = \sigma_{SM}(gg \to H)(0.95k_f^2 + 0.05k_f k_V)$$

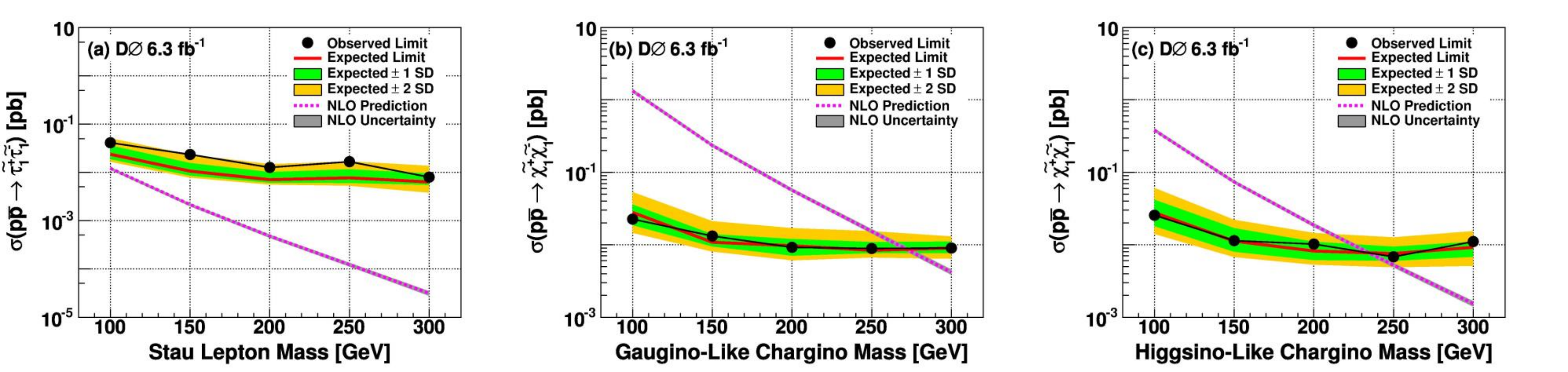
$$\sigma(WH) = \sigma_{SM}(WH)k_V^2 \qquad \sigma(ZH) = \sigma_{SM}(ZH)k_V^2 \qquad \sigma(VBF) = \sigma_{SM}(VBF)k_V^2$$

BSM

Searches for physics Beyond the Standard Model

Search for charged massive long-lived particles

PRD 87, 052011 (2013)

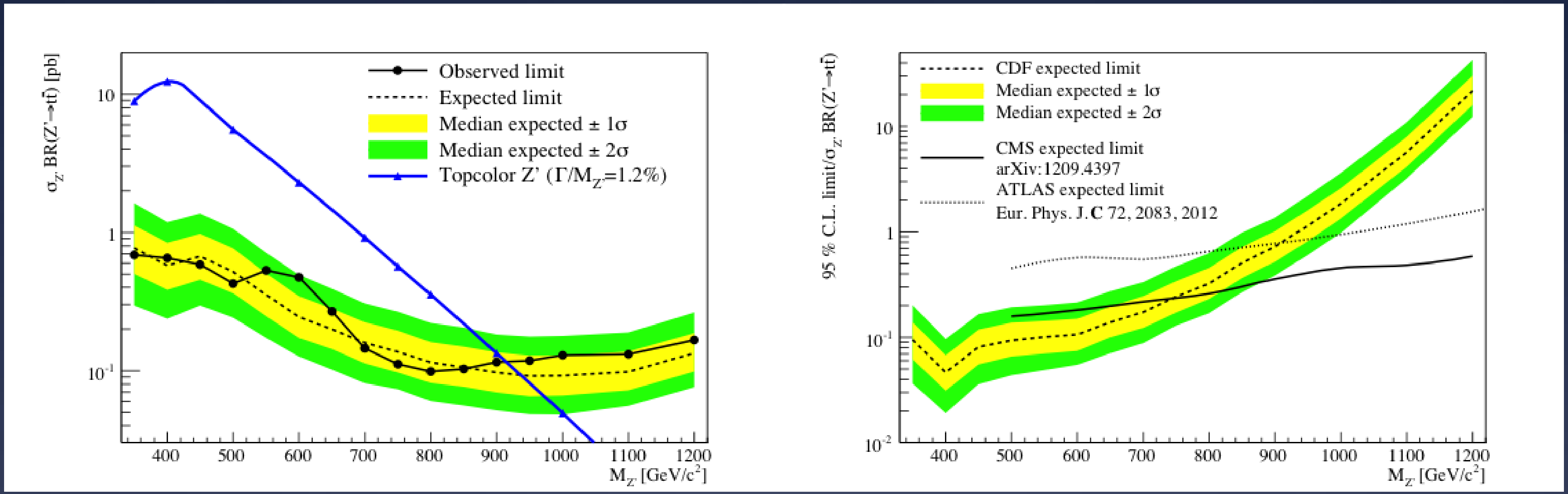


Searched for events with 1 or 2 μ–like particles having both speed and dE/dx different from μ's. Excluded @ 95% C.L. :

- Long-lived gaugino-like charginos with mass < 278 GeV/c^2
- Long-lived Higgsino-like charginos with mass < 244 GeV/c^2

Search for top-pair resonances

PRL 110, 121802 (2013)

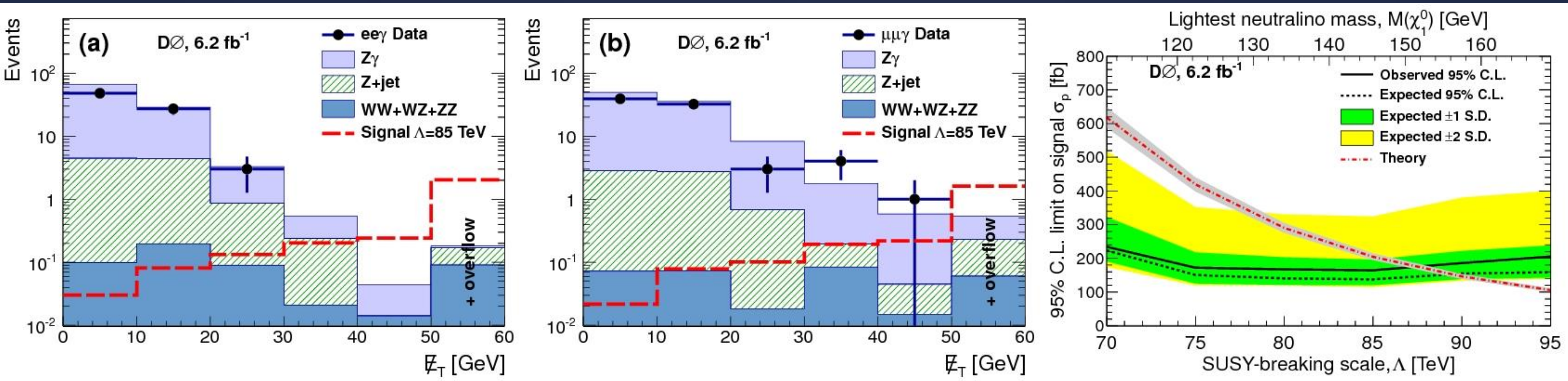


tt events selected in the l+jets channel (3j & ≥4j categories) requiring at least one b-tagged jet

- Topcolor model Z' excluded up to 915 GeV/c^2 @ 95% C.L.
- Best exclusion limit below 700 GeV/c^2

Search for $Z\gamma + \not\!E$ events

PRD 86, 071701(R) (2012)

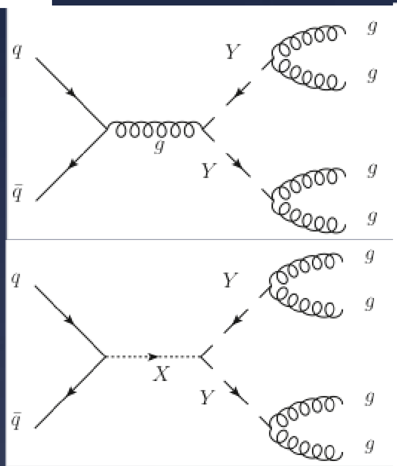


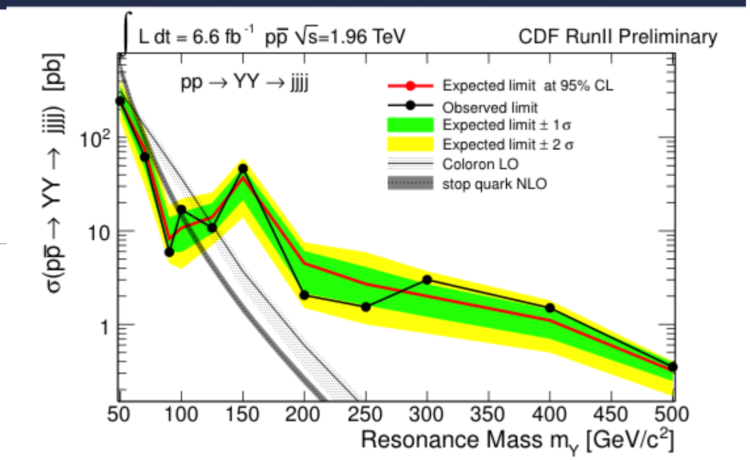
Signature predicted in GMSB where pair-produced NLSP neutralinos decay into Z /γ + gravitino

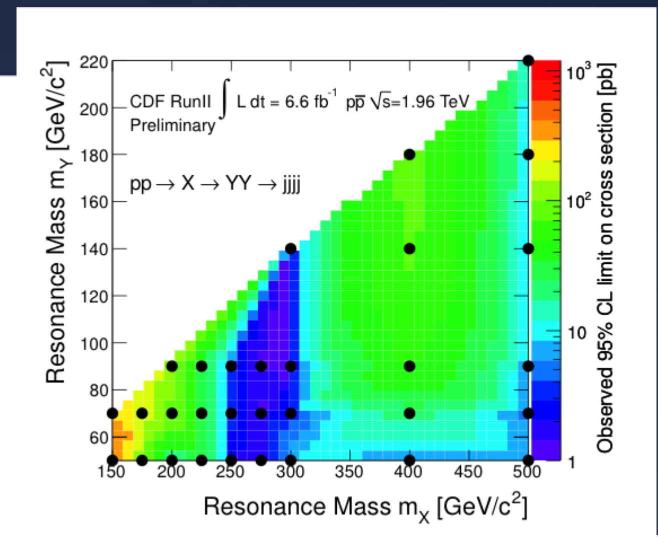
➢ Model excluded up to GMSB scale Λ< 87 TeV @ 95% C.L.

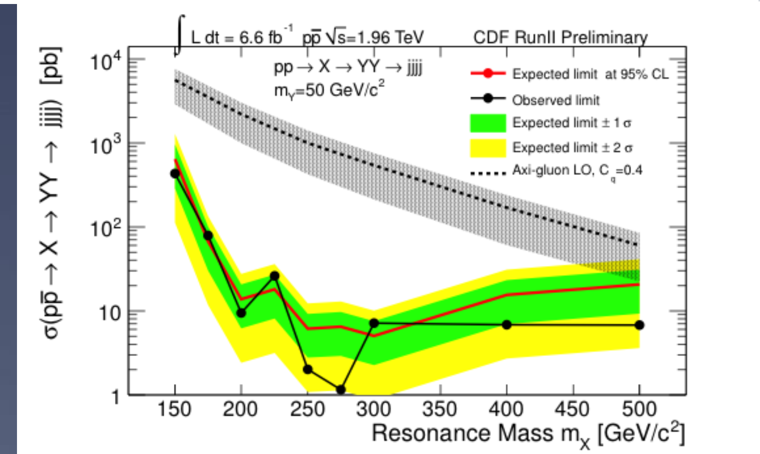
Search for resonances in 4j events

arXiv:hep-ex/1303.2699, submitted to PRL









Searching for narrow resonances in 2-jet & 4-jet mass spectra, excluded:

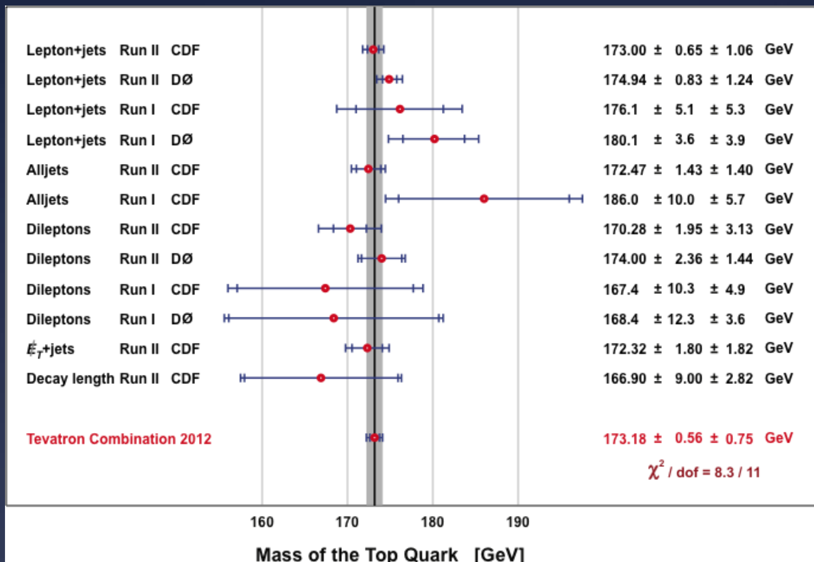
- Coloron in [50,125] GeV/c^2
- RPV stop in [50,100] GeV/c^2
- Axi-gluon→hyperpions in [150,450] GeV/c^2 for couplings preferred by CDF top A_{FB}

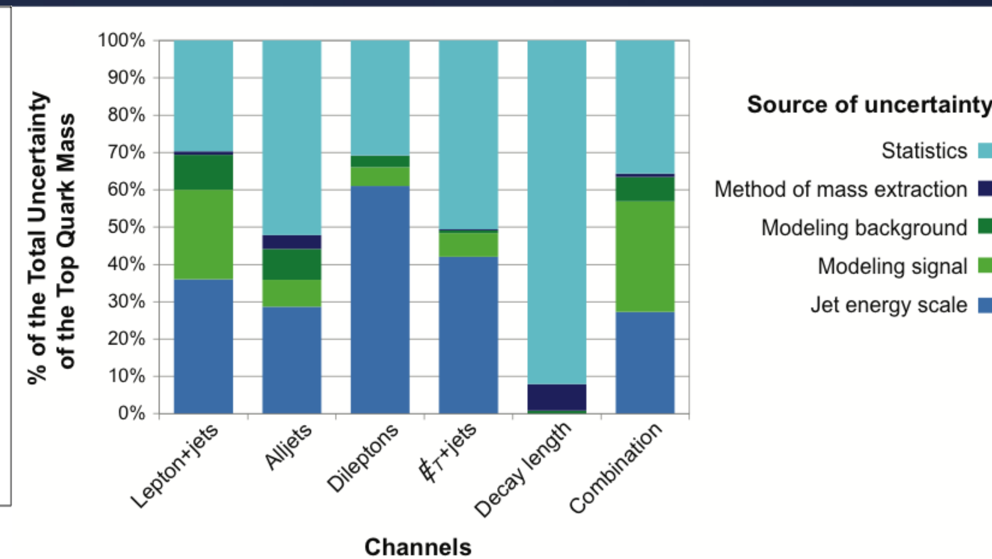
Top

Exploring the heaviest known elementary particle
A potential gateway to new physics

Tevatron M_{top} combination

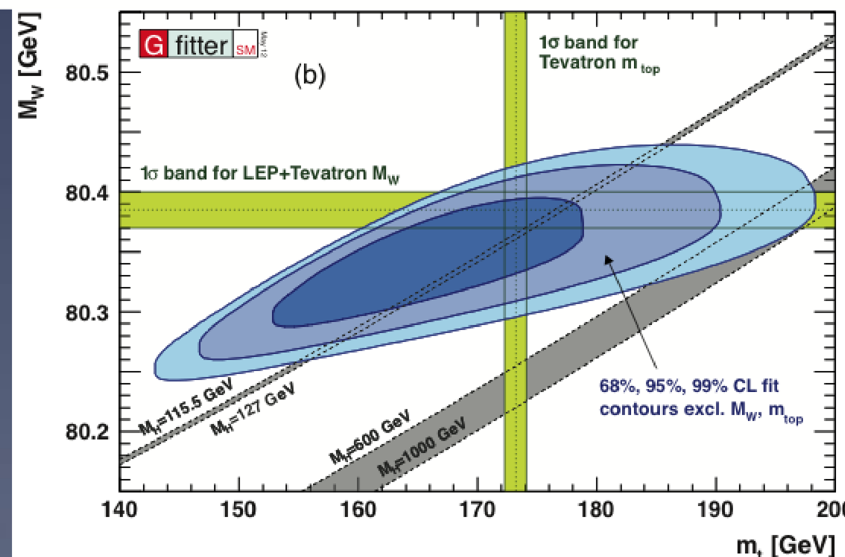
PRD 82, 096003 (2012); CDF public note 10976





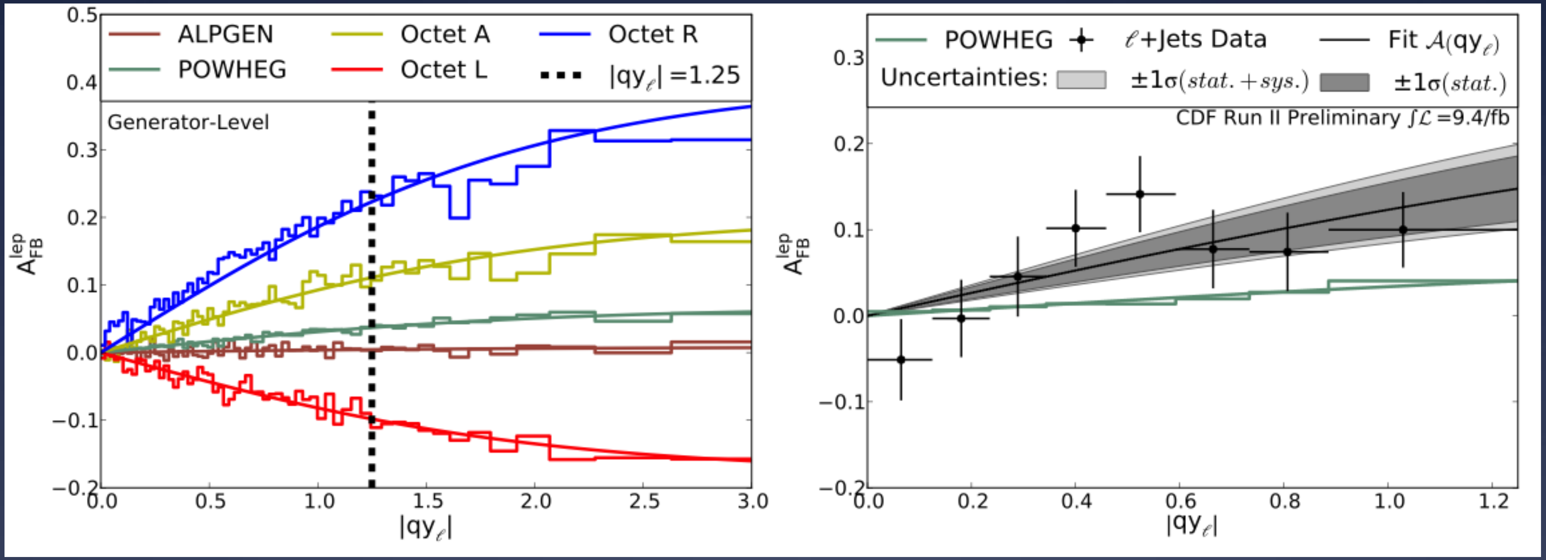
- M_{top} = (173.20 ± 0.87) GeV/c²
- 0.50% precision!

M_H measured at the LHC and [M_W & M_{top}] measured at the Tevatron consistent at 68% C.L.



Lepton A_{FB} in $t\bar{t} \rightarrow l$+jets decays

CDF public note 10975

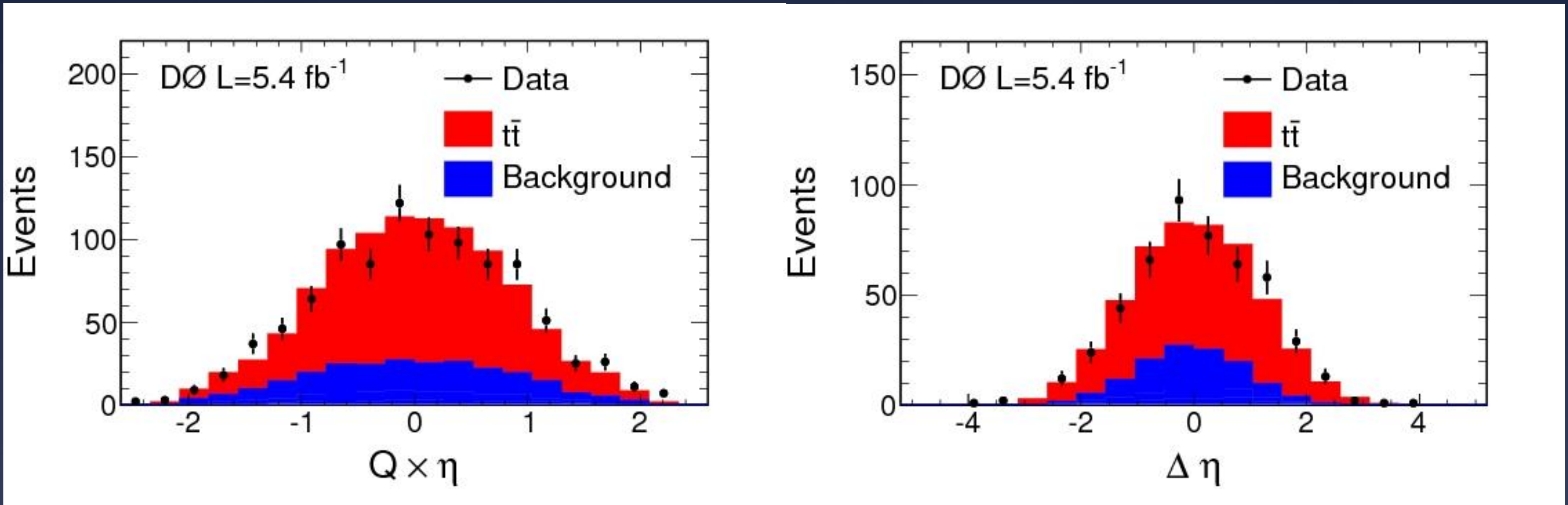


Partially correlated with $A_{FB}(t\bar{t})$ (if $t\bar{t}$ production polarized), essentially free of event reconstruction uncertainties

- Measured total $A_{FB}^{lep} = 0.094 \pm 0.032_{stat} \pm 0.029_{syst}$
- SM@NLO $A_{FB}^{lep} = 0.036$

Lepton A_{FB} in $t\bar{t} \rightarrow$ dilepton decays

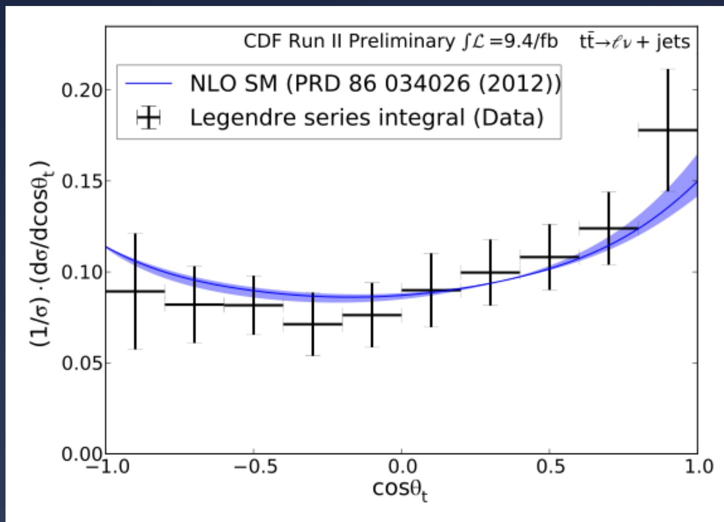
PRD 87, 011103(R) (2013)

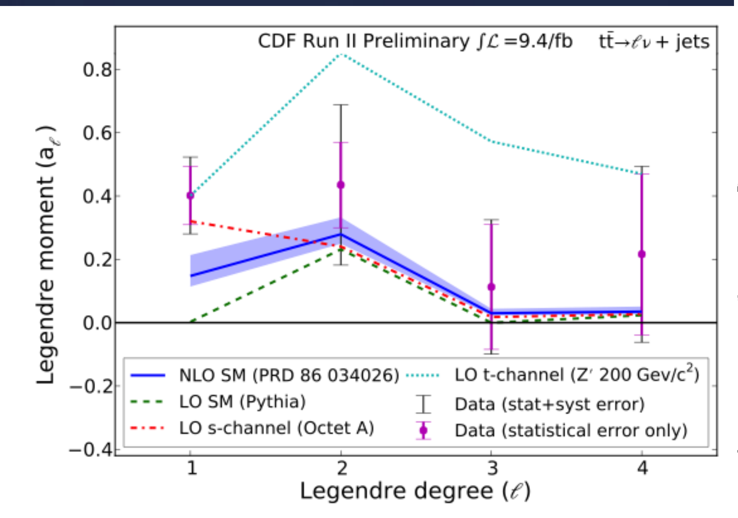


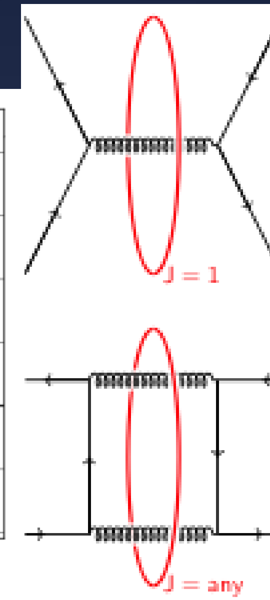
- Measured total $A_{FB}^{lep} = 0.058 \pm 0.051_{stat} \pm 0.013_{syst}$
- Combined with l+jets result, $A_{FB}^{lep} = 0.112 \pm 0.032$
- SM@NLO $A_{FB}^{lep} = 0.047$

$d\sigma/d\cos\theta_t$ in $t\bar{t}\rightarrow l$+jets decays

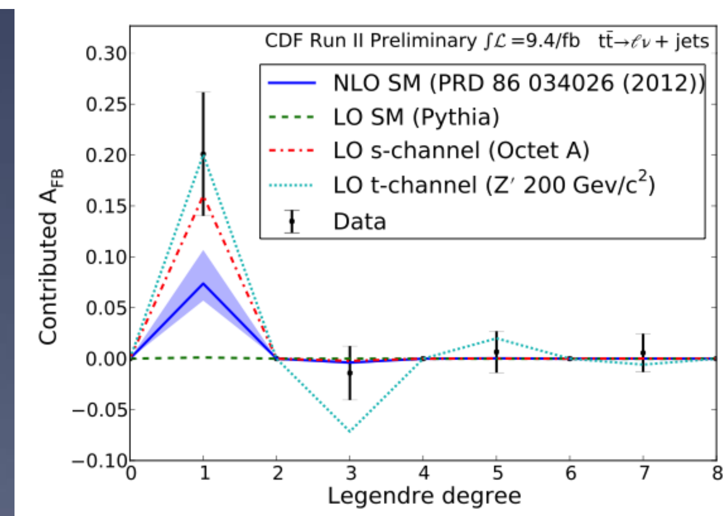
CDF public note 10974







Legendre moments characterize
the shape of the cross section



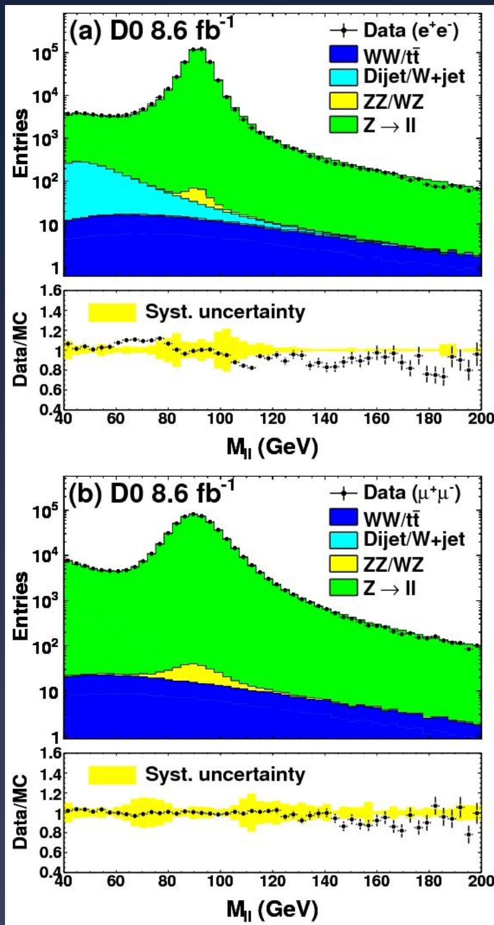
- Agreement with SM@NLO for all but 1st moment
- A_{FB} dominated by anomalously large 1st moment

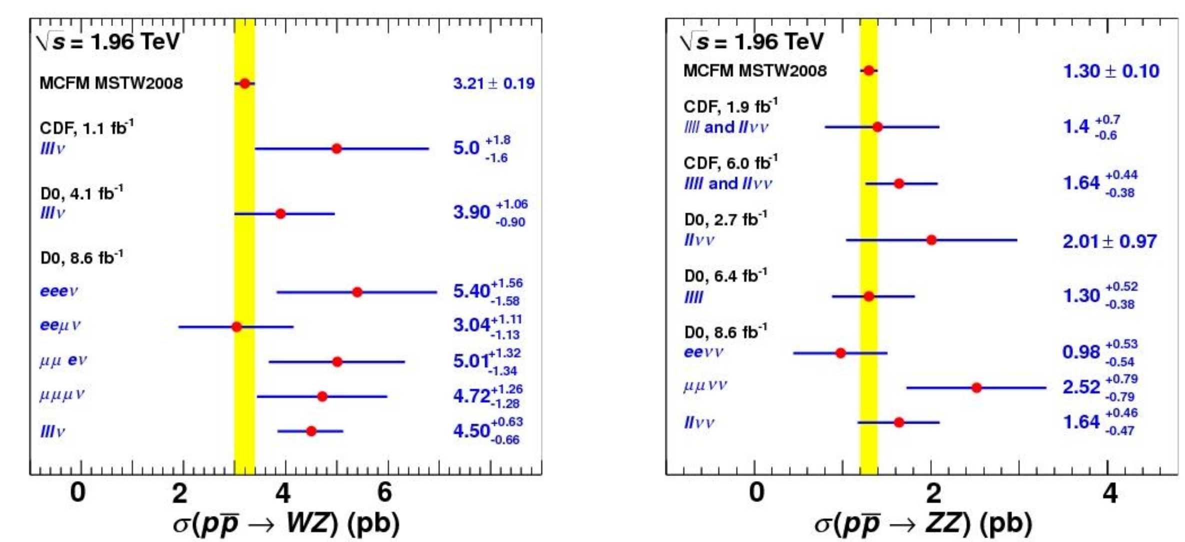
Electroweak interactions

Pushing precision
Testing the gauge symmetry of the SM

WZ & ZZ cross sections

PRD 85, 112005 (2012)

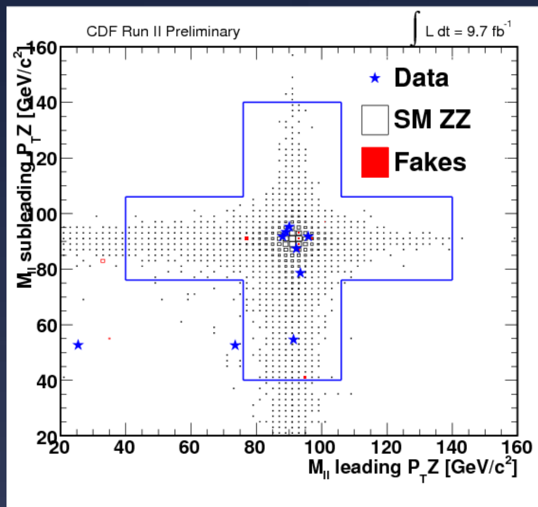


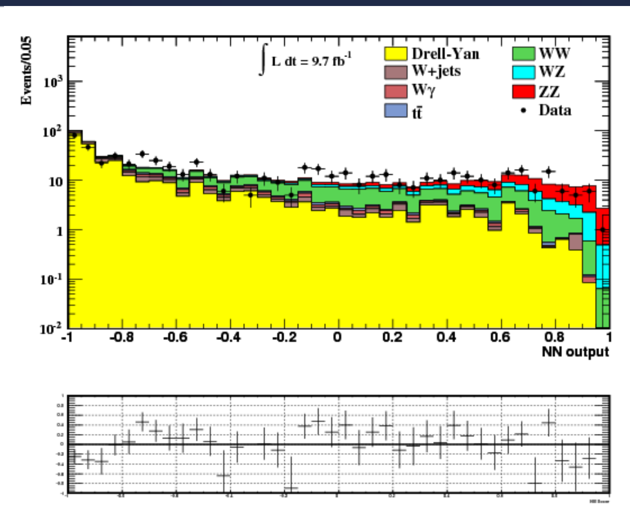


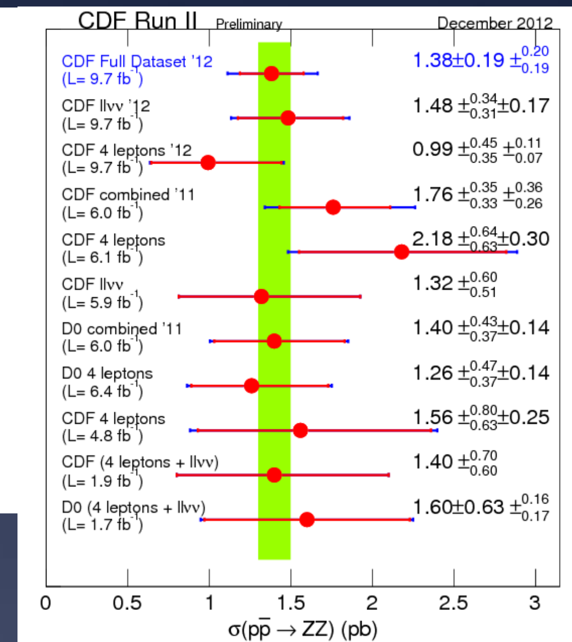
- ✧ WZ→lνll & ZZ→llνν: measured relative to Z→ll, then normalized to theory
- ✧ Combining ZZ→llνν with ZZ→llll(6.4 fb^{-1}):

ZZ cross section

CDF public note 10957







ZZ→llll: counting experiment; ZZ→llvv: NN fit

- ZZ→llll

$$\frac{\sigma(p\bar{p}\to ZZ)}{\sigma_{SM}} = 0.73^{+0.31}_{-0.24}(\text{stat.})^{+0.08}_{-0.05}(\text{syst.}) = 0.73^{+0.32}_{-0.25}$$

$$\sigma(p\bar{p}\to ZZ) = 0.99^{+0.45}_{-0.35}(\text{stat.})^{+0.11}_{-0.07}(\text{syst.})\ \text{pb} = 0.99^{+0.45}_{-0.35}\ \text{pb}$$

- ZZ→llvv

$$\frac{\sigma(p\bar{p}\to ZZ)}{\sigma_{SM}} = 1.06^{+0.24}_{-0.22}(\text{stat.}) \pm 0.12(\text{syst.}) = 1.06^{+0.27}_{-0.25}$$

$$\sigma(p\bar{p}\to ZZ) = 1.48^{+0.34}_{-0.31}(\text{stat.}) \pm 0.17(\text{syst.})\ \text{pb} = 1.48^{+0.38}_{-0.35}\ \text{pb}$$

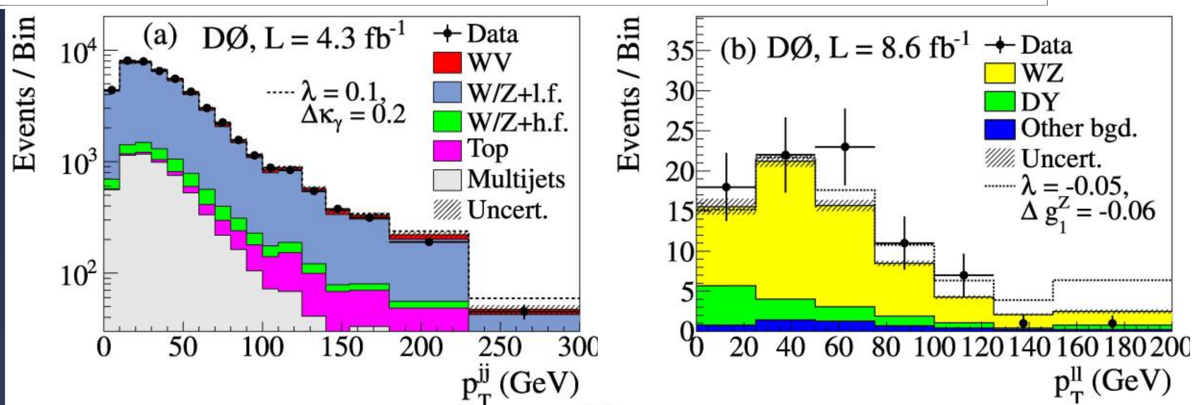
- Combined

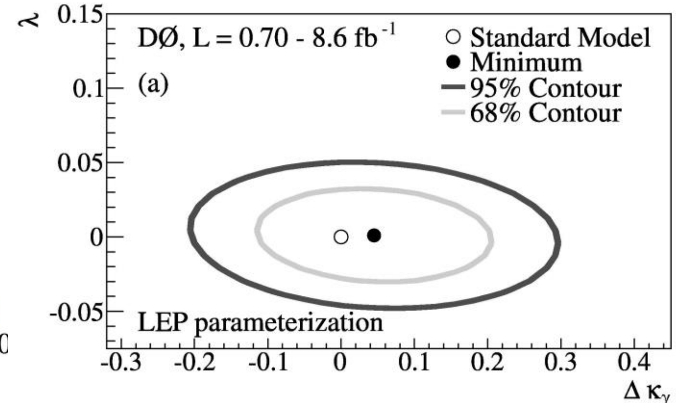
$$\frac{\sigma(p\bar{p}\to ZZ)}{\sigma_{SM}} = 0.99 \pm 0.14(\text{stat.})^{+0.14}_{-0.13}(\text{syst.}) = 0.99^{+0.20}_{-0.19}$$

$$\sigma(p\bar{p}\to ZZ) = 1.38 \pm 0.19(\text{stat.})^{+0.20}_{-0.19}(\text{syst.})\ \text{pb} = 1.38^{+0.28}_{-0.27}\ \text{pb}$$

WWZ & WWγ couplings

PLB 718, 451 (2012)





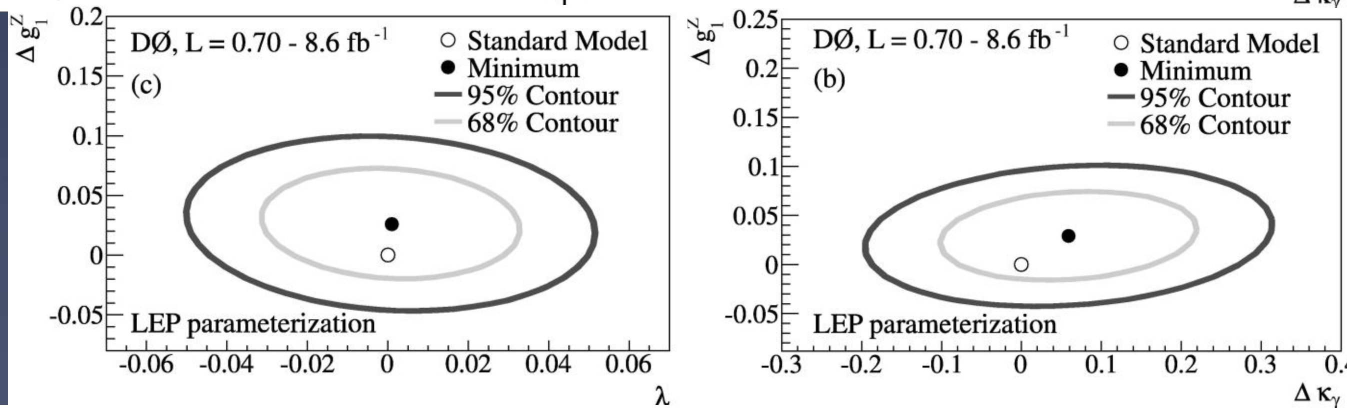
WW+WZ→lvjj

WW→lvlv

WZ→lvll

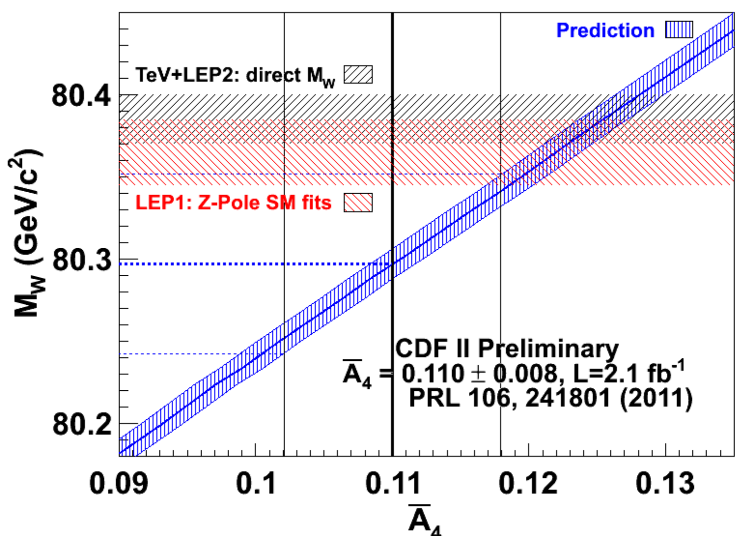
Wγ→lvγ

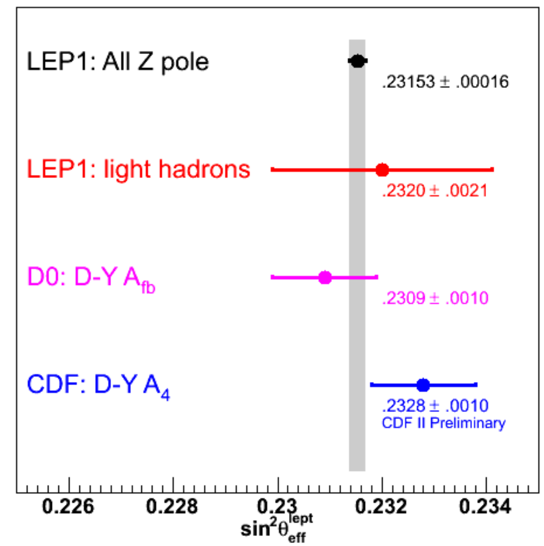
Λ= 2 TeV

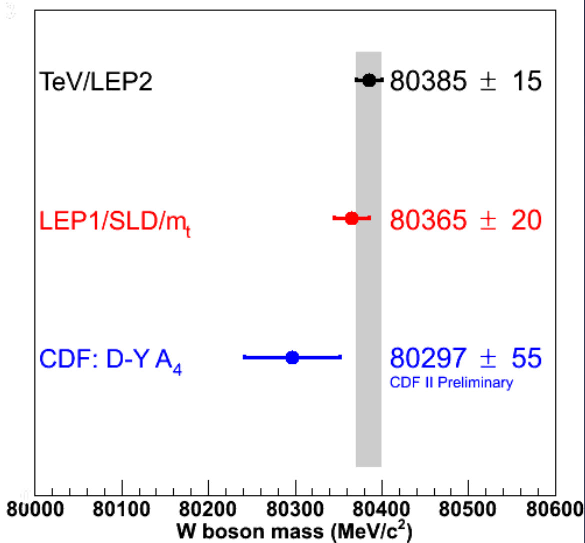


$\sin^2\theta_W$ (or M_W)

PRL 106, 241801 (2011)
CDF public note 10952







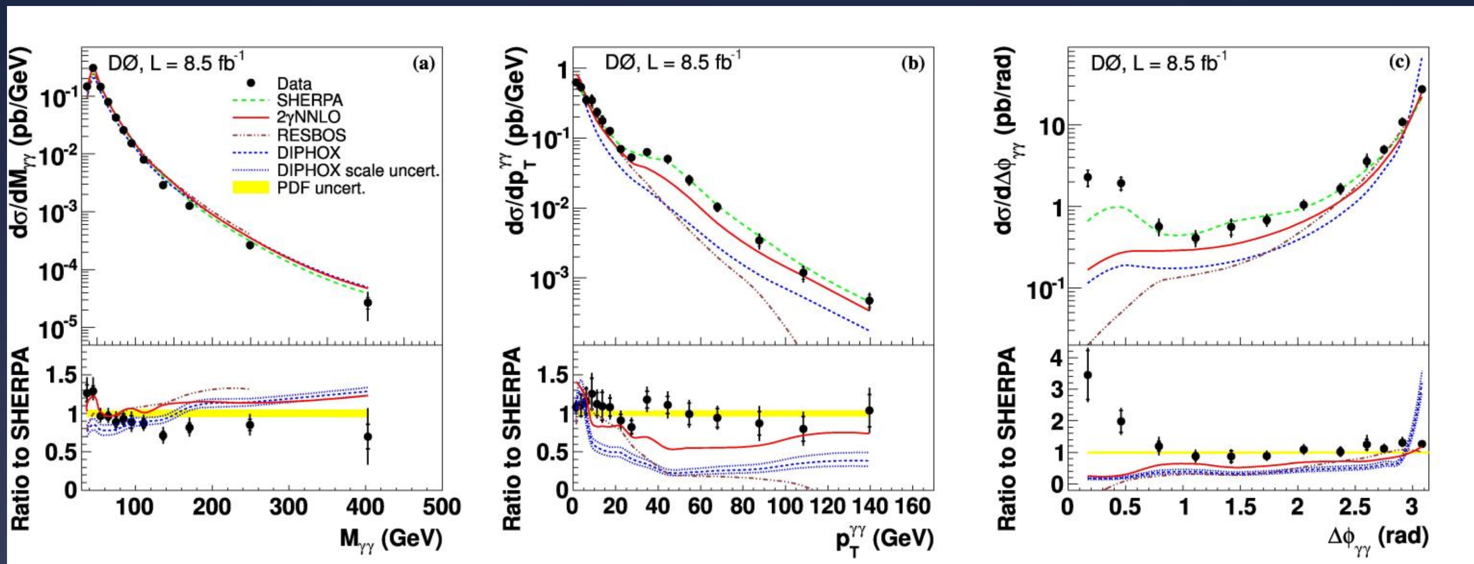
- ✧ Measured A_4 (V-A interference) from $\cos\theta$ term of the angular distribution of e^+e^- pairs with M_{ee} in [66,116] GeV/c^2
- ✧ Derived $\sin\theta_{eff}^{lep}$ and M_W from A_4 and ResBos prediction

QCD

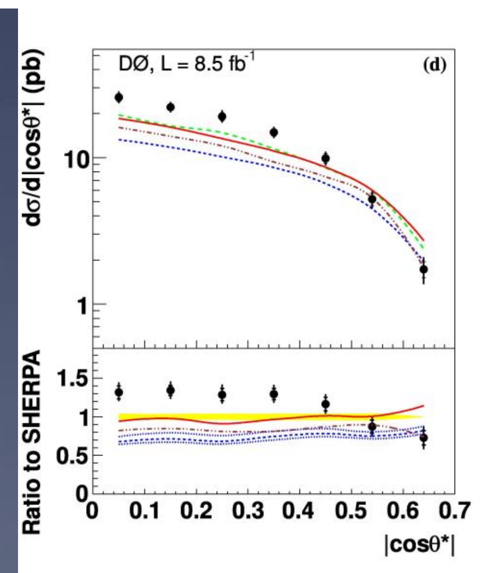
Challenging the predictive power
of a weakly converging theory

γγ cross section

arXiv:hep-ex/1301.4536, submitted to PLB

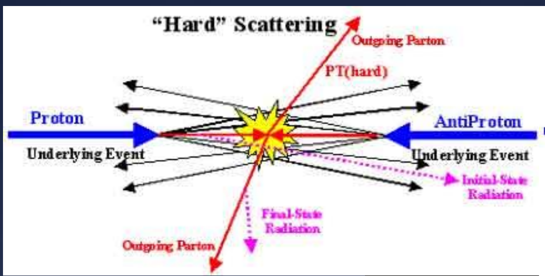


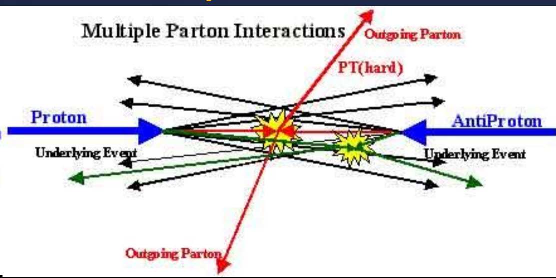
QCD@NNLO needed to describe the data

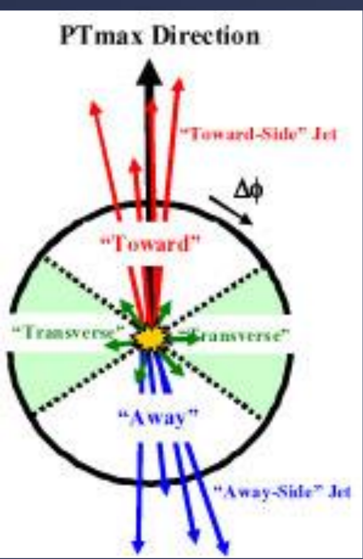


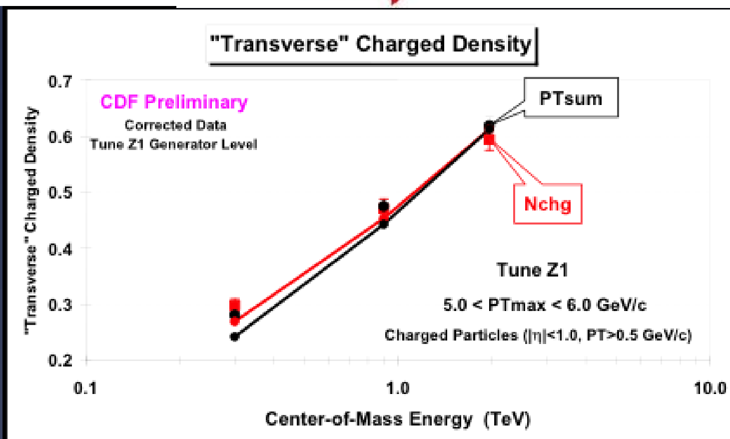
Underlying event @ 3 energies

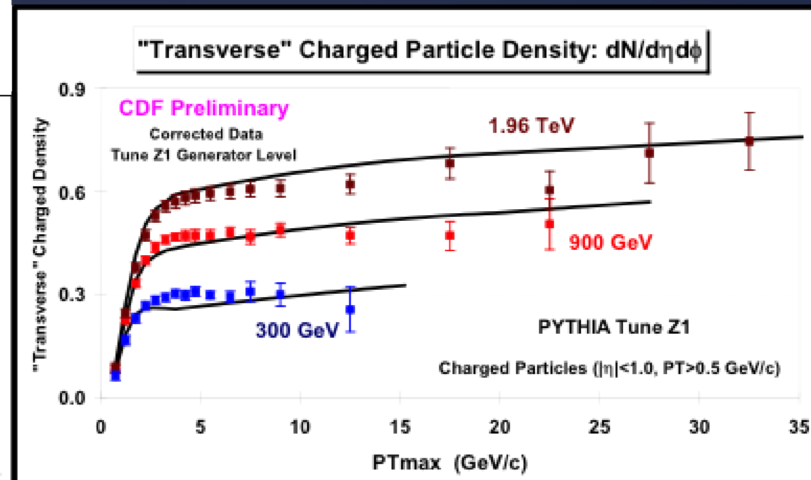
CDF public note 10874

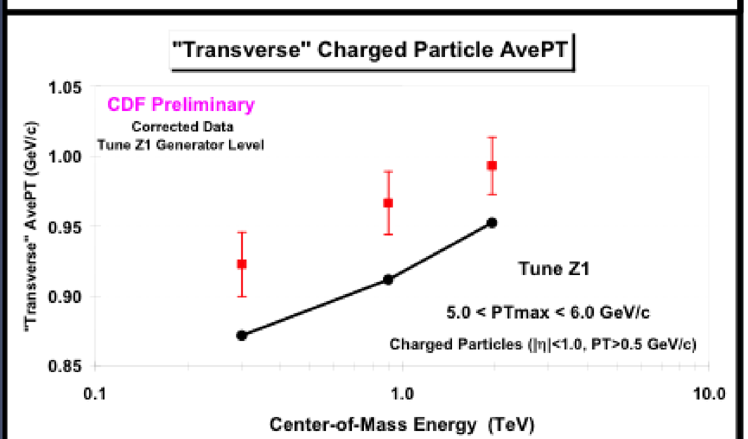


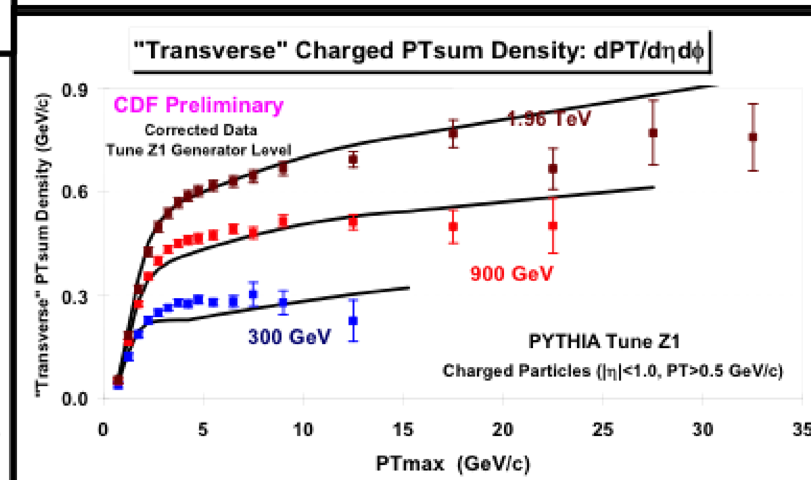






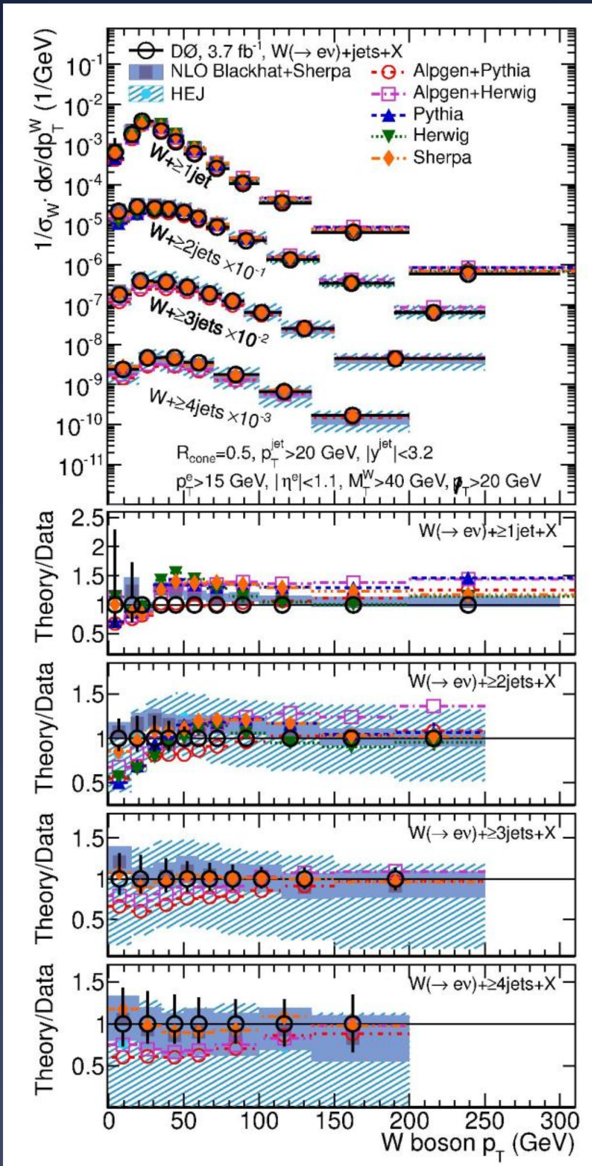


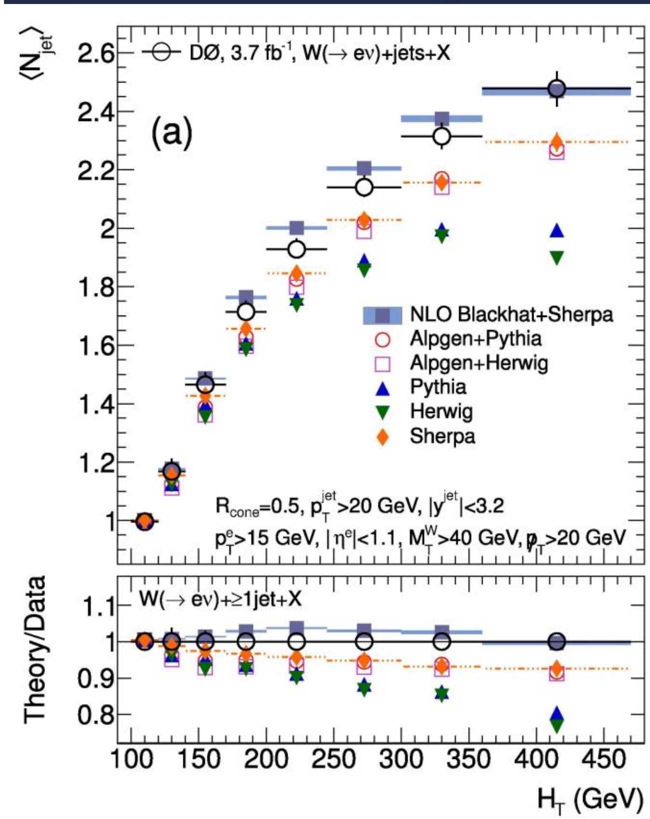


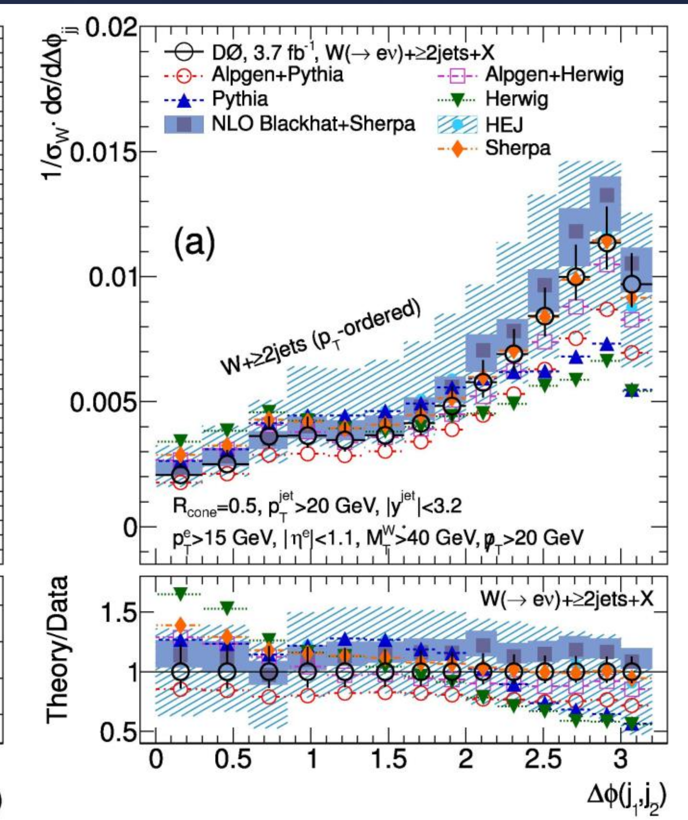


W(eν) + jets cross sections

arXiv:hep-ex/1302.6508, submitted to PRD





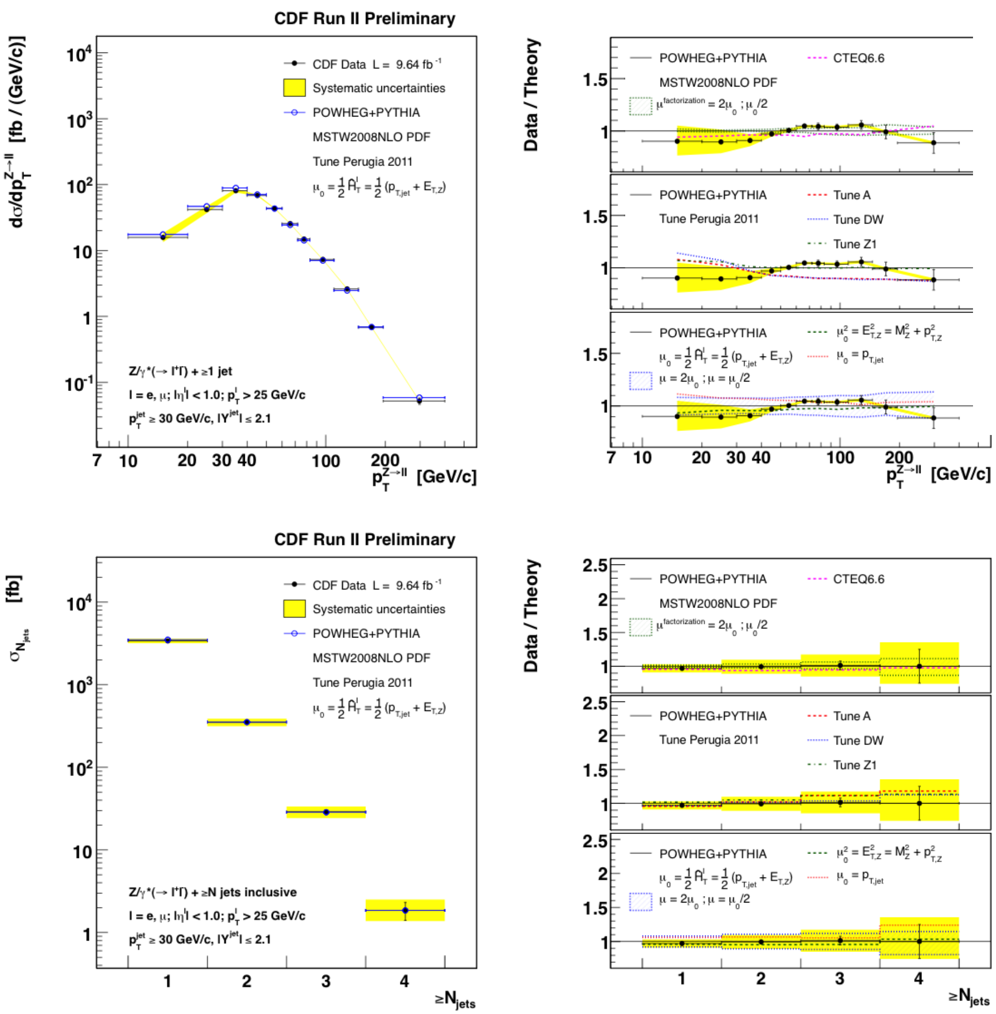


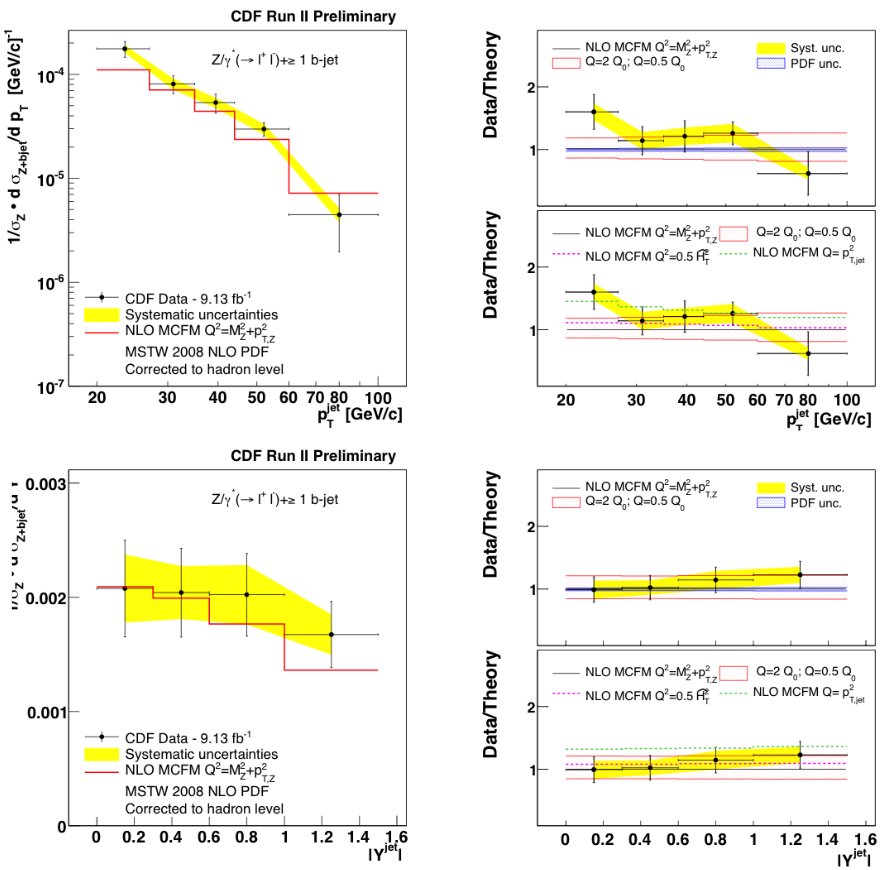
QCD@NLO works well

Z(ll) + jets cross sections

CDF public note 10216

M_{ll} in [66,116] GeV/c^2, ΔR=0.7





QCD@NLO works well

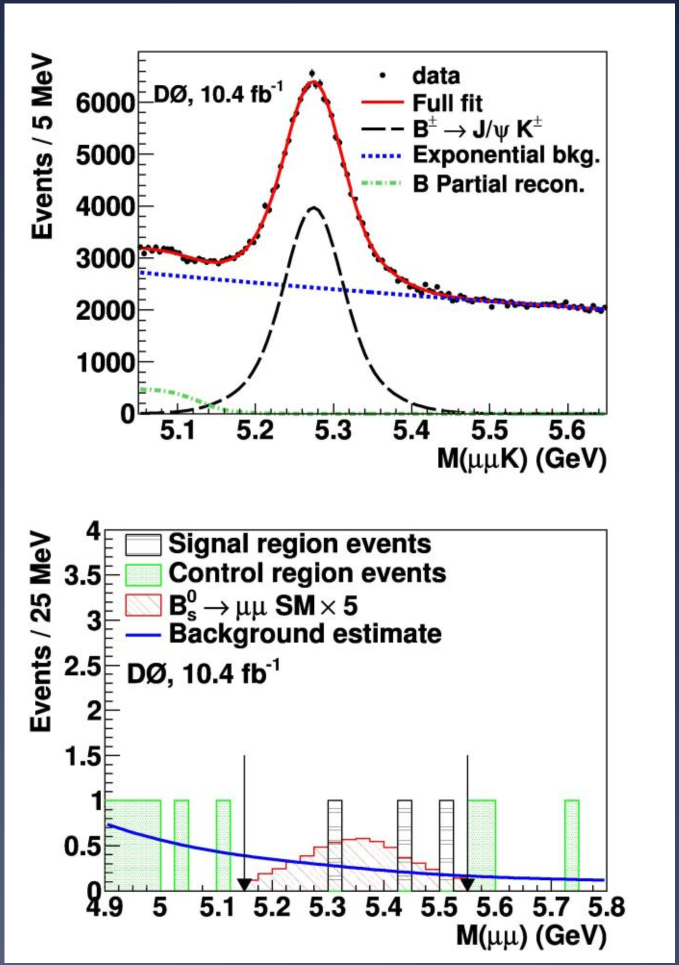
Flavor

SM and bound states
Looking for fine-tuning effects

Search for $B^0_s \to \mu\mu$ decay

PRD 87, 072006 (2013)

- ✧ FCNC suppressed: $BR_{SM} = 3.5\times10^{-9}$
- ✧ Used $B^{\pm}_d \to J/\psi K^{\pm} \to \mu^+\mu^- K^{\pm}$ for normalization
- ✧ Trained BDT against MC for signal & data sidebands for background

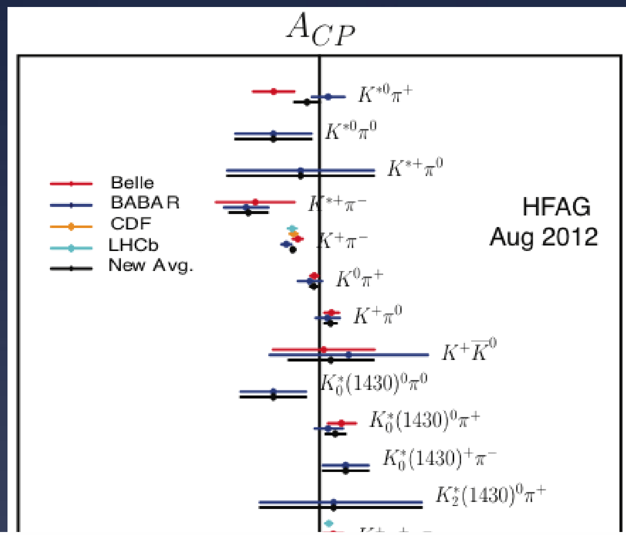


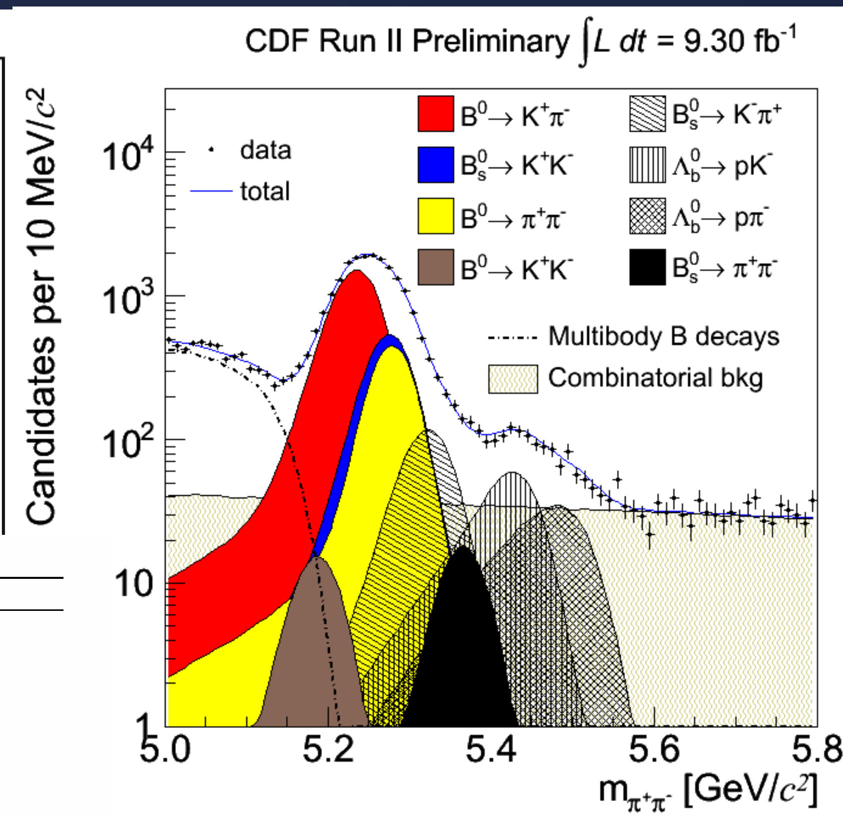
Experiment	Observed limits at 95% C.L. ($\times10^{-9}$)
ATLAS	22
CMS	7.7
LHCb	0.94
CDF	13
D0	15

A_{CP} in charmless bottom decays

CDF public note 10726

Consistent with e^+e^- colliders & LHCb





Quantity	Measurement
$\frac{\mathcal{B}(\overline{B}^0\to K^-\pi^+)-\mathcal{B}(B^0\to K^+\pi^-)}{\mathcal{B}(\overline{B}^0\to K^-\pi^+)+\mathcal{B}(B^0\to K^+\pi^-)}$	$\mathcal{A}_{CP}(B^0\to K^+\pi^-)= -0.083 \pm 0.013 \pm 0.003$
$\frac{\mathcal{B}(\overline{B}_s^0\to K^+\pi^-)-\mathcal{B}(B_s^0\to K^-\pi^+)}{\mathcal{B}(\overline{B}_s^0\to K^+\pi^-)+\mathcal{B}(B_s^0\to K^-\pi^+)}$	$\mathcal{A}_{CP}(B_s^0\to K^-\pi^+)= +0.22 \pm 0.07 \pm 0.02$
$\frac{\mathcal{B}(\Lambda_b^0\to p\pi^-)-\mathcal{B}(\overline{\Lambda}_b^0\to \overline{p}\pi^+)}{\mathcal{B}(\Lambda_b^0\to p\pi^-)+\mathcal{B}(\overline{\Lambda}_b^0\to \overline{p}\pi^+)}$	$\mathcal{A}_{CP}(\Lambda_b^0\to p\pi^-)= +0.07 \pm 0.07 \pm 0.03$
$\frac{\mathcal{B}(\Lambda_b^0\to pK^-)-\mathcal{B}(\overline{\Lambda}_b^0\to \overline{p}K^+)}{\mathcal{B}(\Lambda_b^0\to pK^-)+\mathcal{B}(\overline{\Lambda}_b^0\to \overline{p}K^+)}$	$\mathcal{A}_{CP}(\Lambda_b^0\to pK^-)= -0.09 \pm 0.08 \pm 0.04$

5σ $A_{CP}(B^0)$ significance

2.9σ in $A_{CP}(B^0_s)$ (4.5σ combined with LHCb)

CP violation in $B^{\pm}$ decays

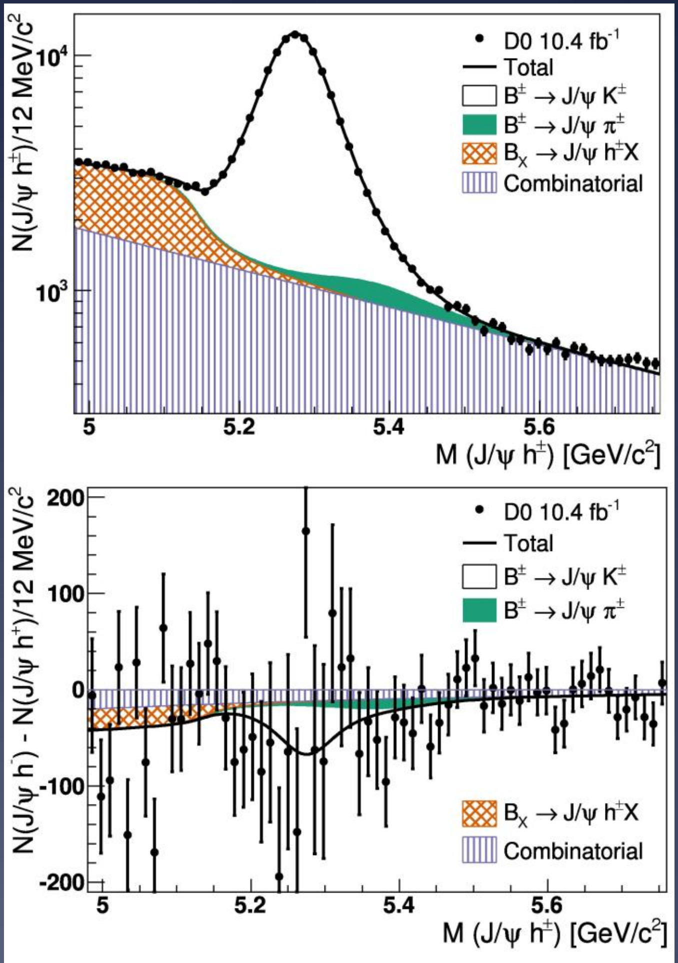
arXiv:hep-ex/1304.1655, submitted to PRL

Analyzed $B^{\pm} \rightarrow J/\psi K^{\pm} \rightarrow \mu^{+}\mu^{-}K^{\pm}$ & $B^{\pm} \rightarrow J/\psi \pi^{\pm} \rightarrow \mu^{+}\mu^{-}\pi^{\pm}$

- $A^{J/\psi K} = (0.59 \pm 0.36)\%$
- $A^{J/\psi \pi} = (-4.2 \pm 4.8)\%$

Most precise measurement, thanks to the ability to reverse the magnetic fields at D0

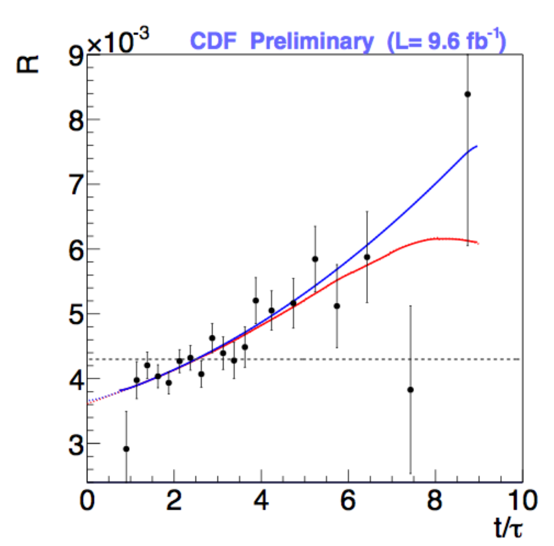
Consistent with SM expectations

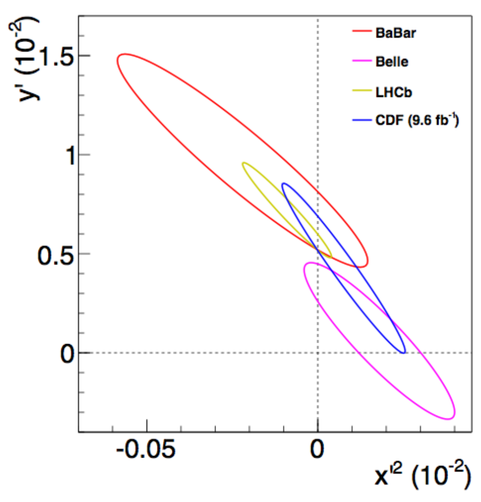


Charm mixing

CDF public note 10990

Experiment	R_D ($\times 10^{-3}$)	y' ($\times 10^{-3}$)	x'^2 ($\times 10^{-3}$)	Excl. No-Mix Significance	R_B ($\times 10^{-3}$)
Belle	3.64 ± 0.17	0.6 ± 4.0	0.18 ± 0.22	2.0	3.77 ± 0.09
BaBar	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9	3.53 ± 0.09
LHCb	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13	9.1	4.25 ± 0.04
CDF	3.51 ± 0.35	4.27 ± 4.30	0.08 ± 0.18	6.1	4.30 ± 0.06





$$R(t/\tau) = R_D + (t/\tau)\sqrt{R_D}\,y' + (t/\tau)^2\,\frac{x'^2 + y'^2}{4}$$

DCS to CF ratio | Interference | Mixing

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \qquad x \equiv \frac{M_2 - M_1}{\Gamma}$$

$$y' = y\cos\delta_{K\pi} - x\sin\delta_{K\pi} \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

Confirmed recent LHCb observation of charm mixing (from single decay channel)

Future

Priorities: Tevatron-relevant measurements with full luminosity,
including combinations of results (CDF + D0 and LHC + Tevatron, when appropriate)

BSM: Relevant searches where triggers/backgrounds favor Tevatron vs. LHC

SM: Exhaust precision limits of legacy measurements (M_W, M_{top}, A_{FB}, s-channel σ_t)

Flavor: Exploit advantage in production with CP-invariant initial state

Conclusions

- ✧ Tevatron experiments keep producing high-quality results
- ✧ Higgs program completed, independent evidence from a proton-antiproton collider
- ✧ Precision measurements of M_W & M_{top} consistent with M_H measured at the LHC
- ✧ Stringent tests of SM & constraints on new physics models are driving theory
- ✧ Ongoing joint effort by Fermilab and Tevatron experiments to preserve data and analysis knowledge of the unique Tevatron proton-antiproton sample