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FOR NUCLEAR RESEARCH

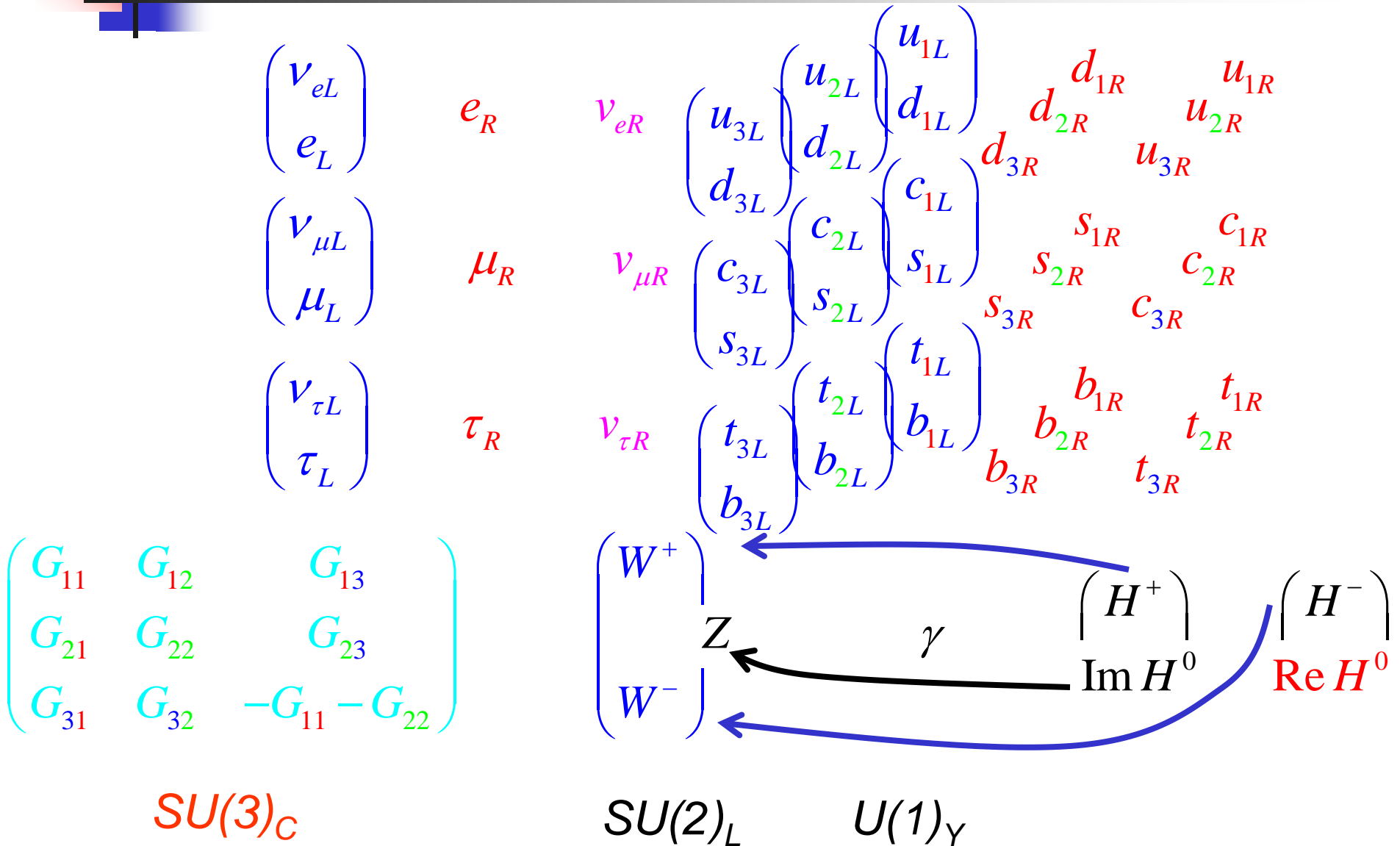


Precision Measurements and Tevatron Legacy

M.V. Chizhov

Sofia University and JINR

Standard Model (SM)



Gauge group of the SM

$SU(3)_C$

\otimes

$SU(2)_L$

\otimes

$U(1)$

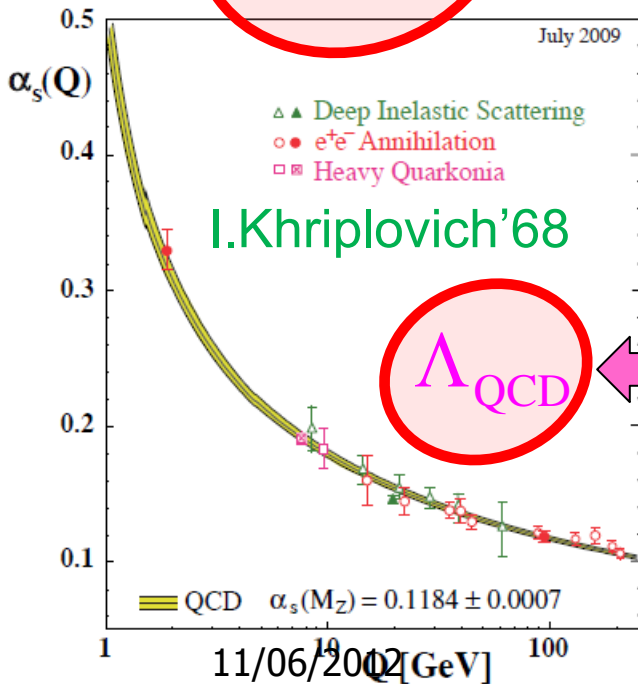
g_3

$$\alpha_s = \frac{g_3^2}{4\pi}$$

$$g = \frac{e}{\sin \theta_W}$$

$$g' = \frac{e}{\cos \theta_W}$$

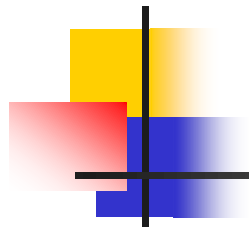
$$\alpha = \frac{e^2}{4\pi}$$



Spontaneous Symmetry Breaking

$$G_F = \frac{\pi \alpha}{\sqrt{2} \sin^2 \theta_W \cos^2 \theta_W M_Z^2 (1 - \Delta r)}$$

...contains one more independent parameter: the Higgs mass $\Delta r(M_H)$



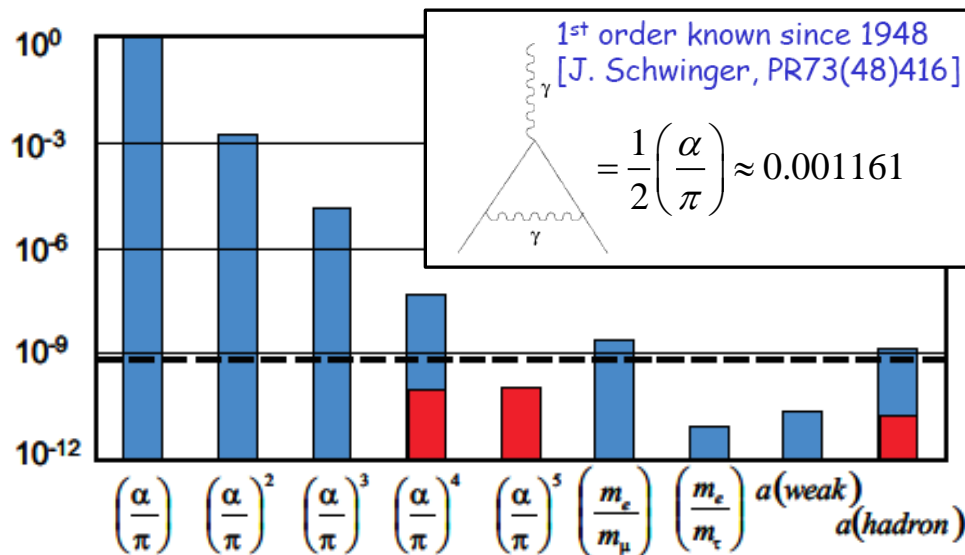
α

The electron anomalous magnetic moment and the fine-structure constant measurements

$$g/2 [0.28 \text{ ppt}] \rightarrow a_e^{\text{exp}} \equiv \frac{g-2}{2} = 0.001159\,652\,180\,73(28) \quad [0.24 \text{ ppt}]$$

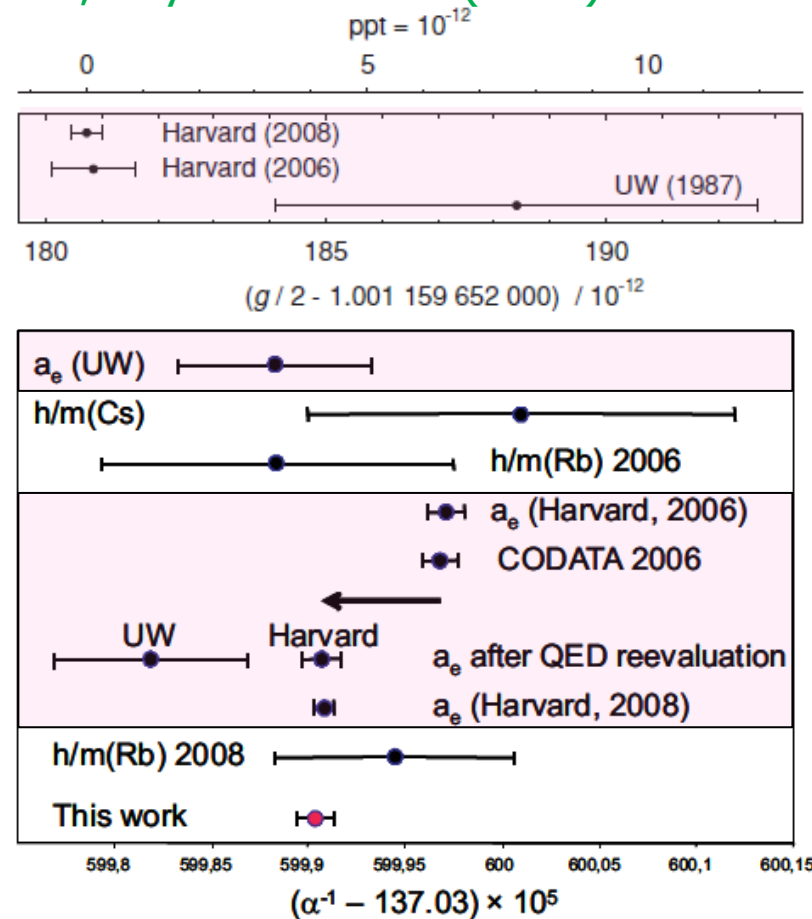
D. Hanneke, S. Fogwell and G. Gabrielse, Phys. Rev. Lett. **100** (2008) 120801;

D. Hanneke, S. Fogwell Hoogerheide and G. Gabrielse, Phys. Rev. A **83** (2011) 052122



$$\alpha^{-1}(\text{Rb}) = 137.035\,999\,037(91) \quad [0.66 \text{ ppb}]$$

R. Bouchendir, P. Clade, S. Guellati-Khelifa, F. Nez and F. Biraben, Phys. Rev. Lett. **106** (2011) 080801



Fine-structure constant determination

arXiv:1205.5368v1 [hep-ph] 24 May 2012

Tenth-Order QED Contribution to the Electron $g-2$ and an Improved Value of the Fine Structure Constant

Tatsumi Aoyama,^{1,2} Masashi Hayakawa,^{3,2} Toichiro Kinoshita,^{4,2} and Makiko Nio²

¹*Kobayashi-Maskawa Institute for the Origin of Particles and the Universe (KMI), Nagoya University, Nagoya, 464-8602, Japan*

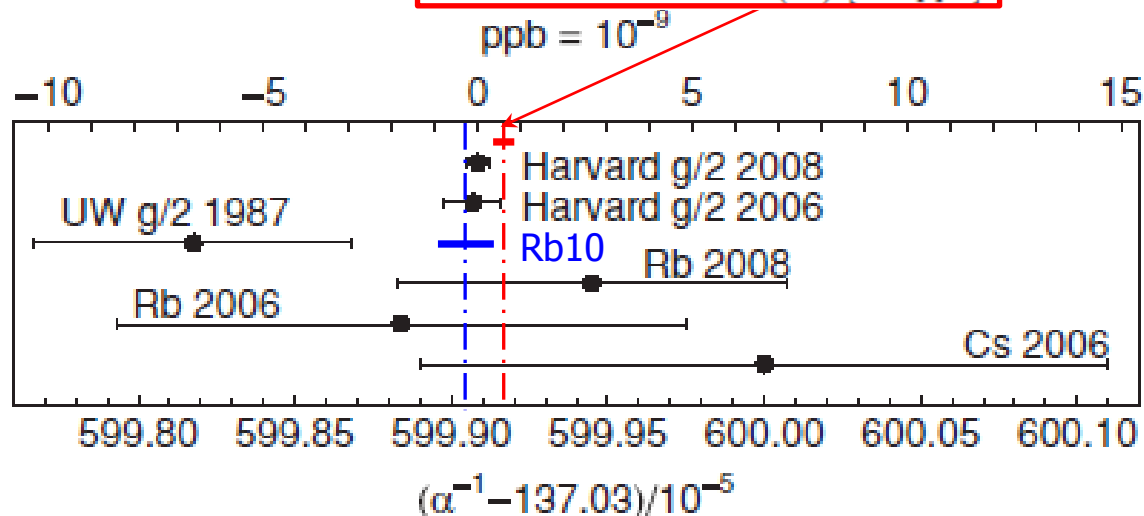
²*Nishina Center, RIKEN, Wako, Japan 351-0198*

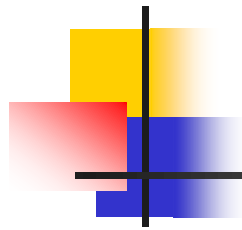
³*Department of Physics, Nagoya University, Nagoya, Japan 464-8602*

⁴*Laboratory for Elementary Particle Physics, Cornell University, Ithaca, New York, 14853, U.S.A*

(Dated: May 25, 2012)

This paper presents the complete QED contribution to the electron $g-2$ up to the tenth order. With the help of the automatic code generator, we have evaluated all 12672 diagrams of the tenth-order diagrams and obtained $a_e^{(10)} = 9.16 (58)$ in units of $(\alpha/\pi)^5$. We have also improved the eighth-order contribution obtaining $a_e^{(8)} = -1.9097 (20)$ in units of $(\alpha/\pi)^4$, which includes the mass-dependent contributions. These results together with the measurement of a_e lead to the improved value of the fine-structure constant $\alpha^{-1} = 137.035 999 166 (34) [0.25\text{ppb}]$.





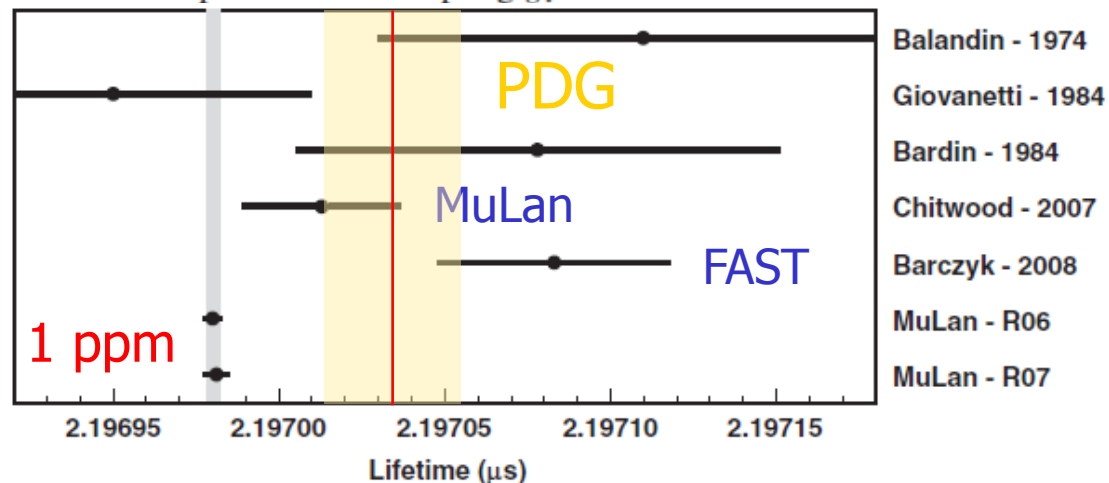
G ***F***

Measurement of the Positive Muon Lifetime and Determination of the Fermi Constant to Part-per-Million Precision

D. M. Webber,¹ V. Tishchenko,² Q. Peng,³ S. Battu,² R. M. Carey,³ D. B. Chitwood,¹ J. Crnkovic,¹ P. T. Debevec,¹ S. Dhamija,² W. Earle,³ A. Gafarov,³ K. Giovanetti,⁴ T. P. Gorringer,² F. E. Gray,⁵ Z. Hartwig,³ D. W. Hertzog,¹ B. Johnson,⁶ P. Kammel,¹ B. Kiburg,¹ S. Kizilgul,¹ J. Kunkle,¹ B. Lauss,⁷ I. Logashenko,³ K. R. Lynch,³ R. McNabb,¹ J. P. Miller,³ F. Mulhauser,^{1,7} C. J. G. Onderwater,^{1,8} J. Phillips,³ S. Rath,² B. L. Roberts,³ P. Winter,¹ and B. Wolfe¹

(MuLan Collaboration)

We report a measurement of the positive muon lifetime to a precision of 1.0 ppm; it is the most precise particle lifetime ever measured. The experiment used a time-structured, low-energy muon beam and a segmented plastic scintillator array to record more than 2×10^{12} decays. Two different stopping target configurations were employed in independent data-taking periods. The combined results give $\tau_{\mu^+}(\text{MuLan}) = 2\,196\,980.3(2.2)$ ps, more than 15 times as precise as any previous experiment. The muon lifetime gives the most precise value for the Fermi constant: $G_F(\text{MuLan}) = 1.166\,378\,8(7) \times 10^{-5} \text{ GeV}^{-2}$ (0.6 ppm). It is also used to extract the μ^-p singlet capture rate, which determines the proton's weak induced pseudoscalar coupling g_P .



Fermi constant determination

Theoretical uncertainty in the determination of G_F is less than 0.3 ppm

$$\tau_\mu^{-1} = \frac{G_F^2 m_\mu^2}{192 \pi^3} F(\rho) \left(1 + \frac{3}{5} \frac{m_\mu^2}{M_W^2} \right) \left[1 + H_1(\rho) \frac{\hat{\alpha}(m_\mu)}{\pi} + H_2(\rho) \frac{\hat{\alpha}^2(m_\mu)}{\pi^2} \right],$$

where $\rho = m_e^2/m_\mu^2$ and $F(\rho) = 1 - 8\rho + 8\rho^3 - \rho^4 - 12\rho^2 \ln \rho \approx 0.999813$,

$$H_1(\rho) = \frac{25}{8} - \frac{\pi^2}{2} - (9 + 4\pi^2 + 12 \ln \rho) \rho + 16\pi^2 \rho^{3/2} + O(\rho^2) \approx -1.8079,$$

R. K. Behrends, R. J. Finkelstein, & A. Sirlin, Phys. Rev. **101** (1955) 866;
T. Kinoshita & A. Sirlin, Phys. Rev. **113** (1959) 1652

$$H_2(\rho) = \frac{156815}{5184} - \frac{518}{81} \pi^2 - \frac{895}{36} \zeta(3) + \frac{67}{720} \pi^4 + \frac{53}{6} \pi^2 \ln 2 - \frac{5}{4} \pi^2 \sqrt{\rho} + O(\rho) \approx 6.7,$$

T. van Ritbergen & R.G. Stuart, Phys. Rev. Lett. **82** (1999) 488

A. Pak & A. Czarnecki, Phys. Rev. Lett. **100** (2008) 241807

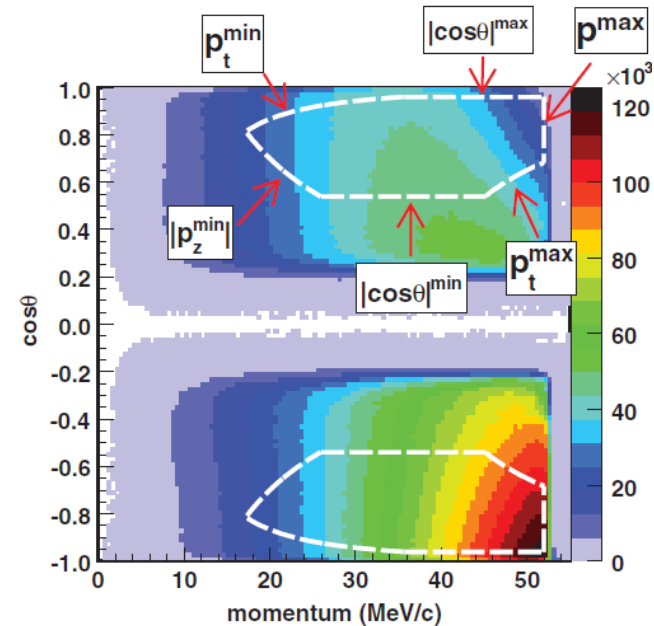
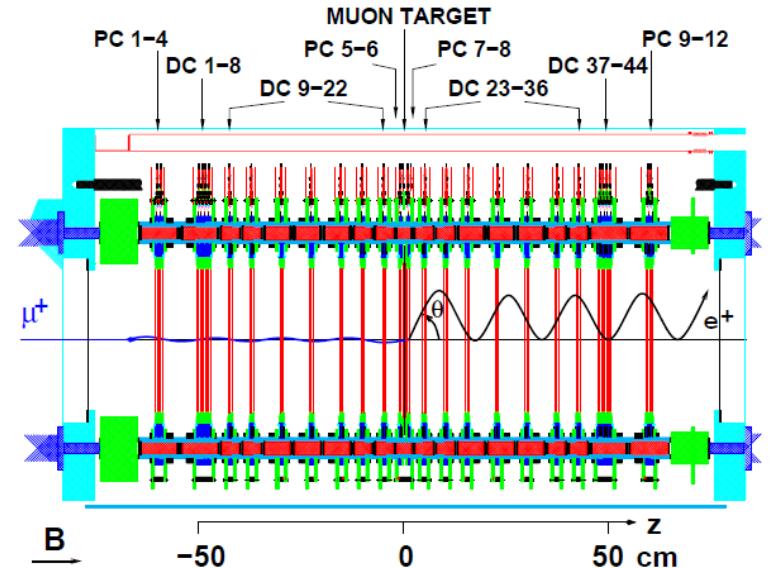
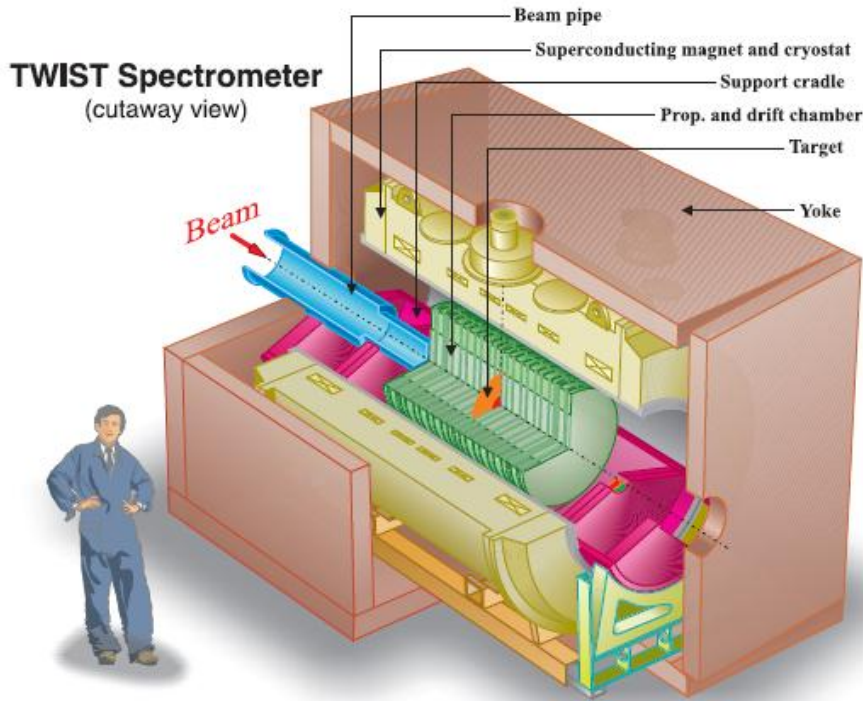
$$\hat{\alpha}(m_\mu)^{-1} = \alpha^{-1} + \frac{1}{3\pi} \ln \rho \approx 135.9. \quad G_F^{\text{PDG}} = 1.166\,364\,(5) \times 10^{-5} \text{ GeV}^{-2} [4.3 \text{ ppm}]$$

$$G_F = 1.166\,378\,8\,(7) \times 10^{-5} \text{ GeV}^{-2} [0.6 \text{ ppm}]$$

$$11/06/2012 \quad |V_{ud}^{\text{PDG}}| = 0.97425(22) \quad |V_{ud}| = 0.97423(22)$$

TWIST

TRIUMF Weak Interaction Symmetry Test



$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

$$\frac{d^2\Gamma}{dE d\cos\theta} \sim F_{\text{IS}}(E, \rho, \eta) + P_\mu F_{\text{AS}}(E, \delta, \xi) \cos\theta$$

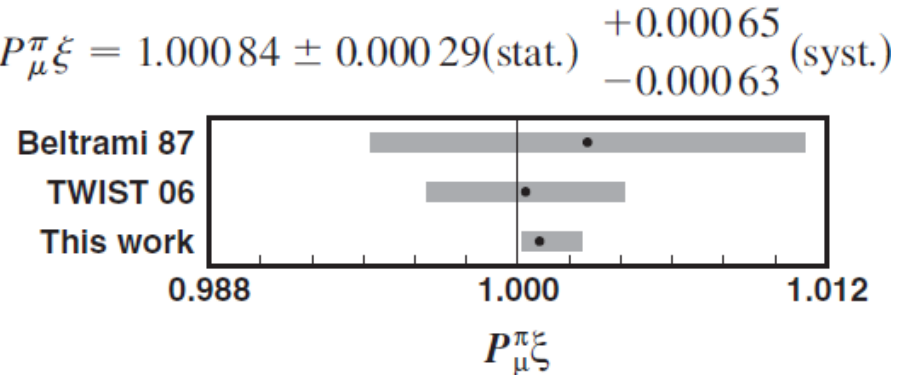
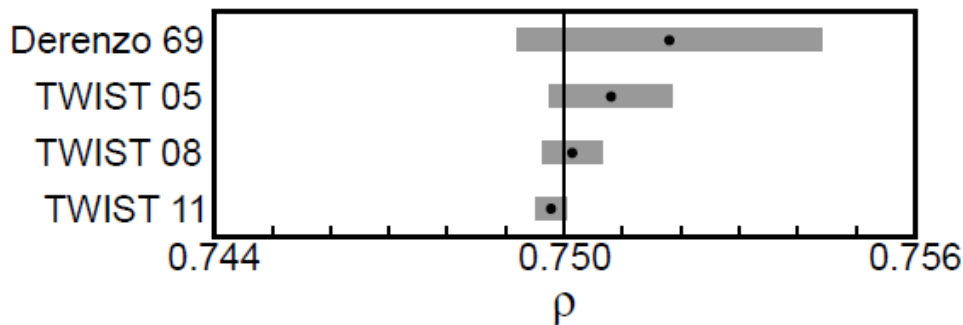
L. Michel, Proc. Phys. Soc. A**63**, 514 (1950).

TWIST final results

Phys. Rev. D **85** (2012) 092013

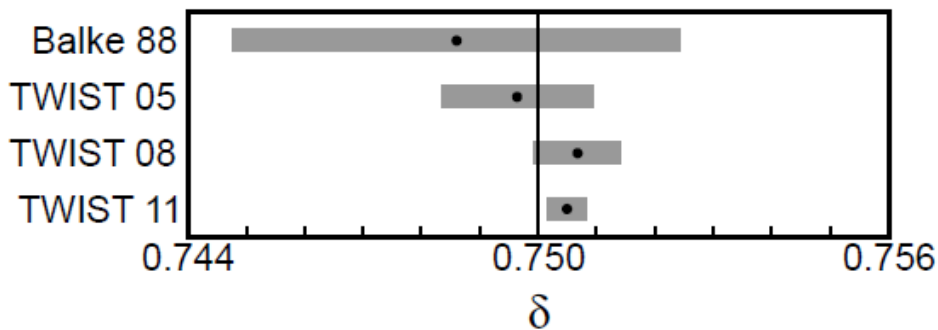
Phys. Rev. D **84** (2011) 032005

$$\rho = 0.74977 \pm 0.00012(\text{stat.}) \pm 0.00023(\text{syst.}) \quad P_{\mu\xi}^{\pi} = 1.00084 \pm 0.00029(\text{stat.}) \begin{matrix} +0.00065 \\ -0.00063 \end{matrix} (\text{syst.})$$



$$\delta = 0.75049 \pm 0.00021(\text{stat.}) \pm 0.00027(\text{syst.})$$

$$P_{\mu}^{\pi} \xi \delta / \rho = 1.00179 \begin{matrix} +0.00156 \\ -0.00071 \end{matrix} \leq 1$$



$$-0.009 < g_{RR}^T < +0.0005$$

C. A. Gagliardi, R. E. Tribble,
and N. J. Williams

Phys. Rev. D **84** (2011) 032005

$$\eta = -0.0036 \pm 0.0069$$

$$G_F = 1.1663788(7)(781)_{\eta} \times 10^{-5} \text{ GeV}^{-2}$$

M.V. Chizhov, Mod. Phys. Lett. A **9** (1994) 2979

Choosing the third constant

PDG 2010: [Journal of Physics G 37, 075021 \(2010\)](#)

$$M_Z = 91.1876 \pm 0.0021 \text{ GeV} \quad 23 \text{ ppm}$$

$$\sin^2 \theta_W^{\text{eff}} = 0.23146 \pm 0.00012 \quad 518 \text{ ppm}$$

| α | G_F | M_Z^2 |
|-------------|---------|---------|
| 0.00025 ppm | 0.6 ppm | 46 ppm |

$$\alpha = 1/137.035\,999\,166\,(34) \quad 0.25 \text{ ppb}$$

$$G_F = 1.166\,378\,8\,(7) \times 10^{-5} \text{ GeV}^{-2} \quad 0.6 \text{ ppm}$$

$$M_Z = 91.1876\,(21) \text{ GeV} \quad 23 \text{ ppm}$$

$$\hat{\alpha}(M_Z) = \frac{\alpha}{1 - \Delta\alpha(M_Z)} = 1/127.916\,(15) \quad 117 \text{ ppm}$$

For scales above a few hundred MeV extra uncertainty due to the low energy hadronic contribution to vacuum polarization is introduced.

Electroweak Quantum corrections (M_W , m_t and M_H)

All coupling constants are functions of a scale (by the way, definition of the mass is also scale dependent). Therefore, different definitions of the $\sin^2 \theta_W$, which are equivalent in the Born (tree) approximation, depend on the renormalization prescription. There are a number of popular schemes leading to values which differ by small factors depending on m_t and M_H .

On-shell scheme $\sin^2 \theta_W \rightarrow s_W^2 \equiv 1 - \frac{M_W^2}{M_Z^2}$: $M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F (1 - M_W^2/M_Z^2)(1 - \dots)}$

$$\Delta r = \Delta r_0 - \Delta r_t + \Delta r_H, \quad \text{where } \Delta r_0 = 1 - \alpha / \alpha(M_Z) = 0.06655(\dots)$$



$$\Delta r_t = \frac{3G_F m_t^2}{8\sqrt{2}\pi^2 \tan^2 \theta_W} \quad \Delta r_H \approx 0.00$$

$$= 0.03269 \left(\frac{m_t}{173.2 \text{ GeV}} \right)^2$$

$$\Delta r = 0.03617 \mp 0.00034_{m_t} \pm 0.00011_{\alpha(M_Z)}; \quad \Delta M_W = 0.006$$

M. Awramik, M. Czakon, A. Freitas, and G. Weiglein, Phys. Rev. D **69** (2004) 053006



What about Appelquist–Carazzone decoupling theorem?

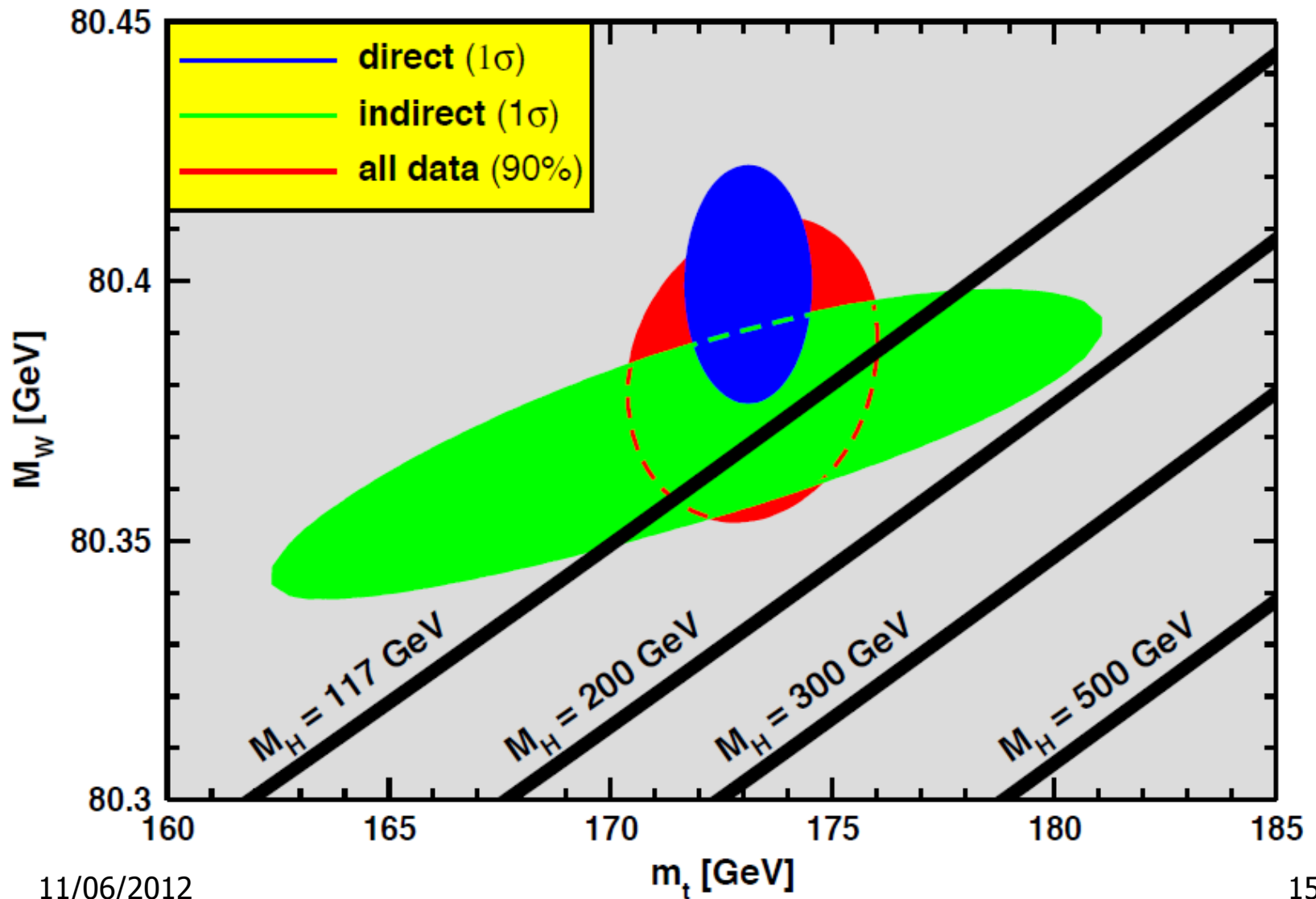
T. Appelquist & J. Carazzone, Phys. Rev. D **11** (1975) 2856

In QED and QCD the vacuum polarization contribution of a heavy fermion pair is suppressed by inverse powers of the fermion mass. At low energies, the information on the heavy fermions is then lost. This ‘decoupling’ of the heavy fields happens in theories with only **vector couplings** and an **exact gauge symmetry**, where the effects generated by the heavy particles can always be reabsorbed into a redefinition of the low-energy parameters.

The SM involves, however, a broken chiral gauge symmetry. Therefore, the electroweak quantum corrections offer the possibility to be sensitive to heavy particles, which cannot be kinematically accessed, through their virtual loop effect. The vacuum polarization contributions induced by a heavy top generate corrections to the W^\pm and Z propagators, which increase **quadratically** with the top mass [M. Veltman, Nucl. Phys. B **123** (1977) 89]. Therefore, a heavy top does not decouple. For instance, with $m_t = 173$ GeV, the leading quadratic correction to M_W^2 amounts to a sizeable 3% effect. The quadratic mass contribution originates in the strong breaking of weak isospin generated by the top and bottom quark masses, i.e., the effect is actually proportional to $m_t^2 - m_b^2$.

Owing to an accidental $SO(3)_C$ symmetry of the scalar sector (the so-called custodial symmetry), the virtual production of Higgs particles does not generate any quadratic dependence on the Higgs mass at one loop [M. Veltman]. The dependence on M_H is only logarithmic. The numerical size of the corresponding correction to M_W^2 varies from a 0.1% to a 1% effect for M_H in the range from 100 to 1000 GeV.

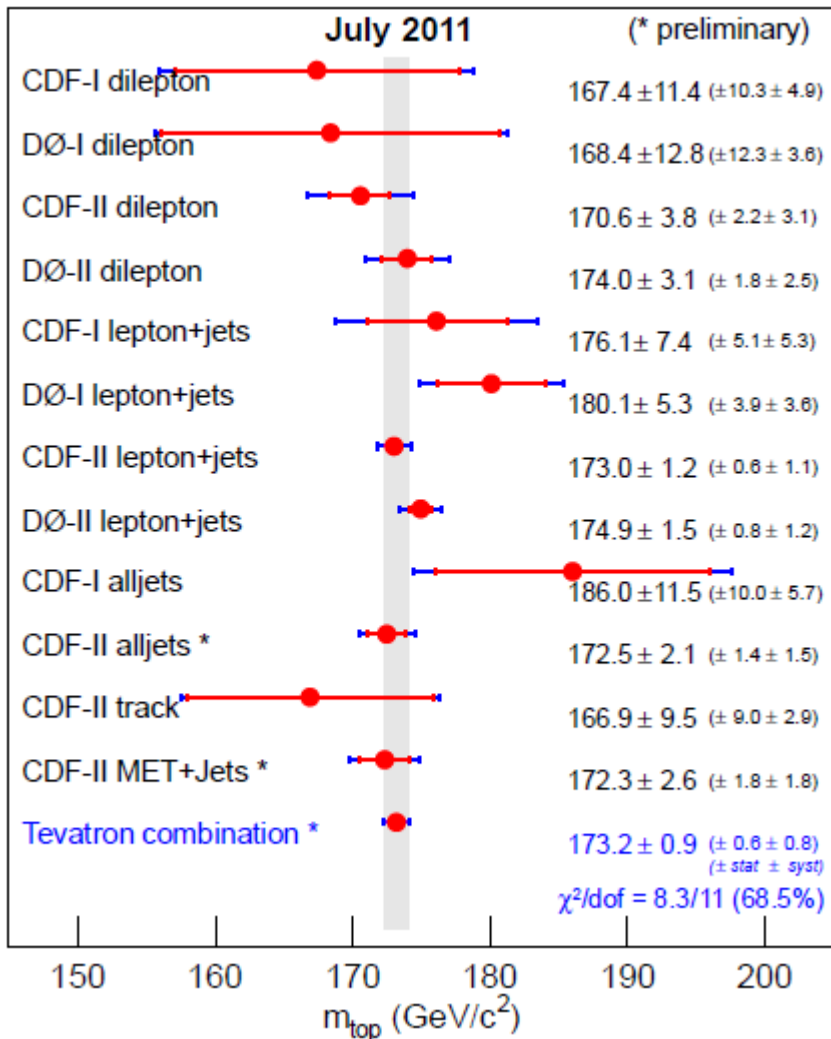
SM prediction versus data (PDG)



Tevatron: $m_t = 173.18 \pm 0.94$ GeV

arXiv:1107.5255

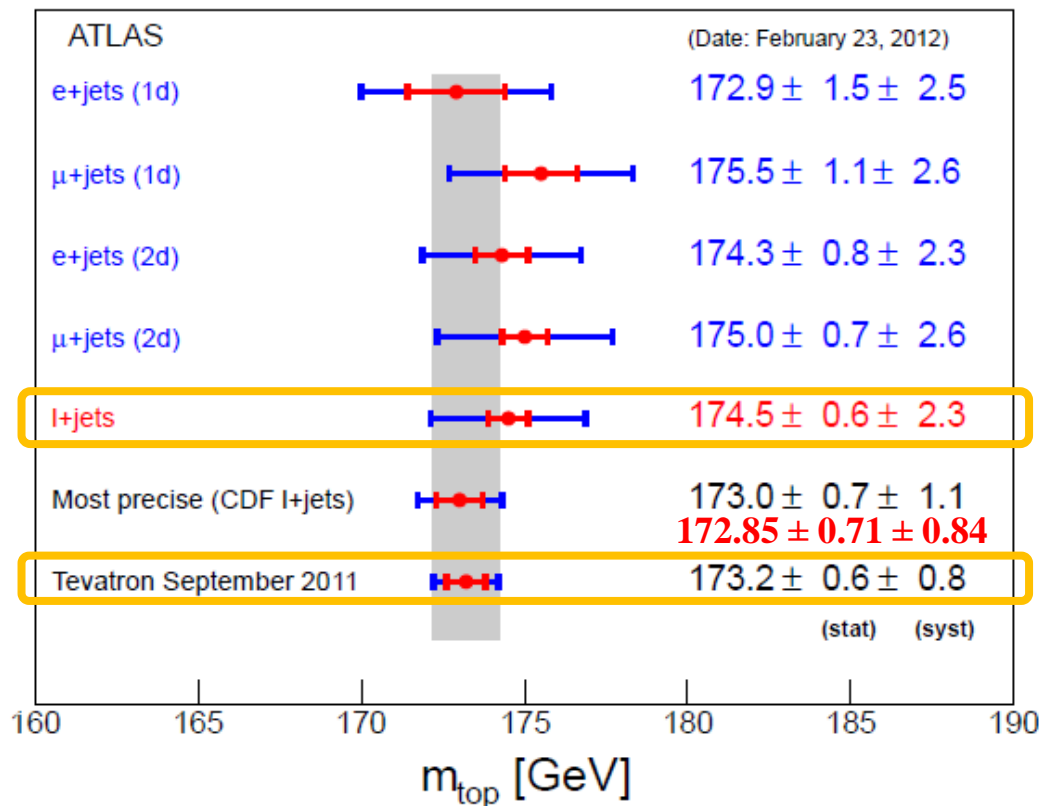
Mass of the Top Quark



11/06/2012

ATLAS 1.04 fb^{-1} !

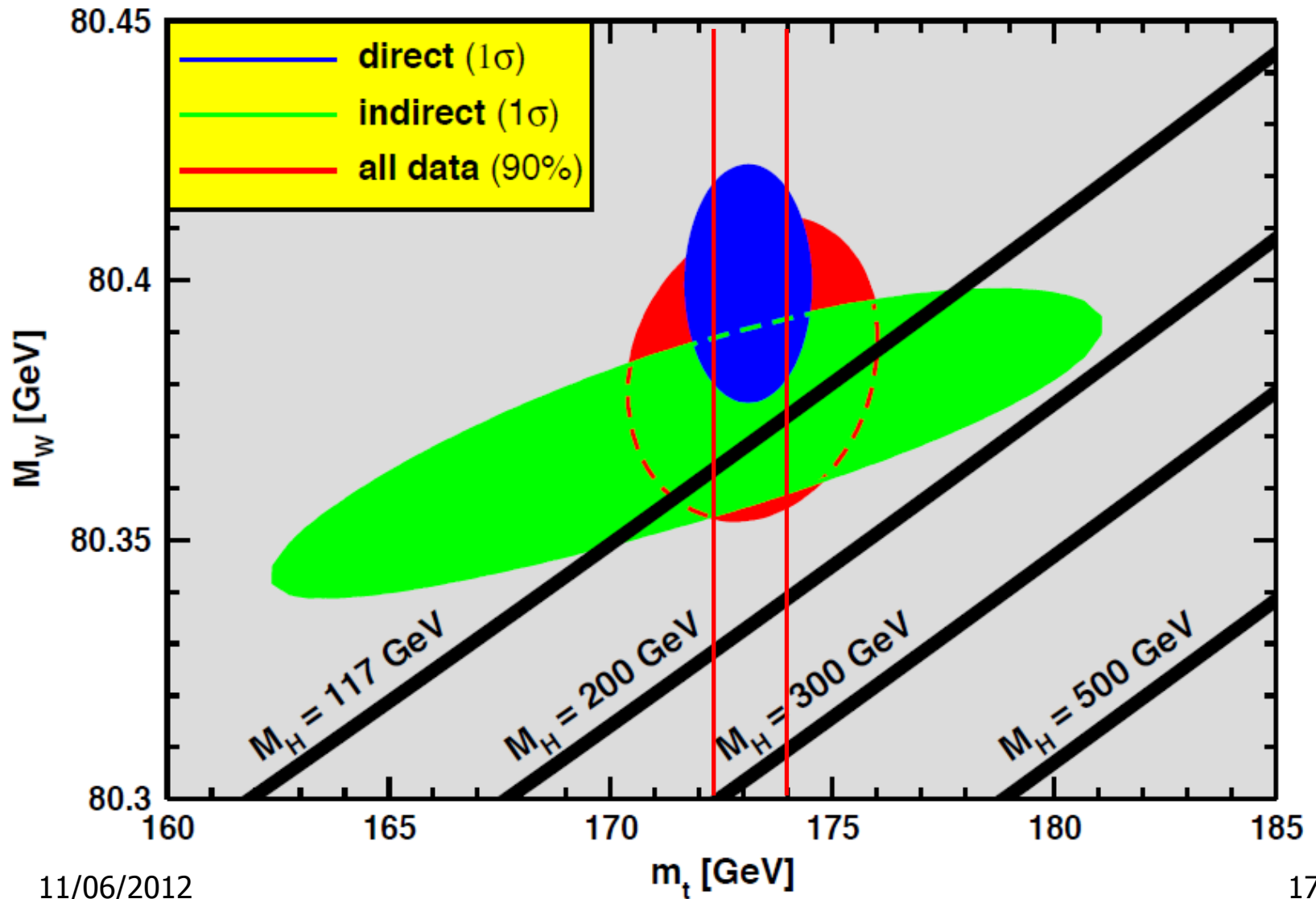
arXiv:1203.5755



CDF 8.7 fb^{-1} !

Conf Note 10761

SM prediction versus data & new m_t



Tevatron: $M_W = 80.387 \pm 0.016$ GeV

arXiv:1204.0042

Mass of the W Boson

Measurement

CDF-0/I

DØ-I

DØ-II (1.0 fb⁻¹)

CDF-II (2.2 fb⁻¹)

DØ-II (4.3 fb⁻¹)

Tevatron Run-0/I/II

LEP-2

World Average

M_W [MeV]

80432 ± 79

80478 ± 83

80402 ± 43

80387 ± 19

80369 ± 26

80387 ± 16

80376 ± 33

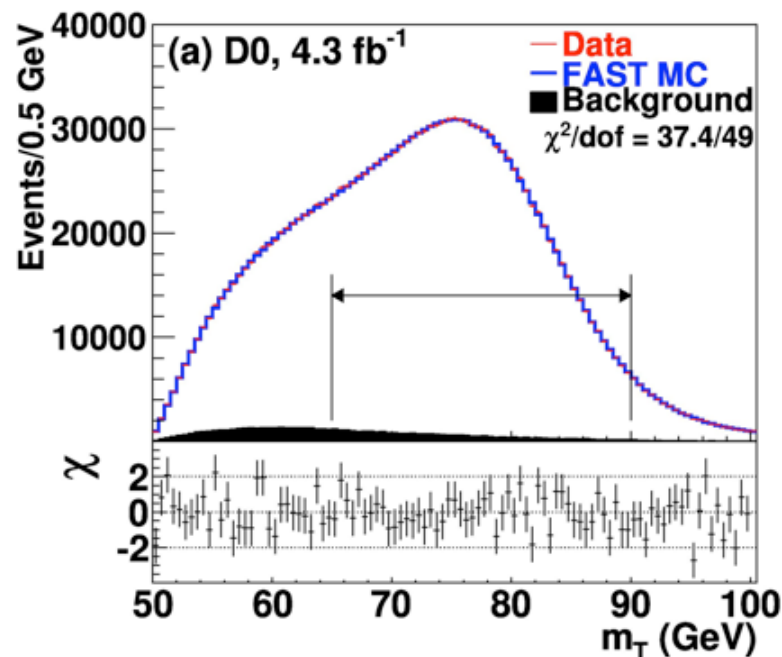
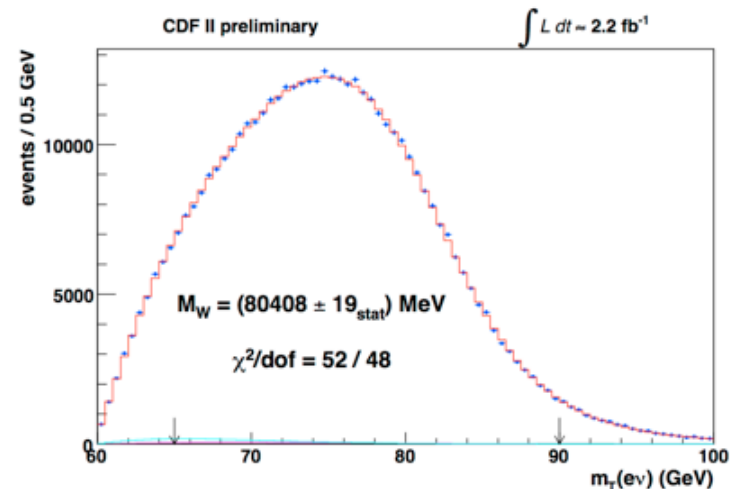
80385 ± 15

80200 80400 80600

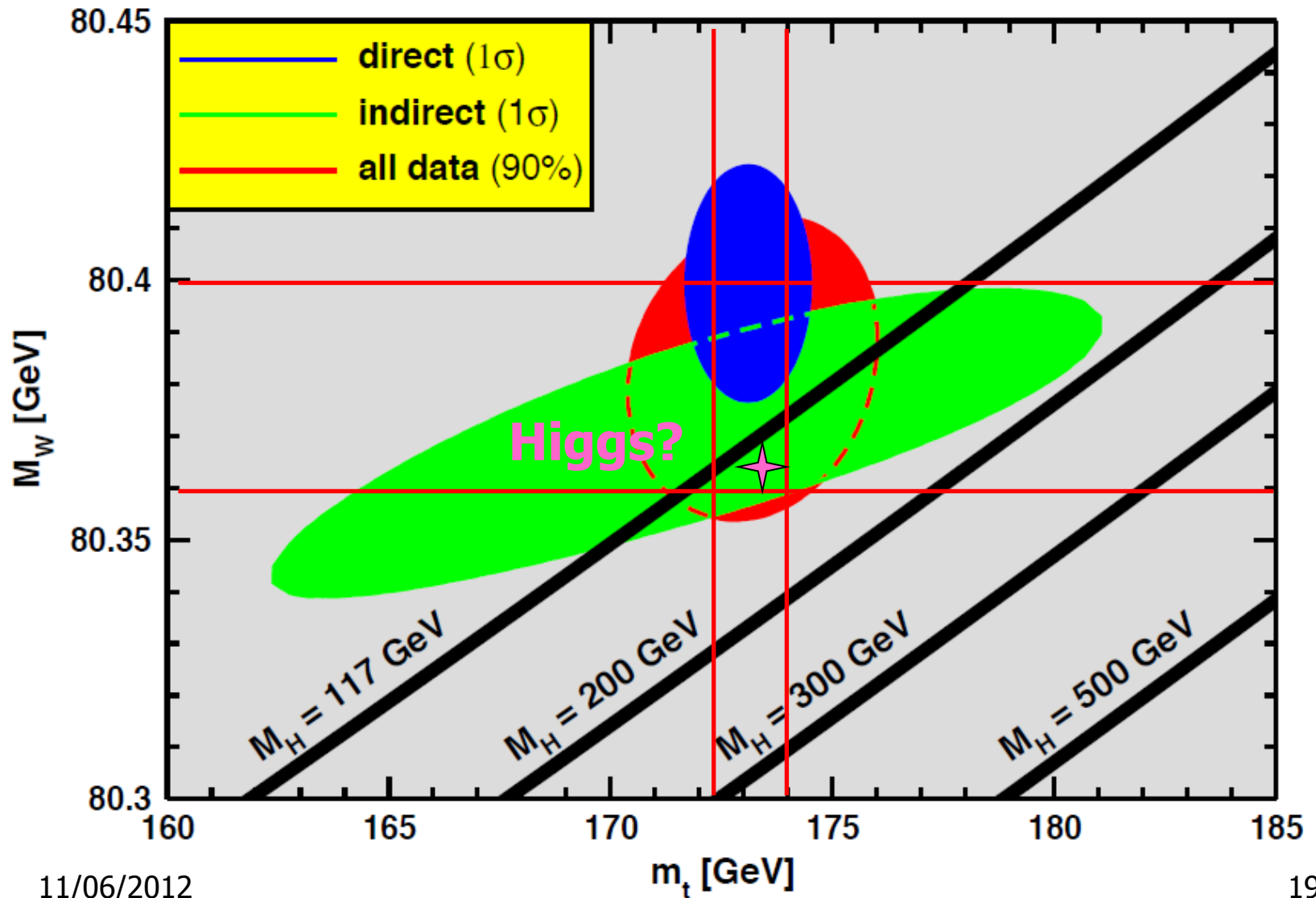
M_W [MeV]

11/06/2012

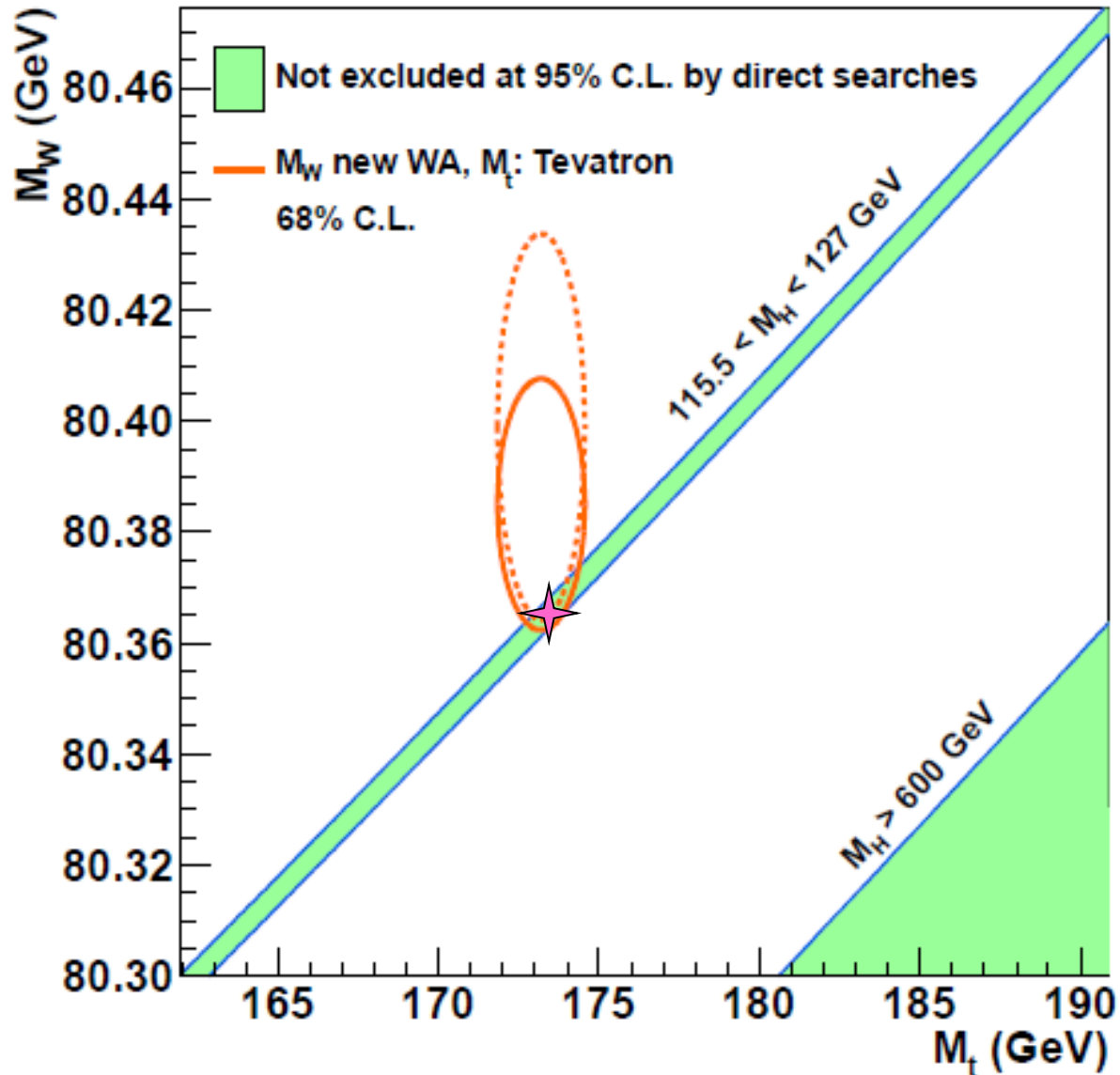
March 201



SM prediction vs new Tevatron data



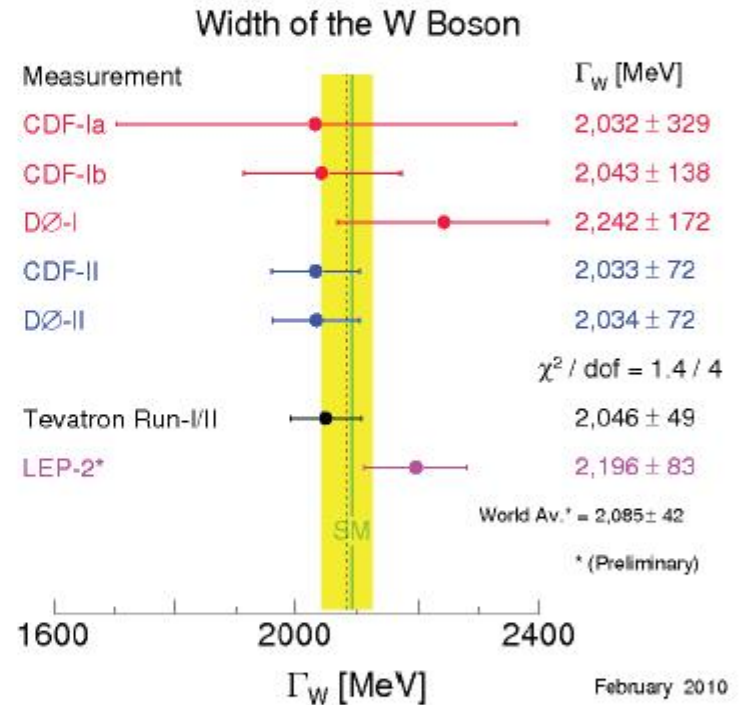
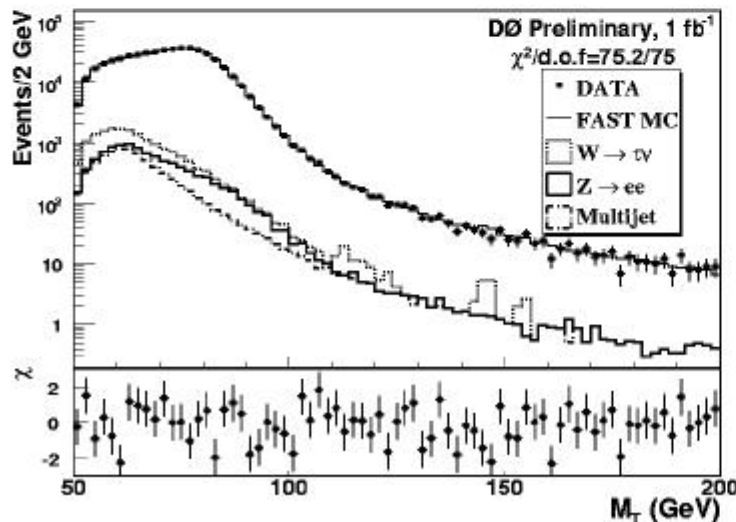
SM, Tevatron and LHC



W-WIDTH Γ_W

- The high m_T tail contains information on Γ_W
 - Exploit slower falloff of Breit-Wigner compared to Gaussian resolution
- Γ_W is expected to agree with SM almost irrespective of any new physics

$$\Gamma_W \approx (3 + 2f_{QCD}) \frac{G_F M_W^3}{6\sqrt{2}\pi} (1 + \delta_{SM}) = 2.089 \pm 0.002 \text{ GeV}$$

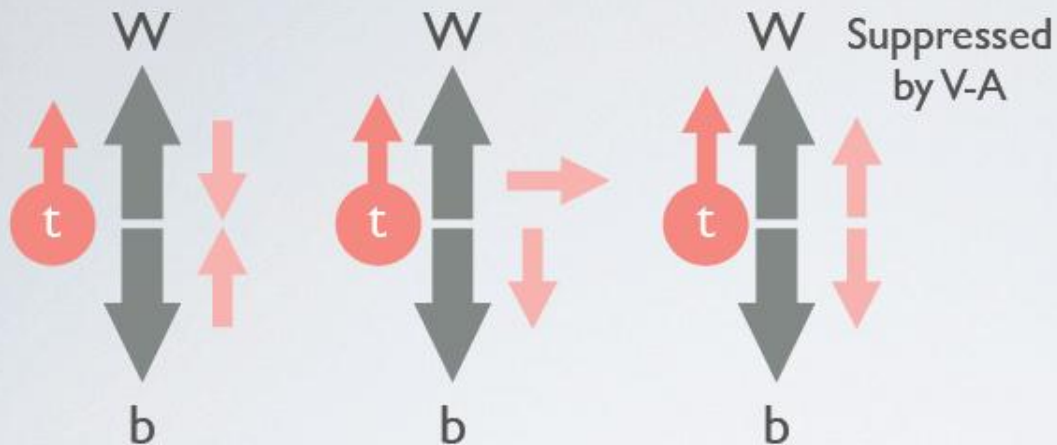


New world average:

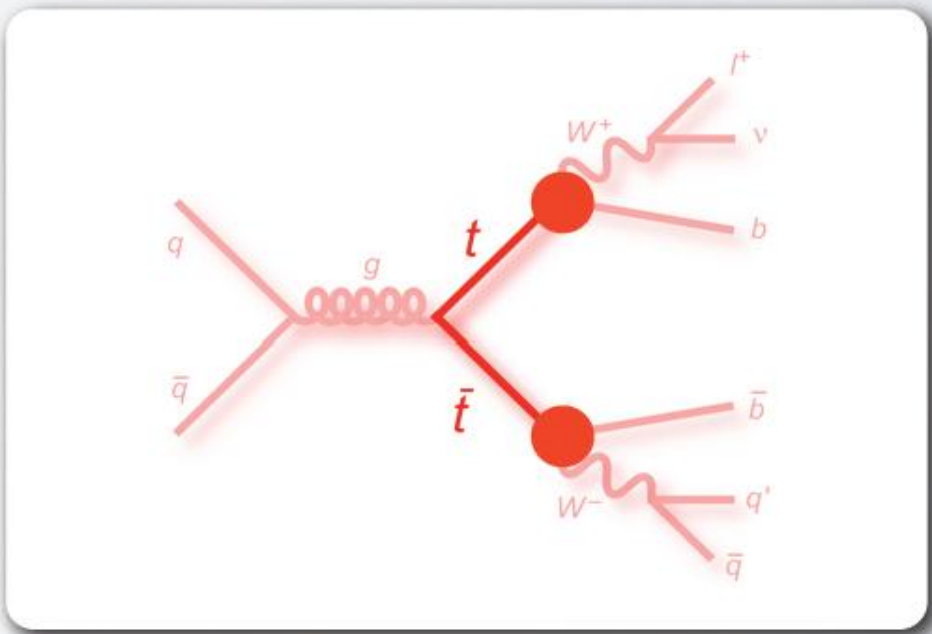
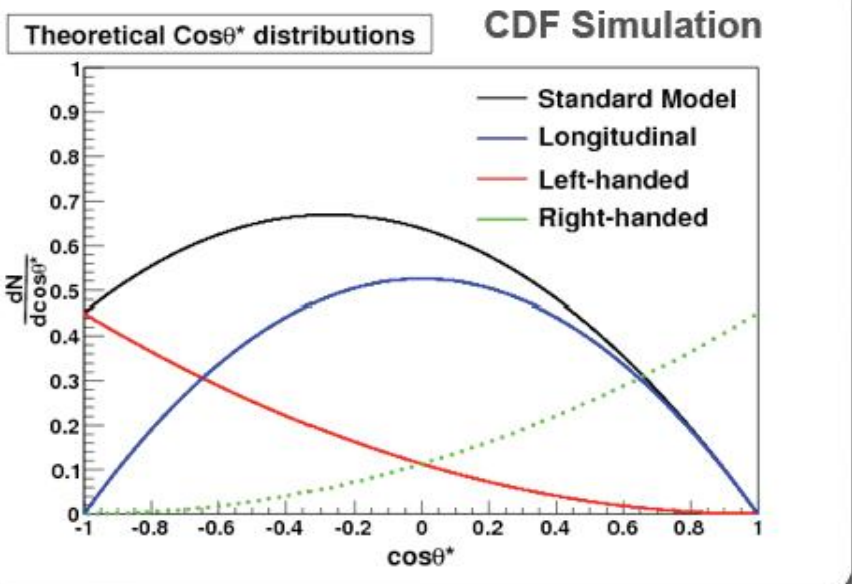
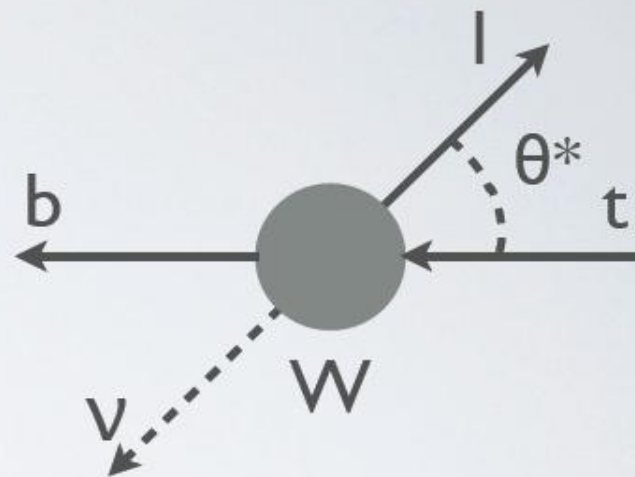
$$\Gamma_W = 2085 \pm 42 \text{ (stat + syst) MeV}$$

Theory: $\Gamma_W = 2089 \pm 2 \text{ MeV}$

W Boson Helicity Fractions



W- left-handed fraction F_- W0 longitudinal fraction F_0 W+ right-handed fraction F_+



W Boson Helicity Fractions

Combination inputs:

- Phys. Rev. Lett. 105, 042002 (2010)
- [Conf. Note 10543](#)
- Phys. Rev. D 83, 032009 (2011)

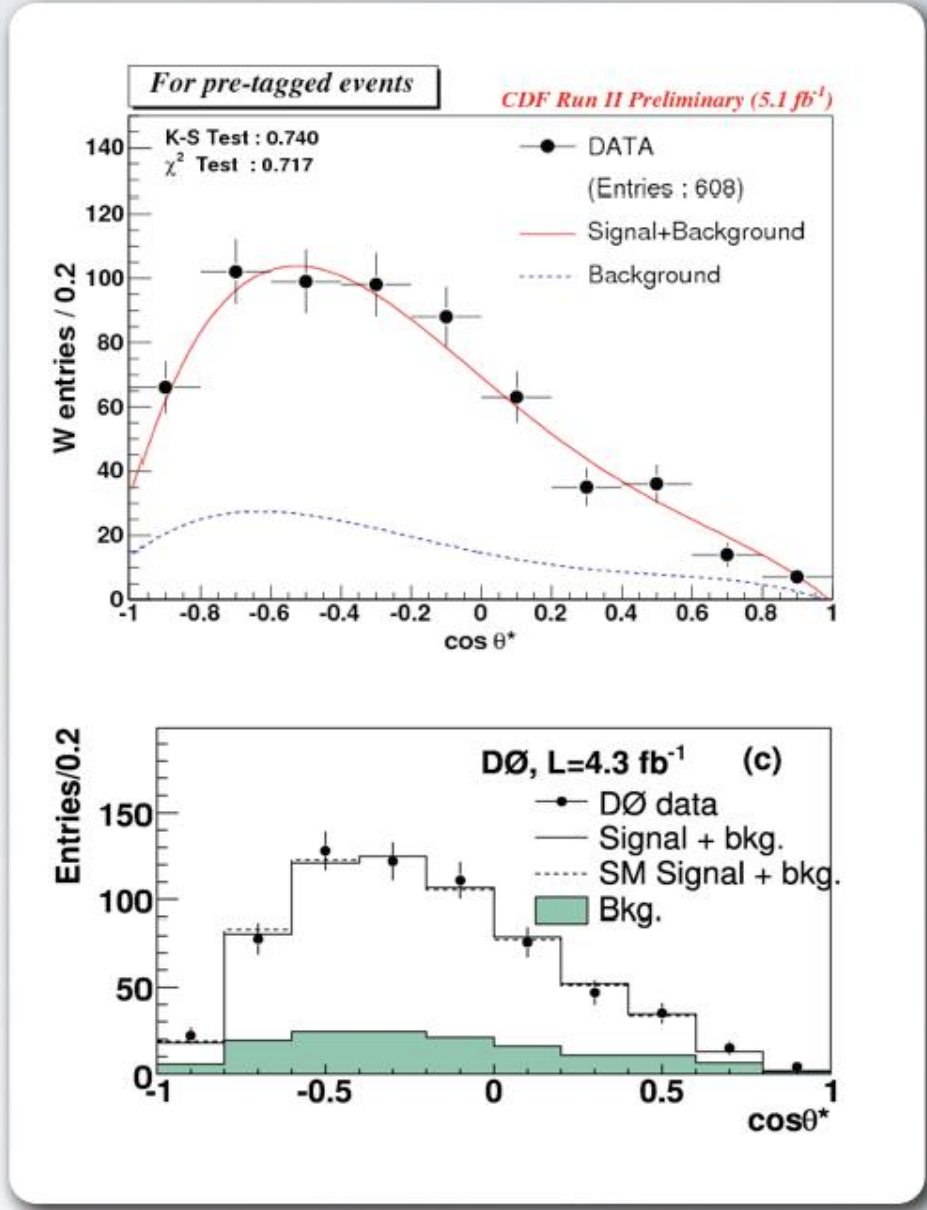
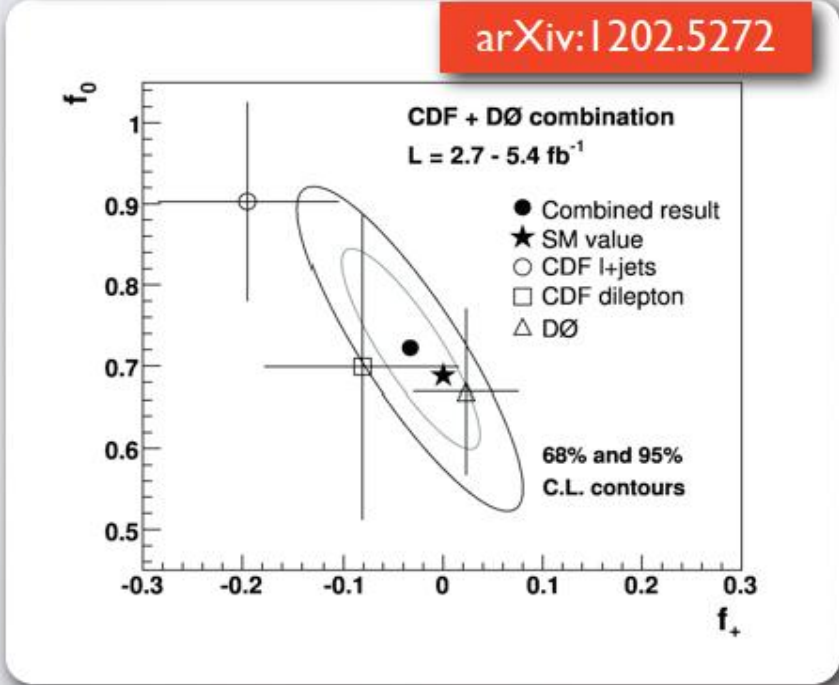
$$f_0 = 0.682 \pm 0.057$$

$$[\pm 0.035 \text{ (stat.)} \pm 0.046 \text{ (syst.)}],$$

$$f_+ = -0.015 \pm 0.035$$

$$[\pm 0.018 \text{ (stat.)} \pm 0.031 \text{ (syst.)}]$$

arXiv:1202.5272



TEVATRON A DISCOVERY MACHINE

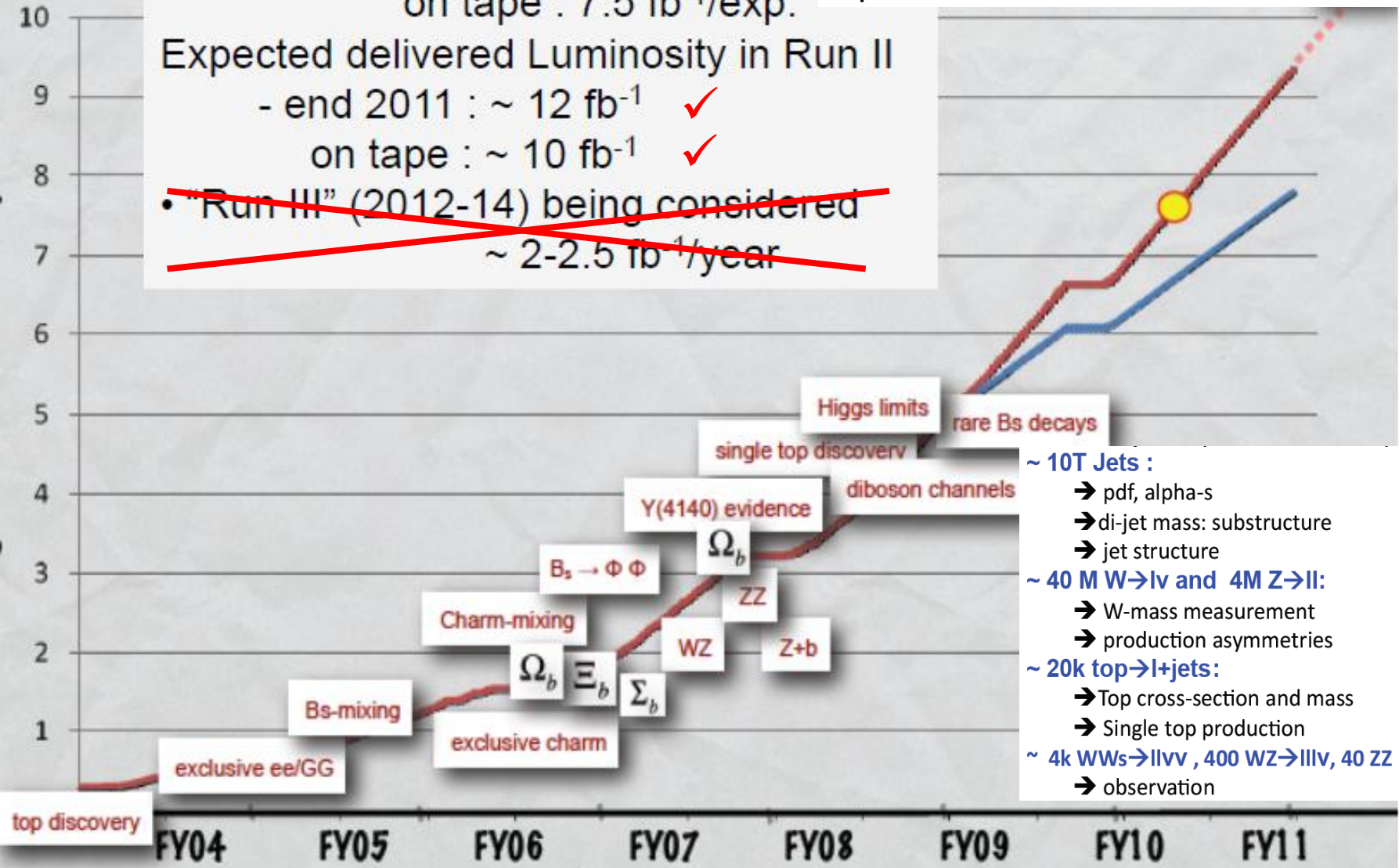
Luminosity delivered : $\sim 9 \text{ fb}^{-1}$
 on tape : $7.5 \text{ fb}^{-1}/\text{exp.}$

$$L_{\text{peak}} = 4.3 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$$

Expected delivered Luminosity in Run II
 - end 2011 : $\sim 12 \text{ fb}^{-1}$ ✓
 on tape : $\sim 10 \text{ fb}^{-1}$ ✓

~~• "Run III" (2012-14) being considered
 $\sim 2\text{-}2.5 \text{ fb}^{-1}/\text{year}$~~

Integrated luminosity (fb⁻¹)



- ~ 10T Jets :
 - pdf, alpha-s
 - di-jet mass: substructure
 - jet structure
- ~ 40 M W → lν and 4M Z → ll:
 - W-mass measurement
 - production asymmetries
- ~ 20k top → l+jets:
 - Top cross-section and mass
 - Single top production
- ~ 4k WWs → llνν, 400 WZ → llνν, 40 ZZ → llll:
 - observation

DIBOSONS PHYSICS

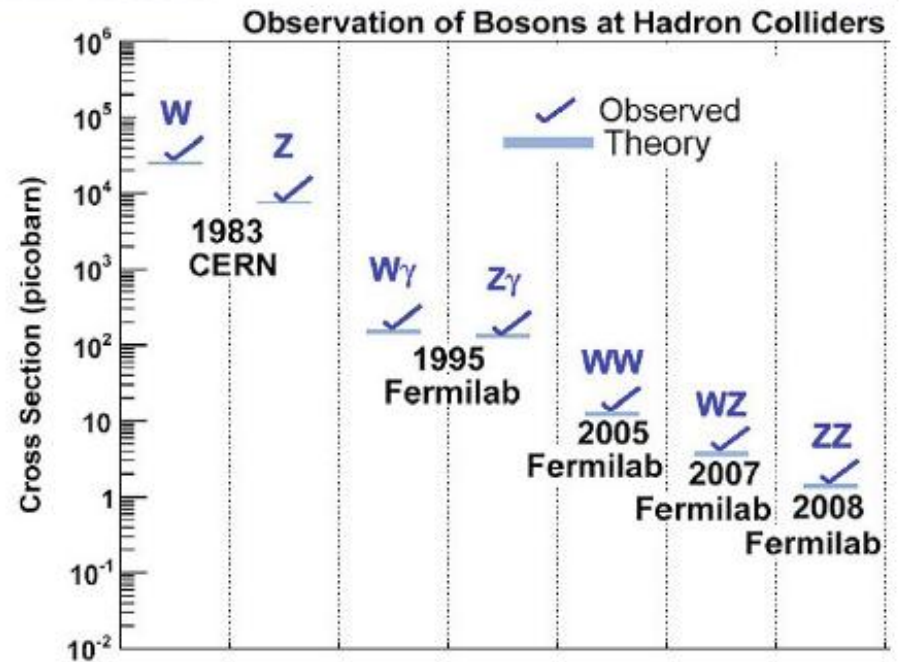
- **Probe of electroweak sector of the standard model**
 - cross sections
 - gauge boson couplings
- **Background for Higgs searches**
- **“Validation” of multivariate analysis techniques**

Charged Triple Gauge Couplings

- probed by WW, WZ, W γ
- 5 TGC parameters:
 $g1^Z, \kappa_\gamma, \kappa_Z = 1$ in SM
 $\lambda_\gamma, \lambda_Z = 0$ in SM

Neutral Triple Gauge Couplings

- probed by ZZ, Z γ
- 4 TGC parameters:
 $h3^Z, h3^Z, h4^Z, h4^Z$ all 0 in SM !



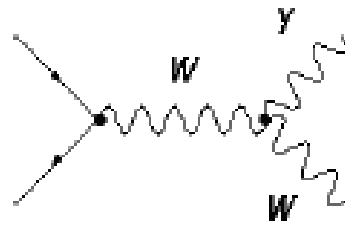
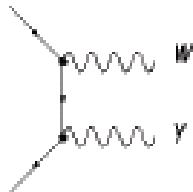
WW+WZ+ZZ \rightarrow 2 jets + mE $_T$
CDF (3.5fb⁻¹): $\sigma = 18.2 \pm 3.7$ pb
observation at 5.3 σ

WW+WZ \rightarrow lv + 2 jets

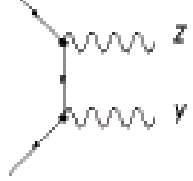
D ϕ (1.1fb⁻¹): $\sigma = 20.2 \pm 4.5$ pb **evidence at 4.4 σ**
CDF(4.6fb⁻¹): $\sigma = 16.5^{+3.3}_{-3.0}$ pb **observation at 5.4 σ**

Diboson Final State

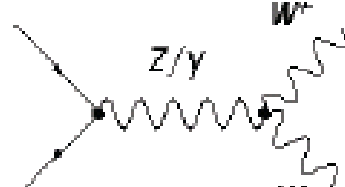
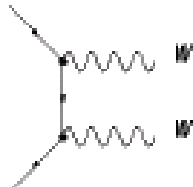
$W\gamma$



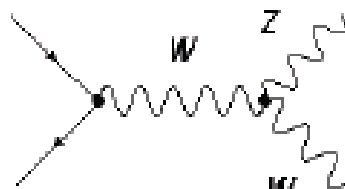
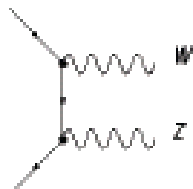
$Z\gamma$



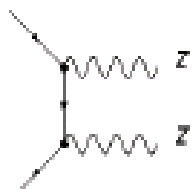
WW



WZ



ZZ



SM Tests:

- 1) Test SM production predictions
 - 2) Look for "anomalous couplings"
- Cross sections similar to Higgs

Triple Gauge Couplings

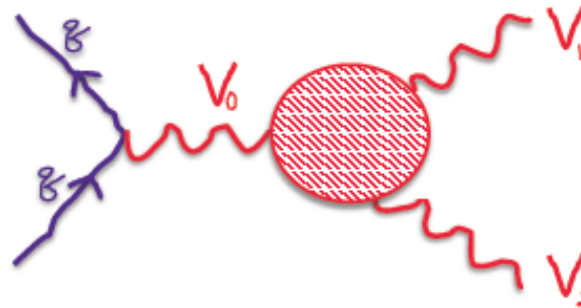
Standard Model



Anomalous



anomalous Triple Gauge Couplings



The effective Lagrangian for model independent triple gauge couplings can be expressed as:

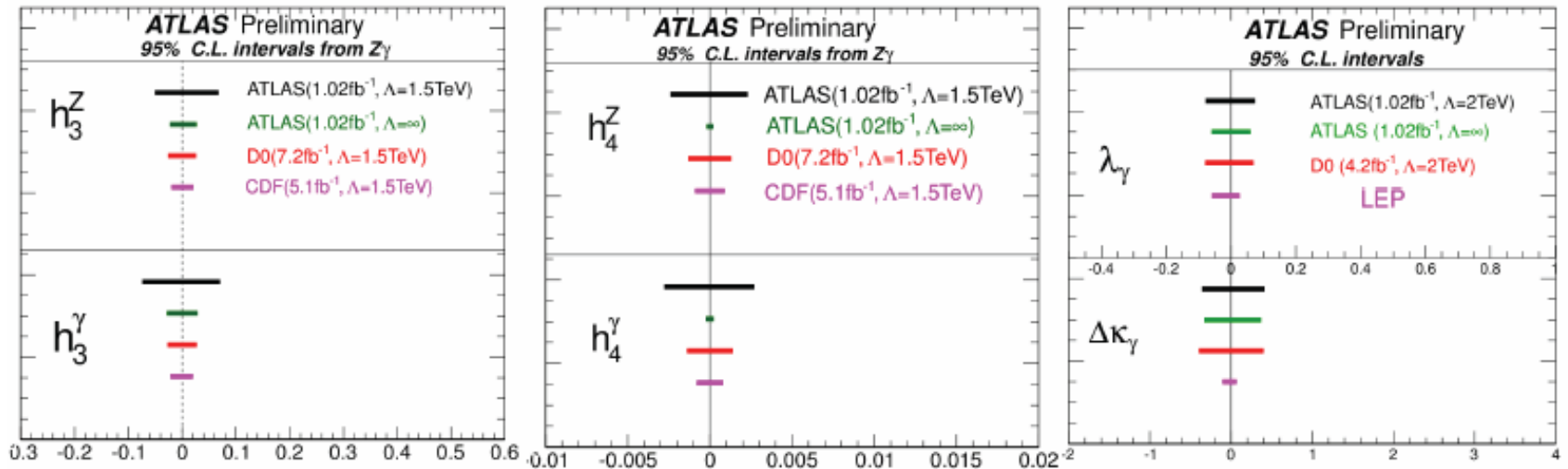
$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i \left[g_1^V (W_{\mu\nu}^\dagger W^\mu V^\nu - W_{\mu\nu} W^{\dagger\mu} V^\nu) + \kappa^V W_\mu^\dagger W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2} W_{\rho\mu}^\dagger W_\nu^\mu V^{\nu\rho} \right] \quad (\text{WW, WZ})$$

$$\mathcal{L}_{VZZ} = -\frac{e}{M_Z^2} \left[f_4^V (\delta_\mu V^{\mu\beta}) Z_\alpha (\delta^\alpha Z_\beta) + f_5^V (\delta^\sigma V_{\sigma\mu}) Z^{\mu\beta} Z_\beta \right] \quad (\text{ZZ})$$

In the Standard Model:

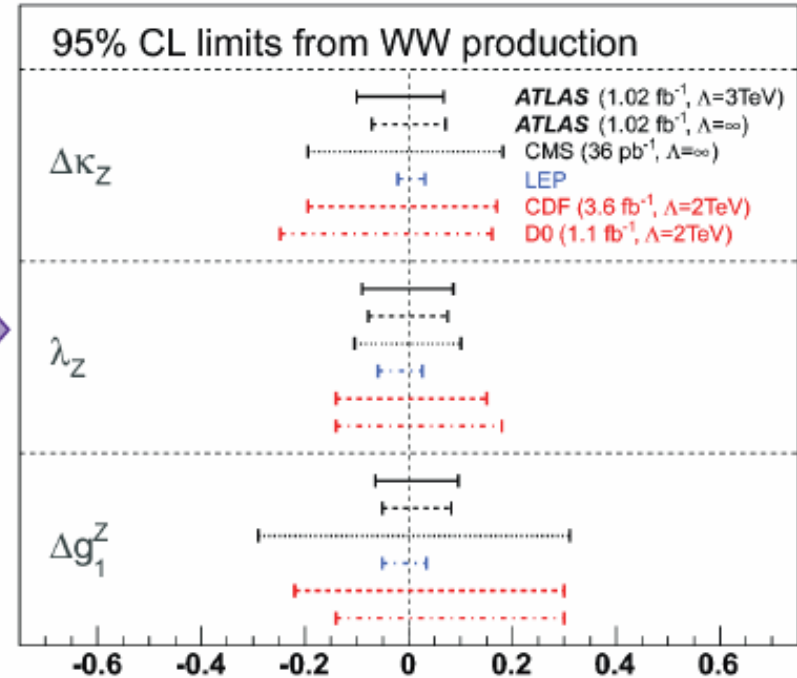
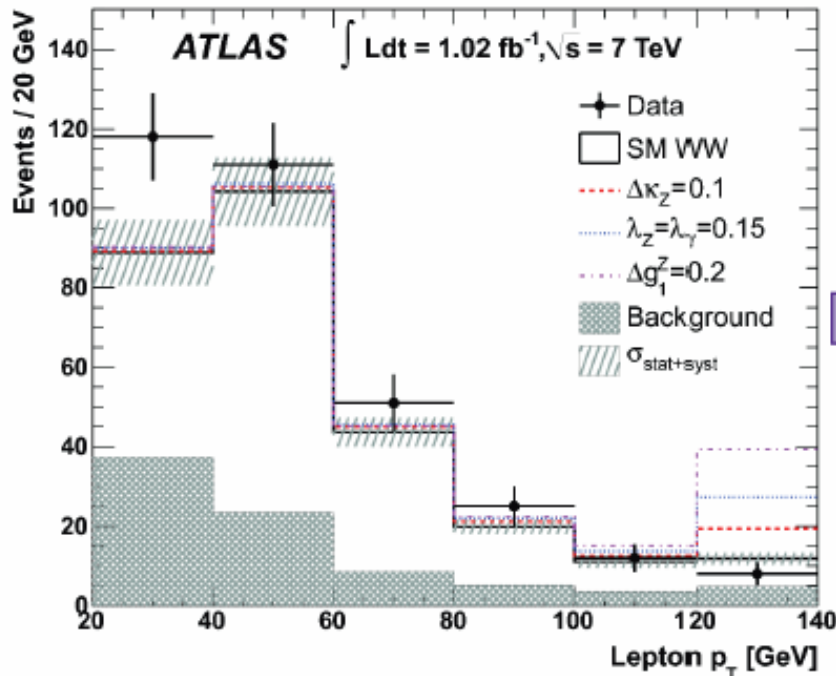
- $g_1^V = \kappa^V = 1$ (set limits on $\Delta g = g - 1$, $\Delta \kappa = \kappa - 1$)
- $\lambda^V = f_4^V = f_5^V = h_3^V = h_4^V = 0$

W_γ, Z_γ aTGC Full Results



W_γ, Z_γ limits

- Limits set using exclusive cross-section (no jets) at high E_T^γ
- ATLAS aTGC limits most stringent for h_3 and h_4

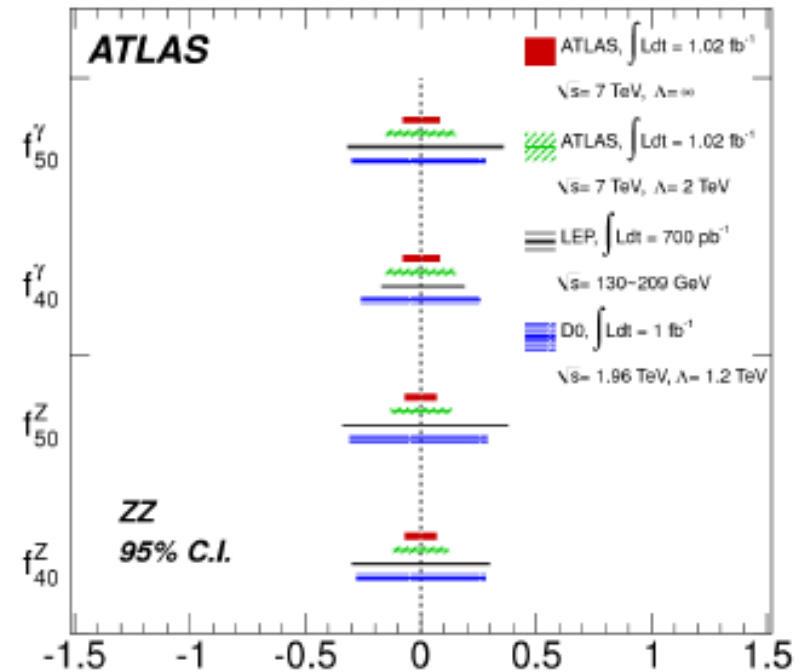
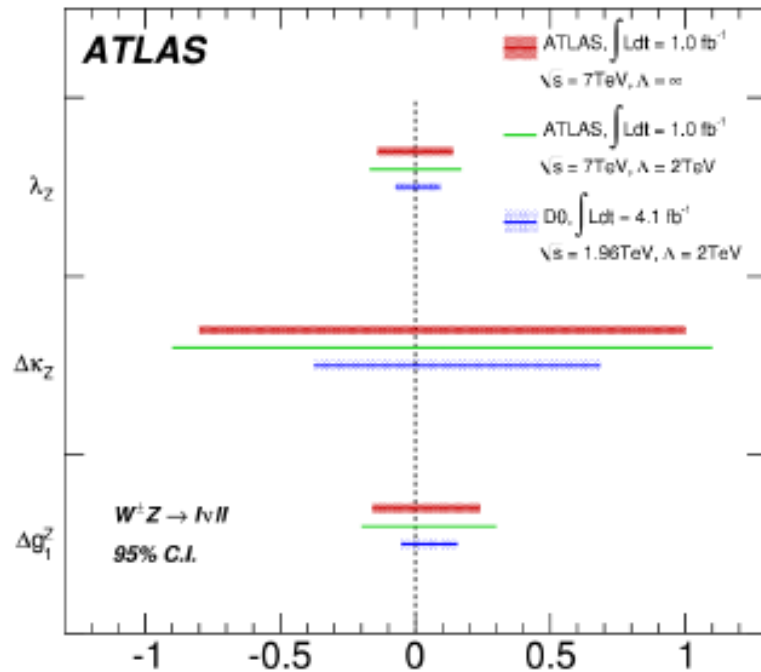


WW limits

- Limits set using leading lepton p_T spectrum
- ATLAS limits tighter than TeVatron limits

WZ → lνll and ZZ → ll ll aTGC results

ATLAS-STD-2011-25
ATLAS-STD-2011-36



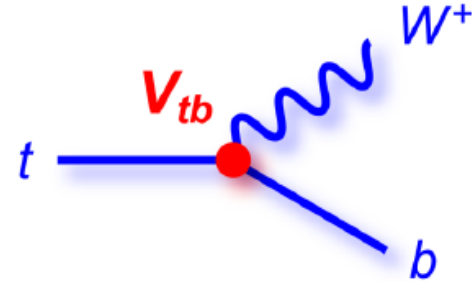
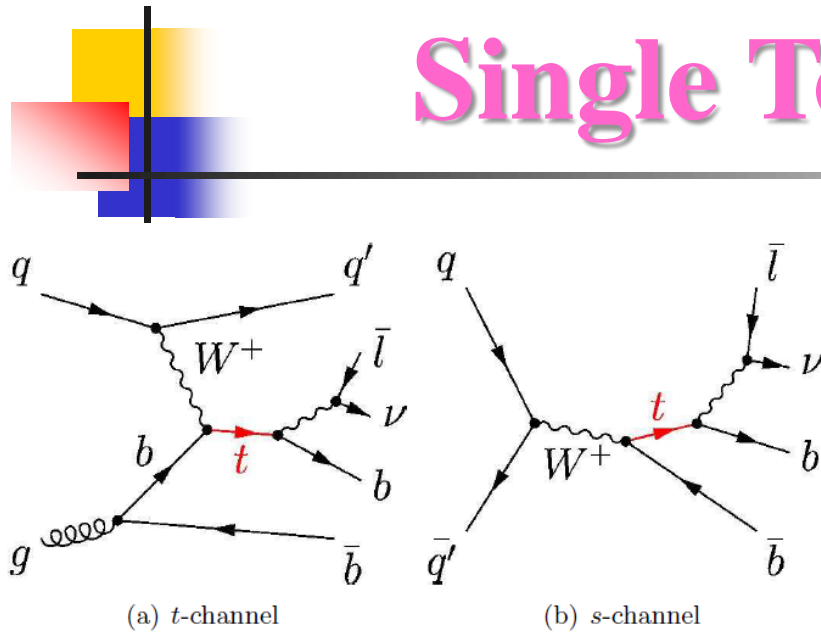
Current limits

- Limits set using total cross section

Near future

- Certain differential distributions more sensitive → will use for next analysis

Single Top Production

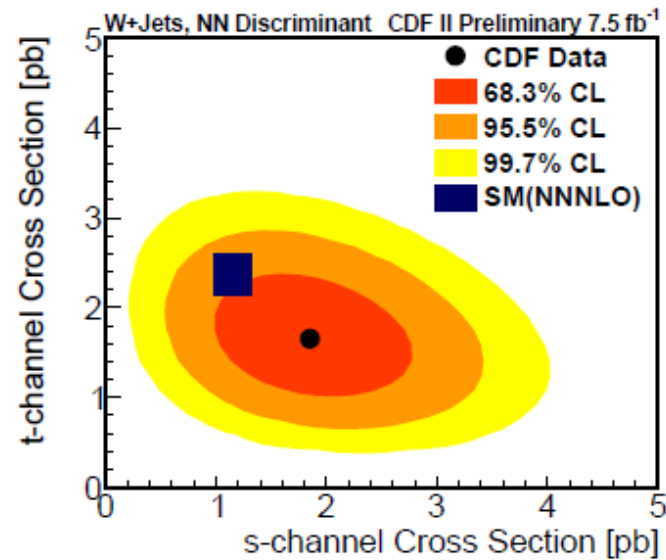


CDF: $|V_{tb}| = 0.96 \pm 0.09(\text{stat+syst}) \pm 0.05(\text{theory})$

$|V_{tb}| > 0.78$ at 95% C.L.

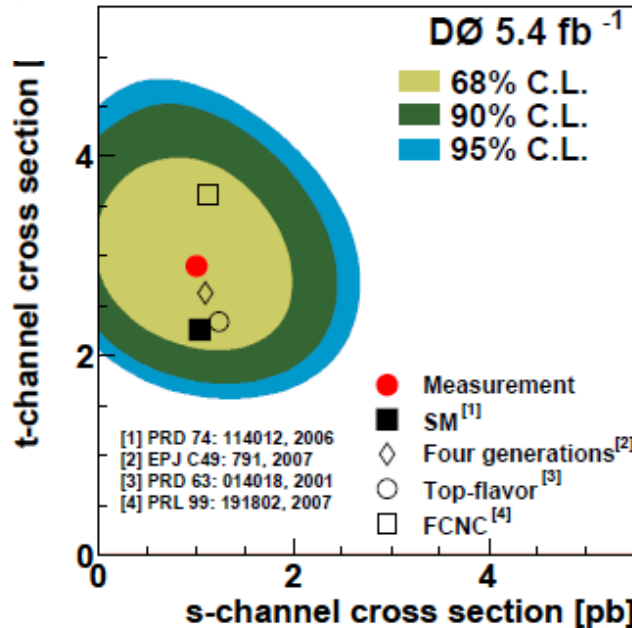
D0:

$|V_{tb}| > 0.79$ at 95% C.L.



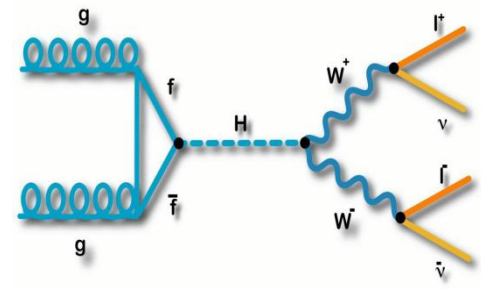
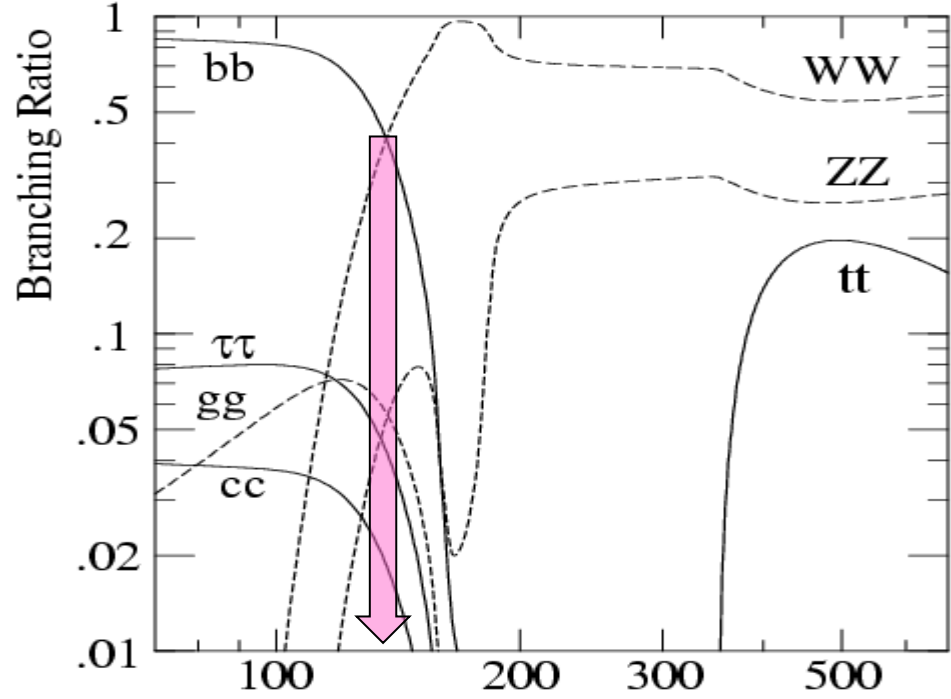
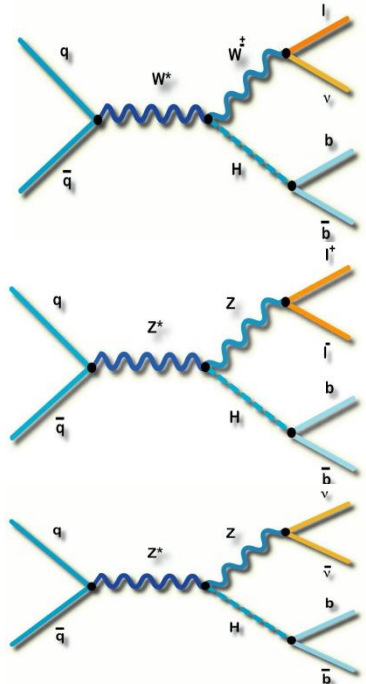
(a)

11/06/2012

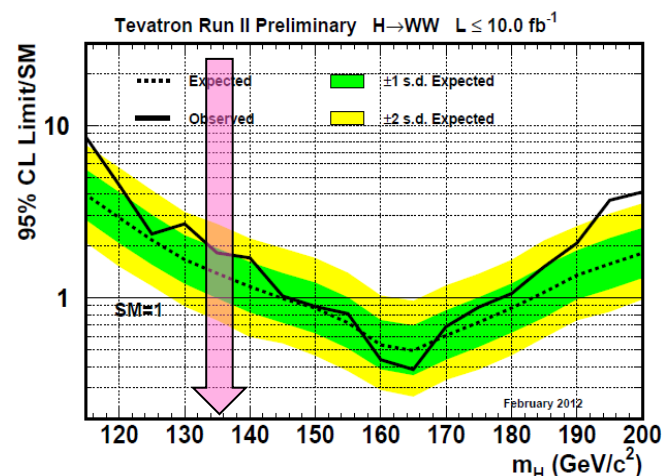
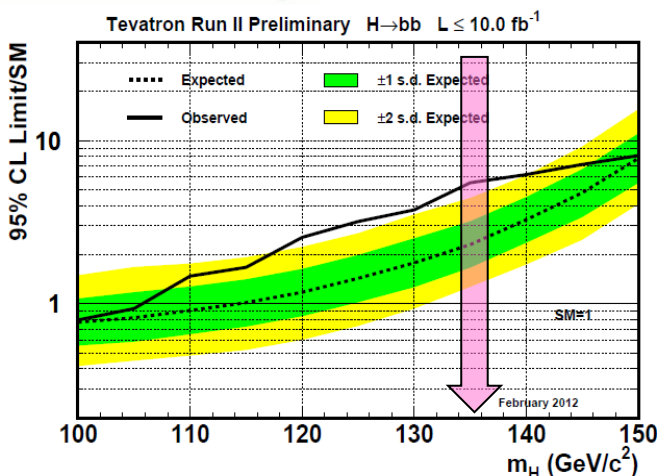


(b)

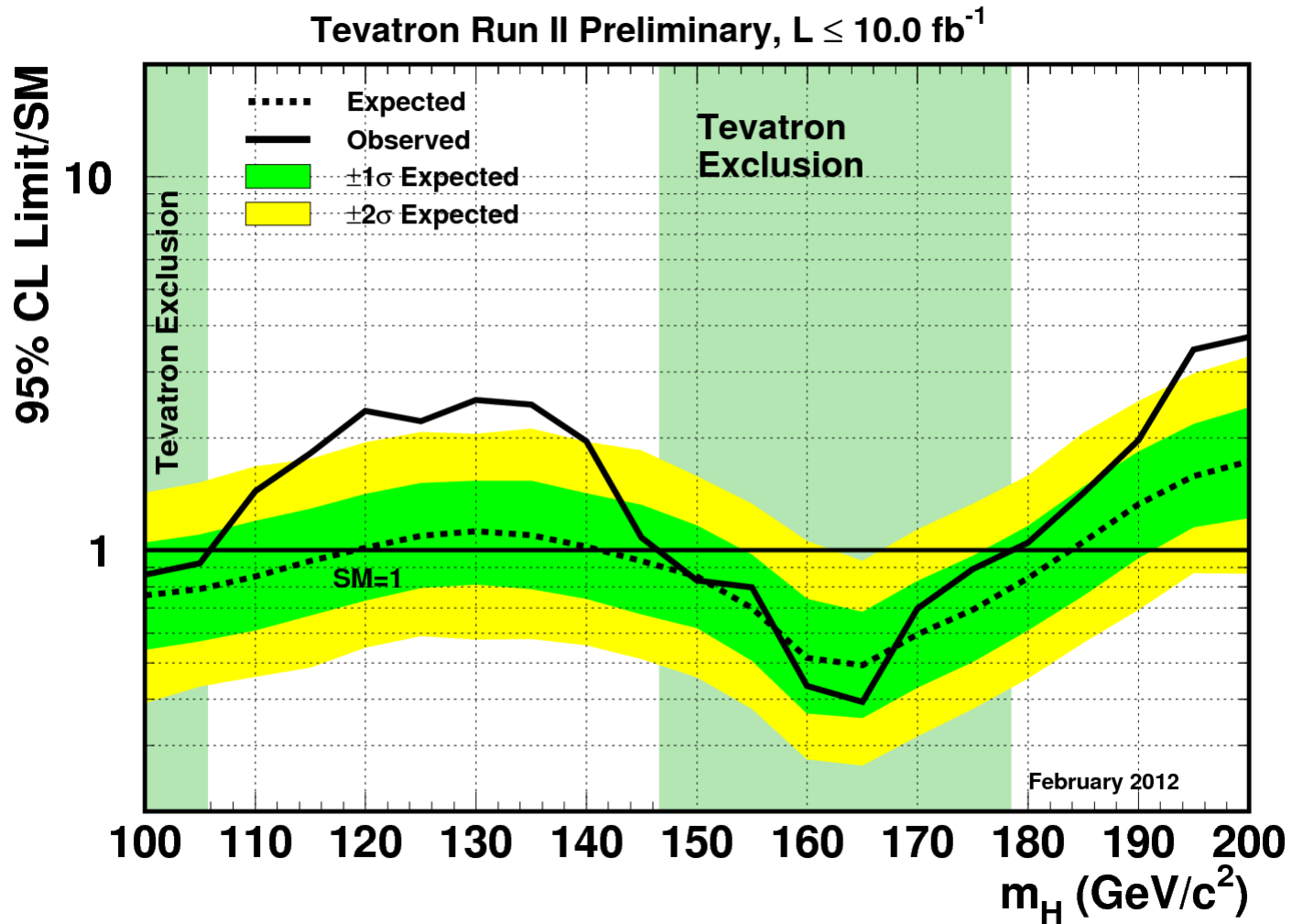
Higgs Search at the Tevatron



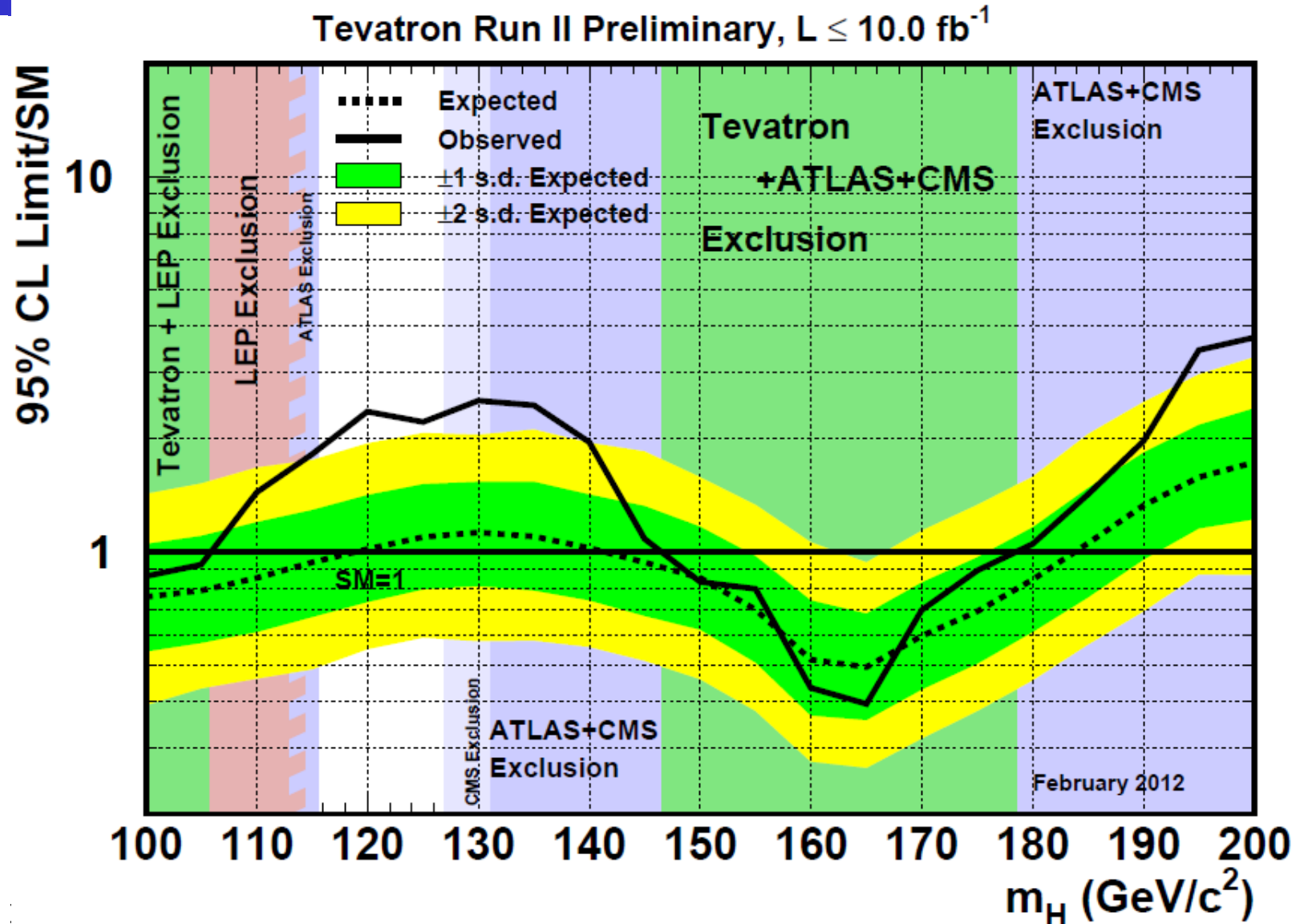
My guess
(unpublished):
 $M_H \sim v/2$
 $\approx 123 \text{ GeV}$



Tevatron Exclusion

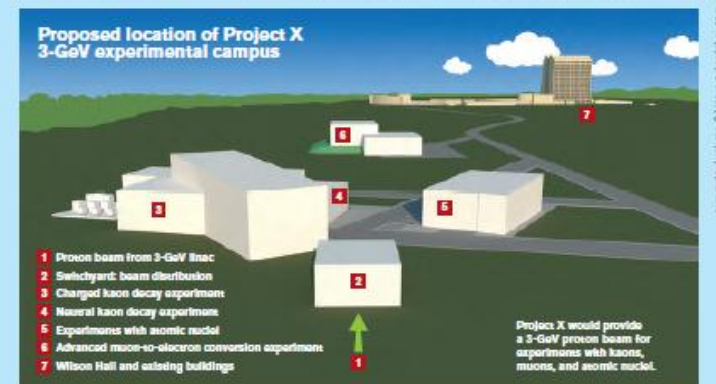
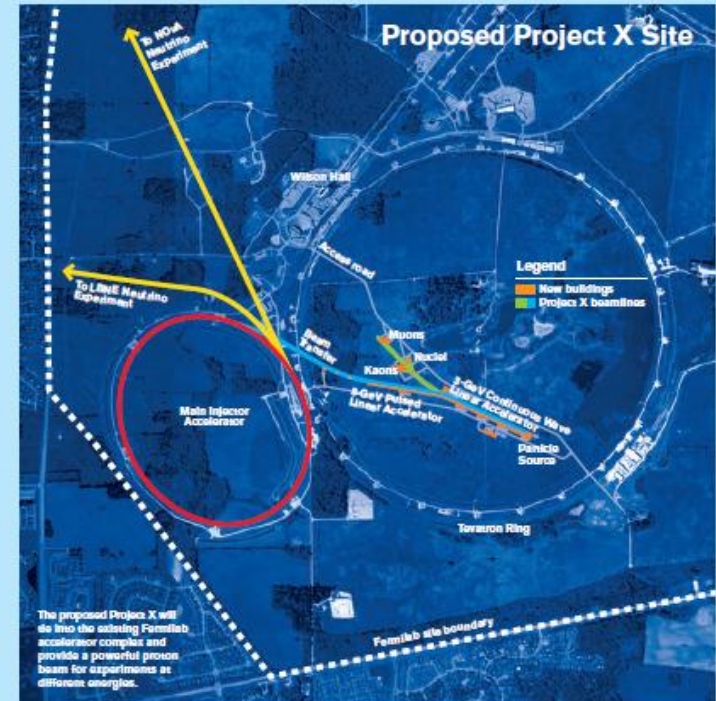
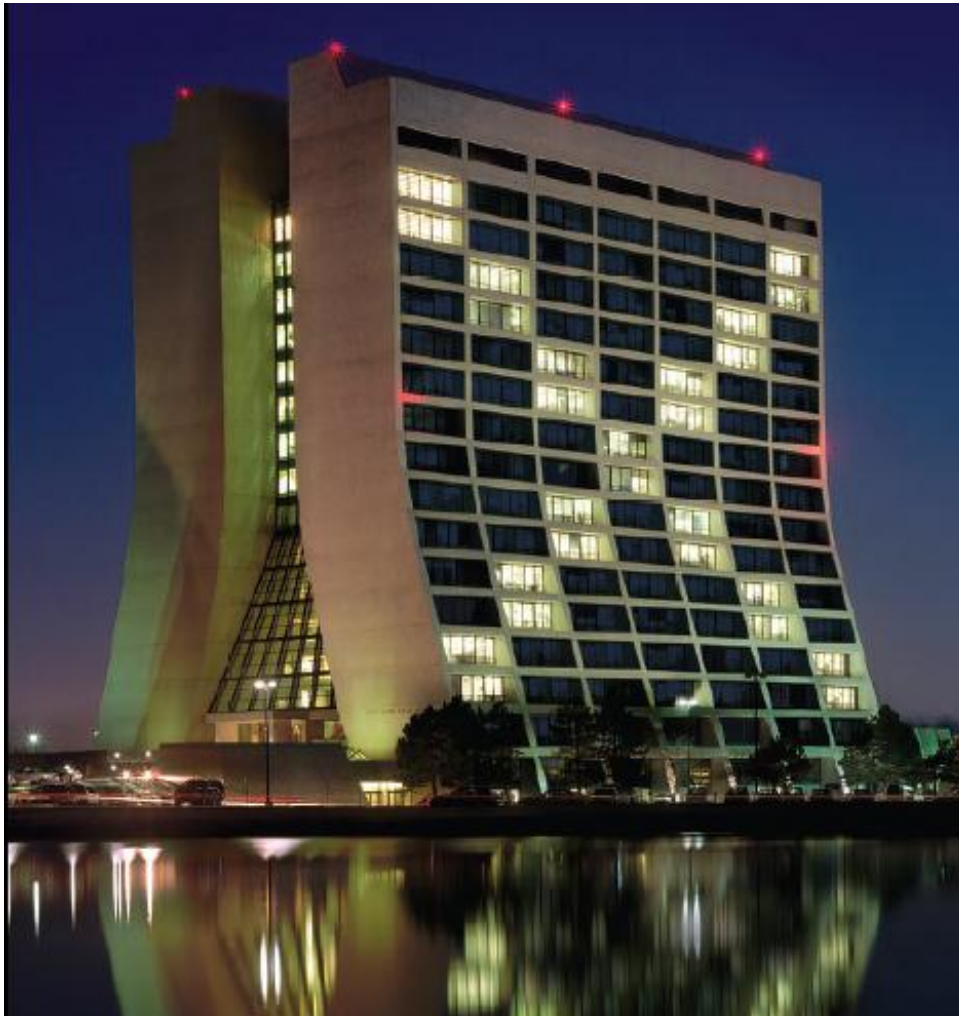


Tevatron Exclusion with LHC results



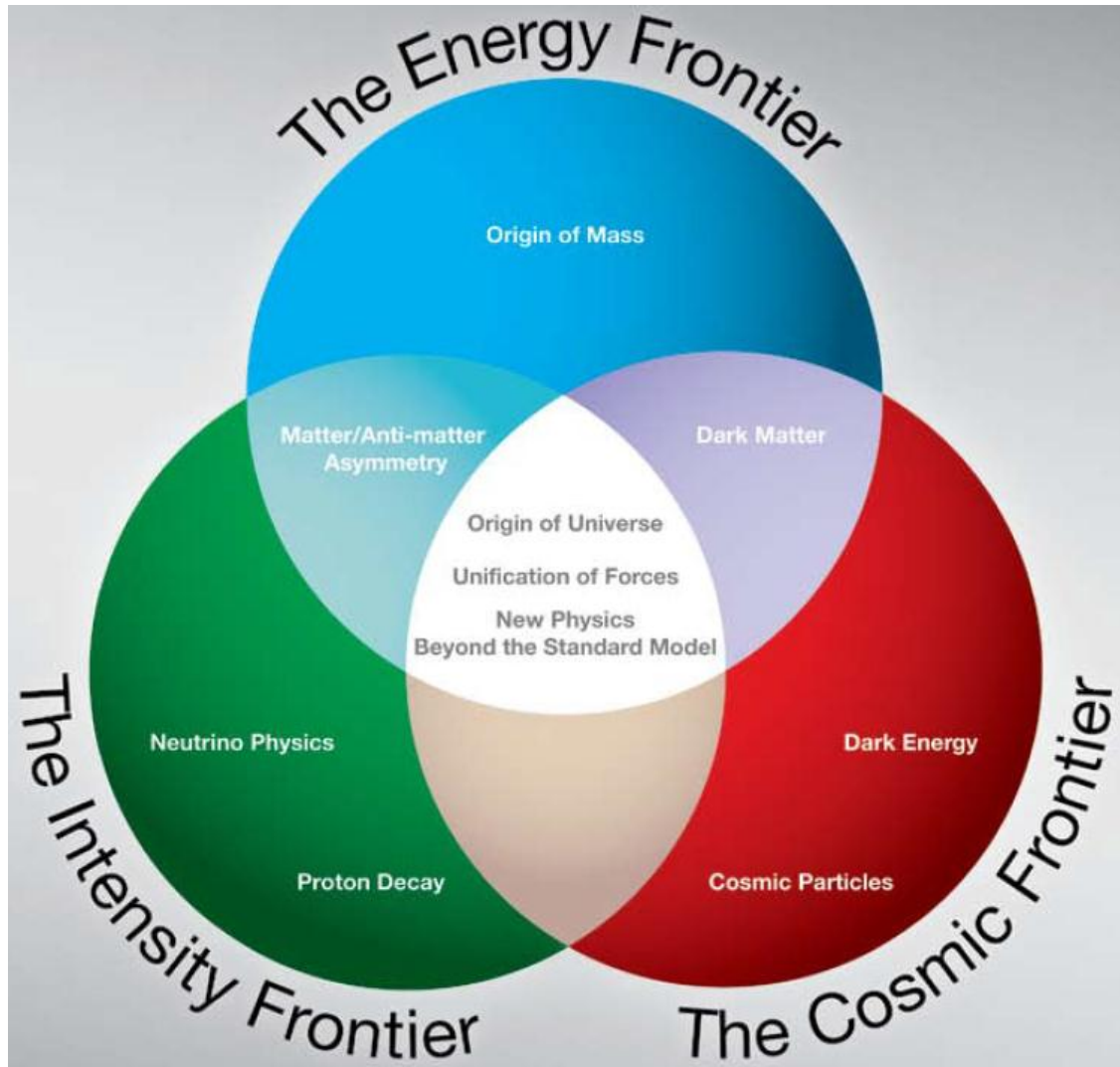
Project X

The Tevatron is shutting down, and a new project is on the horizon: Project X.



Neutrino Physics

Project X will open a path to discovery in neutrino science and in precision experiments with charged leptons and quarks.



CERN
23.11.2011



$$U_v > c$$



11/06/2012

37

Mixing matrices

Cabibbo-Kobayashi-Maskawa

$$V_{CKM} = \begin{matrix} & d & s & b \\ \begin{matrix} u \\ c \\ t \end{matrix} & \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{matrix} \square \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix} \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parameterization

Pontecorvo-Maki-Nakagawa-Sakata

$$U_{PMNS} = \begin{matrix} & \nu_1 & \nu_2 & \nu_3 \\ \begin{matrix} e \\ \mu \\ \tau \end{matrix} & \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix} \end{matrix} \square \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{\lambda}{\sqrt{2}} \\ -\frac{1+\lambda}{\sqrt{6}} & \frac{1-\lambda/2}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1-\lambda}{\sqrt{6}} & -\frac{1+\lambda/2}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix} \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Oscillations

The two necessary conditions for neutrino oscillations:

- ✓ U_{PMNS} is non-identity matrix:
the flavour states are different from the mass states
- ✓ $m_1 \neq m_2 \neq m_3$:
non-degeneracy of the mass states

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 \approx 7.54(20) \times 10^{-5} \text{ eV}^2$$
$$\left| \Delta m_{31}^2 \right| = 2.43(8) \times 10^{-5} \text{ eV}^2 \quad \longrightarrow \quad \text{Oscillations!}$$

$$P(\nu_\mu \rightarrow \nu_e) \approx 4 \left| U_{\mu 3} \right|^2 \left| U_{e 3} \right|^2 \sin^2 \left(\frac{\Delta m_{31}^2 L}{4 E_\nu} \right)$$

First indications of non-zero U_{e3}

$$\nu_\mu \rightarrow \nu_e$$

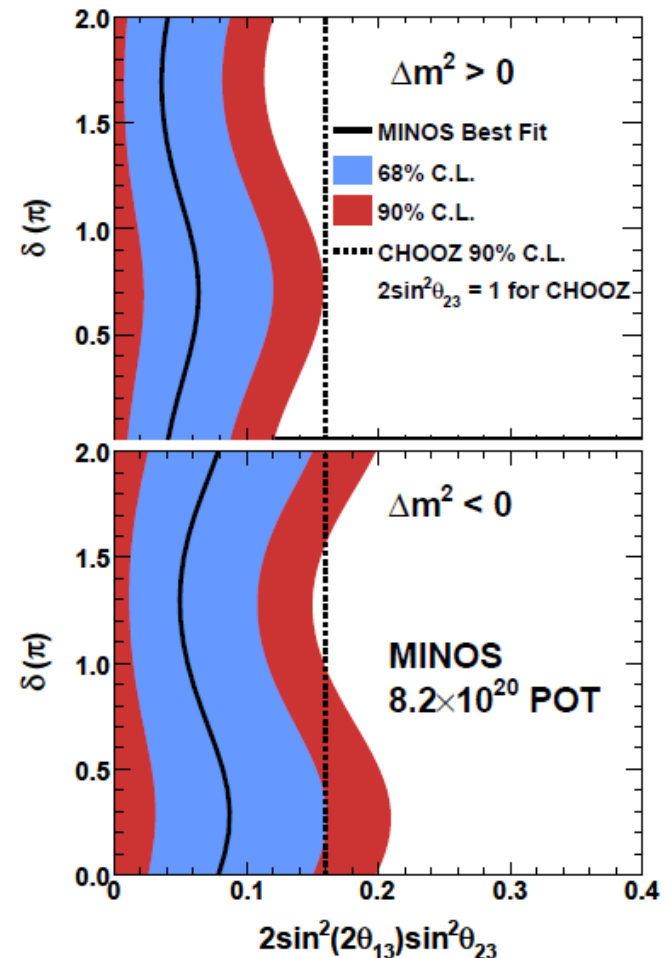
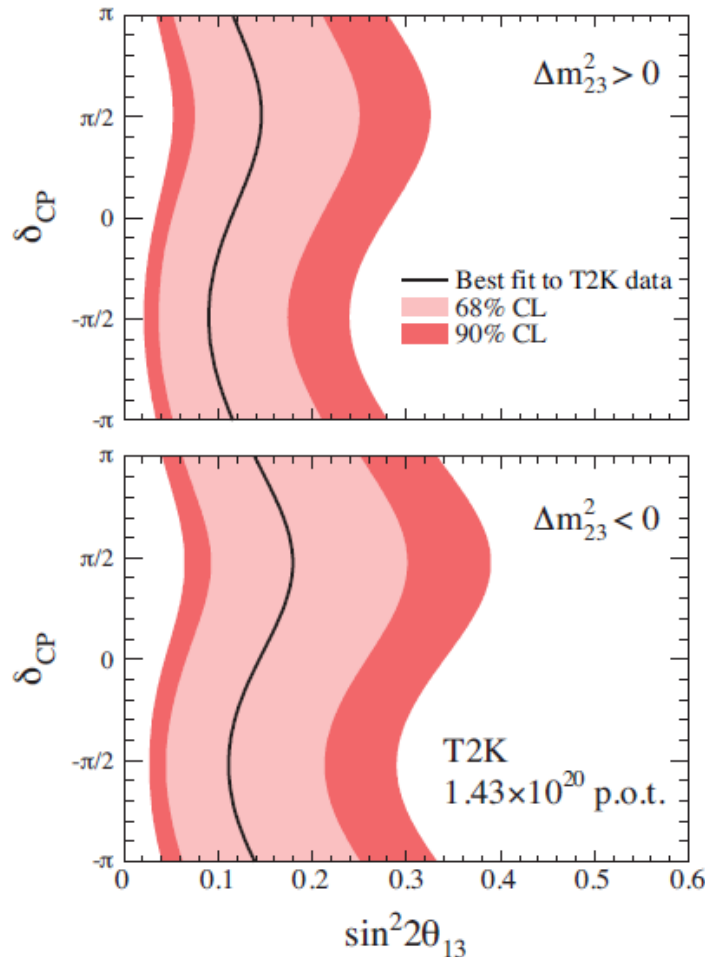
T2K

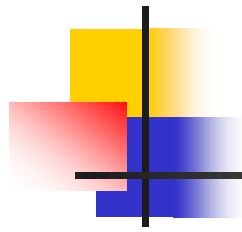
Appearance!

MINOS

Phys.Rev.Lett. 107 (2011) 041801
arXiv:1106.2822 [hep-ex]

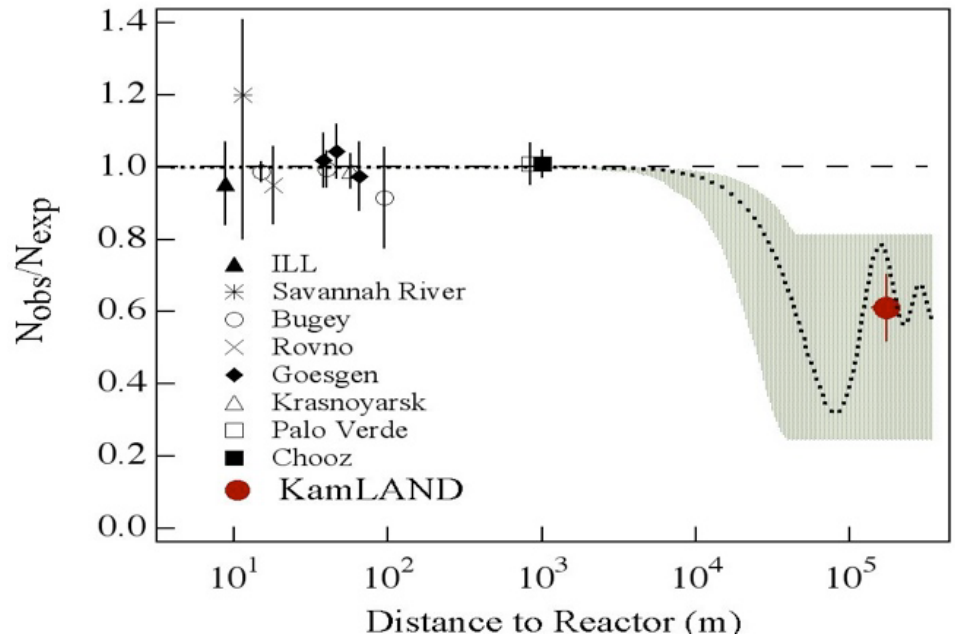
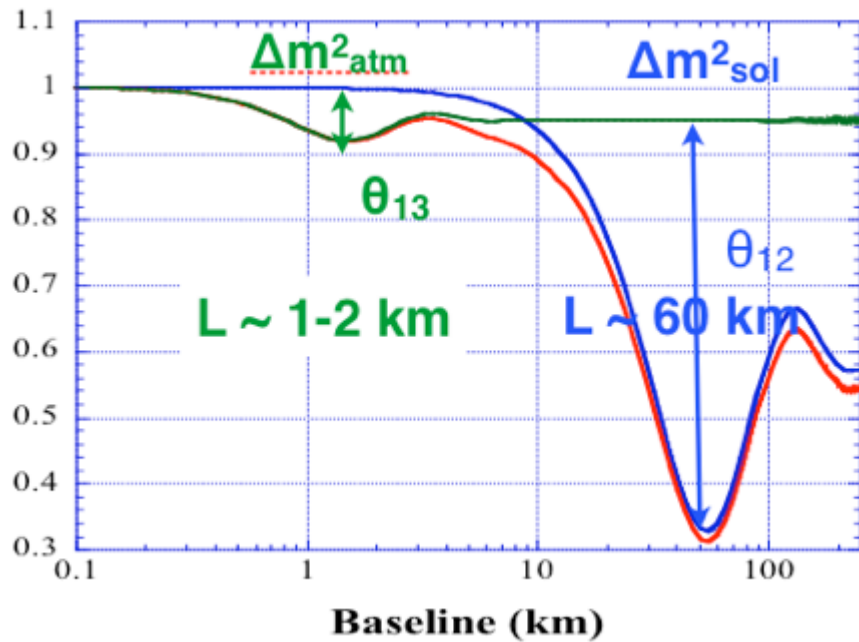
Phys.Rev.Lett. 107 (2011) 181802
arXiv:1108.0015 [hep-ex]





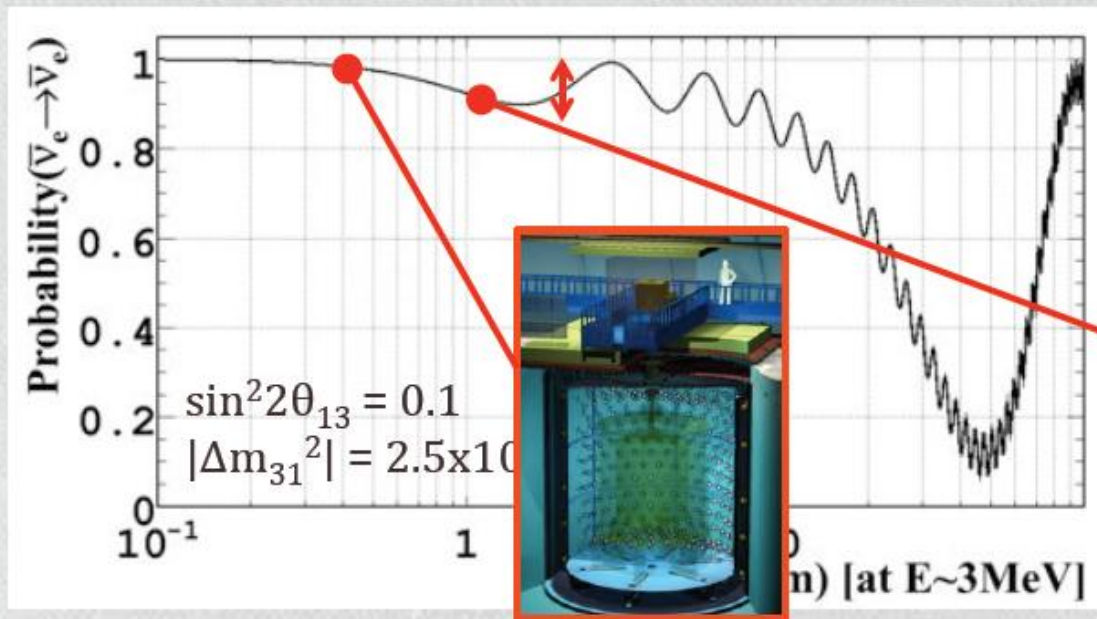
$$U_{e3} = \sin \theta_{13} e^{-i\delta}$$

$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2 \left(\frac{\Delta m_{31}^2 L}{4E_\nu} \right) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2 \left(\frac{\Delta m_{21}^2 L}{4E_\nu} \right)$$



θ_{13} measurement with reactor neutrinos

- Reactor is a free and rich electron antineutrino source
- Direct measurement of θ_{13} with no parameter degeneracy
- Background is strongly suppressed by delayed coincidence
- Flux expectation within 2% uncertainties
- Systematic uncertainties are further reduced (<1%) using two detectors at different baselines



Double Chooz experiment



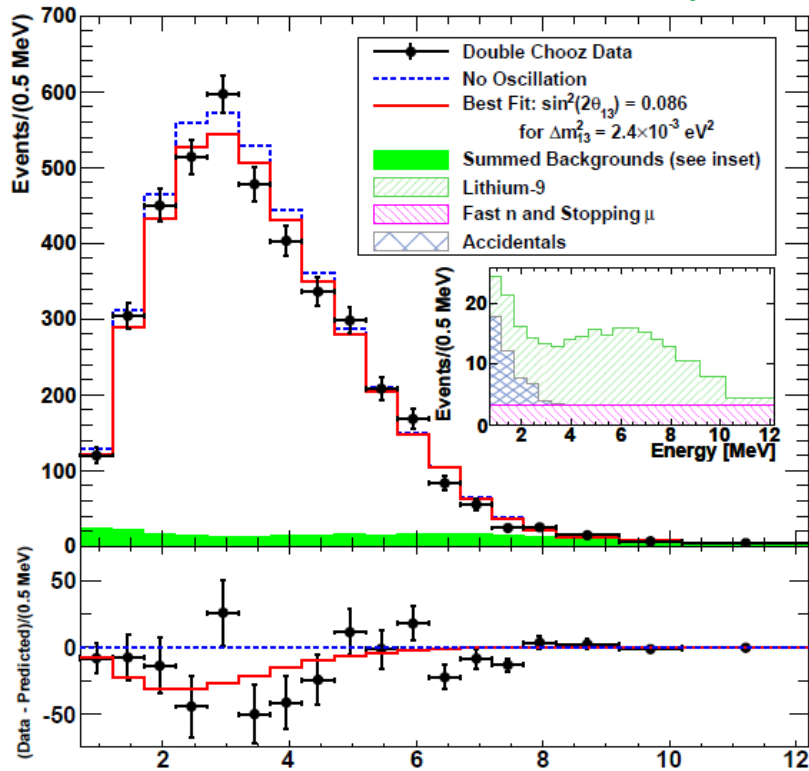
Double Chooz

anti- ν_e disappearance

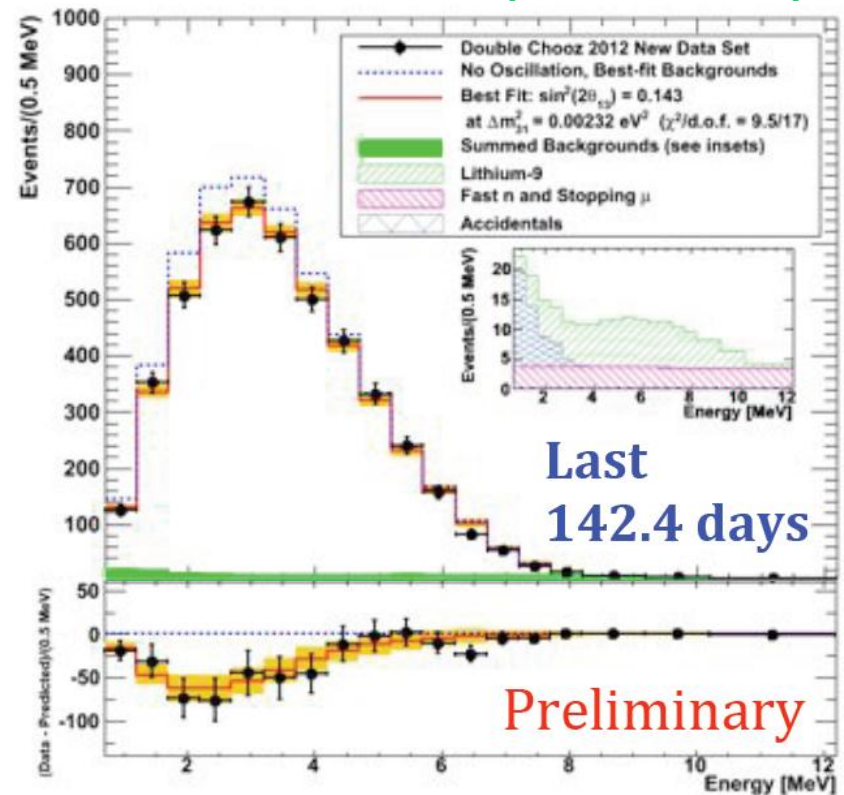
$$\sin^2 2\theta_{13} < 0.15 \text{ at } 90\% \text{ C.L.}$$

Eur. Phys. J. C 27, 331 (2003)

Phys.Rev.Lett. 108 (2012) 131801
e-Print: arXiv:1112.6353 [hep-ex]



NEUTRINO 2012 (June 4, 2012)



$$\sin^2 2\theta_{13} = 0.086 \pm 0.041(\text{stat}) \pm 0.030(\text{syst})$$

$$\sin^2 2\theta_{13} = 0 \text{ is excluded at the } 94.6\% \text{ C.L.}$$

$$\sin^2 2\theta_{13} = 0.109 \pm 0.030(\text{stat}) \pm 0.025(\text{syst})$$

$$\sin^2 2\theta_{13} = 0 \text{ is excluded at the } 99.9\% \text{ C.L.}$$

(3.1 σ)

The Daya Bay Experiment



Adjacent mountains with horizontal access provide 860 (250) m.w.e cosmic shielding.

Daya Bay

Ling Ao I + II

6 commercial reactor cores with 17.4 GW_{th} total power.

6 Antineutrino Detectors (ADs) give 120 tons total target mass.

Via GPS and modern theodolites, relative detector-core positions known to 3 cm.



Antineutrino Detectors

6 'functionally identical' detectors:
Reduce systematic uncertainties

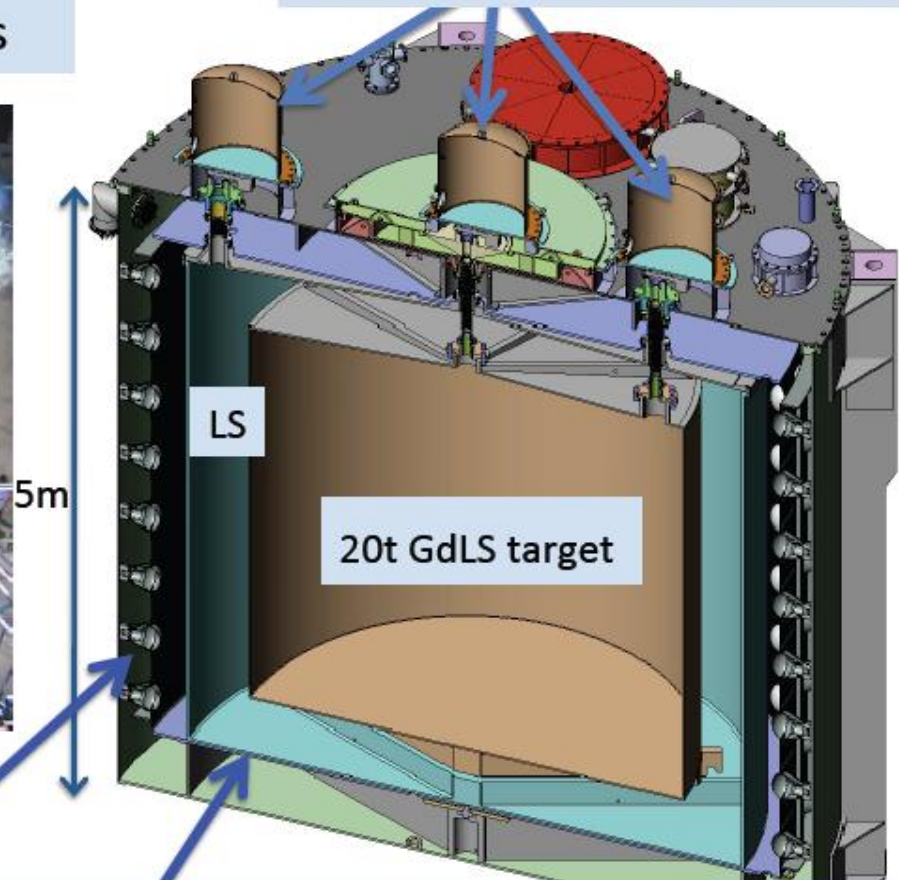
Target mass measured to
3 kg (0.015%) during filling.



All detectors filled from
common GdLS tanks.

192 8" PMTs detect light
in target, ~ 163 p.e./MeV.

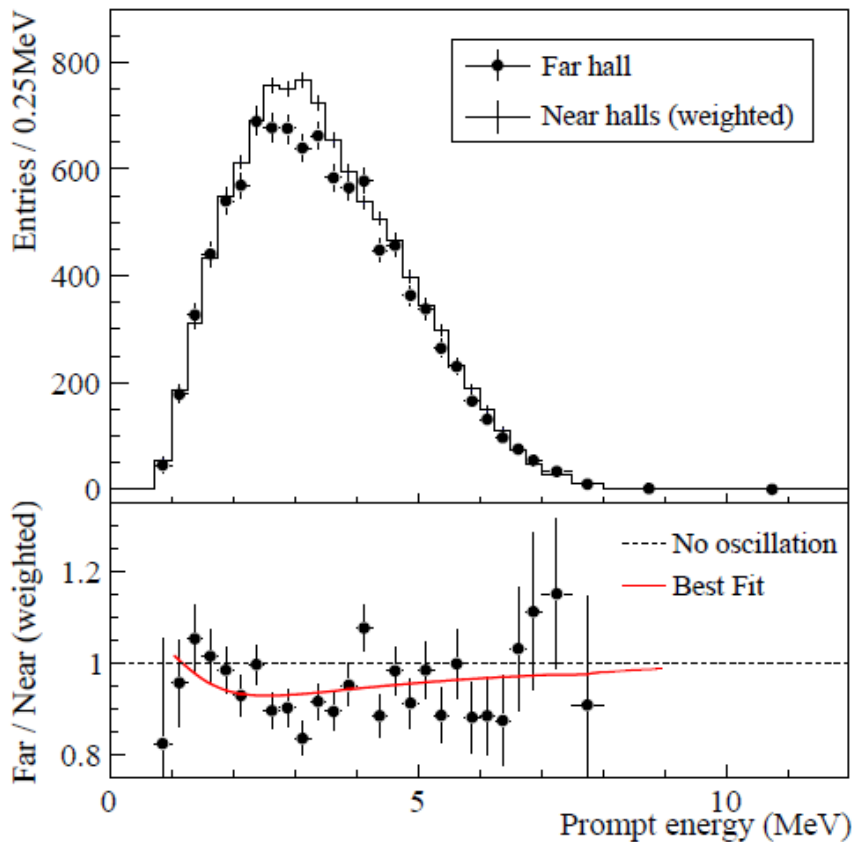
Calibration robots insert
radioactive sources and LEDs.



Reflectors improve light collection uniformity.

Daya Bay R=Far/Near

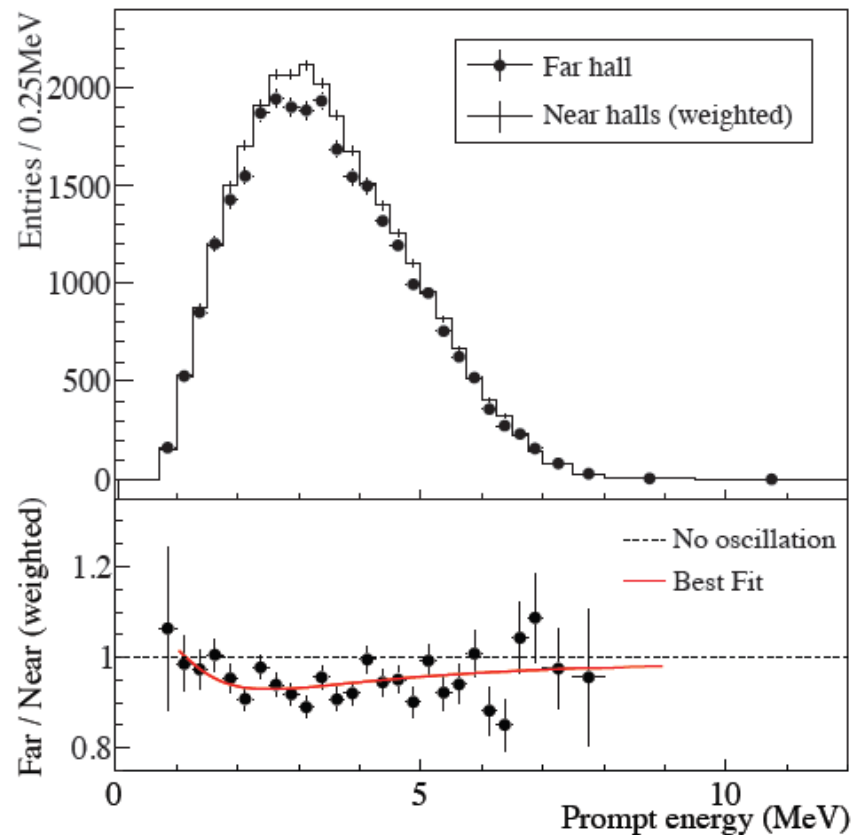
Phys.Rev.Lett.**108** (2012) 171803
e-Print: arXiv: 1203.1669 [hep-ex]



$$R = 0.940 \pm 0.011(\text{stat}) \pm 0.004(\text{syst})$$

11/06/2012

NEUTRINO 2012 (June 4, 2012)



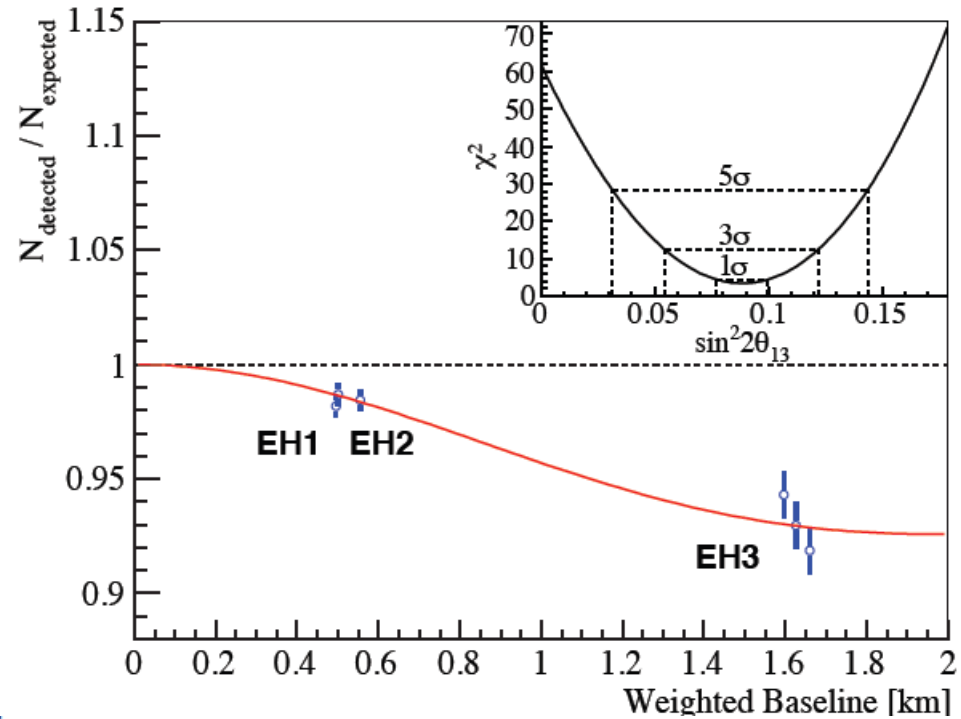
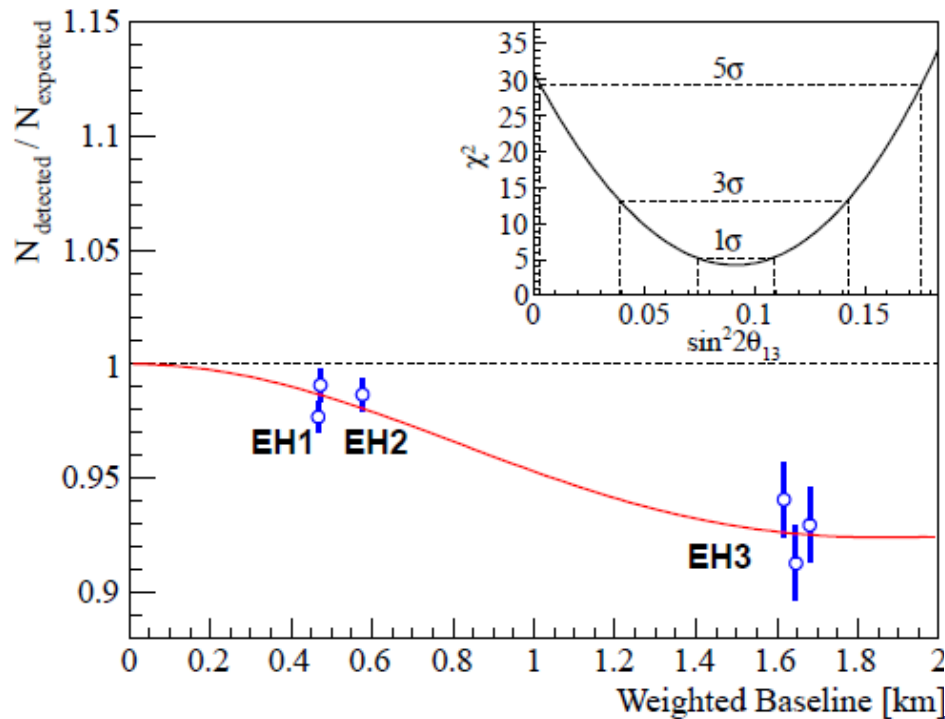
$$R = 0.944 \pm 0.007(\text{stat}) \pm 0.003(\text{syst})$$

47

Daya Bay $\sin^2 2\theta_{13}$ fit

Phys.Rev.Lett.**108** (2012) 171803
e-Print: arXiv: 1203.1669 [hep-ex]

NEUTRINO 2012 (June 4, 2012)



$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$

$\sin^2 2\theta_{13} = 0$ is excluded at 5.2 σ

$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$

$\sin^2 2\theta_{13} = 0$ is excluded at 8 σ !!!

Installation of final pair antineutrino detectors this year.

11/06/2012

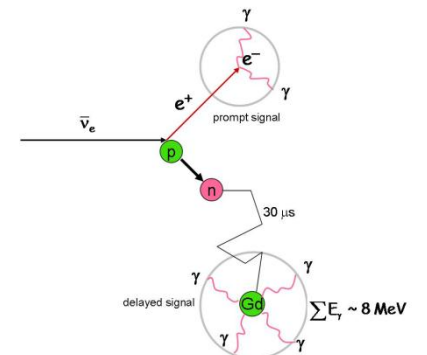
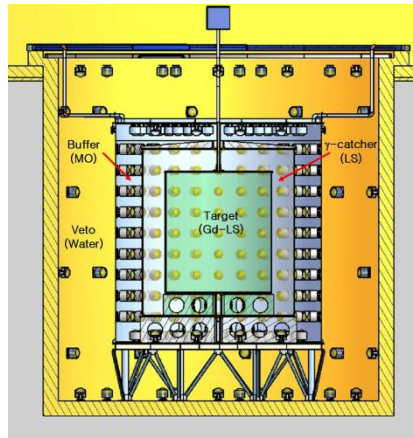
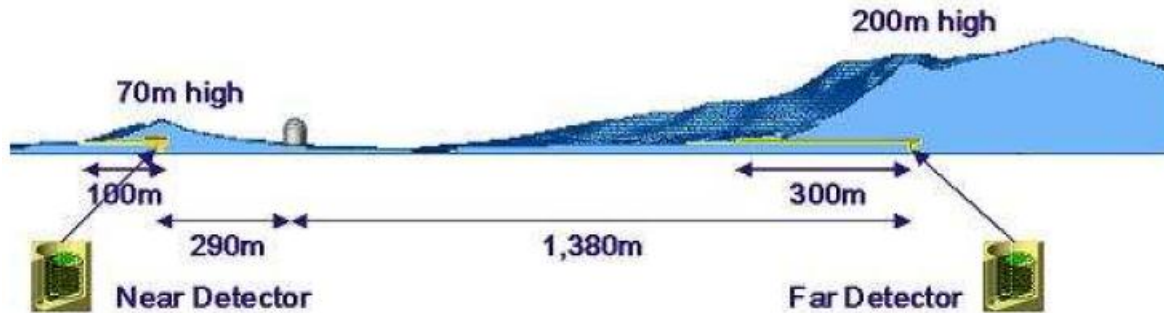
48

RENO

[arXiv:1003.1391v1](https://arxiv.org/abs/1003.1391v1)

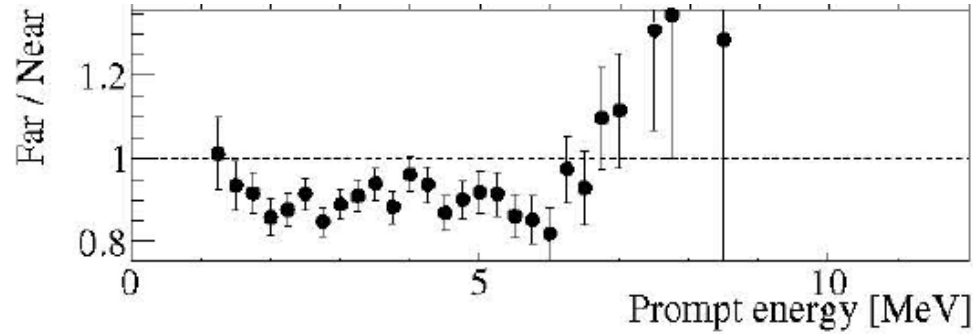


11/06/2012

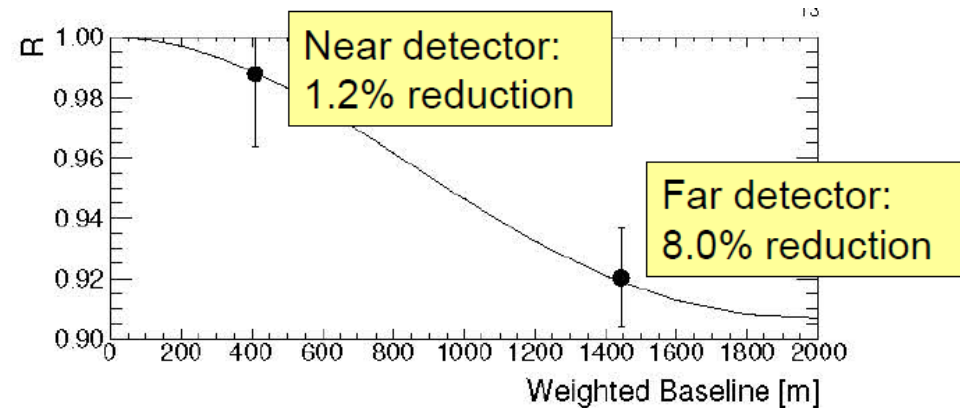


RENO

Phys.Rev.Lett.**108** (2012) 191802
e-Print: arXiv: 1204.0626 [hep-ex]

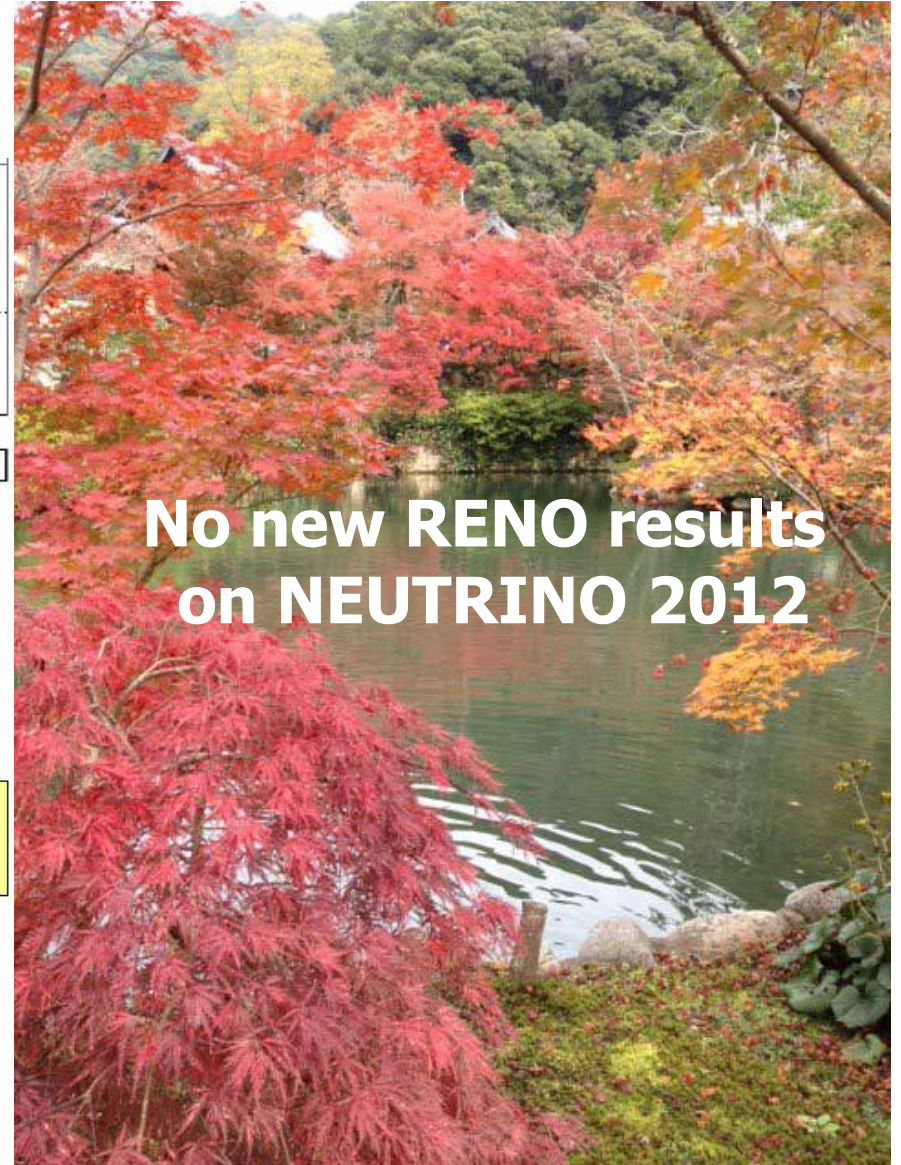


$$R = 0.920 \pm 0.009(\text{stat}) \pm 0.014(\text{syst})$$



$$\sin^2 2\theta_{13} = 0.113 \pm 0.013(\text{stat}) \pm 0.019(\text{syst})$$

11/06/2012



**No new RENO results
on NEUTRINO 2012**



Mixing angles

$$\sin^2\theta_{12}$$

5.4%

$$\sin^2\theta_{13}$$

13%

$$\sin^2\theta_{23}$$

13%

G.L. Fogli, E. Lisi, A. Marrone,
D. Montanino, A. Palazzo, A.M. Rotunno
arXiv:1205.5254 [hep-ph] 25 May 2012

after Neutrino 2012 (beginning of June)

$$\sin^2\theta_{12}$$

5.4%

$$\sin^2\theta_{13}$$

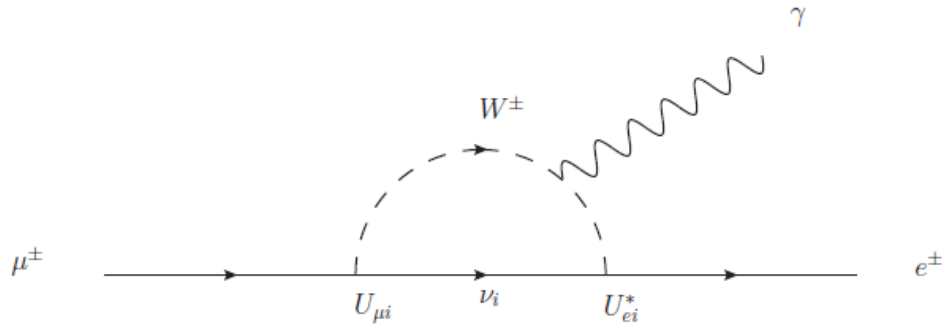
10%

$$\sin^2\theta_{23}$$

13%

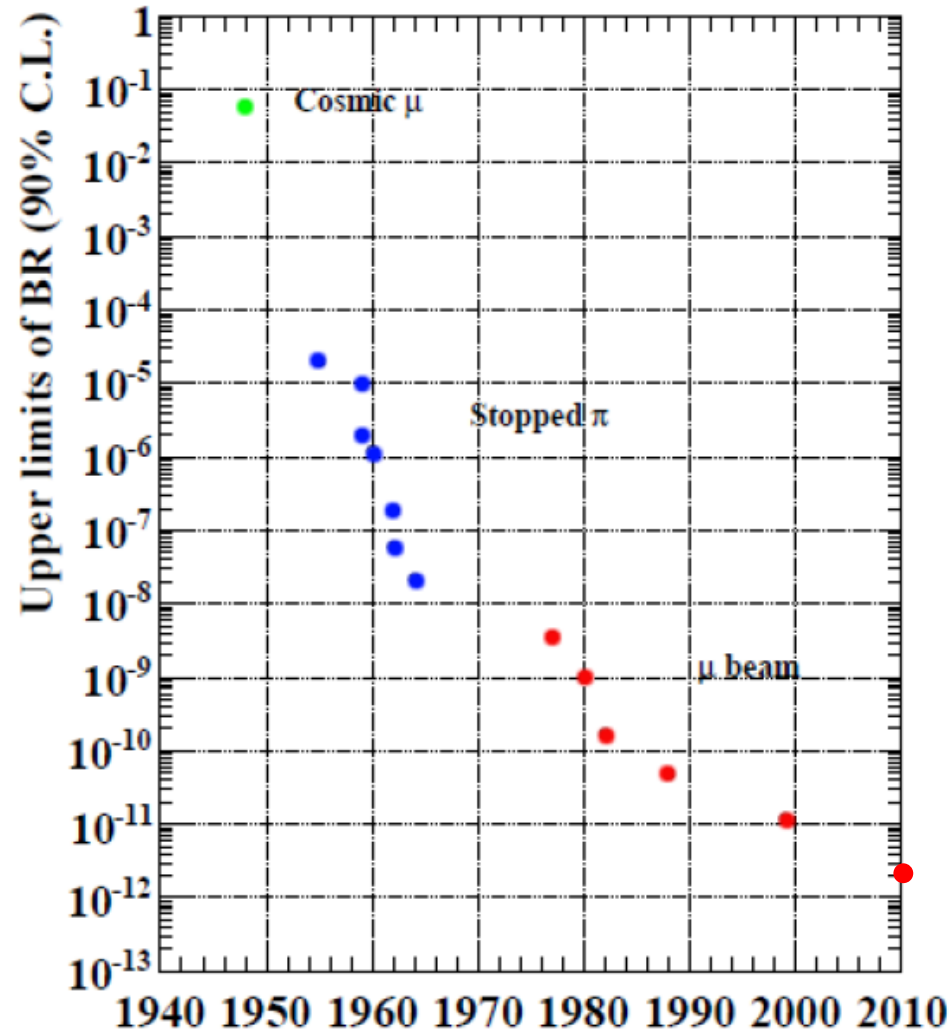
MEG $\mu^+ \rightarrow e^+ \gamma$

Phys. Rev. Lett. **107** (2011) 171801; arXiv:1107.5547v4 [hep-ex]



$$\begin{aligned} \text{BR}(\mu \rightarrow e \gamma) &= \frac{3\alpha}{32\pi} \left| \sum_i U_{\mu i}^* U_{ei} \frac{m_{\nu_i}^2}{M_W^2} \right|^2 \\ &= \frac{3\alpha}{32\pi M_W^4} \left| U_{\mu 2}^* U_{e2} \Delta m_{21}^2 + U_{\mu 3}^* U_{e3} \Delta m_{31}^2 \right|^2 \\ &= (2.4 \div 3.7) \times 10^{-55} \end{aligned}$$

$$\text{BR}(\mu^+ \rightarrow e^+ \gamma) < 2.4 \times 10^{-12}$$



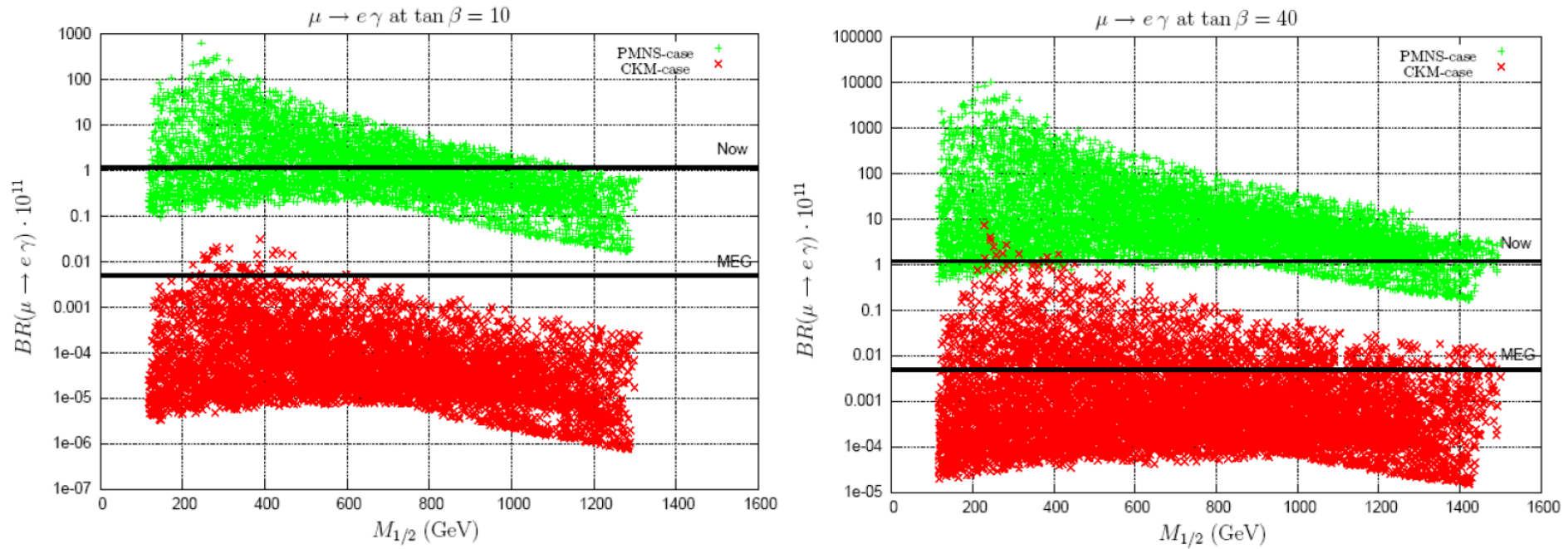
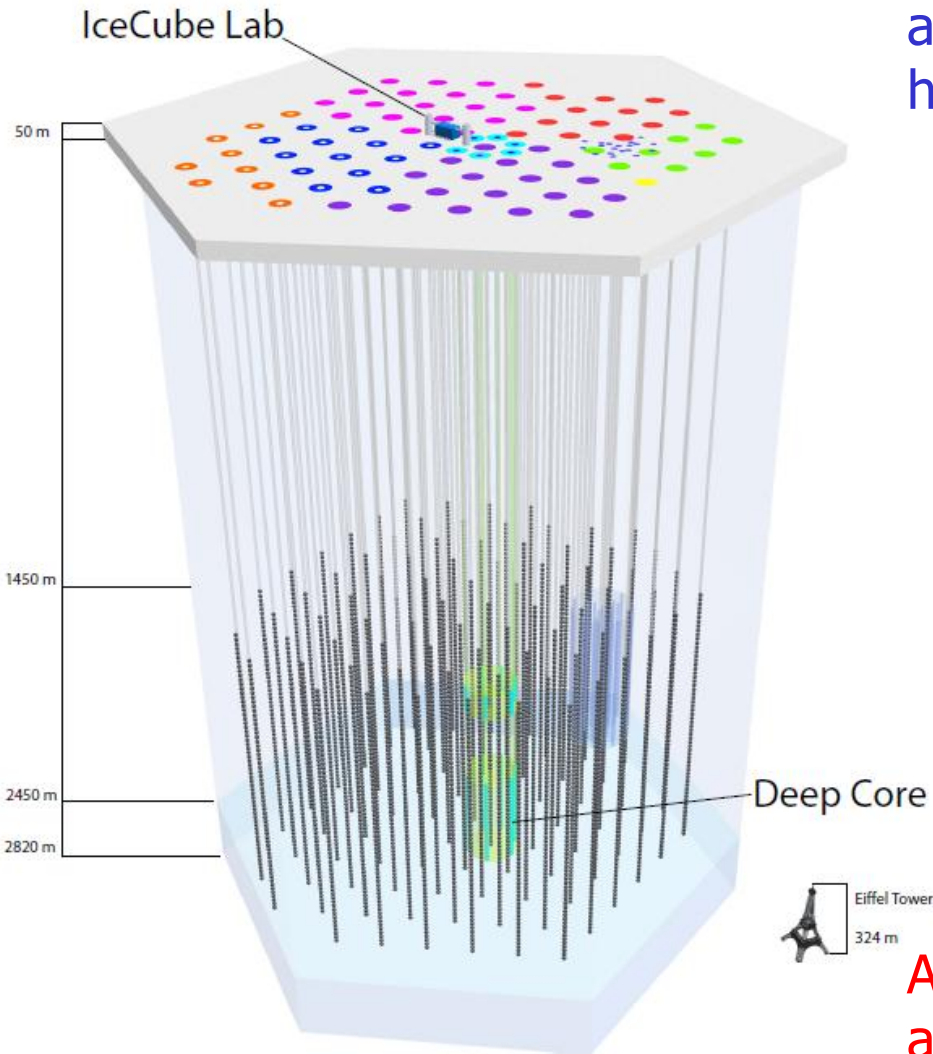


Figure 2.5: Predictions for $BR(\mu \rightarrow e\gamma)$ are shown as a function of the universal gaugino mass for two cases of $\tan\beta$, scanning an LHC relevant space in the parameters describing the Planck scale masses. Both the PMNS case (green) and the CKM case (red) are explored.

IceCube Collaboration

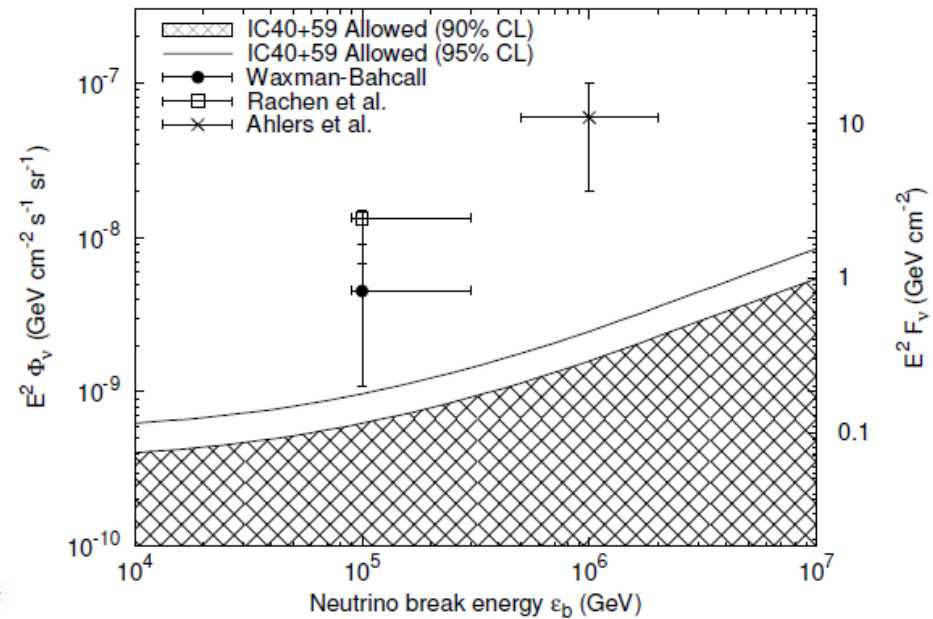
Nature **484** (2012) 351; arXiv:1204.4219 [astro-ph.HE]



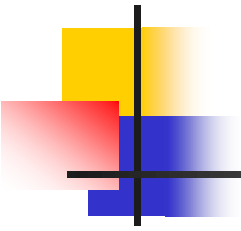
GRBs (γ -ray bursts) have been proposed as possible candidate sources for very high energy (10^{18} eV) cosmic rays.

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ \nu_\mu; \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$



An upper limit on the flux of energetic ν 's associated with GRBs is at least a factor of 3.7 below the predictions!



**Thank you for
your attention!**



Backup slides

Running coupling “constants”

The Standard Model is based on the gauge group $SU(3)_C \times SU(2)_W \times SU(1)_Y$ with the corresponding coupling constants $g_3, g_2 = g$ and g' .

The strong coupling constant $\alpha_s = g_3^2 / (4\pi)$:

$$\alpha_s^{-1}(Q) = \alpha_s^{-1}(M_Z) - \frac{b_3}{2\pi} \ln \frac{Q}{M_Z}, \quad \text{where } b_3 = -\frac{11}{3} N_C + \frac{2}{3} N_q,$$

$N_C = 3$ is number of colors,

N_q is number of quarks with $m_q < Q/2$.



All further evaluations will be done in one-loop leading order radiative correction approximation.

$\alpha_1, \alpha_2, \alpha_3$

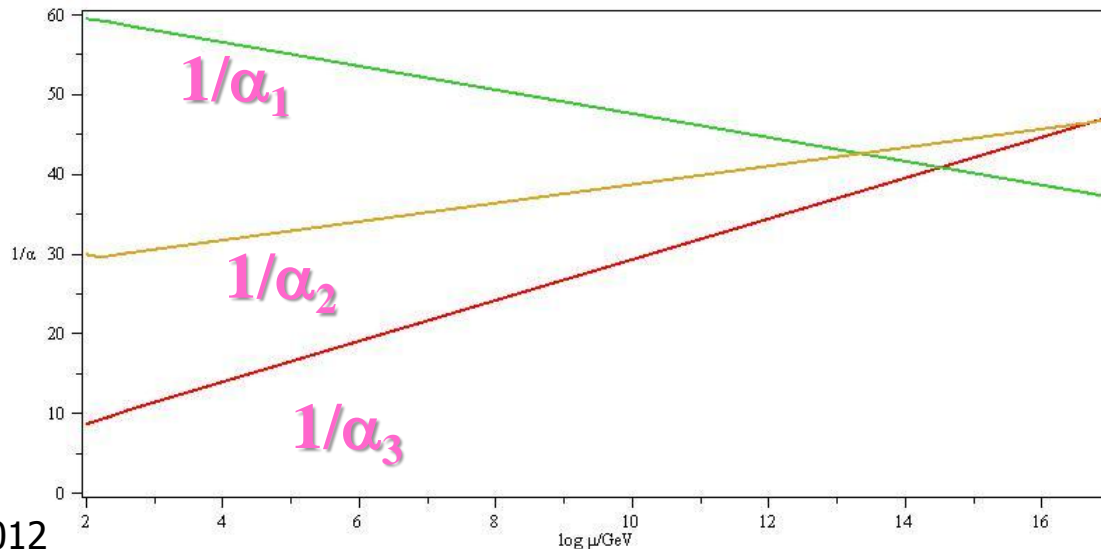
Evolution of the coupling constants $\alpha_1 = \frac{5}{3} \frac{g'^2}{4\pi} = \frac{5\alpha}{3 \cos^2 \theta_W}$, $\alpha_2 = \frac{g^2}{4\pi} = \frac{\alpha}{\sin^2 \theta_W}$, $\alpha_3 = \alpha_s$,

which correspond to proper normalization of the generators, can be found, for example,

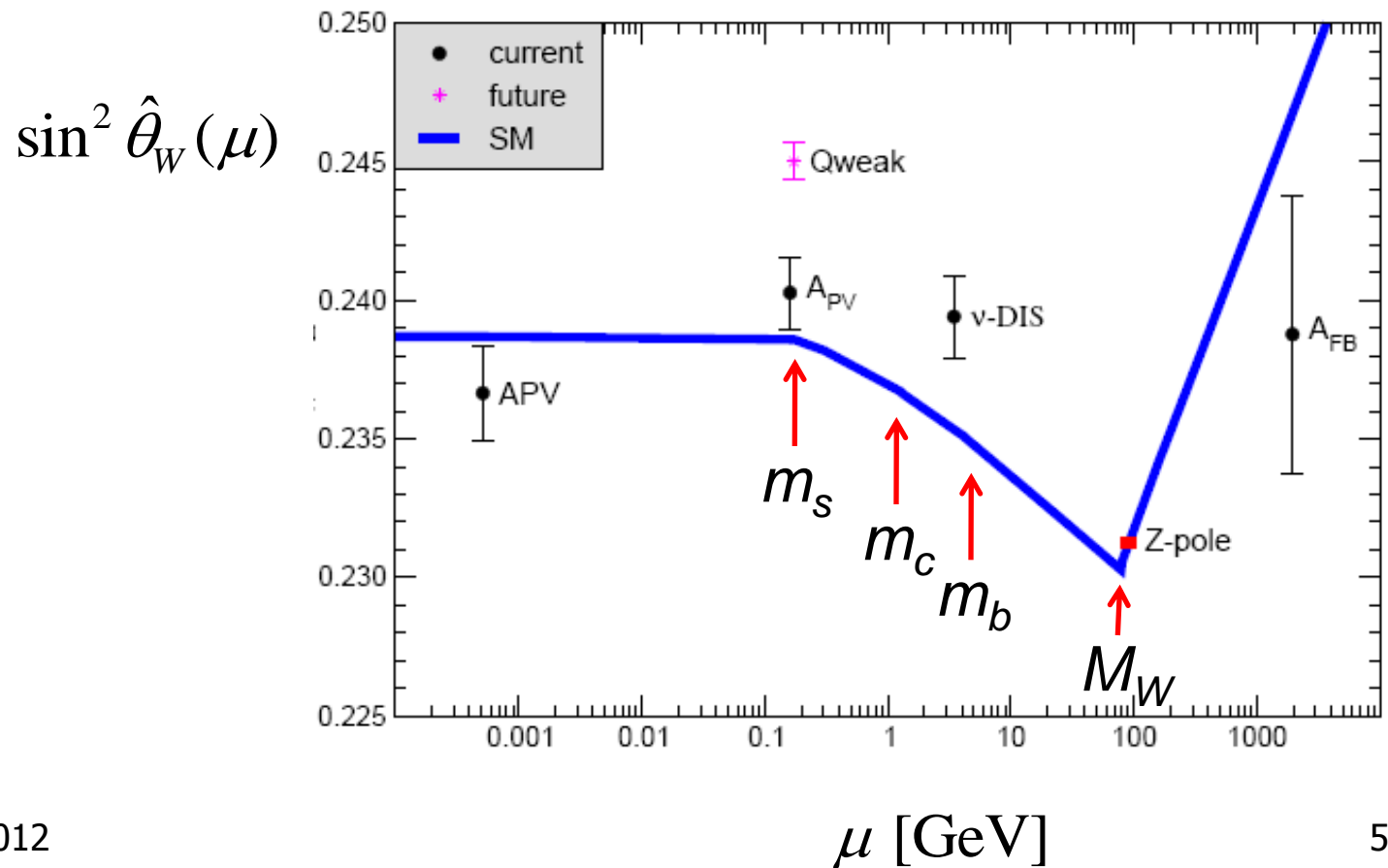
in D. Kazakov, hep-ph/0012288: $\alpha_i^{-1}(\mu) = \alpha_i^{-1}(M_Z) - \frac{b_i}{2\pi} \ln \frac{\mu}{M_Z}$,

$$\text{where } b_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -22/3 \\ -11 \end{pmatrix} + \frac{2}{3} N_f + \begin{pmatrix} 1/10 \\ 1/6 \\ 0 \end{pmatrix} N_{\text{Higgs}}.$$

It is clear, that we can get evolutions of $\alpha^{-1} = \frac{5}{3} \alpha_1^{-1} + \alpha_2^{-1}$ and $\sin^2 \theta_W = \frac{1}{1 + \frac{5\alpha_2}{3\alpha_1}}$, as well.



Evolution of the mixing angle

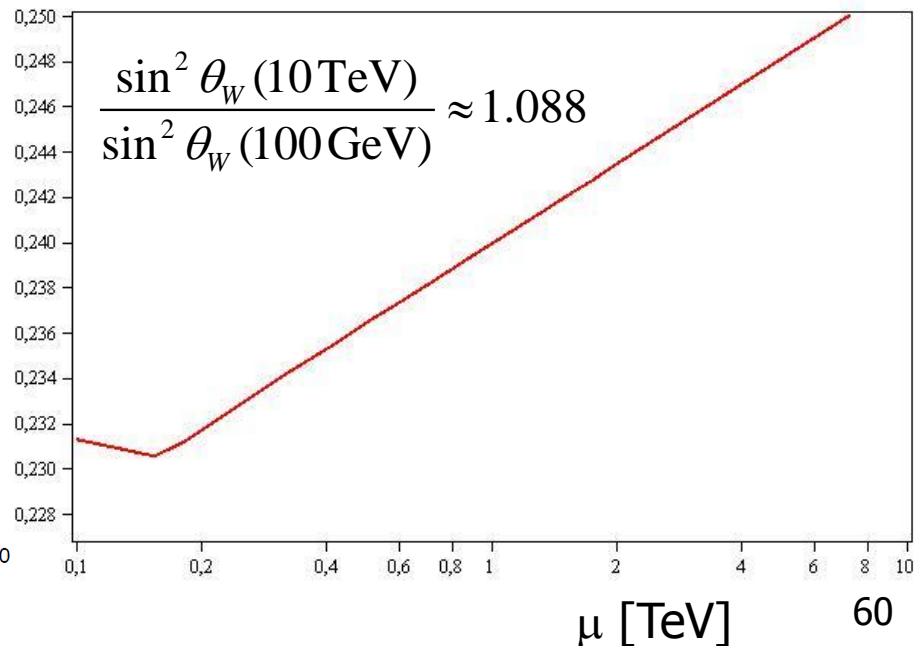
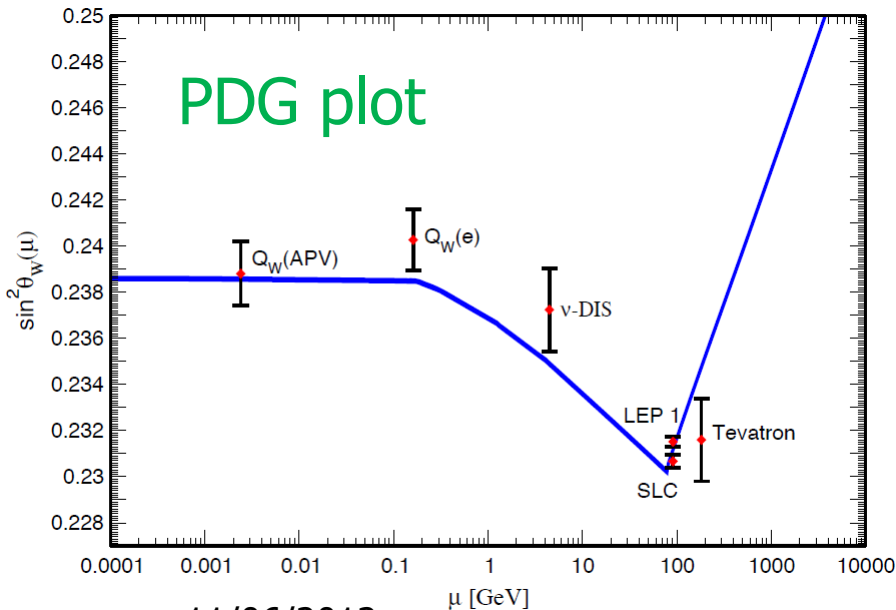


Electroweak coupling constants

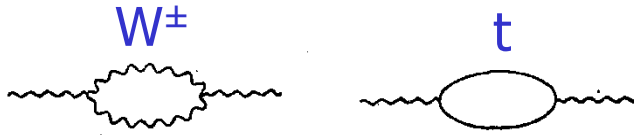
Instead of g and g' , PYTHIA is using α_{em} and $\sin^2\theta_W$.

“The coupling structure within the electroweak sector is usually (re)expressed in terms of gauge boson masses, α_{em} and $\sin^2\theta_W$... Having done that, α_{em} is allowed to run [Kle89], and is evaluated at the s scale. ... Currently $\sin^2\theta_W$ is not allowed to run.”

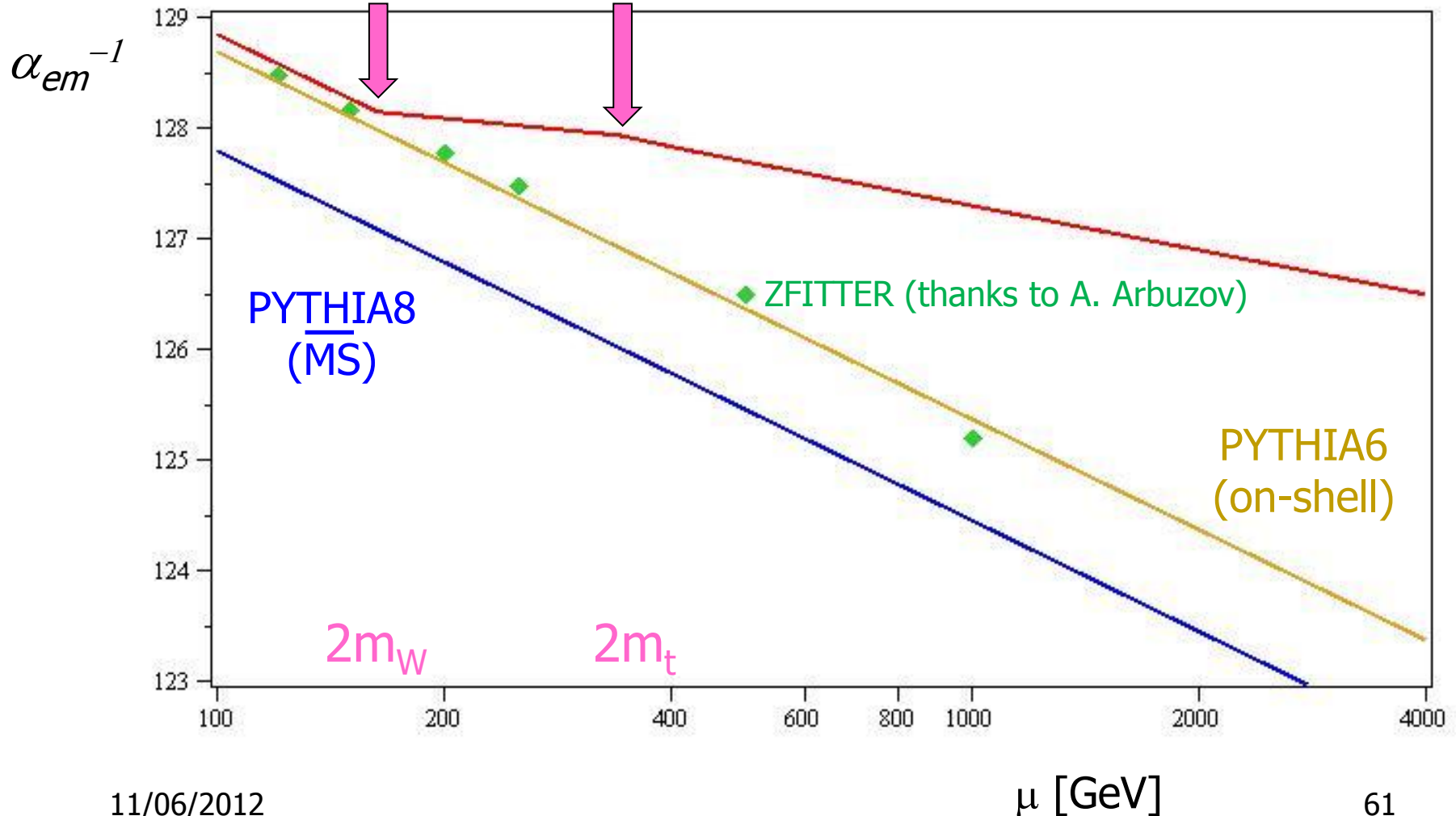
$\sin^2\theta_W$ is fixed. **It is nonsense in TeV region!!!**



Fine structure constant α_{em} evolution

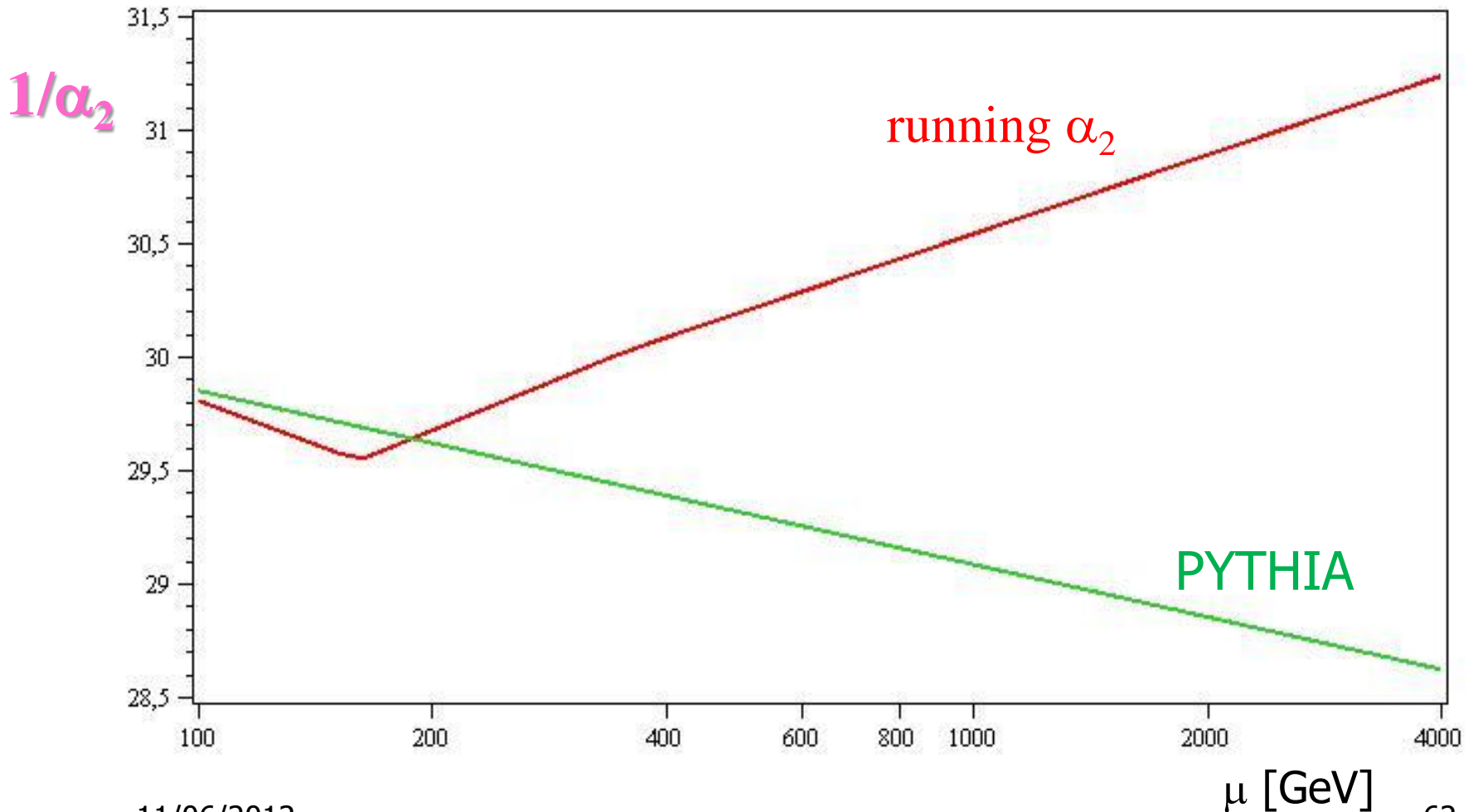


Was not included in PYTHIA



Evolution of $SU(2)_W$ weak coupling constant α_2

The **PYTHIA** result versus **my calculations** with properly running coupling constant



Z'_{SSM} total width

The **PYTHIA** result versus my calculations with properly running coupling constants

