Precision Measurements and Tevatron Legacy

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Standard Model (SM)

$$\begin{pmatrix}\nu_{eL}\\ e_L\end{pmatrix} \quad e_R \quad \nu_{eR} \quad \begin{pmatrix}u_{3L}\\ d_{3L}\end{pmatrix} \begin{pmatrix}u_{2L}\\ d_{2L}\end{pmatrix} \begin{pmatrix}u_{1L}\\ d_{1L}\end{pmatrix} \quad d_{1R}\; d_{2R}\; d_{3R} \quad u_{1R}\; u_{2R}\; u_{3R}$$

$$\begin{pmatrix}\nu_{\mu L}\\ \mu_L\end{pmatrix} \quad \mu_R \quad \nu_{\mu R} \quad \begin{pmatrix}c_{3L}\\ s_{3L}\end{pmatrix} \begin{pmatrix}c_{2L}\\ s_{2L}\end{pmatrix} \begin{pmatrix}c_{1L}\\ s_{1L}\end{pmatrix} \quad s_{1R}\; s_{2R}\; s_{3R} \quad c_{1R}\; c_{2R}\; c_{3R}$$

$$\begin{pmatrix}\nu_{\tau L}\\ \tau_L\end{pmatrix} \quad \tau_R \quad \nu_{\tau R} \quad \begin{pmatrix}t_{3L}\\ b_{3L}\end{pmatrix} \begin{pmatrix}t_{2L}\\ b_{2L}\end{pmatrix} \begin{pmatrix}t_{1L}\\ b_{1L}\end{pmatrix} \quad b_{1R}\; b_{2R}\; b_{3R} \quad t_{1R}\; t_{2R}\; t_{3R}$$

$$\begin{pmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & -G_{11}-G_{22} \end{pmatrix} \qquad \begin{pmatrix} W^+ \\ Z \\ W^- \end{pmatrix} \qquad \gamma \qquad \begin{pmatrix} H^+ \\ \mathrm{Im}\, H^0 \end{pmatrix} \qquad \begin{pmatrix} H^- \\ \mathrm{Re}\, H^0 \end{pmatrix}$$

$SU(3)_C$ $\qquad$ $SU(2)_L$ $\qquad$ $U(1)_Y$

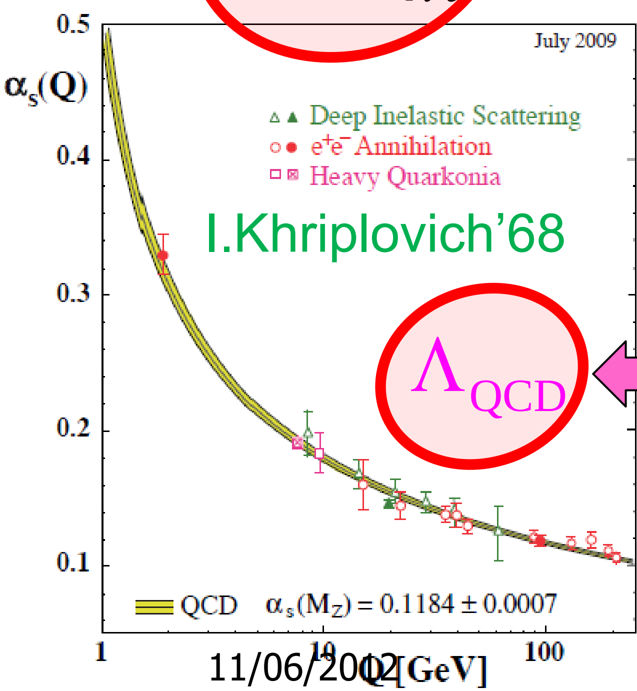
Gauge group of the SM

$SU(3)_C \otimes SU(2)_L \otimes U(1)$

g_3

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

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



I.Khriplovich'68

Spontaneous Symmetry Breaking

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

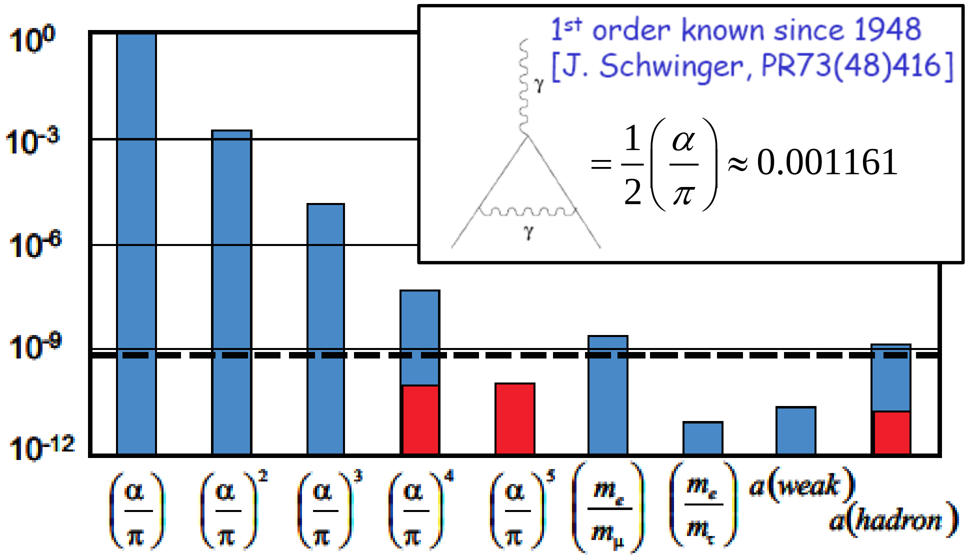
…contains one more independent parameter: the Higgs mass $\Delta r(M_H)$

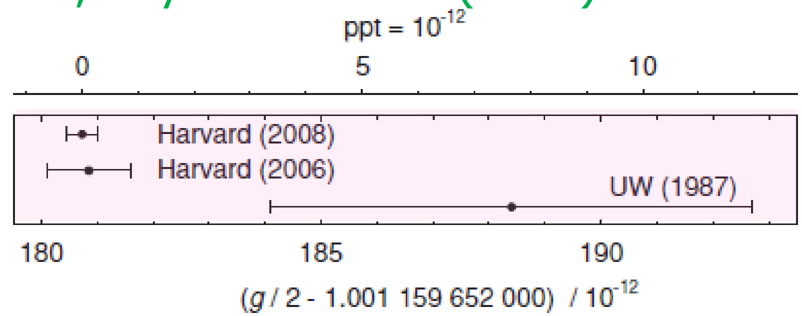
α

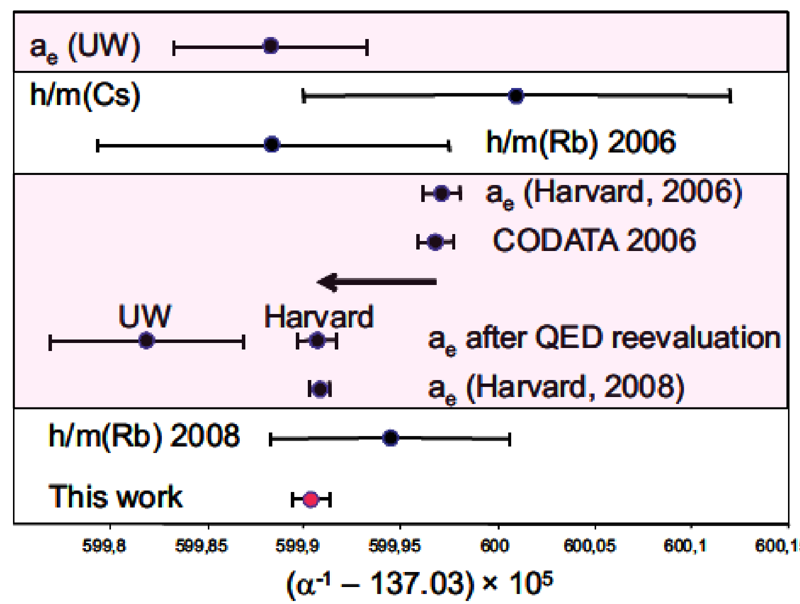
The electron anomalous magnetic moment and the fine-structure constant measurements

$$g/2\,[0.28\ \text{ppt}] \rightarrow a_e^{exp} \equiv \frac{g-2}{2} = 0.001\,159\,652\,180\,73(28) \quad [0.24\ \text{pp}$$

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







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

R. Bouchendira, 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

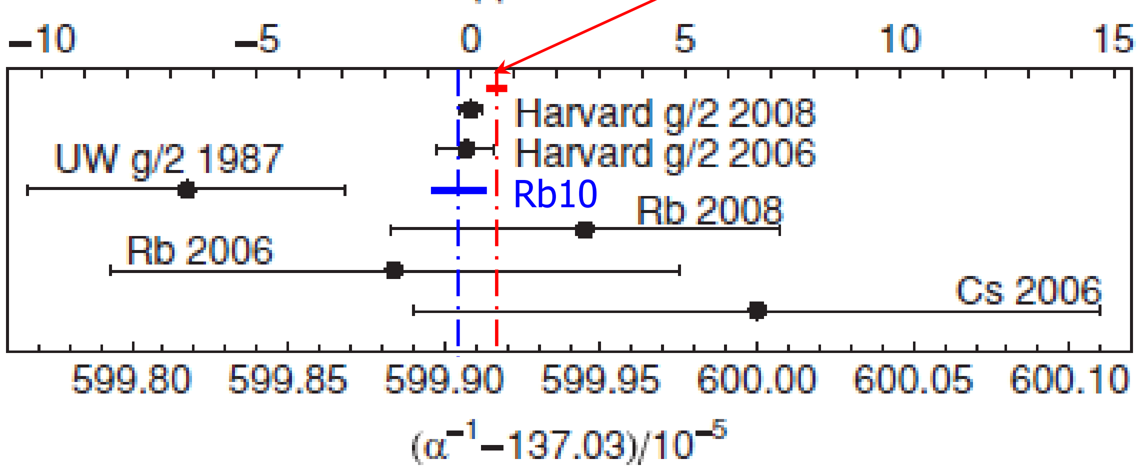
Tatsumi Aoyama,[1,2] Masashi Hayakawa,[3,2] Toichiro Kinoshita,[4,2] and Makiko Nio[2]

[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 $\alpha^{-1} = 137.035\ 999\ 166\ (34)$ [0.25ppb].

ppb = 10^{-9}



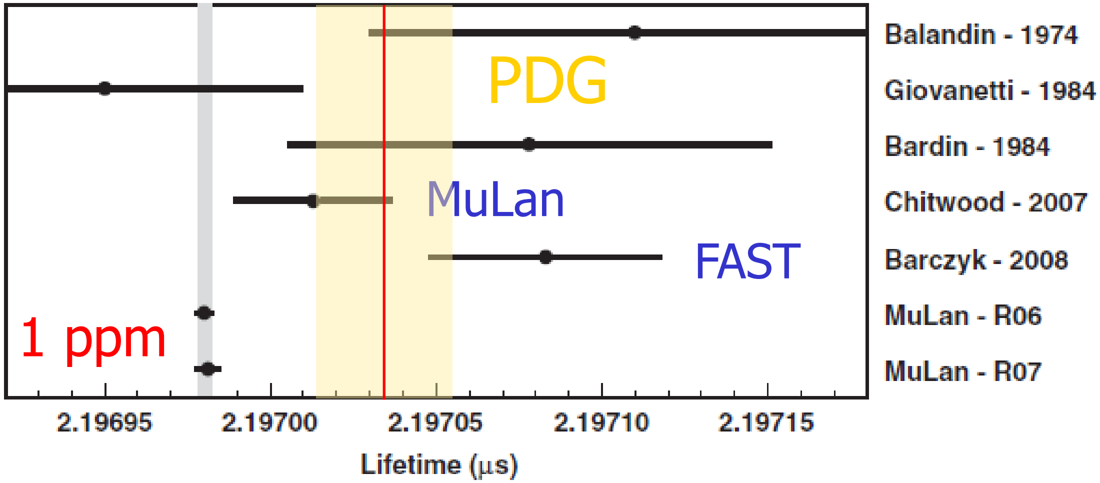
G_F

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. Gorringe,[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. Wolfe[1]

(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 $\mu^- p$ 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

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

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

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

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

$$\hat{\alpha}(m_\mu)^{-1} = \alpha^{-1}+\frac{1}{3\pi}\ln\rho \approx 135.9\ .$$

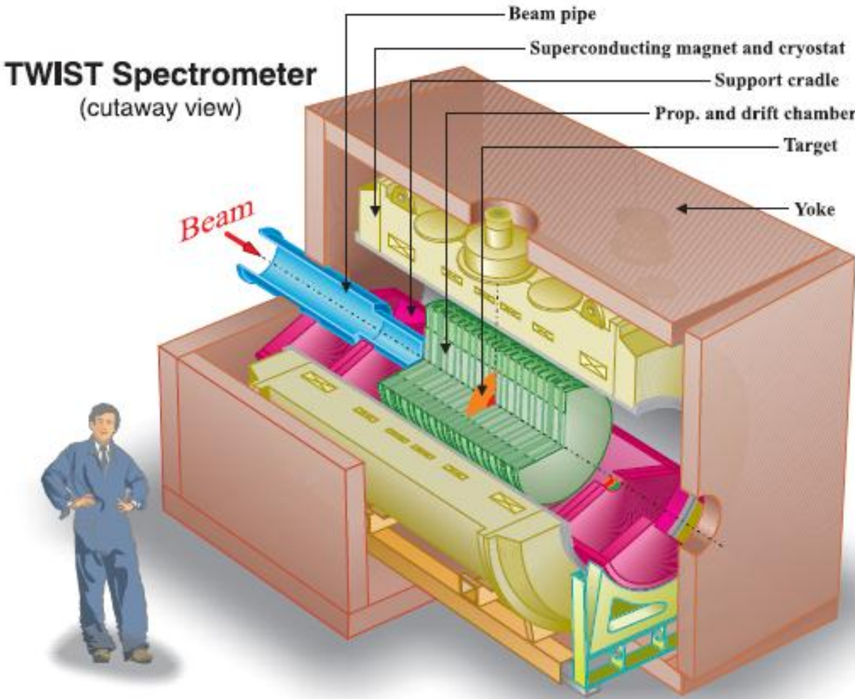
$$G_F^{\rm PDG} = 1.166\ 364\ (5)\times 10^{-5}\ \mathrm{GeV}^{-2}\ [4.3\ \mathrm{ppm}]$$

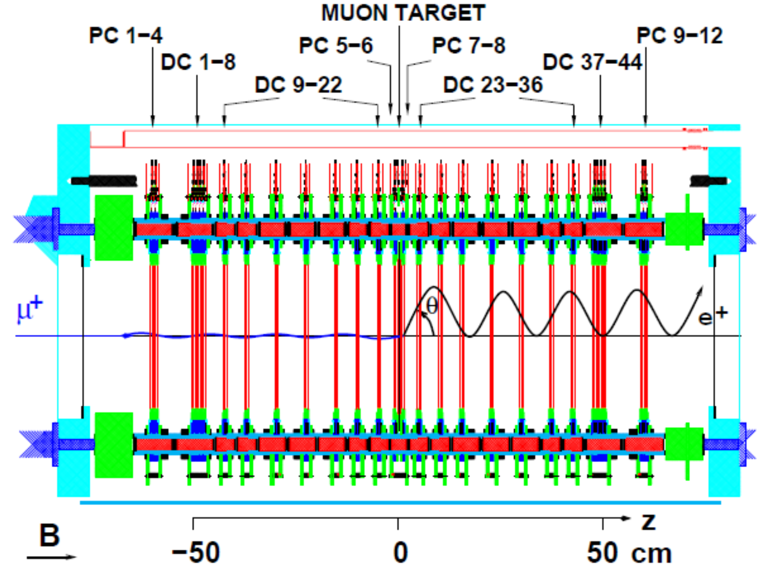
$$G_F = 1.166\ 378\ 8\ (7)\times 10^{-5}\ \mathrm{GeV}^{-2}\ [0.6\ \mathrm{ppm}]$$

$$\left|V_{ud}^{\rm PDG}\right| = 0.97425(22) \qquad \left|V_{ud}\right| = 0.97423(22)$$

TWIST

TRIUMF Weak Interaction Symmetry Test

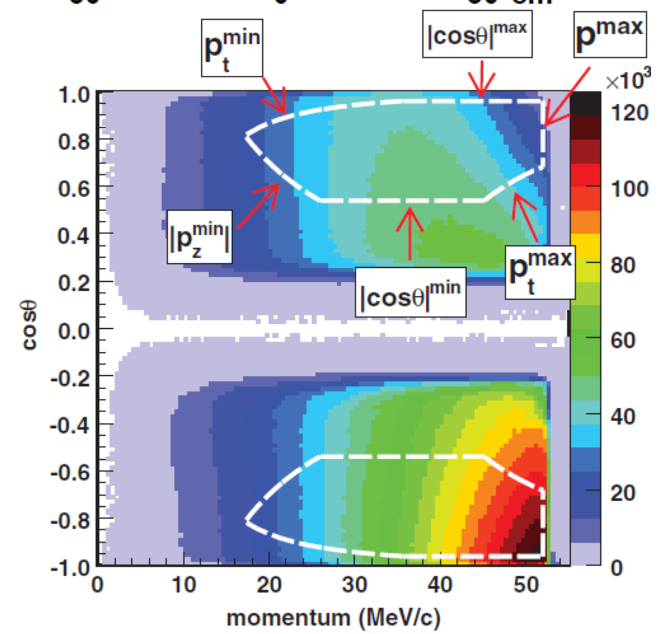




$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

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

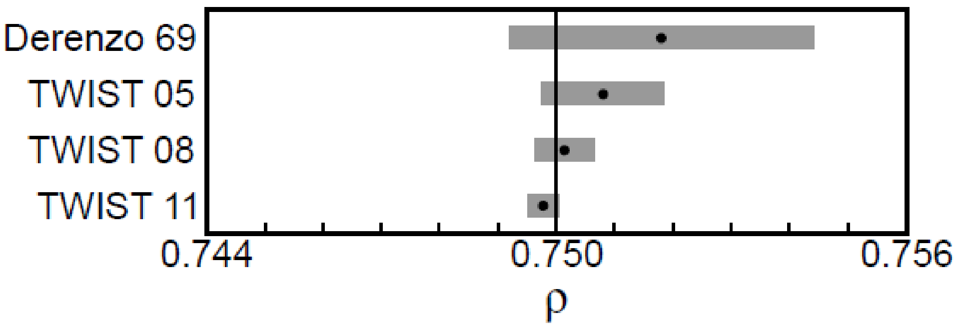
L. Michel, Proc. Phys. Soc. A**63**, 514 (1950).



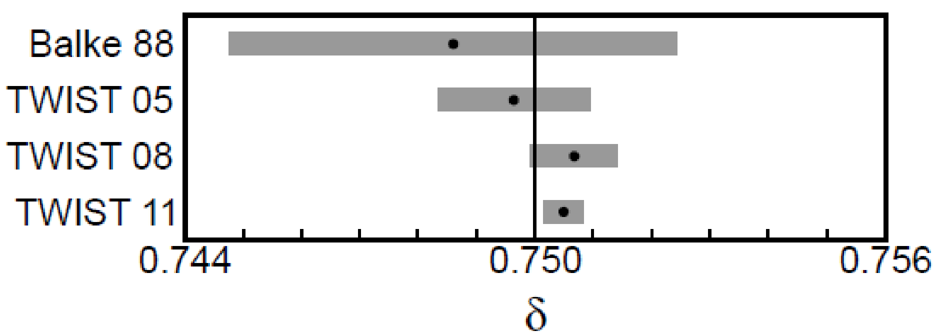
TWIST final results

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

$$\rho = 0.749\,77 \pm 0.000\,12(\mathrm{stat.}) \pm 0.000\,23(\mathrm{syst.})$$



$$\delta = 0.750\,49 \pm 0.000\,21(\mathrm{stat.}) \pm 0.000\,27(\mathrm{syst.})$$

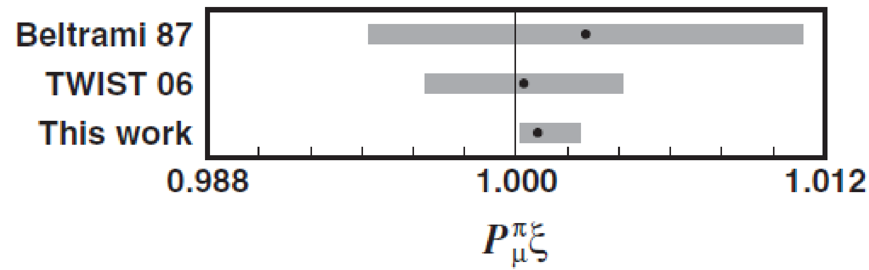


$$-0.009 < g^{T}_{RR} < +0.0005$$

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

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

$$P^{\pi}_{\mu}\xi = 1.000\,84 \pm 0.000\,29(\mathrm{stat.})\ {}^{+0.000\,65}_{-0.000\,63}(\mathrm{syst.})$$



$$P^{\pi}_{\mu}\xi\delta/\rho = 1.00179^{+0.001\,56}_{-0.000\,71} \leq 1$$

C. A. Gagliardi, R. E. Tribble, and N. J. Williams
Phys. Rev. D **84** (2011) 032005

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

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

Choosing the third constant

PDG 2010: Journal of Physics G 37, 075021 (2010)

$M_Z = 91.1876 \pm 0.0021$ GeV 23 ppm

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

α	G_F	M_Z^2
0.00025 ppm	0.6 ppm	46 ppm

$\alpha = 1/137.035\,999\,166\;(34)$ 0.25 ppb

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

$M_Z = 91.1876\;(21)$ GeV 23 ppm

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

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 $\sin^2\theta_W \to s_W^2 \equiv 1 - \frac{M_W^2}{M_Z^2}$: $\quad M_W^2 = \frac{\pi\alpha}{\sqrt{2}G_F\left(1 - M_W^2/M_Z^2\right)(1-$

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

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

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

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

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

m_t^2 **dependence?**

What about Appelquist–Carazzone decoupling theorem?

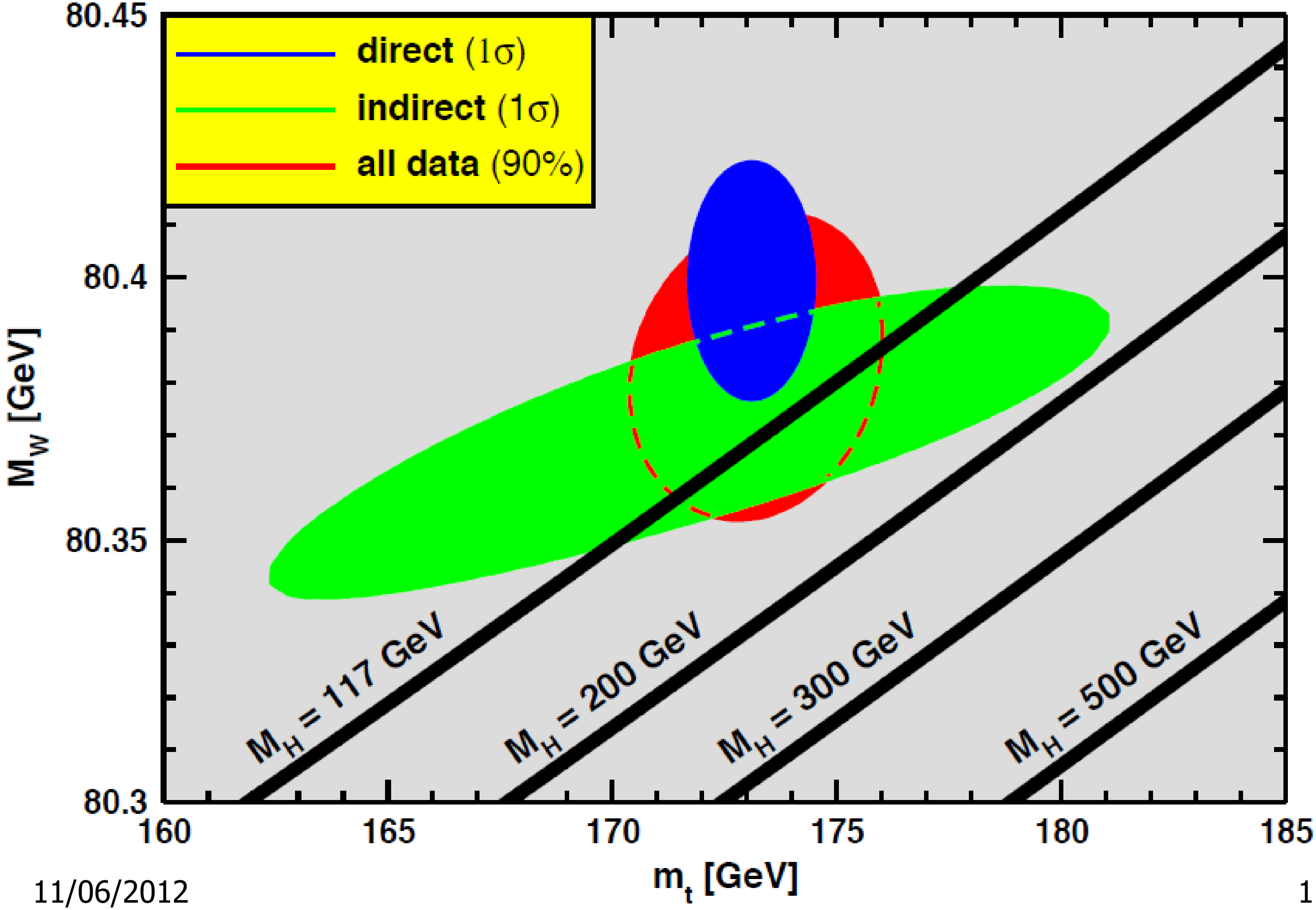
T. Appelquist & J. Carazzone, Phys. Rev. D **11** (1975) 2856

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 $m_t^2 - m_b^2$.

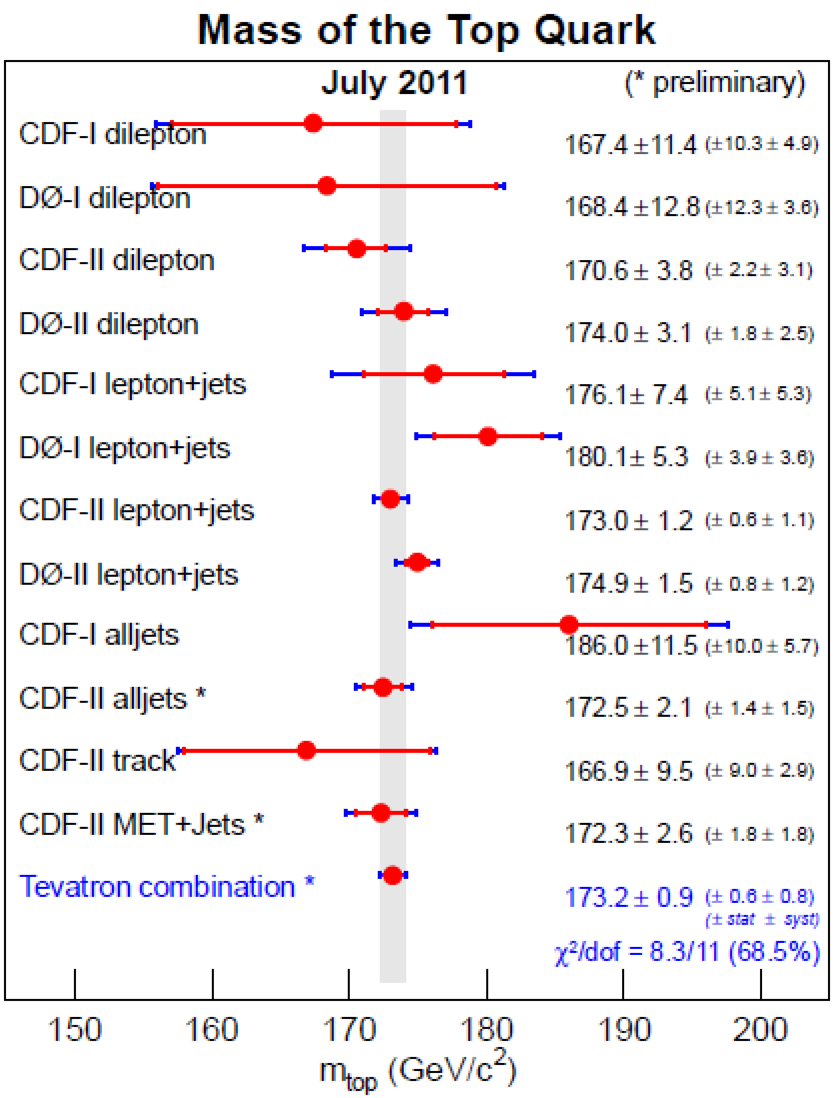
Owing to an accidental $SO(3)_C$ symmetry of the scalar sector (the so-called custodial symmetry), the virtual production of Higgs particles does not generate any quadratic dependence on the Higgs mass at one loop [M. Veltman]. The dependence on M_H is only logarithmic. The numerical size of the corresponding 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)



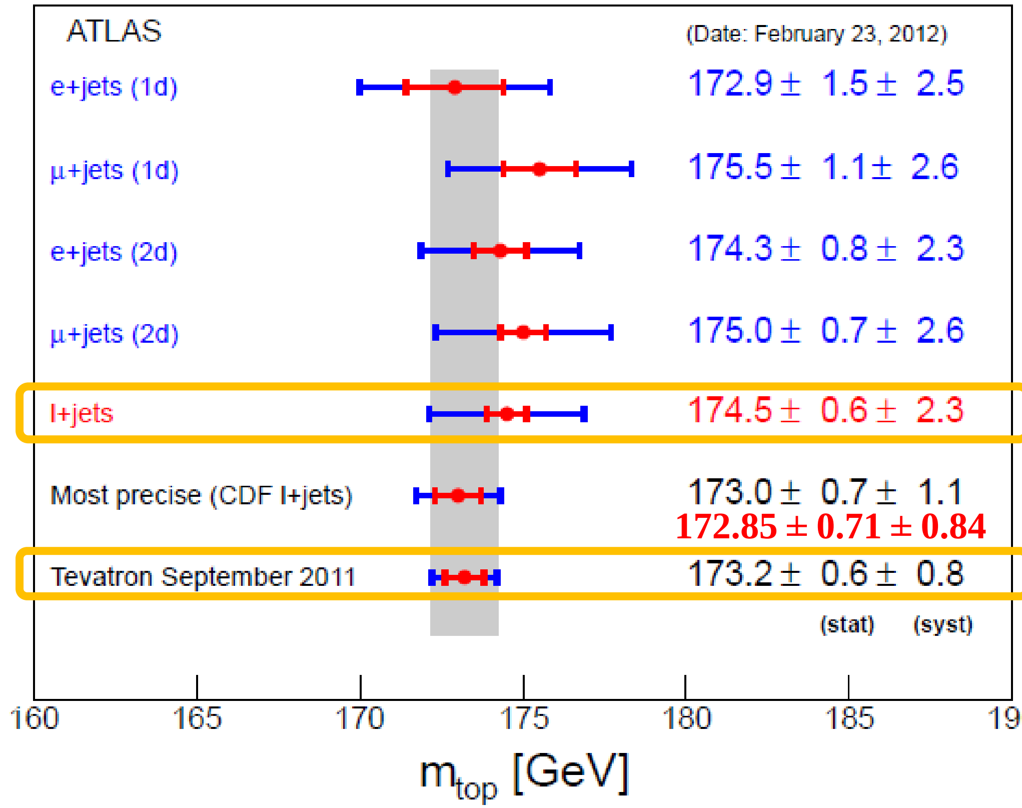
Tevatron: m_t = 173.18 ± 0.94 GeV

arXiv:1107.5255



ATLAS 1.04 fb^{-1} !

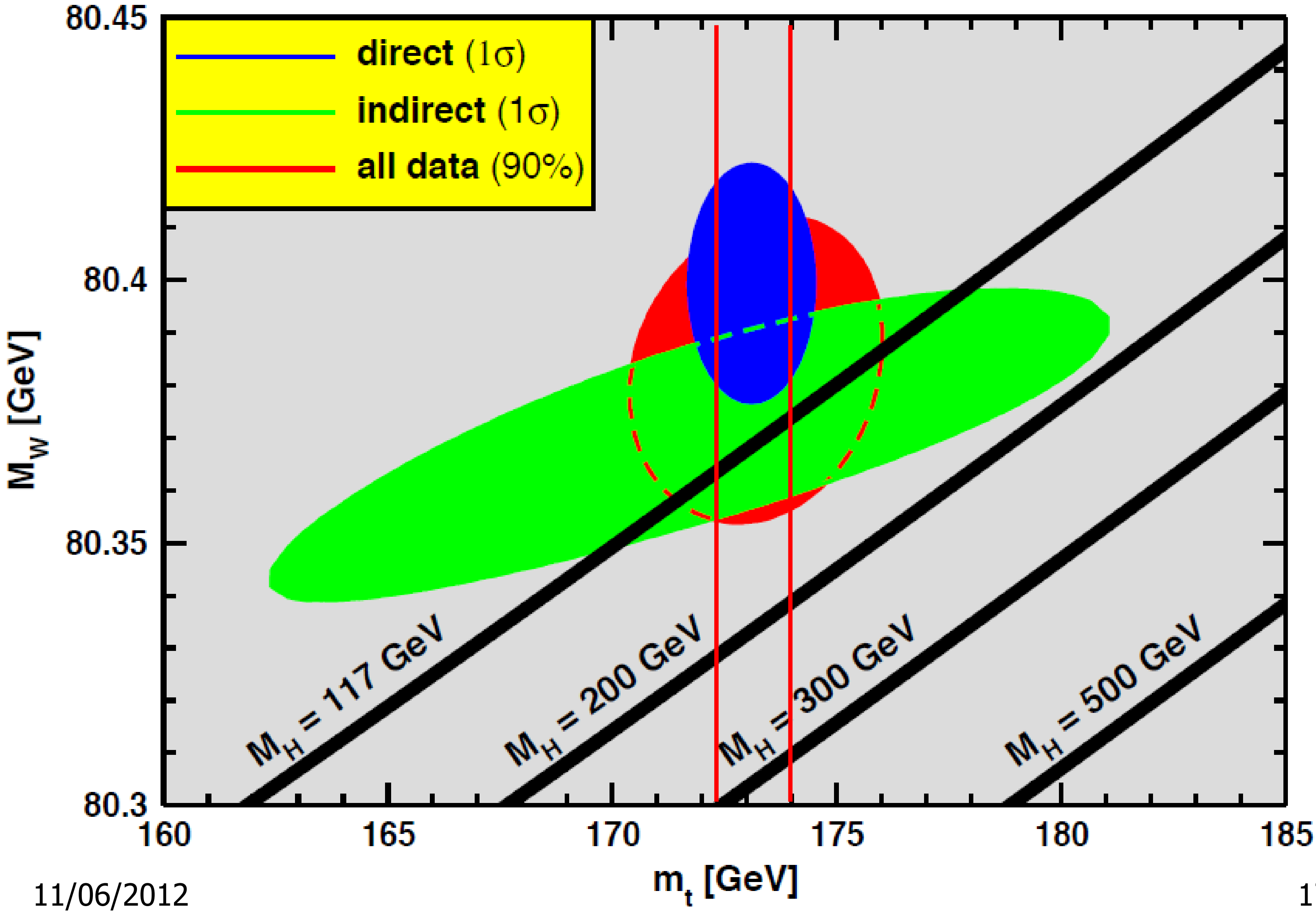
arXiv:1203.5755



CDF 8.7 fb^{-1} !

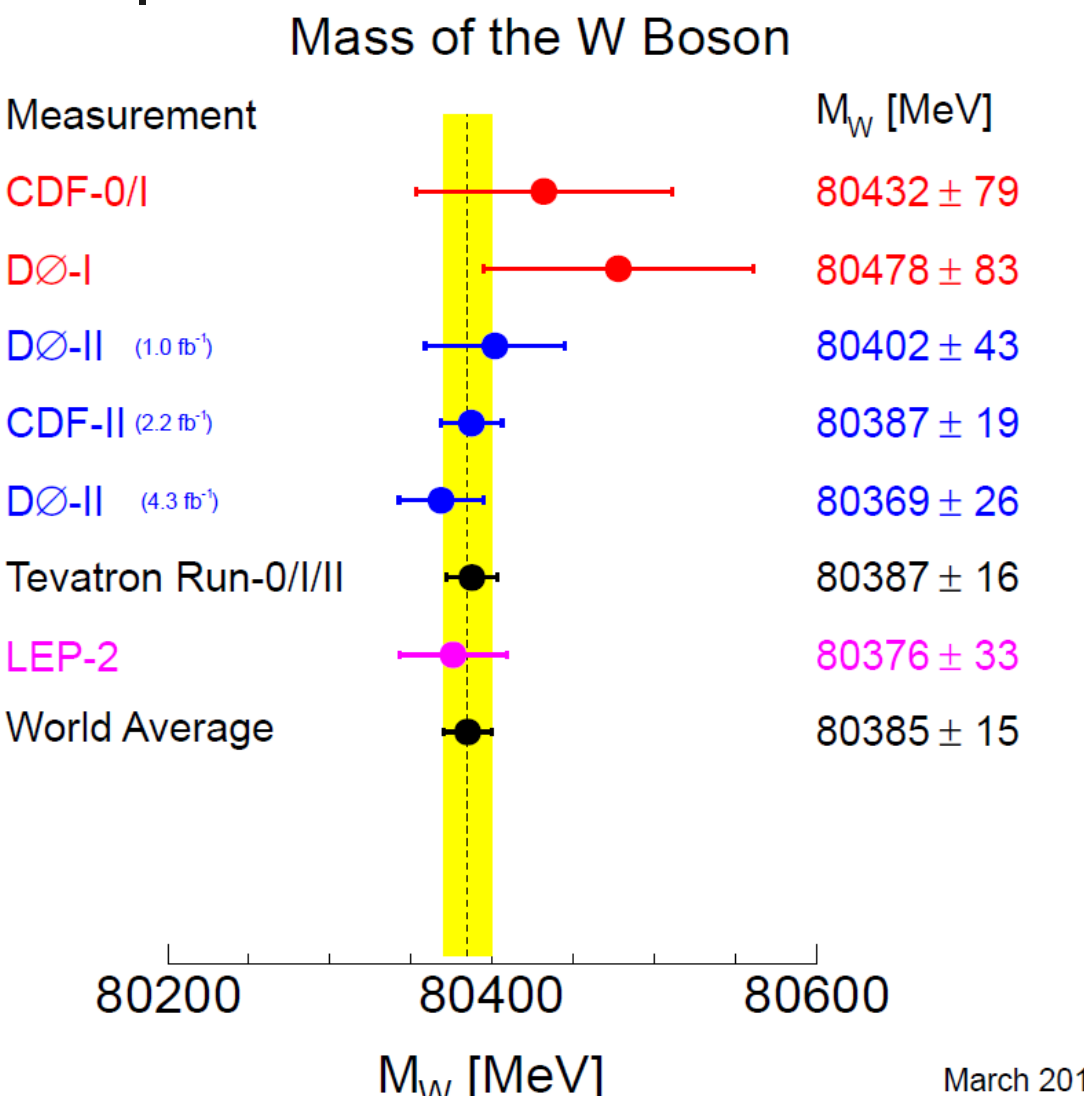
Conf Note 10761

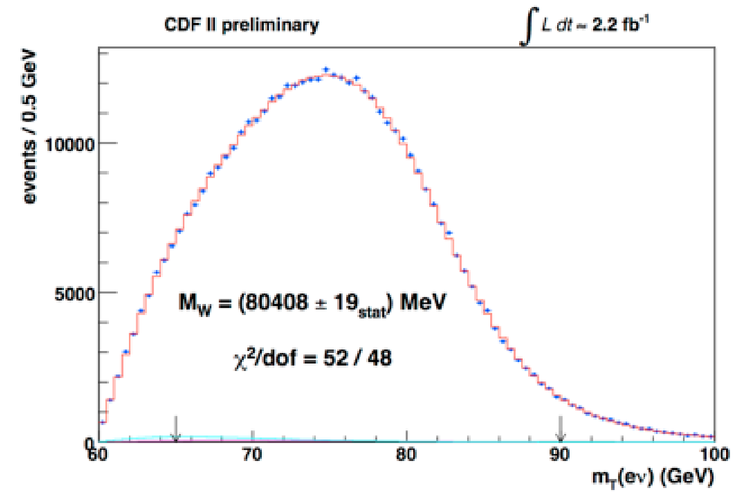
SM prediction versus data & new m_t

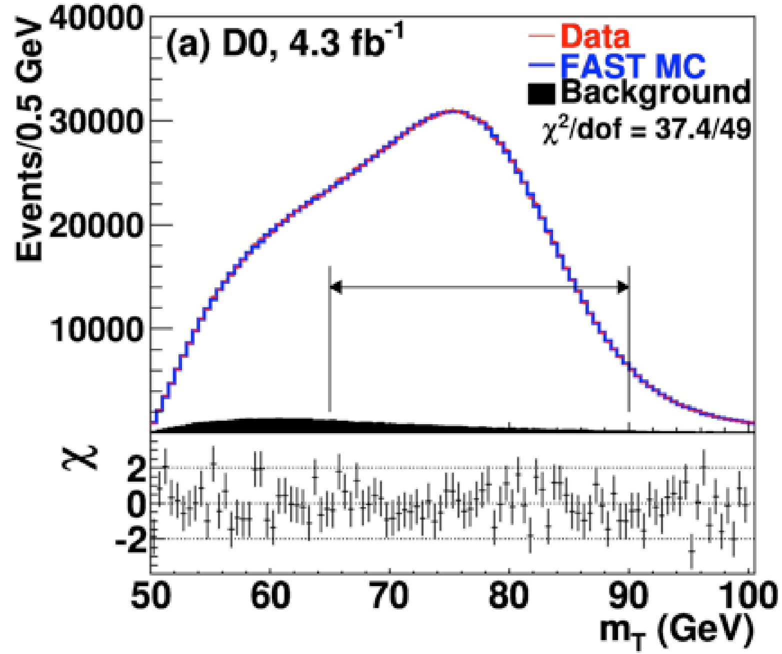


Tevatron: $M_W = 80.387 \pm 0.016$ GeV

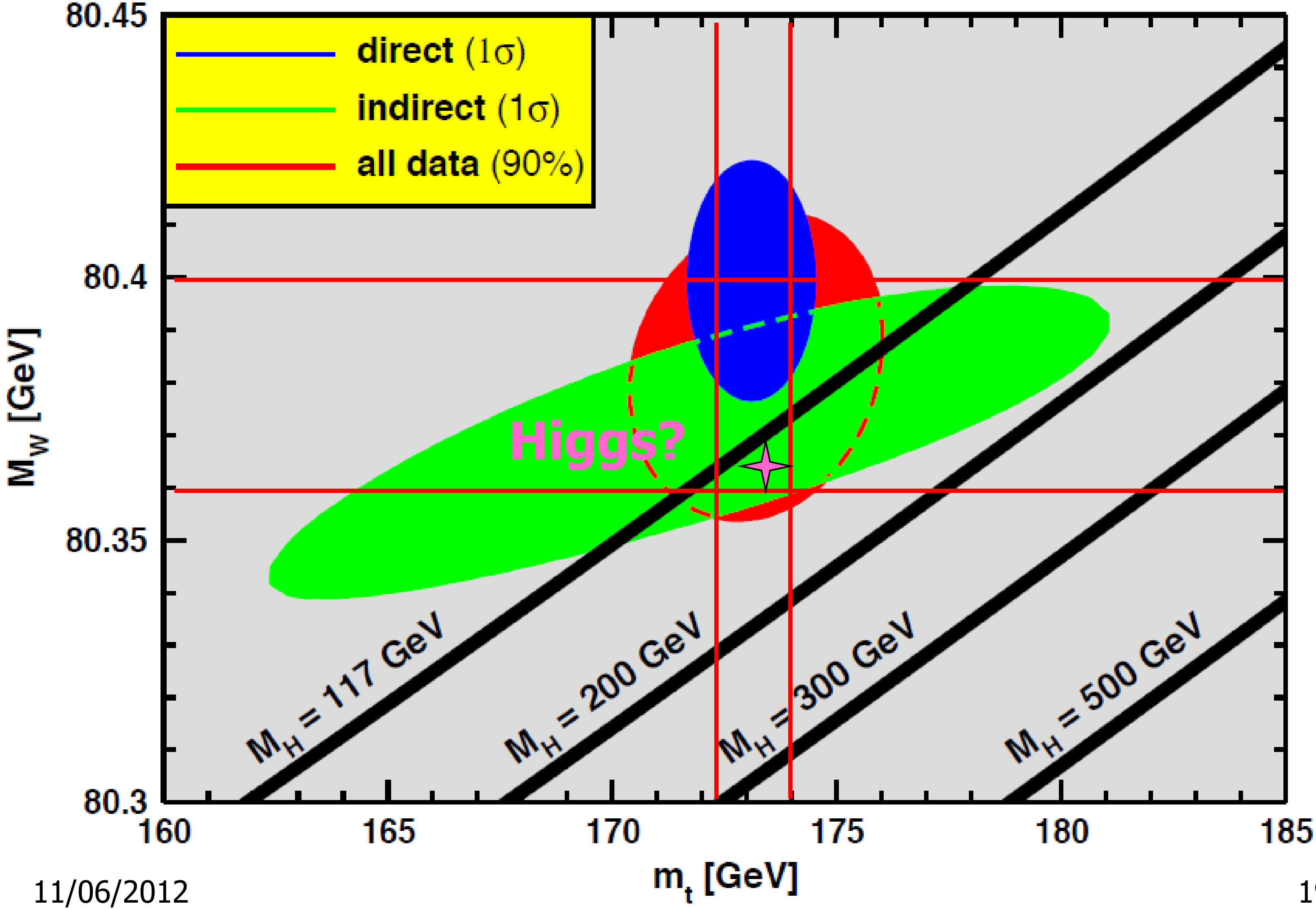
arXiv:1204.0042



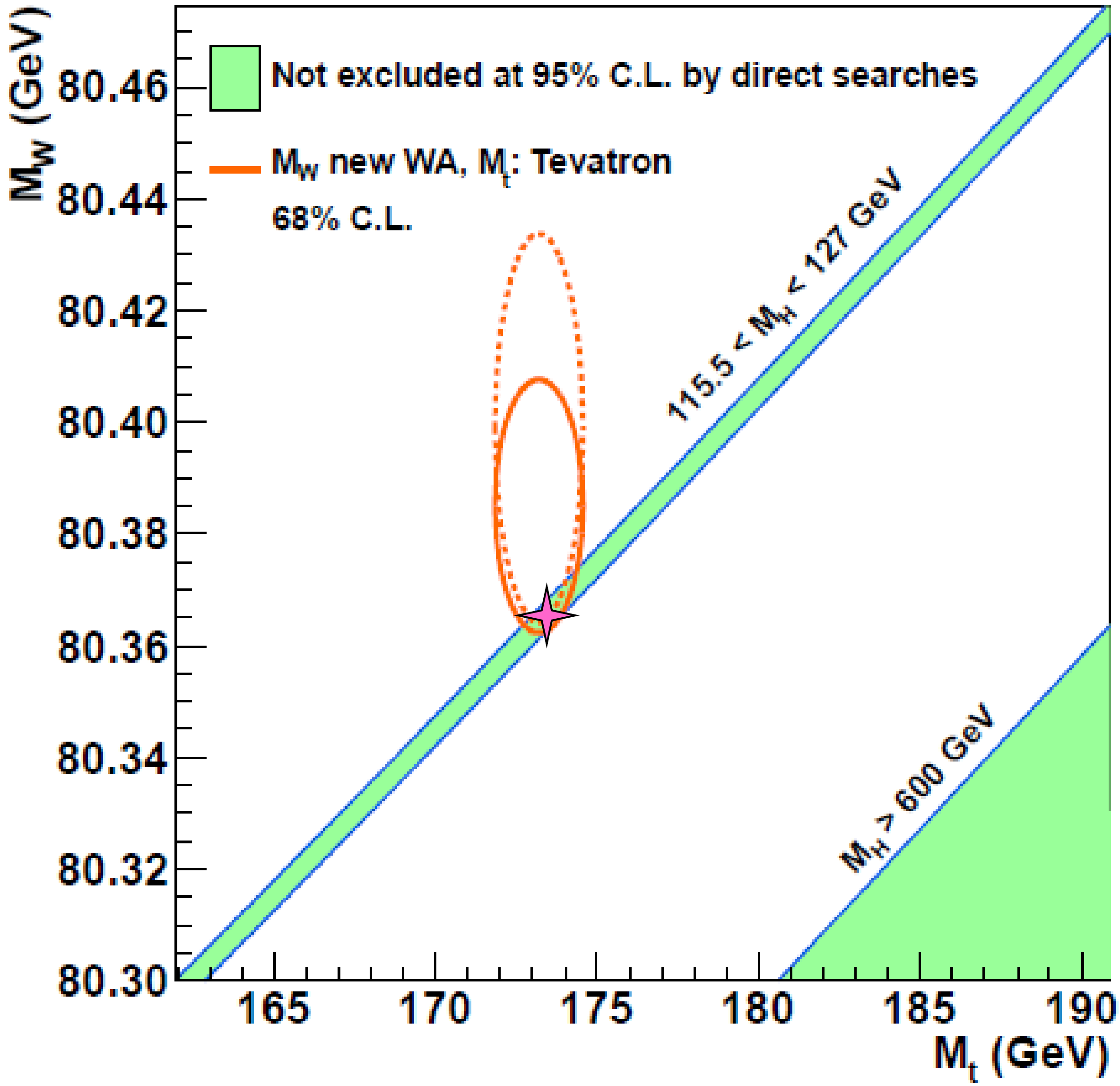




SM prediction vs new Tevatron data



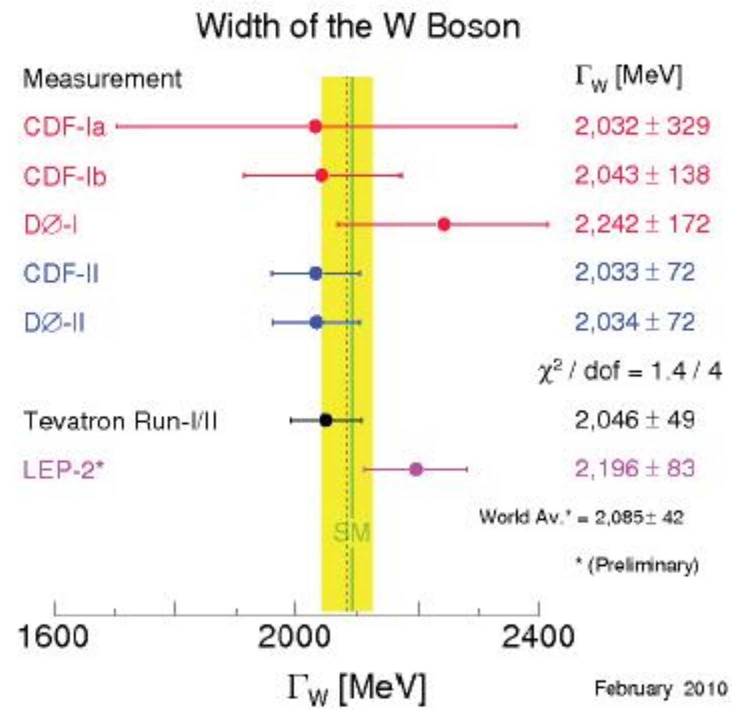
SM, Tevatron and LHC

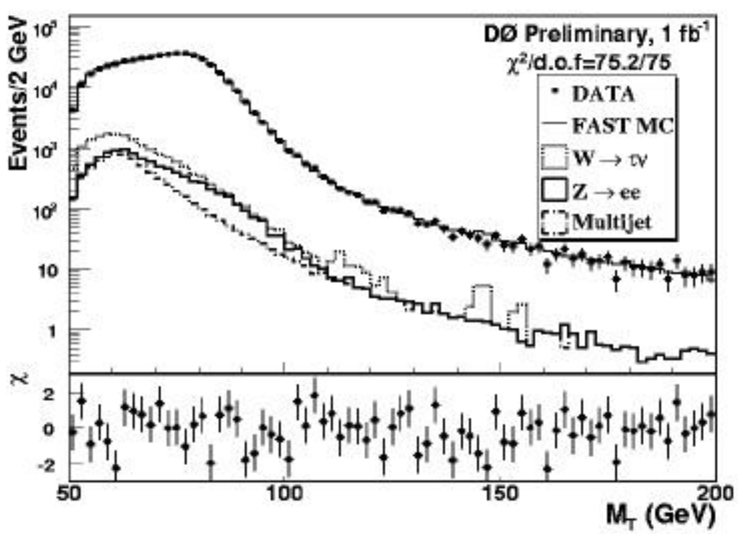


W-WIDTH Γ_W

- 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

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



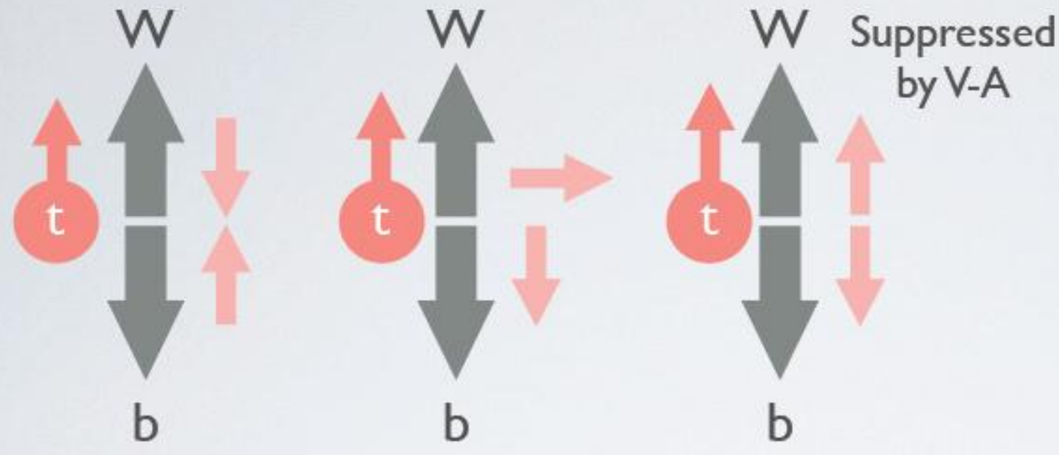


New world average:

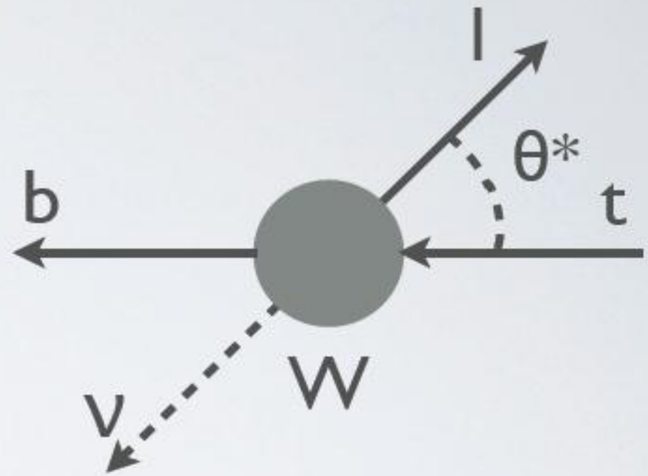
Γ_W = 2085 ± 42 (stat + syst) MeV

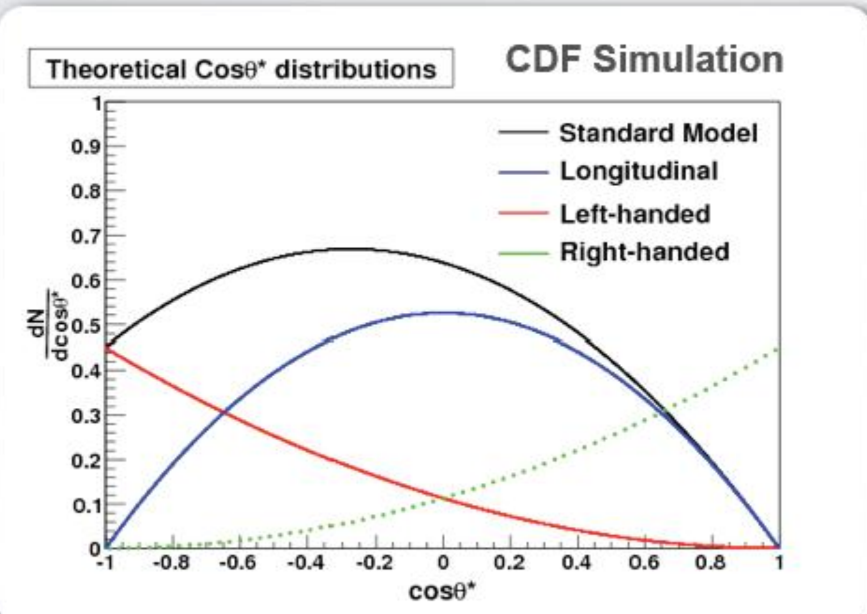
Theory: Γ_W = 2089 ± 2 MeV

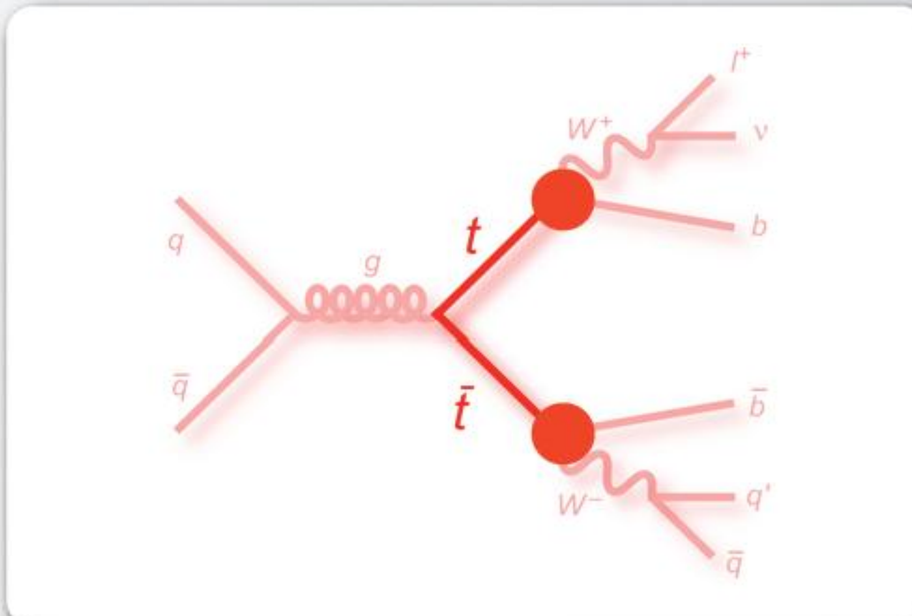
W Boson Helicity Fractions



W_- left-handed fraction F_- | W_- longitudinal fraction F_0 | W_+ right-handed fraction F_+







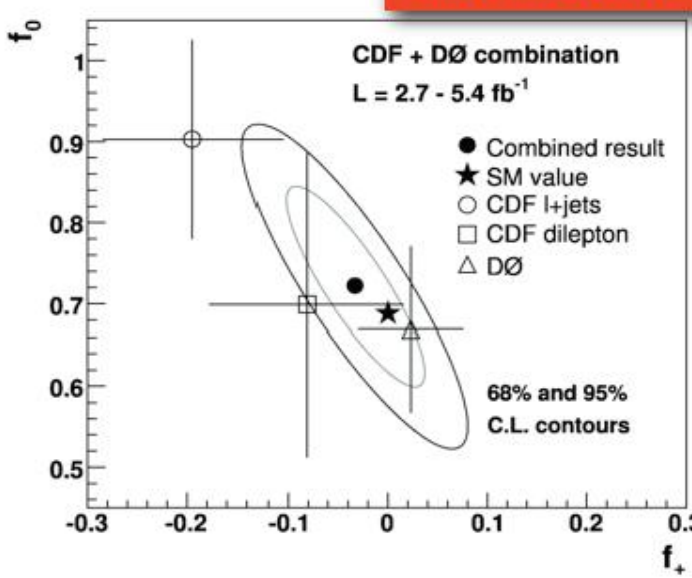
W Boson Helicity Fractions

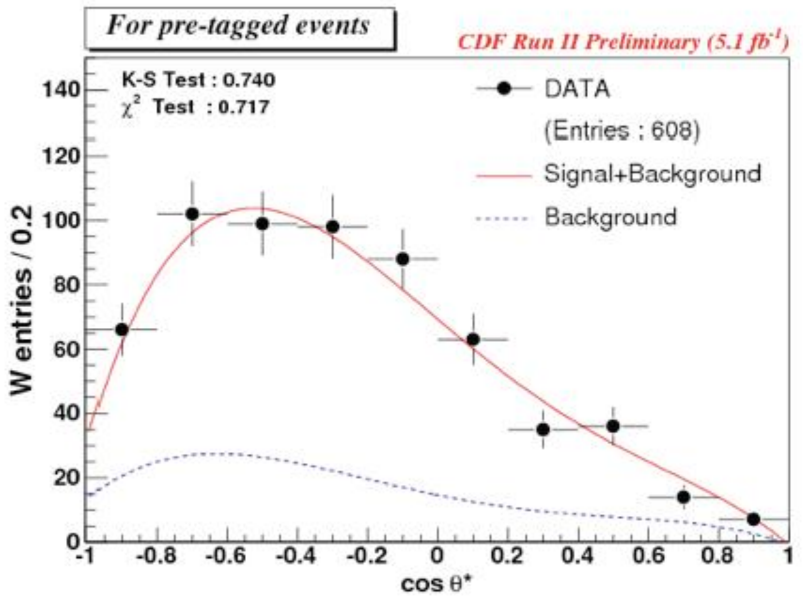
Combination inputs:

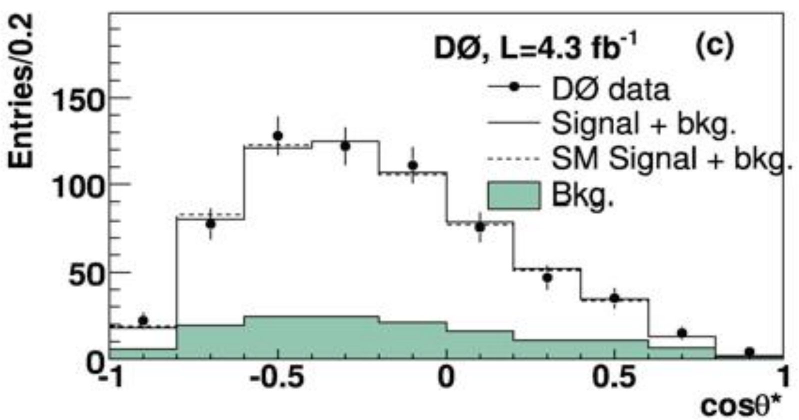
- Phys. Rev. Lett. 105, 042002 (2010)
- Conf. Note 10543
- Phys. Rev. D 83, 032009 (2011)

$$f_0 = 0.682 \pm 0.057$$
$$[\pm 0.035\ (\text{stat.}) \pm 0.046\ (\text{syst.})],$$
$$f_+ = -0.015 \pm 0.035$$
$$[\pm 0.018\ (\text{stat.}) \pm 0.031\ (\text{syst.})]$$

arXiv:1202.5272







TEVATRON A DISCOVERY MACHINE

Luminosity delivered : ~ 9 fb^{-1}

on tape : 7.5 fb^{-1}/exp.

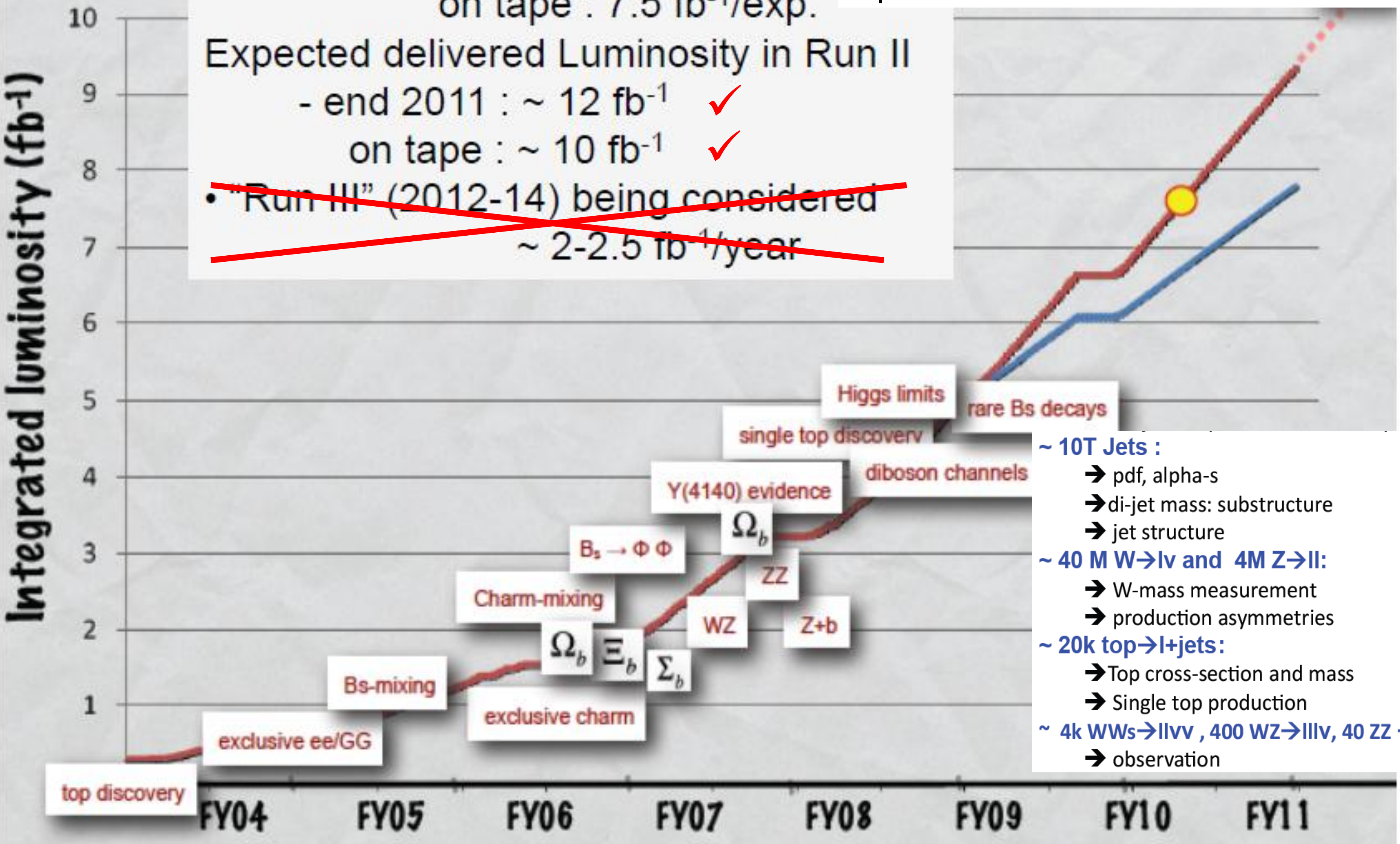
Expected delivered Luminosity in Run II

- end 2011 : ~ 12 fb^{-1} ✓

on tape : ~ 10 fb^{-1} ✓

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

L_{peak}=4.3 x 10^{32} cm^{-2} s^{-1}



~ 10T Jets :
- → pdf, alpha-s
- → di-jet mass: substructure
- → jet structure

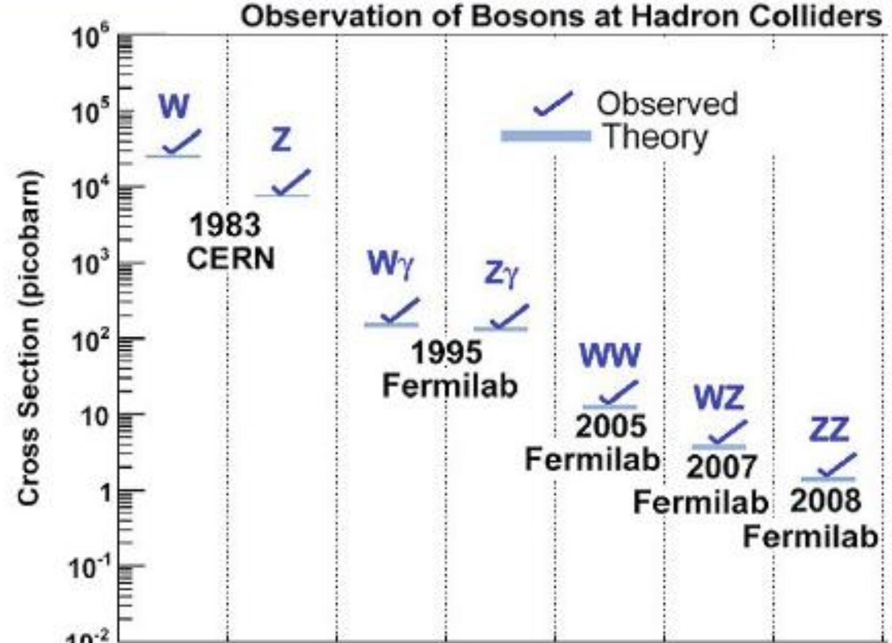
~ 40 M W→lν and 4M Z→ll:
- → W-mass measurement
- → production asymmetries

~ 20k top→l+jets:
- → Top cross-section and mass
- → Single top production

~ 4k WWs→llνν , 400 WZ→lllν, 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, Wγ

5 TGC parameters:

$g1^Z$, κ_γ, κ_Z = 1 in SM

λ_γ, λ_Z = 0 in SM

Neutral Triple Gauge Couplings

- probed by ZZ, Zγ

4 TGC parameters:

$h3^\gamma$, $h3^Z$, $h4^\gamma$, $h4^Z$ all 0 in SM !

WW+WZ+ZZ → 2 jets + mE_T

CDF ($3.5fb^{-1}$): $\sigma = 18.2 \pm 3.7$pb

observation at 5.3σ

WW+WZ → lν + 2 jets

DØ ($1.1fb^{-1}$): $\sigma = 20.2 \pm 4.5$ pb **evidence at 4.4σ**

CDF($4.6fb^{-1}$): $\sigma = 16.5^{+3.3}_{-3.0}$ pb **observation at 5.4σ**

Standard Model Dibosons

Diboson Final State

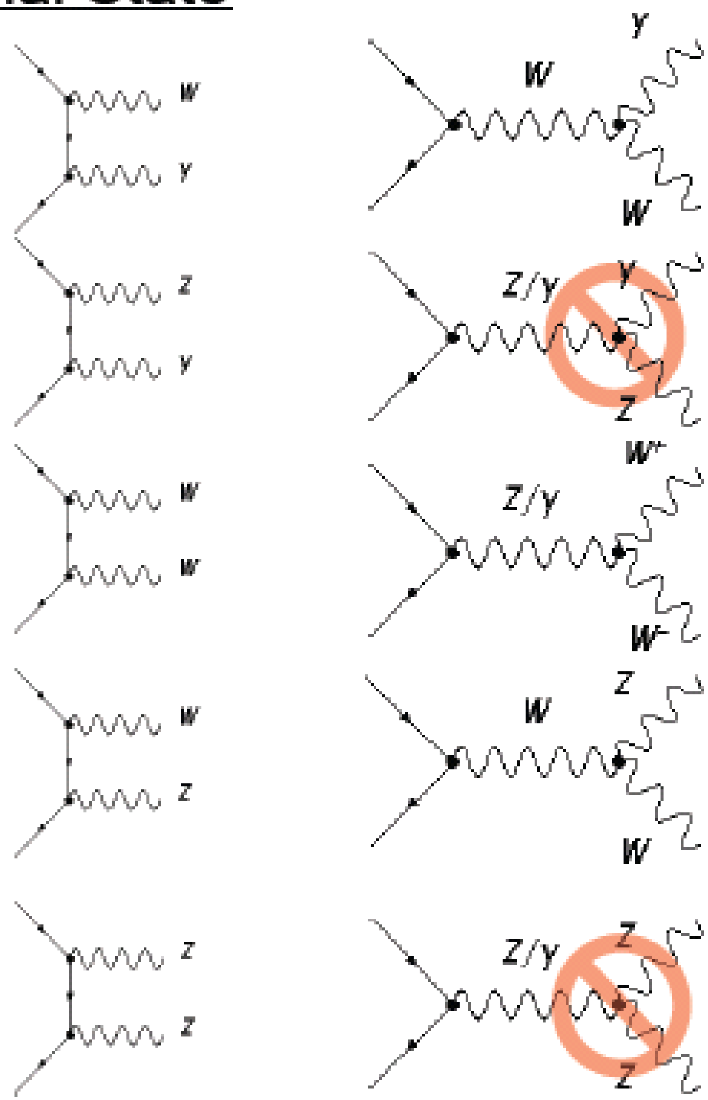
Wγ

Zγ

WW

WZ

ZZ



SM Tests:

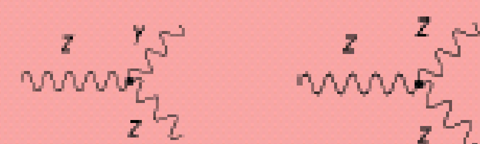
1) Test SM production predictions
2) Look for "anomalous couplings"

Cross sections similar to Higgs

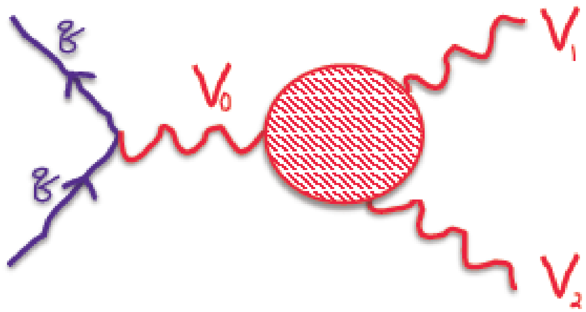
Triple Gauge Couplings

Standard Model

Anomalous



anomalous Triple Gauge Couplings



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

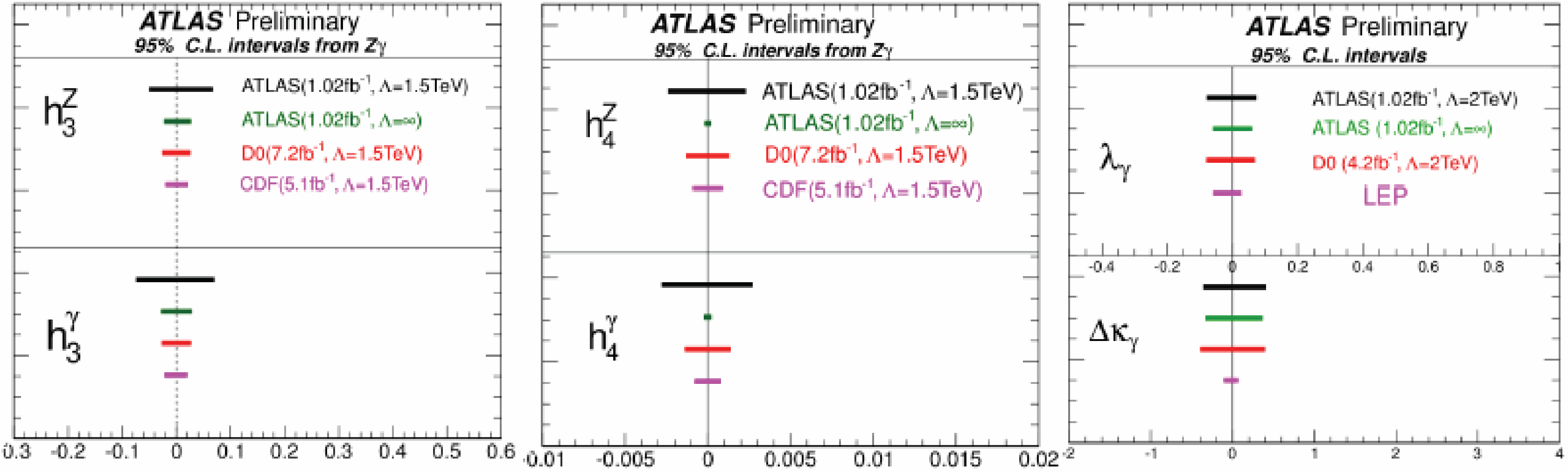
$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\left[g_1^V(W_{\mu\nu}^{\dagger}W^{\mu}V^{\nu} - W_{\mu\nu}W^{\dagger\mu}V^{\nu}) + \kappa^V W_{\mu}^{\dagger}W_{\nu}V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W_{\rho\mu}^{\dagger}W_{\nu}^{\mu}V^{\nu\rho}\right]$$ (WW, WZ)

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

In the Standard Model:

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

Wγ, Zγ aTGC Full Results

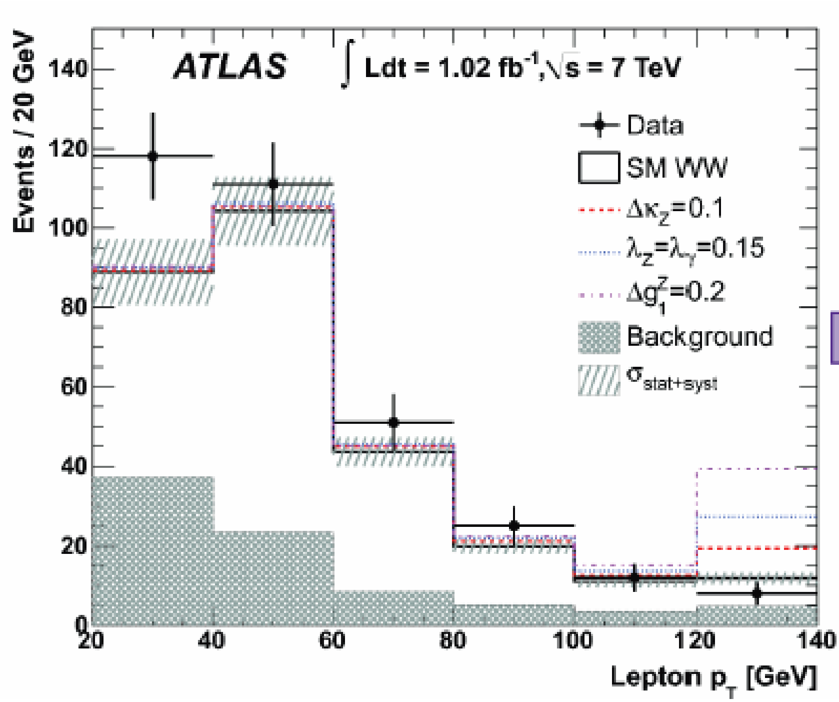


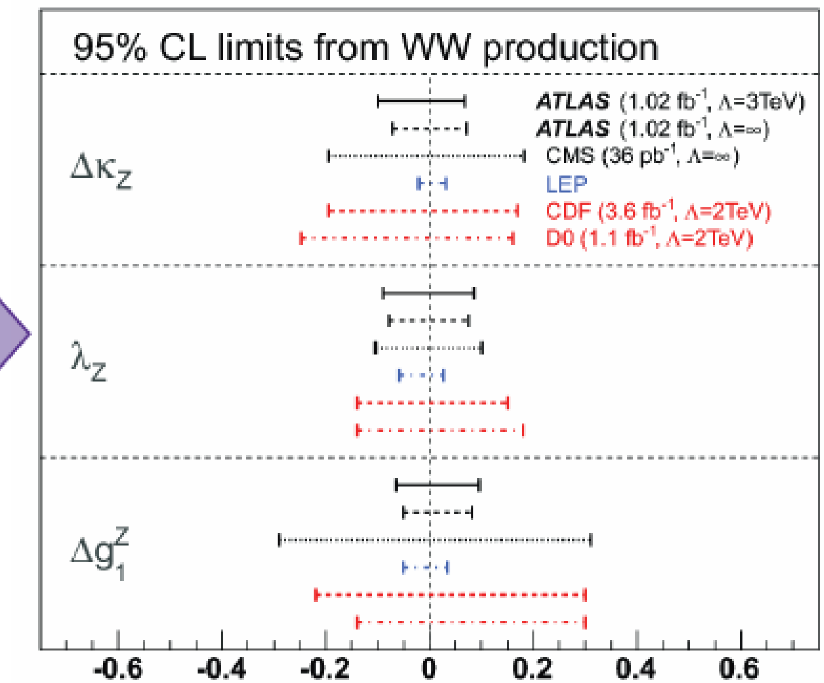
Wγ, Zγ limits

- 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->lνlν aTGC results

ATLAS-STDM-2011-24



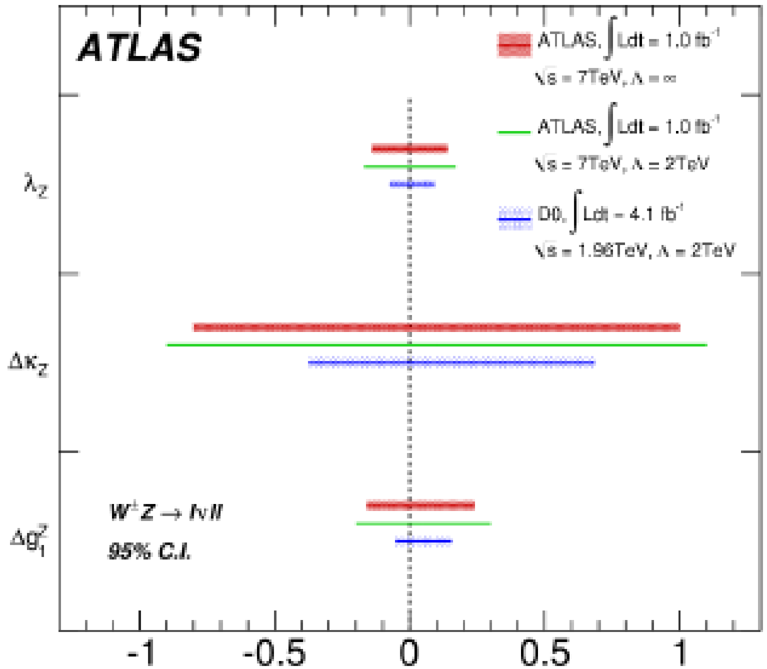


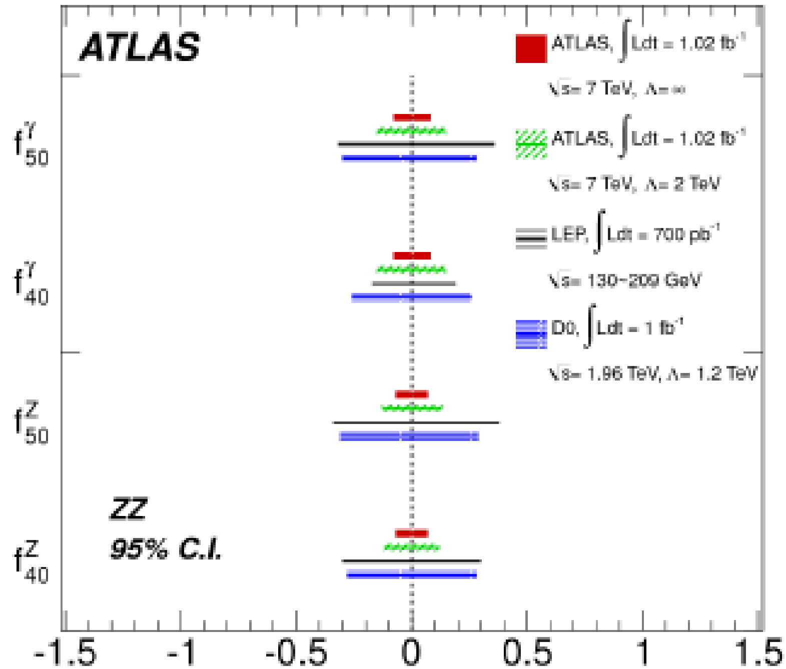
WW limits

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

WZ→lνll and ZZ→llll aTGC results

ATLAS-STDM-2011-25
ATLAS-STDM-2011-36





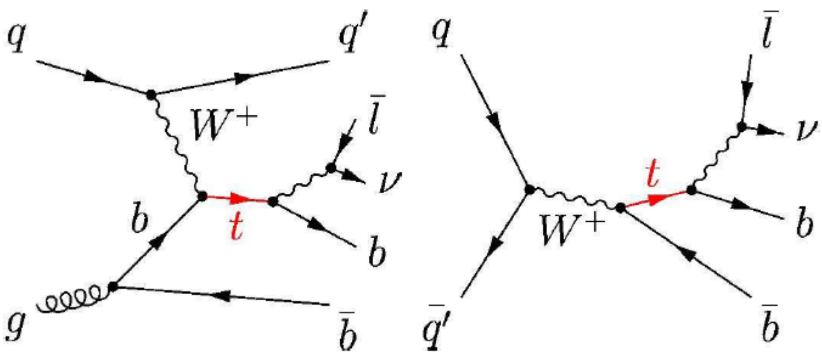
Current limits

- Limits set using total cross section

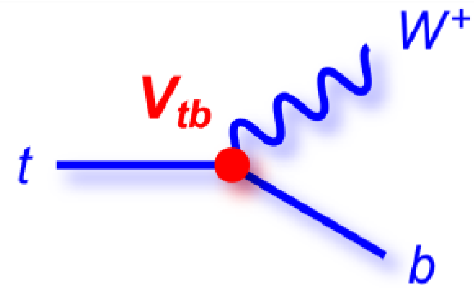
Near future

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

Single Top Production



(a) *t*-channel (b) *s*-channel

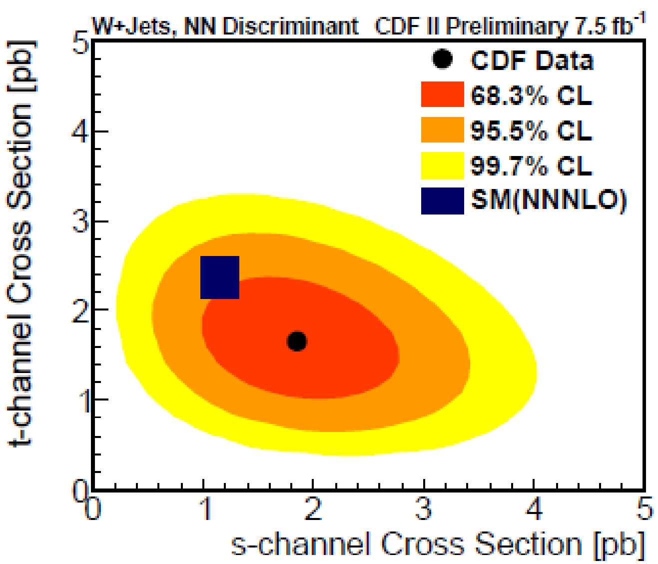


CDF: $|V_{tb}| = 0.96 \pm 0.09(\text{stat+syst}) \pm 0.05(\text{theory})$

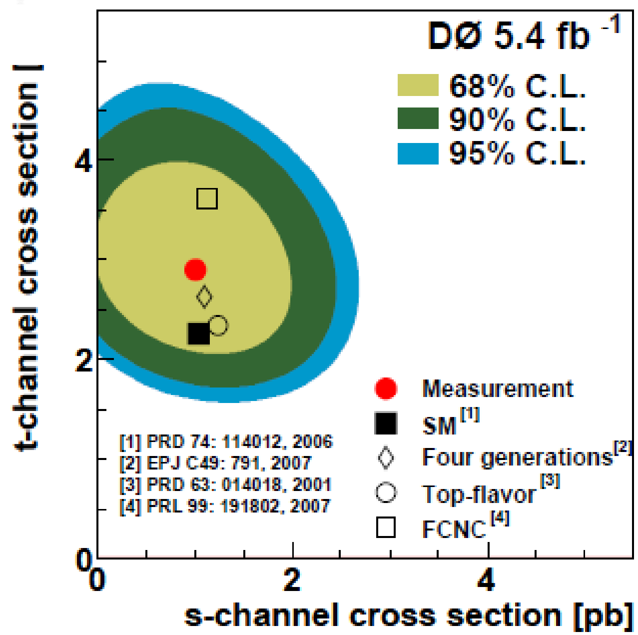
$|V_{tb}| >$ 0.78 at 95% C.L.

D0:

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

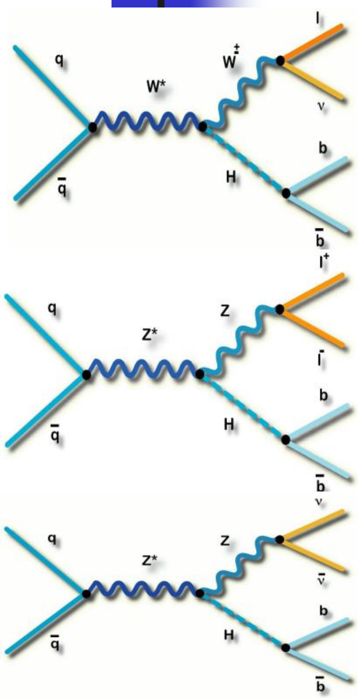


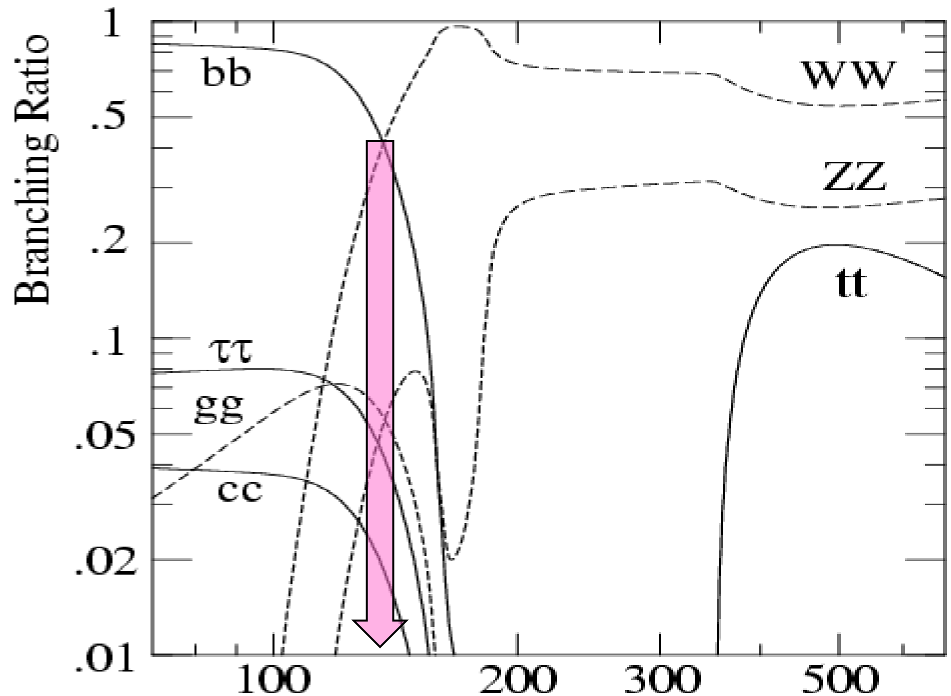
(a)

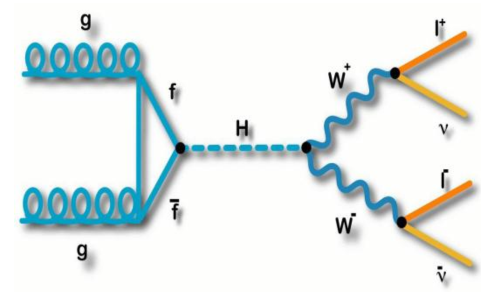


(b)

Higgs Search at the Tevatron



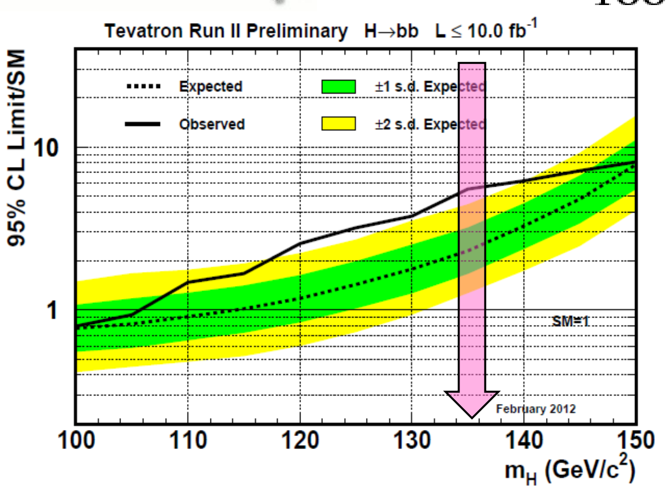


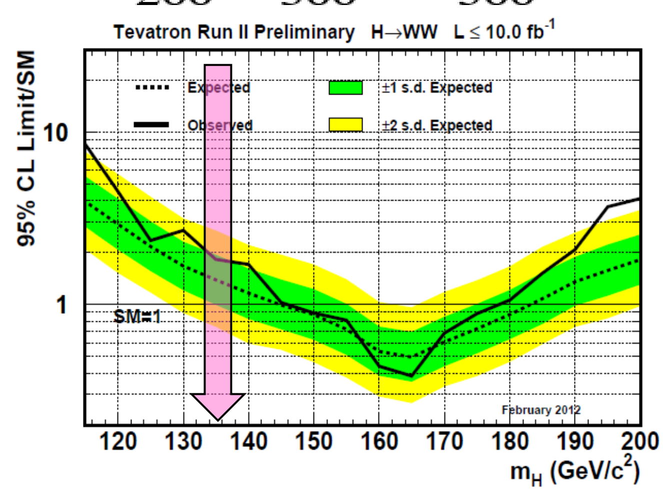


My guess (unpublished):

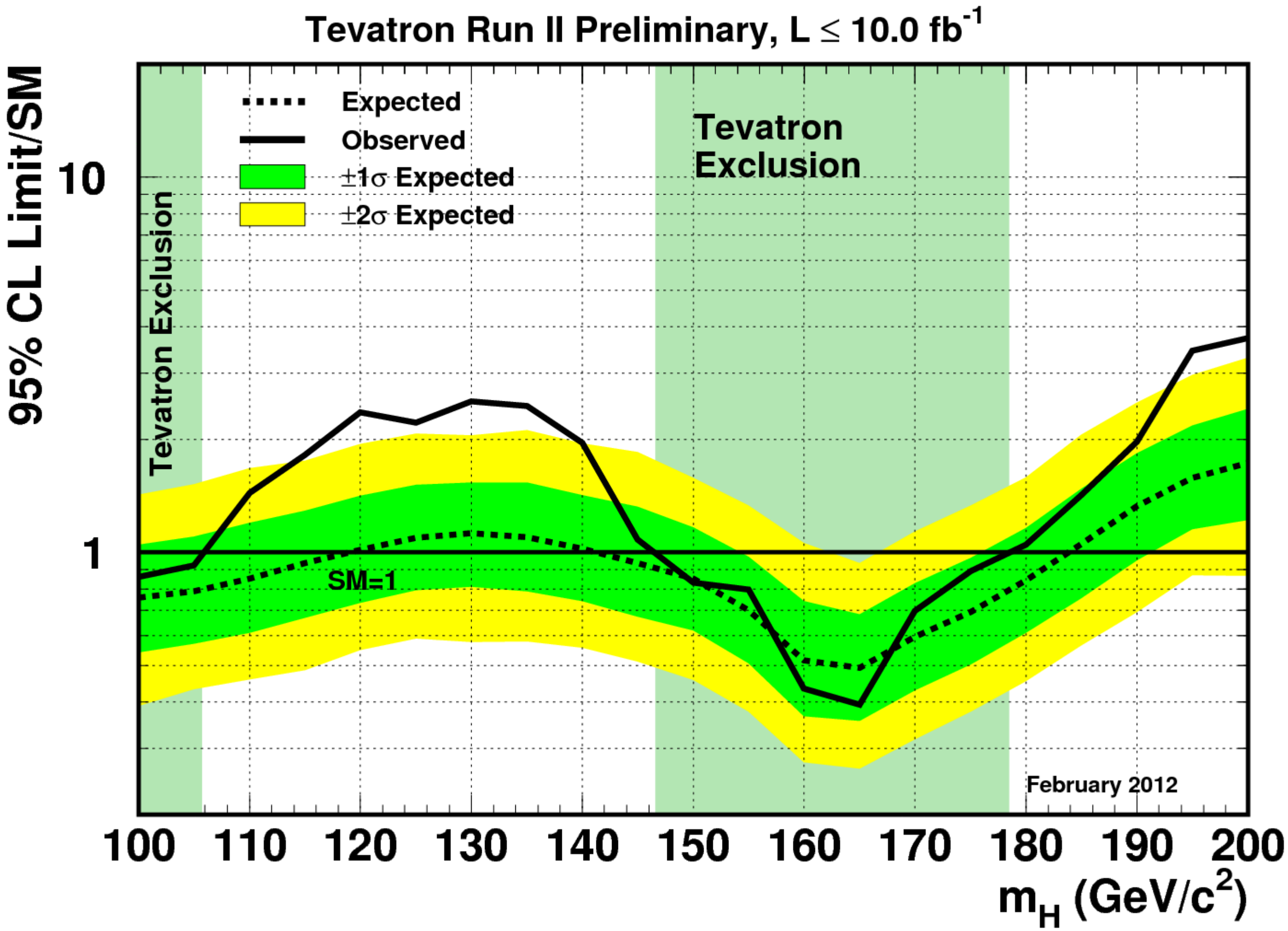
$M_H \sim \upsilon/2$

≈ 123 GeV

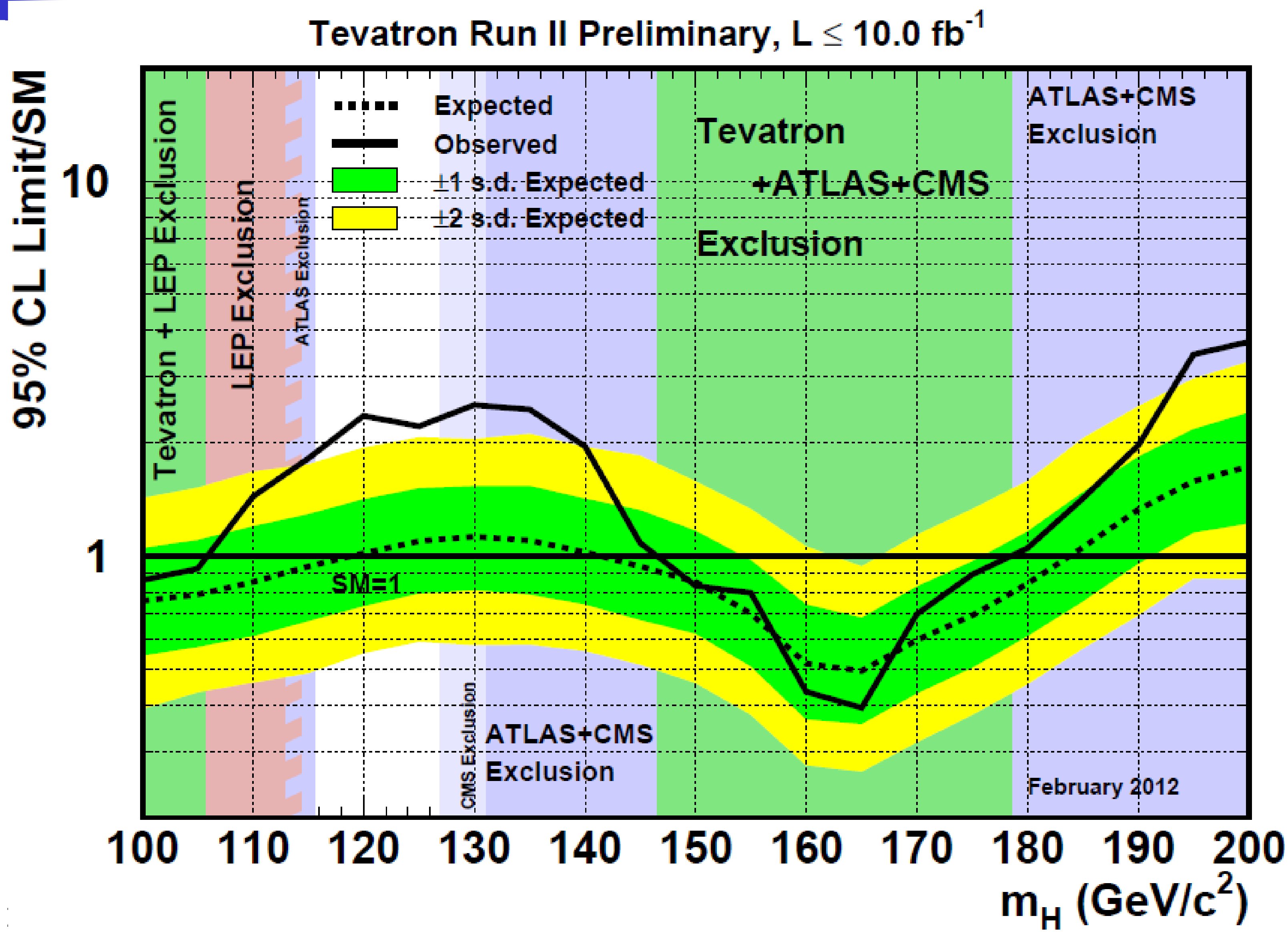




Tevatron Exclusion

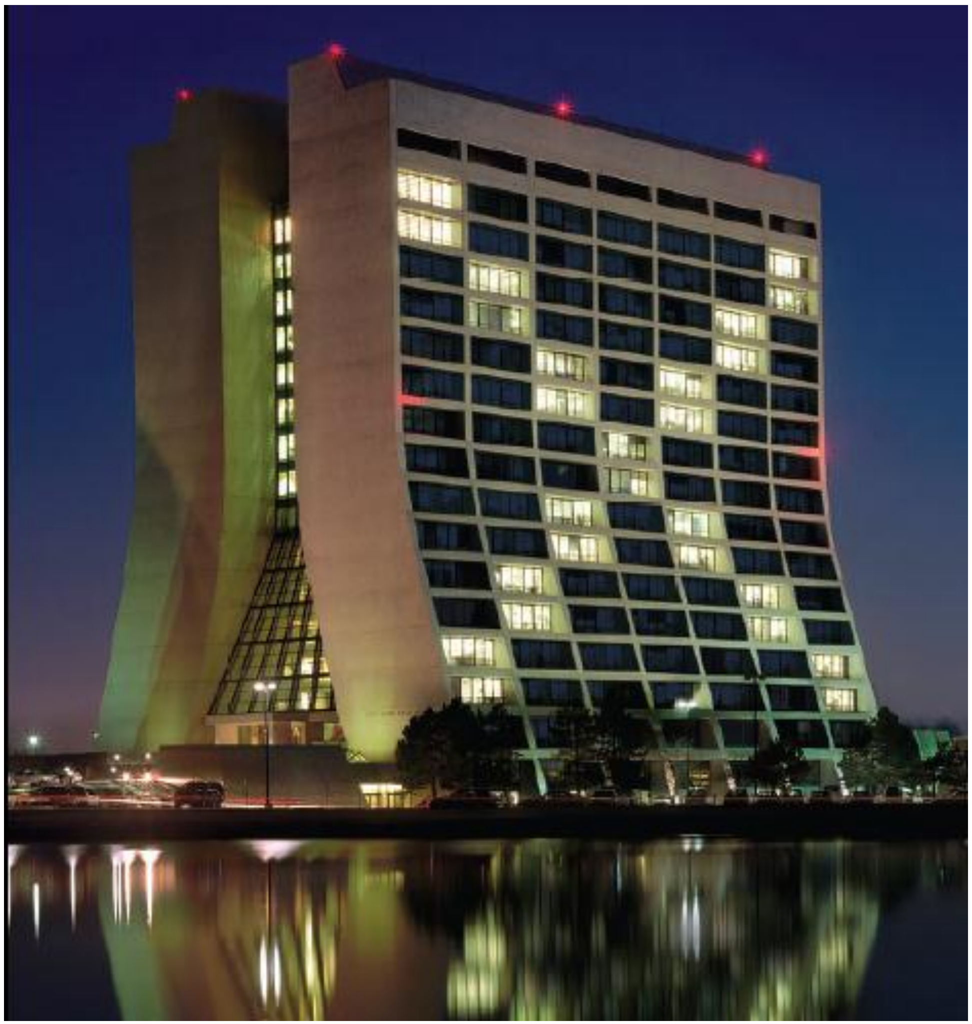


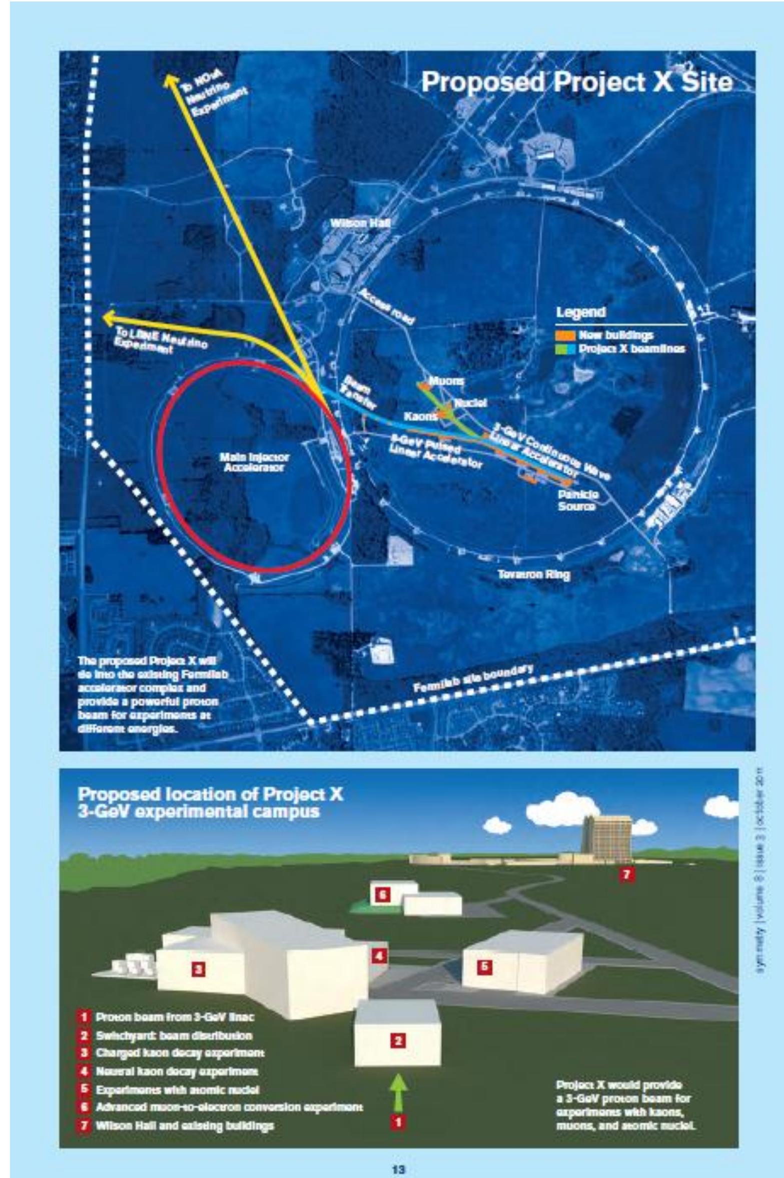
Tevatron Exclusion with LHC results



Project X

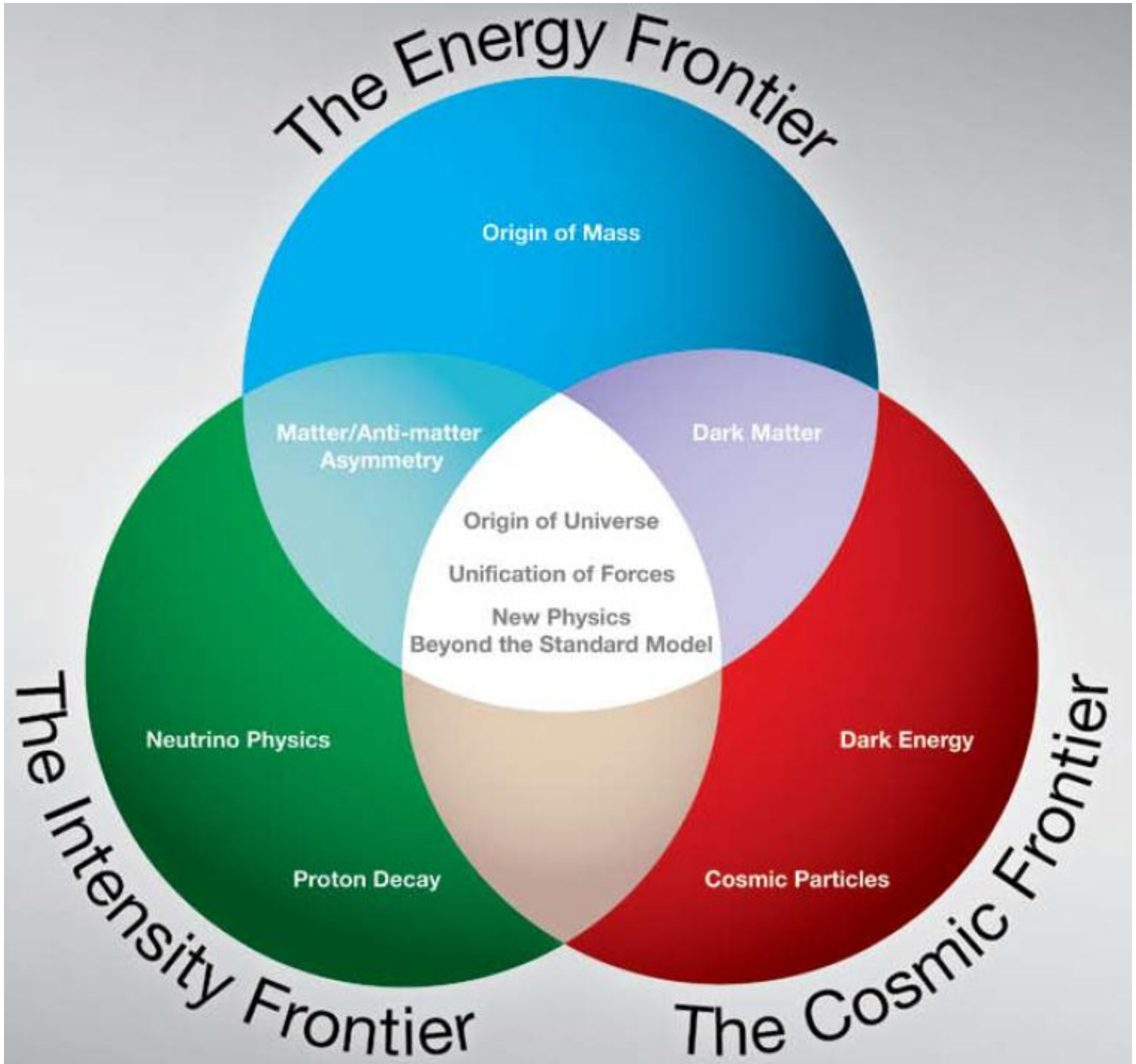
The Tevatron is shutting down, and a new project is on the horizon: Project X.





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

$$v_{\nu} > c$$

Mixing matrices

Cabibbo-Kobayashi-Maskawa

$$V_{CKM} = \begin{matrix} \\ u \\ c \\ t \end{matrix} \begin{matrix} d & s & b \\ \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \end{matrix} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ -\lambda & 1 & \lambda^2 \\ \lambda^3 & -\lambda^2 & 1 \end{pmatrix}$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = V_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Wolfenstein parameterization

Pontecorvo-Maki-Nakagawa-Sakata

$$U_{PMNS} = \begin{matrix} \\ e \\ \mu \\ \tau \end{matrix} \begin{matrix} \nu_1 & \nu_2 & \nu_3 \\ \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \end{matrix} \approx \begin{pmatrix} \frac{\sqrt{2}}{\sqrt{3}} & \frac{1}{\sqrt{3}} & \frac{\lambda}{\sqrt{2}} \\ -\frac{1+\lambda}{\sqrt{6}} & \frac{1-\lambda/2}{\sqrt{3}} & \frac{1}{\sqrt{2}} \\ \frac{1-\lambda}{\sqrt{6}} & -\frac{1+\lambda/2}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

P. F. Harrison, D. H. Perkins and W. G. Scott, Phys. Lett. B 530 (2002) 167

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

$$\Delta m_{21}^2 \equiv m_2^2 - m_1^2 \approx 7.54(20)\times 10^{-5}\ \text{eV}^2$$

$$\left|\Delta m_{31}^2\right| = 2.43(8)\times 10^{-5}\ \text{eV}^2$$

⇒ **Oscillations!**

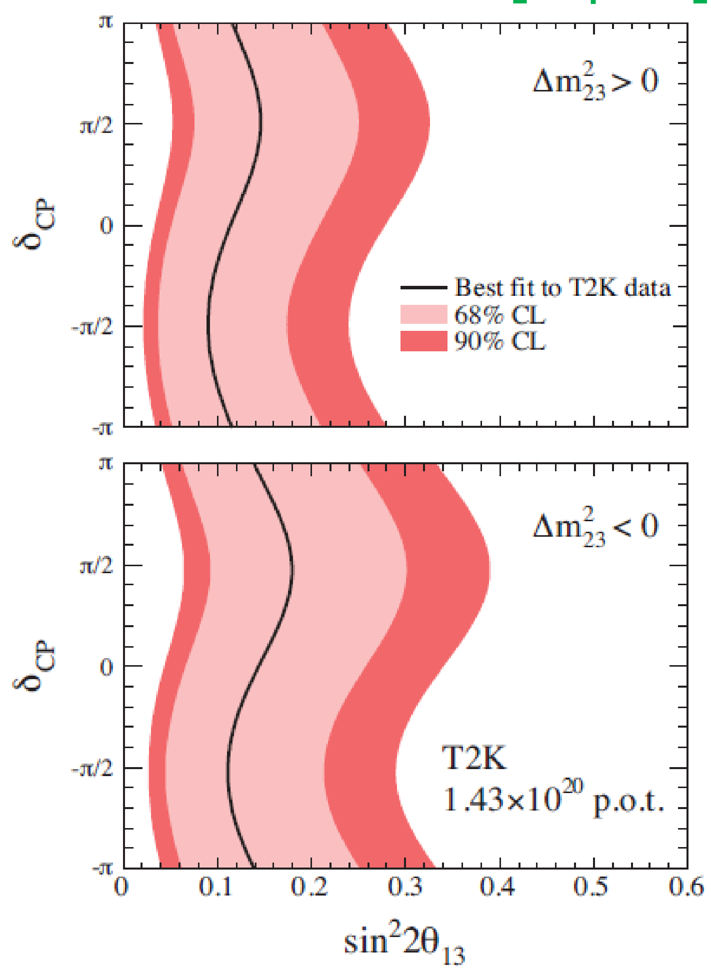
$$P(\nu_\mu \to \nu_e) \approx 4\left|U_{\mu 3}\right|^2 \left|U_{e3}\right|^2 \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right)$$

First indications of non-zero U_{e3}

$\nu_\mu \to \nu_e$ Appearance!

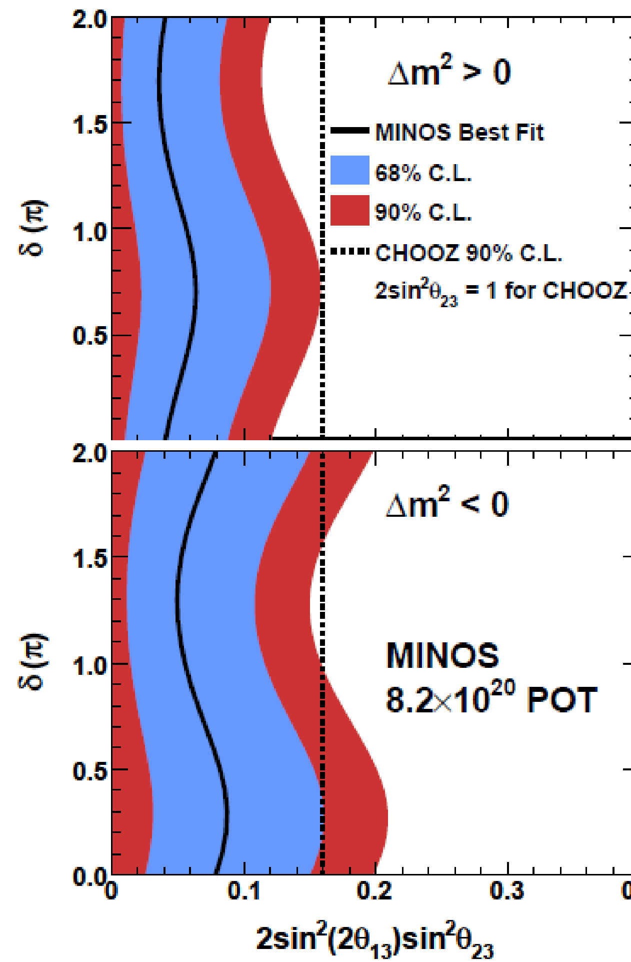
T2K

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



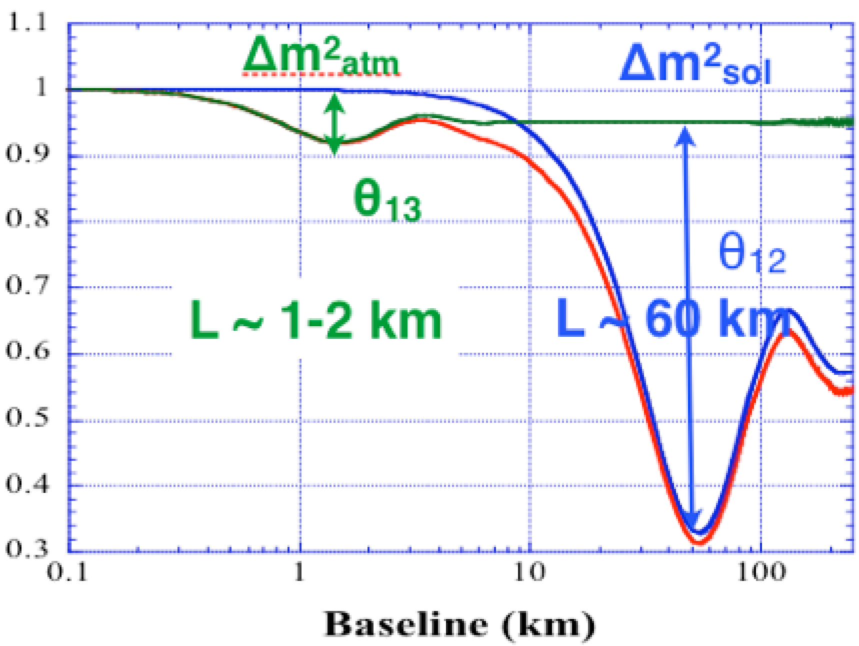
MINOS

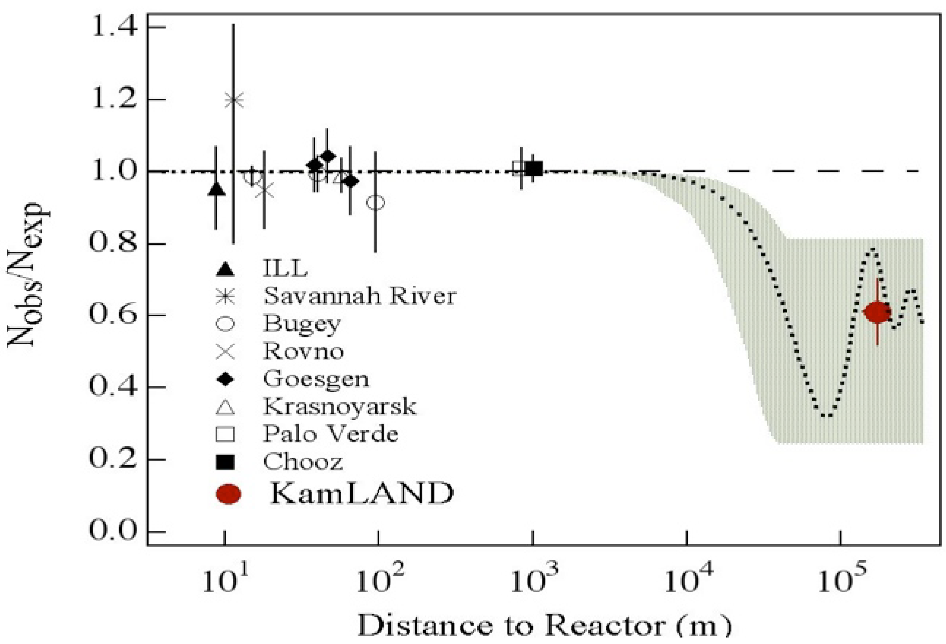
Phys.Rev.Lett. 107 (2011) 181802
arXiv:1108.0015 [hep-ex]



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

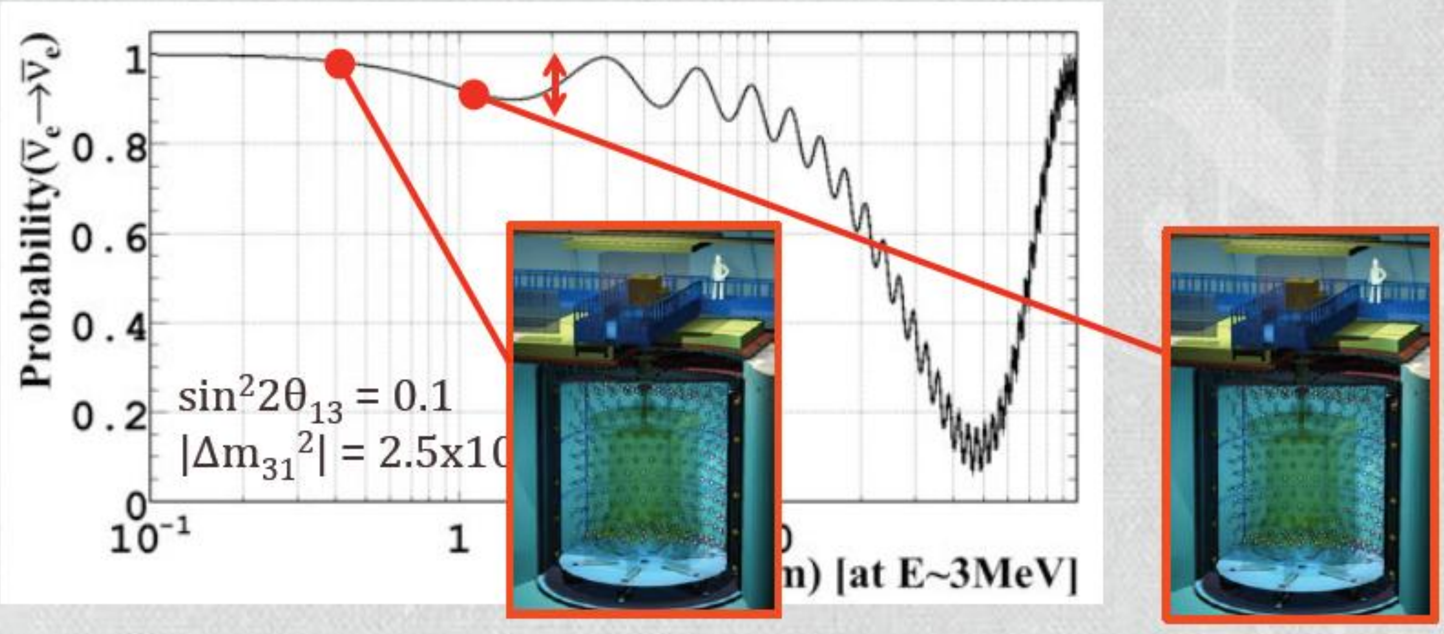
$$P_{ee} \approx 1 - \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m_{31}^2 L}{4E_\nu}\right) - \cos^4\theta_{13} \sin^2 2\theta_{12} \sin^2\left(\frac{\Delta m_{21}^2 L}{4E_\nu}\right)$$





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

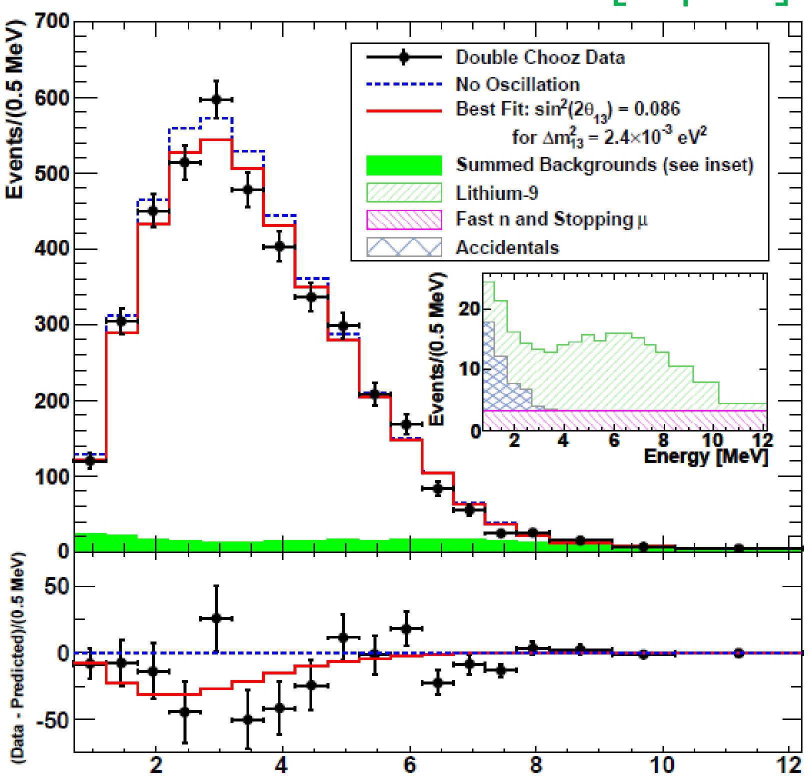
Double Chooz
anti-ν_e disappearance

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

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

Phys.Rev.Lett. 108 (2012) 131801

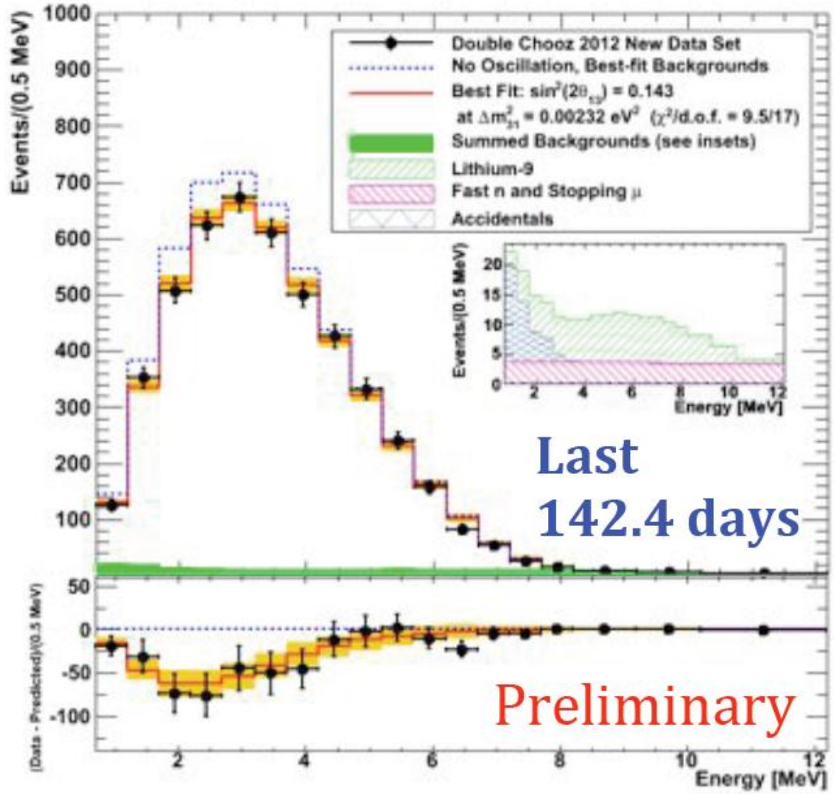
e-Print: arXiv:1112.6353 [hep-ex]



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

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

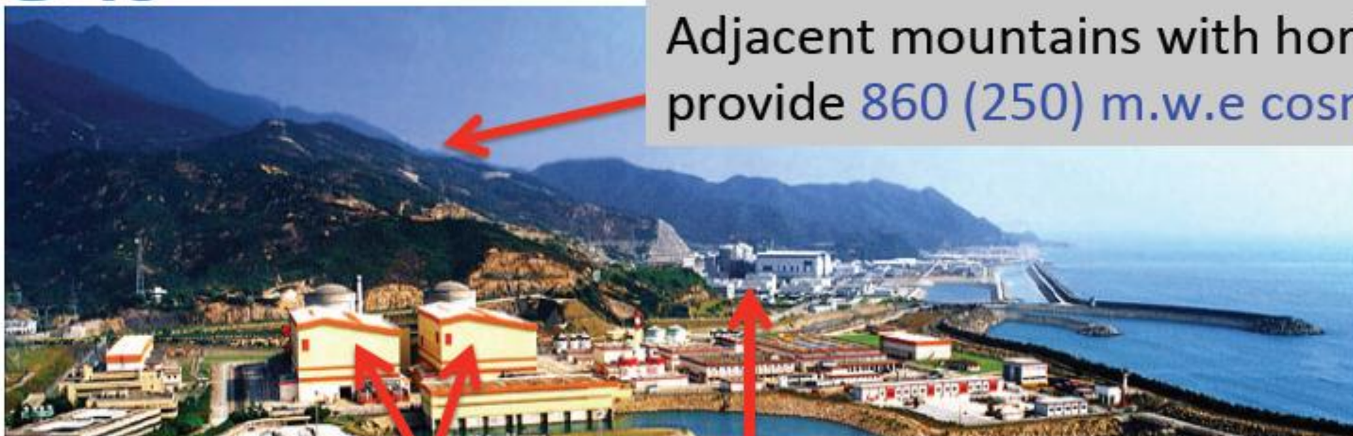
NEUTRINO 2012 (June 4, 2012)



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

$\sin^2 2\theta_{13} = 0$ is excluded at the 99.9% C.L. (3.1σ)

The Daya Bay Experiment



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

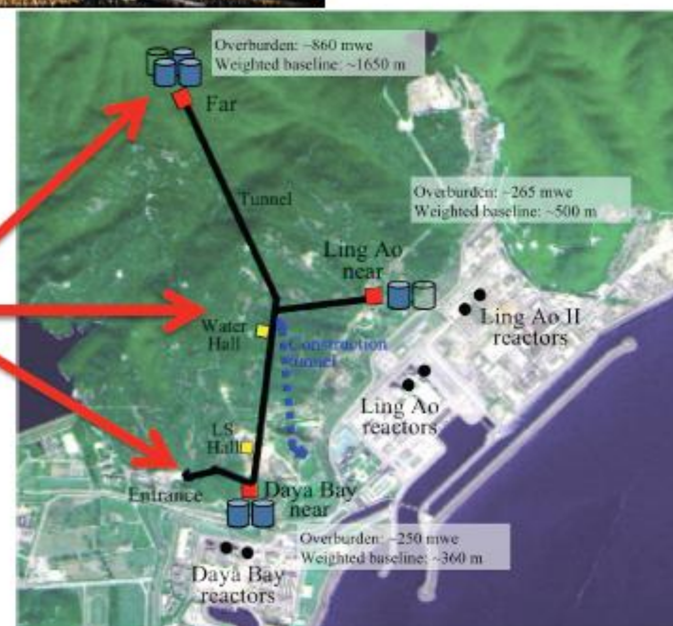
Daya Bay

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.

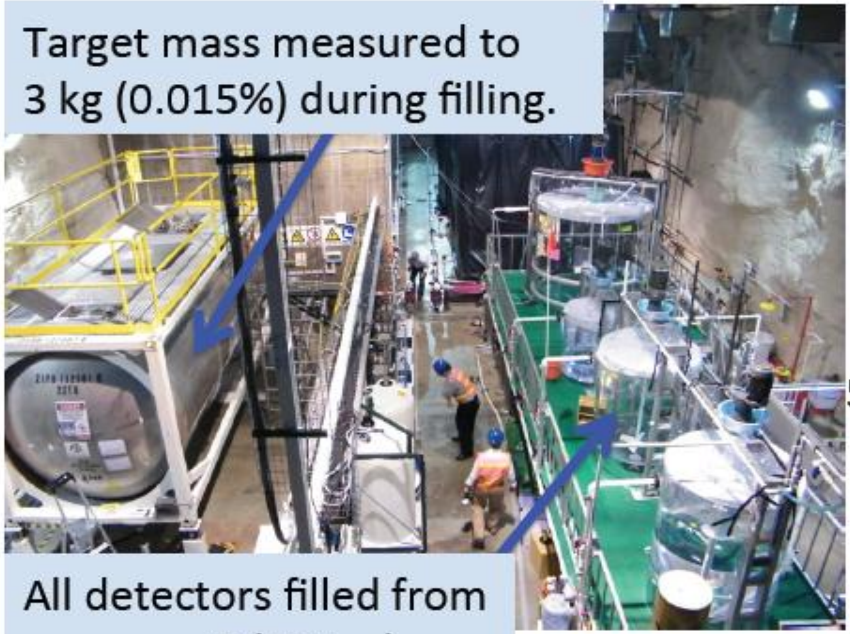


Antineutrino Detectors

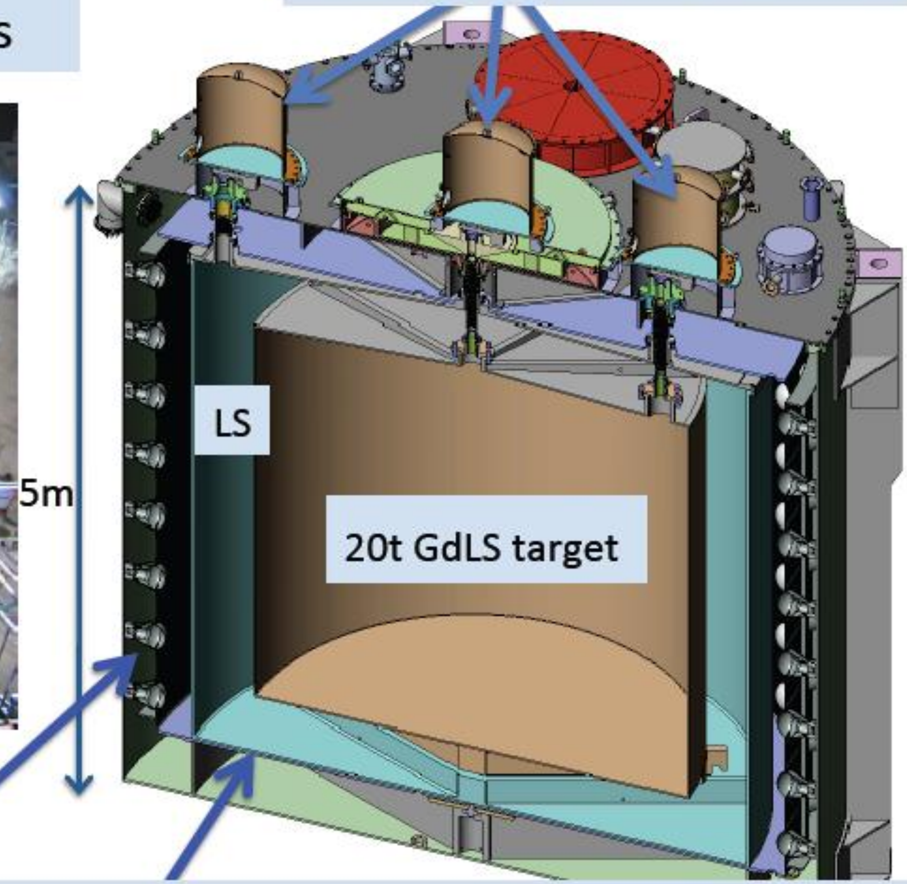
6 'functionally identical' detectors:
Reduce systematic uncertainties

Calibration robots insert radioactive sources and LEDs.

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



All detectors filled from common GdLS tanks.

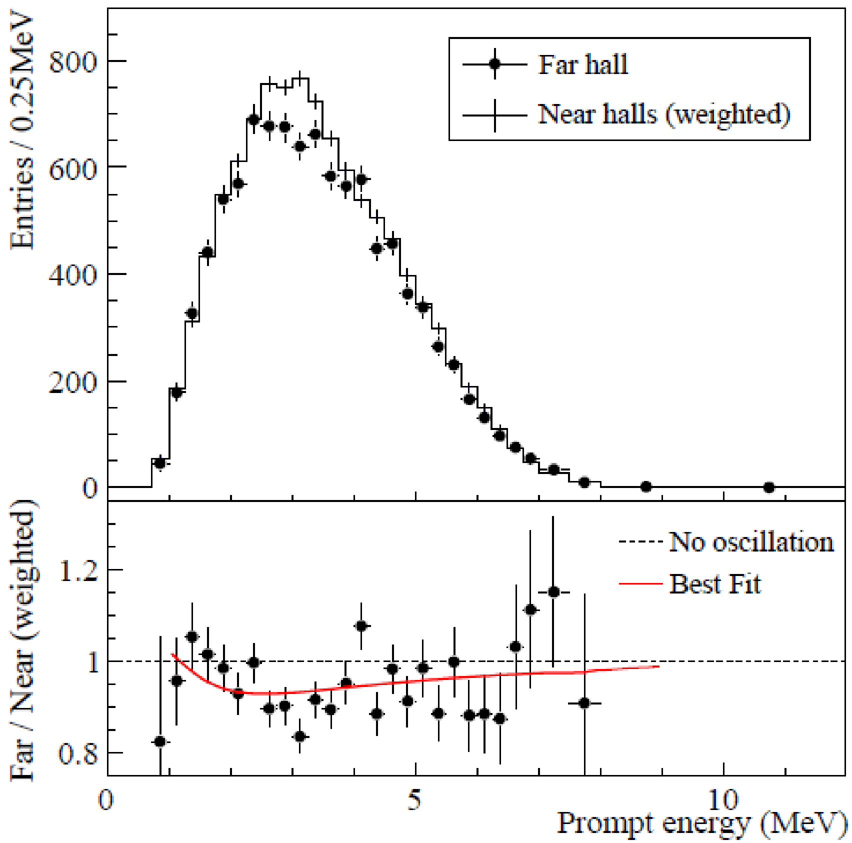


192 8" PMTs detect light in target, ~163 p.e./MeV.

Reflectors improve light collection uniformity.

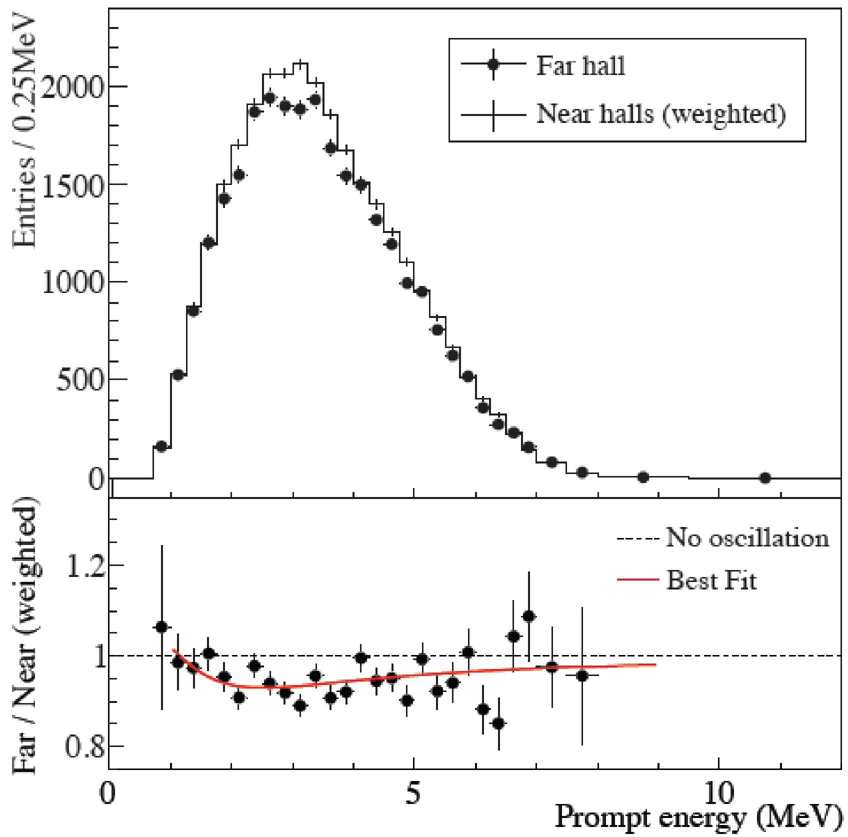
Daya Bay R=Far/Near

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



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

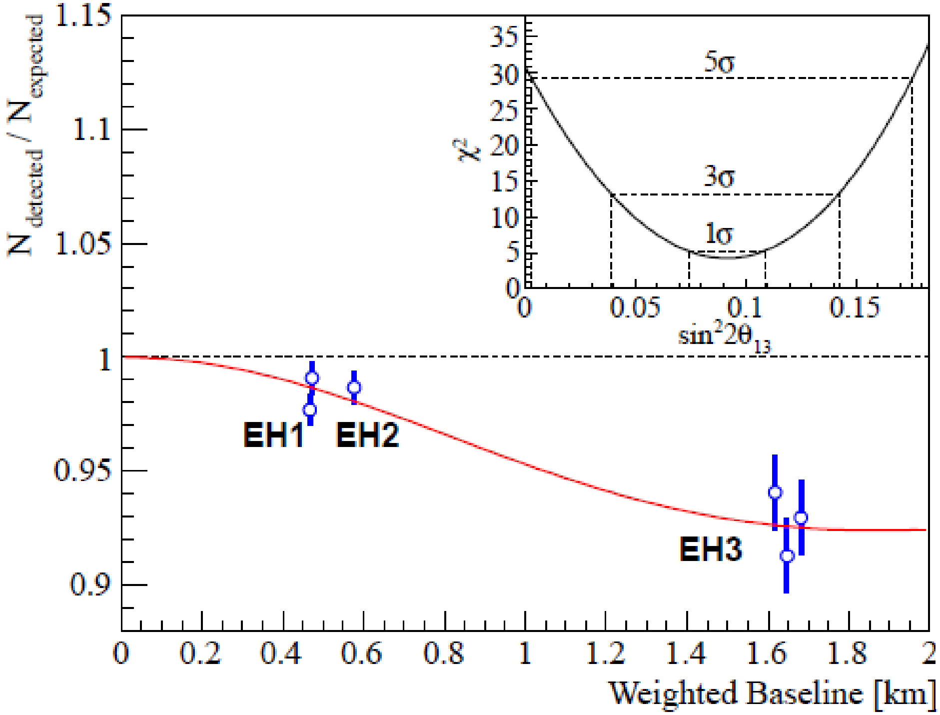
NEUTRINO 2012 (June 4, 2012)



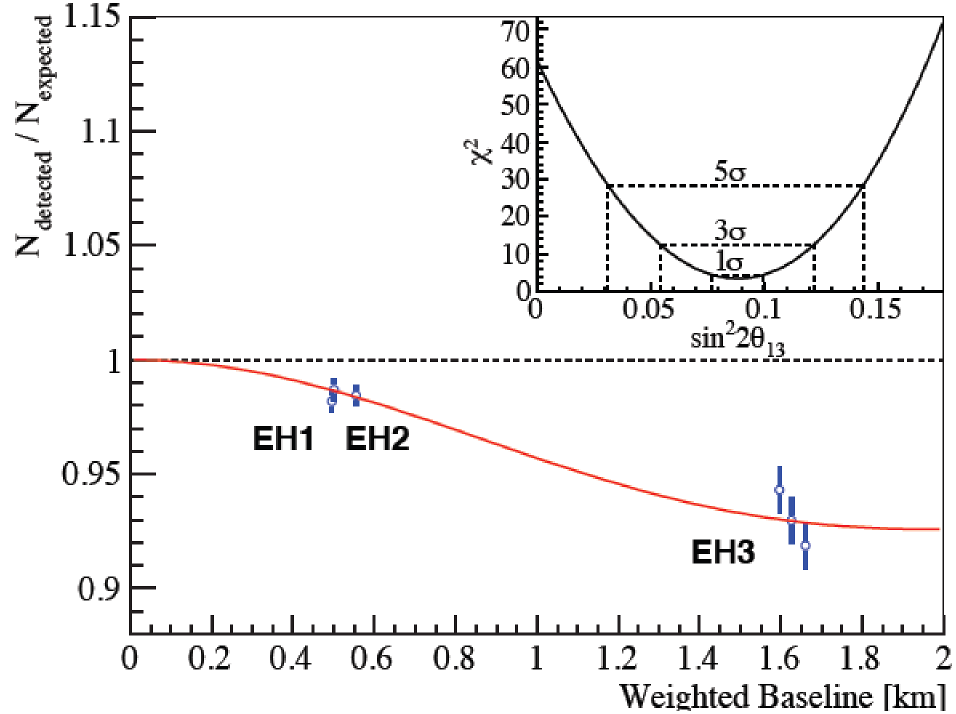
$R = 0.944 \pm 0.007(stat) \pm 0.003(syst)$

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)



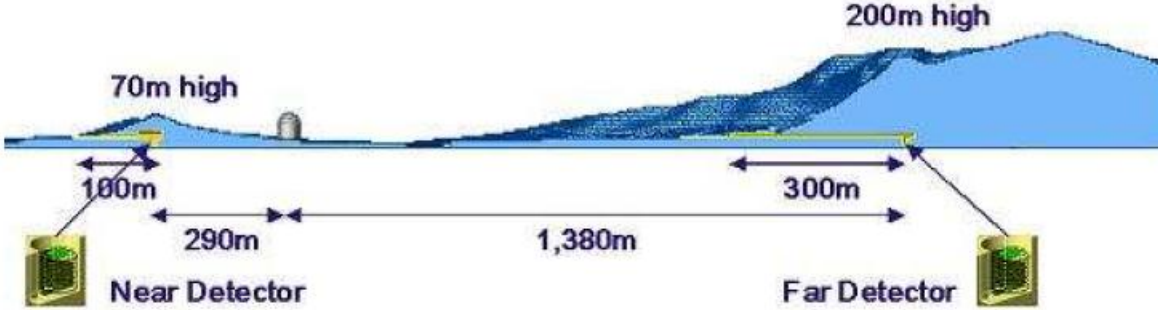
$\sin^2 2\theta_{13} = 0.092 \pm 0.016(\text{stat}) \pm 0.005(\text{syst})$
$\sin^2 2\theta_{13} = 0$ is excluded at 5.2 σ

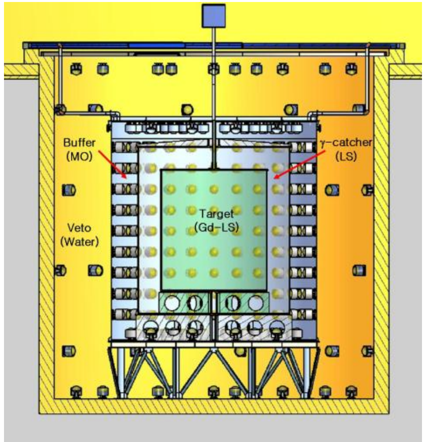
$\sin^2 2\theta_{13} = 0.089 \pm 0.010(\text{stat}) \pm 0.005(\text{syst})$
$\sin^2 2\theta_{13} = 0$ is excluded at 8 σ !!!

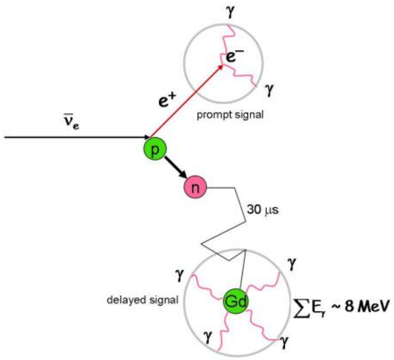
Installation of final pair antineutrino detectors this year.

RENO

arXiv:1003.1391v1

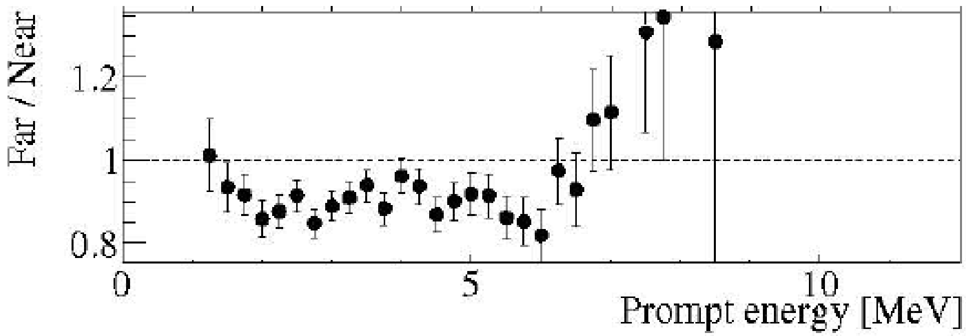




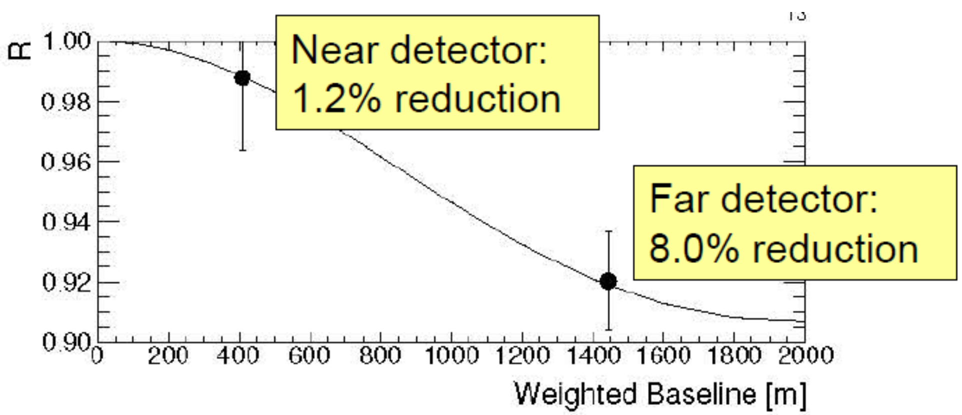


RENO

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



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



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

Mixing angles

$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
5.4%	13%	13%

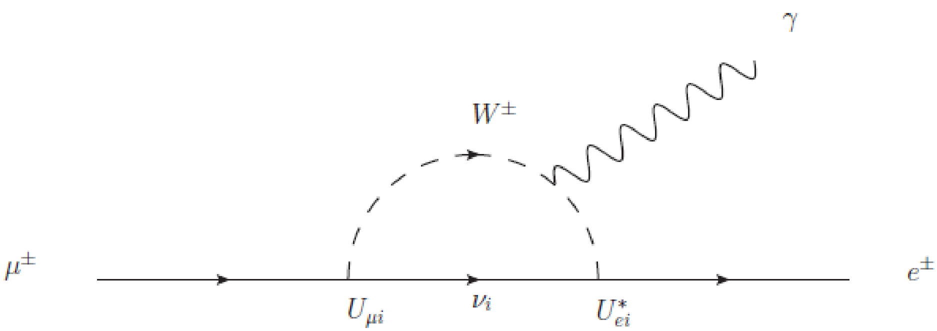
G.L. Fogli, E. Lisi, A. Marrone,
D. Montanino, A. Palazzo, A.M. Rotunno
arXiv:1205.5254 [hep-ph] 25 May 2012

after Neutrino 2012 (beginning of June)

$\sin^2\theta_{12}$	$\sin^2\theta_{13}$	$\sin^2\theta_{23}$
5.4%	10%	13%

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

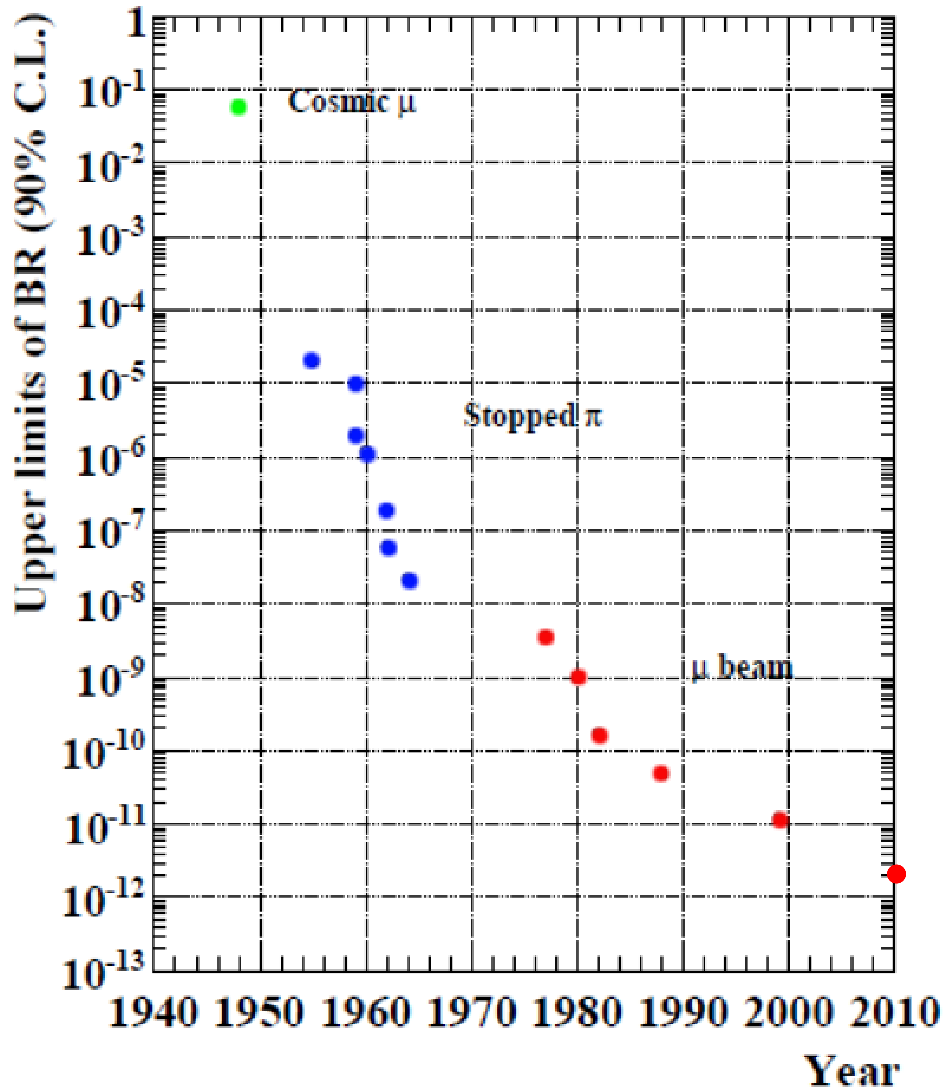
Phys. Rev. Lett. **107** (2011) 171801; arXiv:1107.5547v4 [hep-ex]



$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_i U^*_{\mu i} U_{ei} \frac{m^2_{\nu_i}}{M^2_W}\right|^2$$

$$= \frac{3\alpha}{32\pi M_W^4}\left|U^*_{\mu 2}U_{e2}\Delta m^2_{21} + U^*_{\mu 3}U_{e3}\Delta m^2_{31}\right|$$

$$= (2.4 \div 3.7)\times 10^{-55}$$



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

L. Calibbi, A. Faccia, A. Masiero, and S. K. Vempati, Phys. Rev. D74 (2006) 116002, arXiv:hep-ph/0605139.

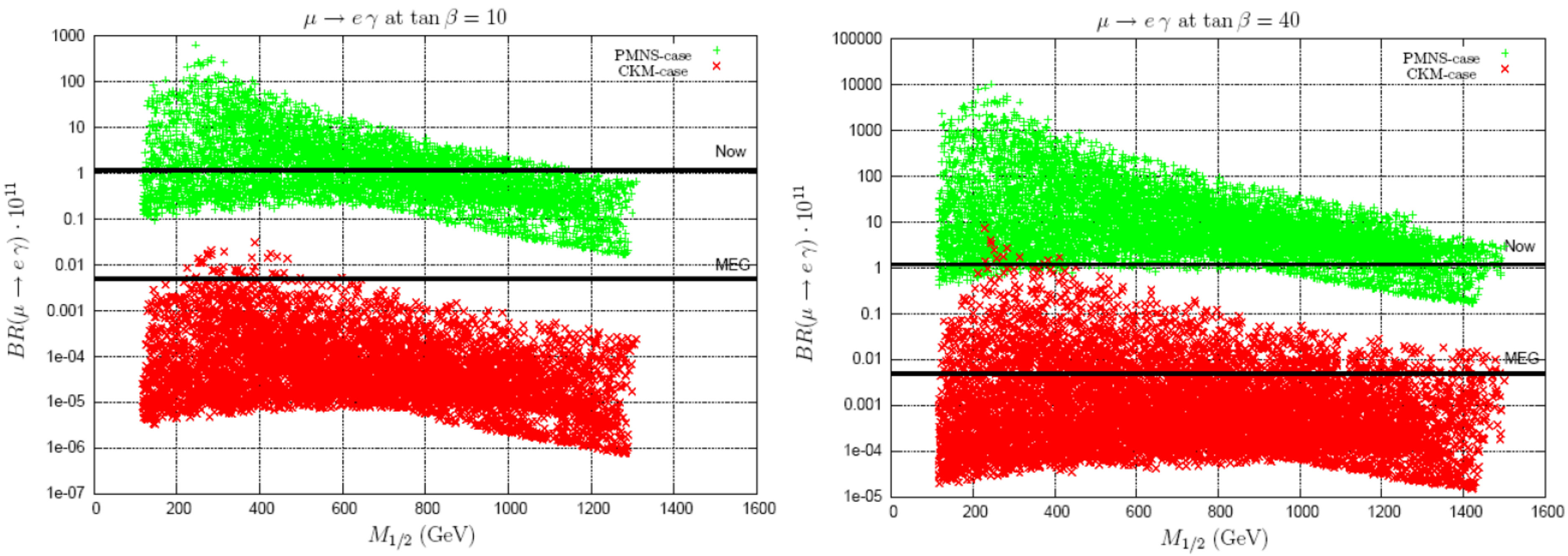
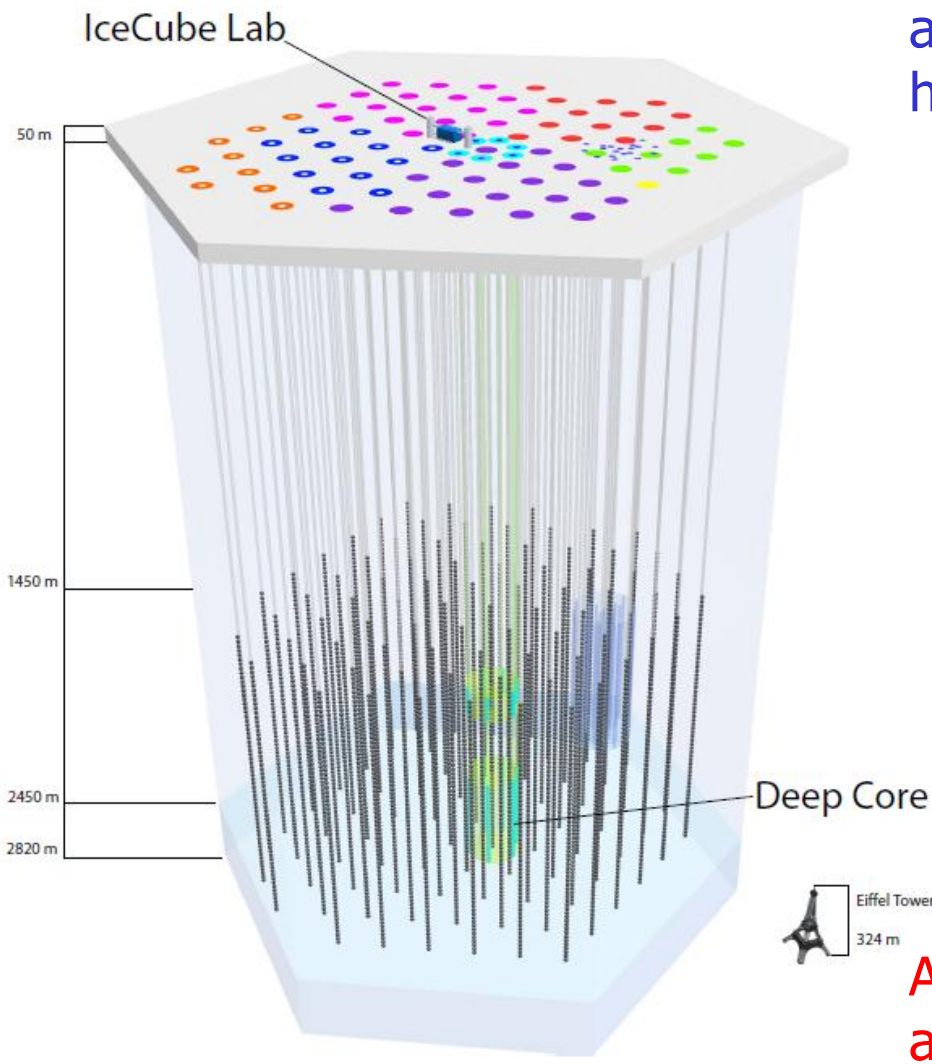


Figure 2.5: Predictions for $BR(\mu \to e\gamma)$ are shown as a function of the universal gaugino mass for two cases of $\tan\beta$, scanning an LHC relevant space in the parameters describing the Planck scale masses. Both the PMNS case (green) and the CKM case (red) are explored.

IceCube Collaboration

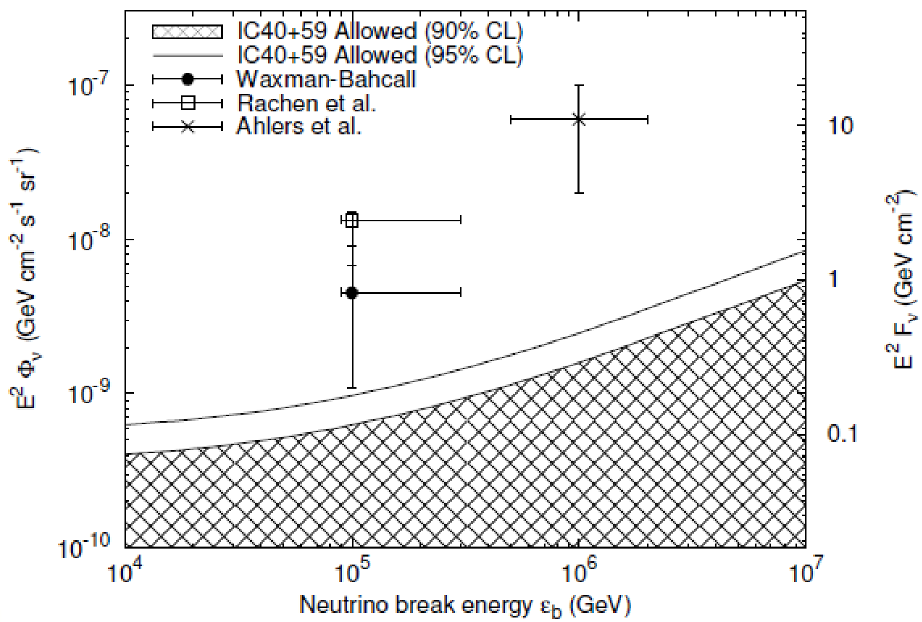
Nature **484** (2012) 351; arXiv:1204.4219 [astro-ph.HE]



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"

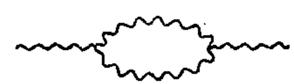
The Standard Model is based on the gauge group $SU(3)_C$ x $SU(2)_W$ x $SU(1)_Y$ with the corresponding coupling constants $\mathbf{g_3}$, $\mathbf{g_2} = \mathbf{g}$ and $\mathbf{g'}$.

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.

$\alpha_1, \alpha_2, \alpha_3$

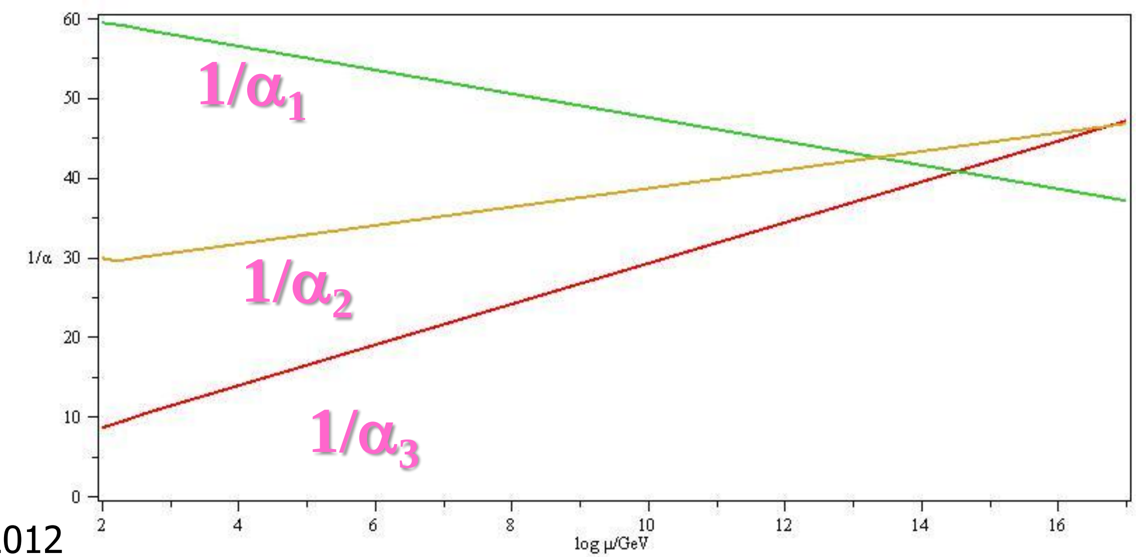
Evolution of the coupling constants $\alpha_1 = \frac{5}{3}\frac{g'^2}{4\pi} = \frac{5\alpha}{3\cos^2\theta_W}$, $\alpha_2 = \frac{g^2}{4\pi} = \frac{\alpha}{\sin^2\theta_W}$, $\alpha_3 = \alpha_s$,

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

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

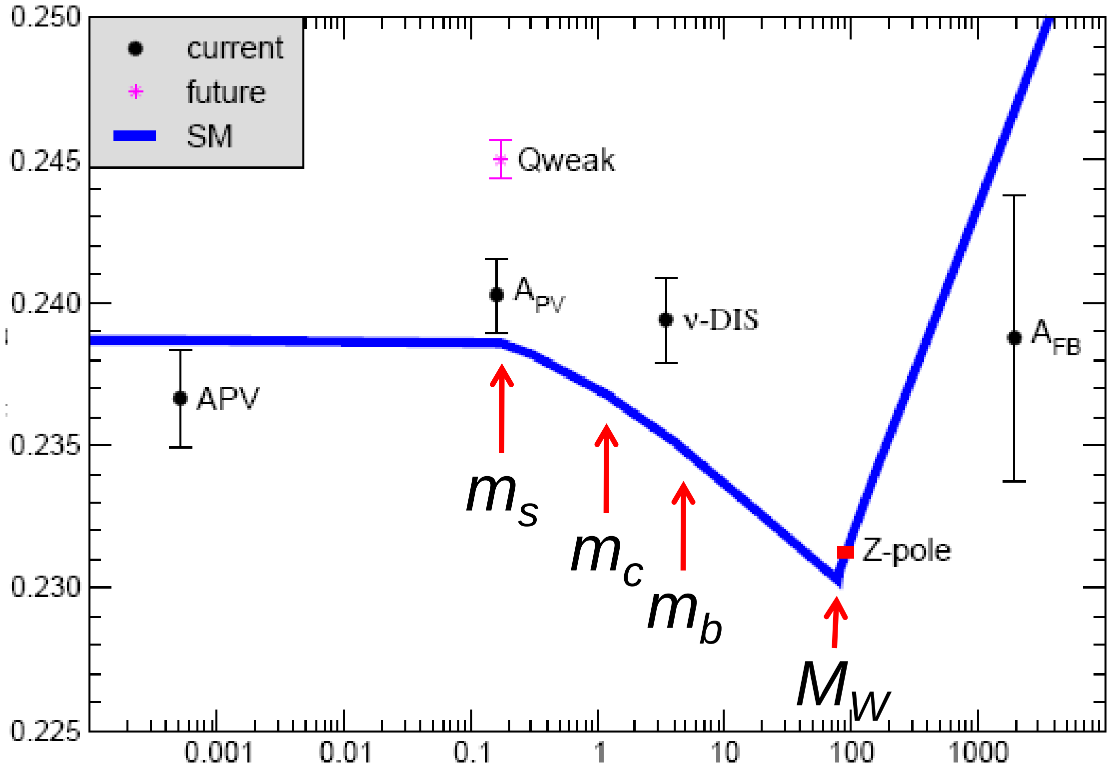
$$\text{where } b_i = \begin{pmatrix} b_1 \\ b_2 \\ b_3 \end{pmatrix} = \begin{pmatrix} 0 \\ -22/3 \\ -11 \end{pmatrix} + \frac{2}{3}N_f + \begin{pmatrix} 1/10 \\ 1/6 \\ 0 \end{pmatrix} N_{\text{Higgs}}.$$

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

$\sin^2 \hat{\theta}_W(\mu)$



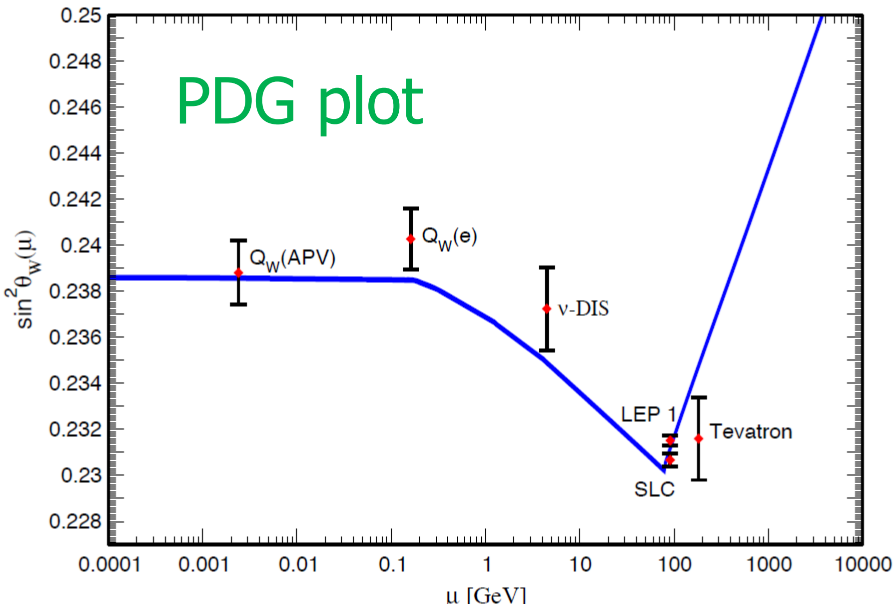
μ [GeV]

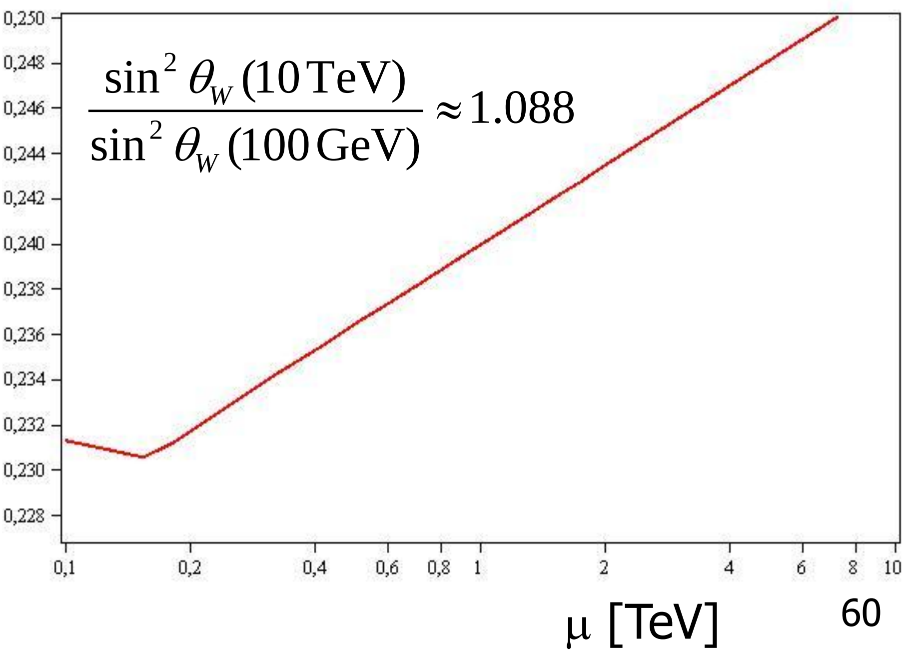
Electroweak coupling constants

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

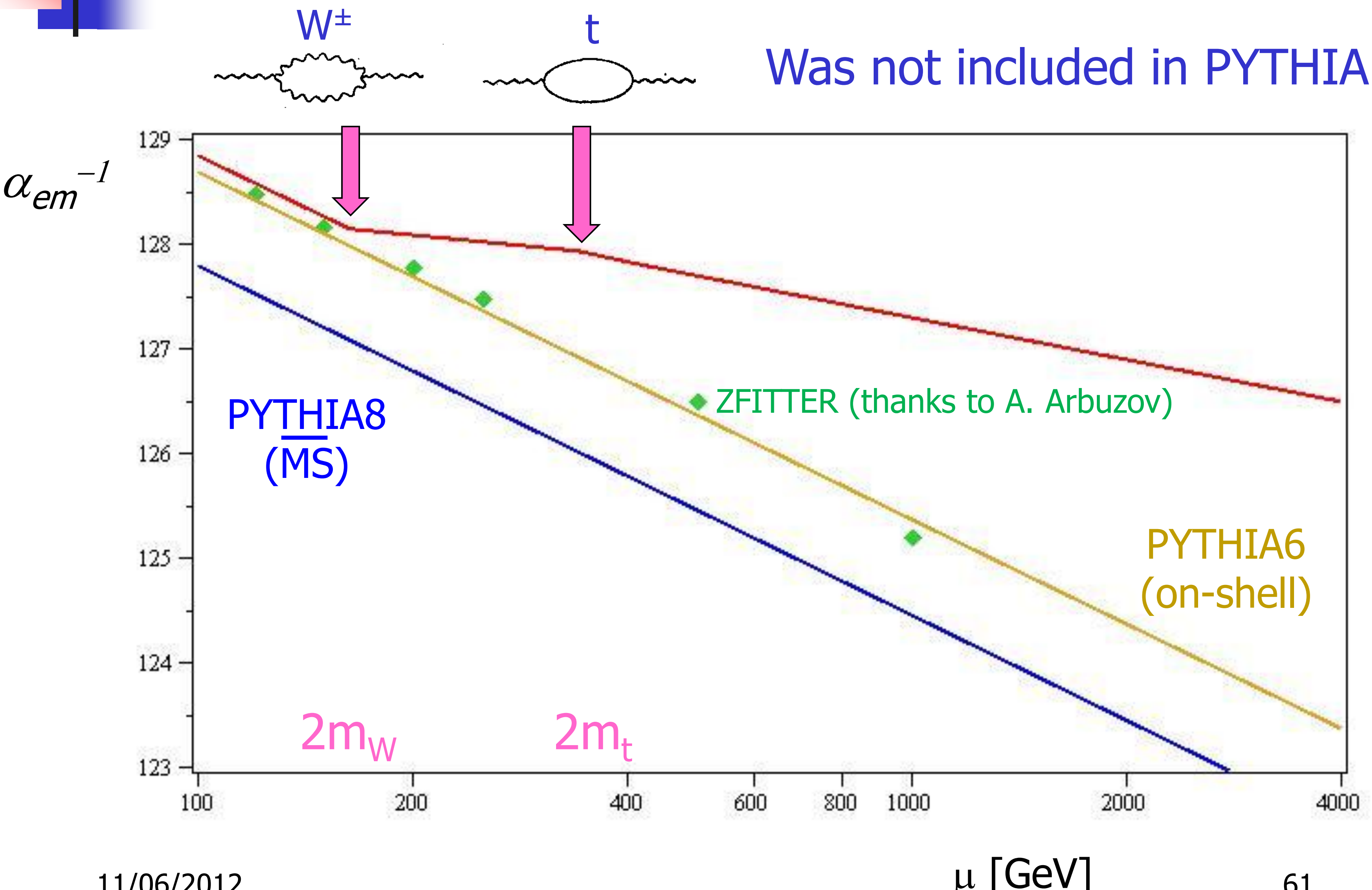
"The coupling structure within the electroweak sector is usually (re)expressed in terms of gauge boson masses, α_{em} and $\sin^2\theta_W$… Having done that, α_{em} is allowed to run [Kle89], and is evaluated at the *s* scale. … Currently $\sin^2\theta_W$ is not allowed to run."

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



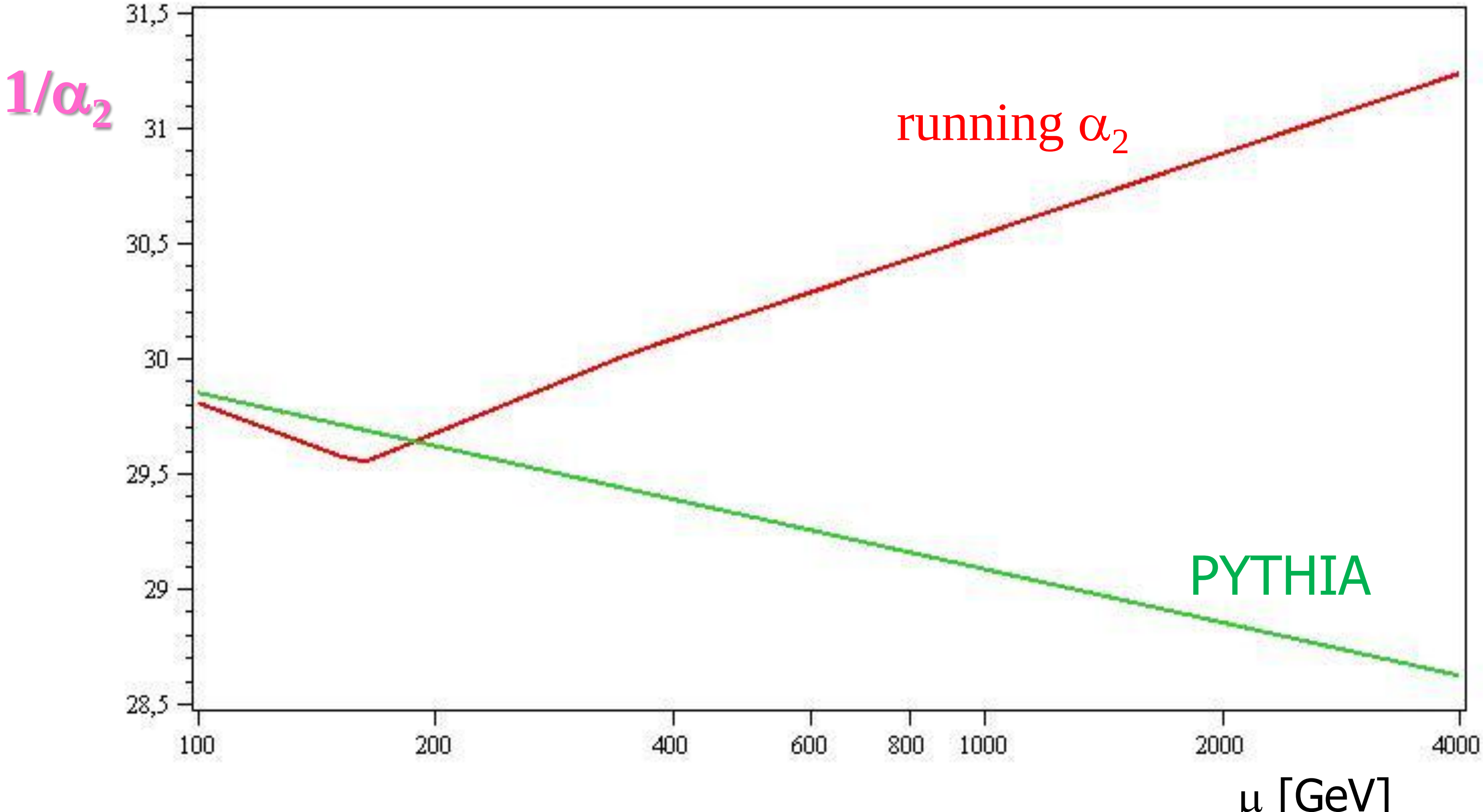


Fine structure constant α_{em} evolution



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