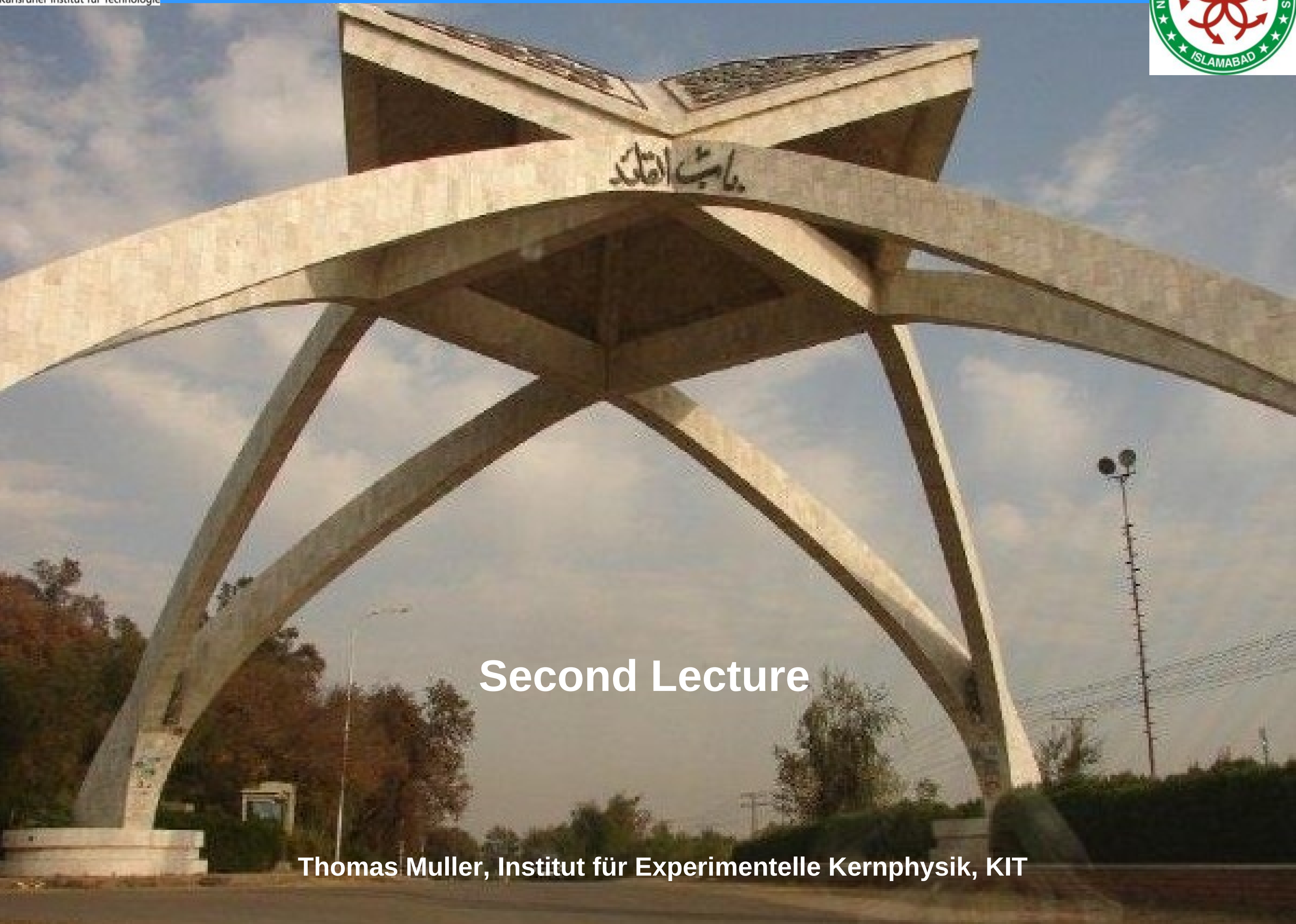
PHYSICS OF THE TOP QUARK



Second Lecture

Thomas Muller, Institut für Experimentelle Kernphysik, KIT

3. SINGLE TOP PRODUCTION

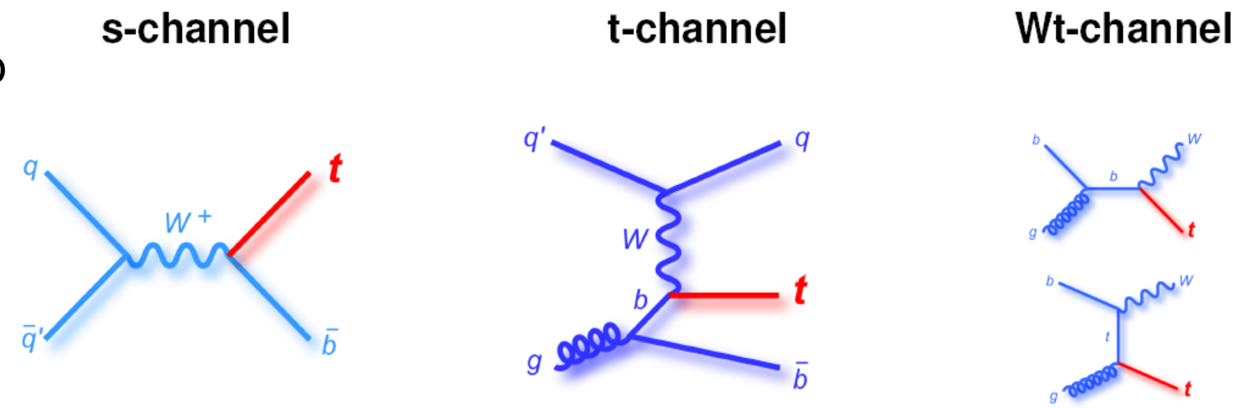
3.1 Cross Section, Couplings

Observation of single top production:

- cross section $\propto V_{tb}^2$
- study top-polarization and EWK top interaction

Test of non-SM phenomena:

- 4th generation
- FCNC couplings
- W' , $H^{\pm}$
- anomalous W_{tb} couplings

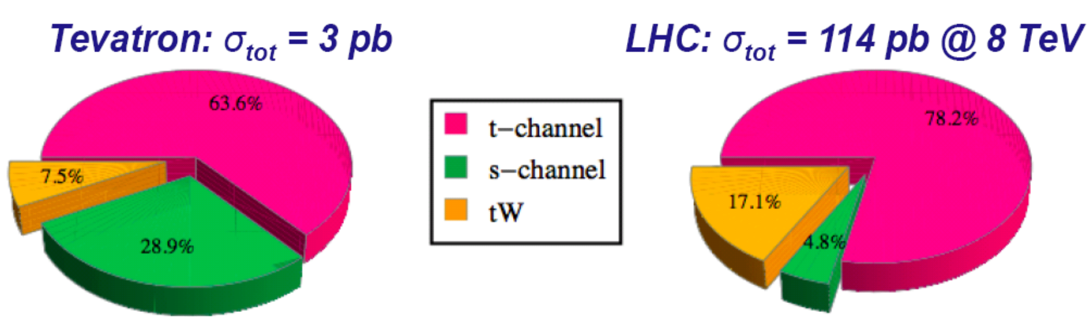


Main backgrounds:

- s-channel: Top pair, W + (HF) jets, QCD
- t-channel: Top pair, W + (HF) jets, QCD
- Wt-channel: Top pair, Z + (HF) jets, QCD

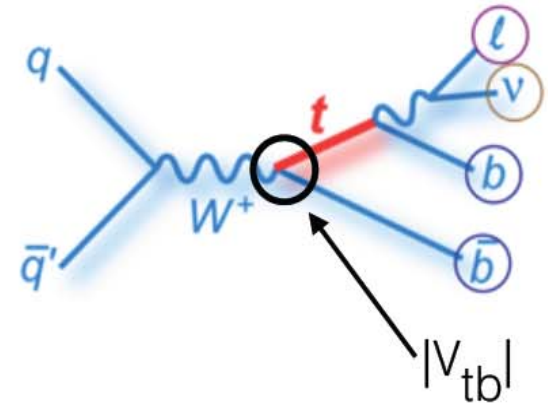
Signal – background discrimination:

- Tevatron: multivariate methods (neural networks, boosted decision trees, matrix element method)
- LHC: cut-based or multivariate method



$\sigma_{\text{single top}} \propto |V_{tb}|^2$

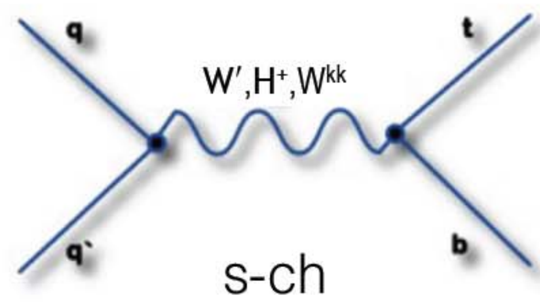
- Direct measurement of $|V_{tb}|$ CKM matrix element;
- Does unitarity holds? $|V_{ub}|^2 + |V_{cb}|^2 + |V_{tb}|^2 = 1$

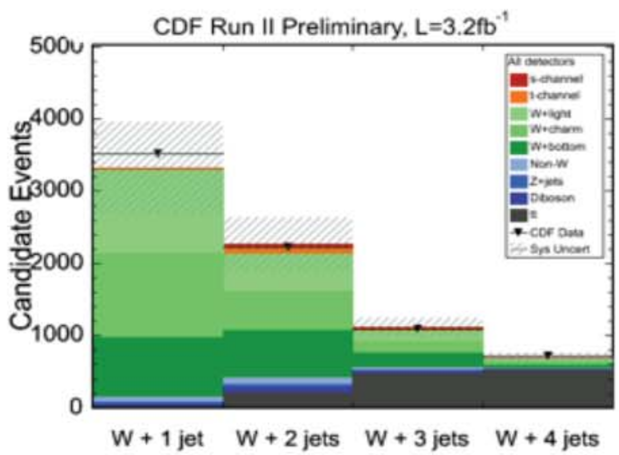


$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} & V_{uX}? \\ V_{cd} & V_{cs} & V_{cb} & V_{cX}? \\ V_{td} & V_{ts} & V_{tb} & V_{tX}? \\ V_{Yd}? & V_{Ys}? & V_{Yt}? & V_{YX}? \end{pmatrix}$$

Sensitivity to new physics

- t-ch: FCNC
- s-ch: heavy W', Top pion





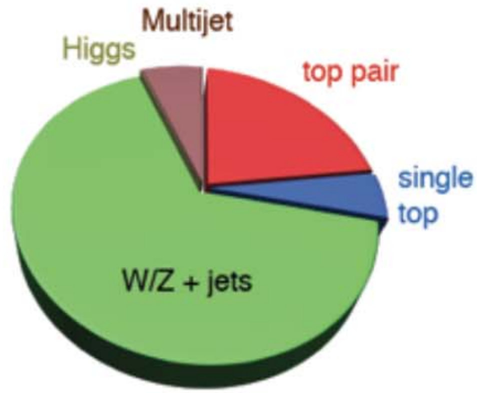
The Challenge

Single top quark production with decay into W + 2 Jets (dominated by W+jets):
final state hidden behind large backgrounds with large uncertainties (i.e. W+HF uncertainty ~ 30%)
➡ MVA using Multiple variables combined into a single more powerful discriminant to separate S from B

Signal, Background

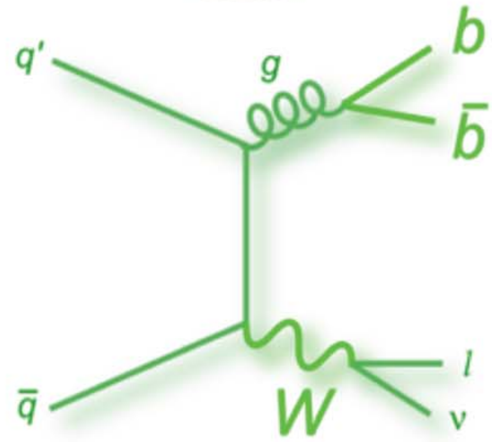
Electroweak/Top: Single Top, ttbar, diboson

- modeled by Monte Carlo (MC)
  - ➡ single top: POWHEG (CDF), COMPHEP (DØ)
  - ➡ ttbar: PYTHIA (CDF), ALPGEN (DØ)
  - ➡ diboson, WH: PYTHIA
- normalized to theoretical cross section



W+jets:

- modeled by ALPGEN+PYTHIA Monte Carlo (MC)
- normalisation and flavour composition from data



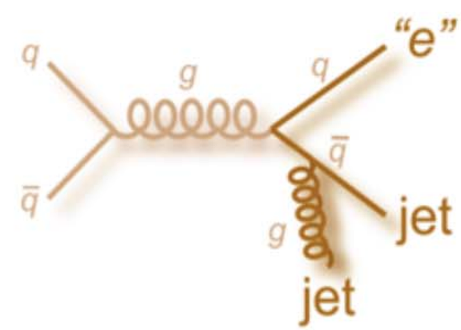
Mistags:

- falsely tagged light quark or gluon jet
- mistag probability from data

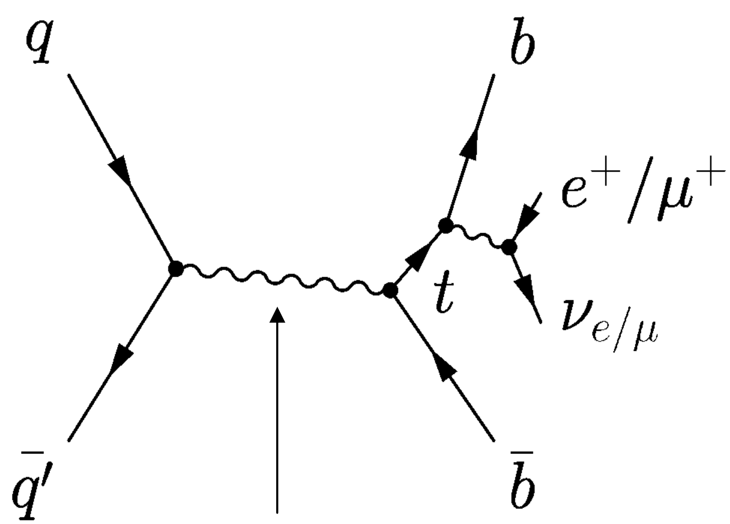
Z+jets: modeled by ALPGEN+PYTHIA MC

Multijet:

- Normalisation and shape from data-driven model

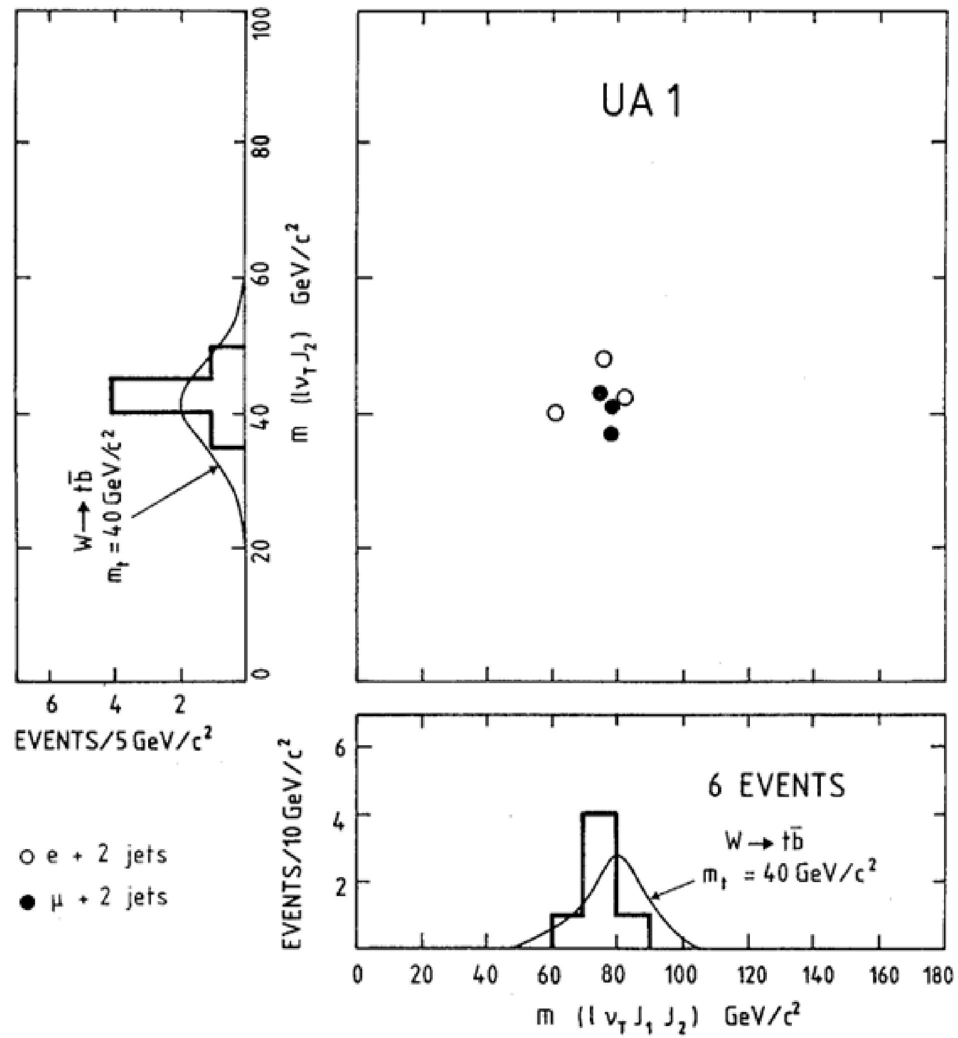


First “Observation” of Single Top



on-shell W boson

… by UA1 at CERN $Sp\bar{p}S$

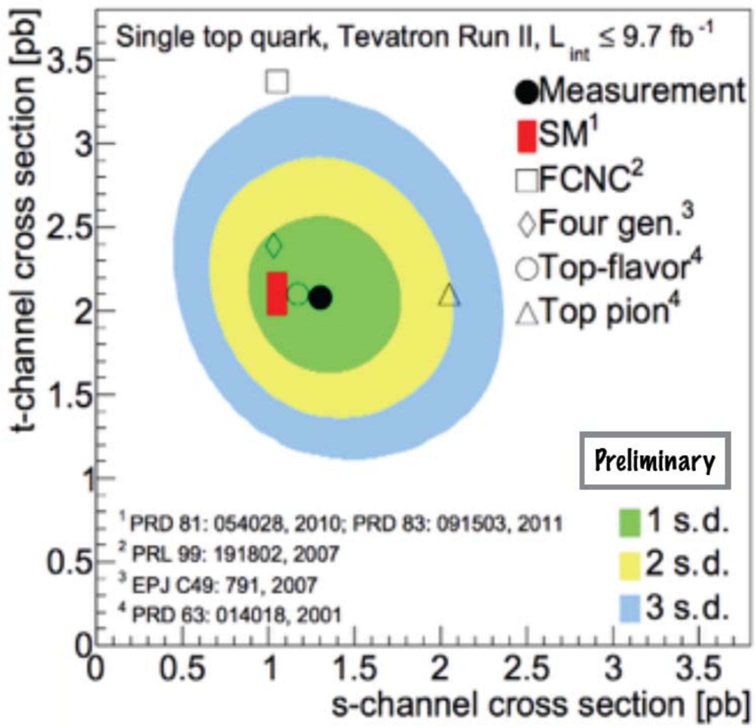


- excess in $M_{l\nu b}$ vs. $M_{l\nu bb}$ scatter plot
- compatible with $m_t = 40 \pm 10$ GeV
- later improved background estimate

Phys. Lett. B 147, 493 (1984)

Single Top at the Tevatron

Combined CDF, D0 Legacy Measurement From the Tevatron!



Fermilab-CONF-14-370-E

$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

- Consistent with NLO+NNLL prediction
- Measure V_{tb} directly (no assumption on CKM unitarity) →
- Precisely measure **s** and **t** channels

$|V_{tb}| = 1.12^{+0.09}_{-0.08}$ (D0)

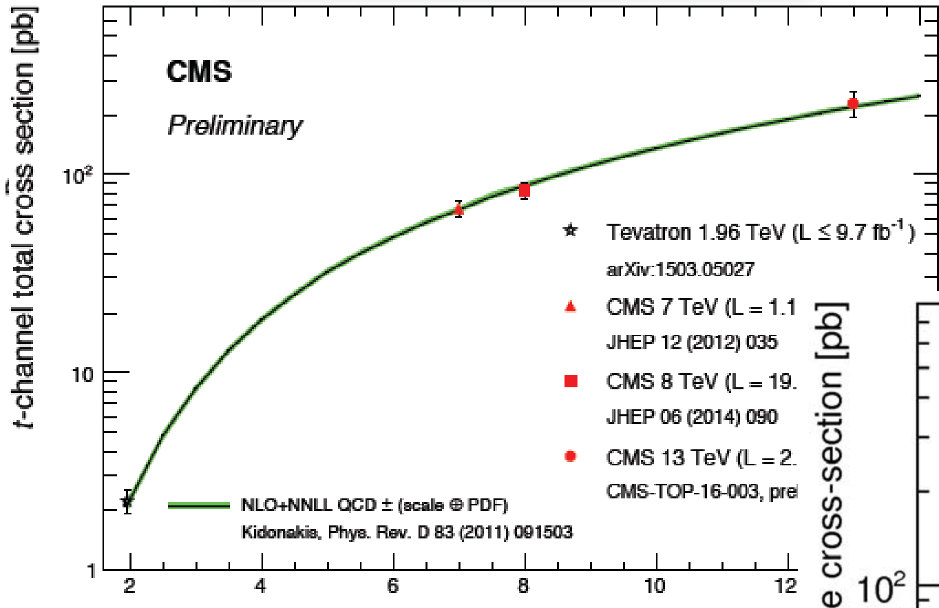
$|V_{tb}| = 0.95 \pm 0.09$ (CDF)

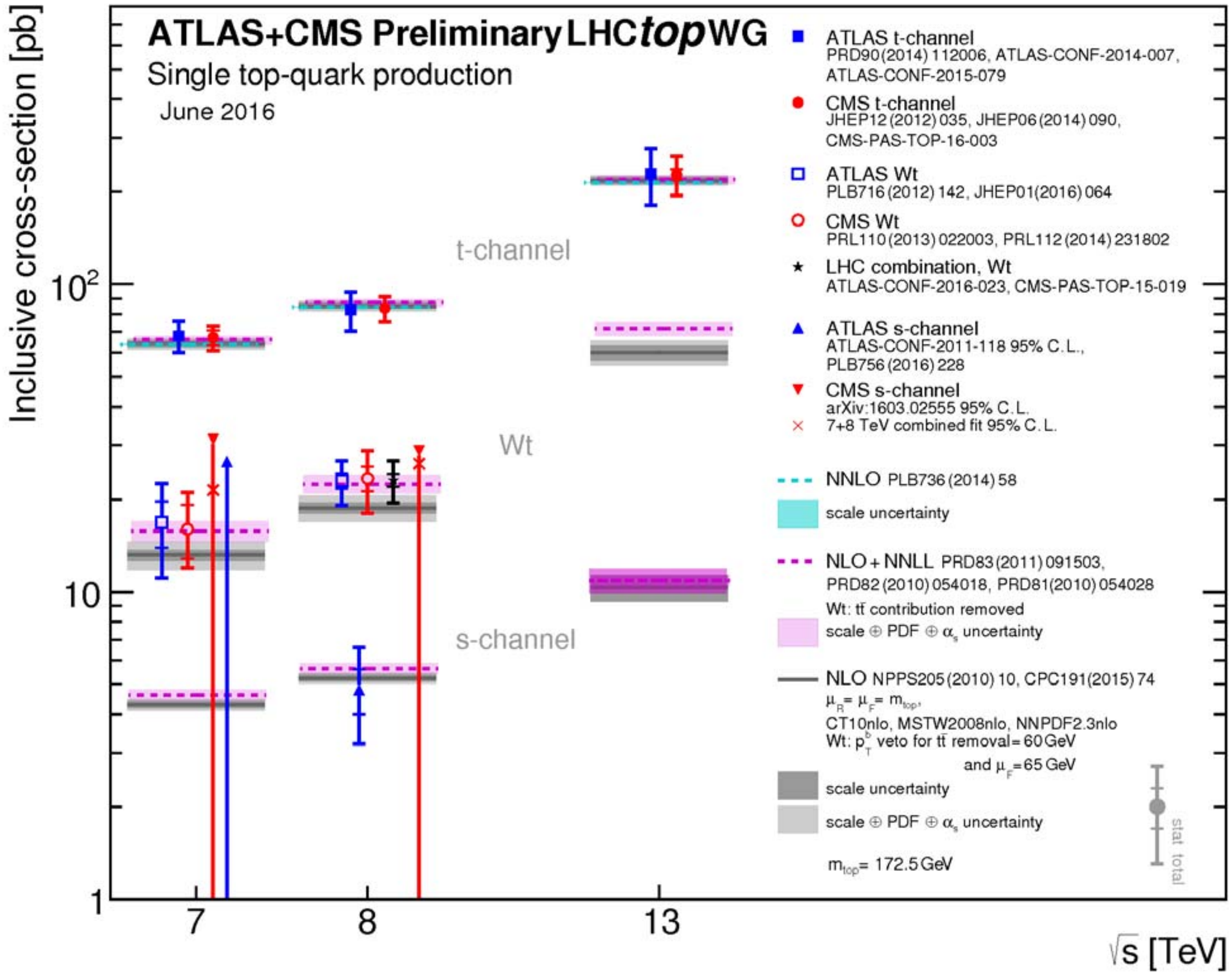
Gregorio Bernardi / LPNHE-Paris

$$|V_{tb,meas}|^2 = \frac{\sigma_{meas}}{\sigma_{SM}} \cdot |V_{tb,SM}|^2$$

- No assumption about number of generations
- Assumption: $|V_{ts}|^2 + |V_{td}|^2 << |V_{tb}|^2$

CMS PAS TOP-16-003





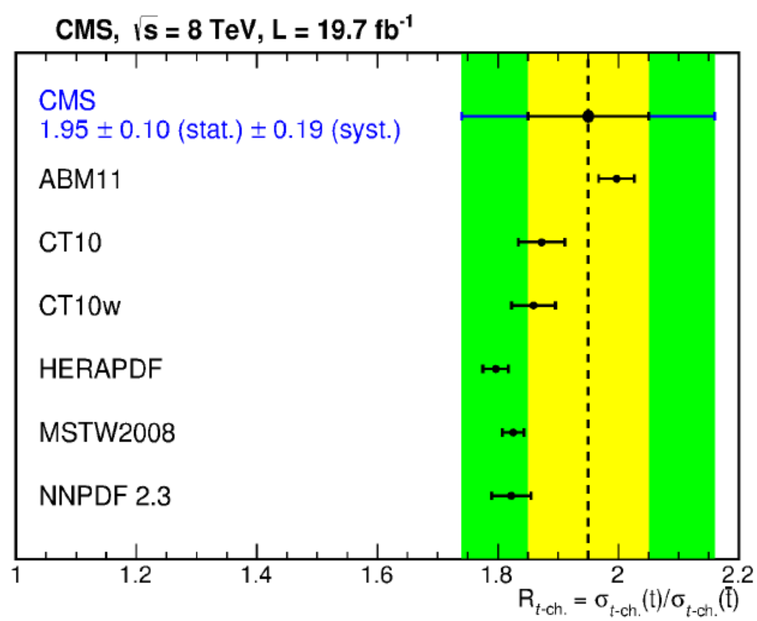
Ratio $R_t = \sigma_t/\sigma_{\bar{t}}$

- R_t is sensitive to the u/d PDFs; naïve expectation $R_t = 2$
- Measurement of σ_t using binned max. likelihood fit to NN output in 2-jets and 3-jets data split according to charge of lepton

- The measured ratio of single t to $\bar{t}$ production cross sections at $\sqrt{s} = 8$ TeV:

$$R_{t\text{-ch.}} = \sigma_{t\text{-ch.}}(\mathrm{t})/\sigma_{t\text{-ch.}}(\bar{\mathrm{t}}) = 1.95 \pm 0.10\,(\mathrm{stat.}) \pm 0.19\,(\mathrm{syst.})$$

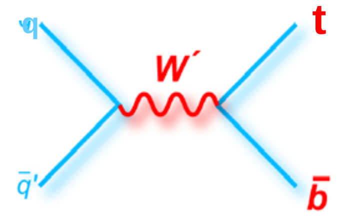
The measurement is in agreement with the predictions based on various global PDF sets that range from 1.86 to 2.07.



Wajid Khan, PhD Thesis.

3.2 Search for tb Resonances

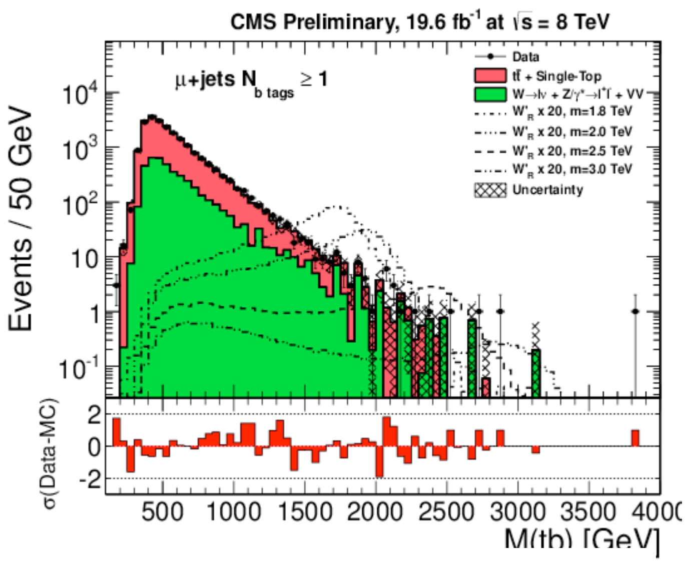
- Right-handed W'_R with SM-like couplings chosen as benchmark model
- Similar signature as single top s-channel (1 lepton, MET, 2 jets and at least 1 *b* tag)

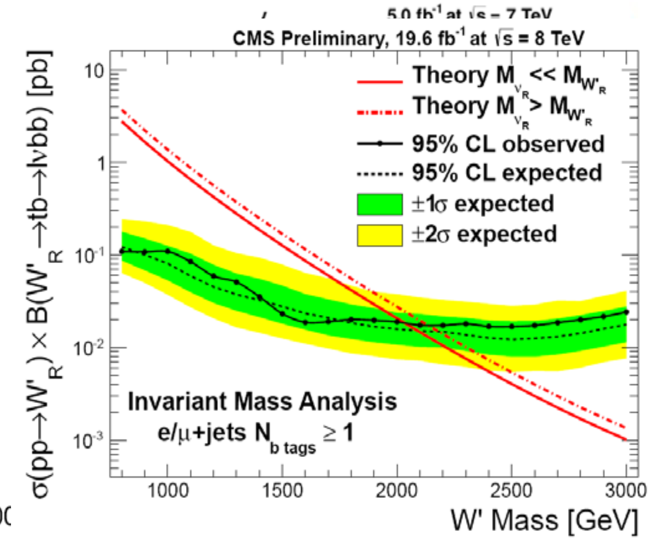


CMS-PAS-B2G-12-010

CMS

- BDT used to discriminate signal from background

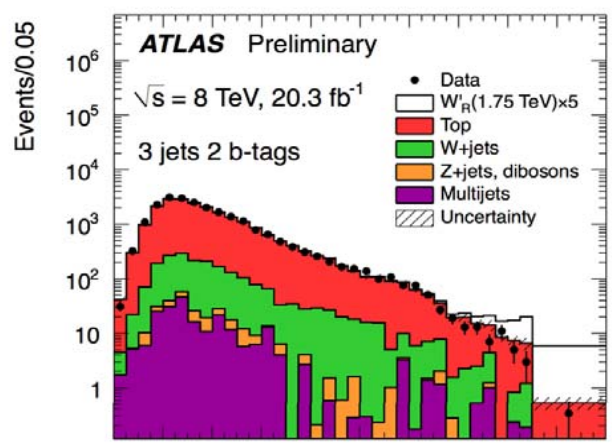


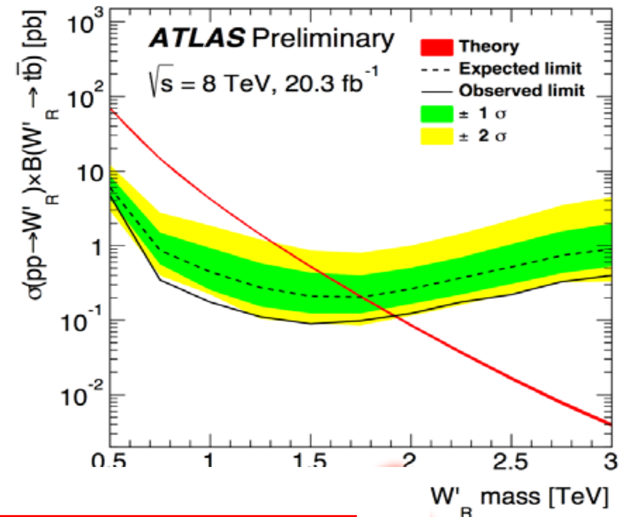


http://arxiv.org/abs/1205.1016

ATLAS

- Invariant mass of *tb* system used as discriminating variable



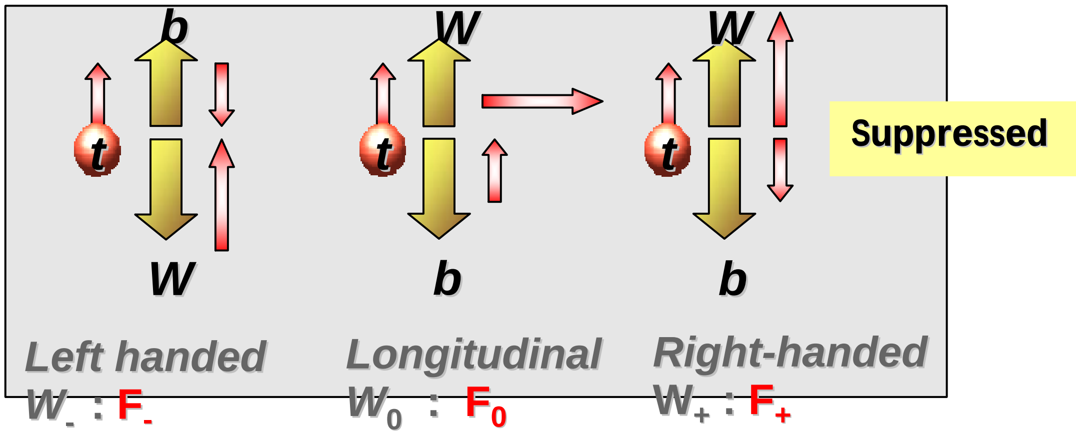


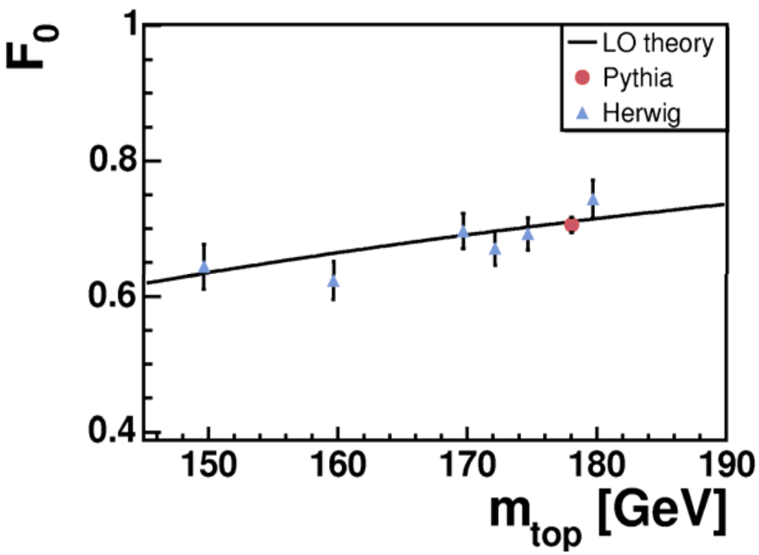
Observed limits (ATLAS, CMS): $m_{W'_R}$ > 1.8/ 2.0 TeV

4. DECAY PHYSICS: W HELICITY

4.1 W-Helicity

Three possible helicities:





$$F_0 = \frac{m_t^2}{2M_W^2 + m_t^2}$$

Distribution of Angle θ* between charged lepton in W system and W-Boson in Top-Quark system:

$$\frac{dN_{h_W=-1}}{d(\cos\theta^*)} \sim \frac{3}{8}(1-\cos\theta^*)^2$$

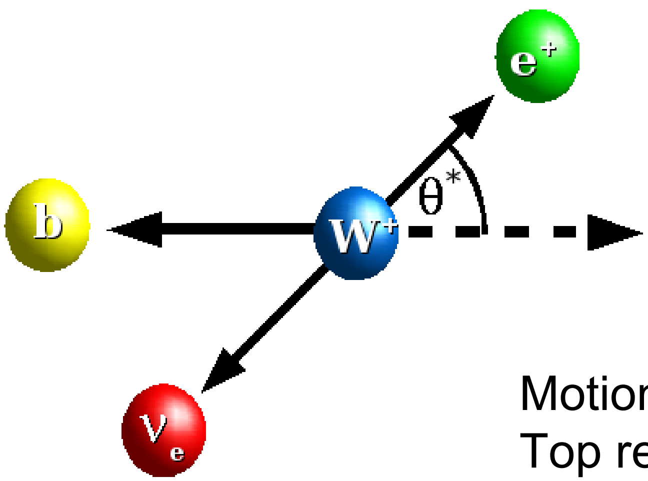
$$\frac{dN_{h_W=0}}{d(\cos\theta^*)} \sim \frac{3}{4}(1-\cos^2\theta^*)$$

$$\frac{dN_{h_W=+1}}{d(\cos\theta^*)} \sim \frac{3}{8}(1+\cos\theta^*)^2$$

SM:
F_- = 0.31

F_0 = 0.69

F_+ = 0.001

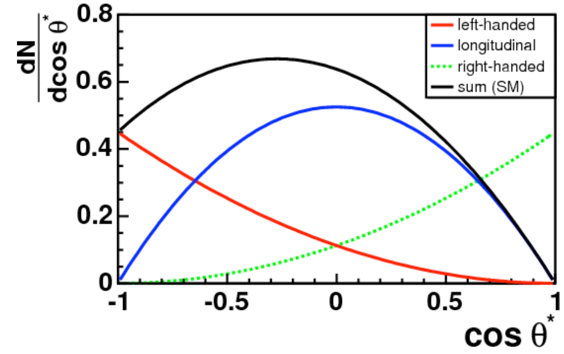


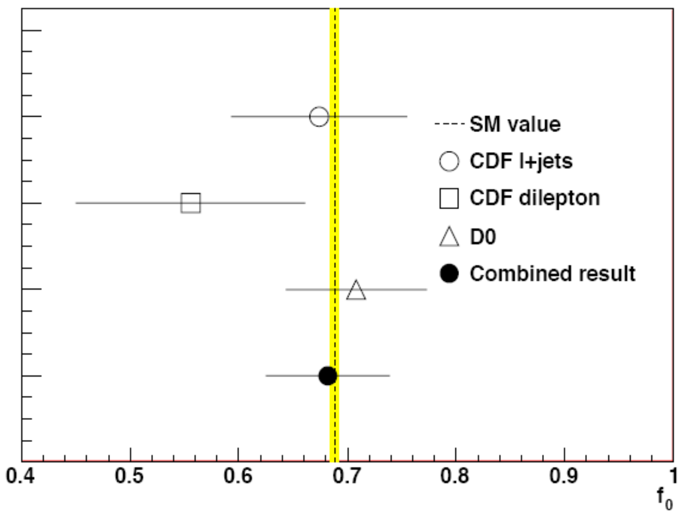
Motion of W in Top rest system

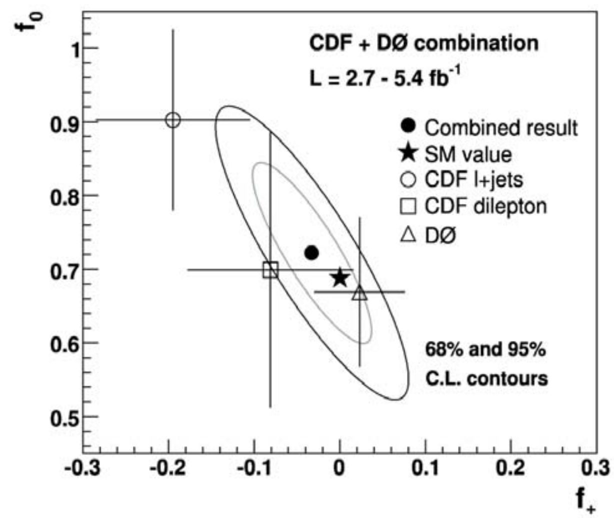
A. Czarnecki, J. G. Körner, J. H. Piclum, Phys. Rev. D 81, 111503 (2010)

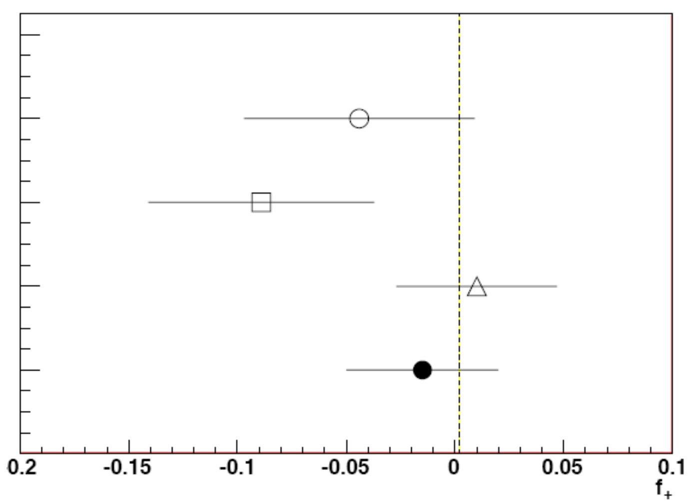
With three helicity fractions, there are two independent quantities to measure (3rd fraction is fixed since $\Sigma f = 1$)

- We choose to measure f_0 and f_+
- Can either measure both fractions simultaneously (2D fit)
- or fix one fraction to its SM value and measure the other (1D fit)









Tevatron Combo

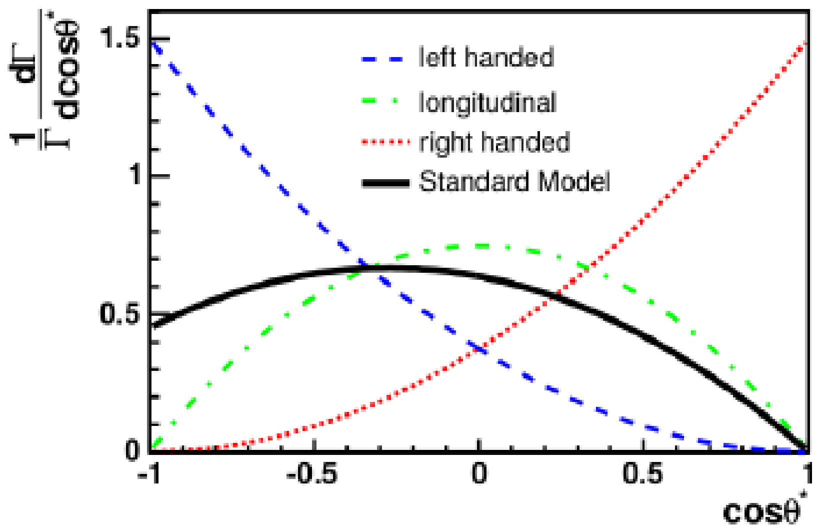
$$2D: f_0 = 0.722 \pm 0.062 \pm 0.052$$
$$f_+ = -0.033 \pm 0.034 \pm 0.031$$
$$1D: f_0 = 0.682 \pm 0.035 \pm 0.046$$
$$f_+ = -0.015 \pm 0.018 \pm 0.030$$

PRD85, 071106 (2012)

CMS Results on W Helicity

$$\frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta^*} = F_0 \cdot \frac{3}{4}(1-\cos^2\theta^*) + F_- \cdot \frac{3}{8}(1-\cos\theta^*)^2 + F_+ \cdot \frac{3}{8}(1+\cos\theta^*)^2$$

(SM: $F_0 = 0.69$ $F_- = 0.31$ $F_+ \sim 0$)



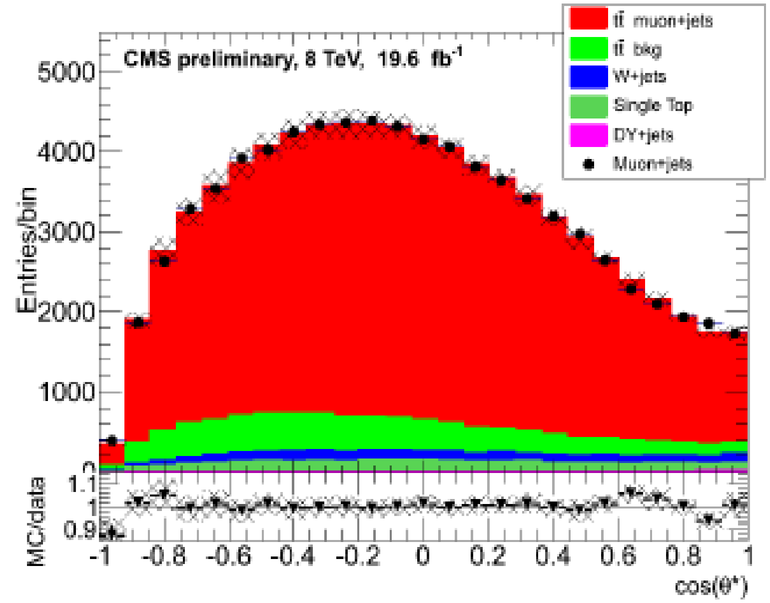
- **μ+jets** channel
- Reconstruct top quark kinematics
- Fit to the **cosθ* distribution**
- Results are based on **$19.6 fb^{-1}$**

$$F_0 = 0.659 \pm 0.015(\text{stat.}) \pm 0.023(\text{syst.})$$
$$F_L = 0.350 \pm 0.010(\text{stat.}) \pm 0.024(\text{syst.})$$

From $F_0 + F_L + F_R = 1$:

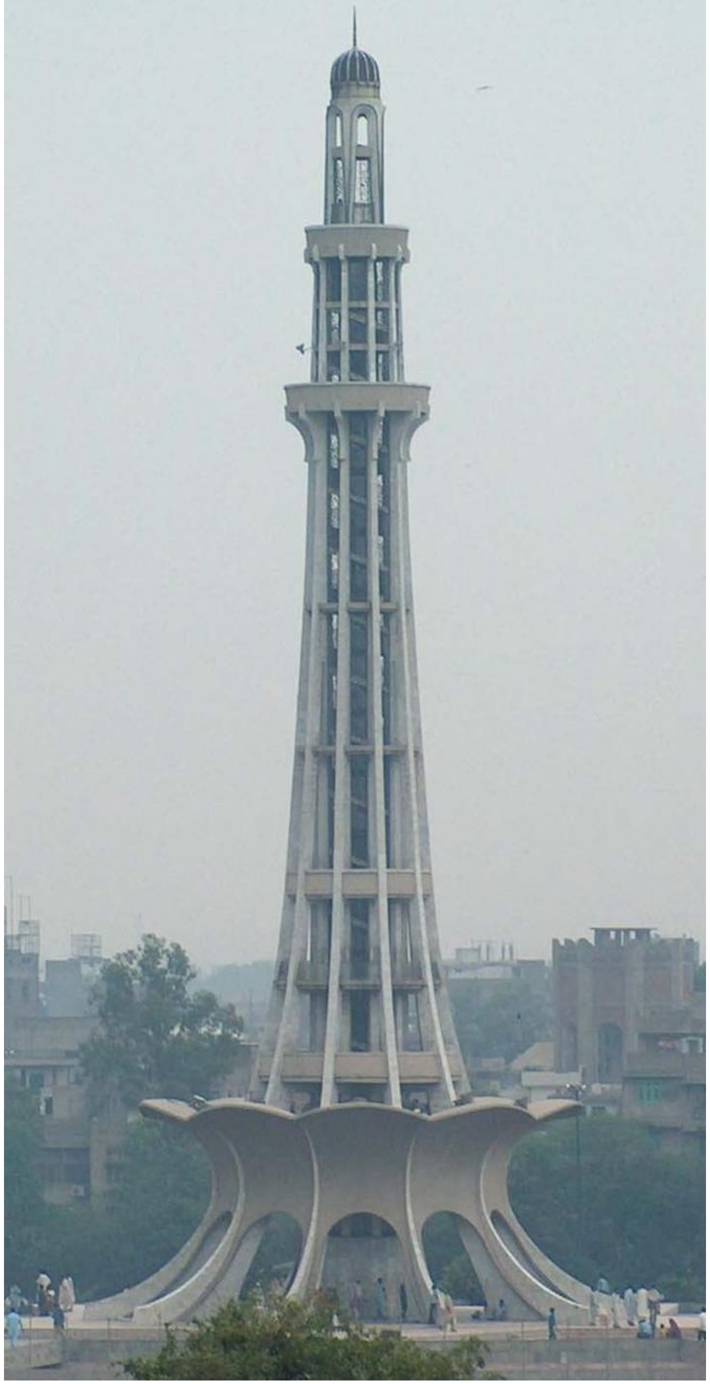
$$F_R = -0.009 \pm 0.006(\text{stat.}) \pm 0.020(\text{syst.})$$

Good agreement with SM-predictions!

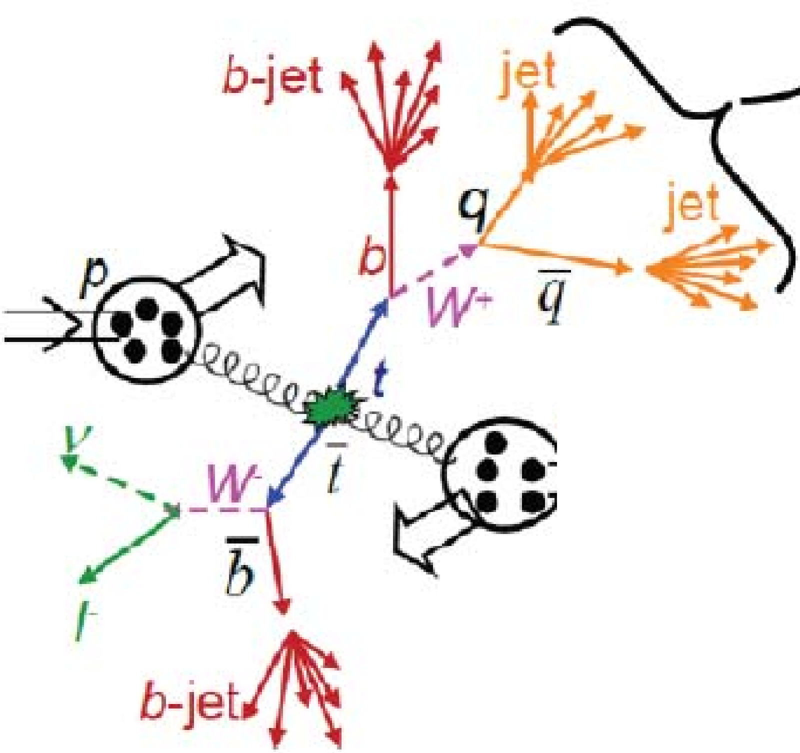


PAS-TOP-13-008

5. TOP QUARK PROPERTIES



Start with calibration…

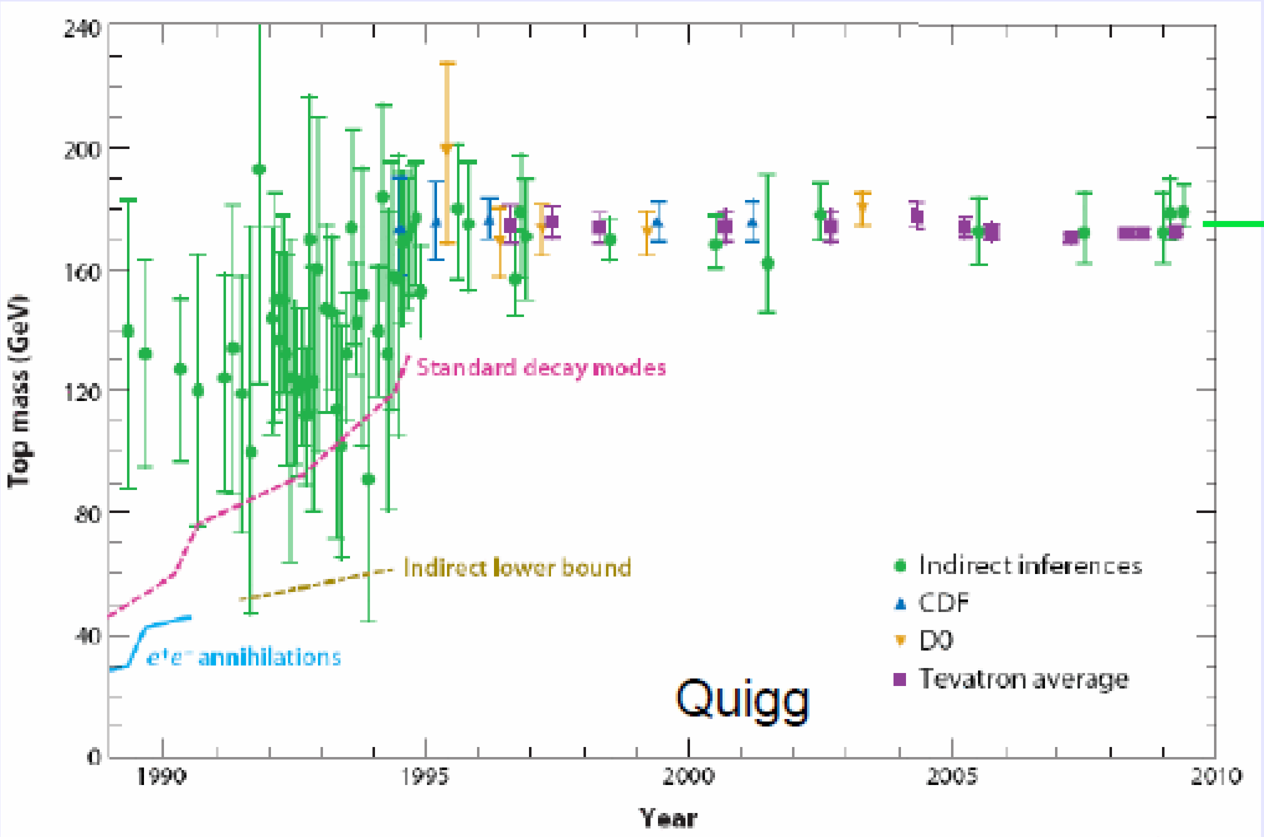


$M_W \sim k_{JES}$ → in-situ calibration

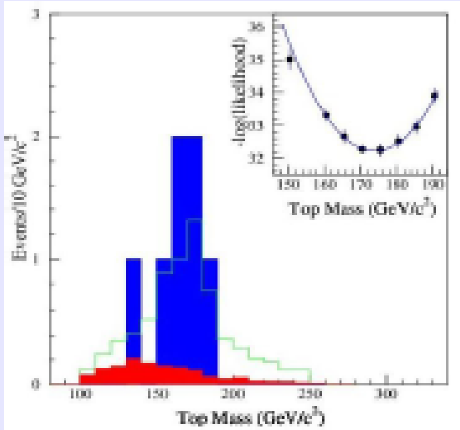
Evolution of Top Quark Mass Determination

Measurement uncertainty on M_T has improved since 1994, but mass value has not changed much

$M_{top} = 173.1 \pm 1.3$ GeV

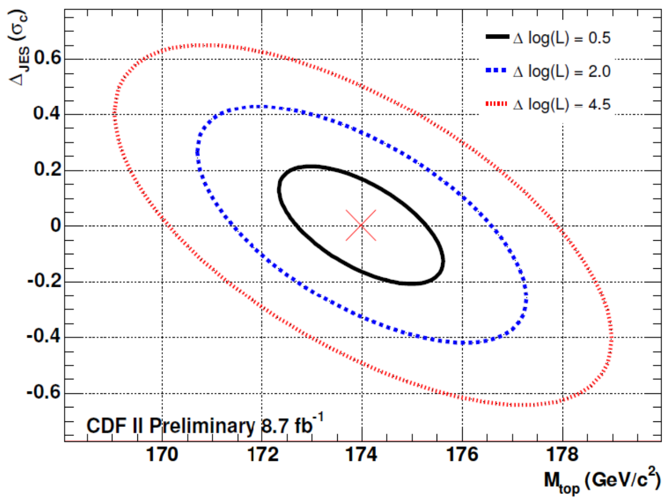


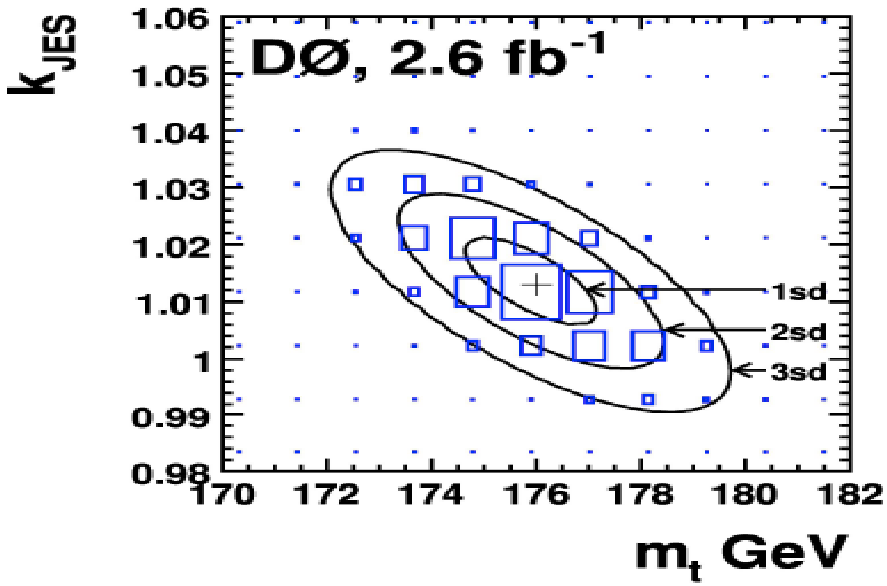
First measurement
7 events (1.4 background)
CDF, PRD **50**, 2966 (1994)

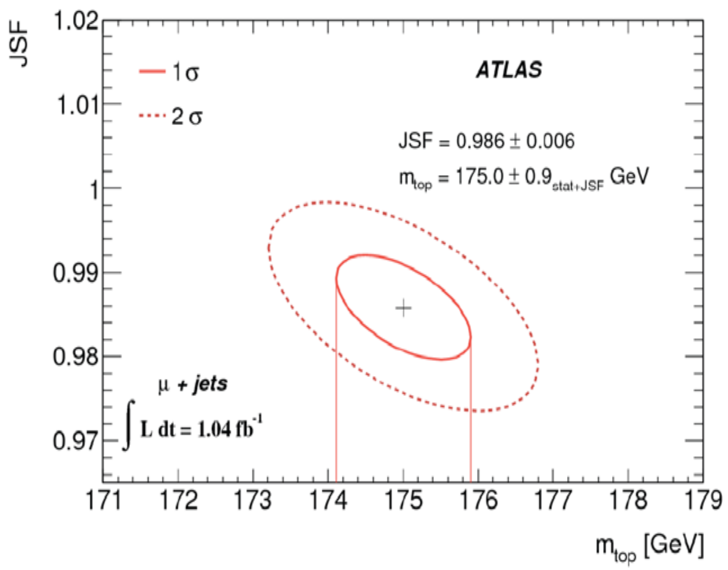


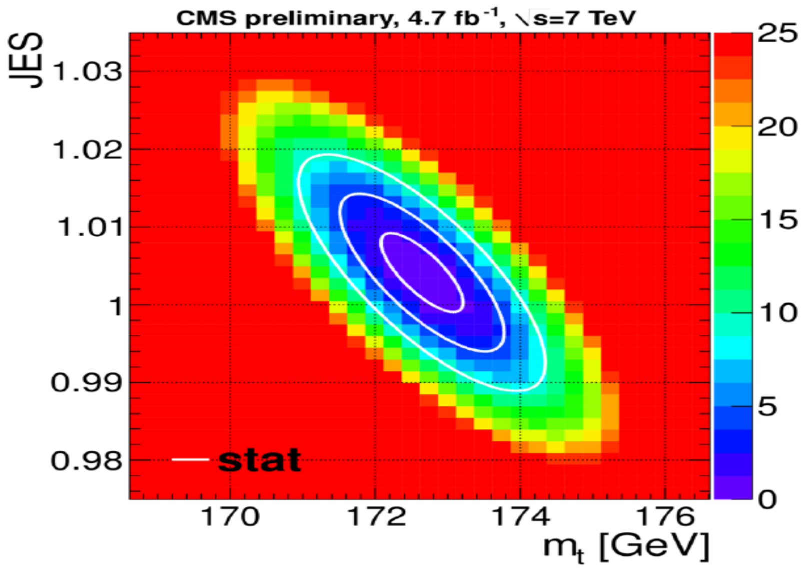
$$M_{top} = 174 \pm 10 \,^{+13}_{-12} \text{ GeV}$$

JES vs M_{top} in all four experiments



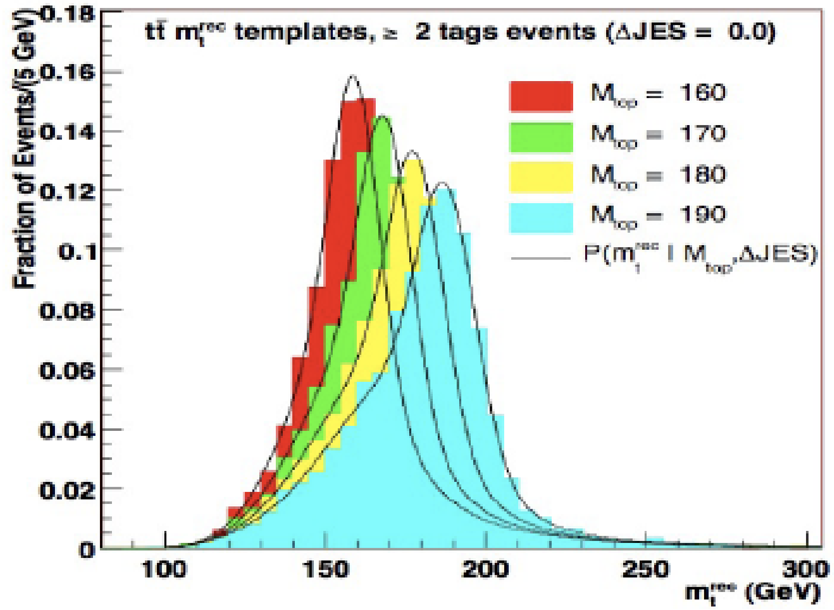




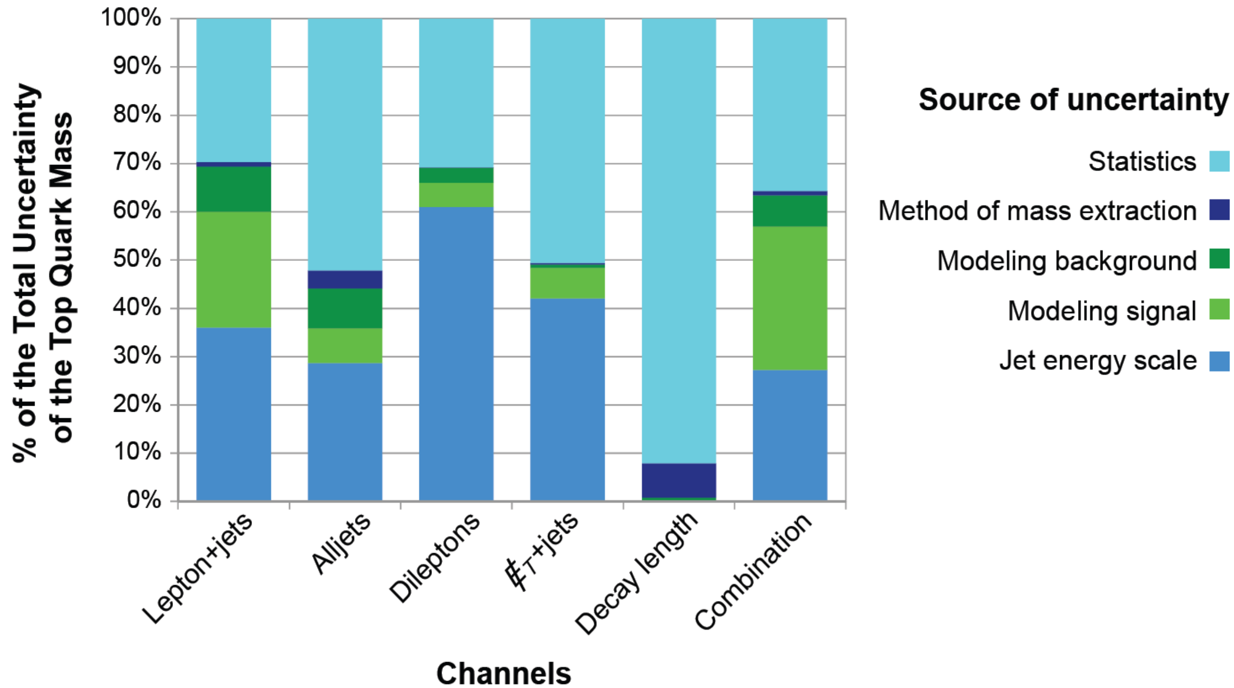


Mass Fitting

- Template method:
  fit MC generated distributions assuming different Mtop to data
- Matrix element method:
  probability based on LO tt matrix element using full kinematics of the event
- Ideogram method
  event likelihood computed as a convolution of a Gaussian resolution function with a Breit-Wigner (signal)
- Calibration curve method
  di-lepton channel using mt2
- b quark lifetime method
  boost propotional to Mtop;
  use of decay length of b jet

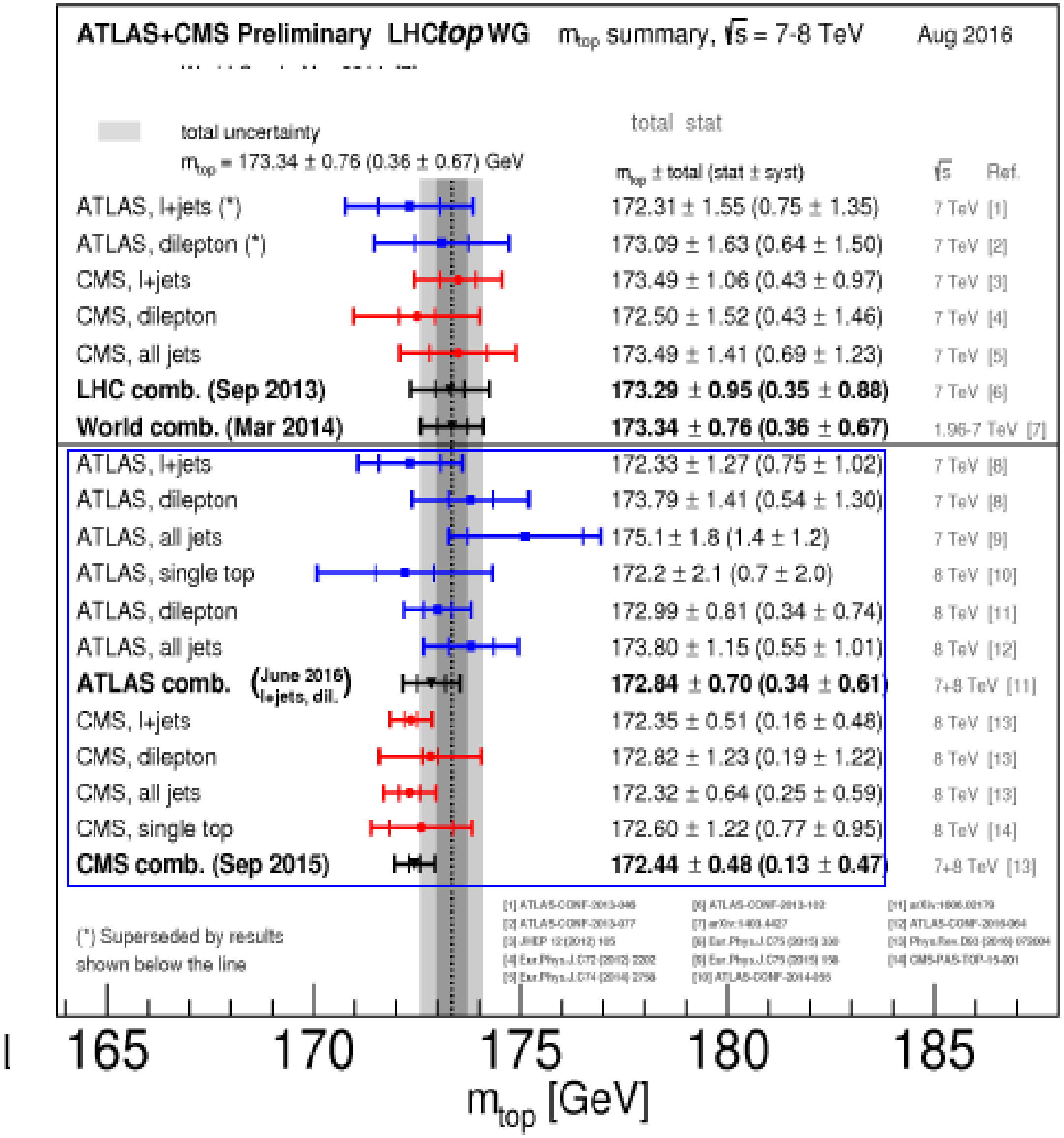


Example: sources of uncertainties at Tevatron

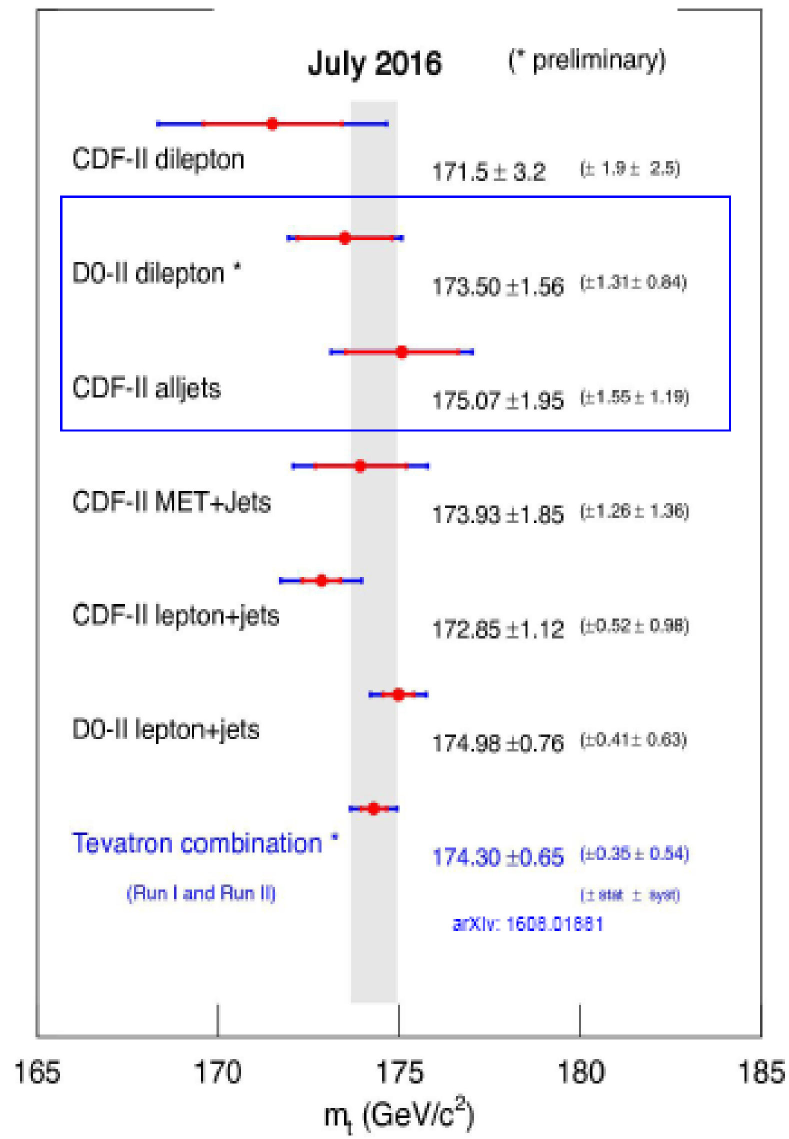


Top Quark Mass Combinations

ATLAS and CMS results



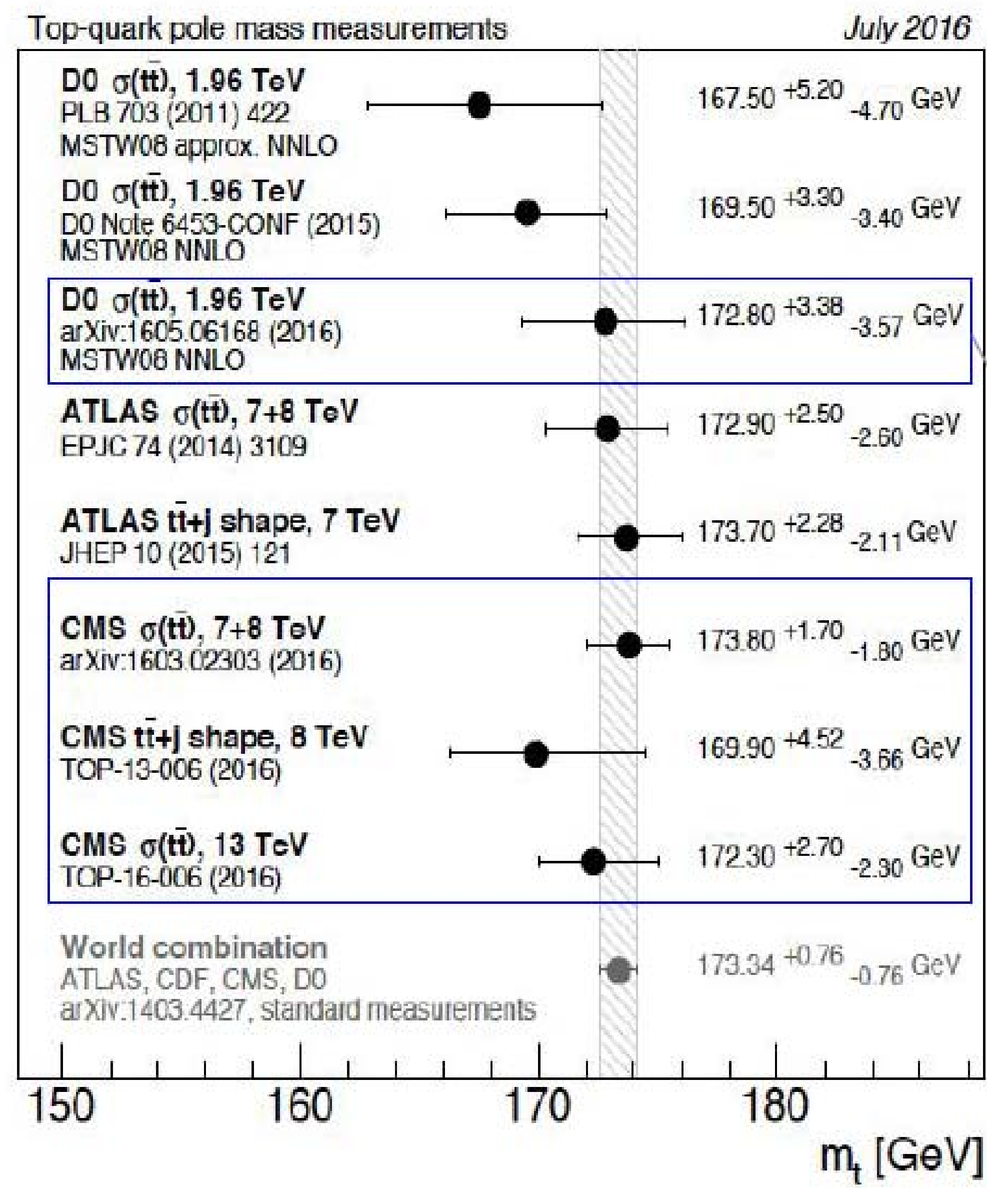
CDF and D0 results



LHC and Tevatron results with nearly comparable precision of 3-4 permille (0.5 GeV)
LHC top mass systematically limited: MC modelling, (b)JES
Template/Matrix element methods → Monte Carlo top mass parameter

Top Quark Mass Determination from fits and from σ_{tt}

Pole mass vs Monte-Carlo mass measurements



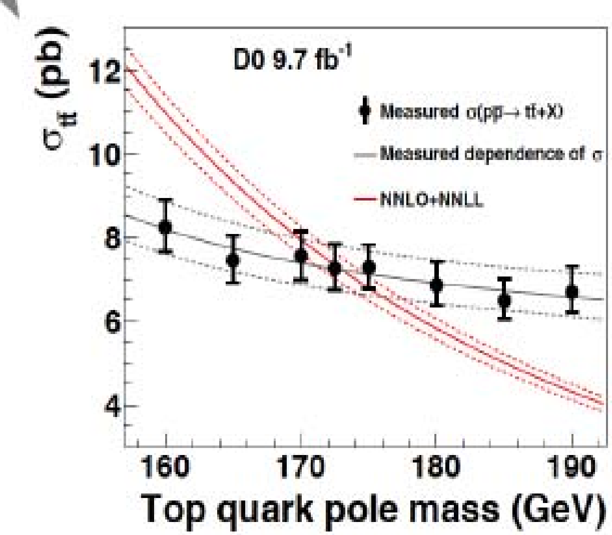
Direct top mass measurements:

- Monte-Carlo mass m_t^{MC}
- precision 0.5 GeV

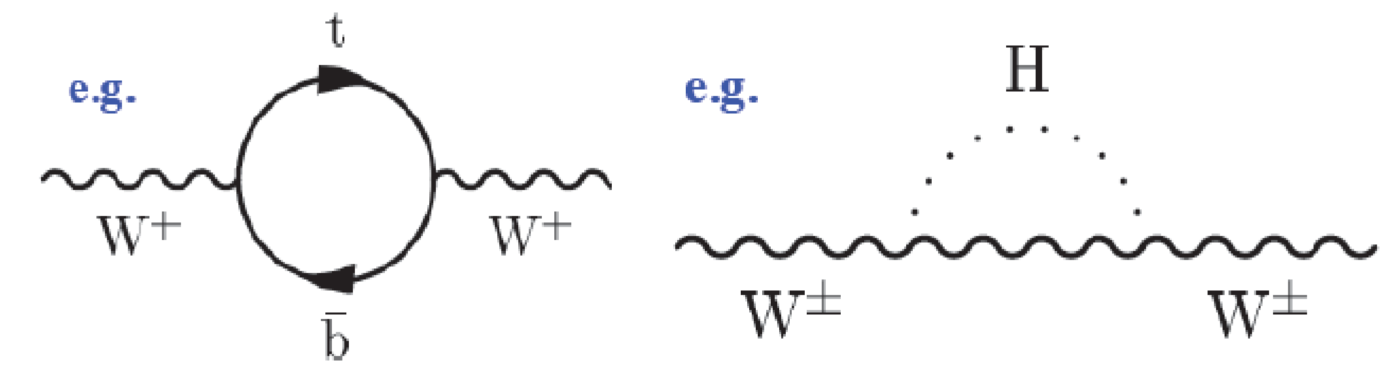
Expect m_t^{MC} - m_t^{pole} ~ 1 GeV

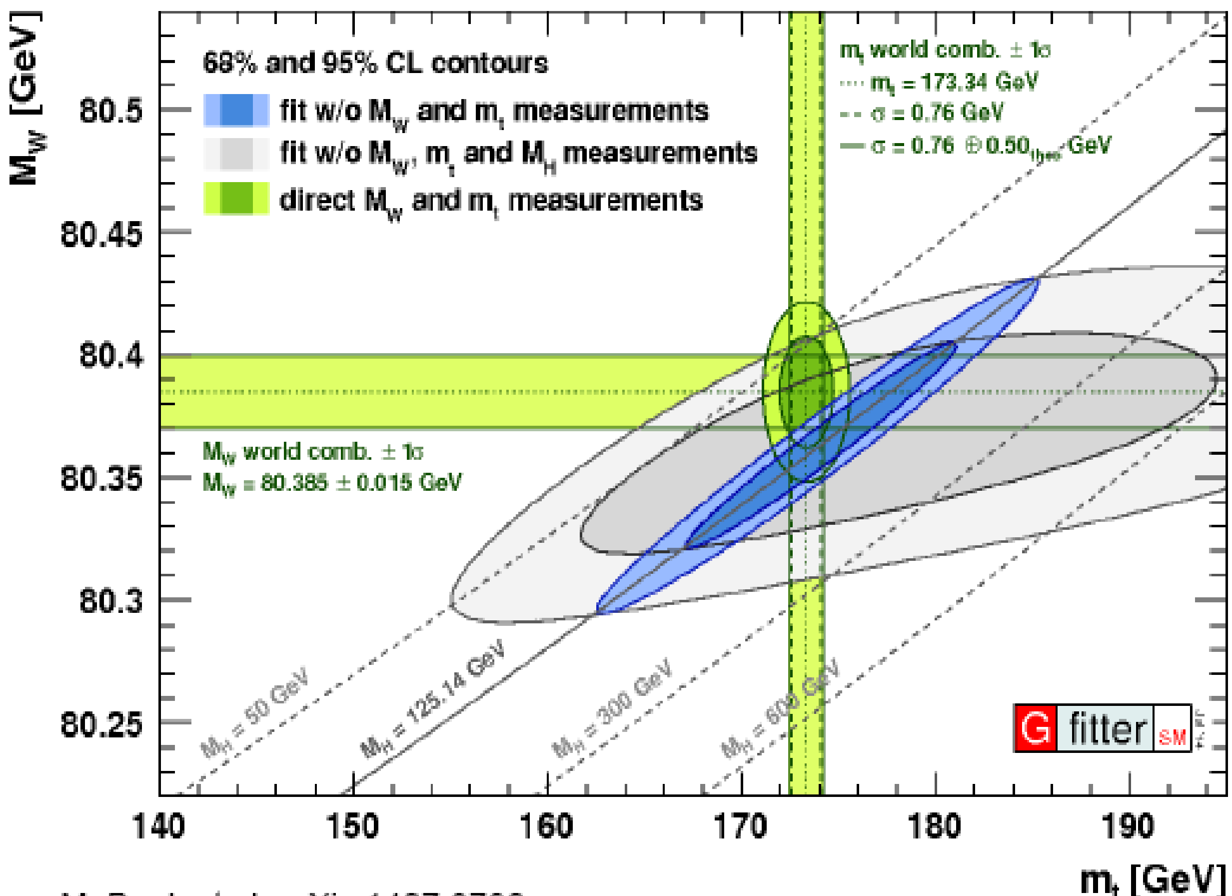
→ Calibrate m_t^{MC}

→ Indirect measurements of m_t^{pole}: compatible with measured m_t^{MC} within precision of ±2 GeV



Masses in EWK Theory





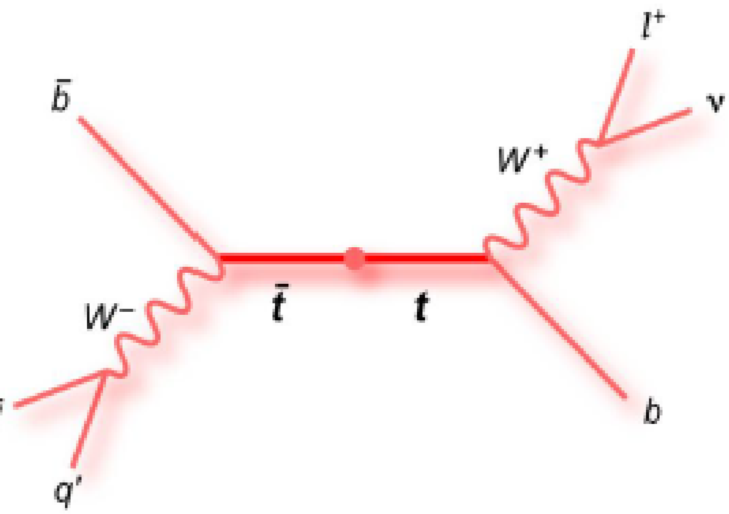
M. Baak et al, arXiv:1407.3792

http://project-gfitter.web.cern.ch/project-gfitter/

5.2 $t\bar{t}$ Mass Difference

- CPT theorem predicts masses of particles and antiparticles to be equal
  - Top-quark only particle with color charge to test this invariance

- Analysis Principle:



Leptonic branch:
Using lepton charge to tag top- or antitop-quark

Hadronic branch:
Reconstruct top-quark to determine mass

- Analysis of μ+jets events
  - 1 isolated muon, 4 high-p_T jets
  - Kinematic event reconstruction of 12 permutations
  - Measurement of top- and antitop-quark masses with Ideogram method
    - Taking b-tagging information into account to reduce background events (mainly W+jets)

Test CPT invariance in the top sector

$$\Delta M_t = M_{top} - M_{\overline{top}}$$

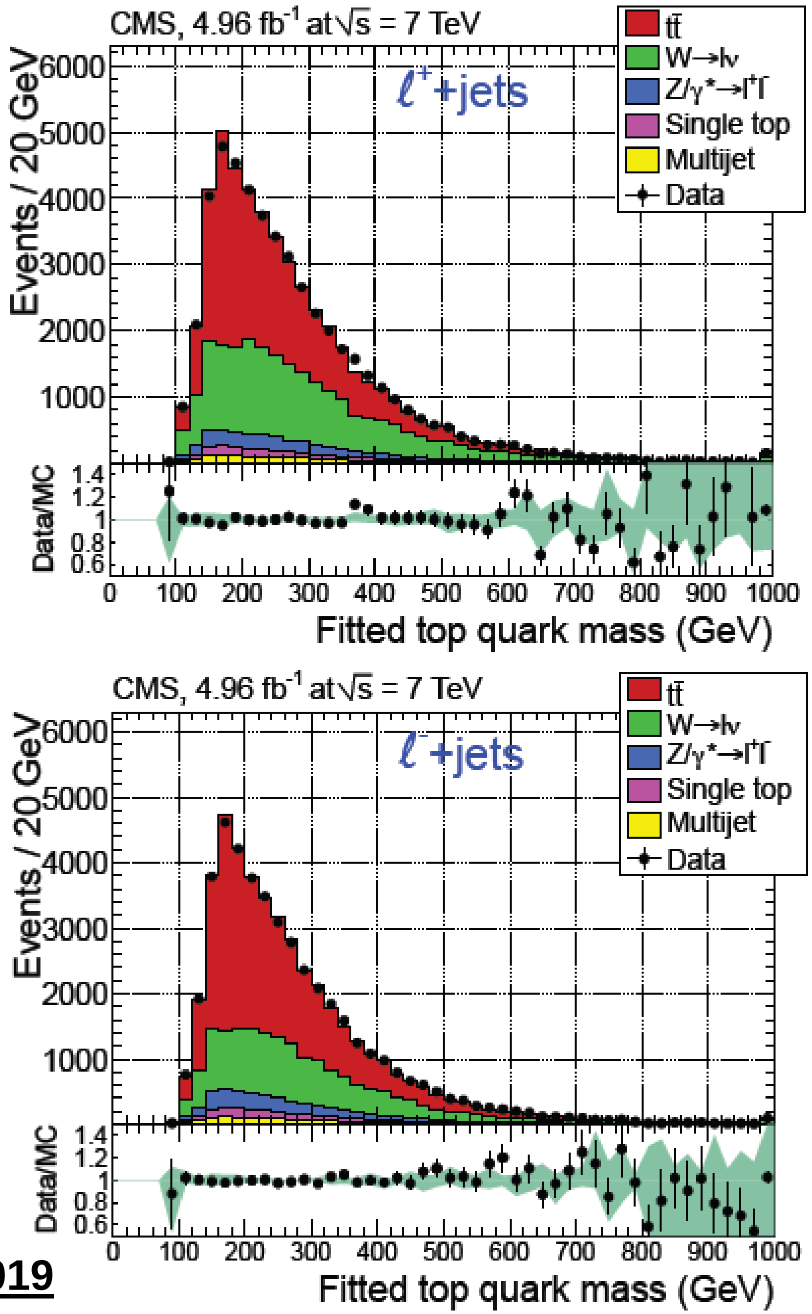
- Reconstruction of the hadronic side: compare ℓ^++jets and ℓ^-+jets events
- Use kinematic fit, and event-per-event likelihood for ℓ^- and ℓ^+ separately

$$\Delta m_t = -0.44 \pm 0.46\ (\text{stat.}) \pm 0.27\ (\text{syst.})\ \text{GeV}$$

Most systematic effects cancel out !
→ the measurement is stat. limited

World's best so far

Consistent with SM,
Consistent between e and μ



CMS-TOP-11-019

5.3 Width of the Top Quark

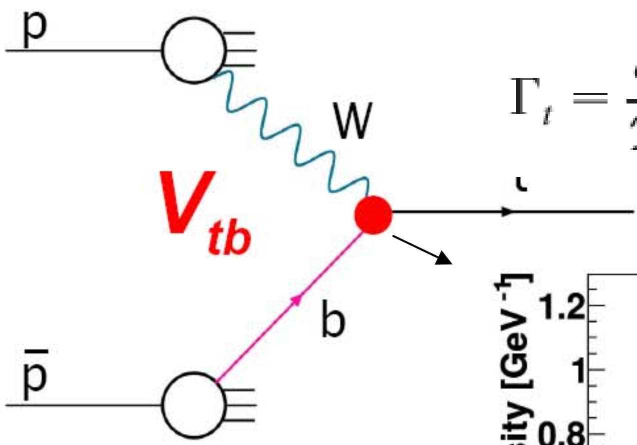
t-channel cross section:

$$\sigma(p\bar{p} \to tqb + X) = 2.90 \pm 0.59 \text{ pb}$$

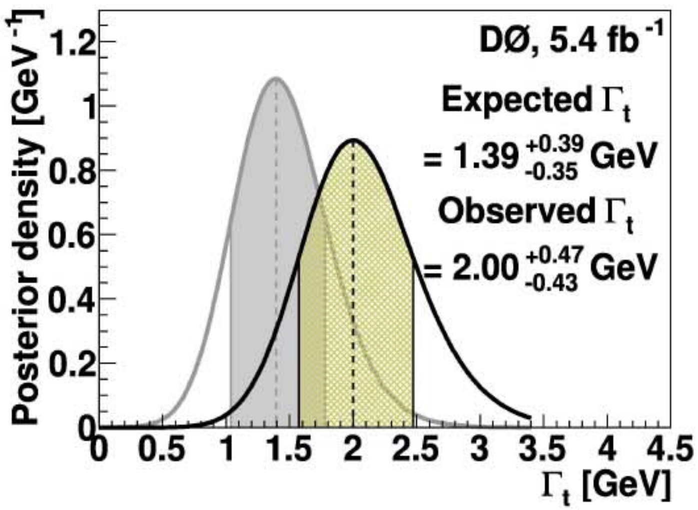
partial decay width:

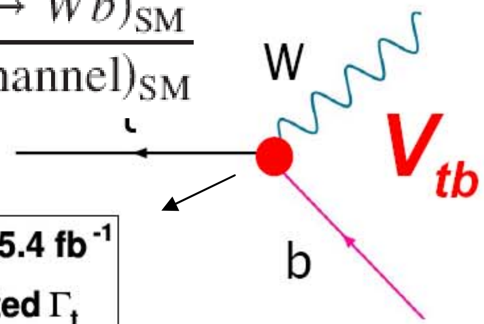
R= 0.90±0.04 (stat+syst)

m_t =172.5 GeV



$$\Gamma_t = \frac{\sigma(t-\text{channel})\Gamma(t \to Wb)_{SM}}{\mathcal{B}(t \to Wb)\sigma(t-\text{channel})_{SM}}$$





$$\tau_{top} \propto \left(\frac{M_W}{M_{top}}\right)^3$$

$$\tau_{top} \approx 4.7 \cdot 10^{-25} \text{ s}$$

Phys. Rev. D84 012008 (2011)

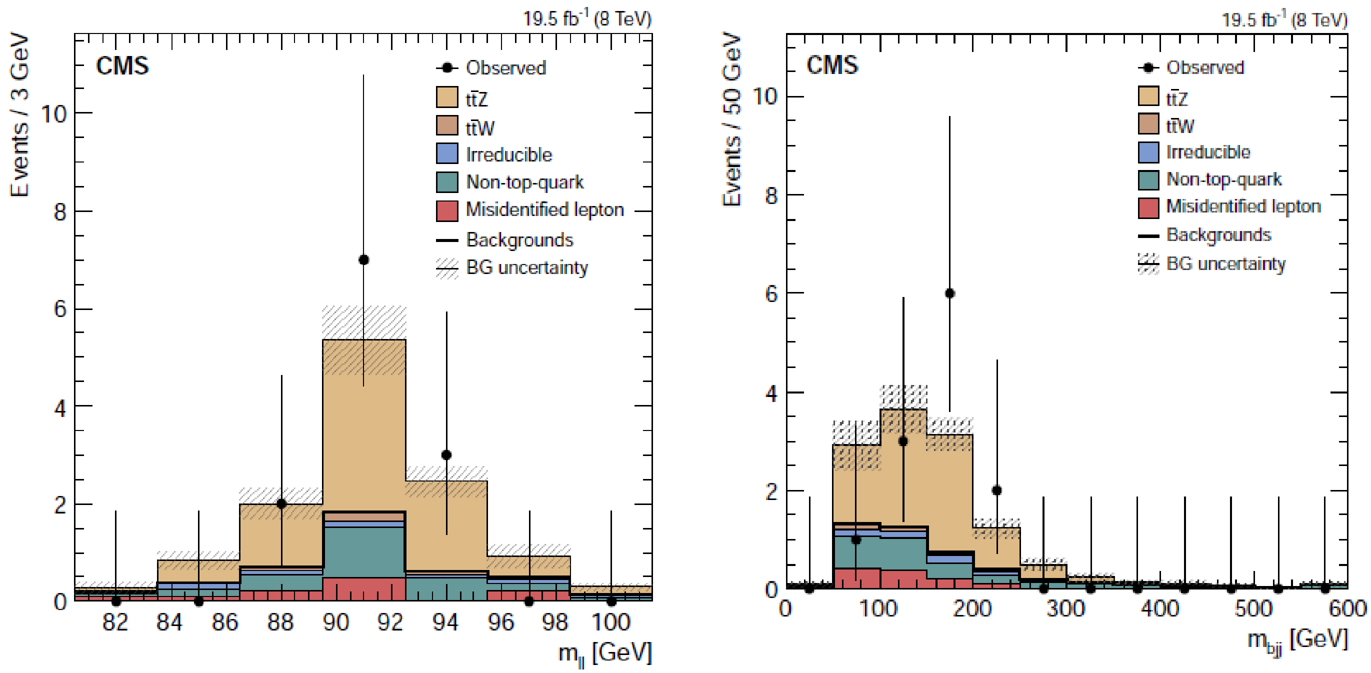
$$\Gamma_t = 2.00^{+0.47}_{-0.43} \text{ GeV}$$

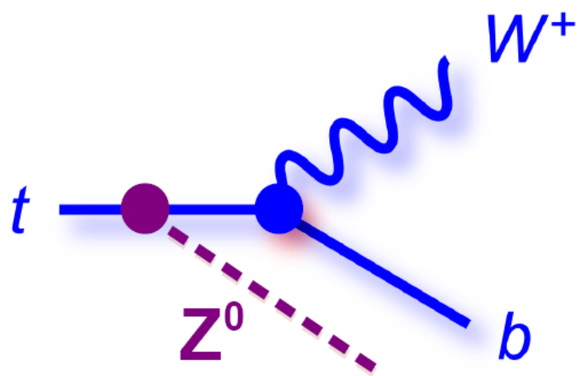
$$\tau_t = (3.29^{+0.90}_{-0.63}) \times 10^{-25} \text{ s}$$

$\Longrightarrow$ **most precise determination**

Phys. Rev. D 85, 091104(2012)

5.4 tt+V Production





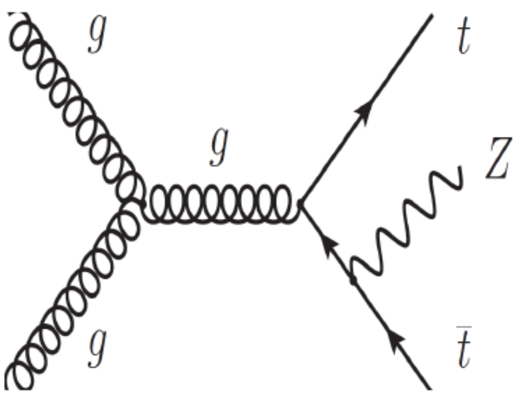
CMS 7 TeV PRL 110 (2013) 172002

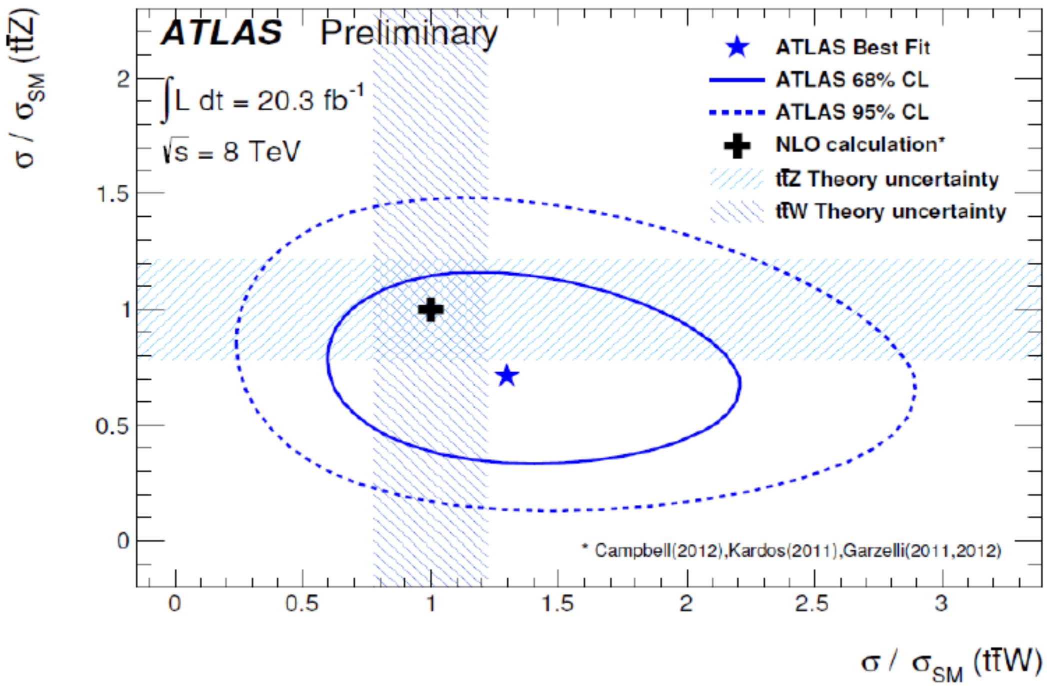
Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}V$	$430^{+170}_{-150}\,(\text{stat.}) \pm^{90}_{70}\,(\text{syst.})\,\text{fb}$	3.0
3ℓ	$t\bar{t}Z$	$280^{+140}_{-110}\,(\text{stat.})^{+60}_{-30}\,(\text{syst.})\,\text{fb}$	3.3

CMS 8 TeV arXiv:1406.7830

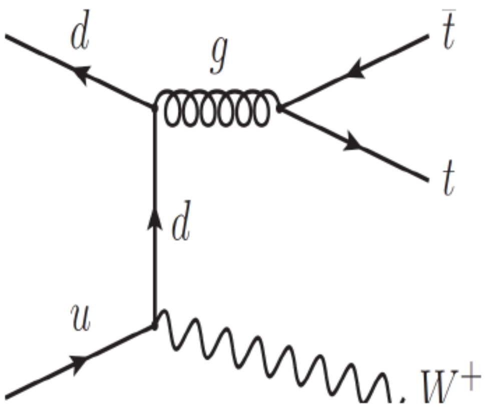
Channels used	Process	Cross section	Significance
2ℓ	$t\bar{t}W$	$170^{+90}_{-80}\,(\text{stat}) \pm 70\,(\text{syst})\,\text{fb}$	1.6
3ℓ+4ℓ	$t\bar{t}Z$	$200^{+80}_{-70}\,(\text{stat})^{+40}_{-30}\,(\text{syst})\,\text{fb}$	3.1
2ℓ+3ℓ+4ℓ	$t\bar{t}W + t\bar{t}Z$	$380^{+100}_{-90}\,(\text{stat})^{+80}_{-70}\,(\text{syst})\,\text{fb}$	3.7

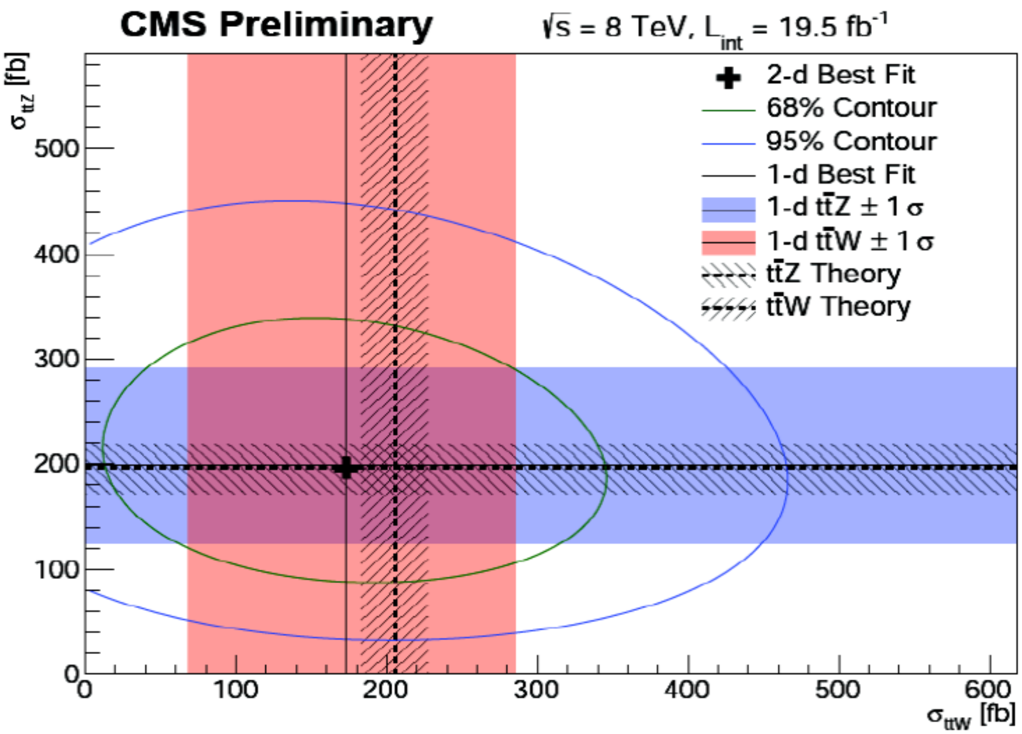
ttZ


g
g
g
t
Z
t̄


ATLAS Preliminary
∫L dt = 20.3 fb⁻¹
√s = 8 TeV
ATLAS Best Fit
ATLAS 68% CL
ATLAS 95% CL
NLO calculation*
tt̄Z Theory uncertainty
tt̄W Theory uncertainty
* Campbell(2012),Kardos(2011),Garzelli(2011,2012)
σ / σSM (tt̄Z)
σ / σSM (tt̄W)
0
0.5
1
1.5
2
2.5
3

ttW

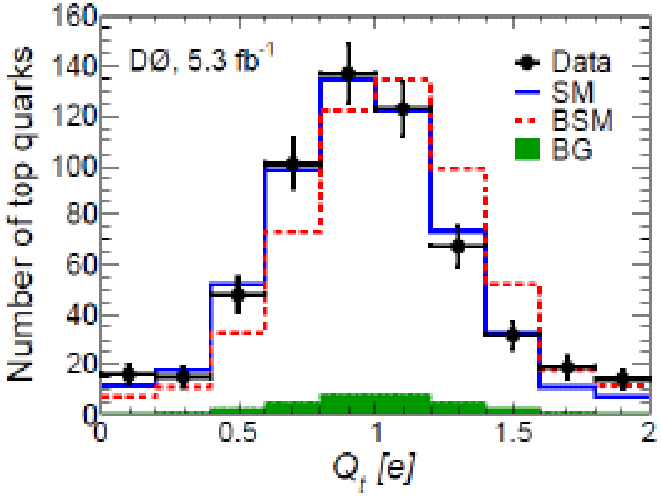

d
g
t̄
t
d
u
W+


CMS Preliminary
√s = 8 TeV, Lint = 19.5 fb⁻¹
2-d Best Fit
68% Contour
95% Contour
1-d Best Fit
1-d tt̄Z ± 1 σ
1-d tt̄W ± 1 σ
tt̄Z Theory
tt̄W Theory
σttZ [fb]
σttW [fb]
0
100
200
300
400
500
600

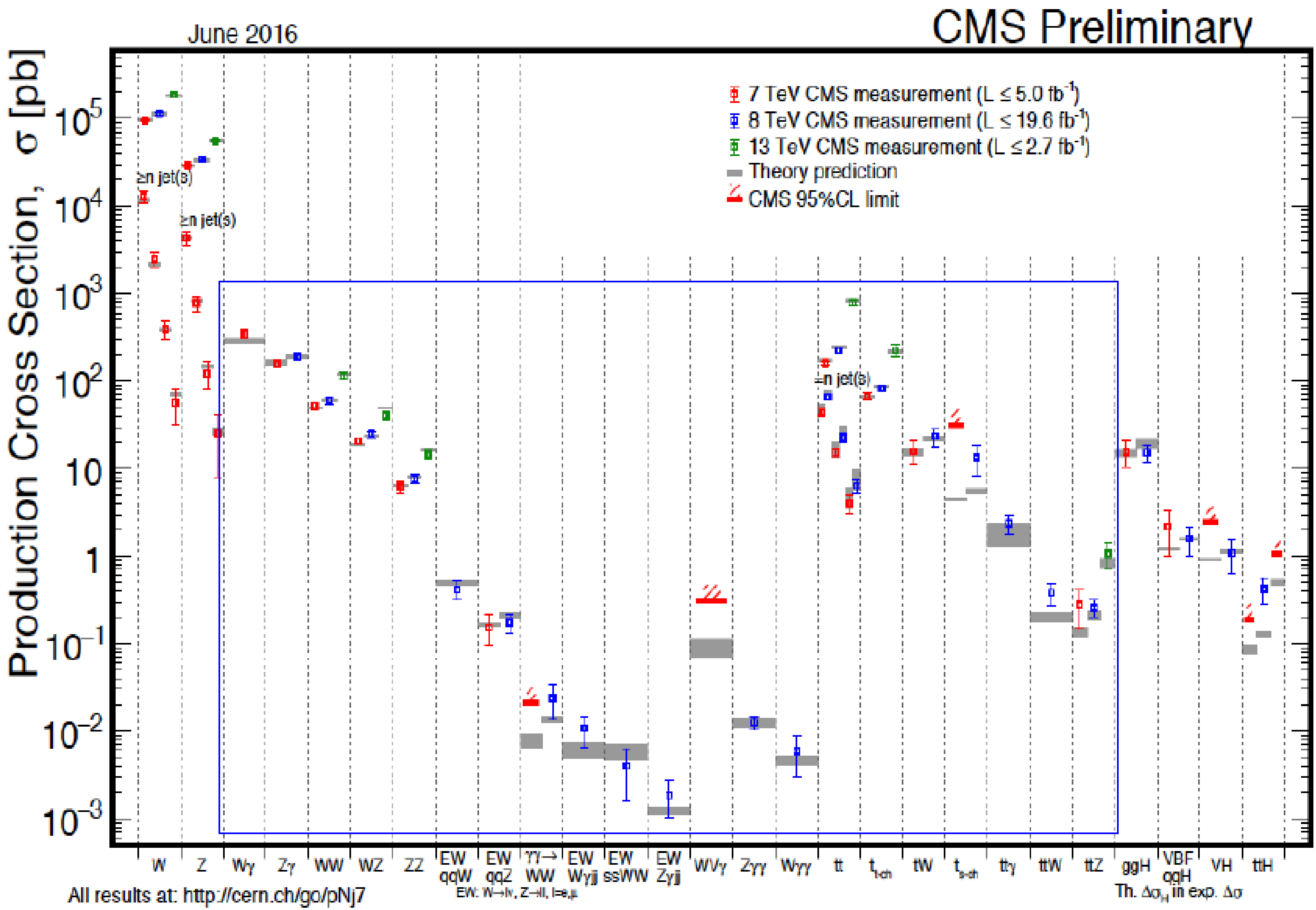
5.5 Electrical Charge of the Top Quark

- **Charge:**

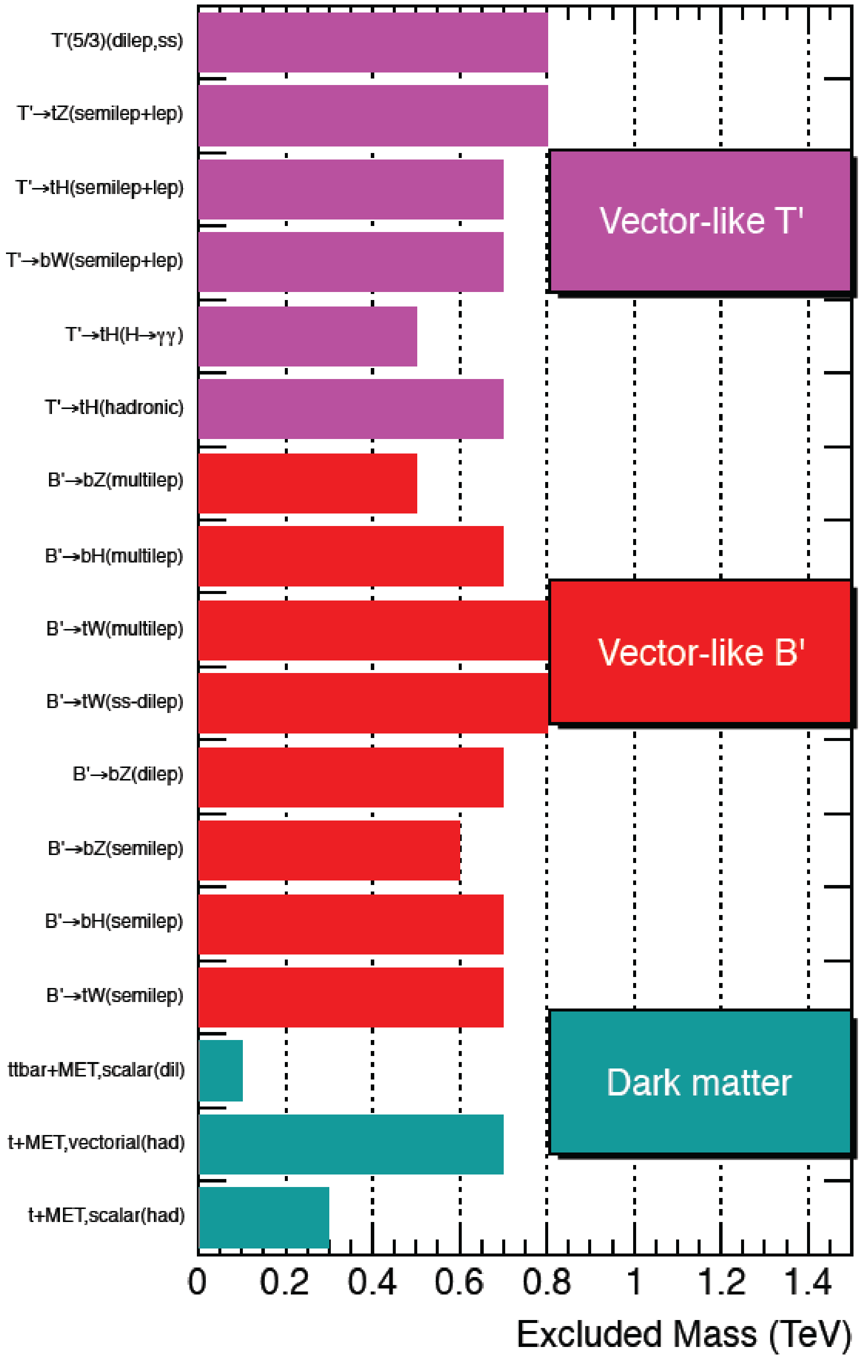
-Using 5.3 fb−1, D0 excludes top quark charge of
Q = −4/3e at > 5 σ level
- Upper limit of 0.46 on the fraction of such quarks in an admixture with SM top quark (Q = +2/3 e) @ 95% C.L.

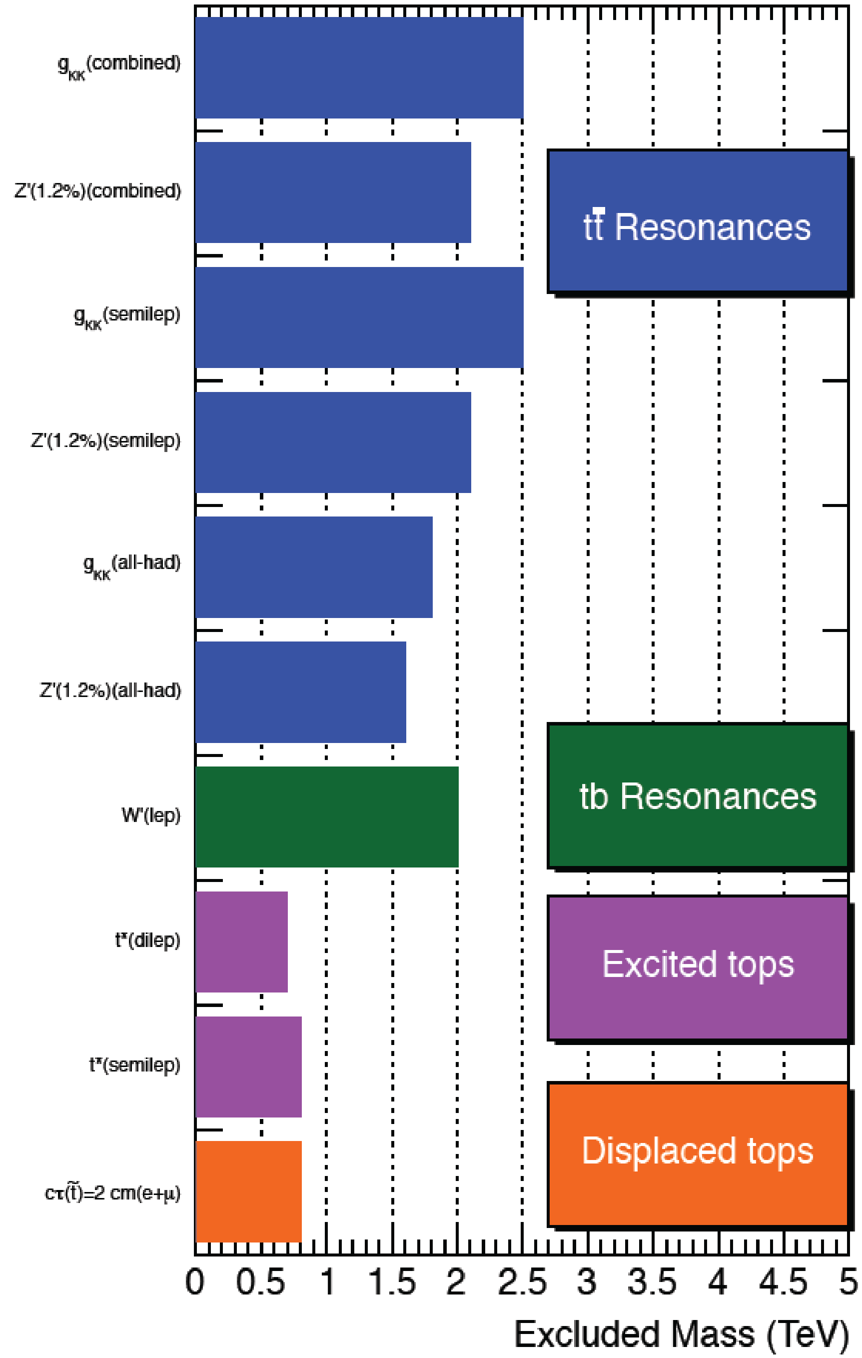


5.6 Measurements of the Standard Model



Searches for New Physics Beyond 2 Generations



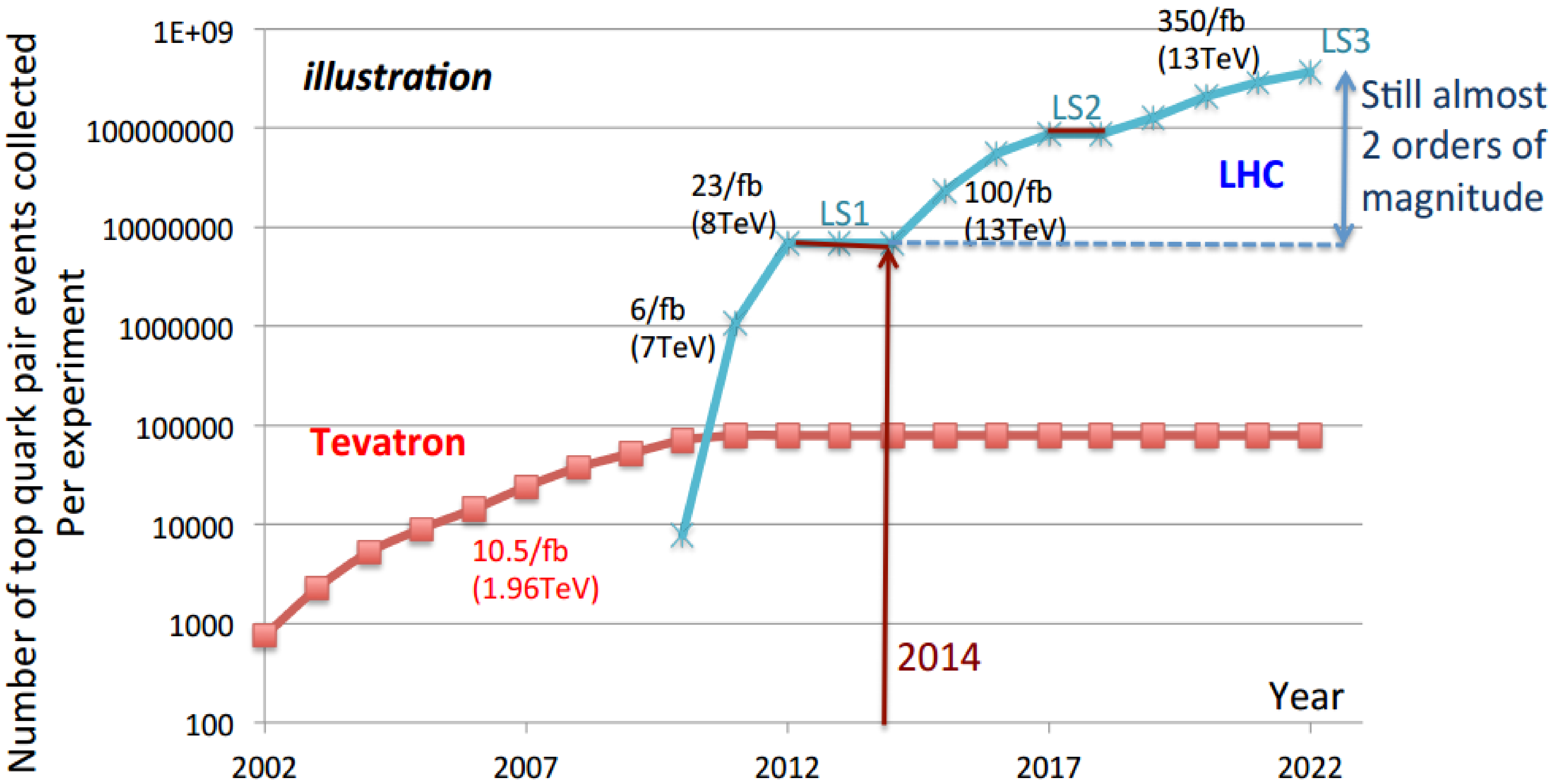


In all cases, the Standard Model holds firmly!

6. The Future

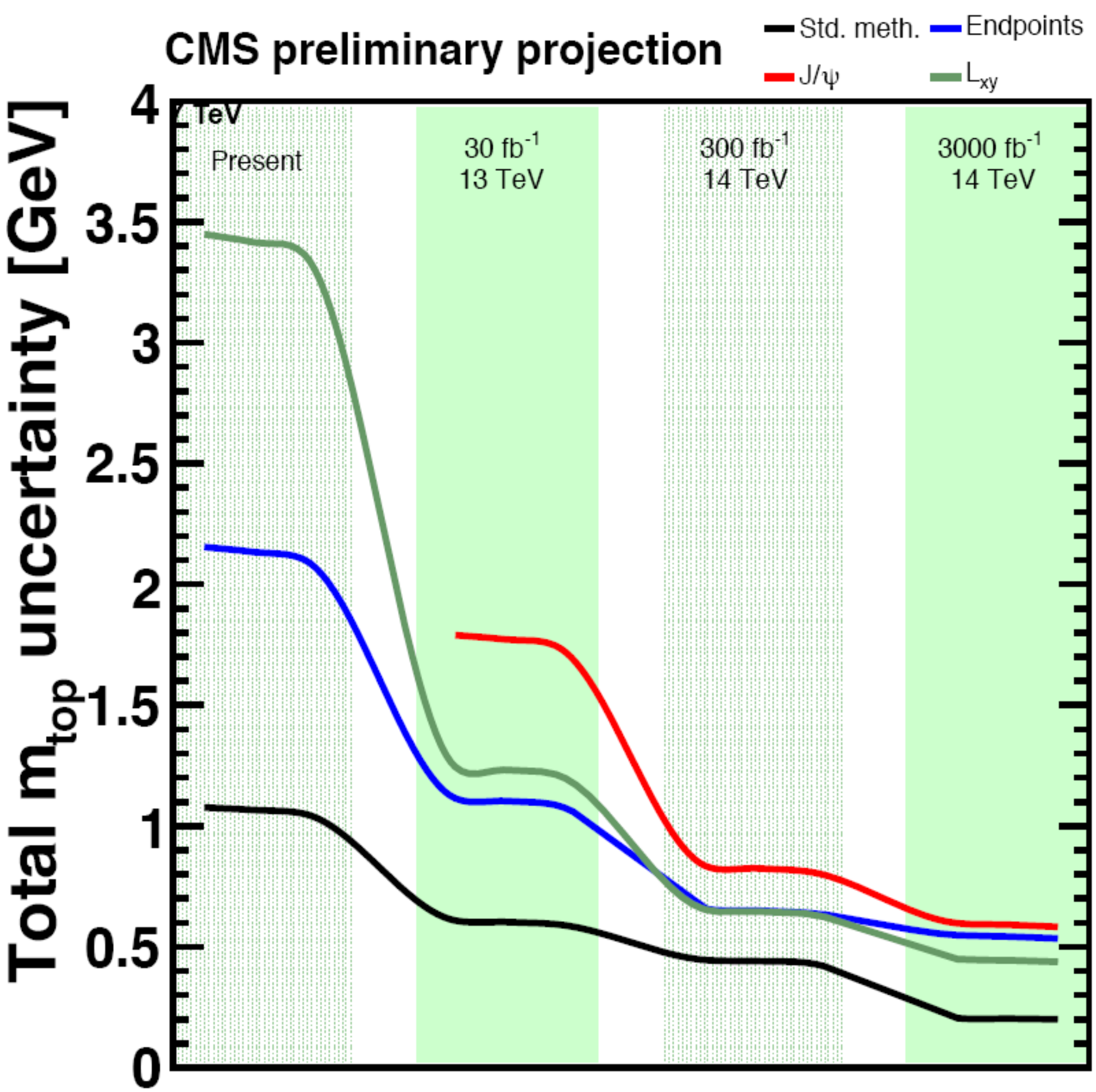
The Growth of the Number of Top-Antitop-Events

20 years for almost 6 orders of magnitude → the Top Quark era

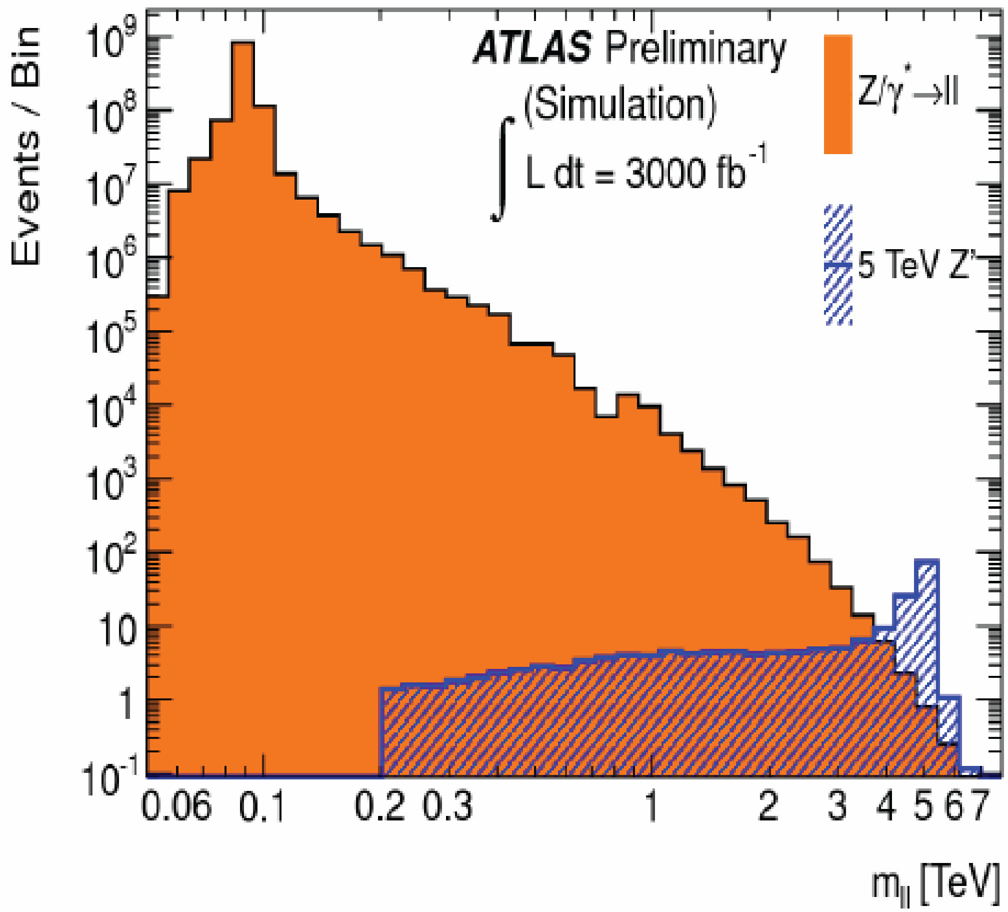


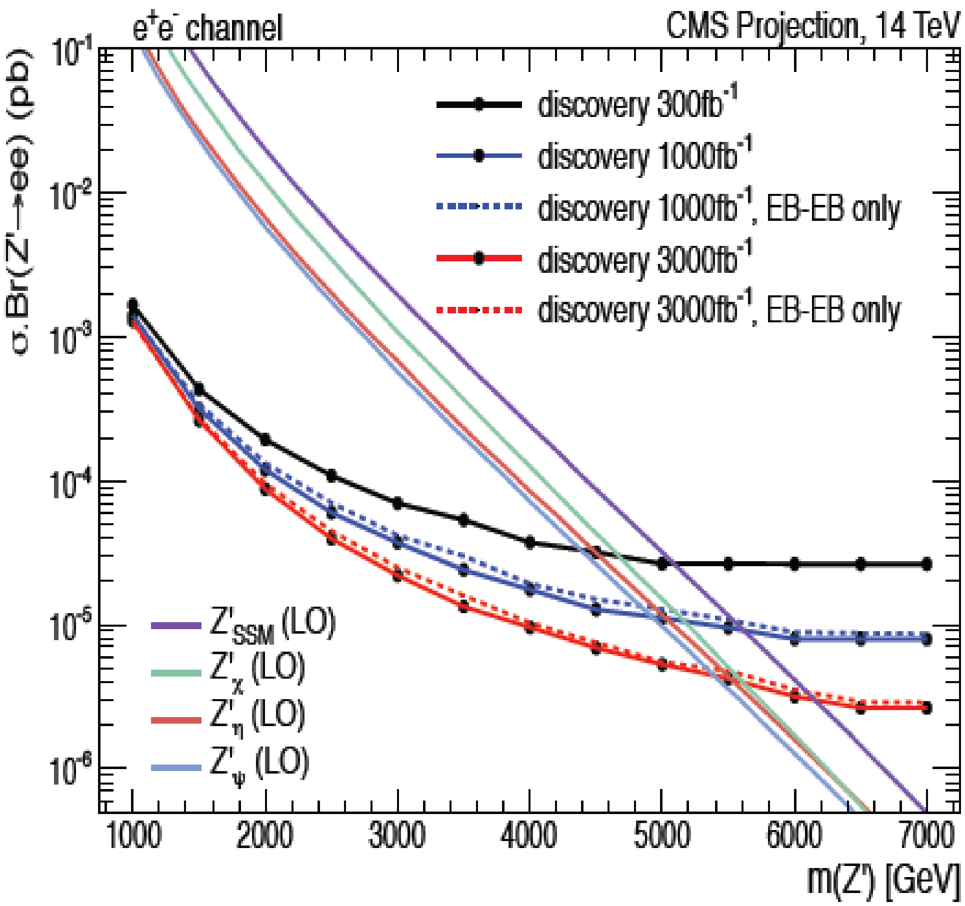
D'Hondt, Talk 2014

Perspectives for the Top Quark Mass

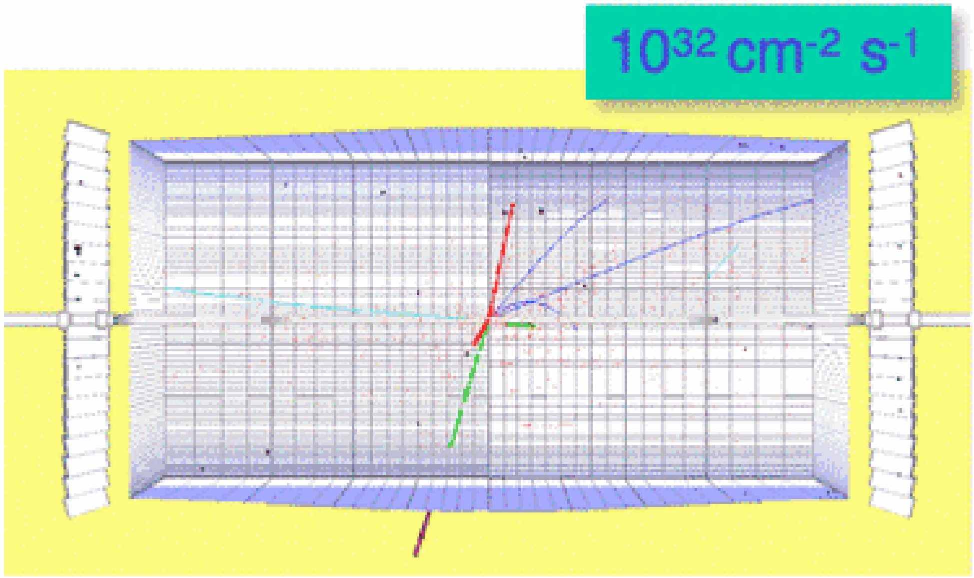


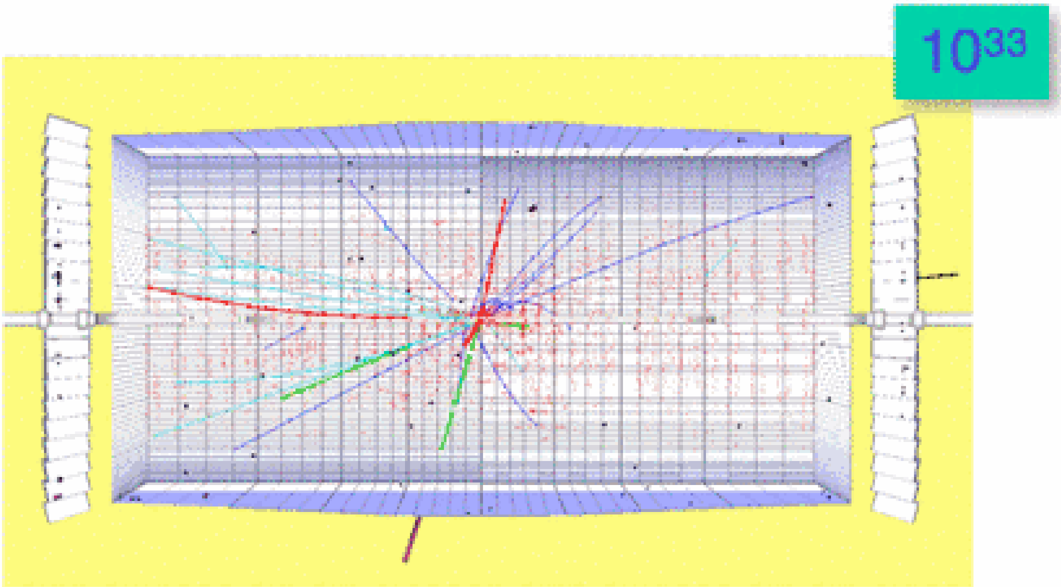
… and for new Bosons

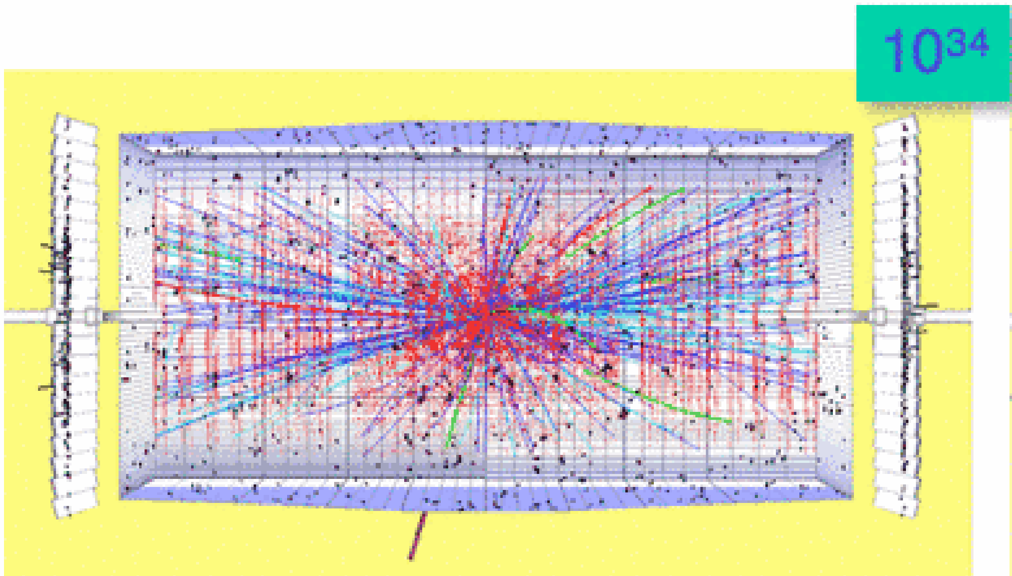


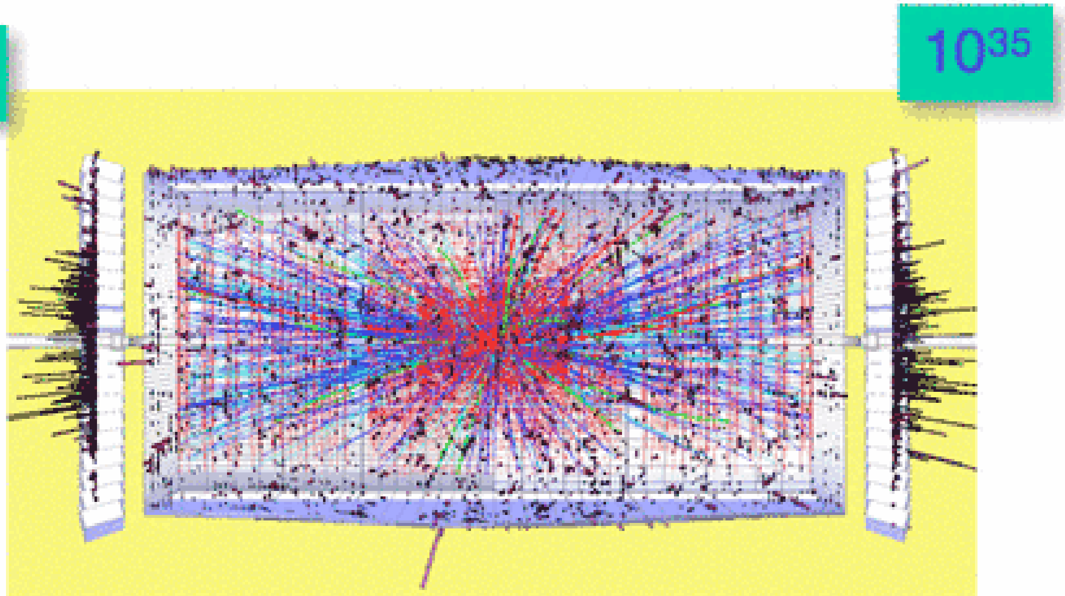


The Cost of High Luminosities: Pile-Up



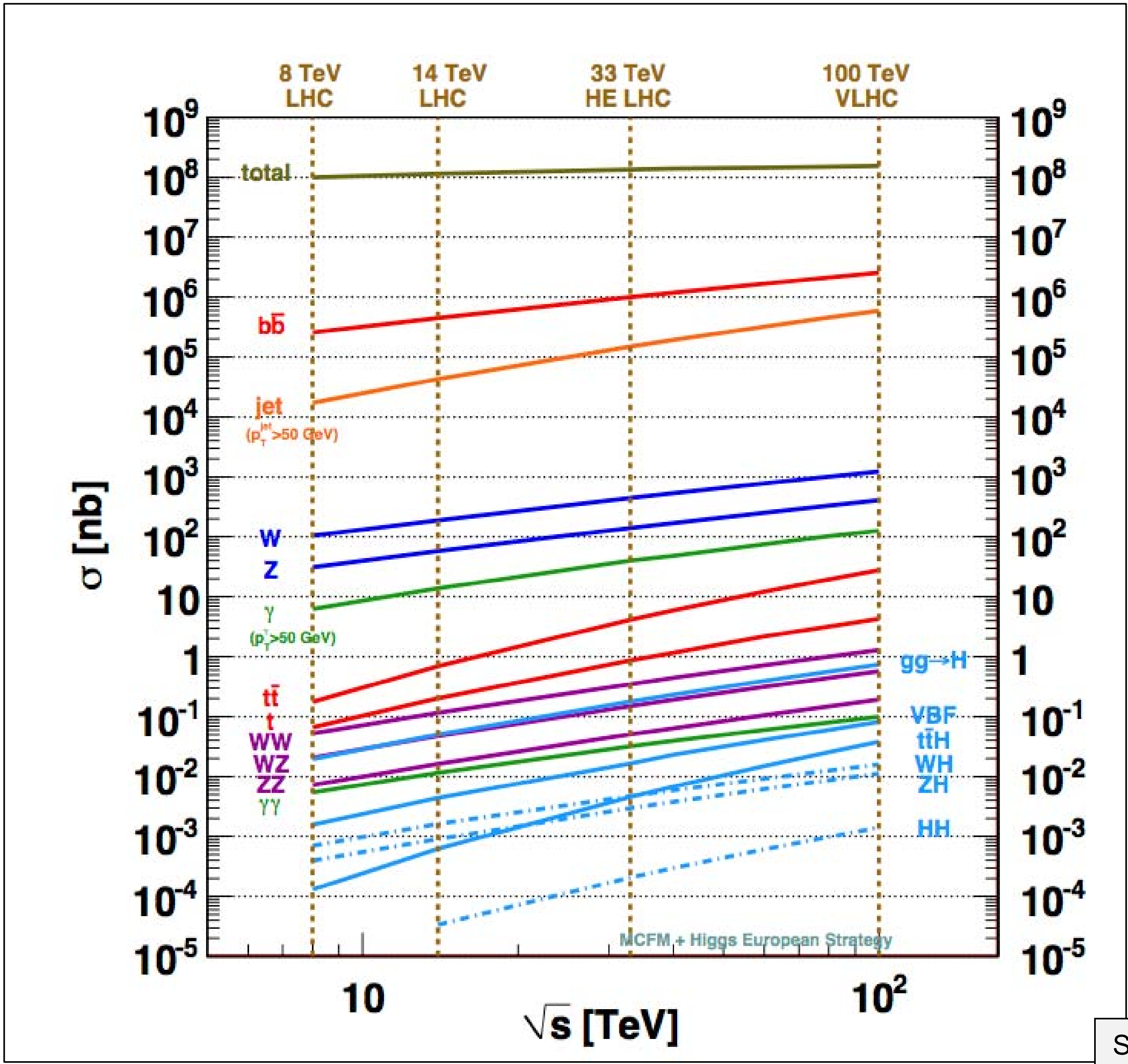






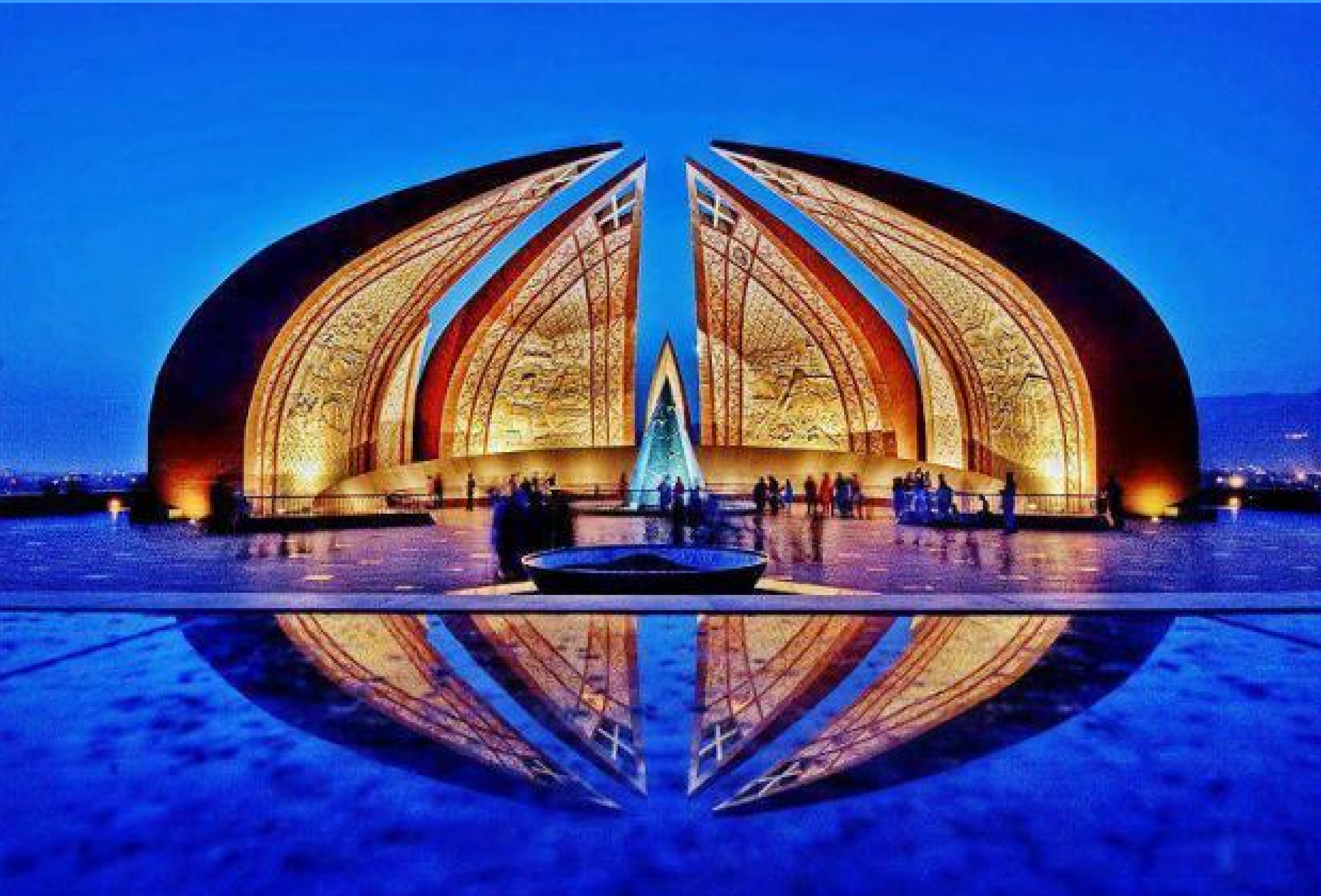
For this we need to rebuild the detector !

Our dreams for the Longterm Future



Snowmass report:
arXiv:1310.5189

CONCLUSIONS



Twentytwo years after first evidence, top quark physics is a fundamental column in particle physics.

The Tevatron has left a legacy in precision measurements, analysis methods and searches at the energy frontier.

The LHC has become a top factory and outperformed the Tevatron in most aspects.

Theory has been accompanying us in this exciting programme, being a match in terms of precision and paving the way in predicting new phenomena.

So far, agreement with SM predicitions is astounding.

But still: exciting times are awaiting us !

Supported by the State of Baden-Württemberg, HGF, the DFG and the BMBF