PHYSICS OF THE TOP QUARK

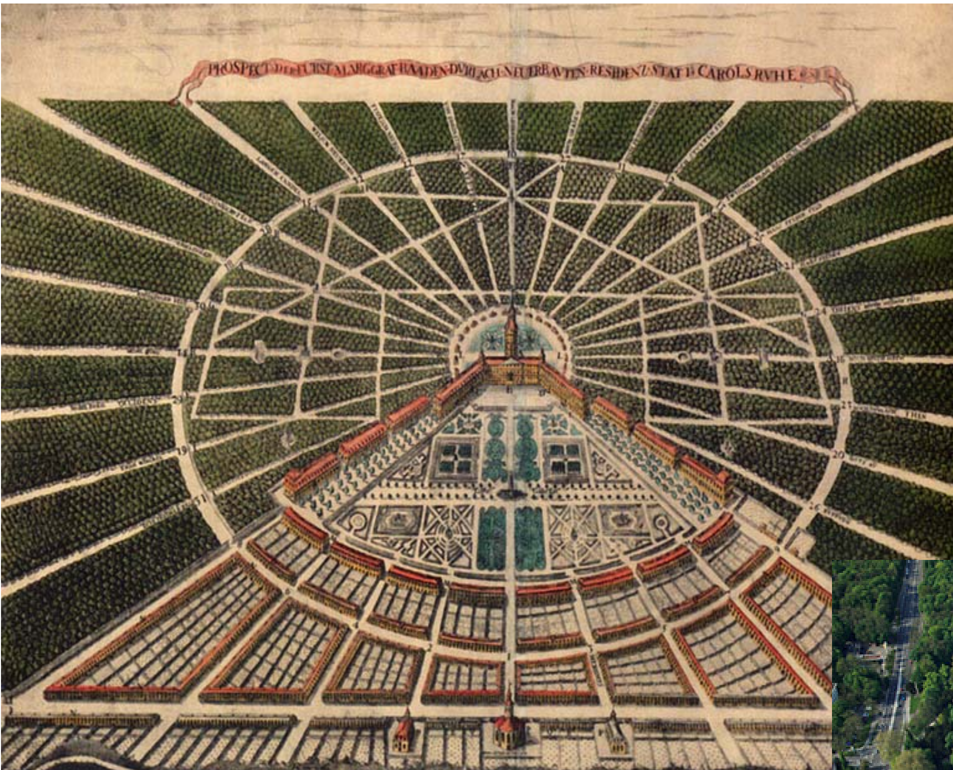
First Lecture

Most up-to-date results can be found in the talks of Top-2016, ICHEP 2016

Thomas Muller, Institut für Experimentelle Kernphysik, KIT

5th ICTP-NCP School on LHC Physics 2016

My Home: the City of Karlsruhe



Like Islamabad, Karlsruhe was newly designed and built as a capital (Kingdom of Baden) in 1715

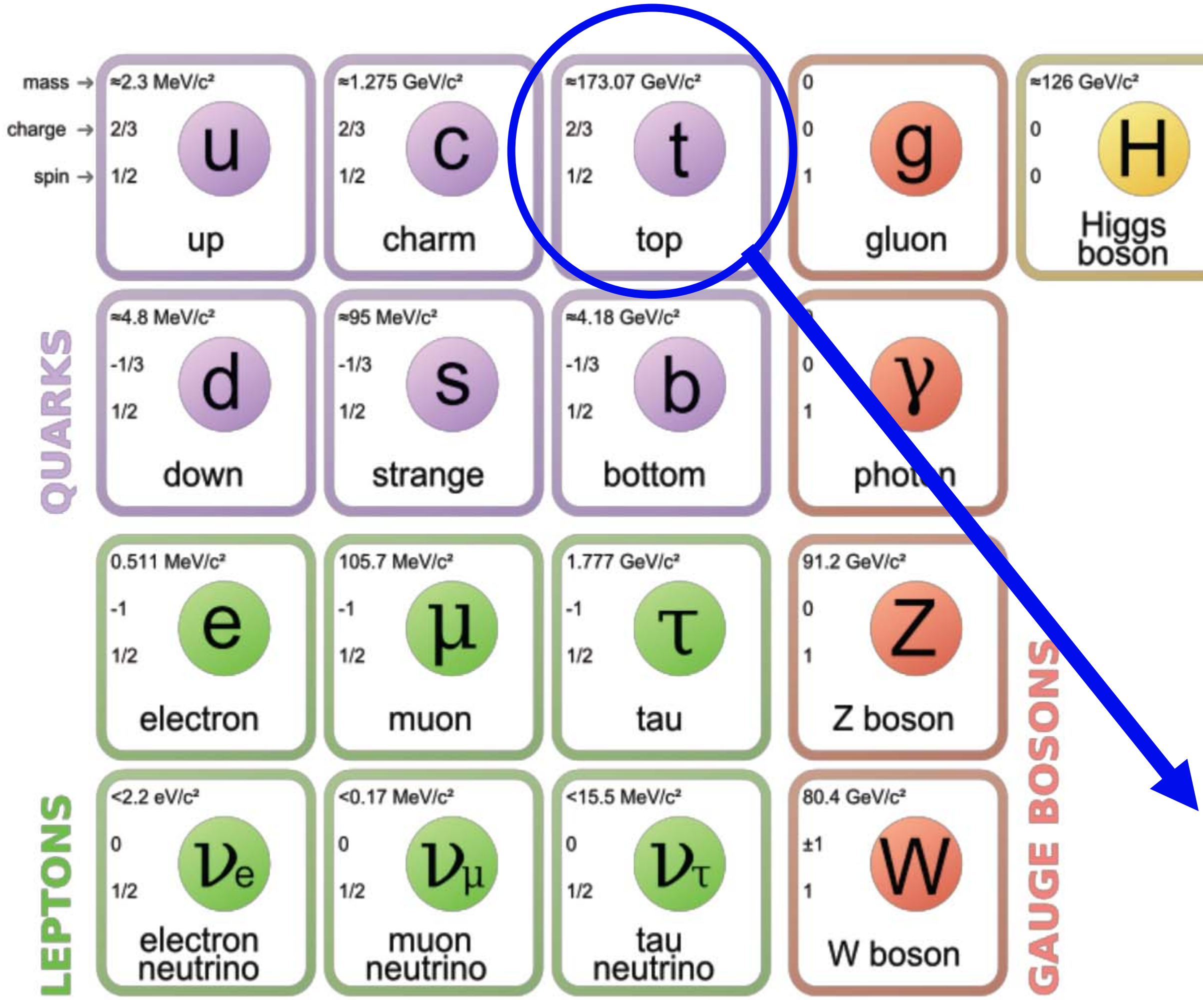
1. INTRODUCTION

Why is the Top Quark so Special?

- It decays before it hadronises: the only chance to inspect partons without having to deal with hadronisation: a great laboratory for perturbative QCD
- It has tight links to electroweak symmetry breaking: due to its large mass a dominant role in running of the Higgs boson mass: important for our understanding of the particle universe
- It is important as a signal or a part thereof (examples: we need to check its Yukawa coupling ttH, we need to check V_{tb} = 1)
- It is the dominant background for nearly every BSM search @ LHC

F. Krauss „Some thoughts on Tops“

1.1 The Building Blocks of the Standard Model



Properties:

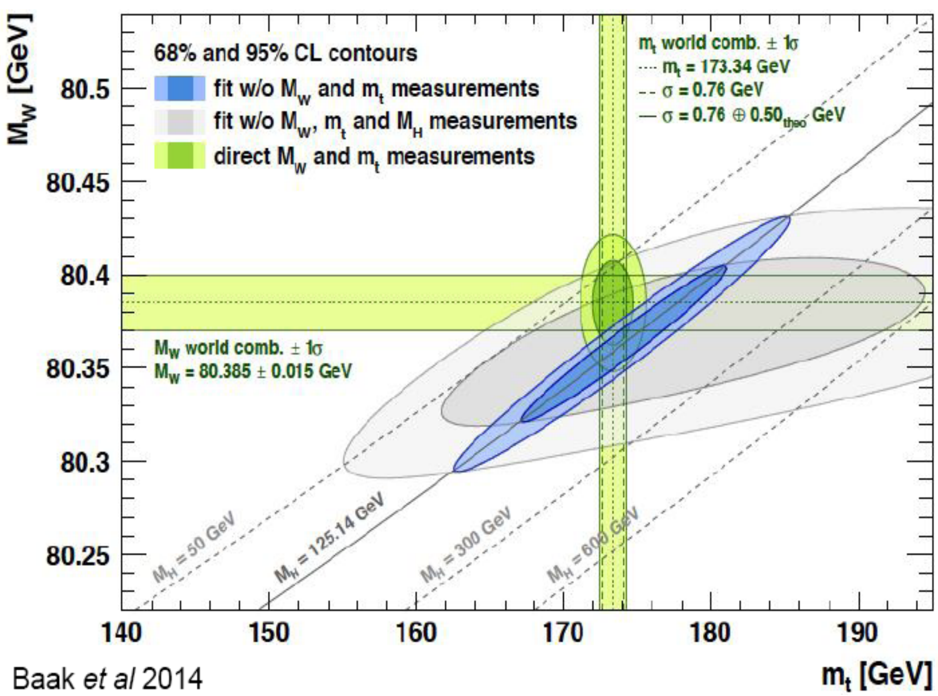
- Mass m ~170 GeV/c^2
- Lifetime τ ~ $4 \cdot 10^{-25}$ s
- Spin s = ½
- Isospin T_3 = +½
- Charge Q =+2/3 e

Role of the Top Quark in the SM

- Four top-quark related parameters:
  - CKM matrix elements
  - Yukawa coupling (top-quark mass)
- Large mass means large Yukawa (Higgs) coupling of roughly unity

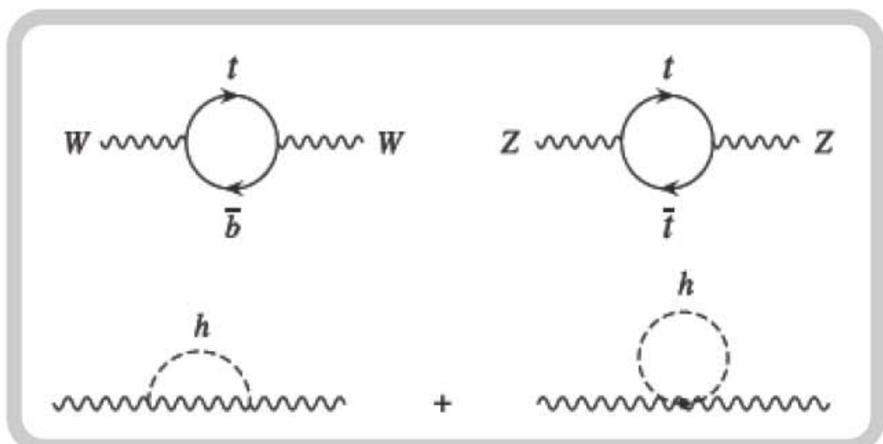
$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

$$L_{Yukawa}(\phi, \psi) = -g \bar{\psi} \phi \psi$$
$$g = \sqrt{2} m_{top} / v \approx 1$$



Baak *et al* 2014

- SM predicts connection between top quark, *W* and Higgs boson



Necessity of the Top

1973: Introduction of a three generation theory to explain CP Violations (Kobayashi, Maskawa)

1975: Identification of τ leptons in $e^+ e^-$ collisions (Perl / Mark I)

1977: Discovery of Y(1S) (bb) in proton-nucleon interactions (Ledermann)

$$\begin{pmatrix} u \\ d \end{pmatrix} \quad \begin{pmatrix} c \\ s \end{pmatrix} \quad \begin{pmatrix} \\ b \end{pmatrix}$$

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix} \quad \begin{pmatrix} \\ \tau \end{pmatrix}$$

Isosinglett **or** sodublett ?

DESY 1984

Measurement of the forward-backward asymmetry in $e^+e^- \rightarrow b\bar{b}$ (JADE):

$$A_{FB} = (-22.8 \pm 6.5)\%$$

SM Dublett: $A_{FB} = -25.2\%$

Singlett: $A_{FB} = 0$

There must be an iso-partner of the b.
What are its properties?

1.2 Early Predictions for the Top Mass

1979 G. Preparata, Phys. Lett. 82B, 398

$m_c \approx 4\ m_s \quad \Rightarrow \quad m_t \approx 4\ m_b\ ? \quad \Rightarrow \quad m_t \approx 21$ GeV

1980 S. Glashow (Nobelpreis 1979), Phys. Rev. Lett. 45, 1914

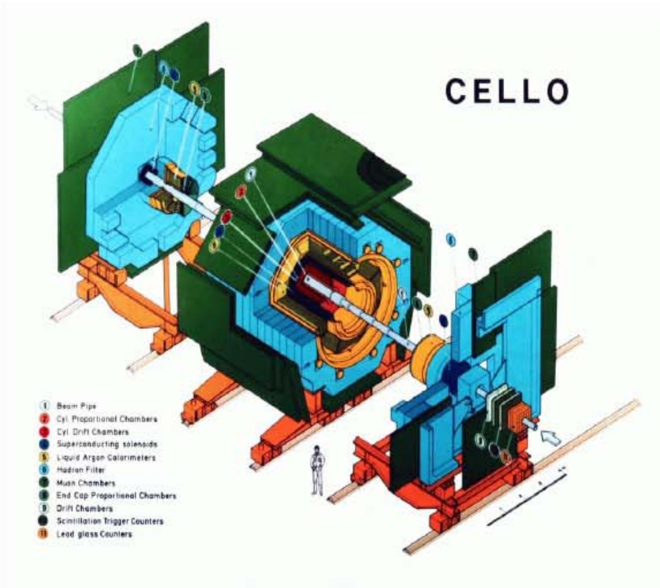
m (Toponium) $\approx (38 \pm 2)$ GeV

1981 A. Buras, Phys. Rev. Lett. 46, 1354

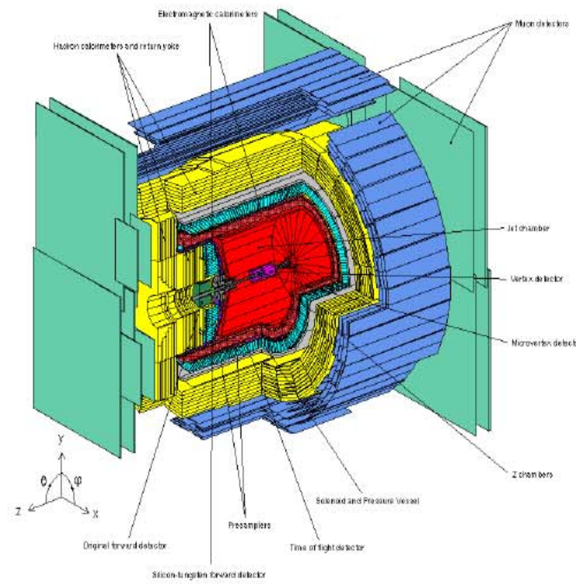
$\Delta M = m(K_L) - m(K_S)$ und Zerfallsrate Γ von $K_L \rightarrow \mu^+ \mu^-$

$\Rightarrow \quad m_t < 47$ GeV

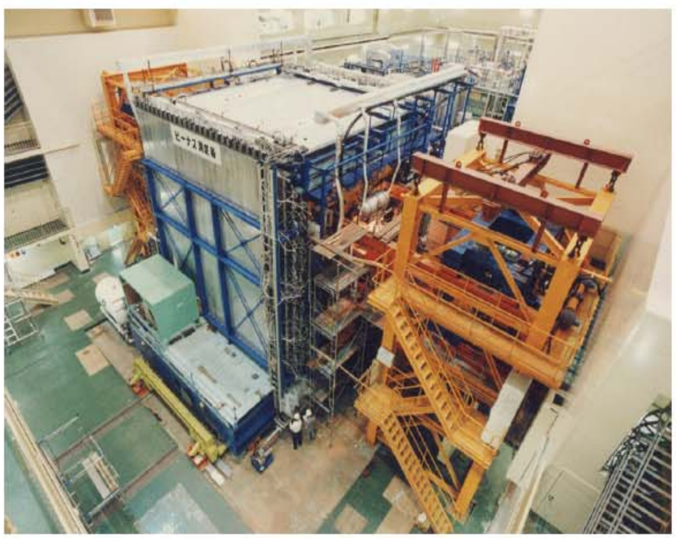
1.3 Direct Searches in the '80-s



CELLO (e^+e^- PETRA, DESY)
m_{top}>23.3 GeV (95% CL)
[Phys. Lett. B **144** (1984) 297]



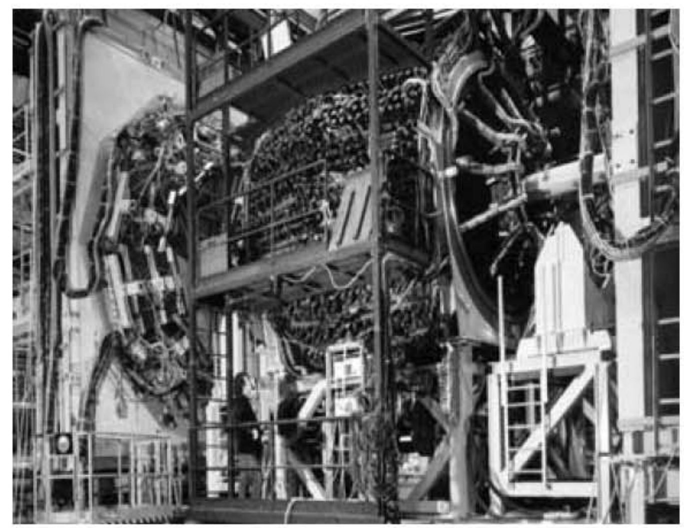
VENUS (e^+e^- TRISTAN, KEK)
m_{top}>30.2 GeV (95% CL)
[Phys. Lett. B **234** (1990) 382]



OPAL (e^+e^- LEP, CERN)
m_{top}>44.5 (95% CL)
[Phys.Lett. B **236** (1990) 364]

UA2 (ppbar SppS, CERN)
m_{top}>69 GeV (95% CL)

[Z. Phys. C **46** (1990) 179]



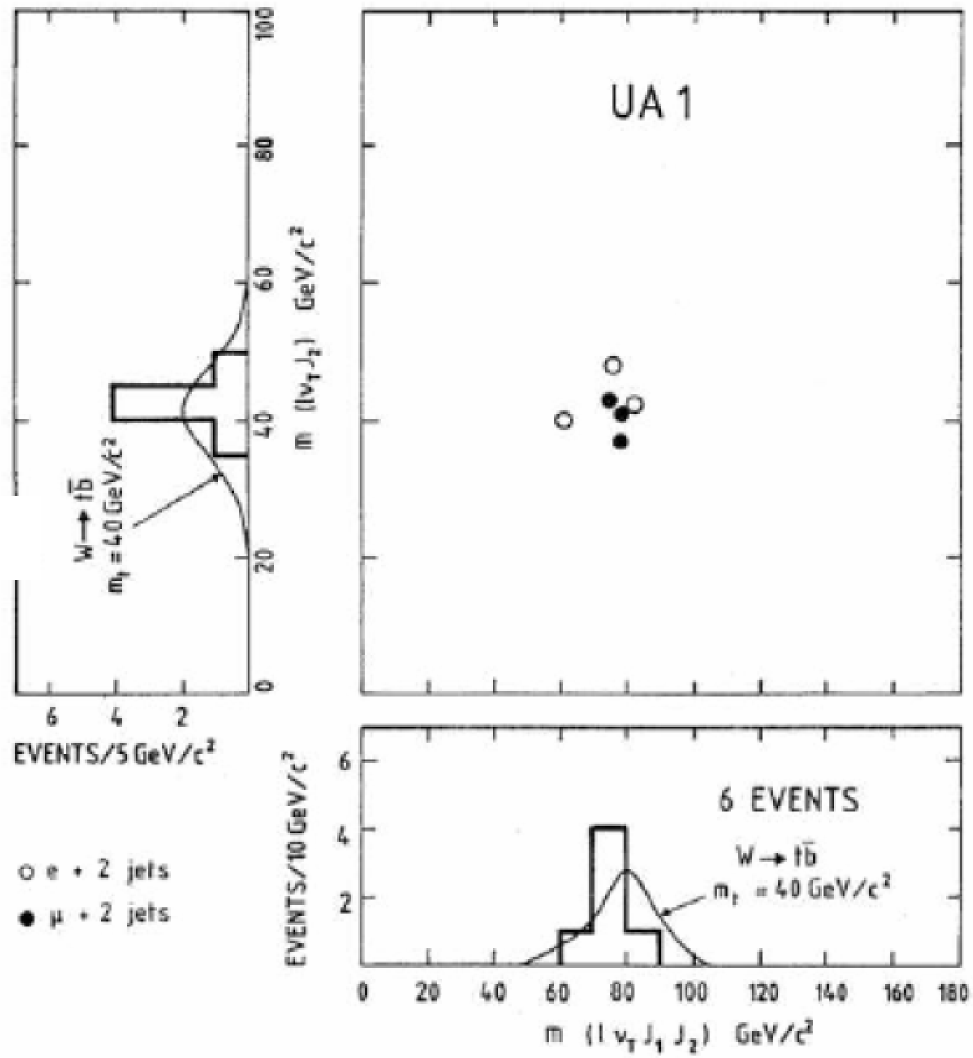
UA 1 am CERN $\mathrm{Sp\bar{p}S}$

1984

Search for electroweak production:

$$p\bar{p} \rightarrow W \rightarrow t\bar{b} \rightarrow \ell\nu b\bar{b}$$

$M_{\ell\nu j}$ and $\ell\nu jj$ distributions consistent with $M_{top} = (40 \pm 10)$ GeV



1986

Background better understood:

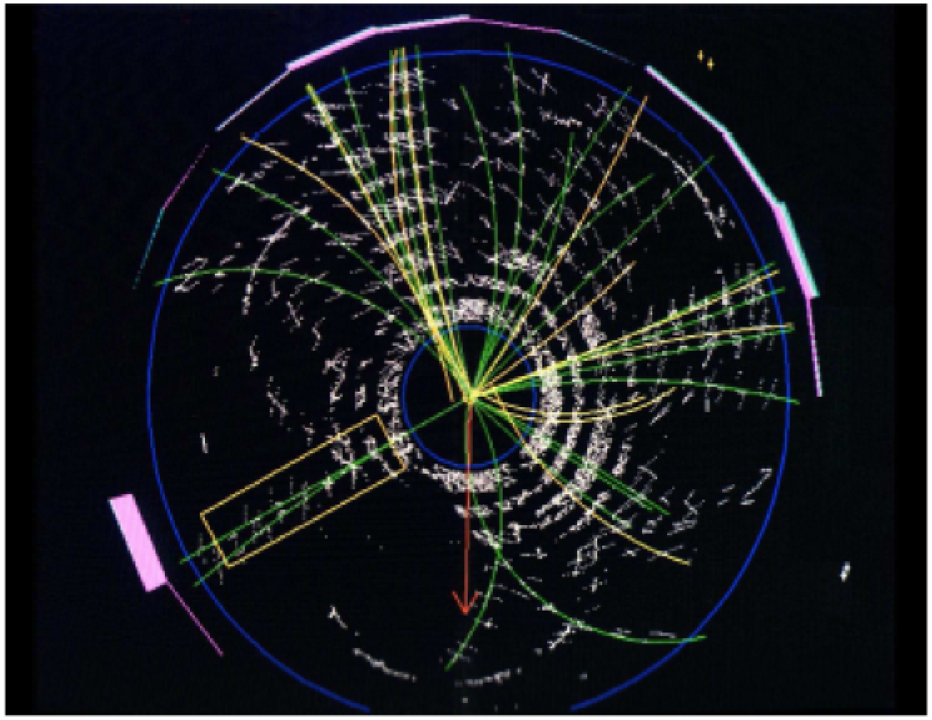
$M_{top} > 60$ GeV

First Evidence and Discovery

CDF Run 0 (1988 – 1989):

$M_{top} > 91$ GeV

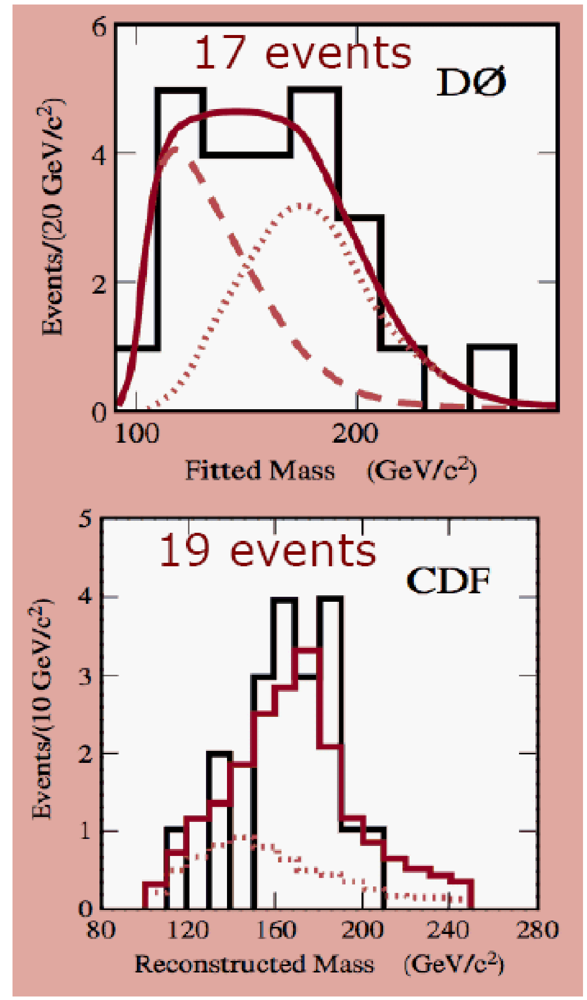
Run 1: 1994



CDF $t\bar{t}$ candidate 24.09.1992

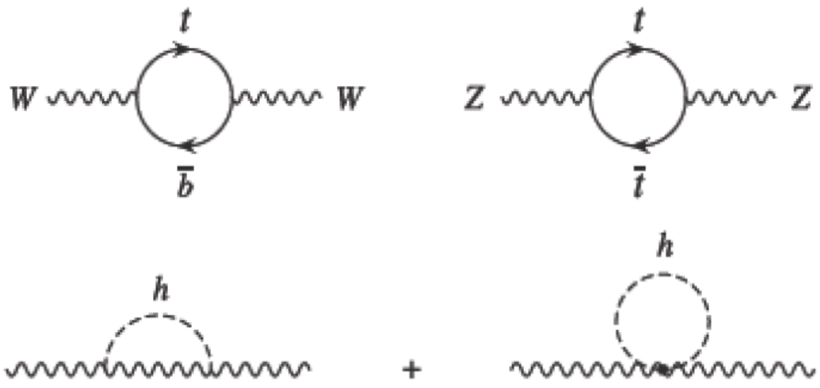
Announcement at Fermilab 1995

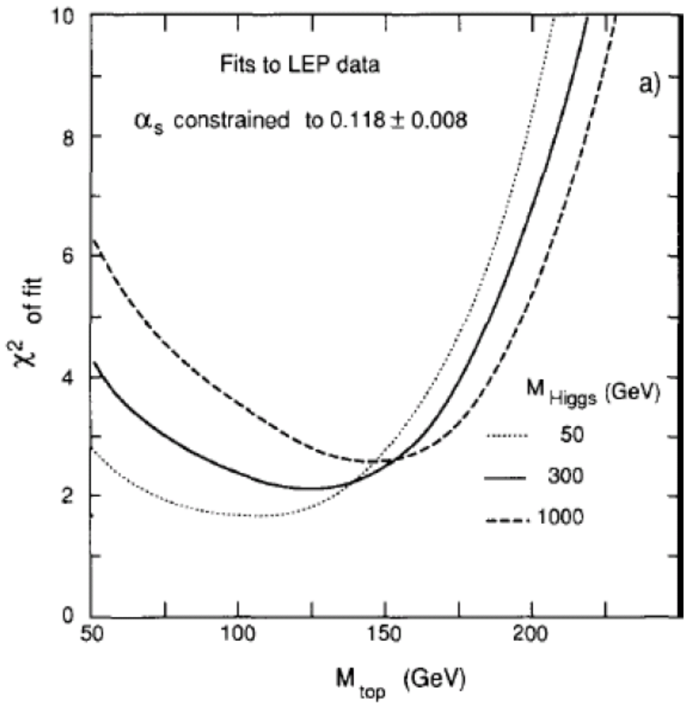
- February 24th 1995: Simultaneous submission of Top Discovery papers to PRL, by CDF and DØ
- 50 pb^{-1} at DØ
  - m_t = 199±30 GeV
  - $\sigma_{t\bar{t}}$ = 6.4±2.2 pb
  - Background-only hypothesis rejected at 4.6σ
- 67 pb^{-1} at CDF
  - m_t = 176±13 GeV
  - $\sigma_{t\bar{t}} = 6.8^{+3.6}_{-2.4}$ pb
  - Background-only hypothesis rejected at 4.8σ



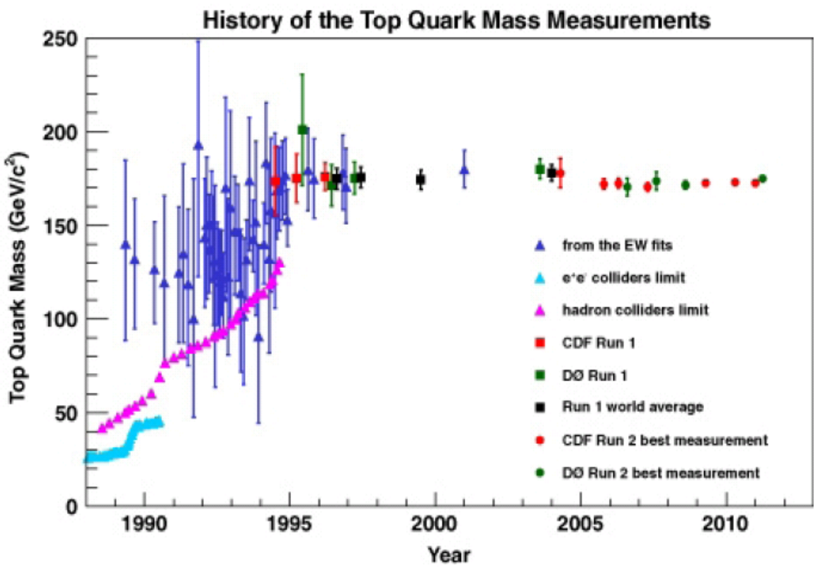
1.4 Predictions using EWk Fits

- Top quark, W boson and Higgs boson masses connected via loop corrections
- Fit of electroweak observables constrains top-quark mass



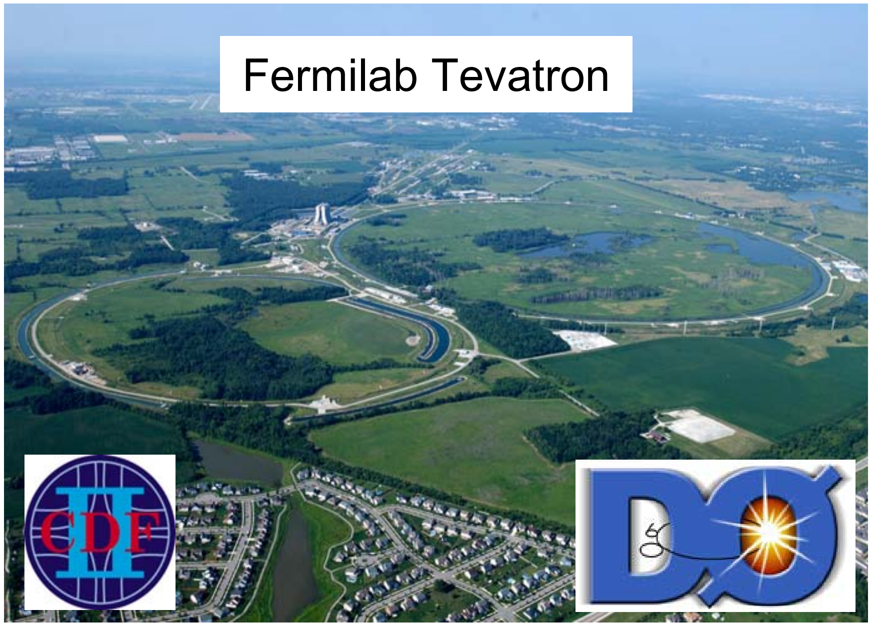


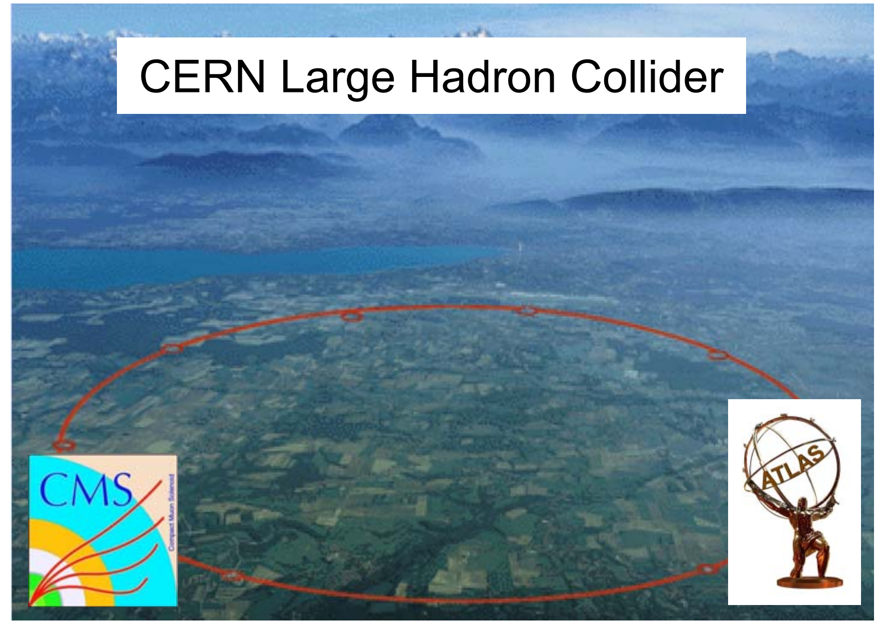
[Phys. Lett. B **276** (1992) 247]



[Ann. Rev. Nucl. Part. Sci. **59** (2009) 505]

1.5 The Sources of Top-Quarks





Tevatron:

- Run 1: $\sqrt{s}$ = 1.8 TeV (1992-1996):
  - Top quark discovery in 1995 with
  - 65pb^{-1} recorded (around 20 events each experiment)
- Run 2: $\sqrt{s}$ = 1.96 TeV (2001-2011):
  - 12 fb^{-1} delivered, on tape 10 fb^{-1}
  - Analyses mostly completed

LHC:

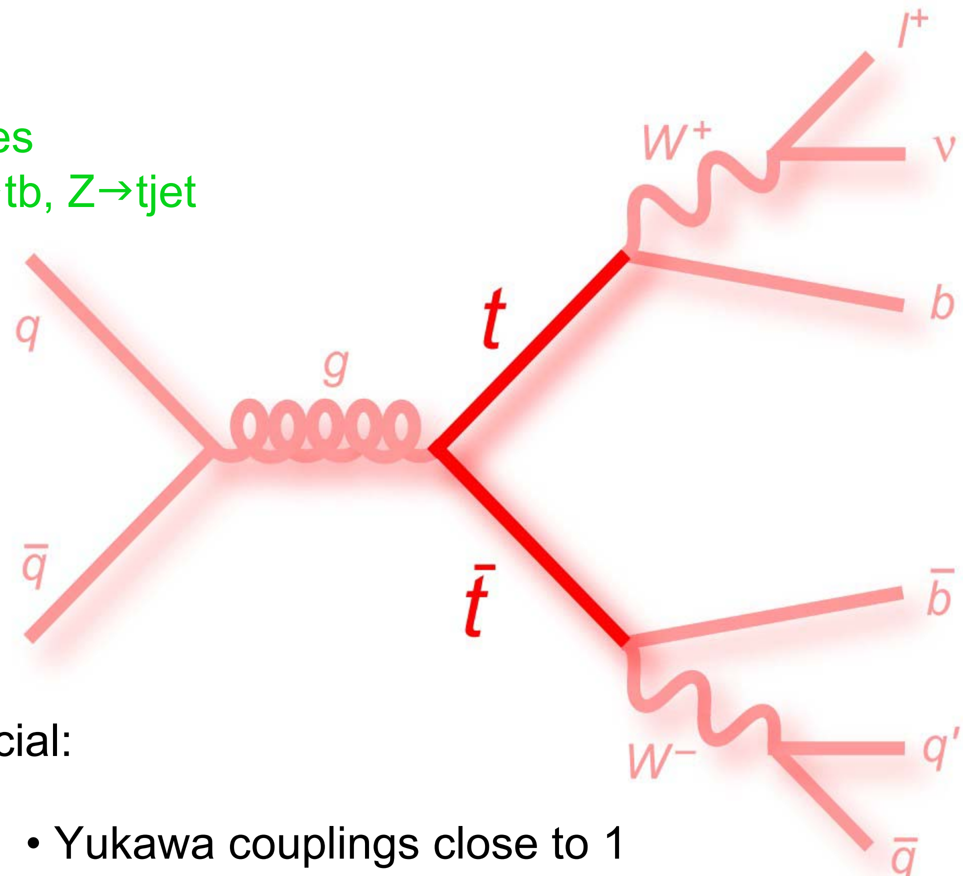
- $\sqrt{s}$ = 7 TeV (2010-2011):
  - 5.7 fb^{-1} delivered, on tape 5 fb^{-1}
  - Around 1M $t\bar{t}$ pairs produced per exp. (60k reconstructed $t\bar{t}$ events)
- $\sqrt{s}$ = 8 TeV (2012):
  - Around 5M $t\bar{t}$ pairs produced in 20 fb^{-1}
  - Analysis in its final stage
- $\sqrt{s}$ = 13 TeV (2016):
  - Around 10M $t\bar{t}$ pairs produced so far
  - Up to 3 fb^{-1} of data analyzed

1.6 Physics all around the Top

TOP PRODUCTION
- Cross sections
- Top polarisation
- Spin-correlations
- Production asymmetries
- Resonances X→tt, Y→tb, Z→tjet
- Fourth generation t'

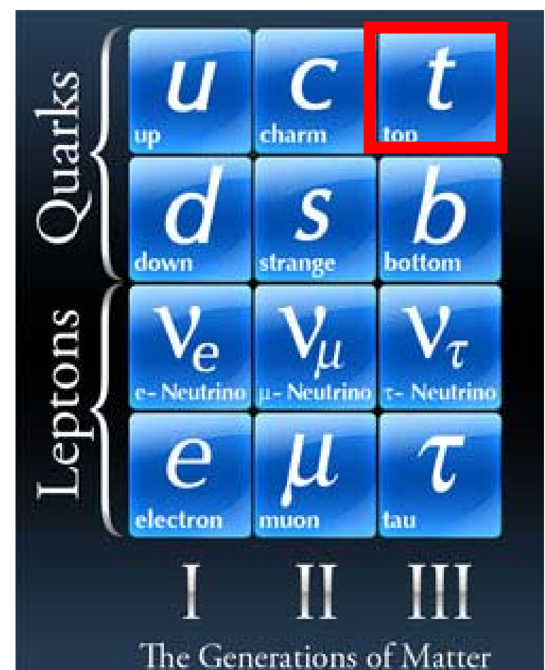
THE PARTICLE
- Mass (matter vs. anti-matter)
- Life-time / width
- Charge
- Radiation of Bosons

TOP DECAY
- Charged Higgs
- W helicity
- Anomalous couplings
- CKM matrix elements



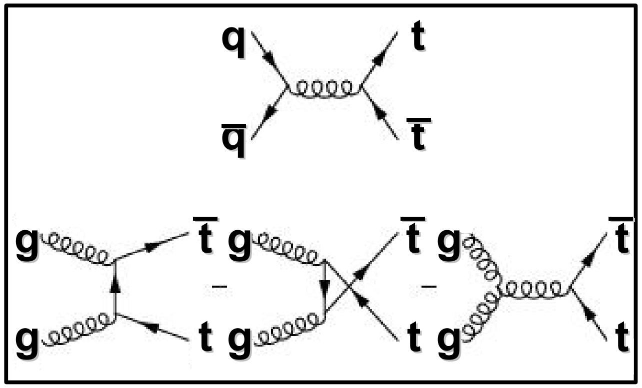
The top quark is very special:

- Yukawa couplings close to 1
- Most massive particle known
- The only „free“ quark
- Appears as signal, background and maybe decay product of new states

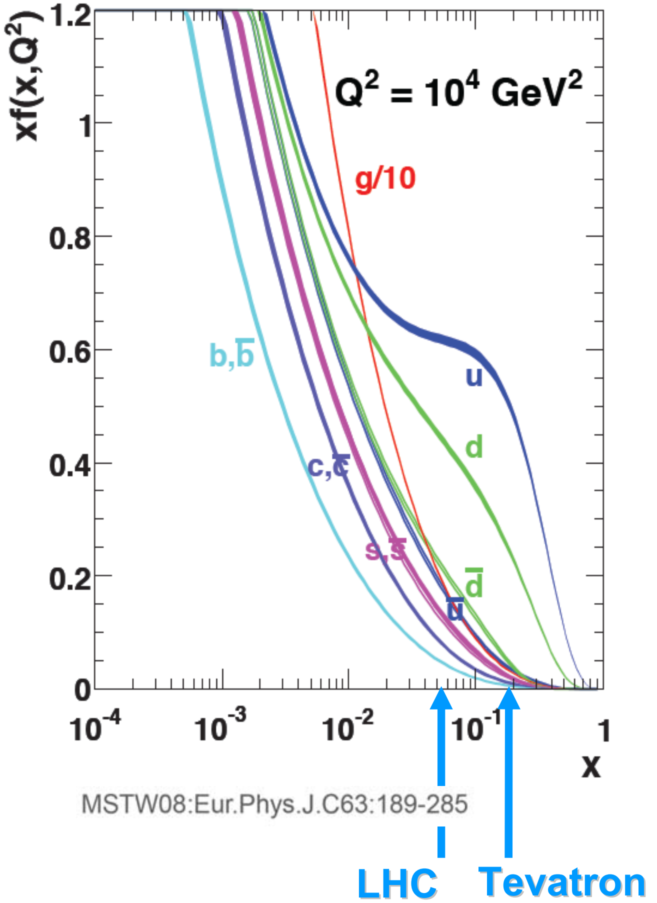


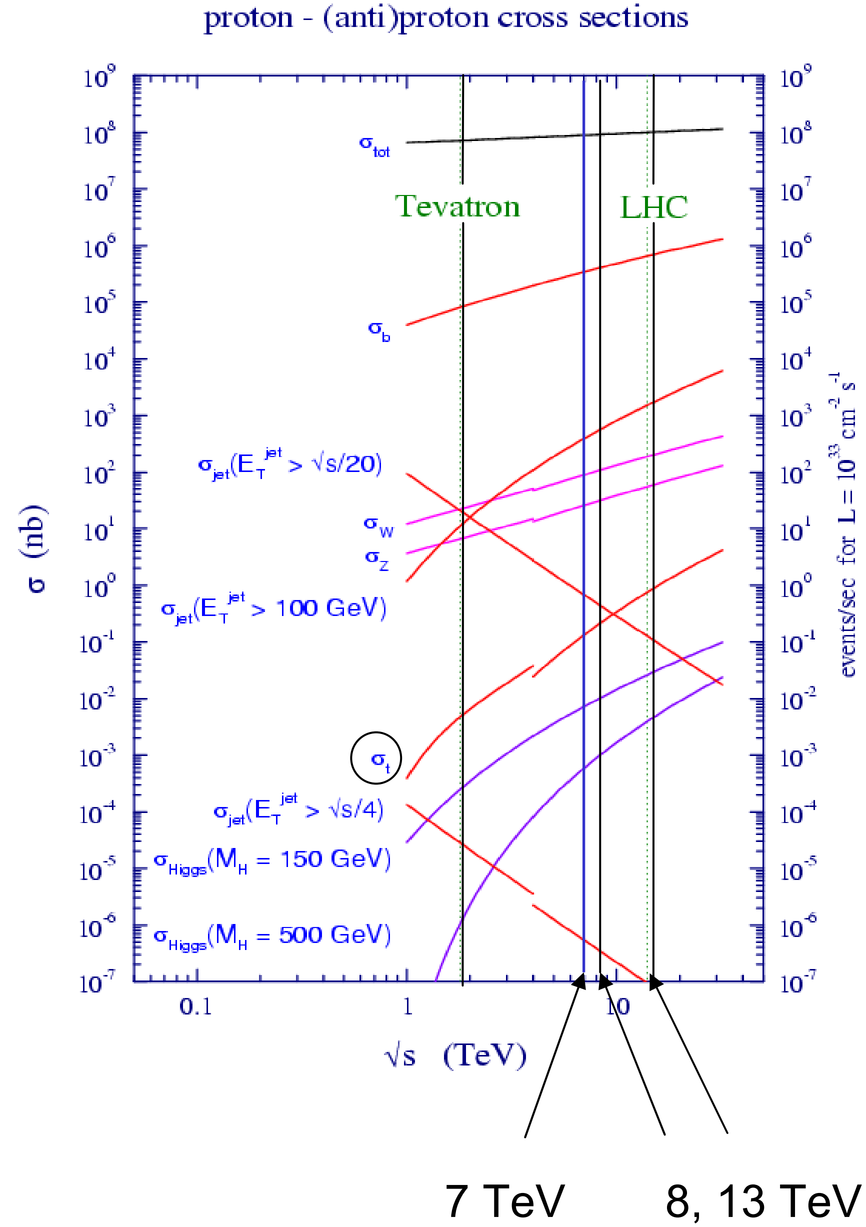
2. PAIR PRODUCTION OF TOP QUARKS

Processes for Pair Production

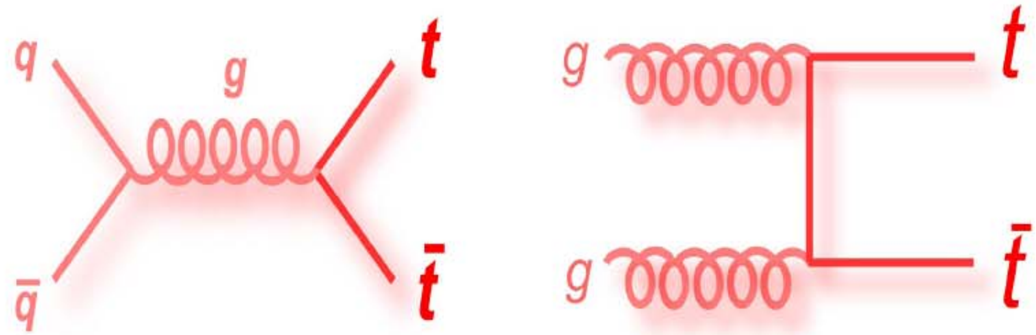


	TEV	LHC
←	~85%	~15%
←	~15%	~85%



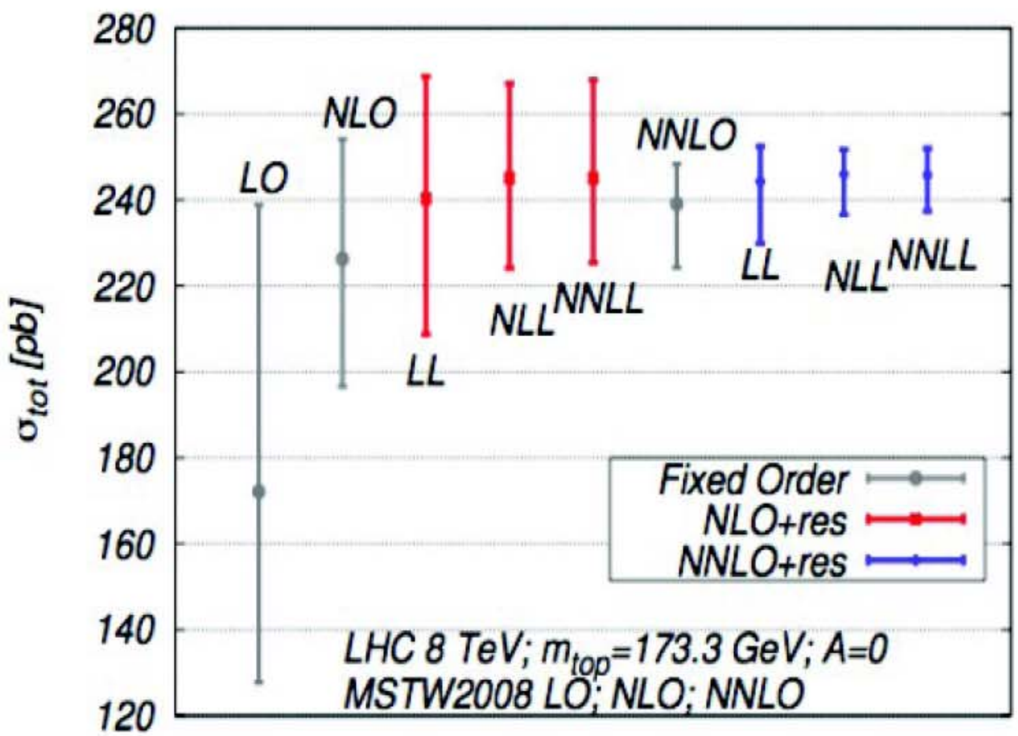


Example diagrams:



	σ_{gg}/σ_{tot}
Tevatron	$\approx 15\%$
LHC 7 TeV	$\approx 85\%$
LHC 14 TeV	$\approx 90\%$

Long standing theoretical effort on fixed order QCD calculations
1989 NLO
1998 NLO+NLL
2008 NLO+NNLL
2013 NNLO+NNLL



Cross-Section rises by about 10%
from NLO to NNLO+NNLL QCD

Precision improves from ~12% to ~3% (scale)
~ 8% to 5% (PDF)

Uncertainty on parton density function dominate

Electroweak corrections also sizeable $\alpha_s^2 \sim \alpha_{ew}$

Figures and numbers from:

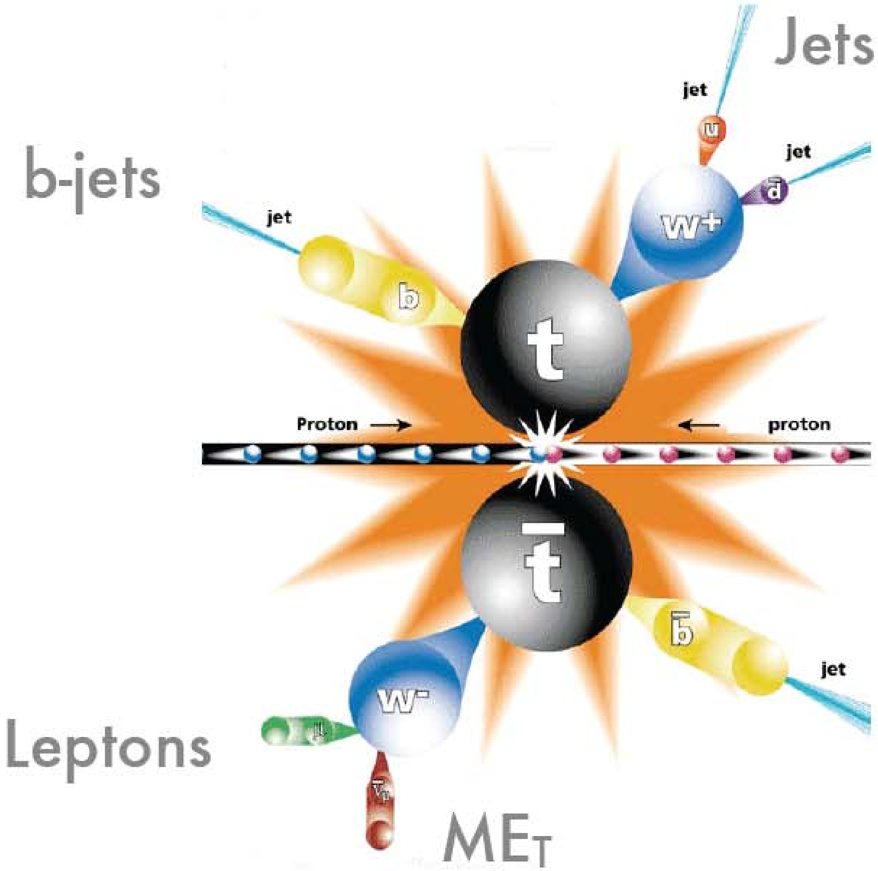
Czakon, Mitov arXiv:1303.6254

Czakon, Mangano, Mitov, Rojo: arXiv:1303.7215

NNLO QCD calculation mandatory for precision analysis

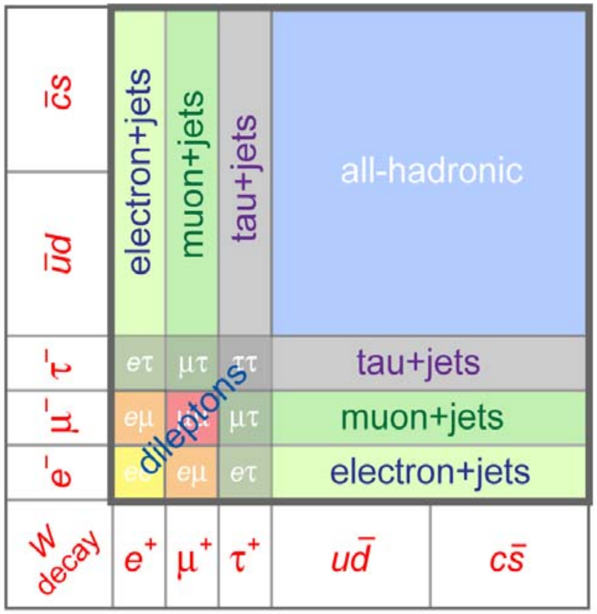
2.1 How to identify Top Quarks

- To find and reconstruct top quarks, a fully operational and hermetic General Purpose Detector is needed
- This is why top quarks were used to confirm and check calibrations and detector performance at the start of the LHC runs at 7 and 8 TeV

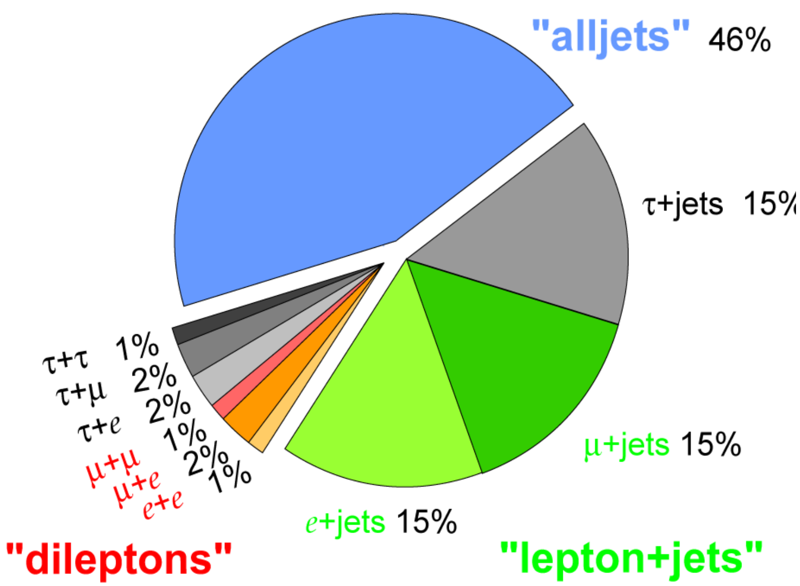


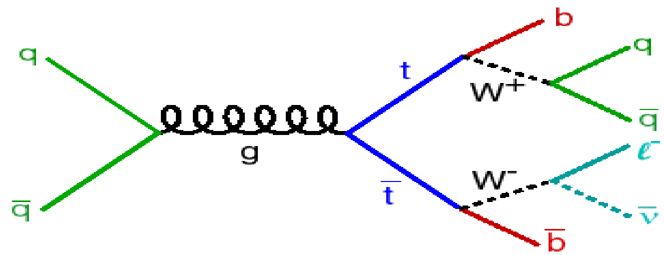
Decay Channels

Top Pair Decay Channels

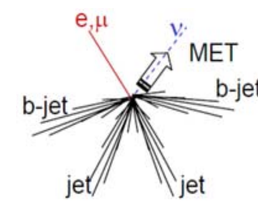


Top Pair Branching Fractions

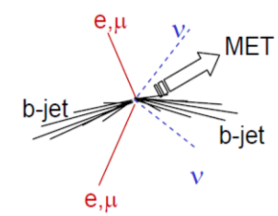




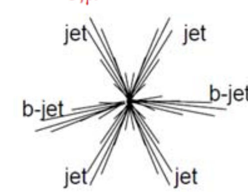
- **$t \to Wb$**
  Events classified by W decay
  - "Lepton [e,μ] + jets" (34%)
    $tt \to bl\nu bqq'$



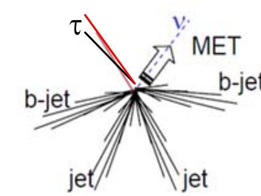
  - "Dilepton [e,μ]" (6%)
    $tt \to bl\nu bl\nu$



  - "All jets" (46%)
    $tt \to bqq'bqq'$



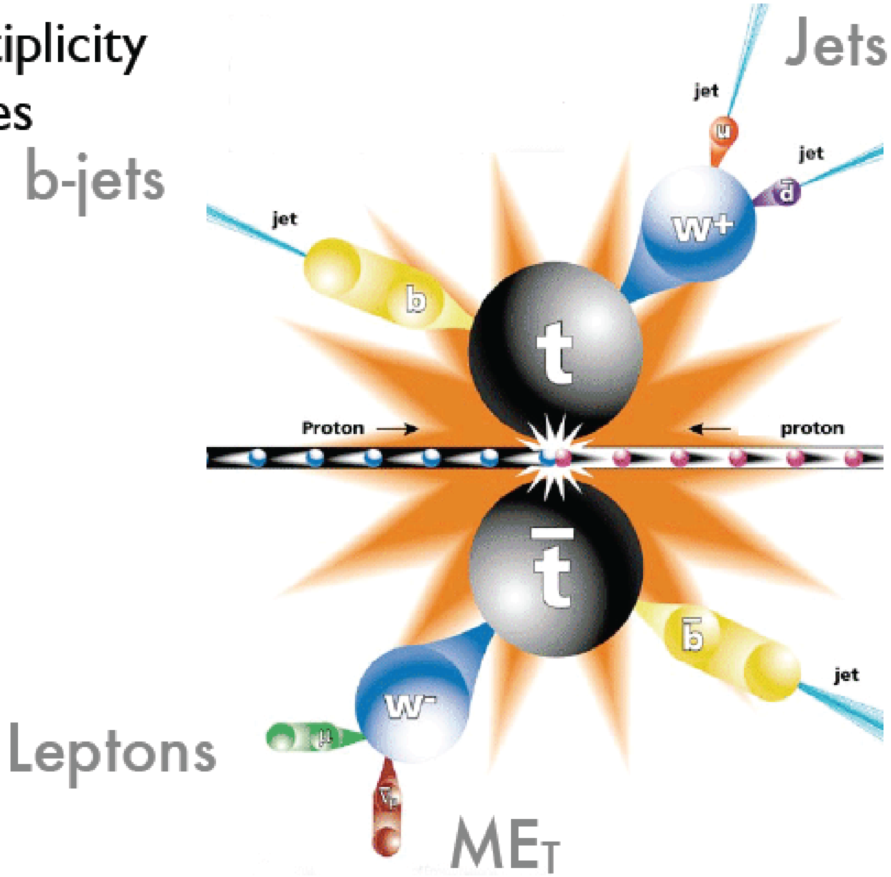
  - "Tau + jets" (15%)
    $tt \to b\tau\nu bqq'$



Object Reconstruction

Background from long lived non-b jets?
Increased track multiplicity from pile-up degrades performance?

Good enough resolution to see W mass peak?



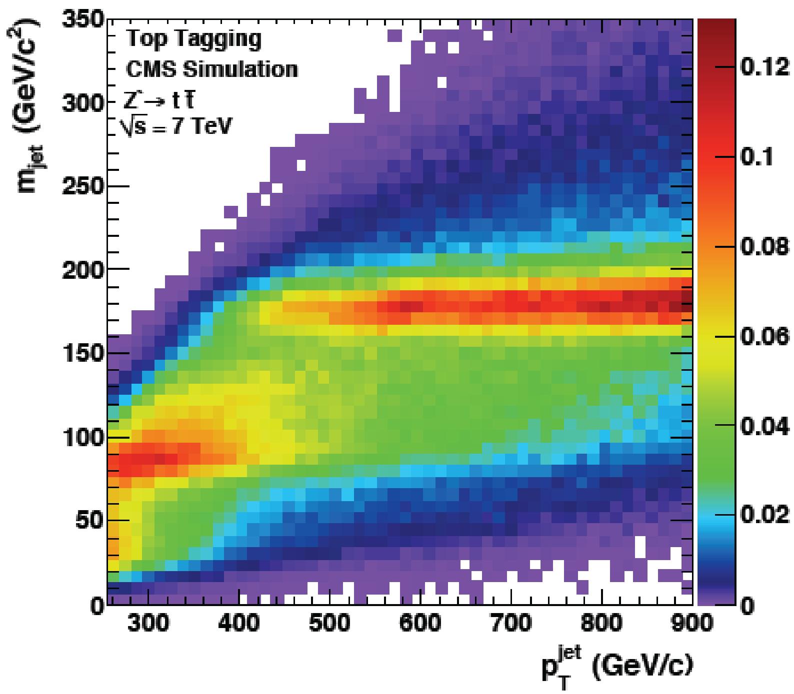
Pile-up affects reconstruction?
Jets where only lepton seen?
Actual fakes?

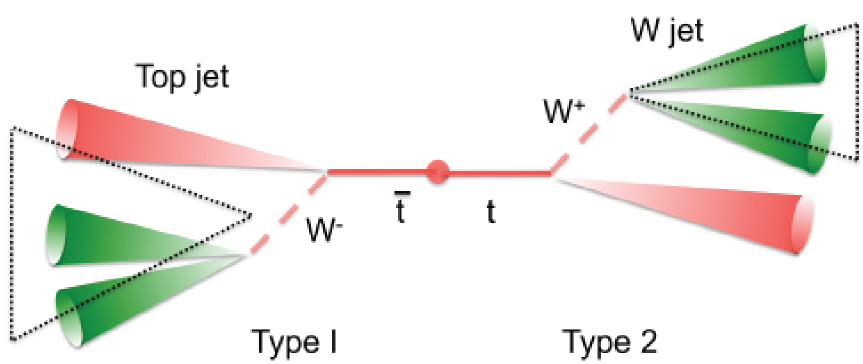
From pile-up?
Electronics/ detector noise?

Affected by pile-up?
Electronics/detector noise?

Reconstruction of Top Quarks with high Momentum

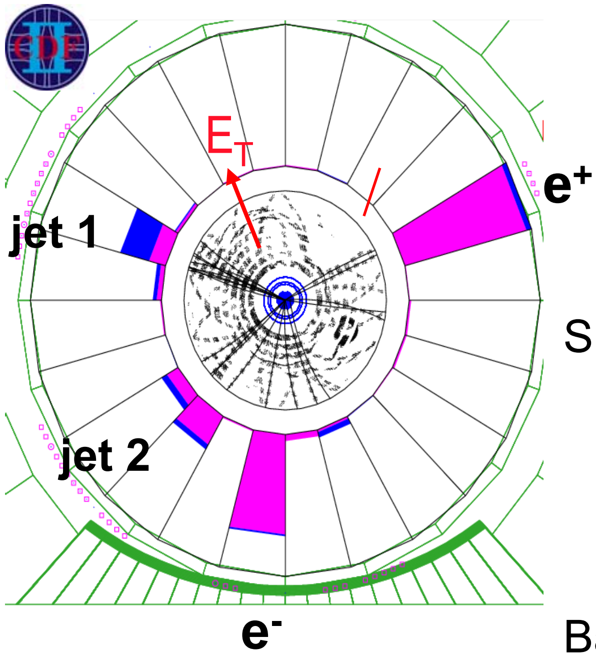
PAS JME-10-013

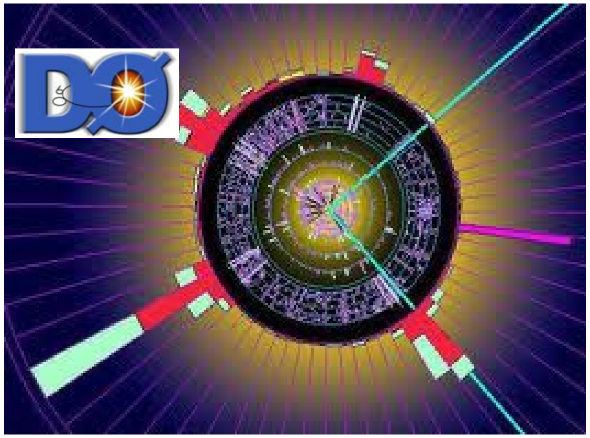




- Once boost of top quarks high enough
- Decay products become collimated
  - W->qq in one jet
  - Or t->bqq in one jet
- Special reconstruction algorithms needed

2.2 Cross Section Measurements





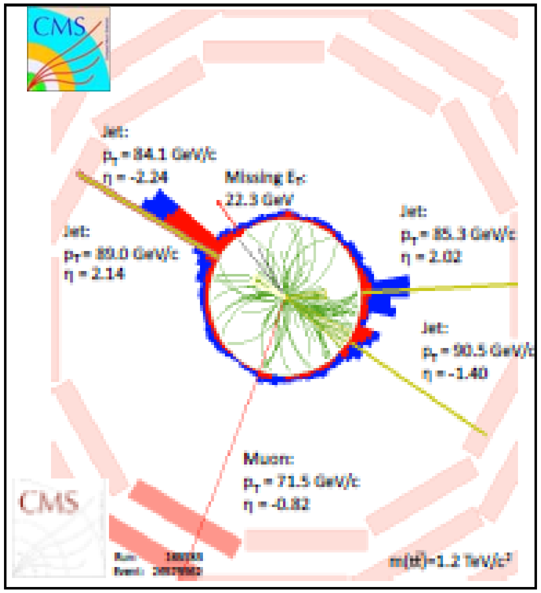
Finding the top:

Signal:

- Triggering on lepton
- High missing transverse energy ($\not{E}_T$)
- High E_T jets, central and spherical
- Two b-jets (displaced vertex)

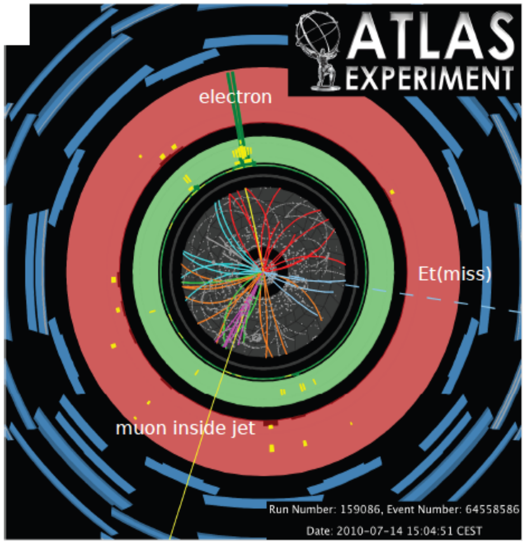
Background:

- Dilepton: Z+Jets, Single Top (tW), QCD, W+Jets
- Lepton+Jets: W+Jets, Single Top
- All Hadronic: QCD multi jet events



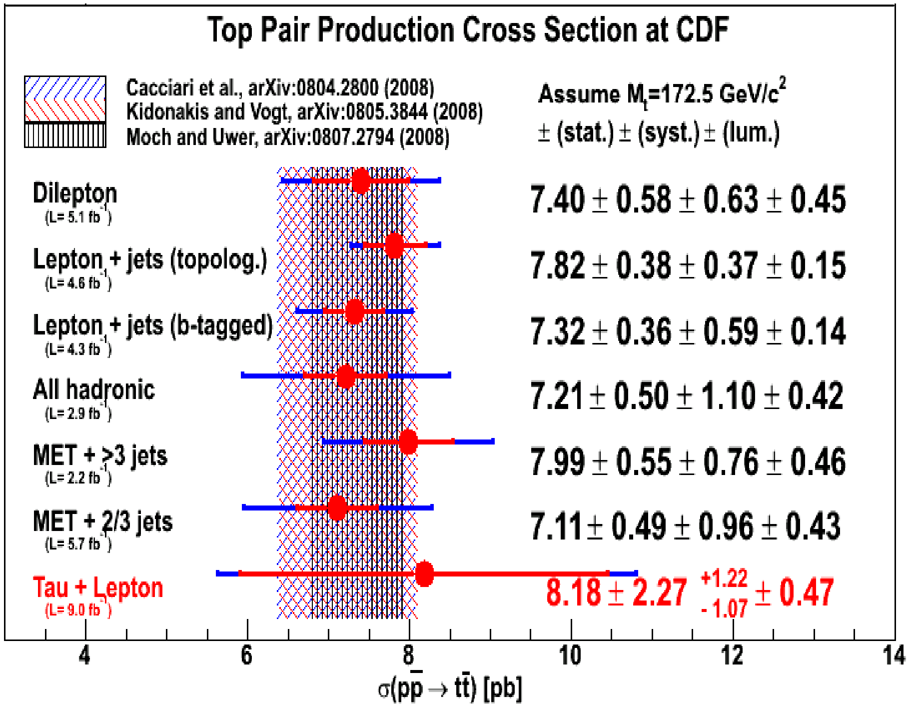
Determination of the cross section

$$\sigma_{t\bar{t}} = \frac{N_{obs} - N_{bgd}}{\varepsilon_{t\bar{t}} \cdot \int L dt}$$

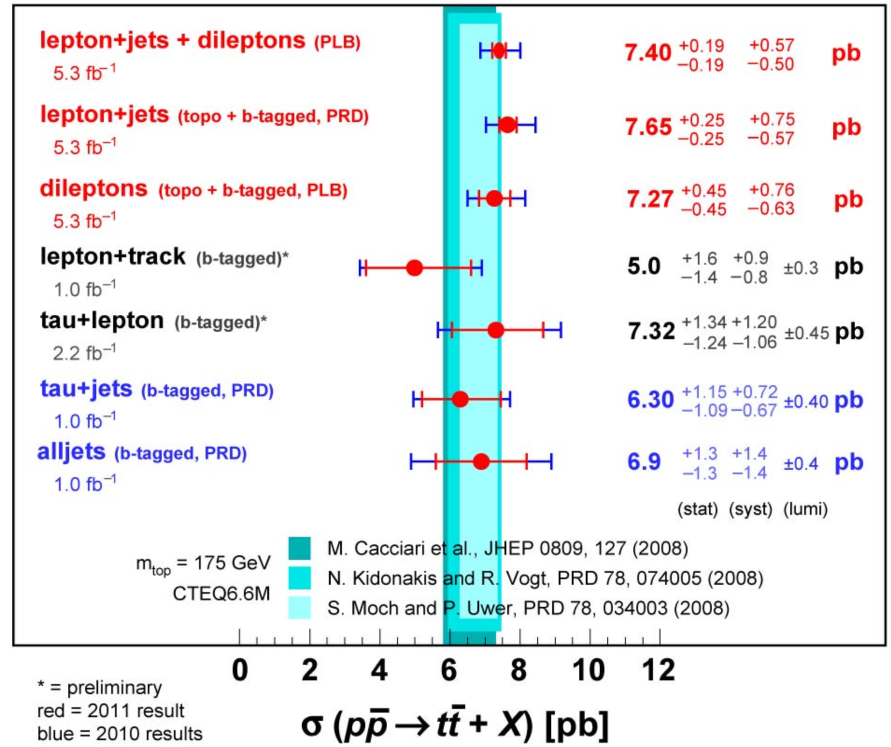


Measurements at the Tevatron

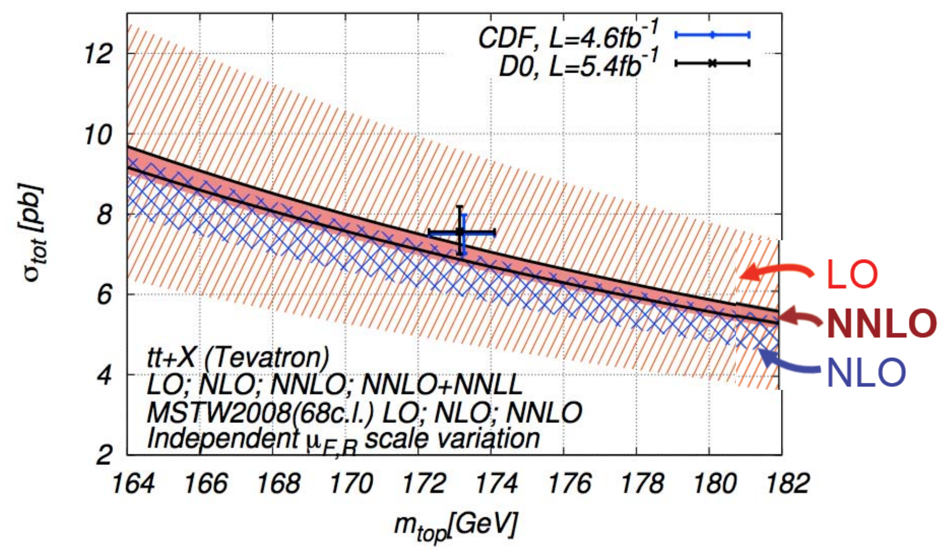
CDF Run II — Conf. Note 10878



D0 Run II — arXiv:1105.5834

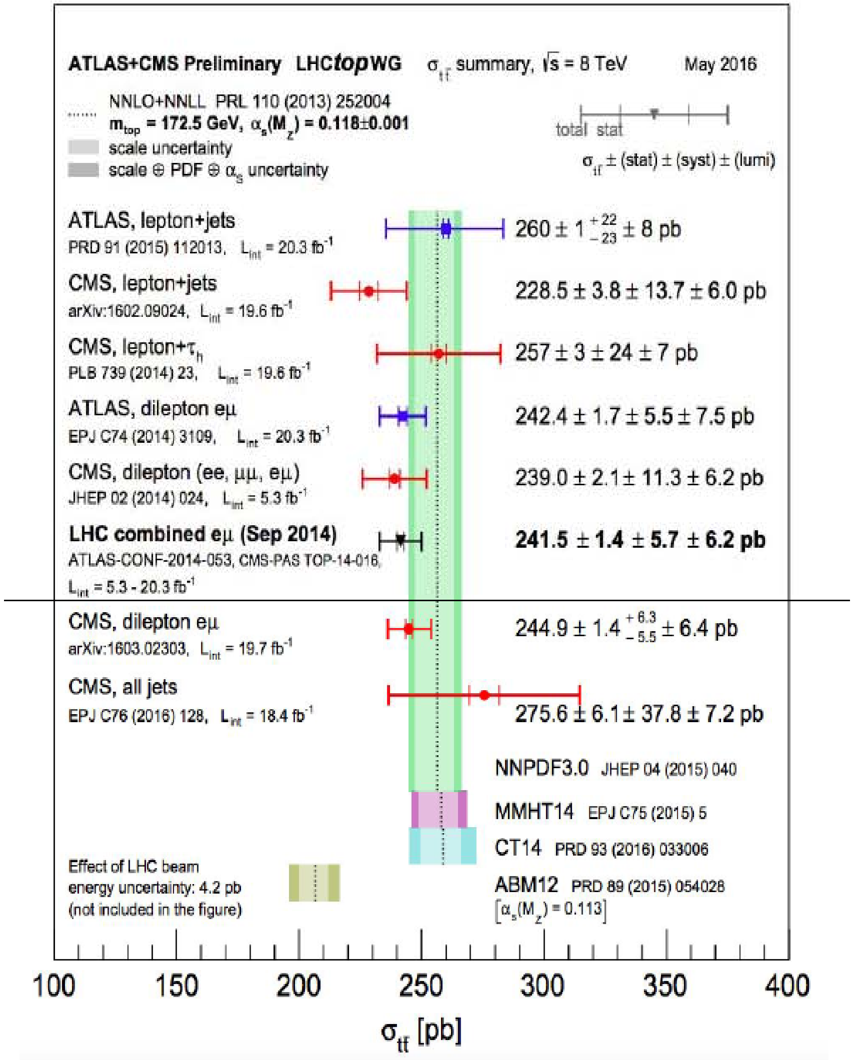


- Consitency amongst various channels
- Limitation from systematic uncertainties (JES, b-tab, W+jets)
- Sensitive to NNLO predictions (Bernreuter, Czakon, Mitov, arXiv:1204.5201)

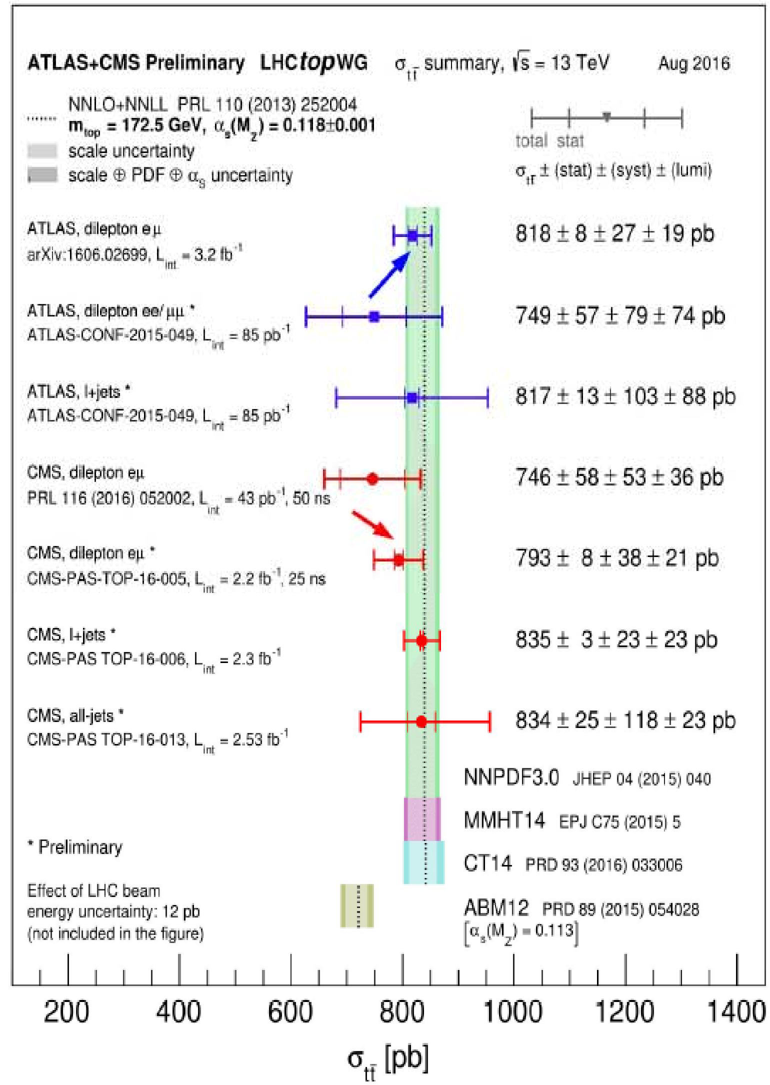


Measurements at the LHC at 7, 8 TeV

ATLAS & CMS 8TeV



ATLAS & CMS 13TeV



Precision of measuremet comparable to theory precision
LHC and Tevatron results consistent and in agreement with NNLO+NNLL

	Tevatron		LHC 8 TeV	
Precision	D0	CDF	ATLAS	CMS
total	7.8%	6.5%	4.3%	5.5%
stat	2.6%	4.0%	0.7%	0.8%
syst	4.3%	4.7%	2.3%	4.7%
lumi	6.1%	2.0%	3.1 %	2.6%

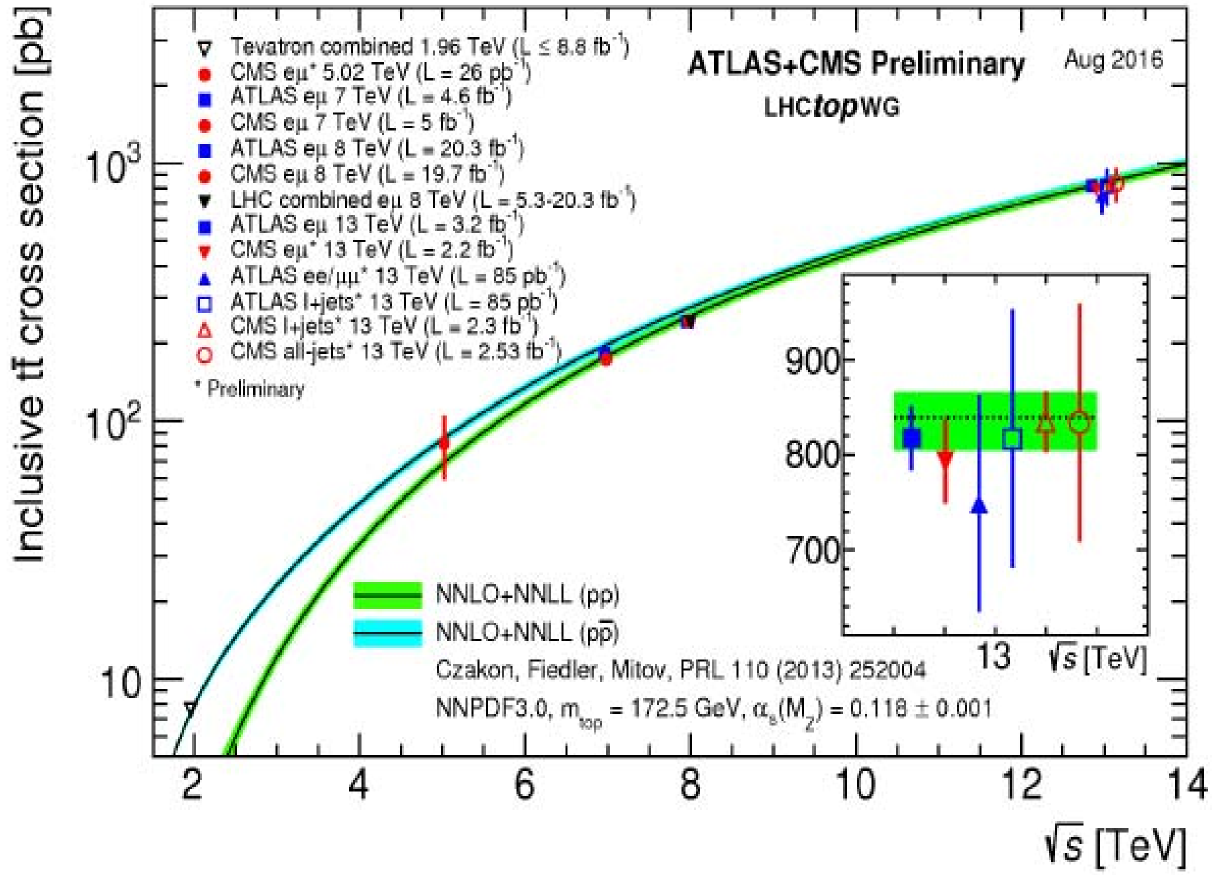
..most recent:

ATLAS, $3.2 fb^{-1}$, 13TeV, Dilept., arXiv:1606.02699

CMS, $2.3fb^{-1}$,13TeV, l+jets CMS-PAS-TOP-16-006

CMS, $2.53fb^{-1}$,13TeV, all jets CMS-PAS-TOP-16-013

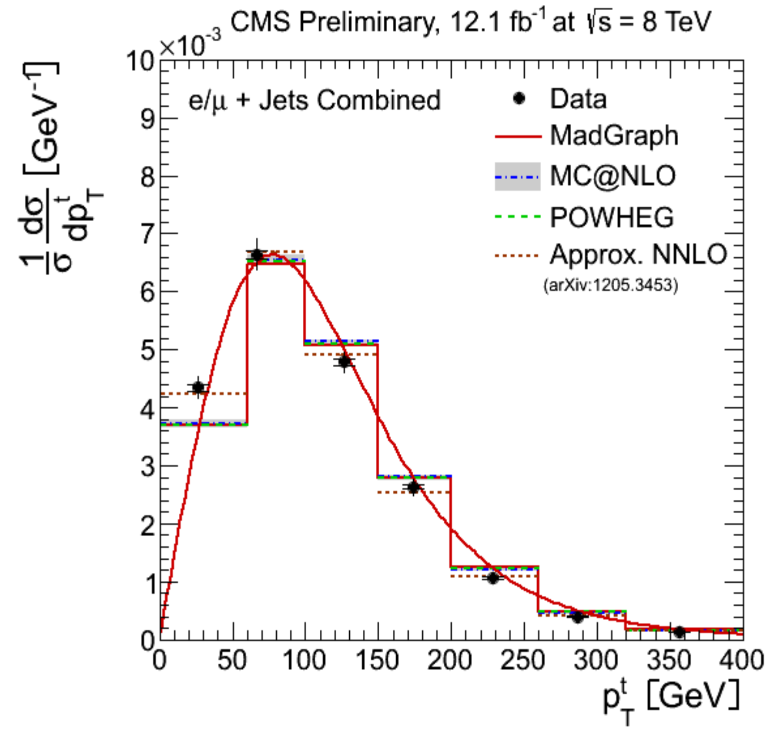
CMS, $26pb^{-1}$,5TeV, dilept. CMS-PAS-TOP-16-015

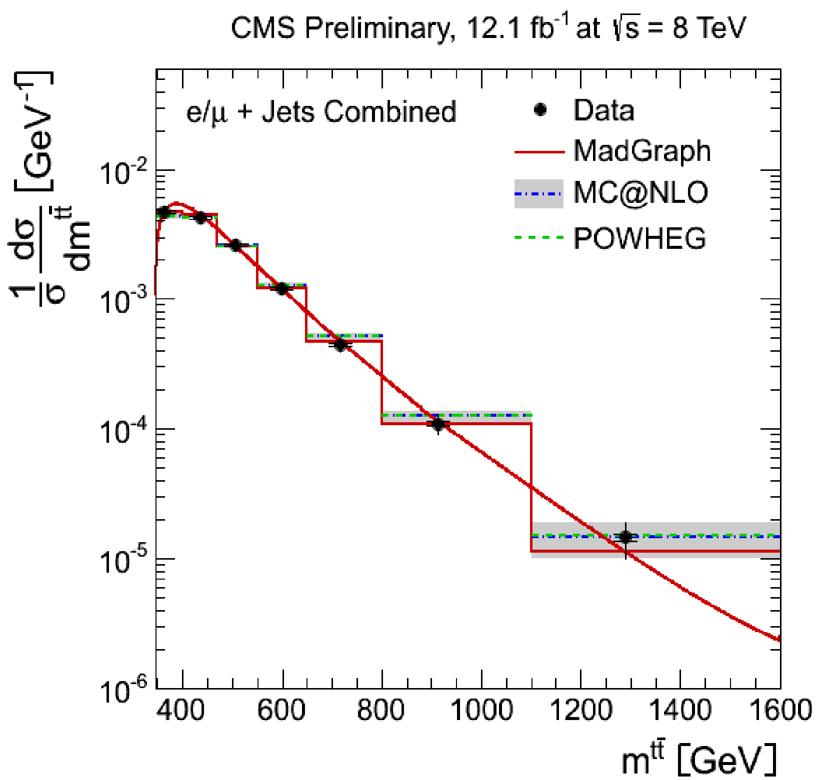


LHC and Tevatron results consistent and in agreement with NNLO+NNLL over a large range of centre-of-mass energies

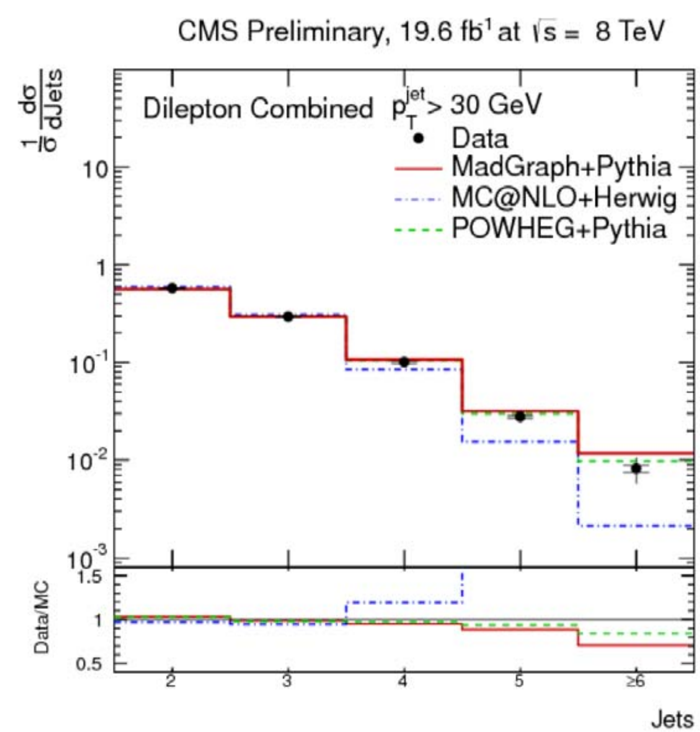
Top-Antitop Differential Cross Sections

- Measure differential cross sections
- Important test of QCD
- Event selections similar to the cross section analyses
- Bin-to-bin unfolding to parton level





CMS PAS-TOP-12-041

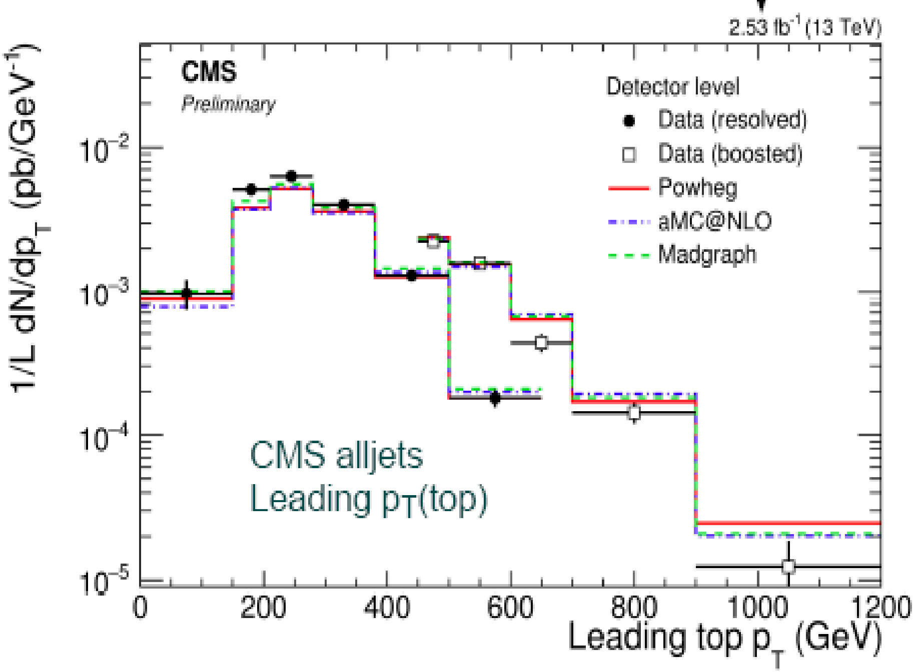


tt production is well described by SM calculations

CMS, 2.5fb^{-1},13TeV, l+jets, differential p_T
CMS-PAS-TOP-16-008

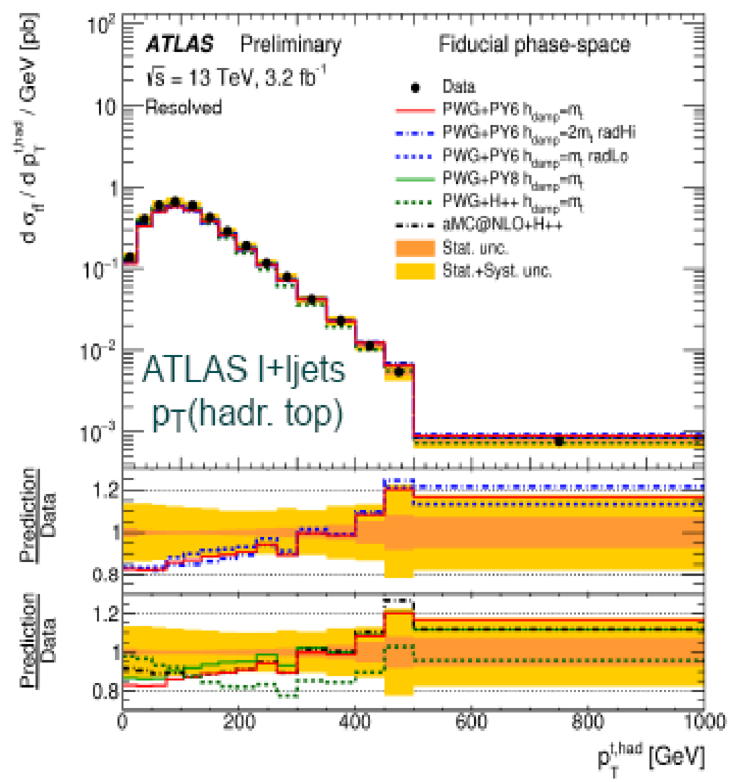
CMS, 2.2fb^{-1},13TeV, dilep, differential $p_T(t)$, y(t), y(tt),m(tt),ΔΦ(tt), CMS-PAS-TOP-16-007

CMS, 2.5fb^{-1},13TeV, all-jets, differential p_T
Resolved & boosted, CMS-PAS-TOP-16-013



CMS, 2.3fb^{-1},13TeV, dilep, ttbb, ttjj
CMS-PAS-TOP-16-010

ATLAS, 3.2fb^{-1},13TeV, l+jets, differential p_T
Resolved & boosted, ATLAS-CONF-2016-040

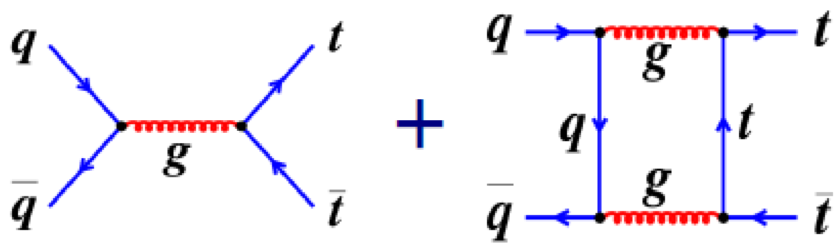


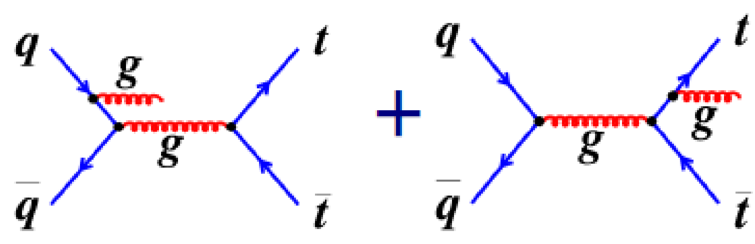
Similar trends as in 8TeV. Top p_T modelled too hard (improves with NNLO pQCD)

2.3 Top-Antitop Charge Asymmetry

NLO QCD: interference of higher order diagrams leads to asymmetry for $t\bar{t}$ produced through $\bar{q}q$ annihilation:

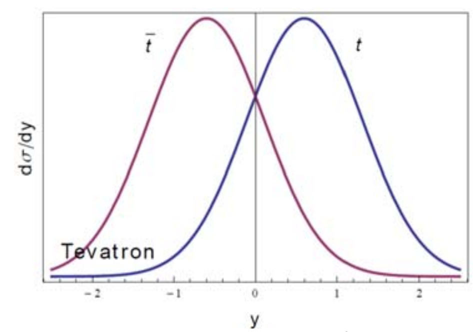
- Top quark is emitted preferentially in direction of the incoming quark
- Antitop quark opposite
- Production through new processes may lead to different asymmetries





- At Tevatron: define forward-backward asymmetry

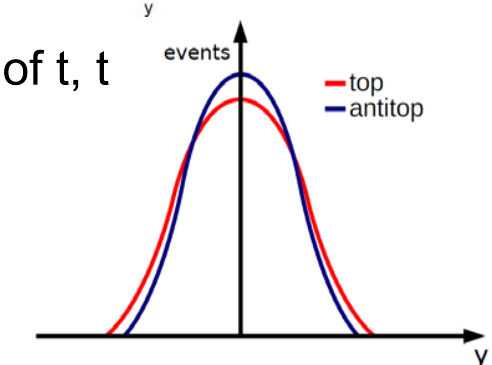
$$A^{t\bar{t}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$$



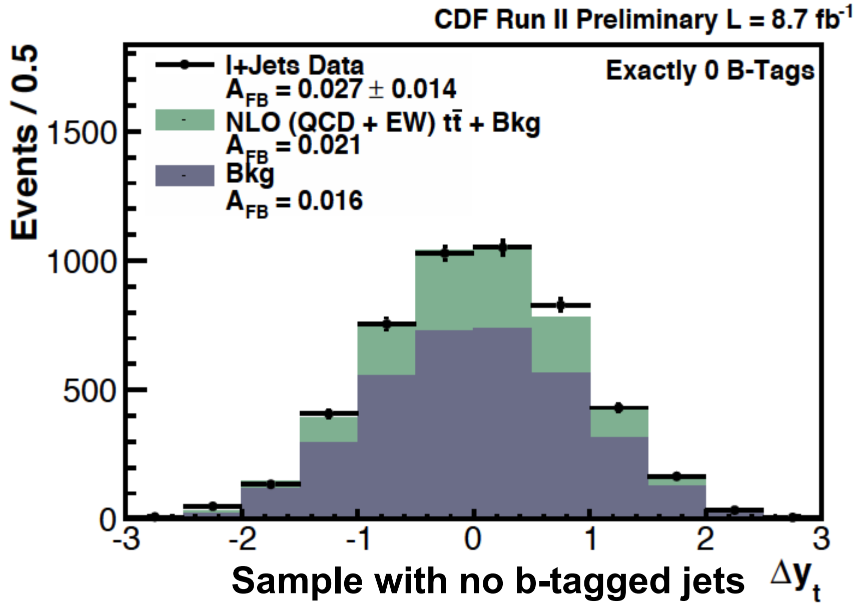
- At LHC: define asymmetry in the widths of rapidity distributions of t, $\bar{t}$

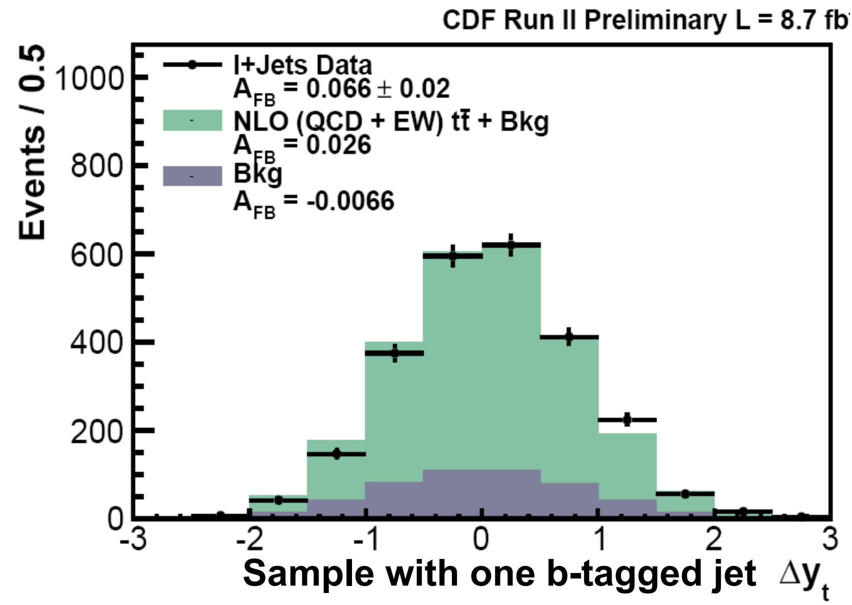
$$A_C = \frac{N(\Delta|y| > 0) - N(\Delta|y| < 0)}{N(\Delta|y| > 0) + N(\Delta|y| < 0)}$$

$$\Delta|y| = |y_t| - |y_{\bar{t}}|$$

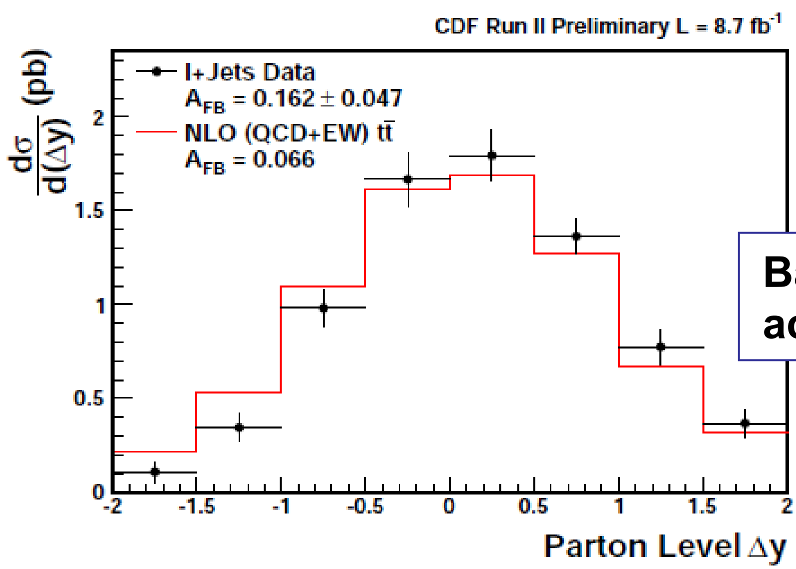


Asymmetries at the Tevatron

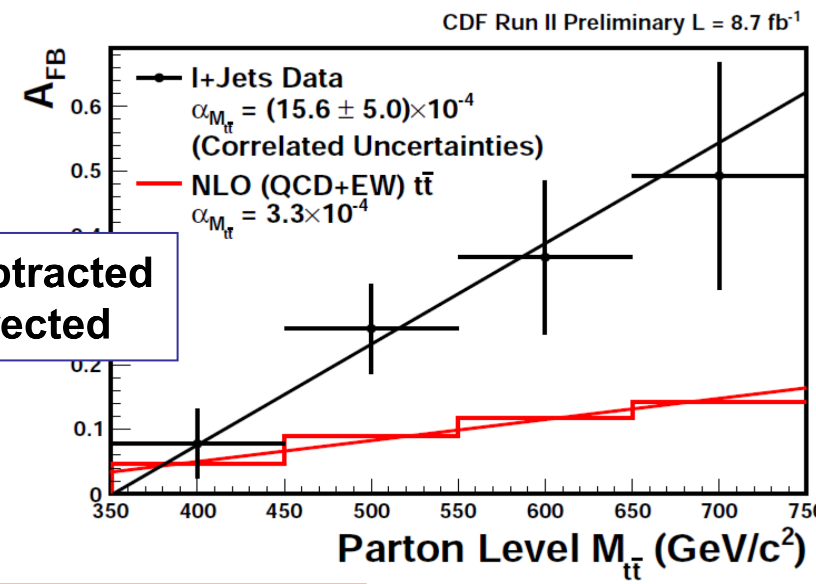




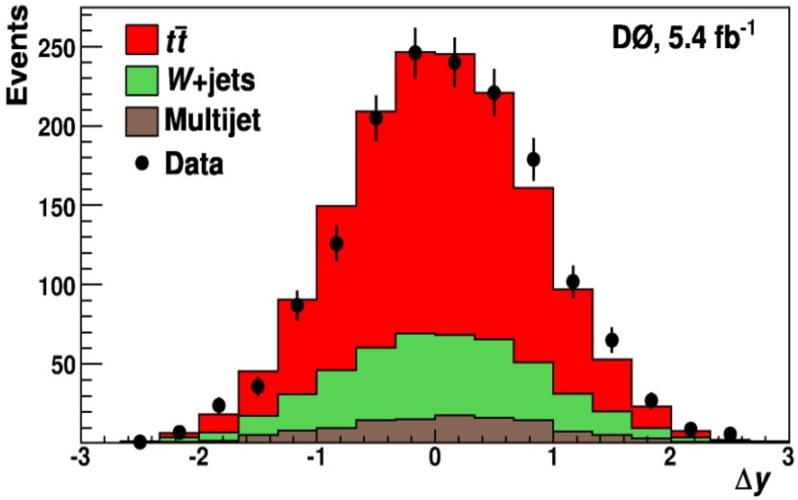
CDF-Note 10807



Background-subtracted acceptance corrected



$$A_{FB} = 0.162 \pm 0.041(\text{stat}) \pm 0.022\ (\text{syst})$$



Δy in the lepton-jets channel

Measured asymmetry on detector level after bkg subtraction:

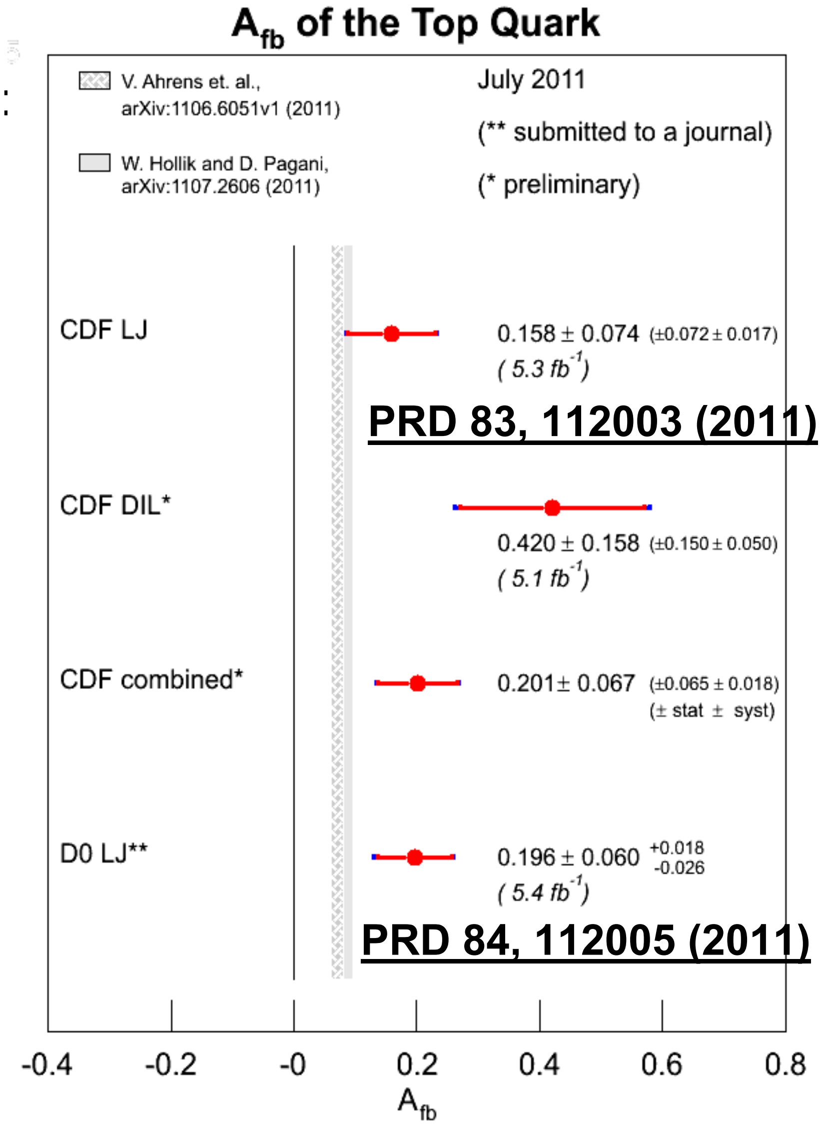
A_{FB} det = 0.092 ± 0.037 (stat+syst)

MC@NLO: A_{FB} det = 0.024 ± 0.007

Measured asymmetry on parton level:

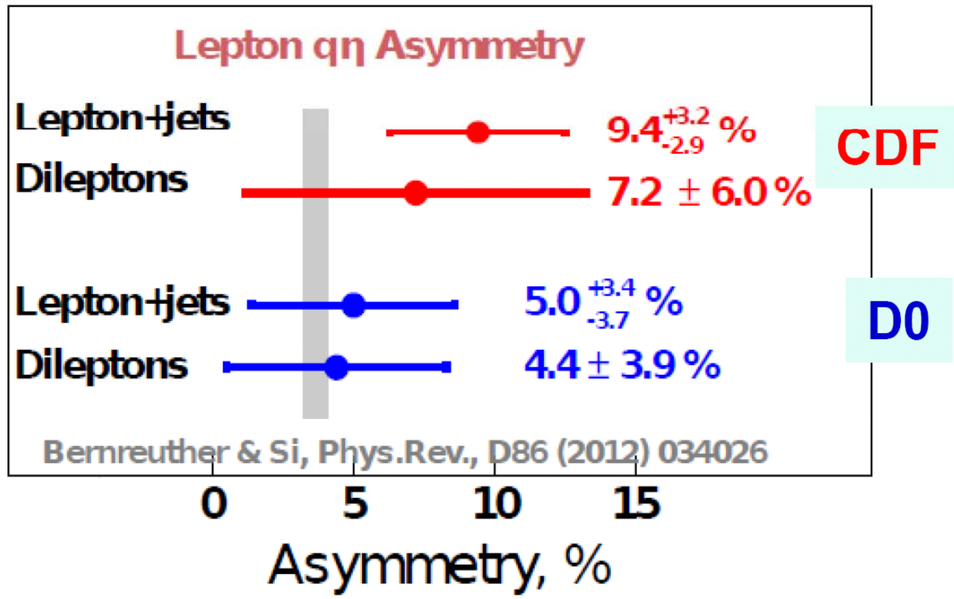
A_{FB} = 0.196 ± 0.065 (stat+syst)

Summary:

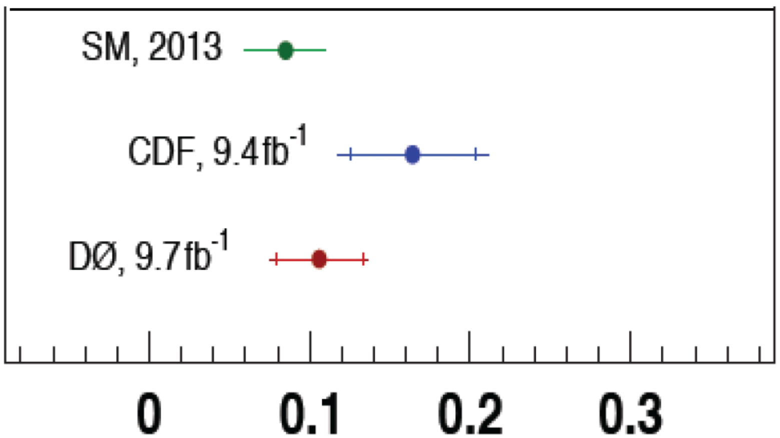


Both CDF and D0 see significant asymmetry in $t\bar{t}$ production in all channels with strong dependence on m_{tt}, in conflict with the SM

- **In A_{FB} leptonic-asymmetry**
  recent results from CDF and DZero are now more consistent with SM prediction (measured asymmetries decreased, theoretical predictions increased)

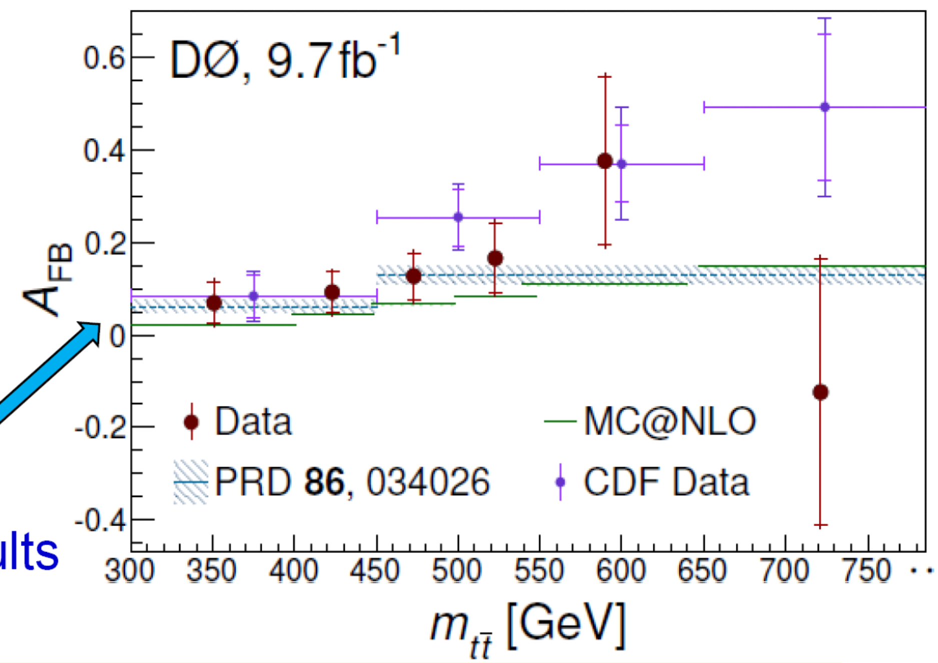


- **In $t\bar{t}$ asymmetry:**



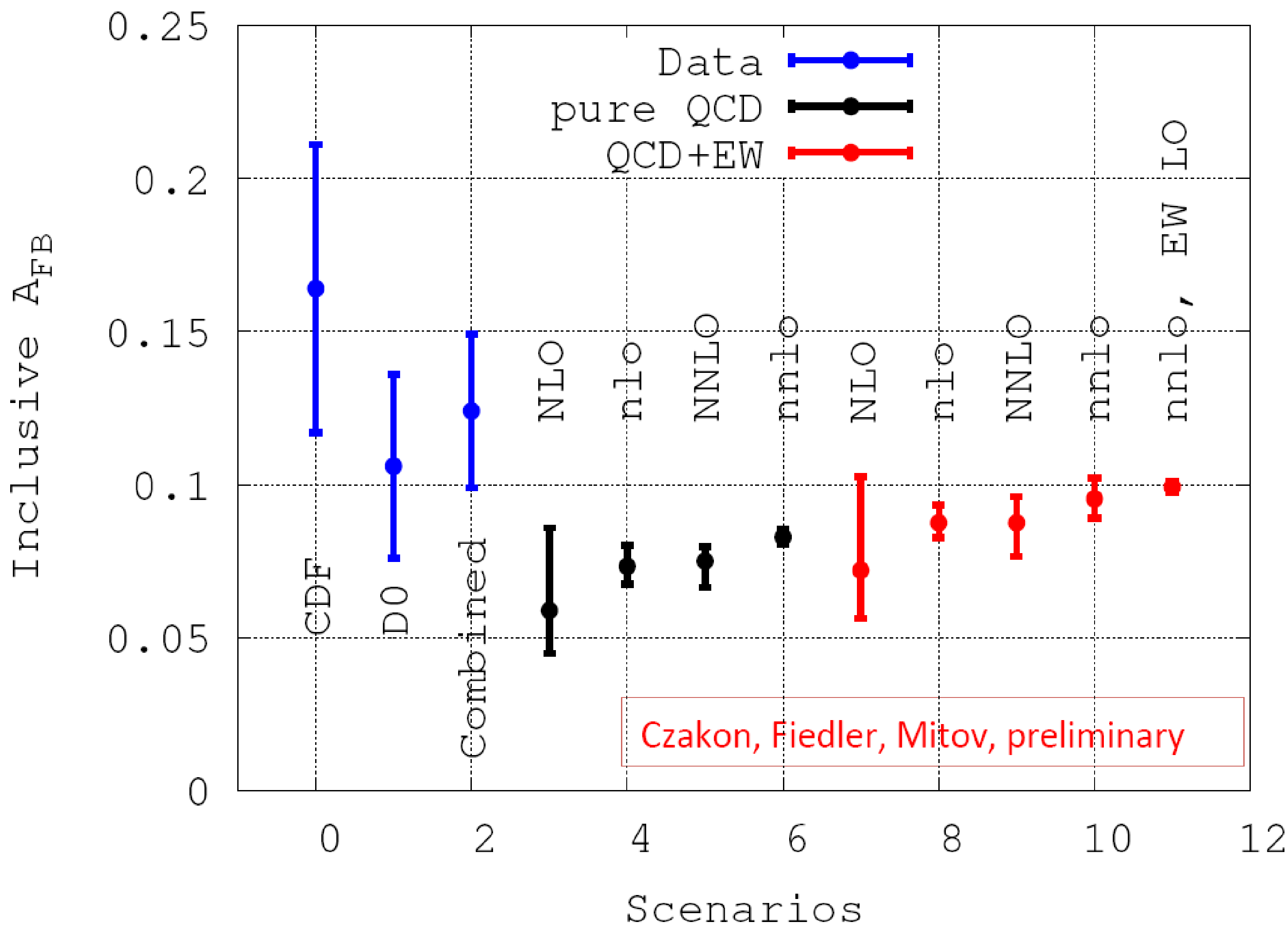
Asymmetry compatible with SM

- **Kinematic dependence with m_{tt}**
  When considering CDF and D0 recent results
  → reduced discrepancy with prediction



Working now on the CDF-D0 combination of these results

Comparison Fermilab-Data with Theory

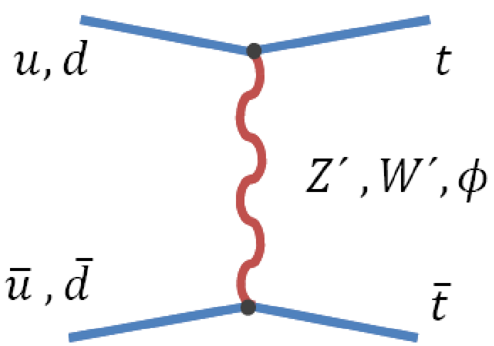


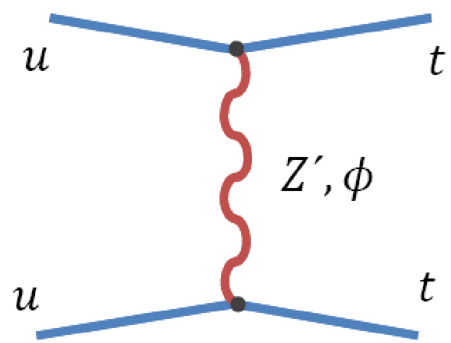
Errors due to scale variation only

Theoretical Speculations for Anomalies

New physics in the t-channel

[Jung, Murayama, Pierce, Wells / Cheung, Keung,Yuan / Cao, Heng,Wu,Yang / Barger, Keung, Yu / Cao, McKeen, Rosner, Saughnessy, Wagner / Berger, Cao, Chen, Li, Zhang / Bhattacherjee, Biswal, Ghosh/ Zhou, Wang, Zhu / Aguilar-Saavedra, Perez-Victoria/ Buckley, Hooper, Kopp, Neil / Rajaraman, Surujon, Tait/ Duraisamy, Rashed, Datta, …]
[Shu,Tait,Wang / Cao,Heng,Wu,Yang / Dorsner, Faifer, Kamenik, Kosnik / Jung,Ko,Lee,Nam. Aguilar-Saavedra, Perez-Victoria / Patel, Sharma / Ligeti, Marques Tavares, Schmalz, …]



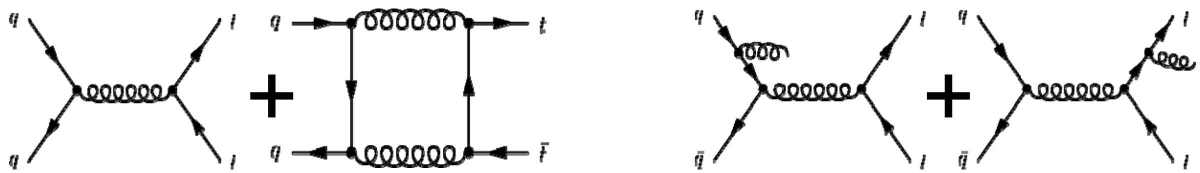


- Because of color algebra a Z' (SM Z) in the s-channel do not interfere with the LO QCD amplitude
- (coloured) scalars do not generate an asymmetry in the s-channel

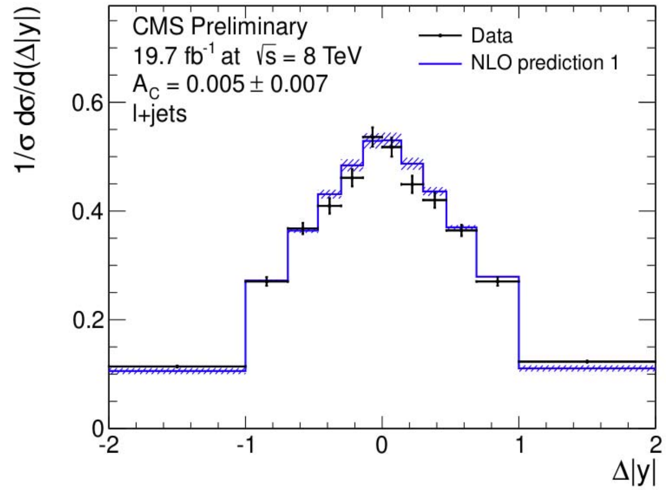
- A sizeable charge asymmetry requires **large flavour violating couplings** [Jung,Murayama,Pierce,Wells]
- Relatively light Z´ and/or W´: O(200-700 GeV), or O(1TeV) colored scalars
- **like sign $tt + \bar{t}\bar{t}$**, very constrained at Tevatron, and the LHC

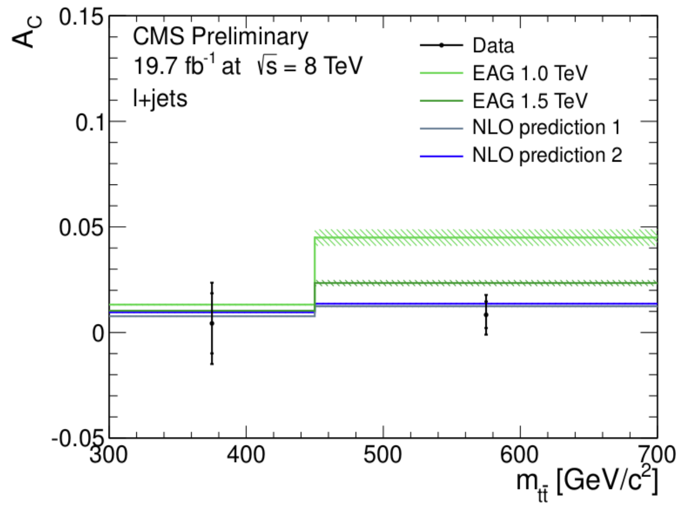
Ac in Lepton+jets @ 8TeV

CMS PAS-TOP-12-033



- **e+jets** and **μ+jets** combined
  - Exactly 1 isolated high-pT lepton
  - At least 4 jets with pT > 30 GeV
  - At least 1 of these jets b-tagged
- BG-contamination about 20%
- Sensitive variable Δ|y| = y(t) - |y(antitop)|
- BG-subtraction and **regularized unfolding**
- **Inclusive** and **differential** (mtt, pTtt, ytt) measurements using **19.7fb-1**





Asymmetry	A_C
Reconstructed	0.003 ± 0.002 (stat.)
BG-subtracted	0.002 ± 0.002 (stat.)
Unfolded	0.005 ± 0.007 (stat.) ± 0.006 (syst.)
Theory prediction [Kühn, Rodrigo] [9, 33]	0.0102 ± 0.0005
Theory prediction [Bernreuther, Si] [34, 35]	0.0111 ± 0.0004

EAG: Effective Axialvector-coupling of the Gluon

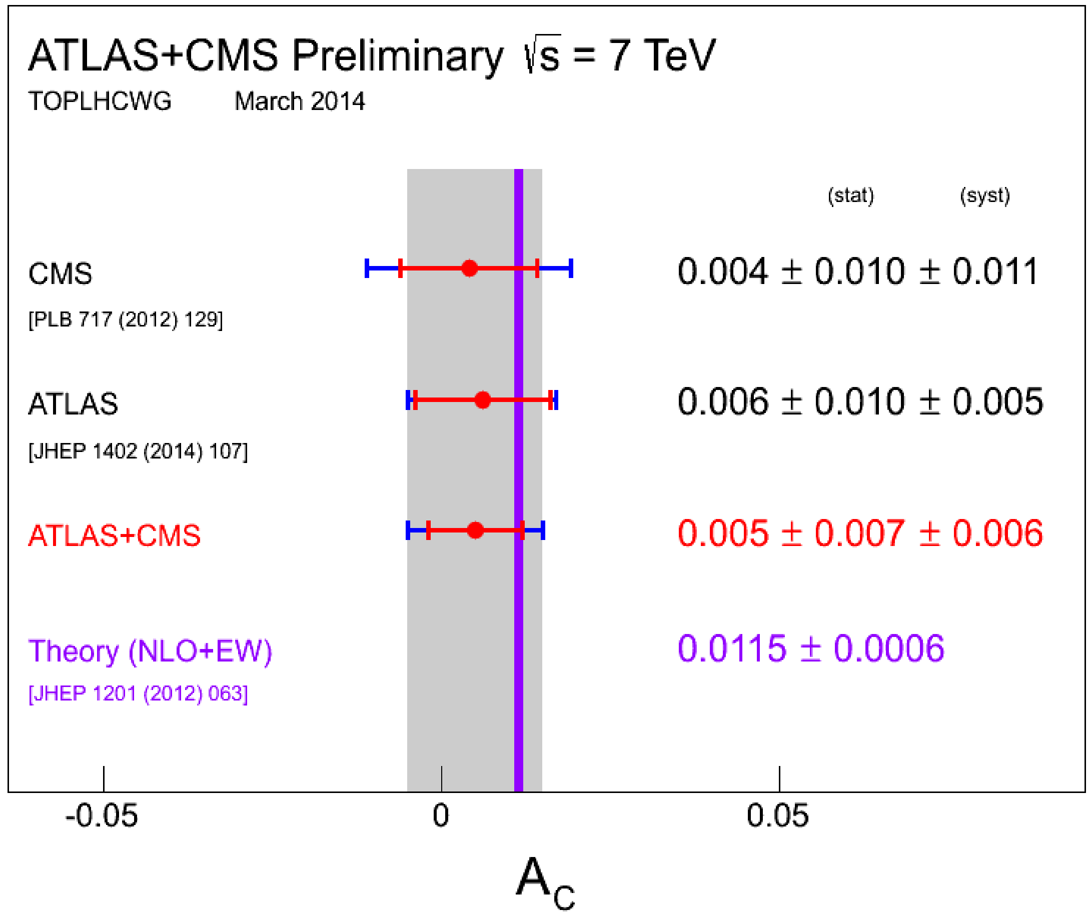
At LHC we see no deviation from the Standard Model!

Ac in Lepton+Jets @ 7TeV PAS-TOP-14-006

CHARGE ASYMMETRY CMS ATLAS COMBINATION

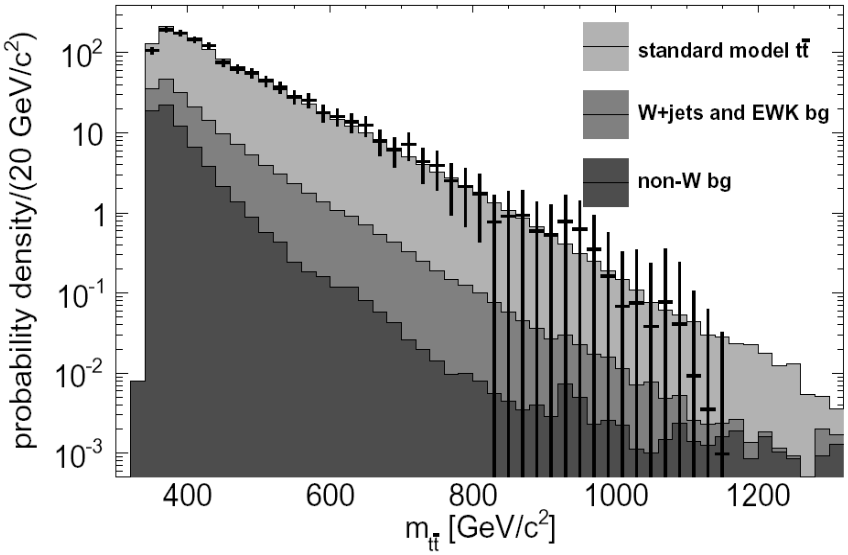
Combination done within the TOPLHC working group

		ATLAS	CMS	Comb.	Corr.
	A_C	0.006	0.004	0.005	0.058
Uncertainties	Statistical	0.010	0.010	0.007	0
	Detector response model	0.004	0.007	0.004	0
	Signal model	< 0.001	0.002	0.001	1
	W+jets model	0.002	0.004	0.003	0.5
	QCD model	< 0.001	0.001	0.000	0
	Pileup+MET	0.002	< 0.001	0.001	0
	PDF	0.001	0.002	0.001	1
	MC statistics	0.002	0.002	0.001	0
	Model dependence				
	Specific physics models	< 0.001	*	0.000	0
	General simplified models	*	0.007	0.002	0
	Systematic uncertainty	0.005	0.011	0.006	
	Total uncertainty	0.011	0.015	0.009	

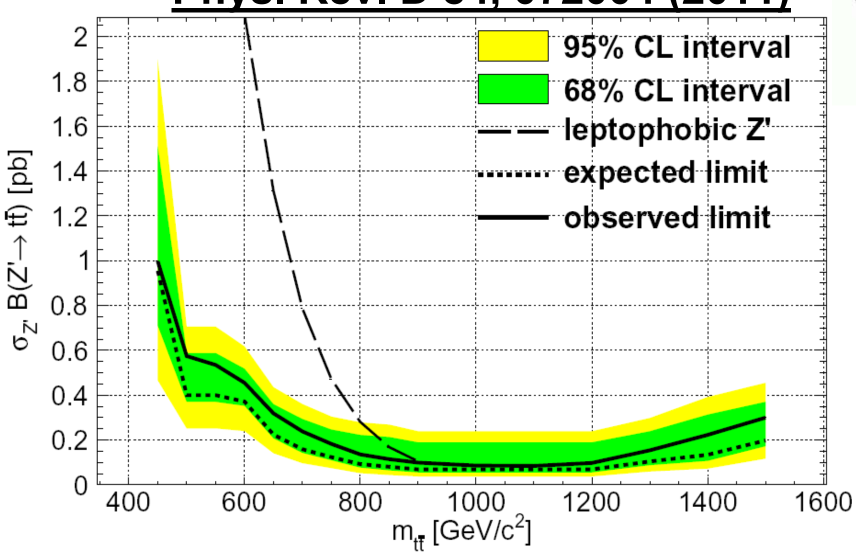


2.4 Search for $t\bar{t}$ Resonances

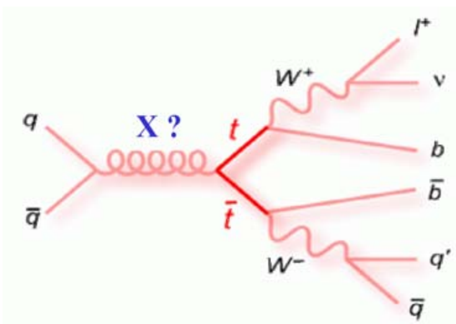
CDF: lepton+jets selection, no b-tagging requirements



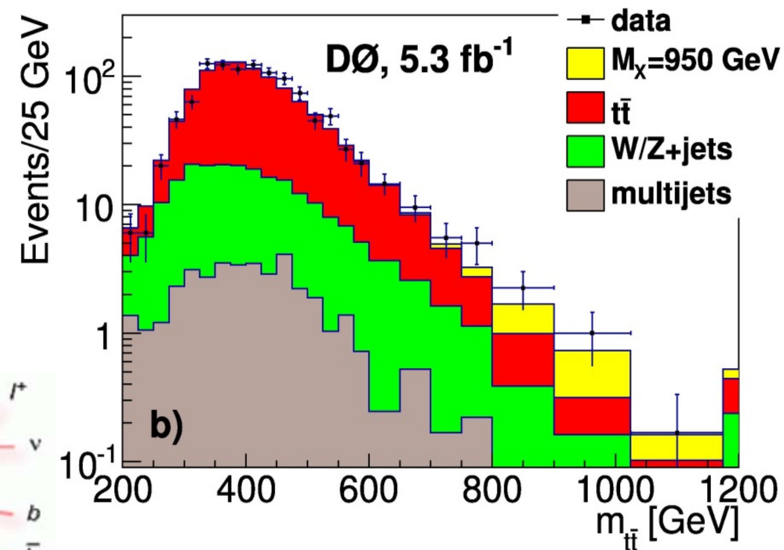
Phys. Rev. D 84, 072004 (2011)



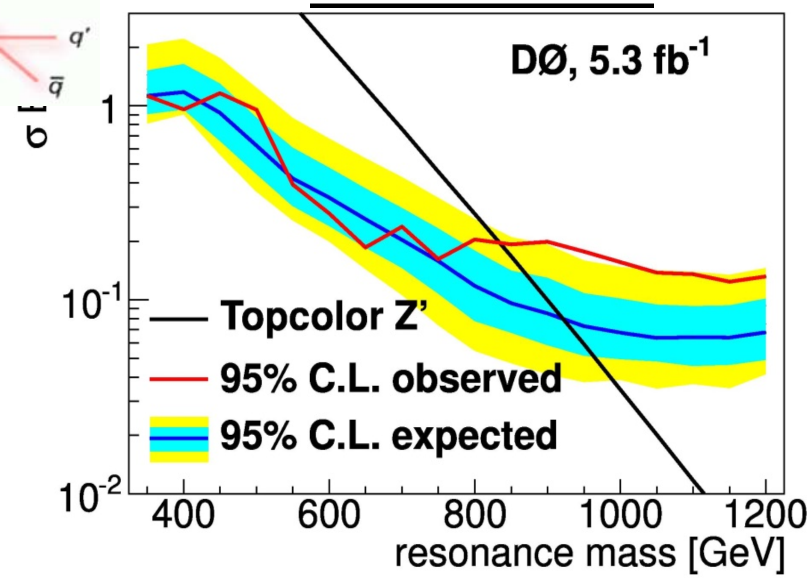
M_X>900 GeV @95% C.L.



DØ: lepton+jets selection, at least one b-tagged jet



arXiv:111.1271v1



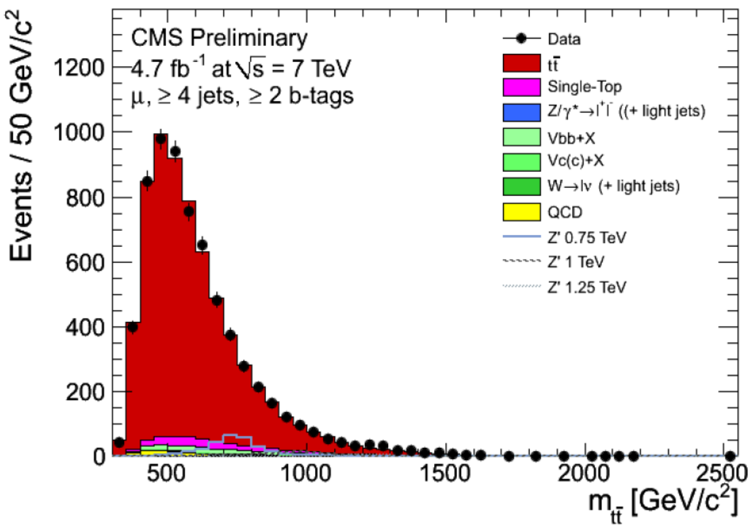
M_X>835 GeV @95% C.L.

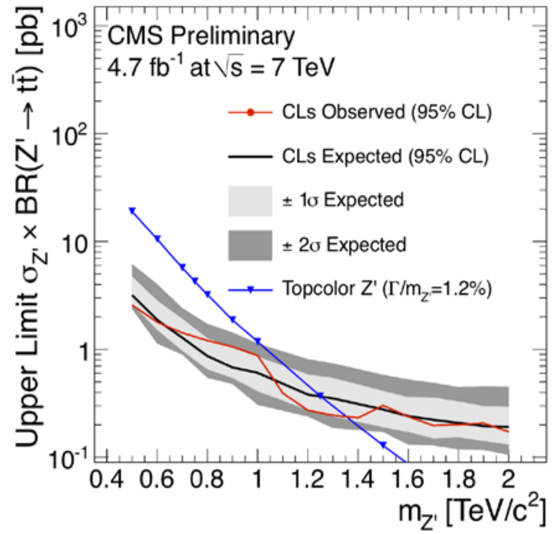
Searches at the LHC

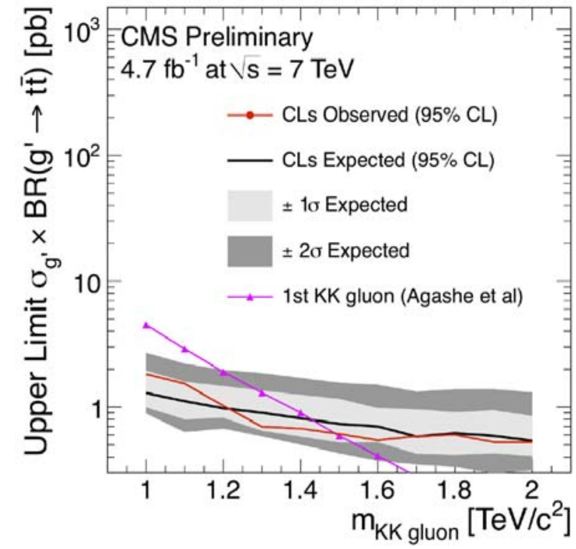
CMS TOP-11-009/010, EXO-11-006/093

Topcolor Z'

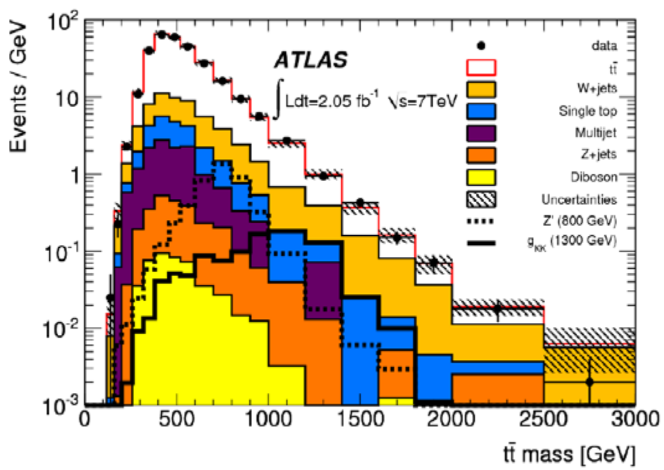
Extra-dimensions

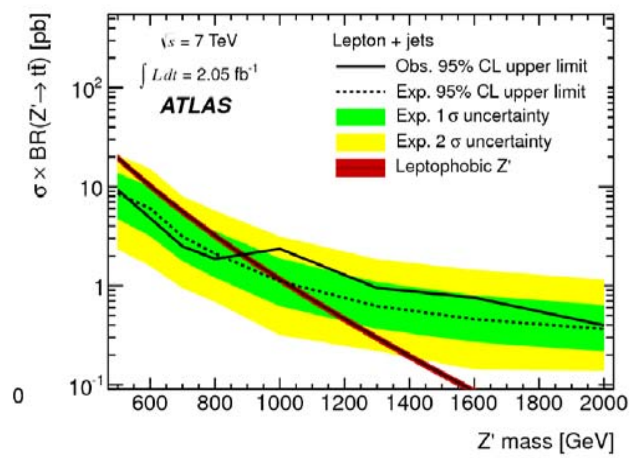


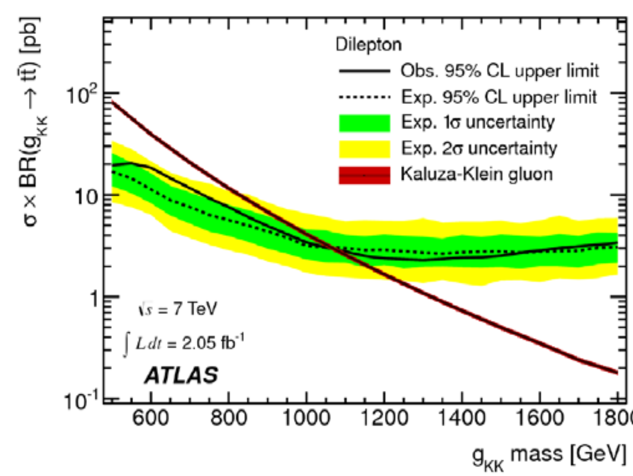




arXiv:1205.5371







So far data compatible with SM up to 1…1.6 TeV

Search for Gluino Decays to Top

Exclusion limits for gluino-gluino production