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Standard Model @ Hadron Colliders
X. Top Quark: production (cont.)

A semileptonic tt event

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Is the top quark a normal fermion?

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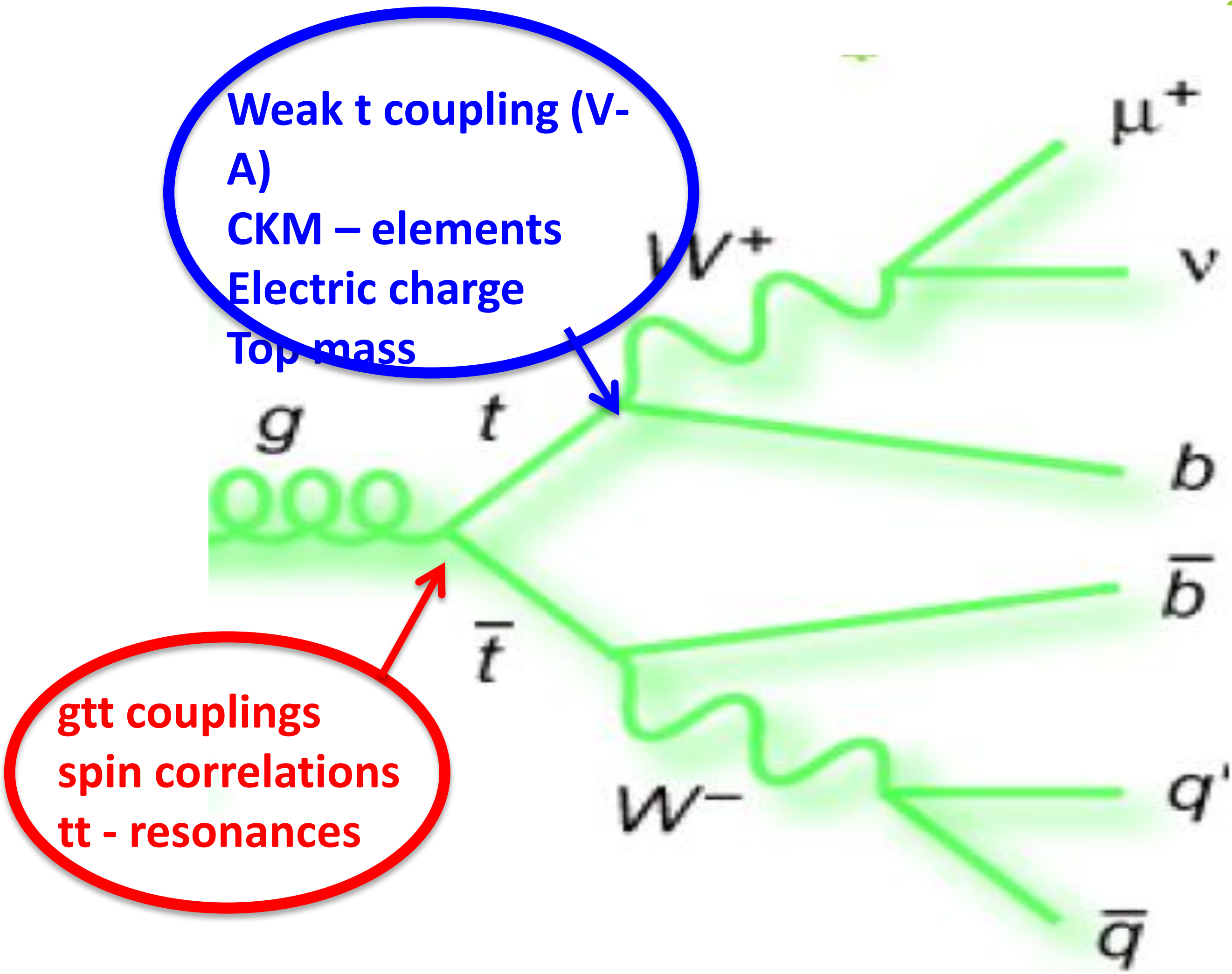

Production of top quarks

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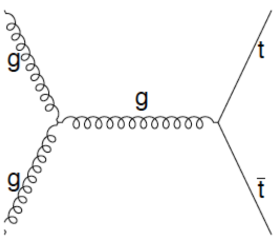
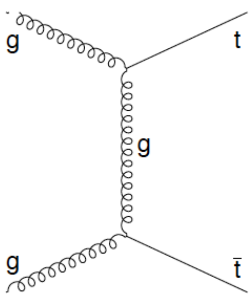
What x required for top production?

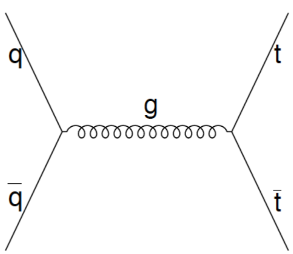
$$\sqrt{x_1 \cdot x_2} \geq \frac{2 \cdot M_t}{E_{pp}}$$

- 0.18 at Tevatron
- 0.05 at LHC (0.025 @ 14 TeV)





Dominant at LHC for low M_{tt}
Suppressed @ Tevatron



Relevant at LHC for high M_{tt}
Dominant @ Tevatron

How to measure tt cross section

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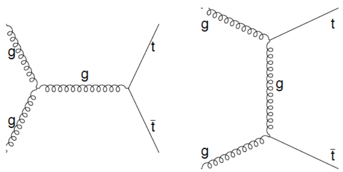
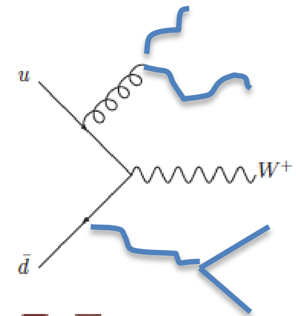
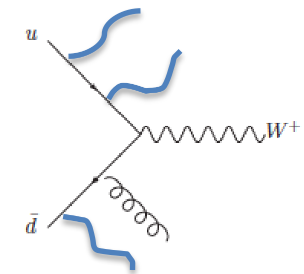


(Why should we?):
Sensitive to gluon –tt couplings
Test of QCD with massive quarks

Select events:

- 4 jets with p_T> 25 GeV
- isolated electron,muon p_T>20 GeV
- missing transverse energy > 20 GeV





$$\sigma_{t\bar{t}} = \frac{N_{measured} - N_{background}}{\epsilon \mathcal{L}}$$

What fraction of tt events are retained after selection

Luminosity:
How many proton-collisions?

Cross section determination

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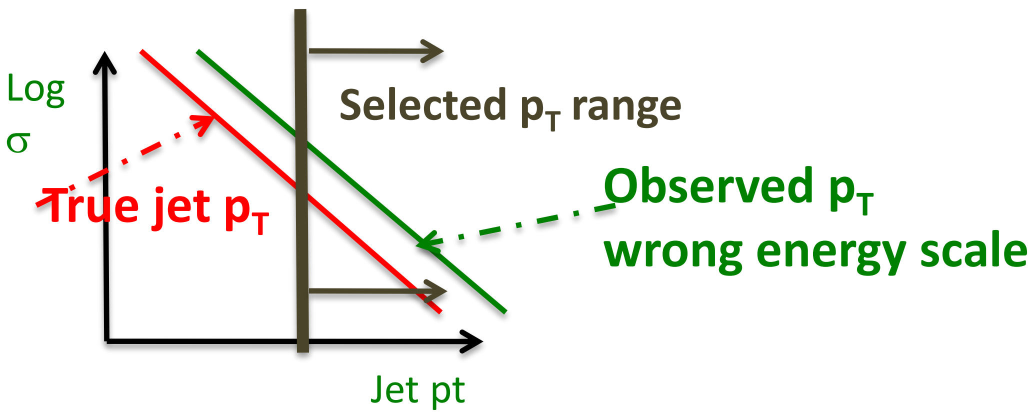
Experimental precision depends on how well
- background, efficiency, luminosity can be controlled

Key issue determine efficiency



Largest uncertainties:
- Jet energy scale
- bottom identification
- Background yield
- Jets from QCD
- selection efficiency e, μ, ...

Experimental uncertainty ~ 9%
Luminosity uncertainty ~ 4.4 %

Background estimatation

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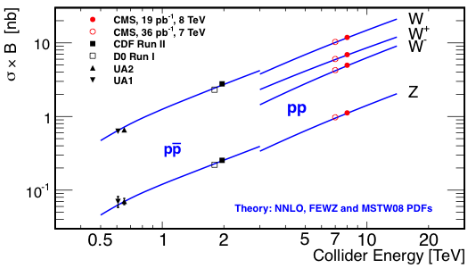
Dominant background: W + 4 jets → same final objects

- assume QCD generators to be correct, i.e templates

- data driven method (ATLAS):

tt – events: same number of W^+, W^-

W+jets method: more W^+ than W^-



$$(N_{W^+} + N_{W^-})^{\text{exp}} = \left(\frac{r_{MC}+1}{r_{MC}-1}\right)(N_{W^+} - N_{W^-})^{\text{data}}$$

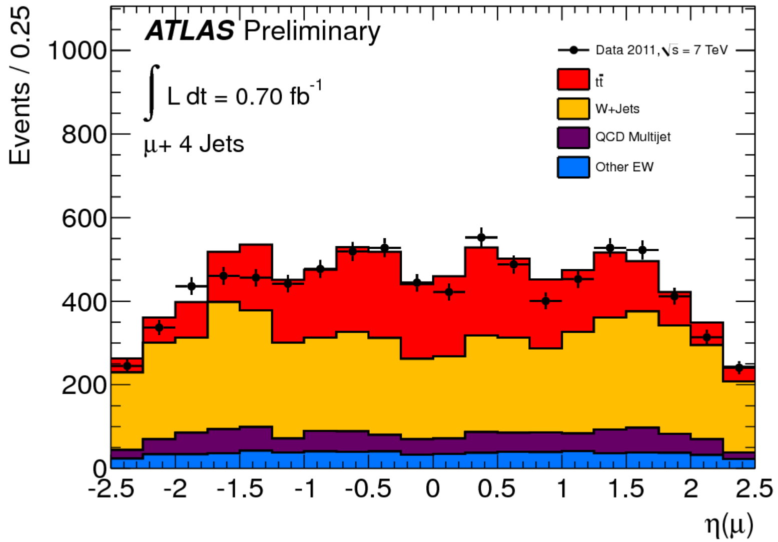
$r_{MC} = N_{W+}/N_{W-}$

→Further step: estimate W+b(b)+2 jets fraction based on bottom tagging in W+2jets → extrapolated to 4 jets via MC

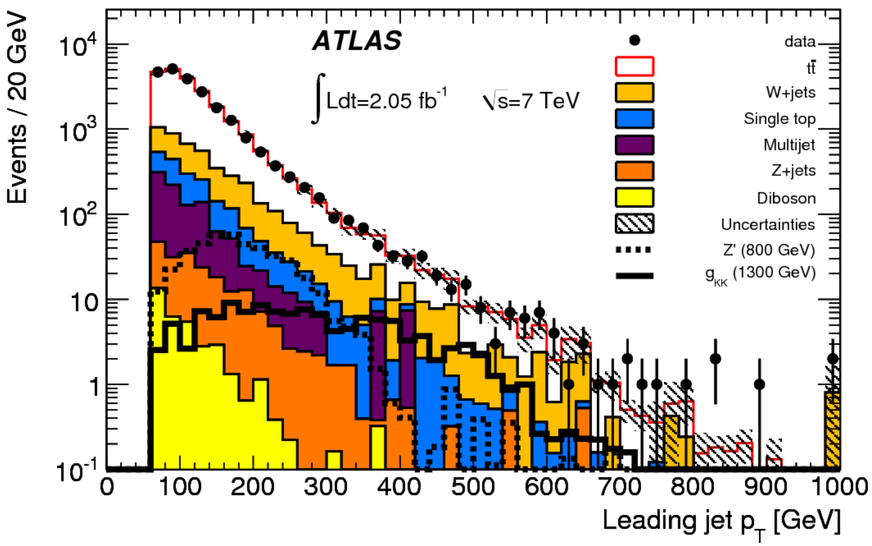
Other background: QCD with b→ lepton with high $x_{Feynman}$

Estimate from ‚non – isolated' leptons

Background in semileptonic tt



Contribution to sample no b – tag
S/B ~ 1/3
W+Jets/tt ~ 1.4



Contribution to sample with b – tag
S/B ~ 4
W+Jets/tt ~ 0.15
price: somewhat reduced statistics
Wb+jets more uncertain

Dileptons + fully hadronic

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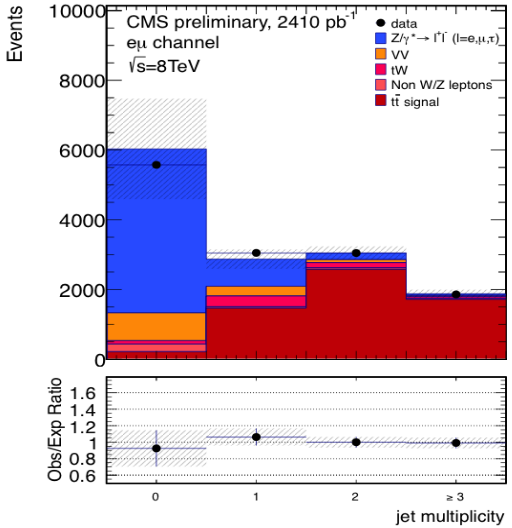
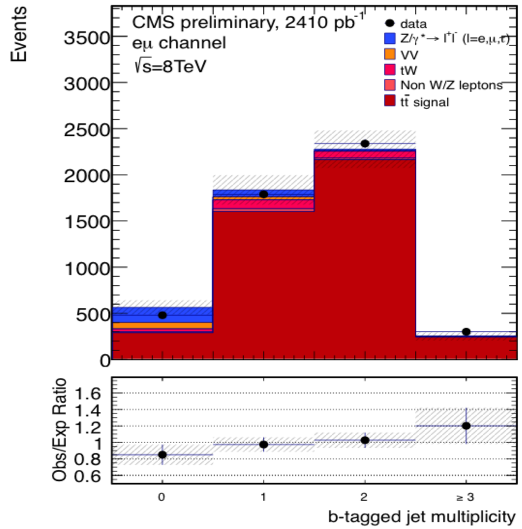


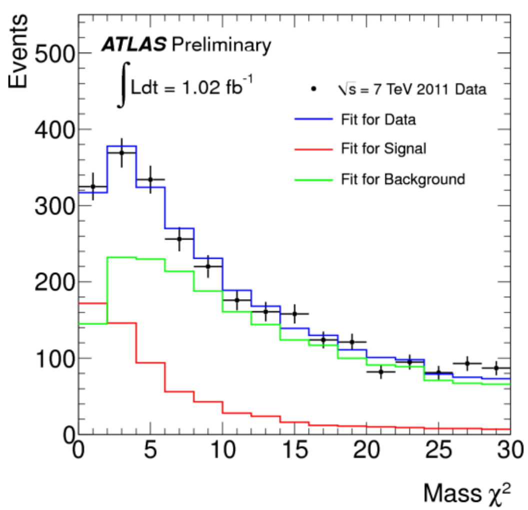


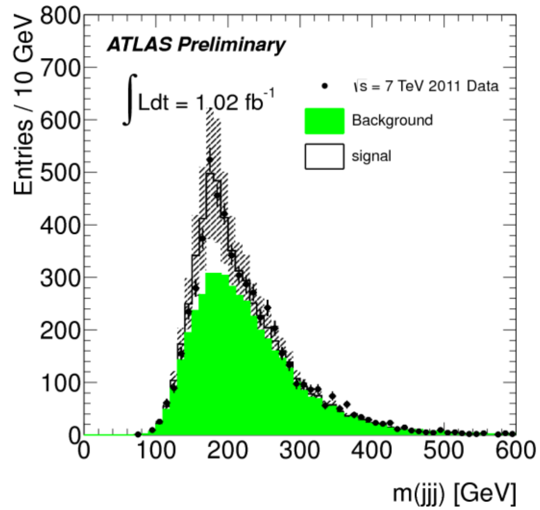
Dileptonic:

Very pure tt – sample

Note: for X-section no need to use any other property

... But loss in statistics





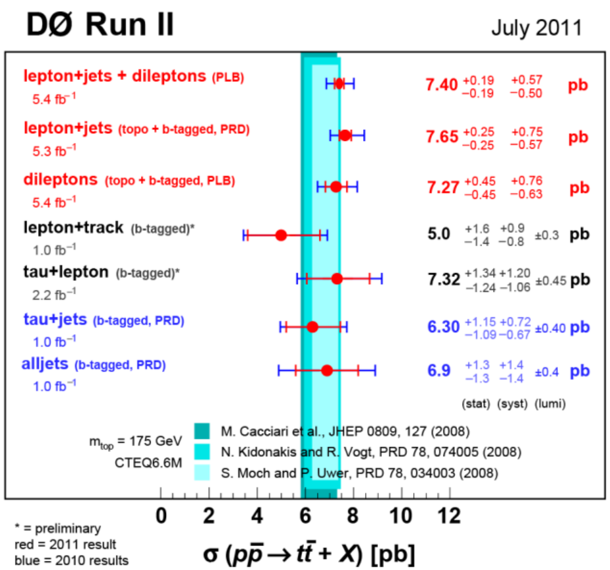
Fully hadronic:

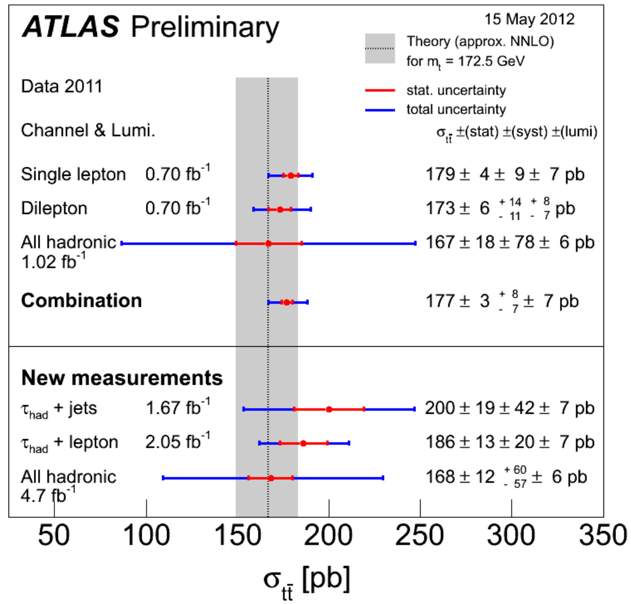
Huge QCD background

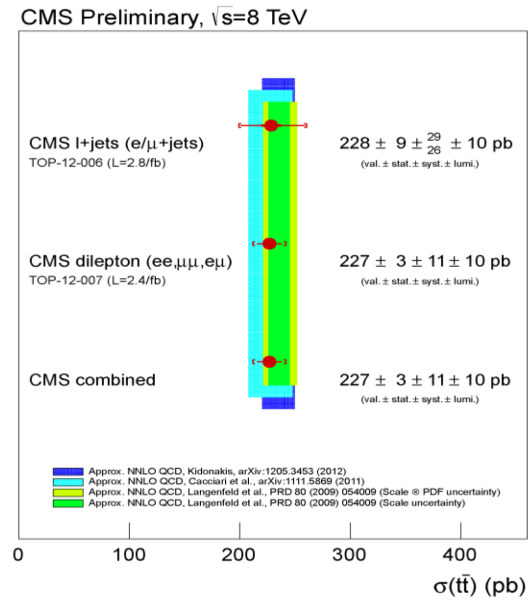
Advantage: M(t), M(W)

➔ Kinematic fit

Summary of Xsection







Dileptonic and semi-leptonic measurements similar precision

All hadronic larger errors

Experiments have smaller uncertainty than theoretical calculation

Cross section measurement

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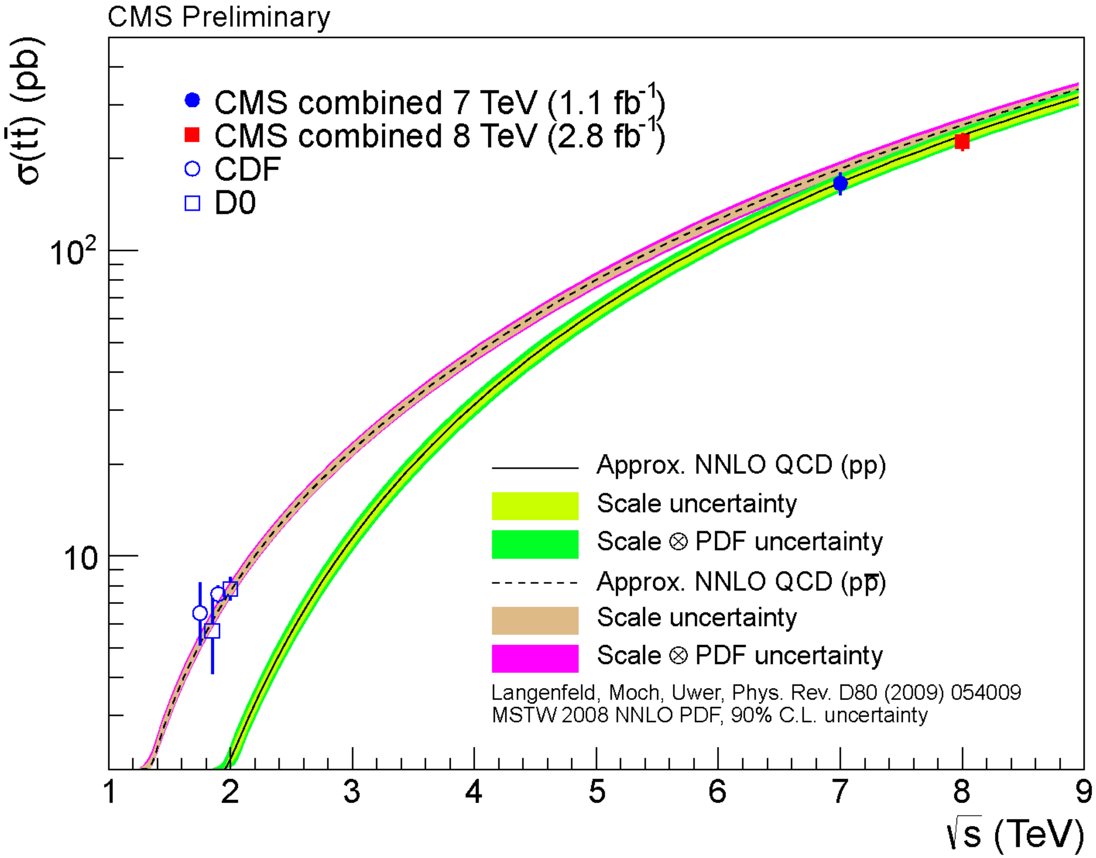
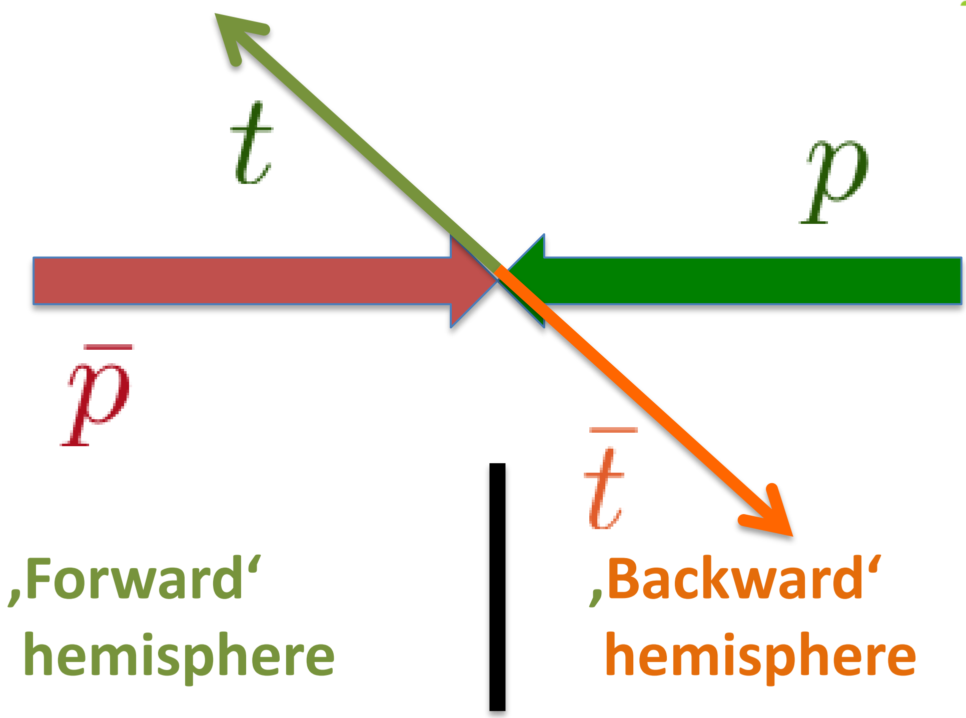


Theoretical uncertainty 7-10% partly NNLO

Theory & experiment uncertainty about equal

Very good agreement between data and expectation

Tevatron fwd-bkw asymmetry



Count

- top quarks in forward hemi N_{fwd}

- top quarks in backward hemi N_{bwd}

$$A_C = \frac{N_{fwd} - N_{bwd}}{N_{fwd} + N_{bwd}}$$

Standard Model: small asymmetry

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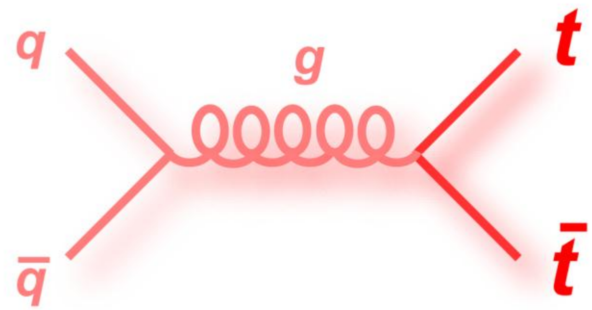


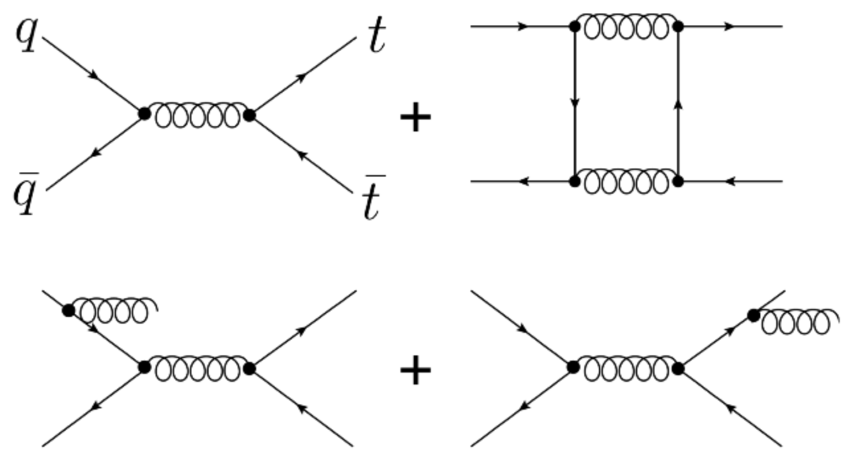
Dominant production @ Tevatron
➔charge direction ‚lost‘

LO: no asymmetry in Standard Model

NLO: Interference ➔ small A_C

Standard Model: (4.8+-0.5)%

C= -1 **C = +1**



Tevatron: larger asymmetry

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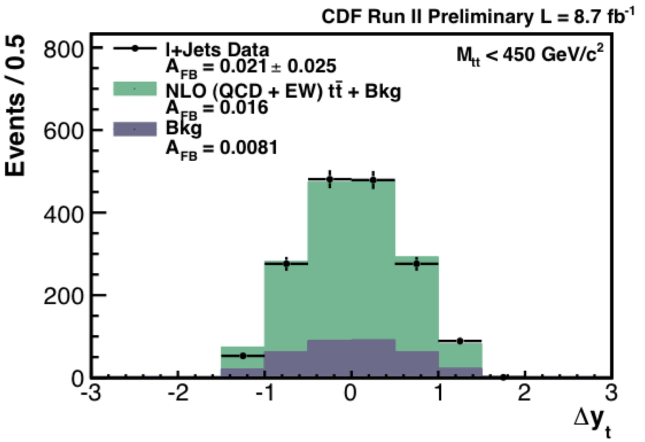

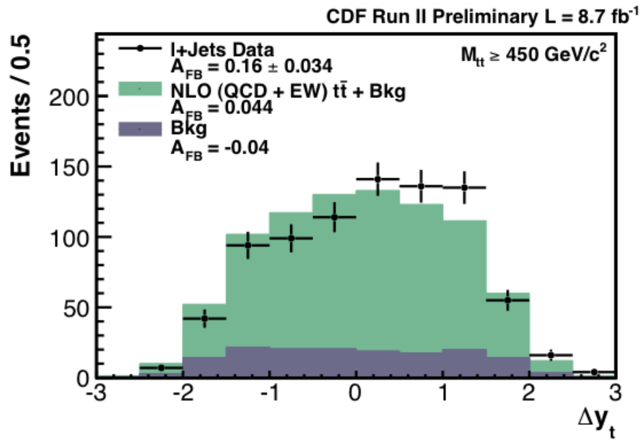

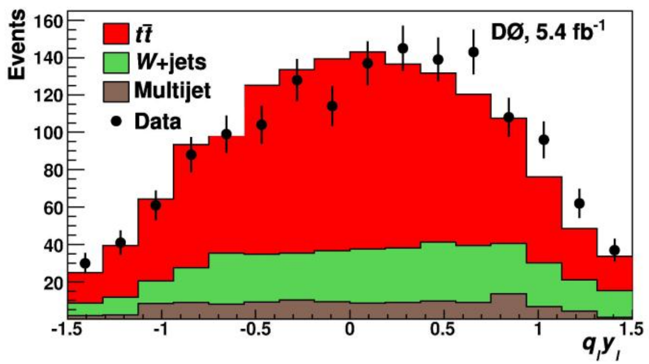

More events with $q_{top} \cdot y_{top} > 0$

Low mass: consistent with Standard Model

Masses > 450 GeV 3 – 4 σ deviation from expectation

A_{FB} vs m_{tt}

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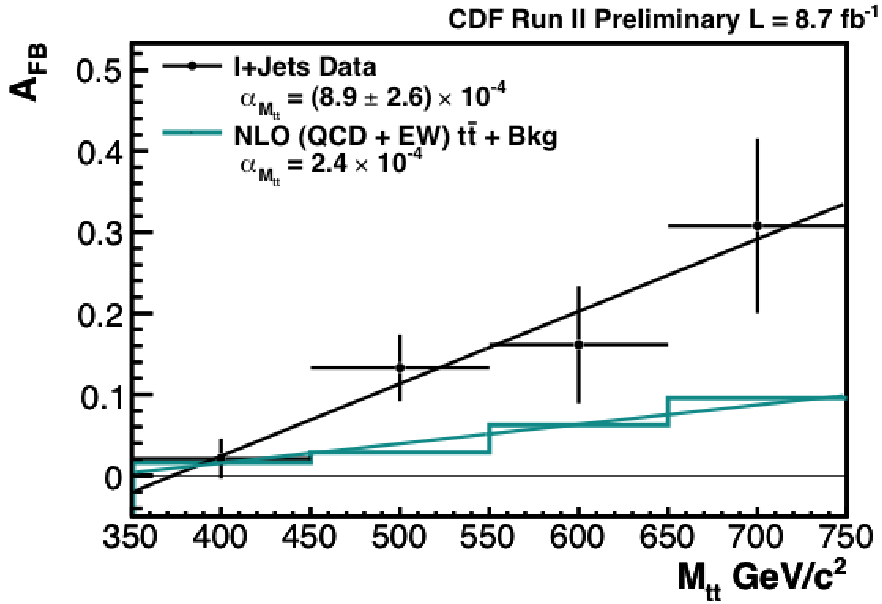

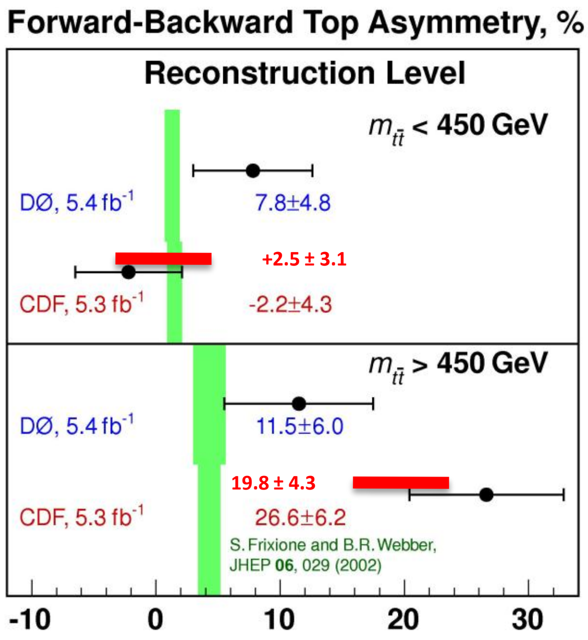

Note:These are earlier CDF results!!

Low mass: consistent with Standard Model

Masses > 450 GeV 3 – 4 σ deviation from expectation (CDF)

A glimpse of multi – TeV physics?

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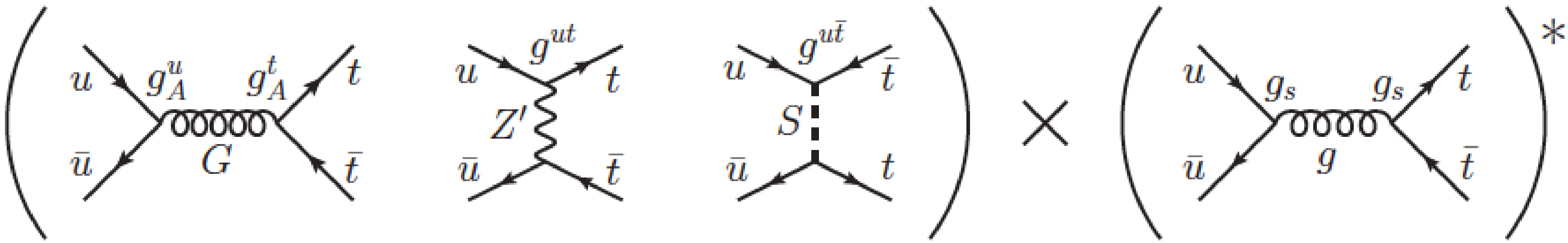
BSM interpretation:

asymmetry due to interference high mass particle + Standard Model



Type 1:
Gluon with
axial coupling

Type 2:
t –channel
Colour neutral
vector
with FCNC

Type 3:
t –channel
coloured
scalar
with FCNC

Such massive particles should become visible @ LHC

$t\bar{t}$ – asymmetries @ LHC

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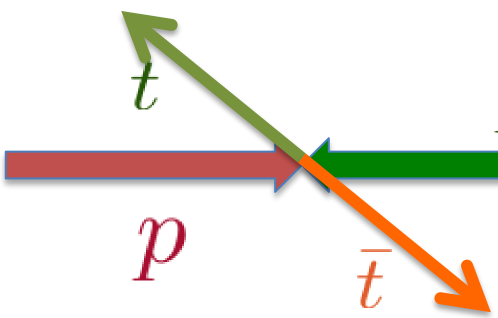
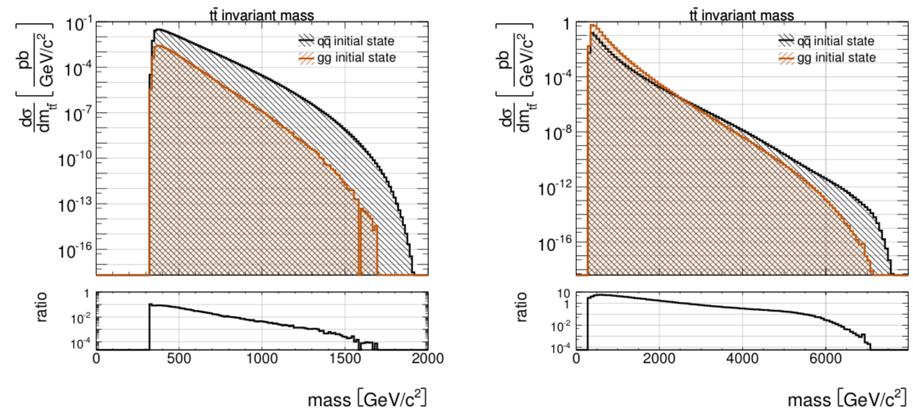
Differences: pp – collider, symmetric initial state



Tevatron → LHC

qq → tt to gg→tt

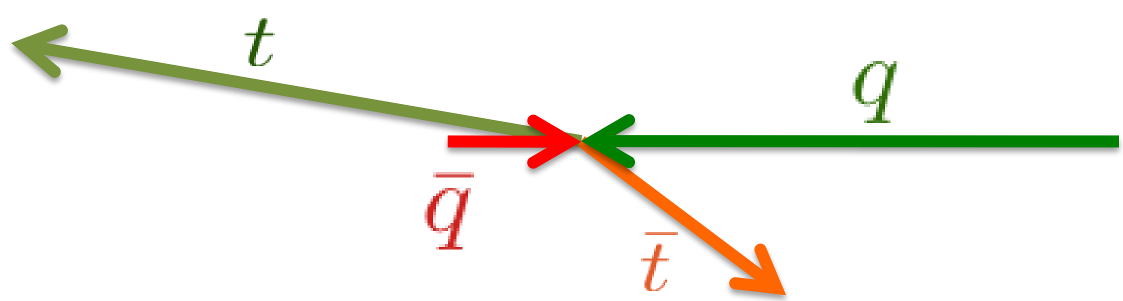


Tevatron   LHC 8 TeV

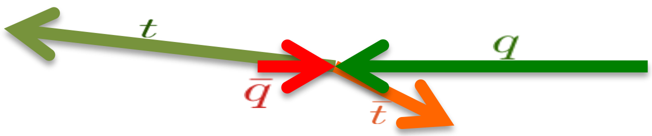
Enhance qq production by large Δy

high x valence quark on

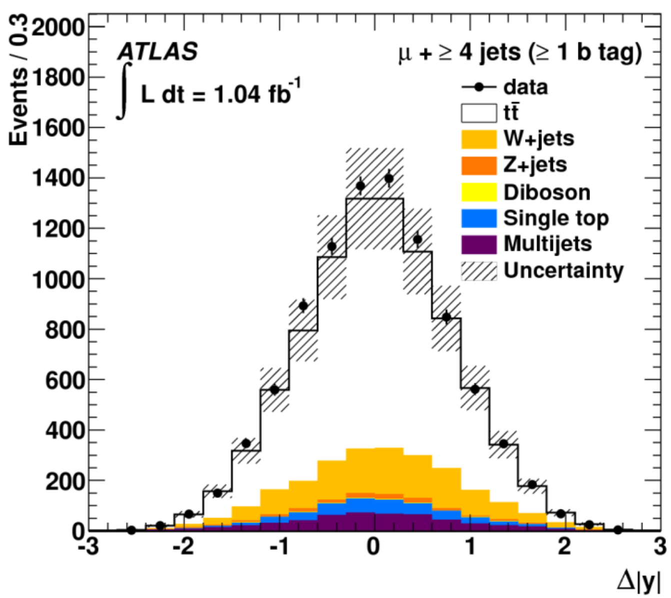
low x sea anti-quark

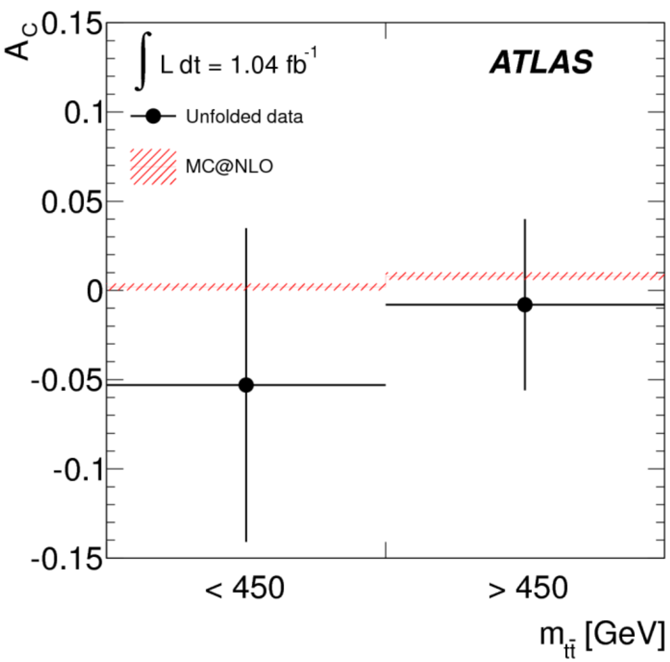


tt – asymmetries @ LHC



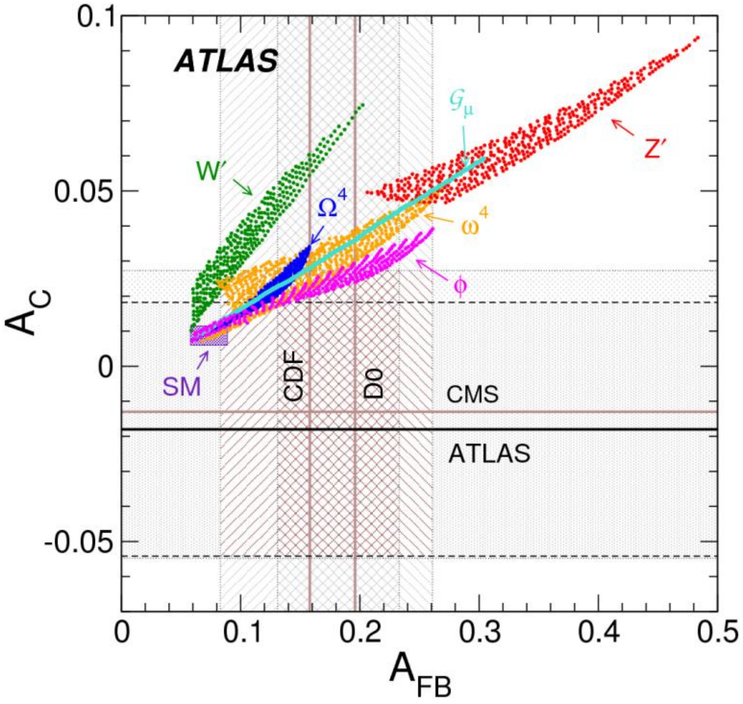
$$A_c = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

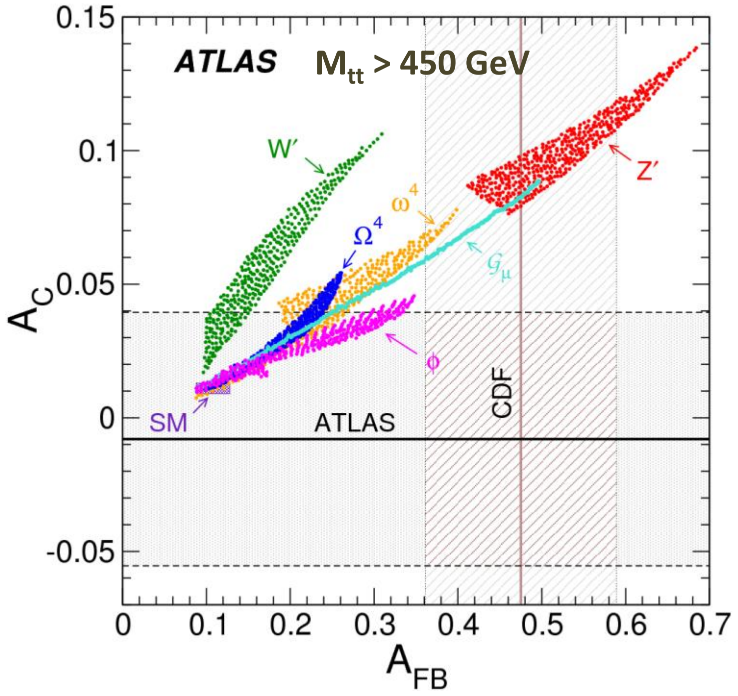




Interpretation in models

For concrete model: compare Tevatron & LHC
vary mass and couplings of new particles





Many of the ‚Tevatron' allowed models disfavoured by ATLAS (and CMS)

Jets in top events

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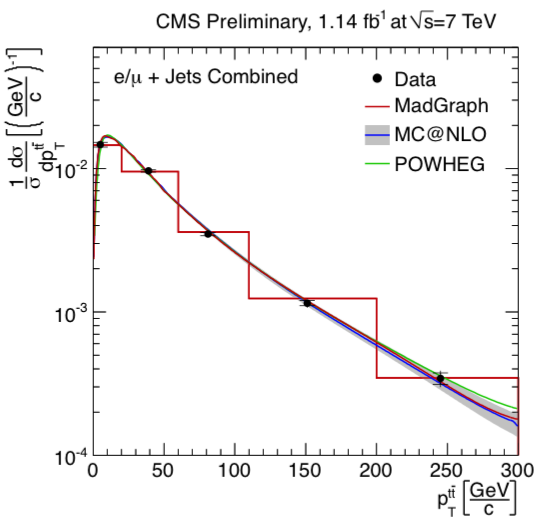
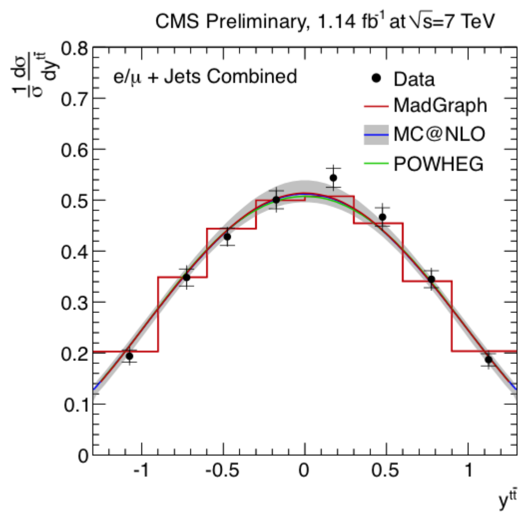
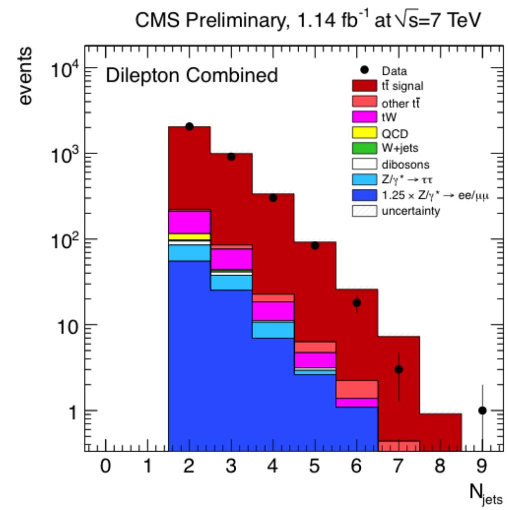
QCD effects imply a potential strong bias to studies







Production properties:
p_T and y of tt – system
Good description by QCD calculations

Jet multiplicities:
Deficiencies at higher N_{jets}

Mass spectrum of tt - events

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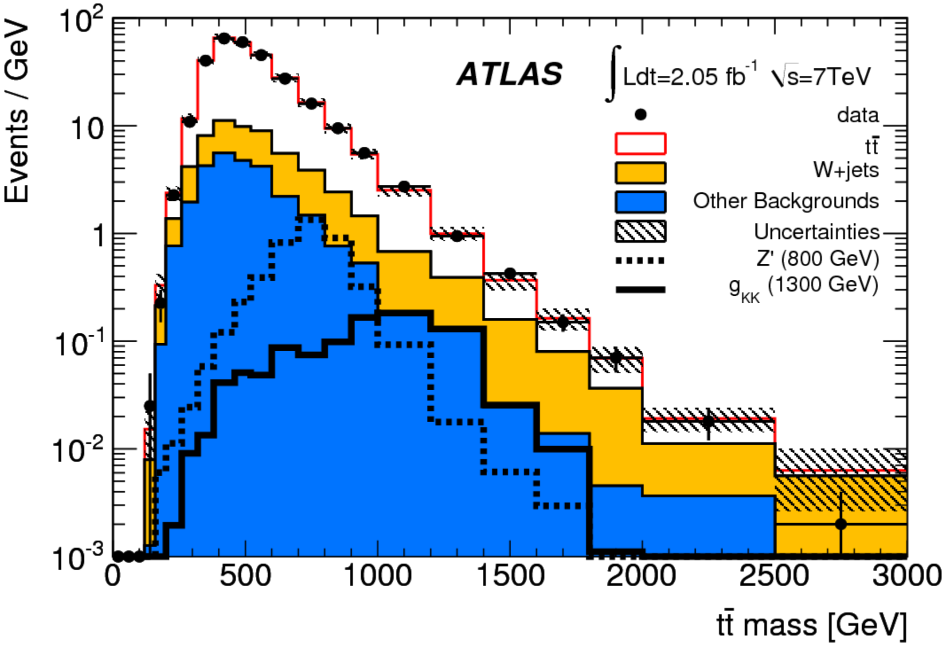
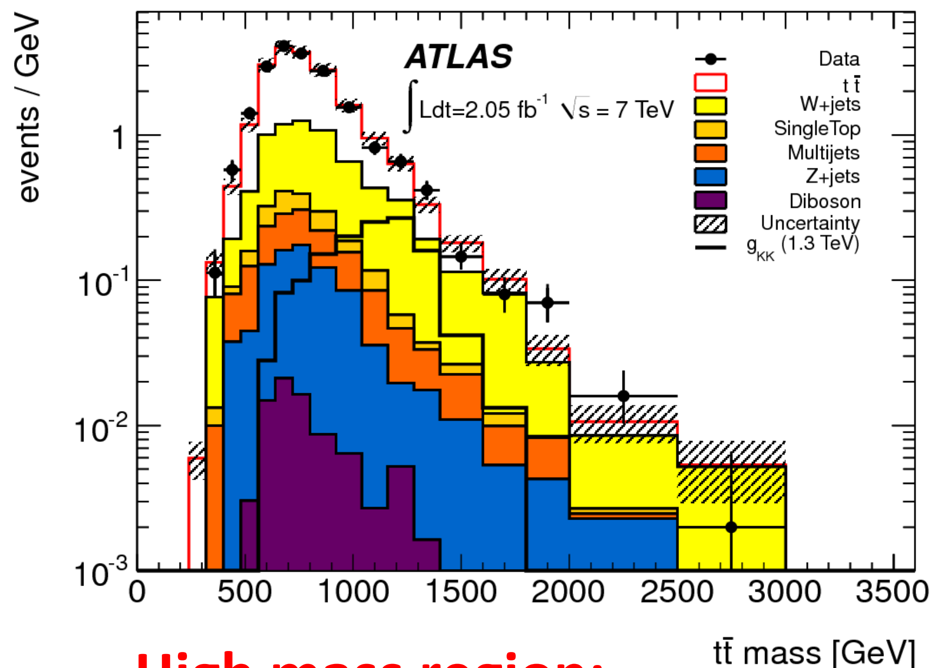
p_T of top quarks & mass of tt – pairs predicted by QCD





‚Resolved' four jet (+ lepton, ν)
Standard top selection

High mass region:
Boosted tops ➔ merged jets
Appropriate algorithms required

Production properties: e.g. M_{tt}

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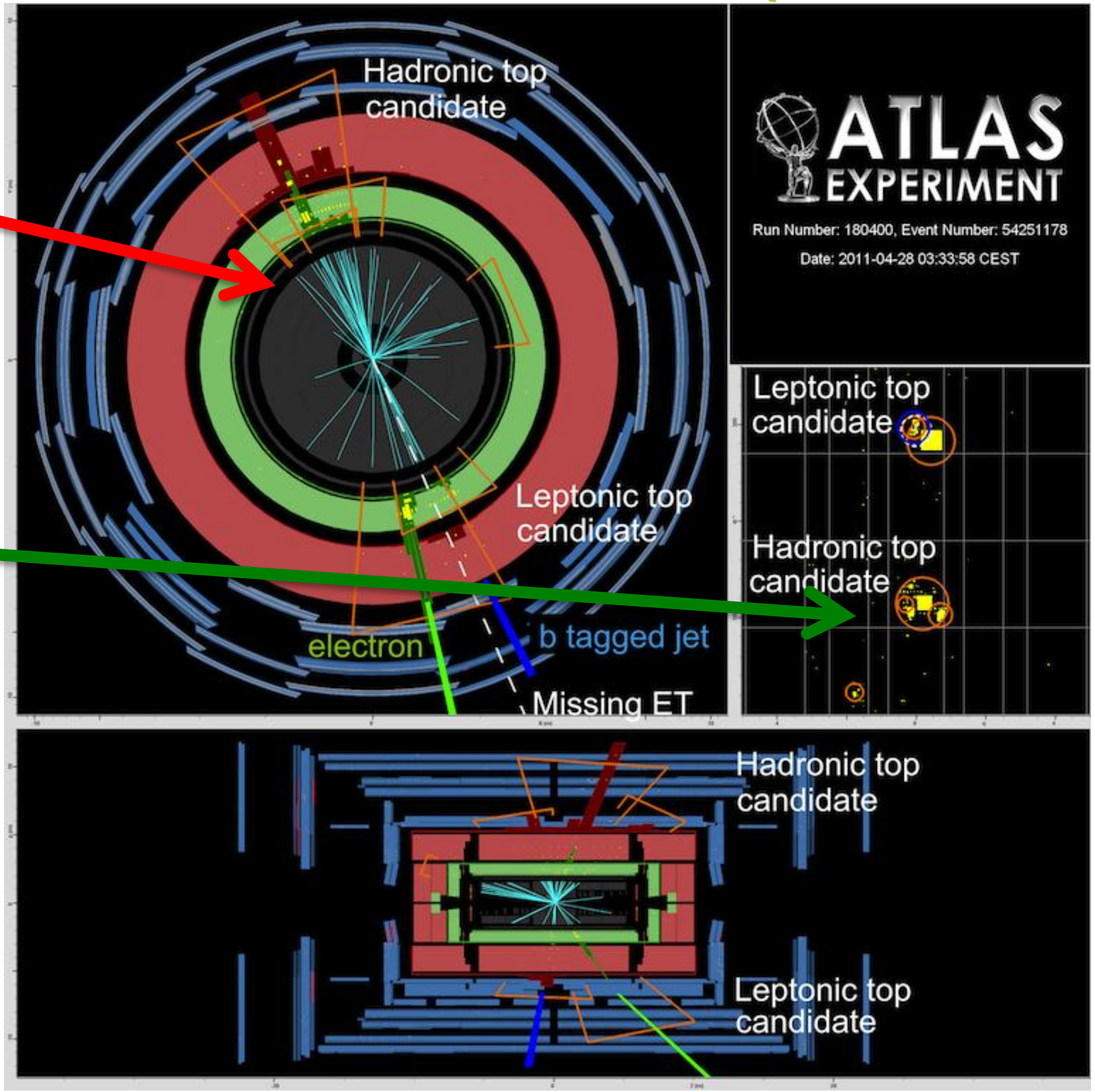
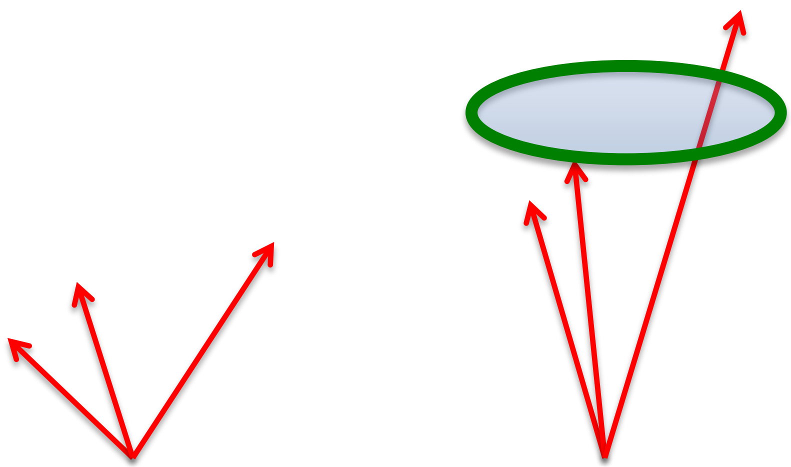
‚Fat jet'

Closer look shows substructure



Fat jet & substructure

Highly boosted tops: close by jets → ‚Fat jet‘ of R = 1.0

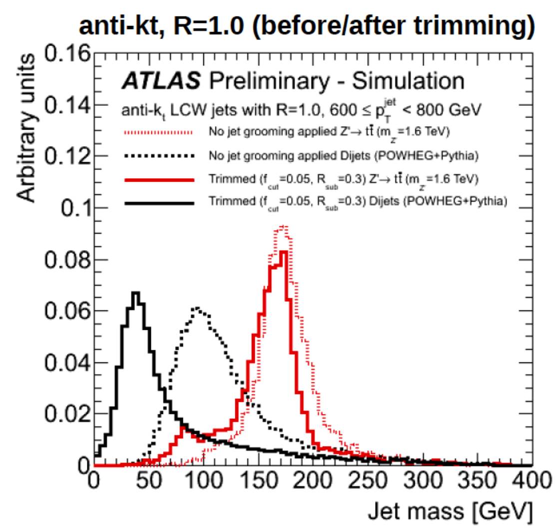


Require: $M_{fat\ jet} > 100$ GeV

Next step: look for substructure

- use k_T jet finder to ‚uncluster‘
- $d_{ij} > (40\ \text{GeV})^2$

Require opposite jet/lepton system



Possible improvements: trimming of jets:
Reject any subjet with some $p_{T,i}/p_{T,jet} < f_{cut}$

Models predict resonances X→tt

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spin [$\hbar$]	colour represen-tation	parities $(1, \gamma_5)$	type	Interference	example
0	[1]	(1,0)	scalar colour singlet	+	SM, MSSM, 2HDM
0	[1]	(0,1)	pseudoscalar colour singlet	+	MSSM, 2HDM
0	[8]	(1,0)	scalar colour octet		techni-π^0
0	[8]	(0,1)	pseudoscalar colour octet		techni-π^0
1	[1]	(SM,SM)	excitation of Z^0		sequential Z'
1	[1]	(1,0)	vector colour singlet		
1	[1]	(0,1)	axial vector colour singlet		
1	[1]	(1,1)	left-handed vector colour singlet		
1	[1]	(1,-1)	right-handed vector colour singlet		
1	[8]	(1,0)	vector colour octet	−	coloron, KK gluon
1	[8]	(0,1)	axial vector colour octet		axigluon

Models predict resonances X→tt

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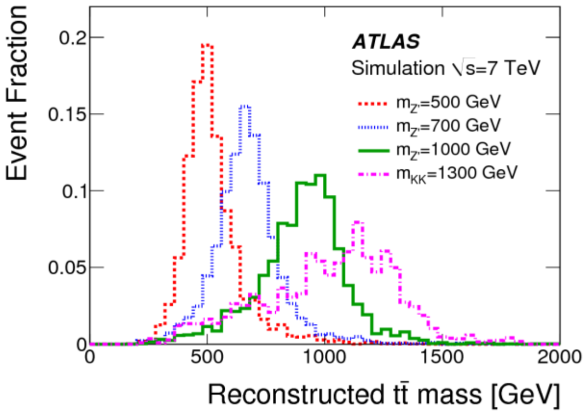
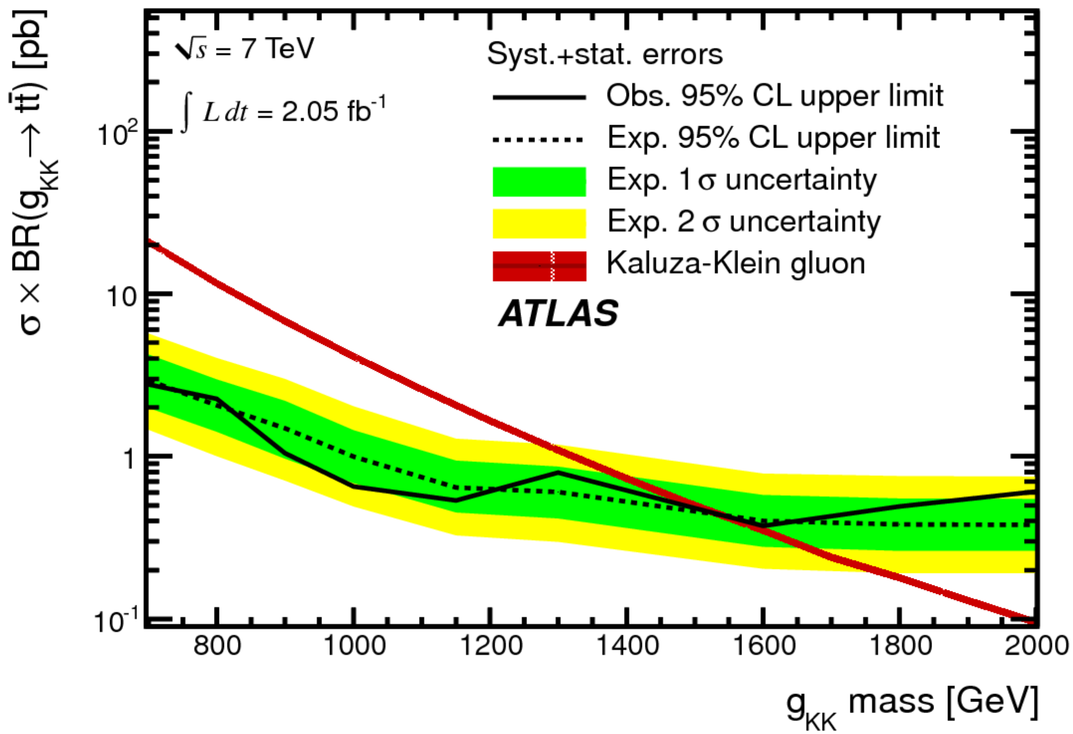


Higher masses:
long tails due to gg/qq luminosity

Example:
5 dim theories, Randall – Sundrum etc. predict Kaluza – Klein gluons



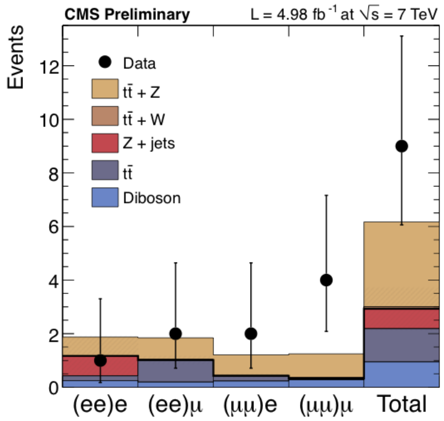
No significant resonance
→ M_{KK} > 1.5 TeV

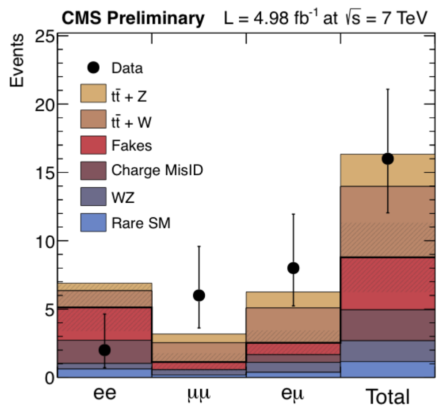
tt + Z/W events

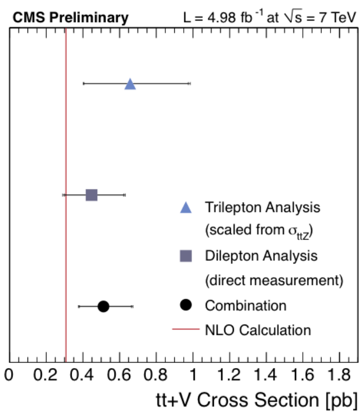
Measurement of Ztt & Wtt coupling
Possible resonance search or heavy quark
Important background for SUSY searches

Search for

a. (Z→ll)+l+b(b), ➔ ttZ
b. equal charge lepton pair + b(b) ➔ ttW/Z







Expected low X- section, fair agreement with expectation

Is the top quark a normal fermion?

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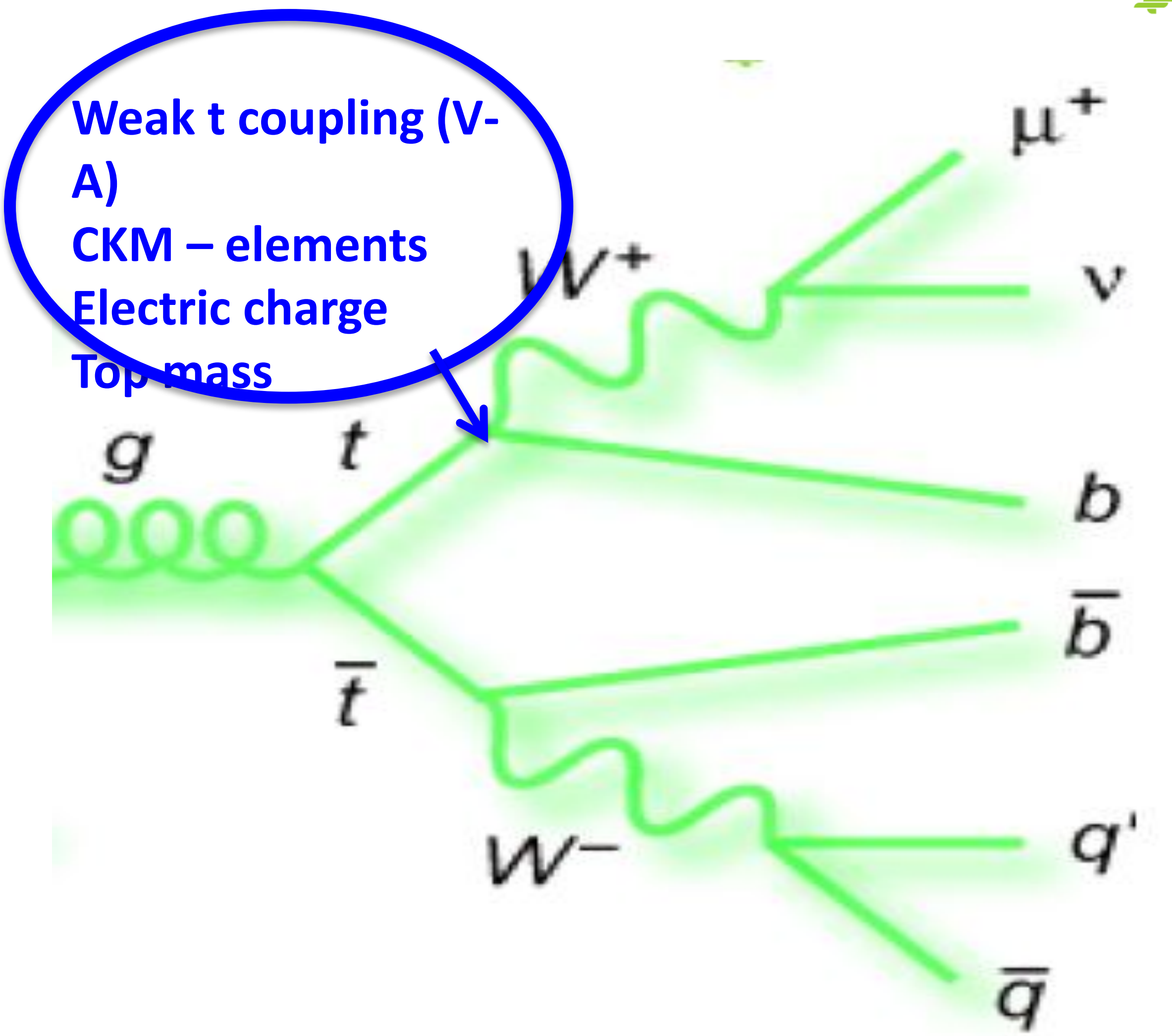
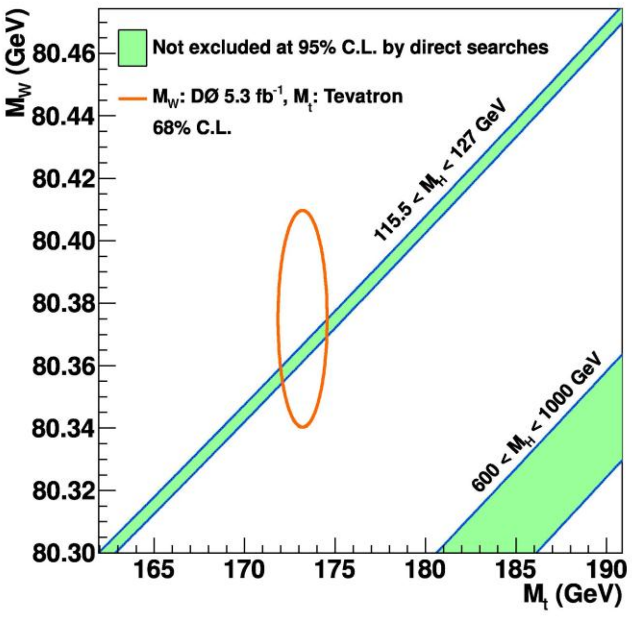


Mass of the top quark

A fundamental parameter of the Standard Model



A broad spectrum of decays and methods

Note: first time a quark mass can be measured directly

(Lighter quarks to be inferred indirectly from hadron masses)

Top mass from l+jet decays

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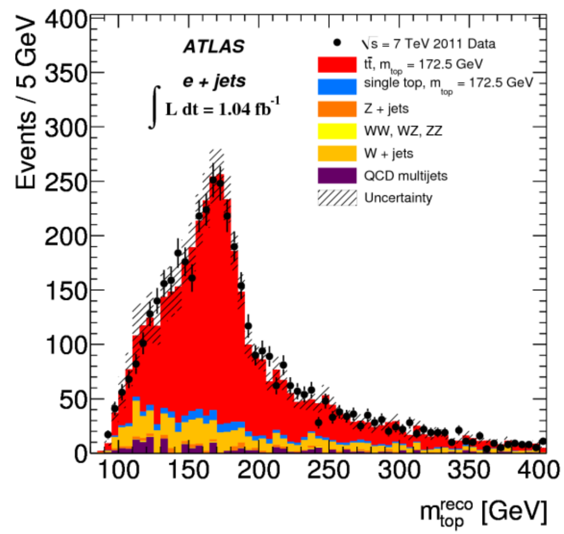
Favoured topology: $t\bar{t}$ ➔ 4 Jets (2 b –jets) + e/μ + ν



$$M^2 = (\sum_{jet\ i} E_{jet\ i} + E_l + E_\nu)^2 - (\sum_{jeti} \tilde{p}_{jeti} + \tilde{p}_l + \tilde{p}_\nu)^2$$

The problems:

- How to get the z – component of ν
- Out of 4 (or more) jets: which jet belongs to which top?
- What is the energy scale of jets (and electrons)

Problem 1: $p_z(\nu)$

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Constraint from W - mass

$$M_W^2 = (E_l + E_\nu)^2 - (p_x(l) + p_x(\nu))^2 - (p_y(l) + p_y(\nu))^2 - (p_z(l) + p_z(\nu))^2$$

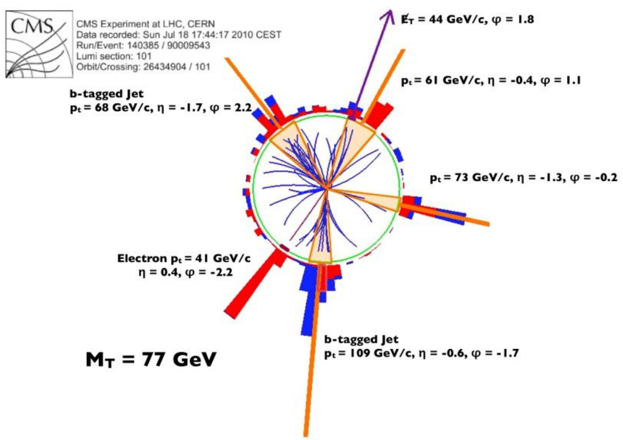
$$E_\nu = \sqrt{p_x^2(\nu) + p_y^2(\nu) + p_z^2(\nu)}$$

Note: ν – mass completely negligible

Quadratic equation → 2 solutions

physics: in 70% the solution with smaller p_z correct

Problem 2: which jets?



Two facettes:

- **if more than 4 jets (initial state rad.)**
  mostly jets with highest p_T
- **if exactly 4 jets: which belongs to which top quark?**

4 jets ➔ 4 possible assigments

($j_A j_B J_C / j_D$, $j_A j_B j_D / j_C$, ...)

Note: if b – jets identified, reduced to 2 possibilities

Important constraints

- **mass (jjj) = mass(jlν) (= M_t)**
- **mass (jj) = M_W**

Problem 3: jet energy scale

Measure signals in calorimeter ➔ derive jet energy

Implies uncertainty!

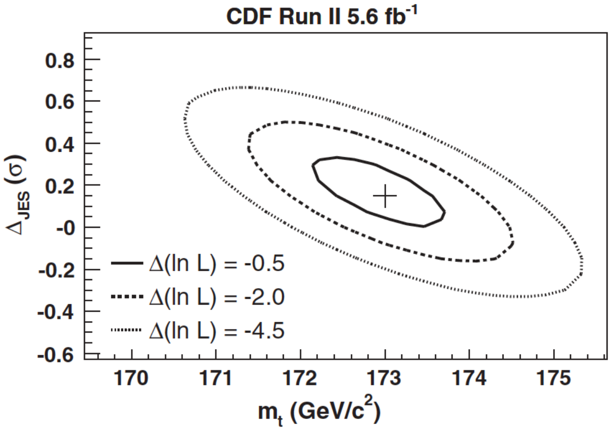
➔ relates directly to top mass

$$M^2 = (\sum_{\text{jet } i} E_{\text{jet } i} + E_l + E_\nu)^2 - (\sum_{\text{jet} i} \tilde{p}_{\text{jet}i} + \tilde{p}_l + \tilde{p}_\nu)^2$$

Top – quarks offer ‚self calibration'

M(jj) has to be equal M_W

➔ change JES such that fulfilled



Still the (slightly) dominant uncertainty of M_t

Most precise: matrix method

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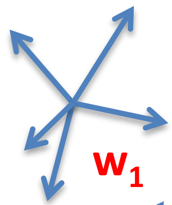
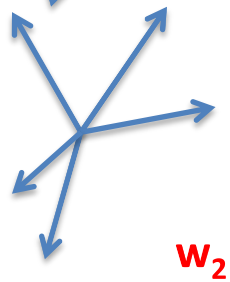
Theoretical pred with M_1(top)

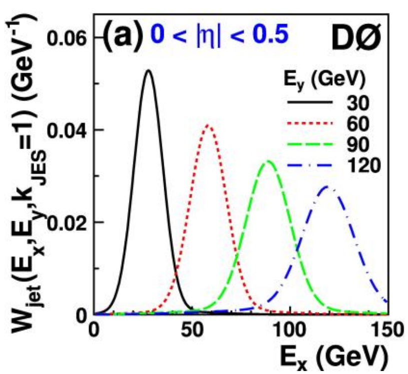


Theoretical pred with M_1(top)



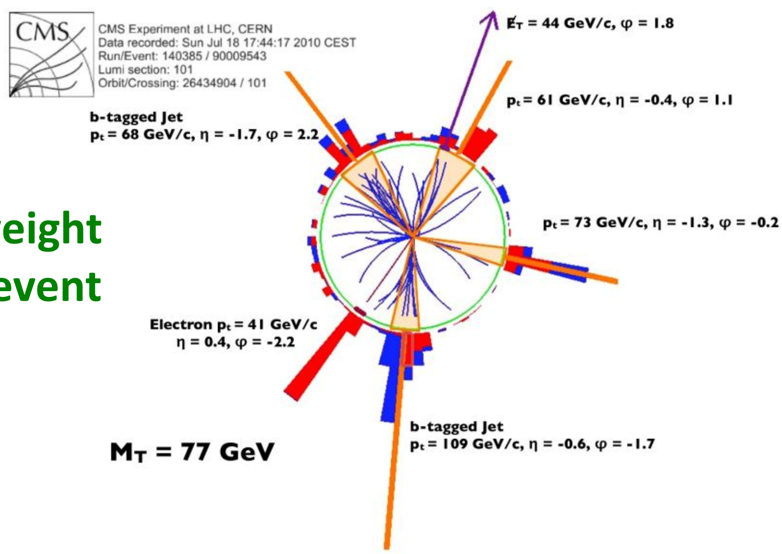
➔probability density for M_1
use 24 integration variables

Next step: convolute with exptl. effects

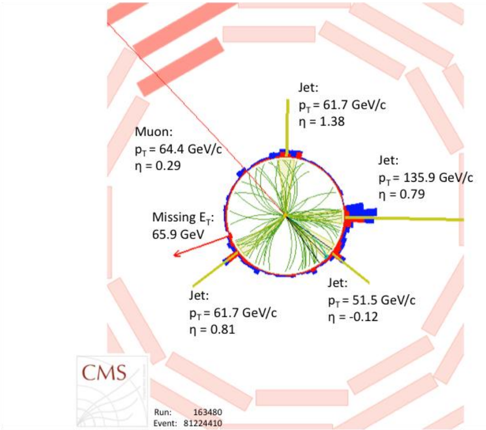


Example: energy resolution

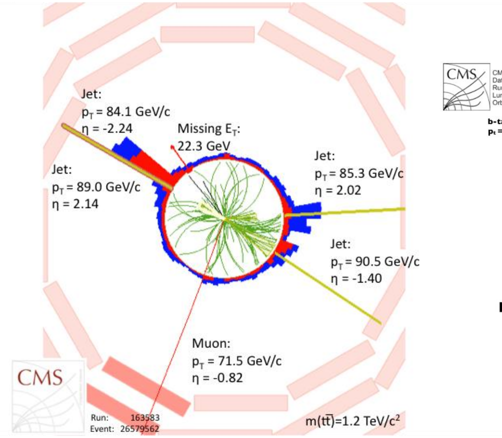
➔Assign weight to each event



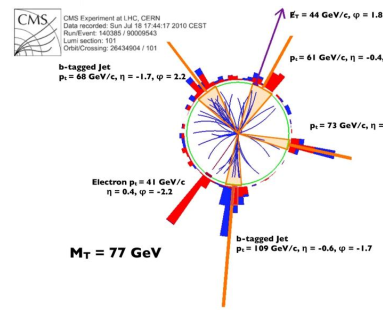
Likelihood from different masses



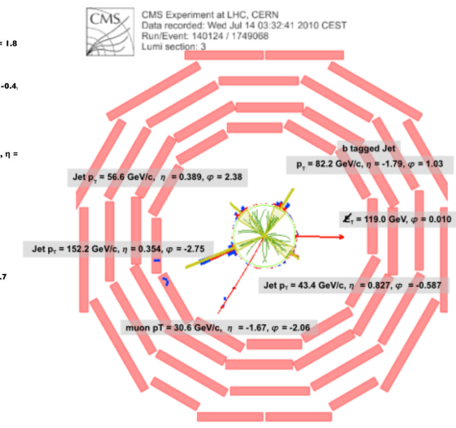
w_A



w_B



w_C



w_D

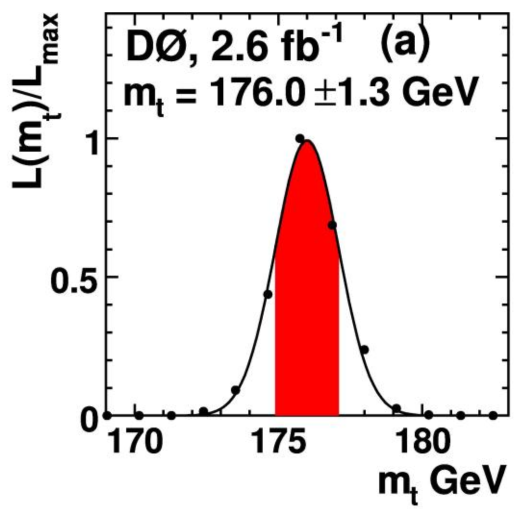
Sum over all events and find combine weights

$$W(M_1(top)) = w_A \cdot w_B \cdot w_C \cdot ...... = \Pi w_i \Longrightarrow \mathcal{L}(M_1(top))$$

$$W(M_2(top)) = w_A \cdot w_B \cdot w_C \cdot ...... = \Pi w_i \Longrightarrow \mathcal{L}(M_2(top))$$

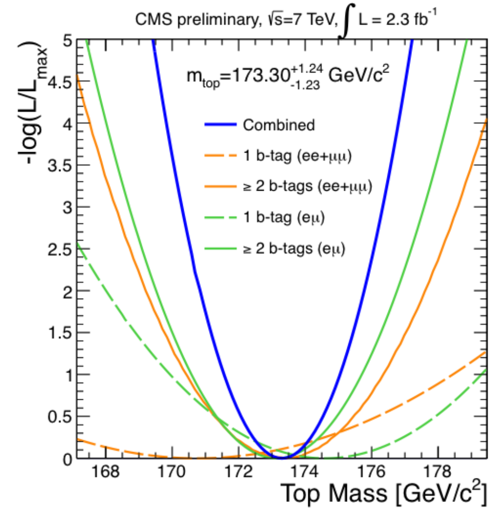
......

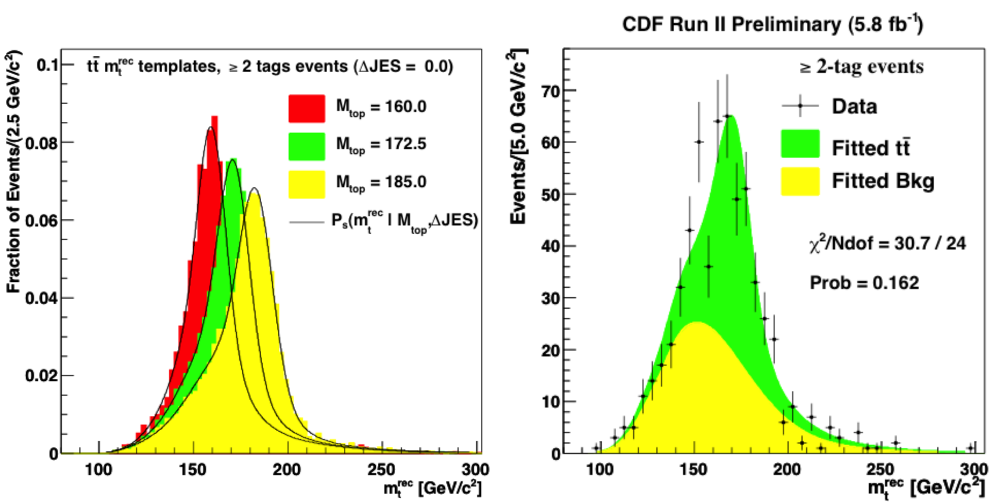
Find M(top) with maximum weight



Top mass from dileptons & hadronic

Dileptons:
No direct mass peak visible
➔ use energies of electrons (& bottom jets)
➔ using MET adjust neutrino energies to yield same M_W and M_{top}





All hadrons:
Fight huge background
➔ suppress by neural network

Measurements of M_{top}

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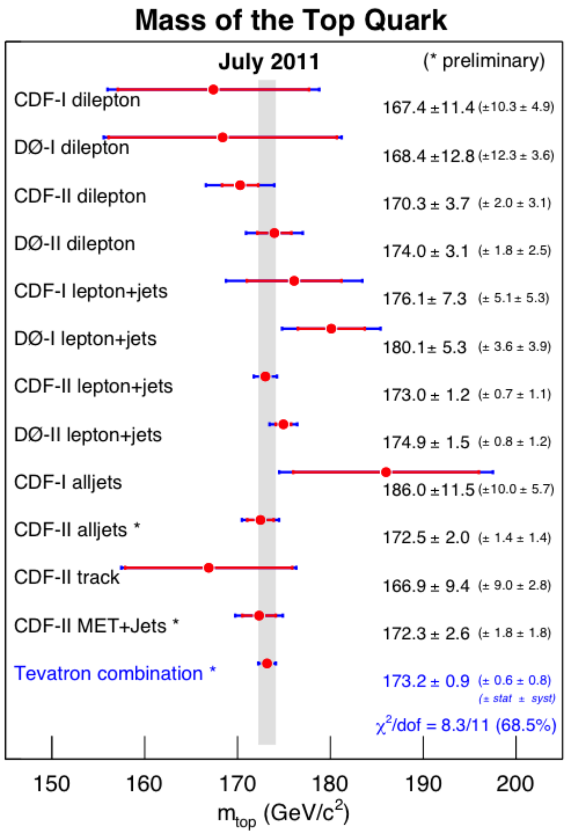

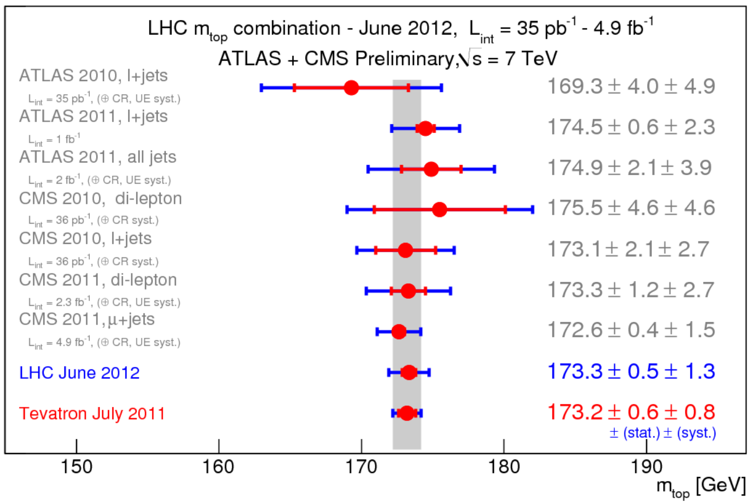

A lot of measurements, a lot of methods

all decay channels by now better than 2 GeV!

Combination 173.2±0.6±0.8 GeV

How to interpret result?

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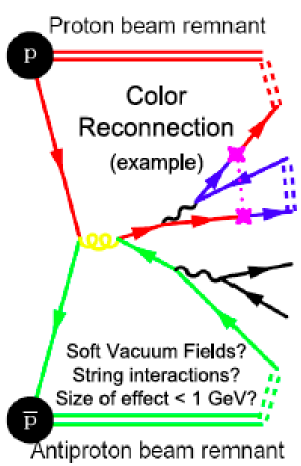
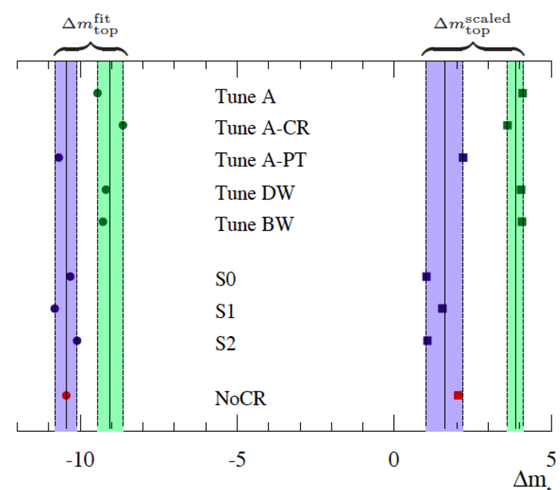
For Standard Model fit → ‚pole mass' required
Instead: all methods based on simulation of QCD effects of mass

‚top quark not totally free':
colour flow - how does this affect mass determination?

e.g. colour reconnection



Different models→ mass differences of a few GeV



Skands&Wicke

Top mass from cross section

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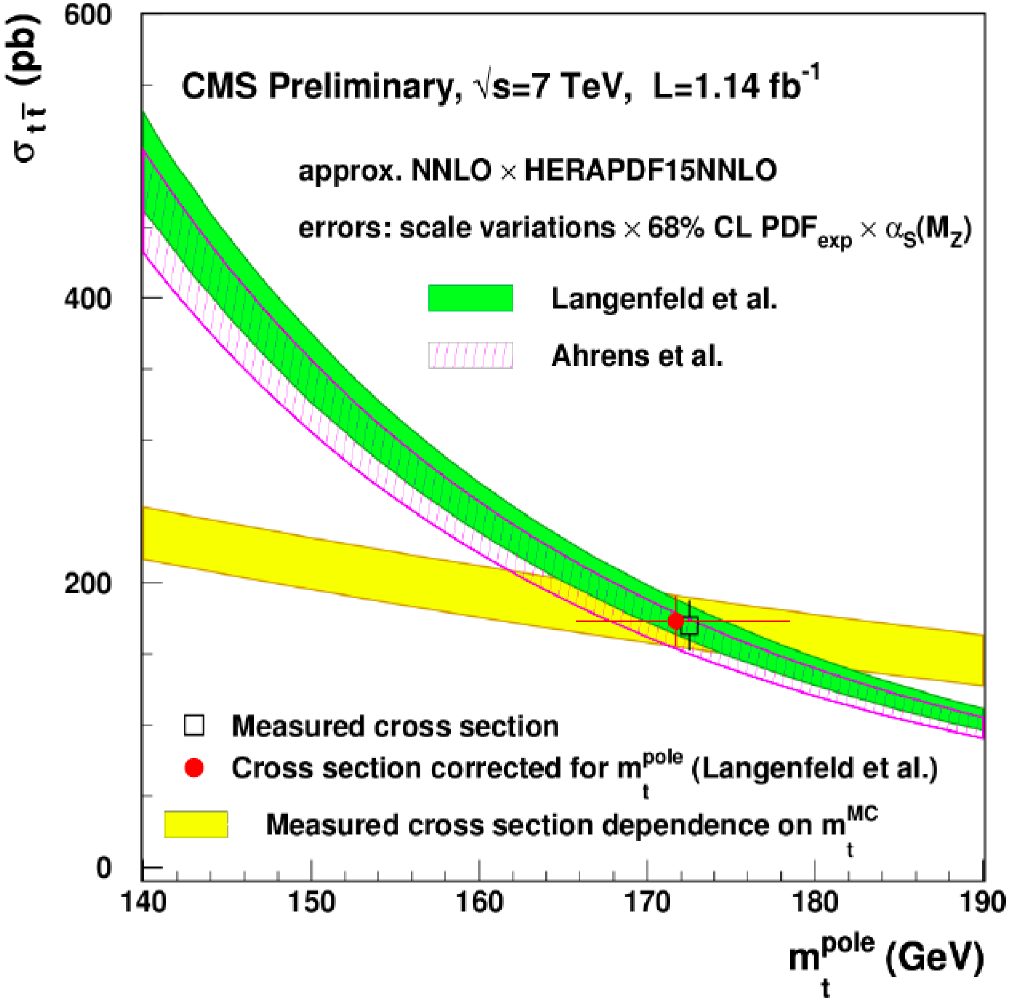

Mass measurements based on MC simulation

→ **not well defined QCD corrections**

Difficult to interpret in Electroweak fits

→ **pole mass from NNLO calculations on Xsection**

Current results

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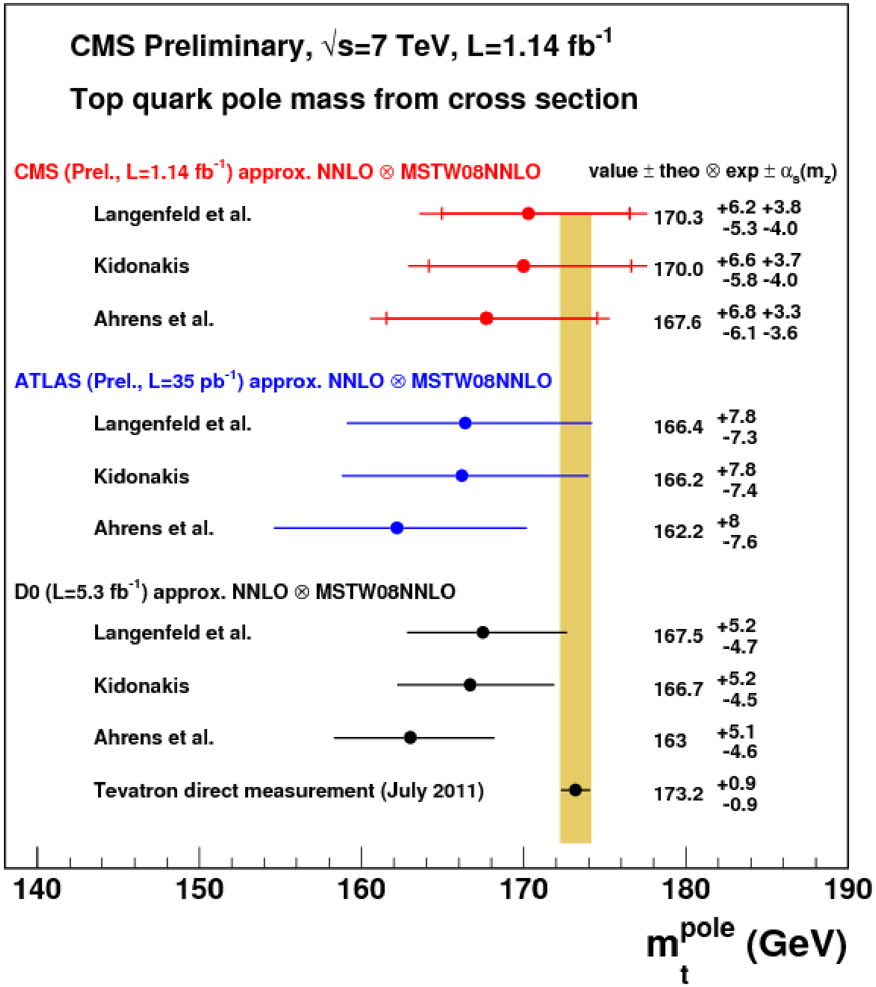

Theoretically better motivated

But errors of ~ 5 -8 GeV mostly due to theory uncertainty

note: MS – mass around 160 GeV!

Speculations about the top mass

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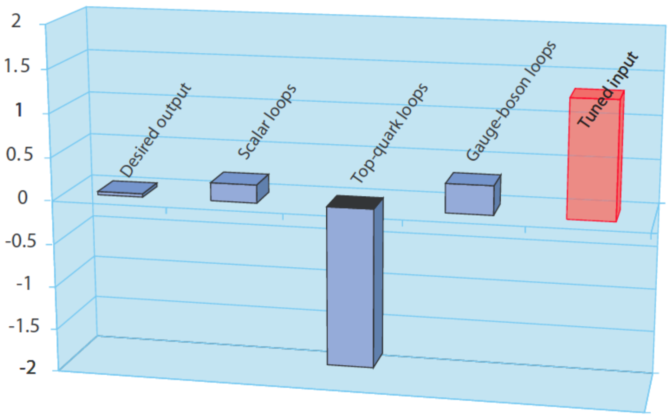
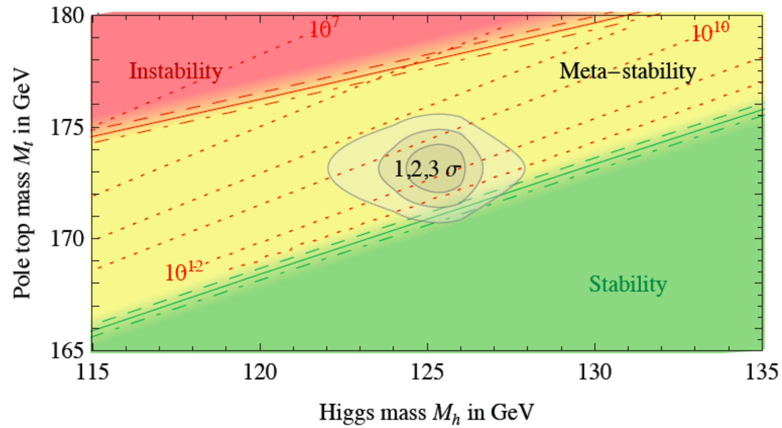
Top mass and the 10^{18} GeV scale





Naturalness problem:
Renormalising the Higgs mass
Contributions to Δm_H
➔ ‚most relevant' compensate top

Higgs potential:
$\lambda(m_H)$ = 0.125 (+uncertainties)
➔ $\lambda(Q^2)$
If $\lambda < 0$ ➔ universe unstable

Nice to speculate .....
But can we really extrapolate safely over 14 orders of magnitude?

Helicity structure of top decay

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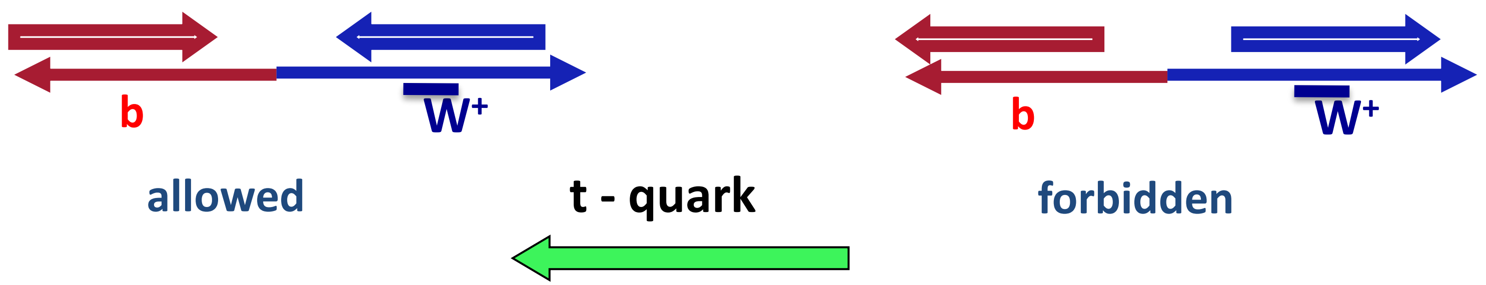
Is the top a normal weakly decaying particle?
Note: first time helicity structure of quark can be determined



W – polarisation against direction of t – quark momentum
Longitudinal polarosation also possible

Polarisation reflected in decay angle of fermions

Helicity structure of top decay

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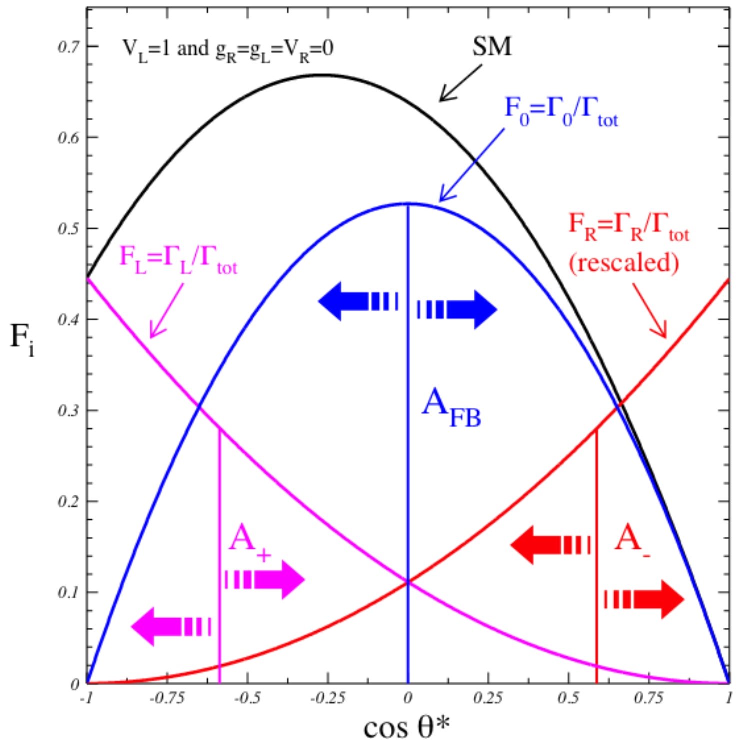
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^*} = \frac{3}{4}(1-\cos^2\theta^*)\cdot F_0 + \frac{3}{8}(1-\cos\theta^*)^2\cdot F_L + \frac{3}{8}(1+\cos\theta^*)^2\cdot F_R$$

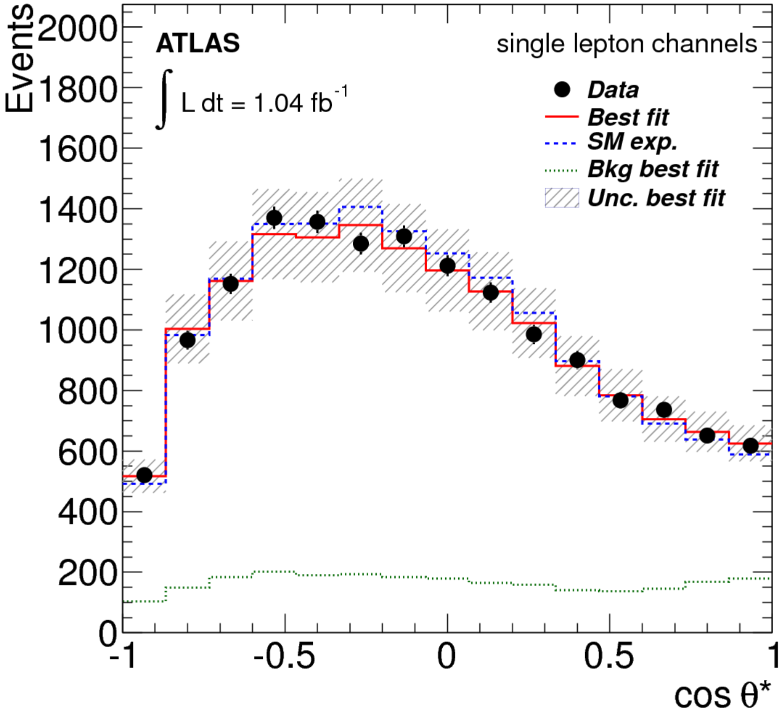


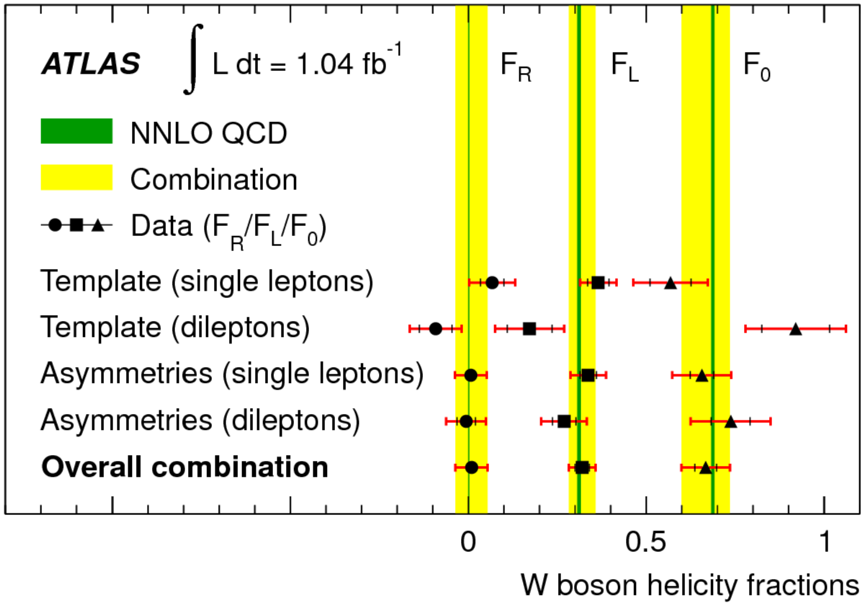
Rather straight forward for e, μ

For W → qq identify q vs. $\bar{q}$
Challenging!

angle related to lepton energy, M_{bl}, ...

Measurements





Agreement with NNLO expectation:
‚no' right handed W's, most W's are longitudinal

Limits on additional couplings

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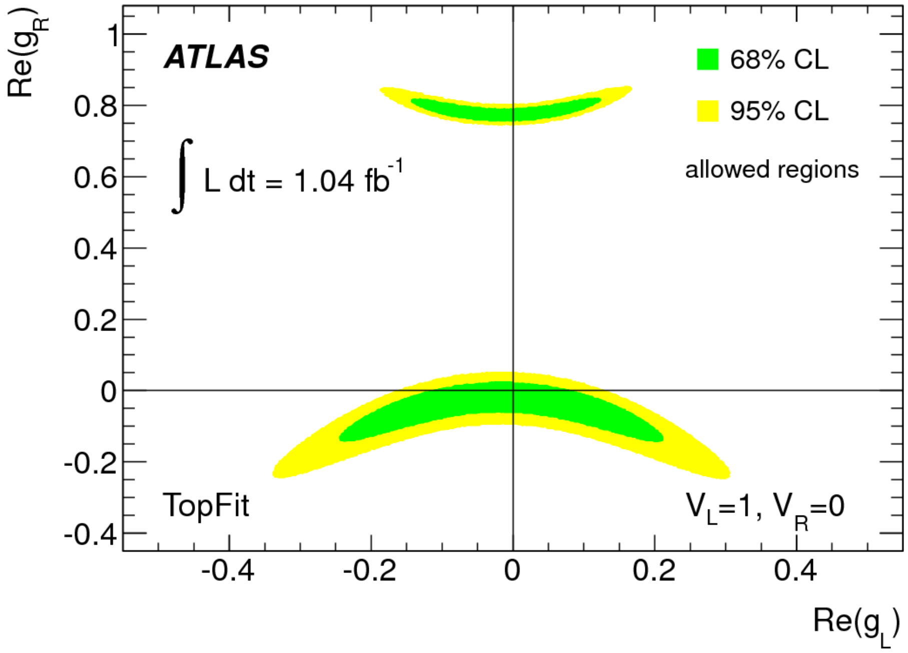
Several BSM models → deviations
General approach Effective Lagrangian:
Parametrisation into higher dimension operators



g_L, g_R:
left/right handed coupling of dim-6 operator

Top spin correlations @ LHC

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‚Bare' quark → direct information on spin configuration
Spin correlations offer test of production of tt – pairs
Potentially important tool to identify new particles

Close to threshold:
S = 0 state, gluon helicities like

↑↑ ↓↓

Top spins aligned

High tt masses:
gg → tt: helicity conservation

↓↑ ↓↑

Top spins opposite

Use leptons to identify spin directions and correlations
Dilepton decay needed → rest system cannot be determined

Experimental method

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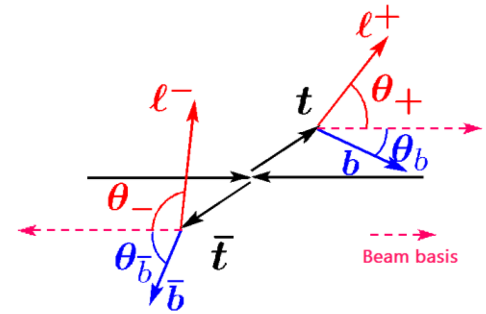
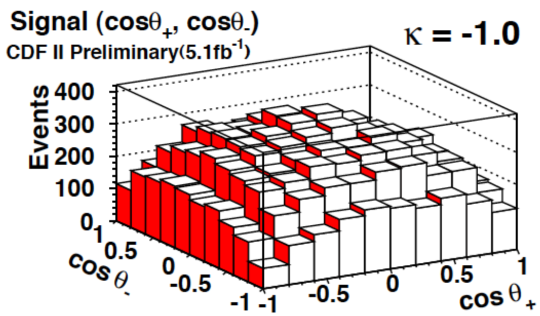
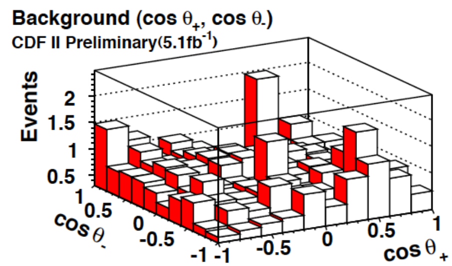
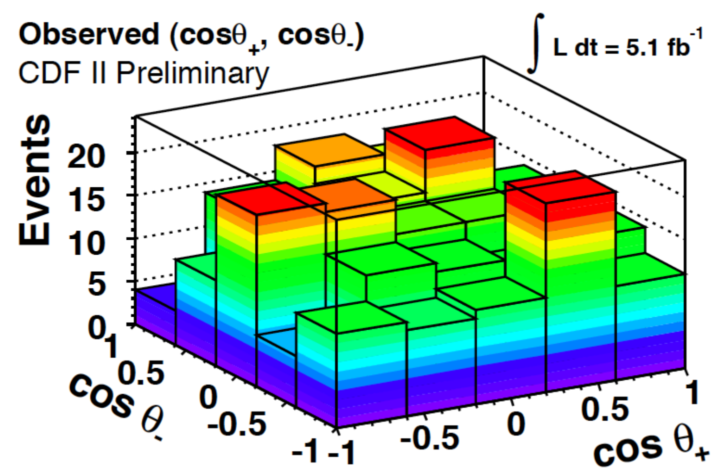
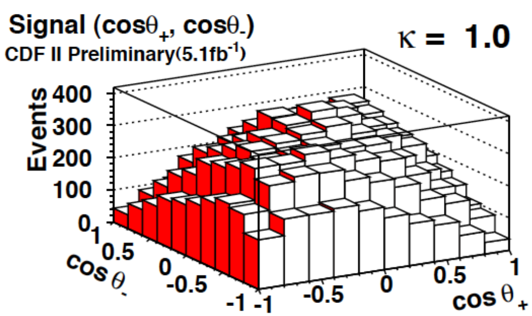


Define quantisation axis, e.g. beam









a*Signal templates + b* background template = DATA

Spin correlations @ Tevatron

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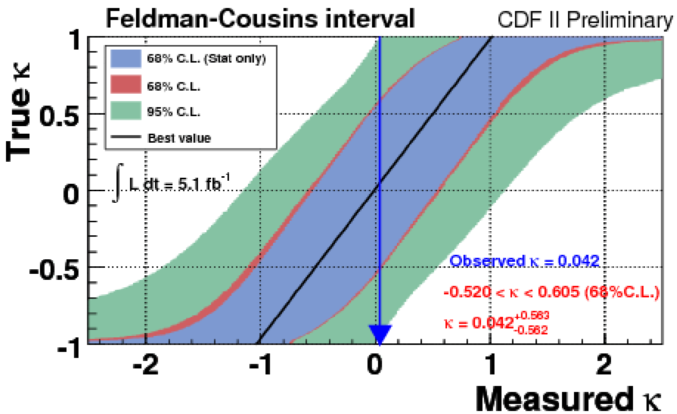
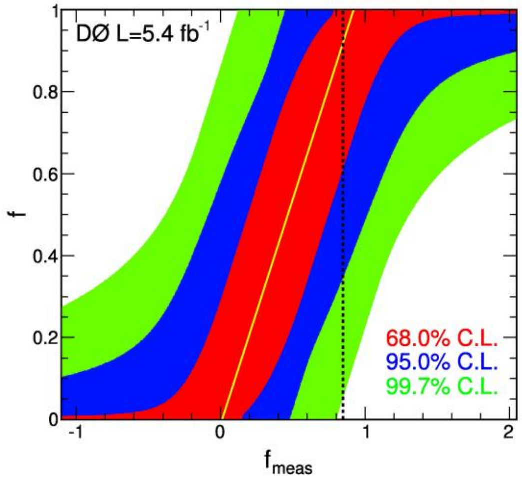
Note: Tevatron tops via qq – scattering!

$$\frac{1}{\sigma}\frac{\mathrm{d}^2\sigma}{\mathrm{d}\cos\theta_+\mathrm{d}\cos\theta_-} = 1 + \frac{1+\kappa\cos\theta_+\cos\theta_-}{4}$$





f = 0.85 ± 0.29

Tevatron no or marginal evidence for spin correlations

Spin correlations @ LHC

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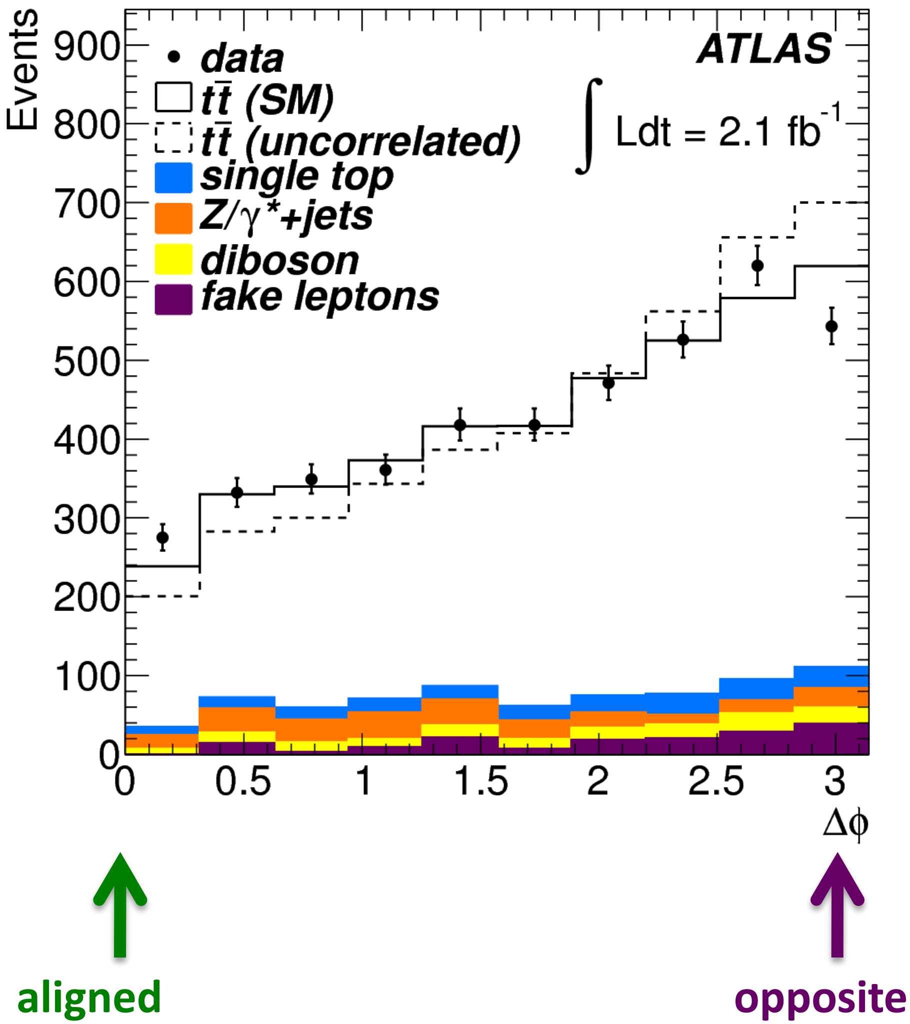

Measure $\Delta\phi$ of leptons in transverse plane

Note experimental distortion: Alignment means on lepton low energetic

Comparison with SM expectation

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Reconstructed asymmetries	Data	Simulation
$A_{\Delta\phi}$, inclusive region	-0.158 ± 0.010	-0.171 ± 0.002
A_{c1c2}, inclusive region	-0.062 ± 0.011	-0.087 ± 0.002
$A_{\Delta\phi}$, $M_{t\bar{t}} > 450$ GeV/c^2	-0.378 ± 0.019	-0.384 ± 0.003
A_{c1c2}, $M_{t\bar{t}} > 450$ GeV/c^2	-0.019 ± 0.016	-0.044 ± 0.003

First significant evidence of spin correlations
Agreement with Standard Model

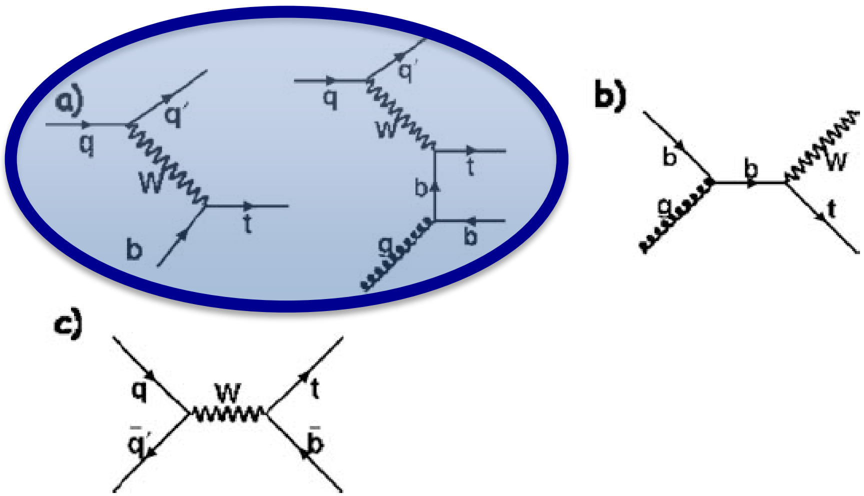
Study of spin correlations:
A method to separate new resonances from QCD continuum (?)

Single top production

top pairs due to strong coupling,
weak coupling ➔ single top quarks

Dominant
σ(7 TeV) = 65 pb

(half of tt – Xsection)



Remember:
W± couples to fermion doublets

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}, \ldots\ldots \begin{pmatrix} t \\ b \end{pmatrix}$$

Single top production

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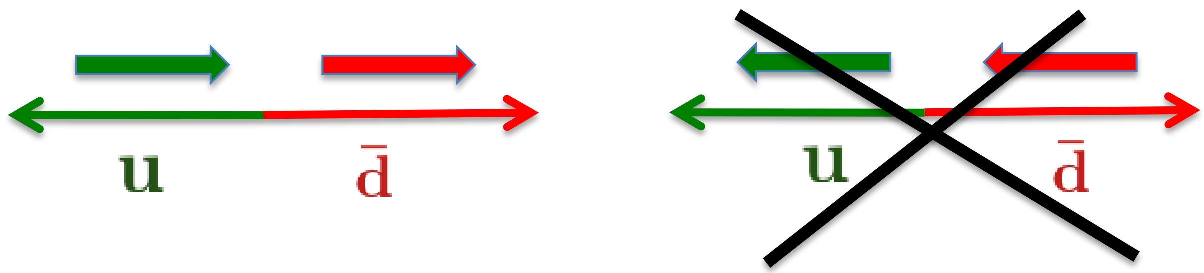
Allows detailed studies of the weak coupling of top quarks

- How often does W→tb (and not ts, td, or something else?)
  i.e. measuring CKM element $|V_{tb}|$
- Does the top couple completely left handed to the W?
  (as all other fermions do)

Example: $W^+ \to u\bar{d}$

Spin direction
Momentum



Forbidden in weak interactions

- new particles, additional couplings ....

Combine observables

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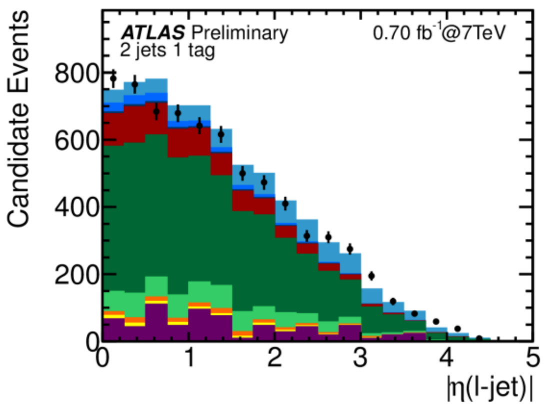
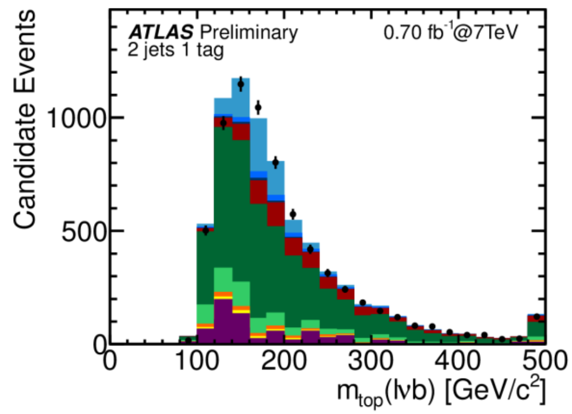
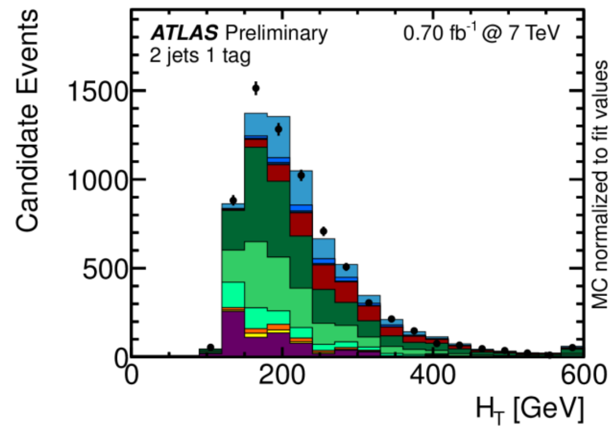
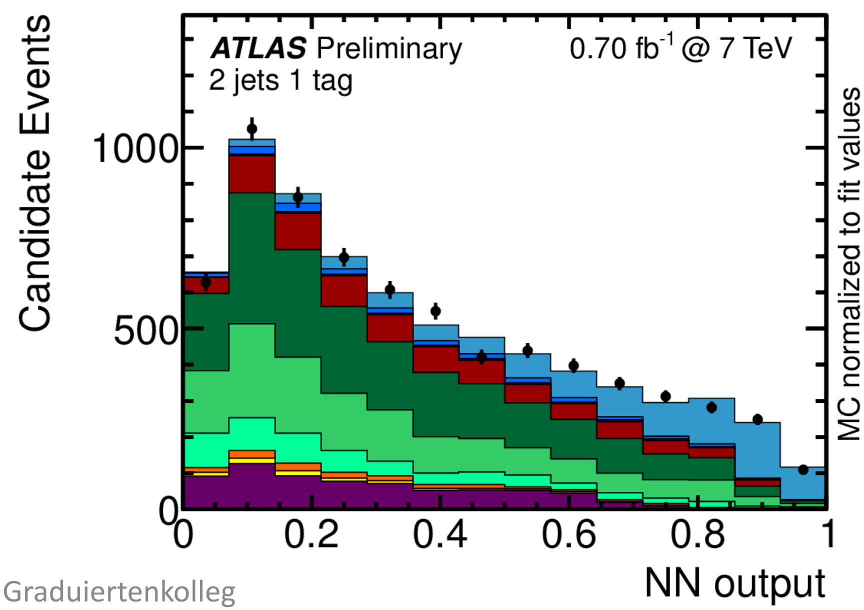




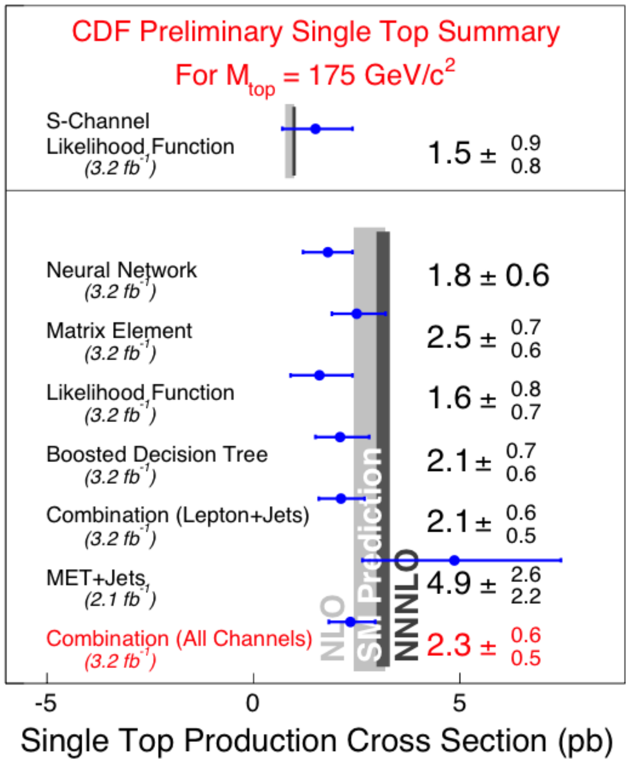


....

Several observables with moderate sensitivity: combine all information likelihood



Measurements



CMS:

$\sigma_{t\text{-channel}}$**(7 TeV) = 70.2 ± 12.1 pb**

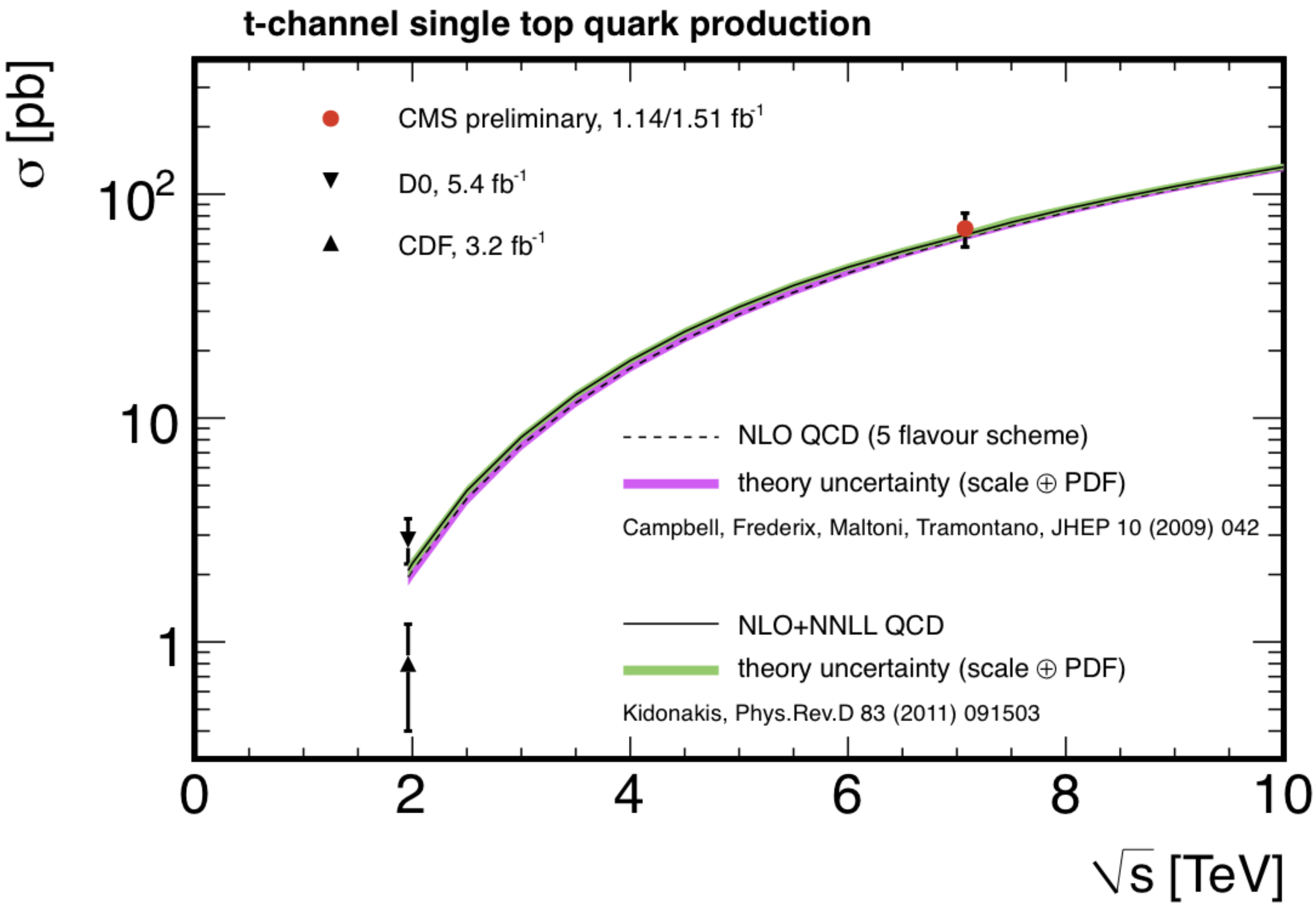
ATLAS

$\sigma_{t\text{-channel}}$**(7 TeV) =** 90.2^{+32}_{-22} **pb**

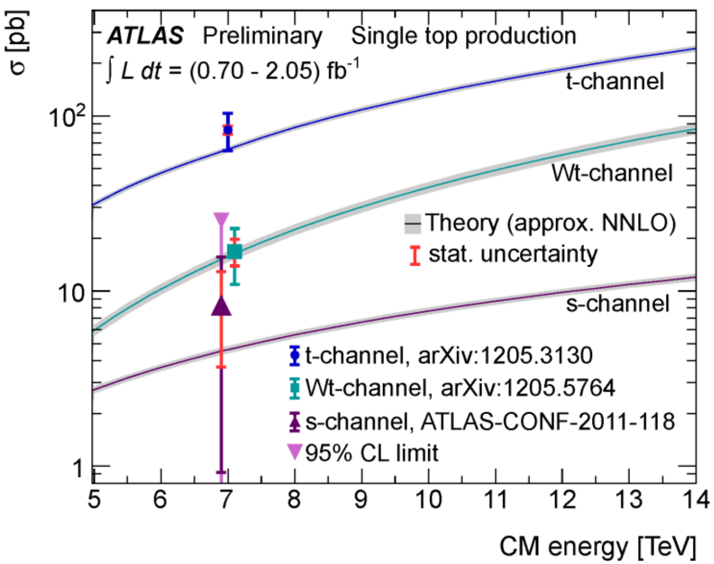
Observation of single top production

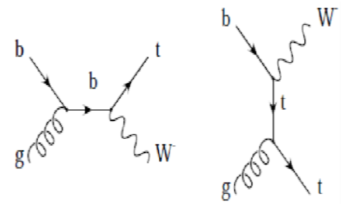
Precision measurements to follow

Measurements

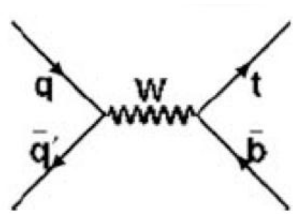


Measurements

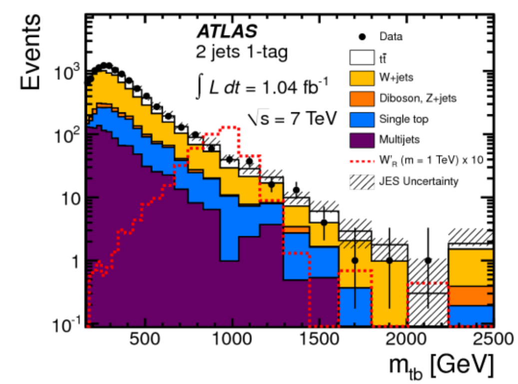




$|V_{tb}| = 1.03^{+0.16}_{-0.19}$



Search for tb resonances



$M_{W'} > 1.2$ TeV

Anomalous couplings

B(t→ug) < 5.7 * 10^{-5}, B(t→cg) < 2.7 * 10^{-4}

Conclusion

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- Standard Model test a crucial element of LHC program
- Understanding SM processes pre – condition for understanding detector
- Studying SM at highest energies charters new territory and may reveal New Physics
- If New Physics will turn up in ‚non- SM signatures‘, SM processes still must be considered as background

LHC: a first go on Standard Model processes
statistics by the end of the year 6 – 1000x higher
detailed systematic studies required
but: whole new phase space can be addressed