Top@LHC: achievements and prospects

(from the rococo of precision measurements to a New Wave of discoveries?)

G.Salamanna (QMUL)

I start with the warnings...

- No way I can go through gory details of all Top results even just of last 1.5 years in 30 mins...
- I'd like you to follow me through couple of examples of:
  - testing SM predictions with precision (and open issues)
  - possible NExT contributions in exploiting Top large potential as gateway to new physics
- One main aim is to **stress contributions and expertise from NExT experimental groups (ATLAS) and to encourage collaboration with theory colleagues**

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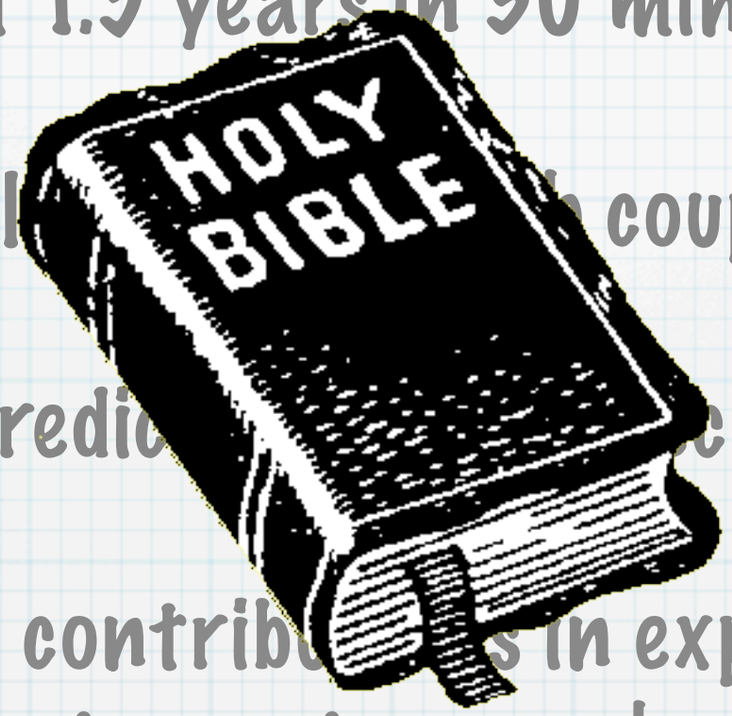

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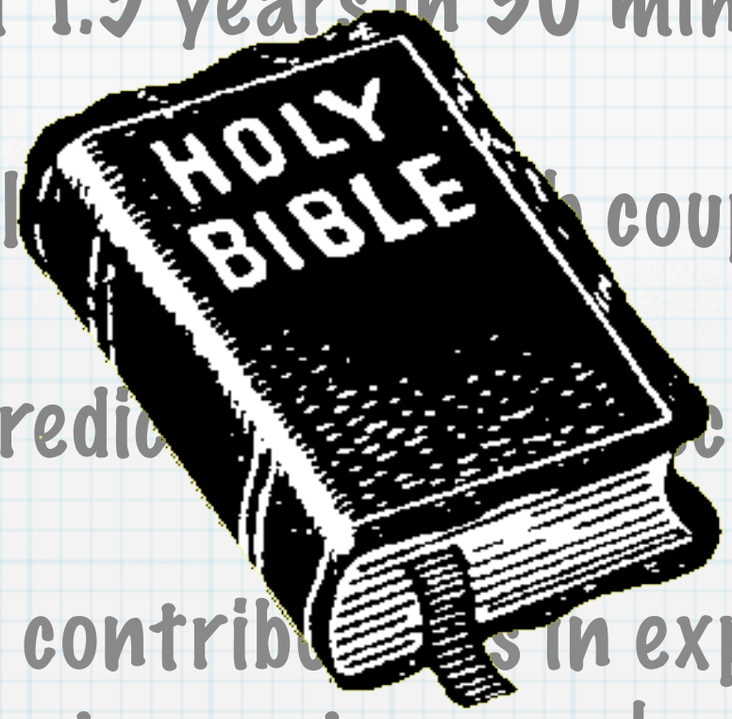

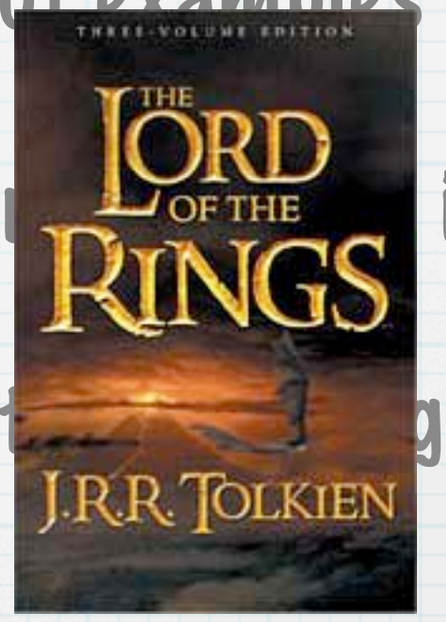

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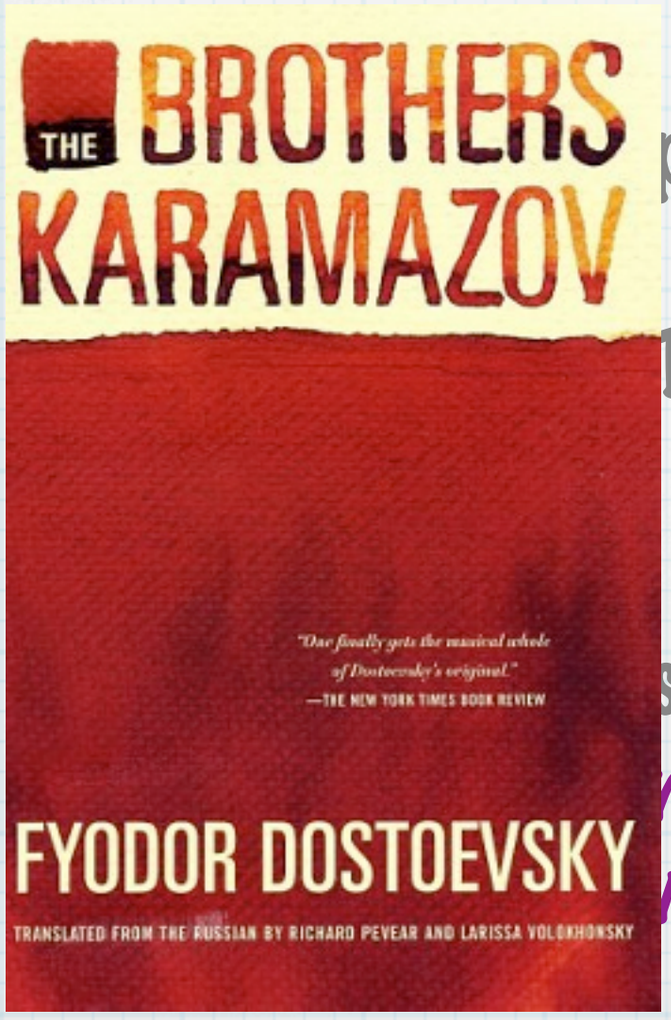
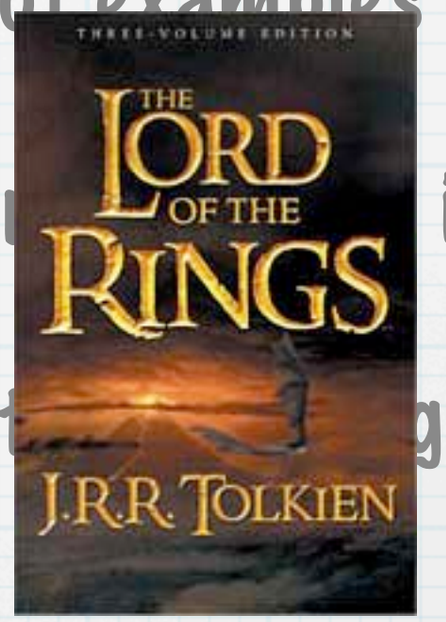




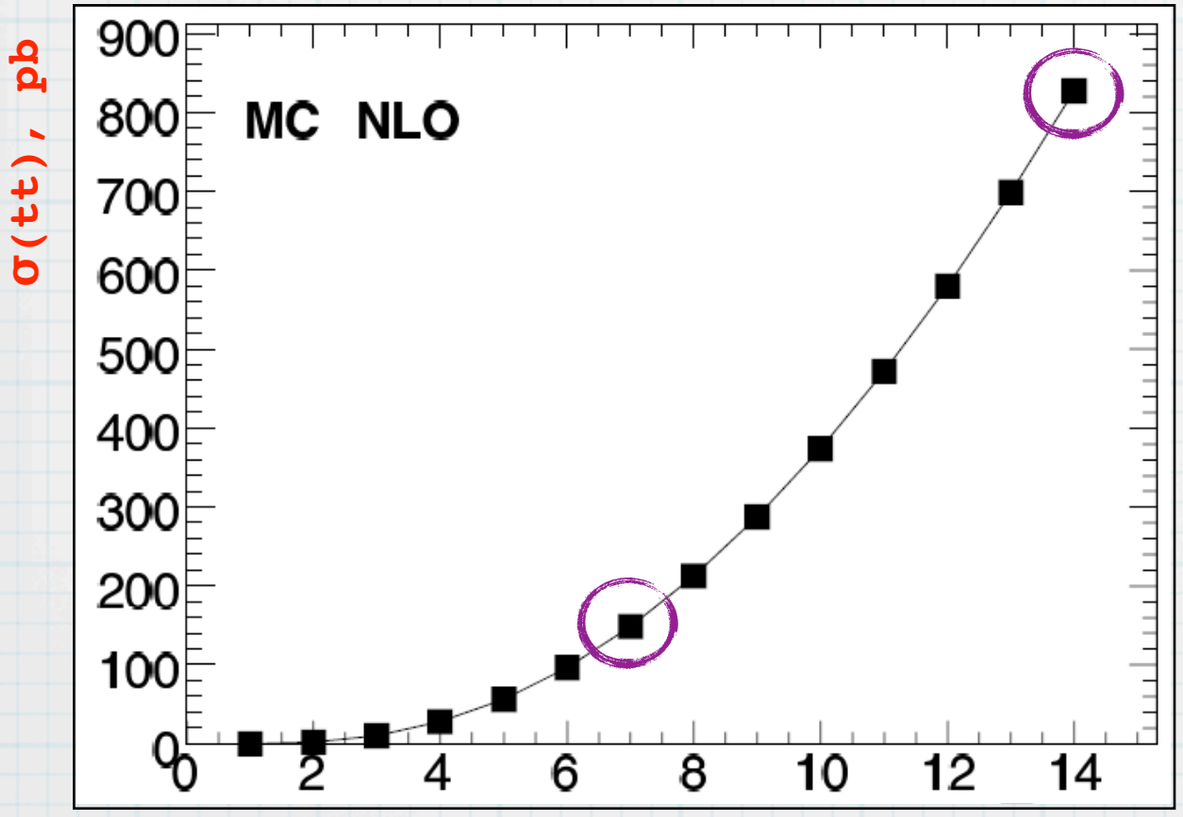
…predic… …cisio… …issues)

…T contrib…s in exploi… …ge
… gateway to new physics …

…s to stress contributions and expertise from …ntal groups (ATLAS) and to encourage …with theory colleagues

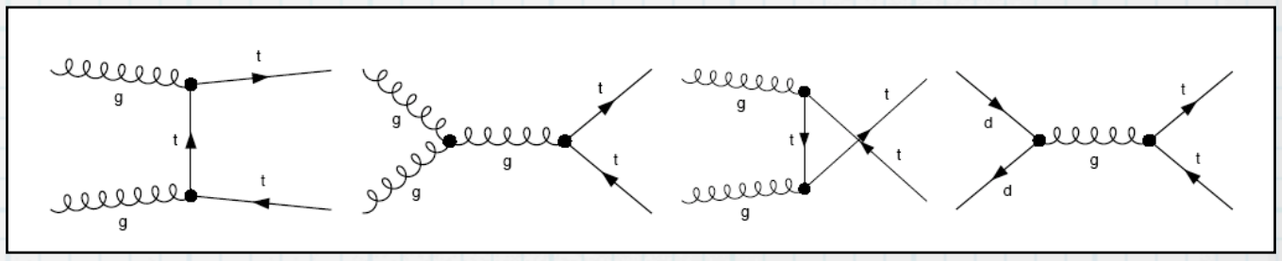
Top Id (just to set the scene)

* $M_{top} \sim 170$ GeV
* $\Gamma \sim 1.4$ GeV ($>> \Lambda_{QCD}$) : the only 'free' quark
* Mainly produced in pairs (LHC, 7 TeV $\sigma(t\bar{t}) \sim 160$ pb, $\sigma(t) \sim 75$ pb)
  * precision measurement tests QCD and EW



~ 880 pb

* At LHC 80-90% from gg



~ 160 pb

7 TeV, 1 fb^{-1}
~160k Top quarks
~ 20000k W bosons

Why is Top "special"?

A question of mass..

A question of mass..

A question of mass..

A question of mass..

40 times heavier than "beauty" quark

A question of mass..

40 times heavier than "beauty" quark...

A question of mass..

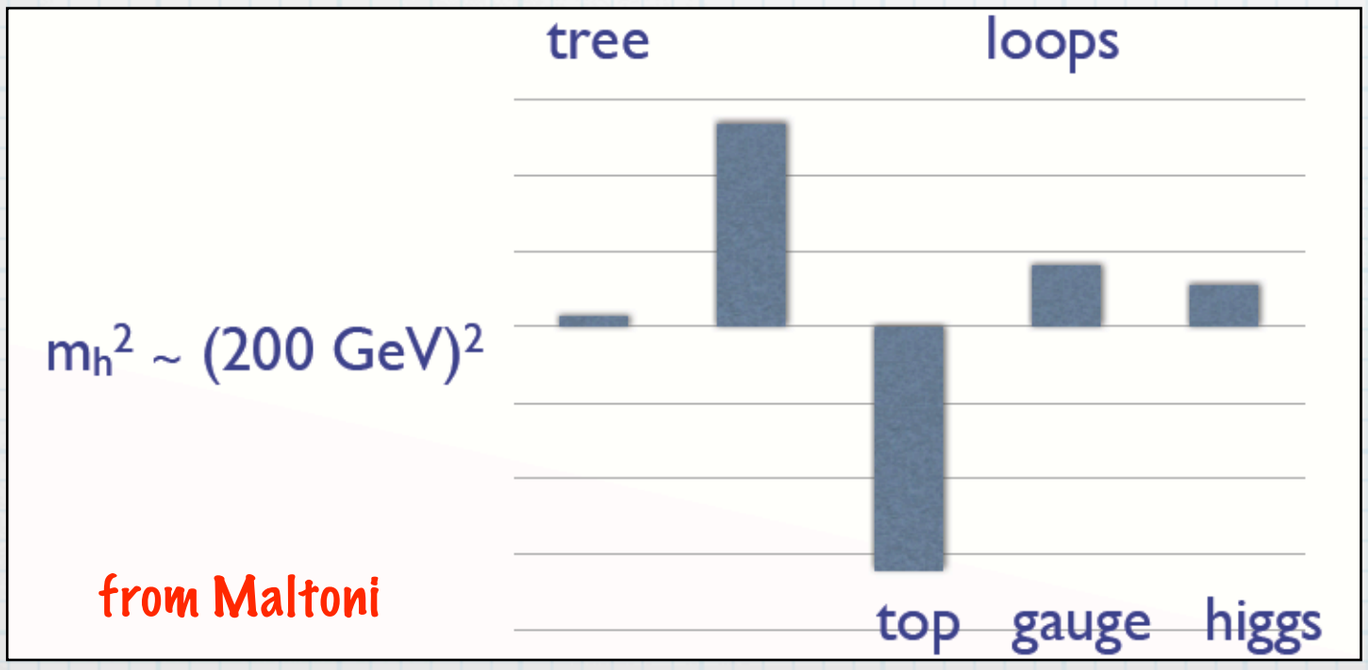
?

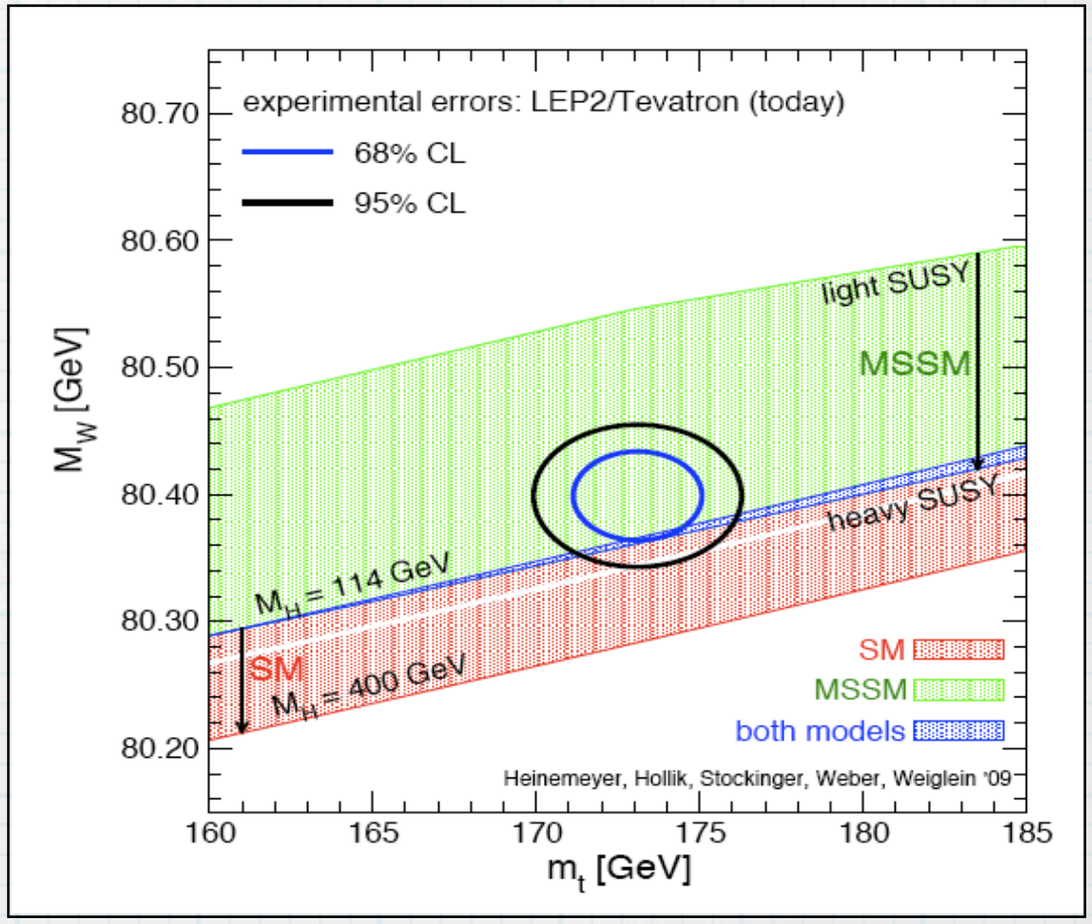
what one finds on google these days...

A question of mass..

- It makes it the only one with a Yukawa coupling around 1
  - only one with large coupling to a Higgs boson of some form
- Obvious to assume it has a special role in EWSB
  - be it weak á la Higgs mechanism' or strong á la Technicolor/alikes'

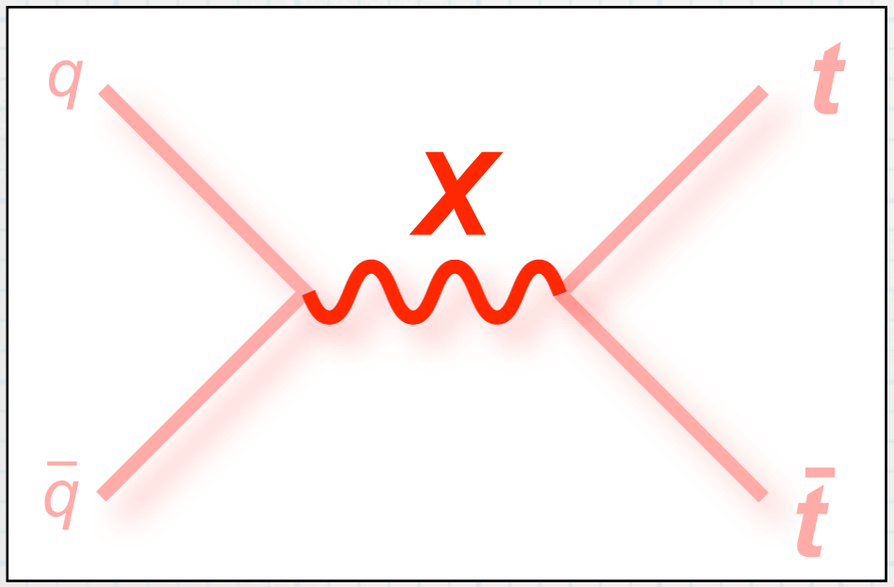
- The radiative corrections of top to Higgs propagator are at the base of so-called hierarchy problem





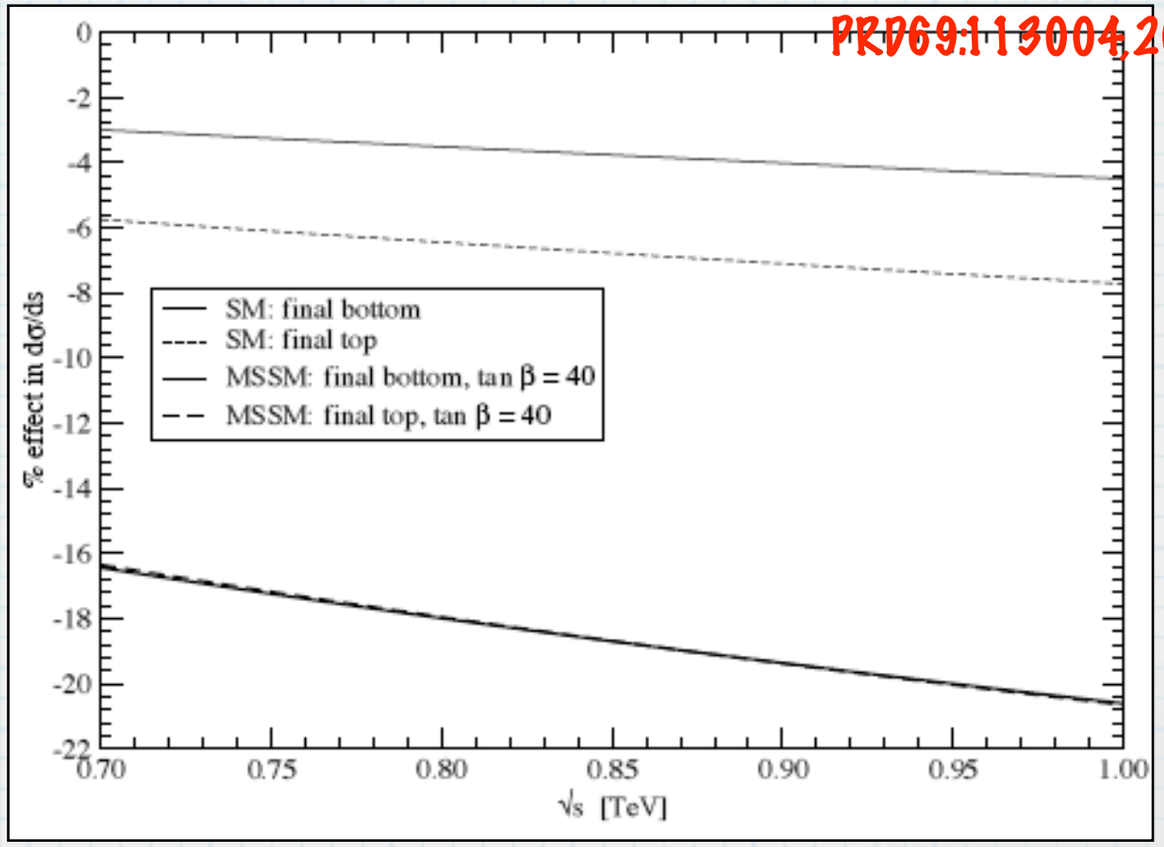
Larger, newer, super..

- Many new theoretical scenarios wait to be tested at E > TeV and in most of them Top has a special role
  - Extra-dimensions with 'leptophobic' couplings (then Top becomes next-of-kin)
  - Strongly-originated EWSB (old technicolor, composite Higgs, etc)
  - SUSY (stops to tops, but also as experimental background!)



cross-section larger than SM

PRD69:113004,2004



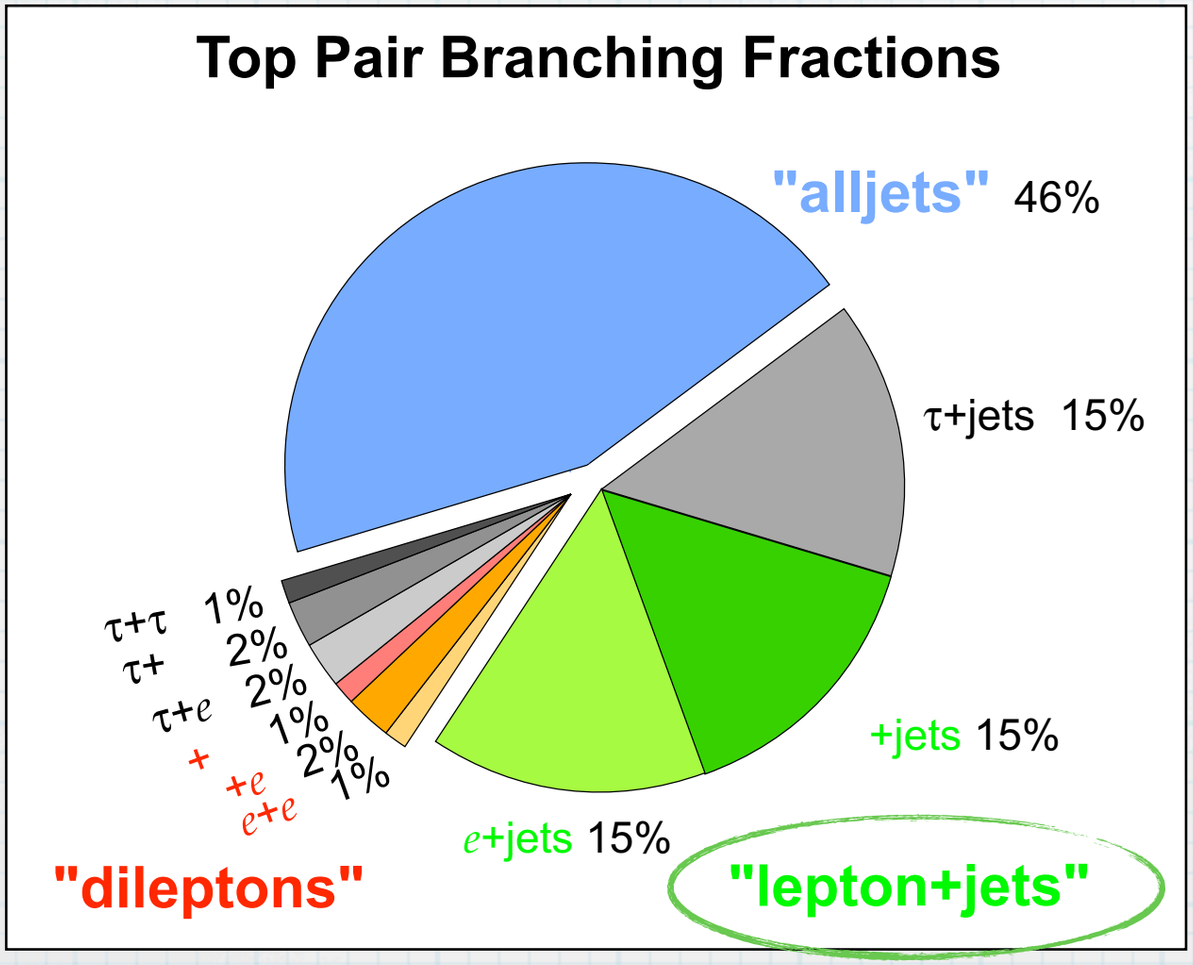
effect of MSSM on x-sec

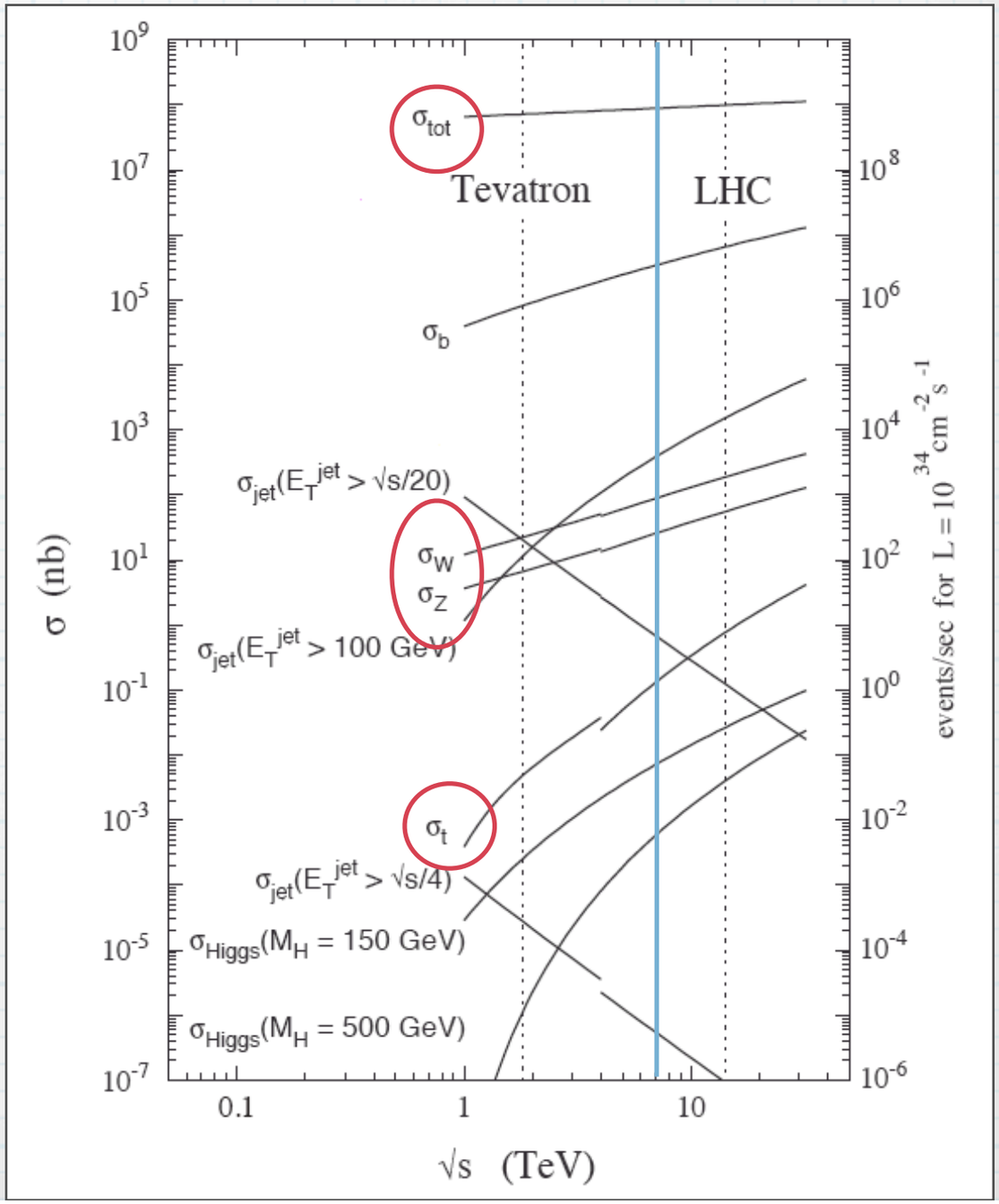
Current status: 3 examples

$t\bar{t}$ x-sec
single top x-sec
top mass

Top Decays

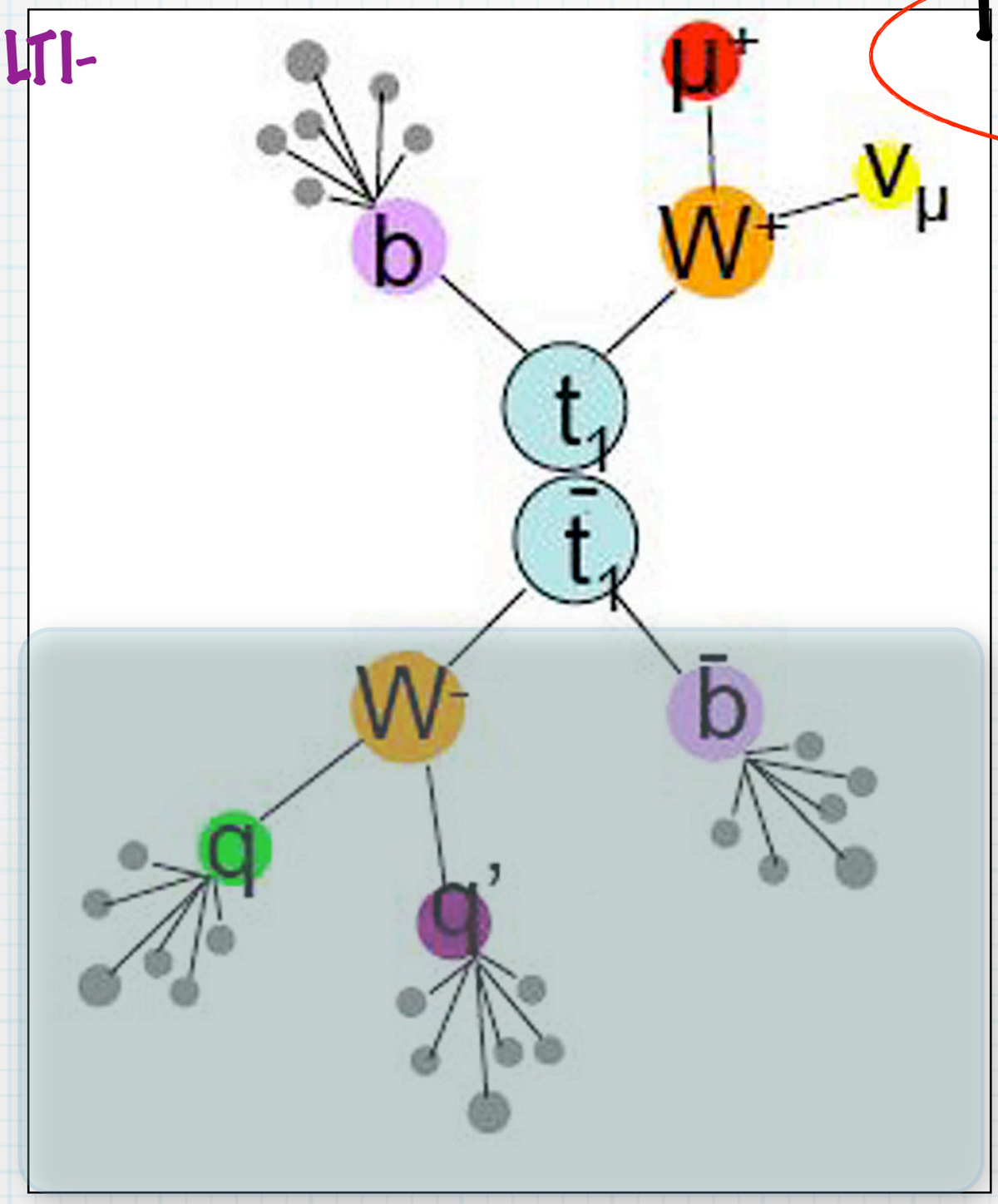
- **lepton + jets:** BR ~ 1/3 (e or μ) only one with reasonable stat, 'almost' close kinematics in event and yet manageable bkg
  - Also **di-leptonic** channel considered and combined for almost all measurements both in ATLAS and CMS





Big handle: Lepton decays

REJECT QCD MULTI-JET EVENTS



1. High-momentum, isolated lepton

QMUL

2. Large missing transverse Energy (Neutrino)

3. ≥ 4 Jets

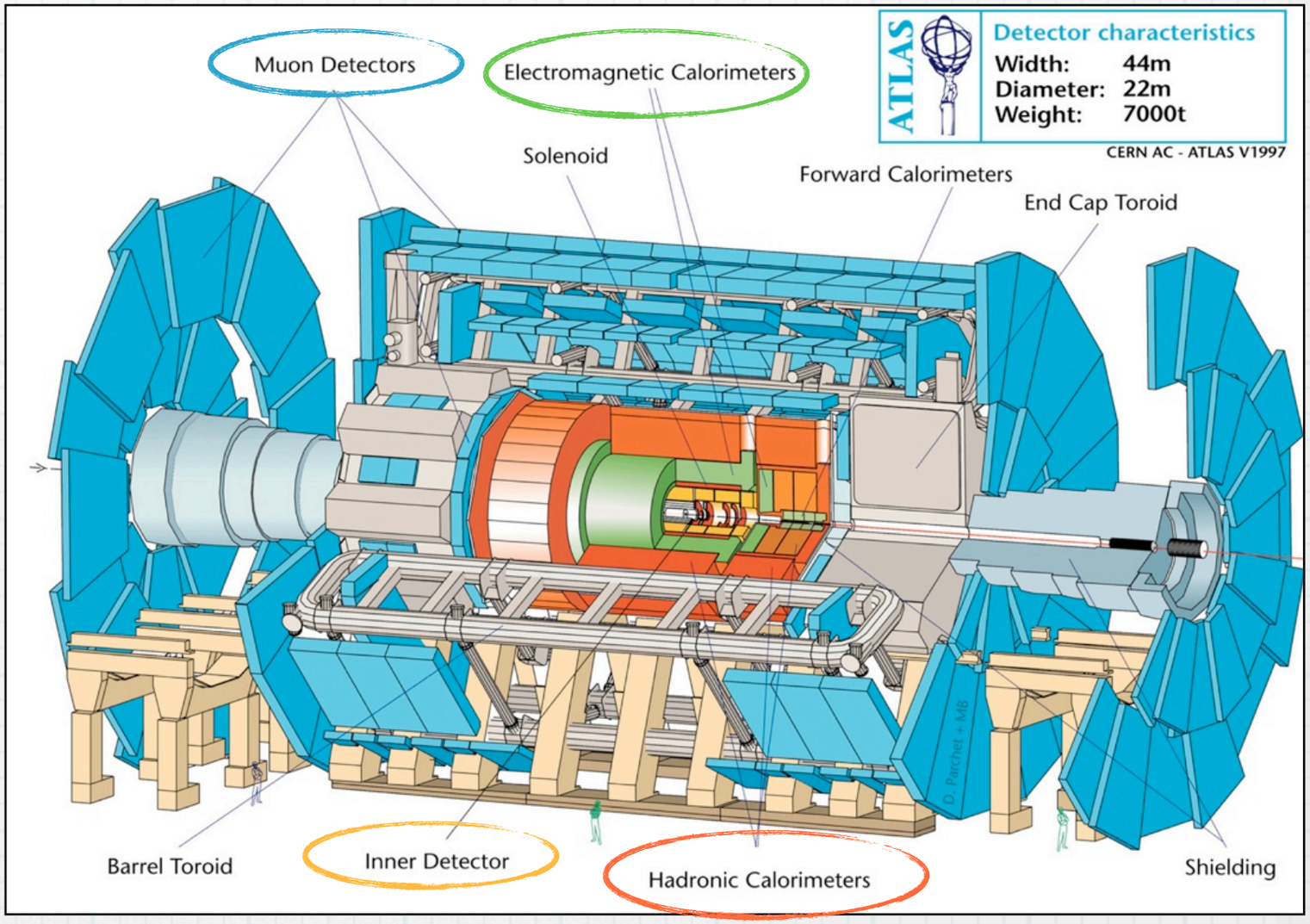
4. b-jet ID

TOP MASS from HADRONIC LEG

Main bkgs are QCD multi-jet faking leptons and W+jets

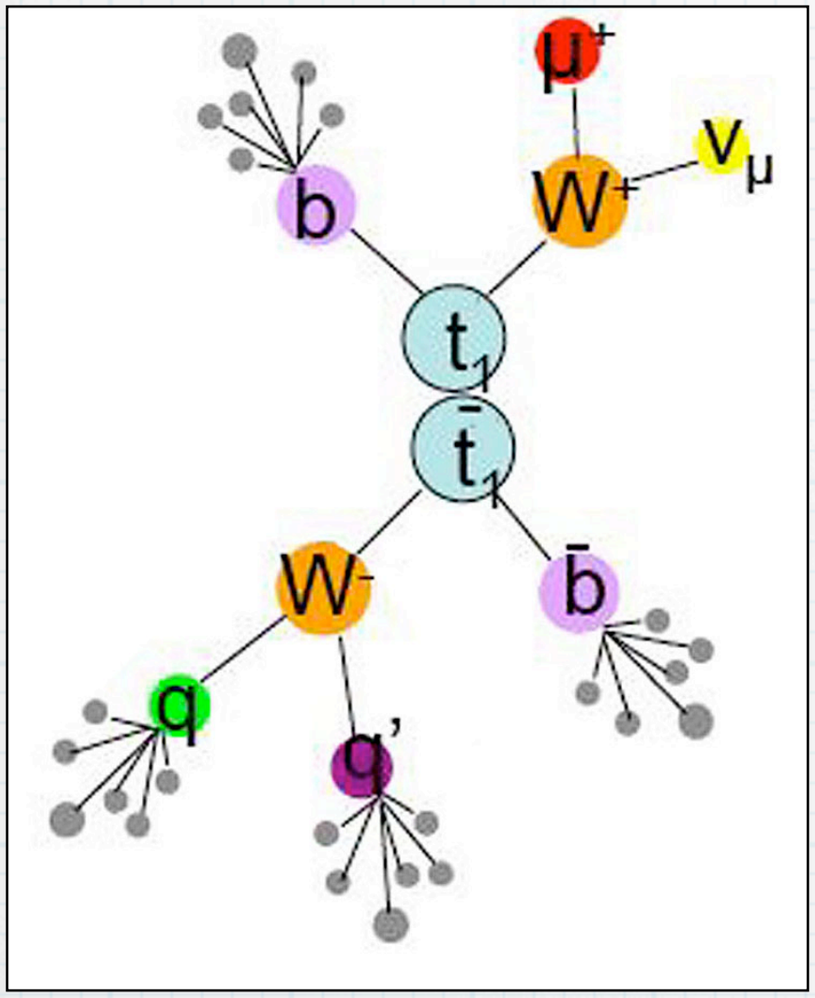
ATLAS

- **Tracking (|η|<2.5, B=2T) :**
  - Silicon pixels and strips
  - Transition Radiation Detector (e/π separation)
- **Calorimetry (|η|<5) :**
  - EM : Pb-LAr
  - HAD: barrel: Fe/scintillator
    forward: Cu/W-LAr
- **Muon Spectrometer (|η|<2.7) :**
  - air-core toroids with muon chambers



- All equally important for Top analyses!

Trickiest parts..



- A typical $t\bar{t}$ event has 4 **jets**
  - plus additional Initial/Final State Radiation
  - **knowing energy response** of calorimeters and offset wrt true Jet E is VITAL for precision meas. (M_t)

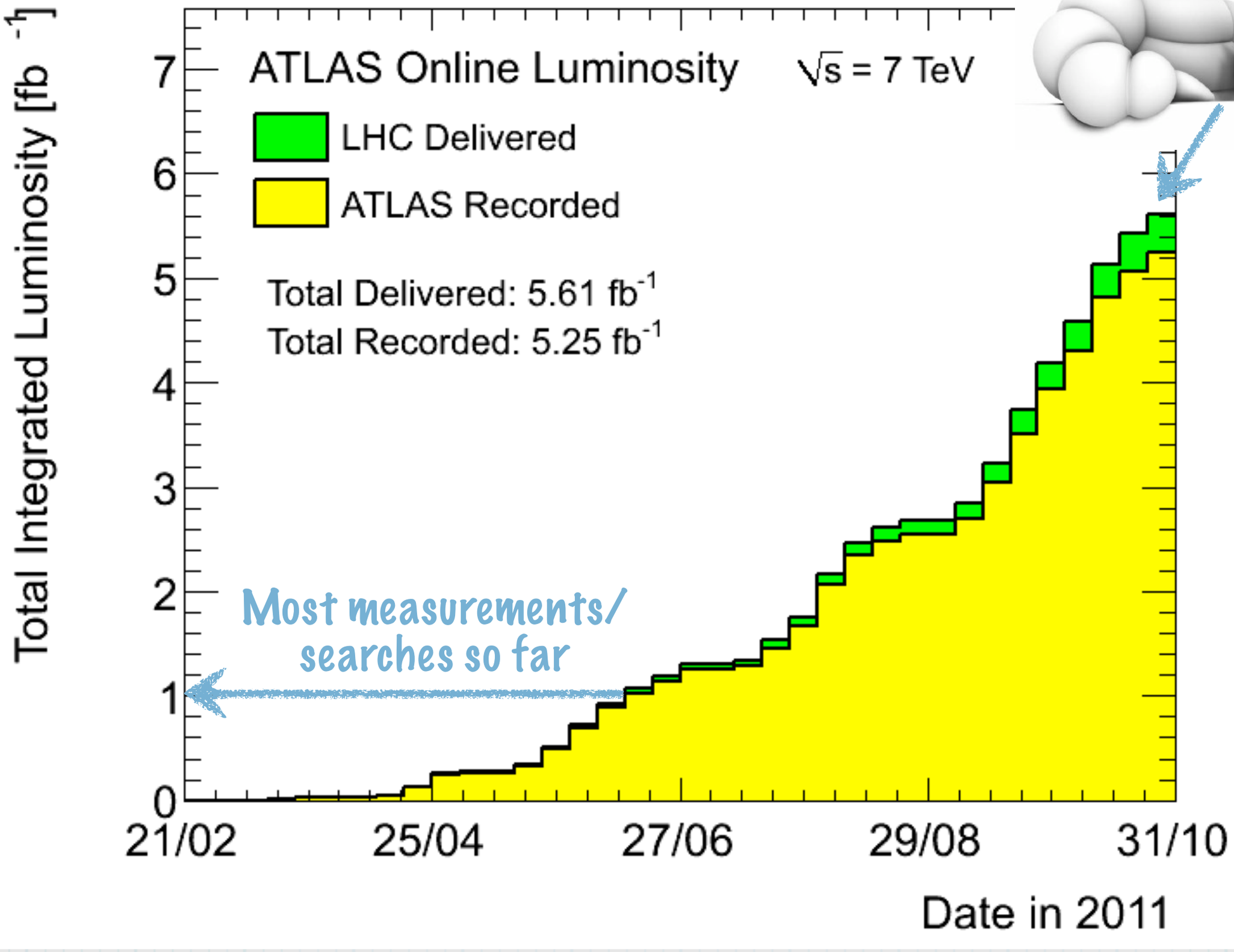
QMUL/RHUL

- A typical $t\bar{t}$ event has 2 **b-jets**
  - b-jet Identification ("b-tagging") very powerful tool against bkgs
  - but comes at price of an **uncertainty on the performance** in data (efficiency of tagging real b-jets and embarking light jets)

Object expertise at home

- Given complexity of top events, need fine understanding of detector response and calibrations for: leptons, jets, b-jets, missing E_t
  - QM expertise in commissioning of detectors (inner tracker, muon spectrometer and L1 trigger)
  - and Identification studies (muons, electrons, b-tagging)
  - QM responsible for convening group handling all ATLAS top reconstruction/obj calibration issues

Data - LHC


ATLAS Online Luminosity
√s = 7 TeV
LHC Delivered
ATLAS Recorded
Total Delivered: 5.61 fb-1
Total Recorded: 5.25 fb-1
Total Integrated Luminosity [fb-1]
0
1
2
3
4
5
6
7
21/02
25/04
27/06
29/08
31/10
Date in 2011
Most measurements/ searches so far


next winter...

Simulation - MC

* Signal from NLO+PS approach: MC@NLO (w/ Herwig and CTEQ 6.6)
  * always quote also syst from difference with POWHEG
  * ISR/FSR syst checked with AcerMC+Pythia (one of biggest syst at present)

➡ should work with theorists on common prescription on systematics (now taking envelope of various pdf's; max of different Acer variations I/FSR up/down, ..)

* W/Z+j is ME+PS approach: Alpgen (CTEQ 6.1) + Herwig
  * normalization is at LO only: re-scale using data directly

$t\bar{t}$ cross-section

of signal events after all selections

$$\sigma = \frac{N_{\mathrm{sig}}}{\mathscr{L} \times \varepsilon}$$

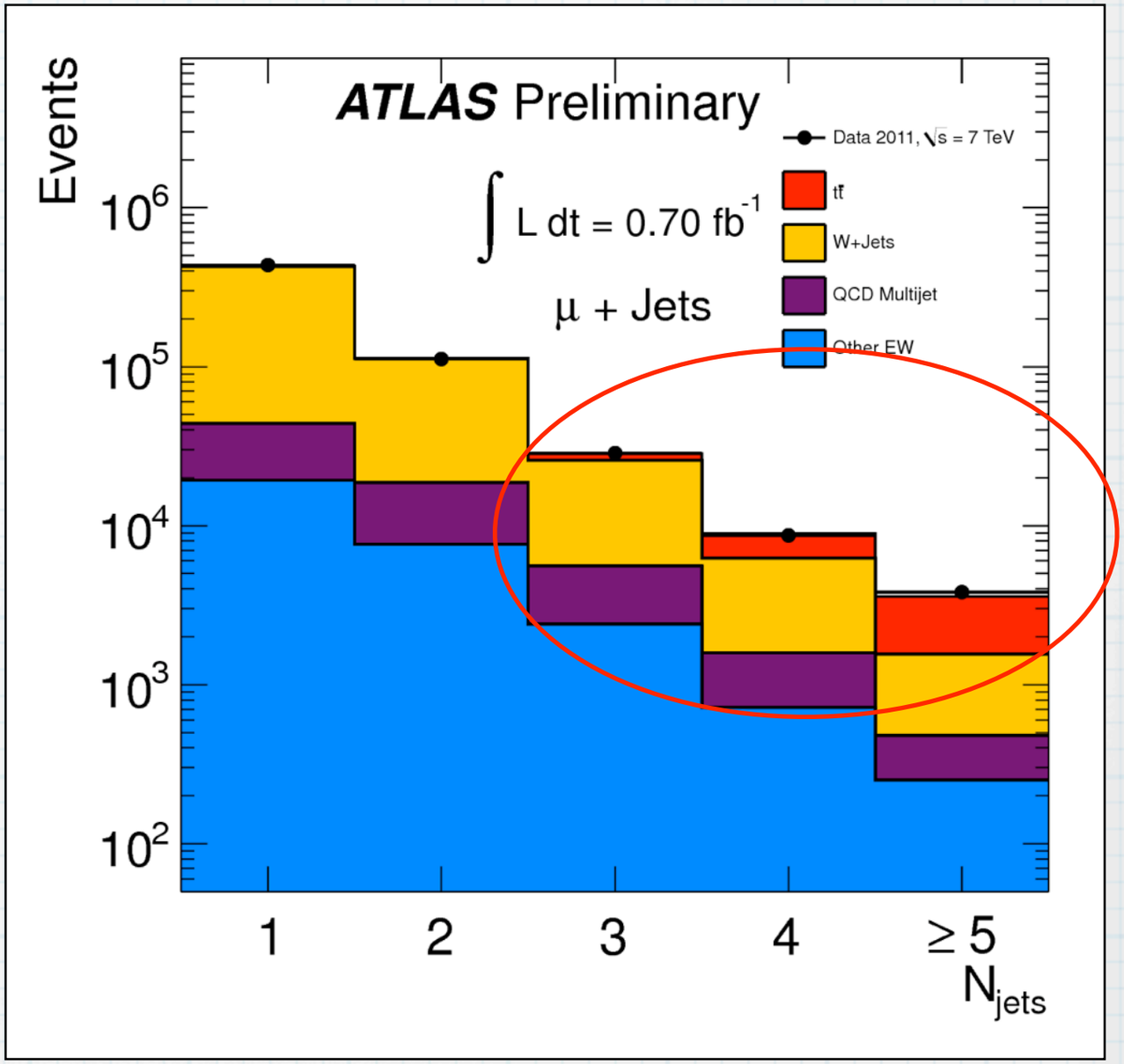
Integrated luminosity

Trigger + Offline efficiency to select signal from initial statistics collected

- Measure number of signal events (separate from bkg)
  - this is where various analysis differ

Event selections

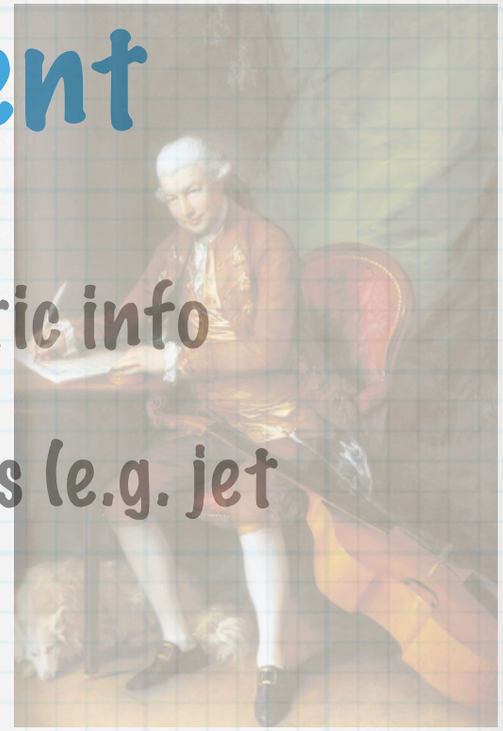
ATLAS	Electron	Muon
Trigger	$p_T > 20$ GeV	$p_T > 18$ GeV
Jets	Anti-Kt 0.4, $p_T > 20$ GeV, $\|\eta\| < 2.5$, ΔR(jet, electron) < 0.2	
Electron	$E_T > 25$ GeV, $\|\eta\| < 2.5$, E_T (cone 0.2) < 3.5 GeV	
Muon	$p_T > 20$ GeV, $\|\eta\| < 2.1$, E_T (cone 0.3) < 4 GeV & P_T (cone 0.3) < 4 GeV, ΔR(muon,jet ($p_T > 20$ GeV)) < 0.4	
Missing E_T	> 35 GeV	> 25 GeV
$m_T(W_{lep})$	> 25 GeV	$E_T + m_T(W_{lep}) > 60$ GeV



$$m_T(W) = \sqrt{2 p_T^l p_T^\nu (1 - \cos(\phi^l - \phi\nu))}$$

- jet multiplicities in agreement with MC predictions
- 3/4/5 jet bin used as "signal" region
- 2 jet bin is used to control backgrounds

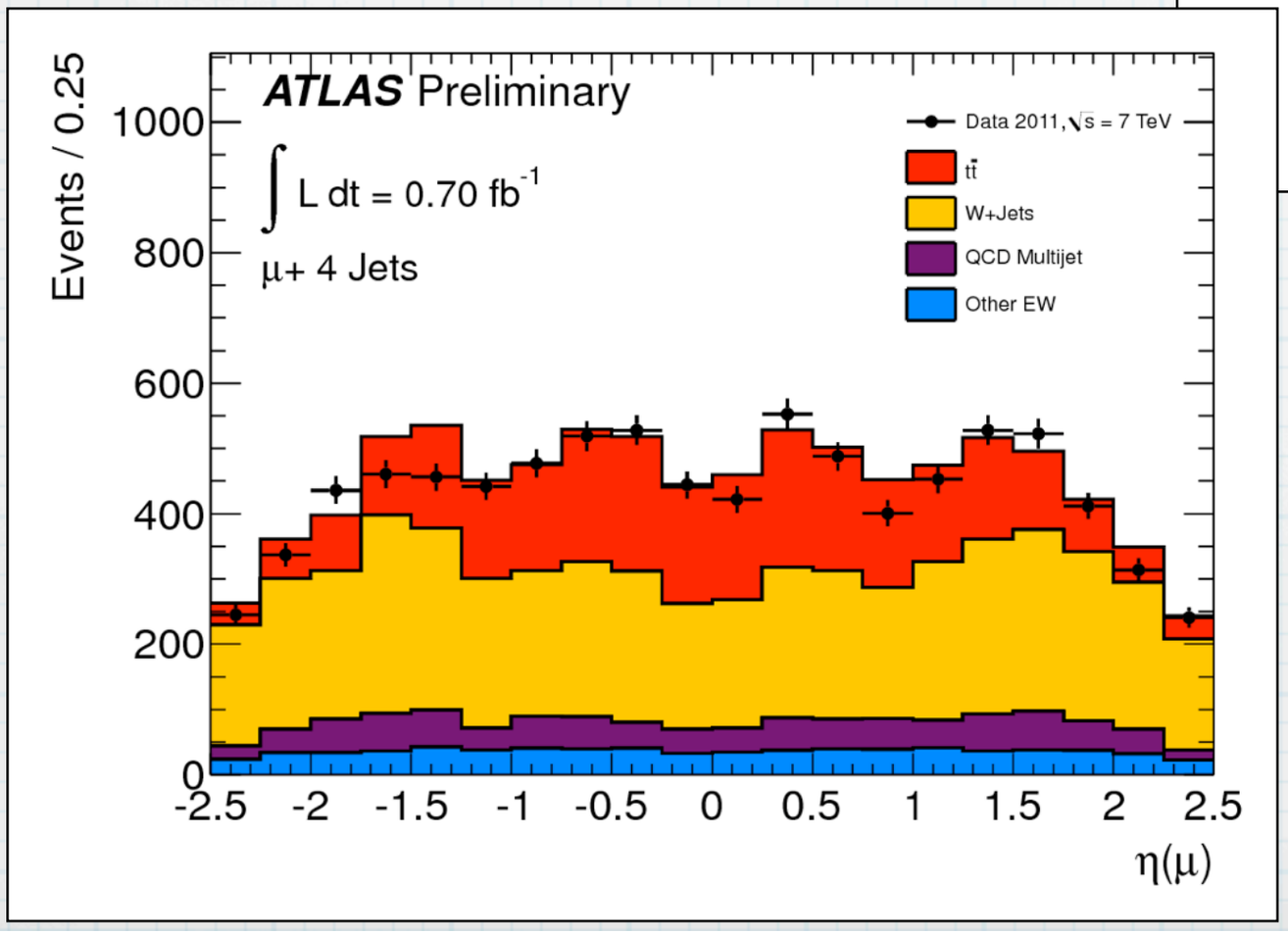
World most precise measurement



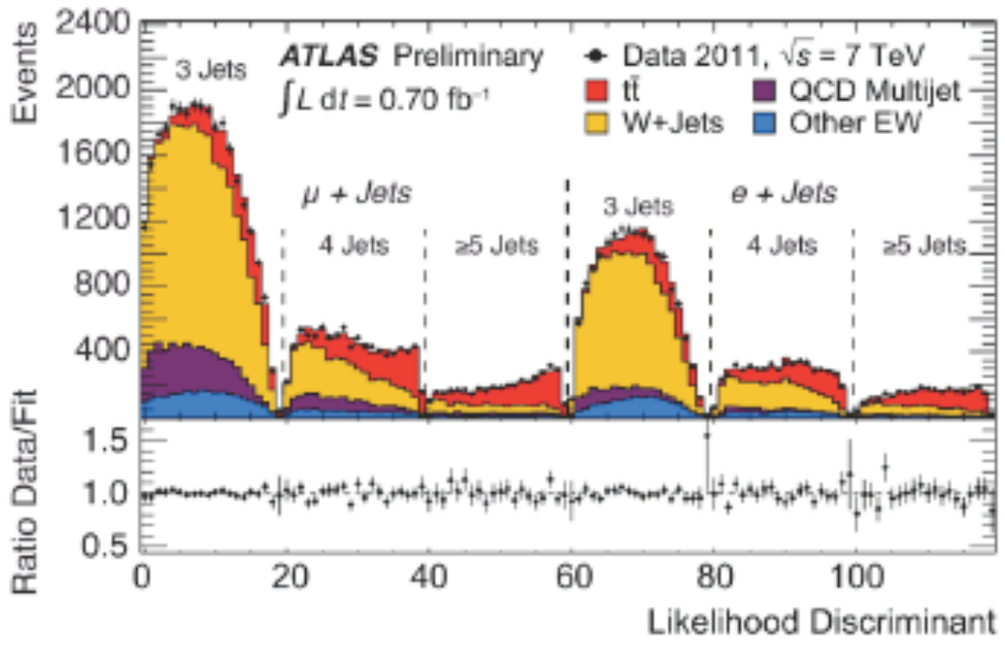
* Uses a profile likelihood technique with multiple kinematic info
  * and constrain the entity of systematic uncertainties (e.g. jet energy scale) directly with data
* accurate shapes (and not only rates) are needed

$$-2\ln L(k_{t\bar{t}}, k_{W+jets}, \vec{\alpha}) \propto -2\sum_{i=1}^{N_{bins}} n_i \ln \mu_i - \mu_i + \sum_{j=1}^{N_{Syst}} \alpha^2$$

$$\mu_i = \mu_i(k_{t\bar{t}}, k_{W+jets}, \vec{\alpha})$$



Result, no-b tagging



Uncertainty	up (pb)	down (pb)	up (%)	down (%)
Statistical	3.9	−3.9	2.2	−2.2
Detector simulation				
Jets	3.2	−4.3	1.8	−2.4
Muon	4.1	−4.1	2.3	−2.3
Electron	2.7	−3.0	1.5	−1.7
$E_{\mathrm{T}}^{\mathrm{miss}}$	2.0	−1.6	1.1	−0.9
Signal model				
Generator*)	5.4	−5.4	3.0	−3.0
Hadronization*)	0.9	−0.9	0.5	−0.5
ISR/FSR	3.0	−2.3	1.7	−1.3
PDF*)	1.8	−1.8	1.0	−1.0
Background model				
QCD shape*)	0.7	−0.7	0.4	−0.4
W shape*)	0.9	−0.9	0.5	−0.5
Monte Carlo statistics*)	3.2	−3.2	1.8	−1.8
Systematic	9.0	−9.0	5.0	−5.0
Stat. & Syst.	9.8	−9.8	5.4	−5.4
Luminosity	6.6	−6.6	3.7	−3.7
Total	11.8	−11.8	6.6	−6.6

This is the most precise top pair cross-section measurement so far:

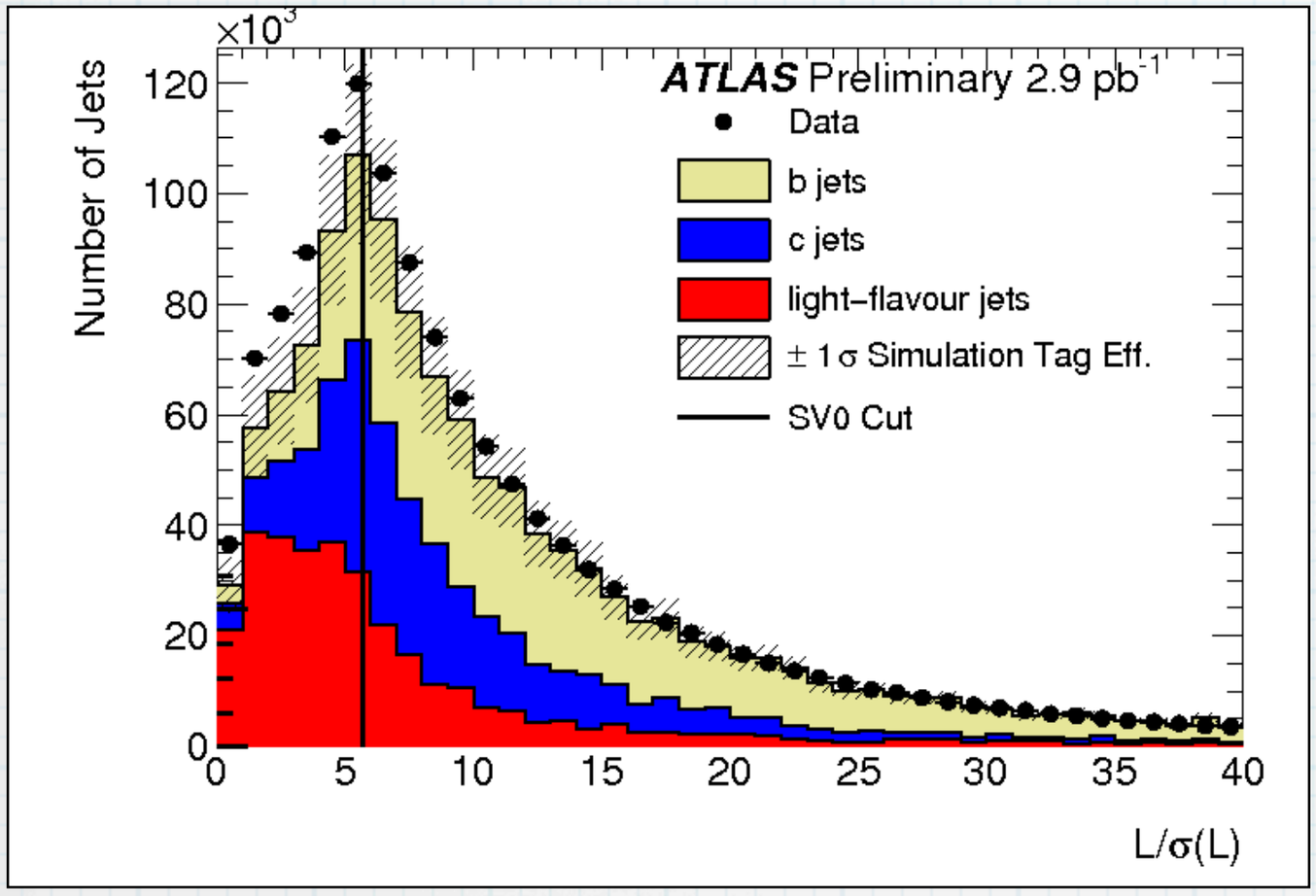
$$\sigma_{t\bar{t}} = 179.0^{+7.0}_{-6.0}(stat + syst) \pm 6.6(lumi)pb \qquad \frac{\delta\sigma}{\sigma} \sim 6.6\%$$

J.Nadal, Top2011

Already challenging for theoretical uncertainties!

- compatible with approx NNLO (164.57 $^{+11.45}_{-15.78}$ pb @ M=172.5 GeV, CTEQ66)
- $\Delta\sigma$ (theo)/ σ (theo) ~ 10% (equally from scales and parton pdf + α_s): new NNLO developments reduce scale dependence - precision on α_s matters!
- experiments: better understanding of I/FSR (theo) and jet enery (expt) needed!

Using b-taggers..



- b-hadron lifetime (450 um) much longer than others (secondary vertex)

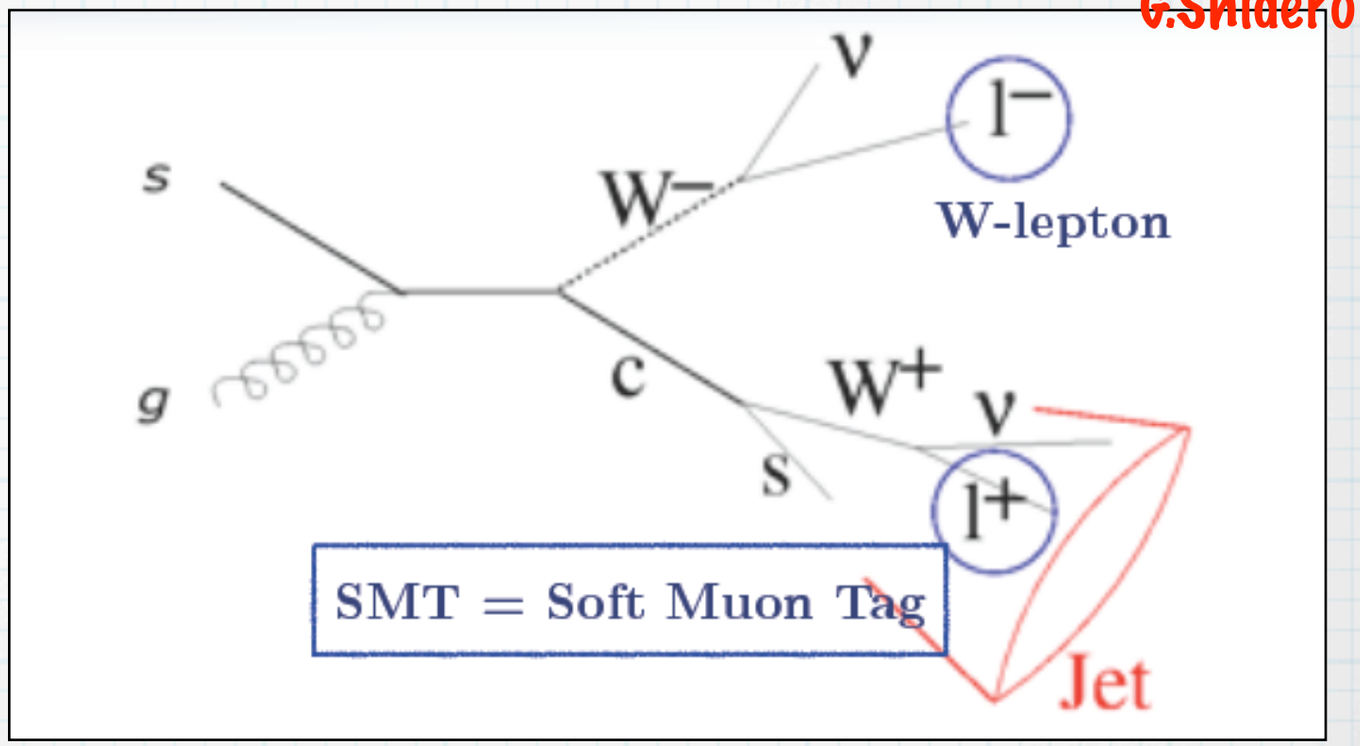
- Measurement with 2010 data and using sec vtx tagger also compatible with SM (also R_b measured); 13% unc
- Uncert. on b tagging efficiency and W+HF largely dominates overall syst

- We as QM and RH are working on this
  - QM also responsible of convening ATLAS top cross-section group

QM/RH current activities

- Soft Muon from b and c decays
- uses no secondary vertex information
  - just muon ID
  - different systematics on x-sec!

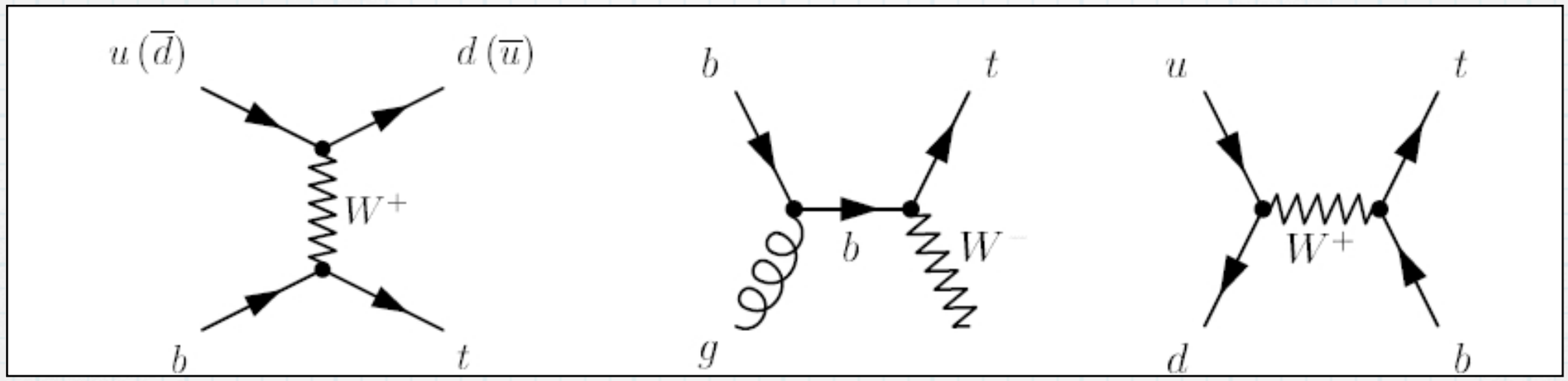
G.Snidero



- Measurement of ttbar x-sec with SMT
  - as a cross-check of precision measurements
- Measurement of W+c x-sec with SMT
  - bkg to top: now unc. on fraction of W+c in W+j is 30%!
  - test of strange quark content in proton
  - exploit charge correlation between lepton from W and lepton from c

Single top production

- Single top production is an EW process
- From coupling of t and W boson
- 3 production mechanisms



t-channel	Wt channel	s-channel
64.57+2.71-2.01 pb	15.74+1.06-1.08 pb	4.63+0.19-0.17 pb

- Verify unitarity of CKM matrix
- If > 3 families, $V_{tb} \neq 1 \Rightarrow$ large production
- NOW: V_{tb} only known at 8% level through Tevatron

Single top at QM

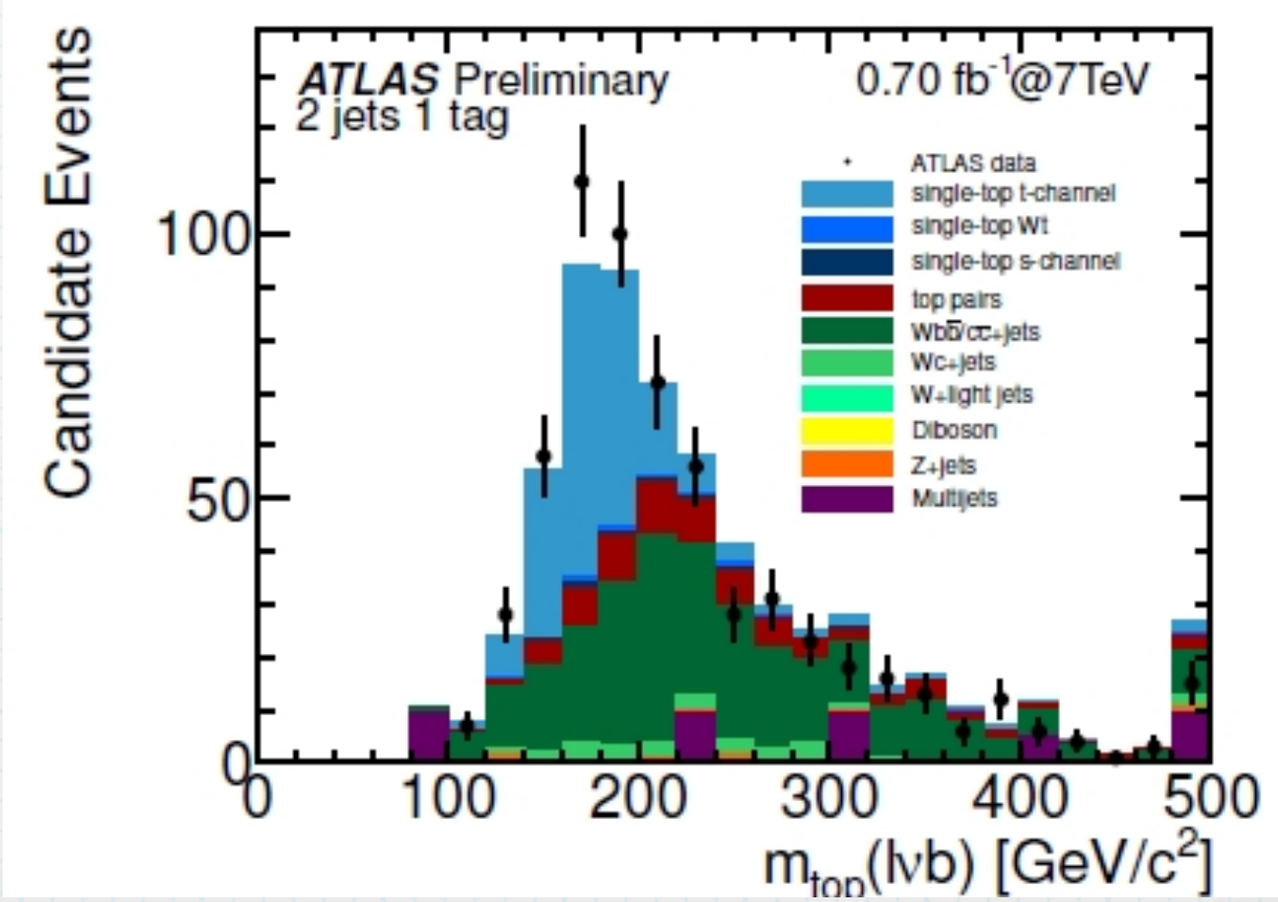
- Difficult to measure, because topology is very similar to each leg of tt
  - Dominant backgrounds are same as ttbar PLUS $t\bar{t}$

- LHC expts observed t-channel and measured σ with ~30% unc. (20% on V_{tb})

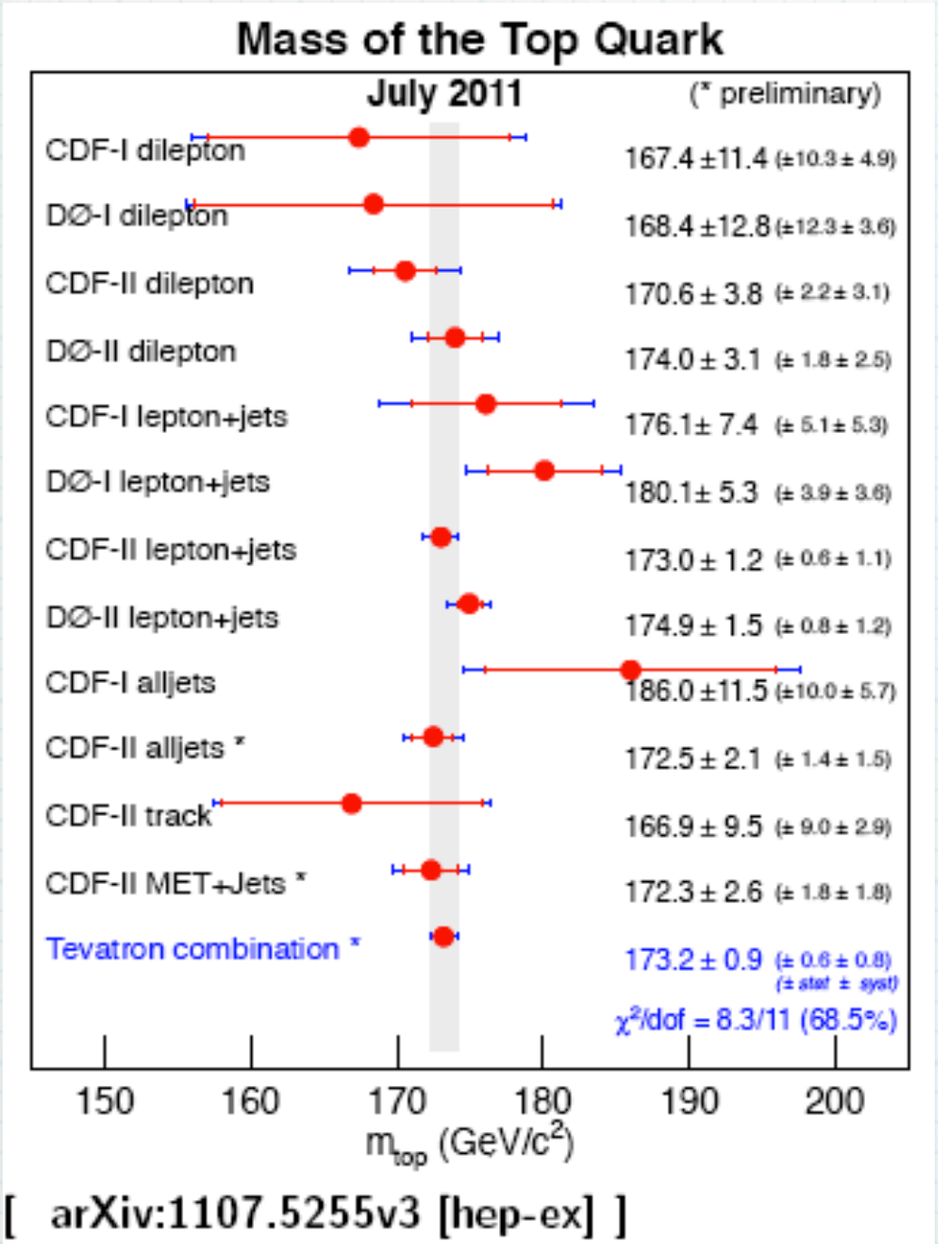
  main syst are jet E and b-tagging again..

ATLAS (0.7 fb^{-1}), pb	CMS (35 pb^{-1}), pb
90 ± 9 (stat) $^{+31}_{-20}$ (syst)	83.6 ± 29.8 (stat+ syst)

- With 5 fb^{-1} (2011):
  - Measurement of the t-channel section using a likelihood method
  - Start s-channel analysis (may require multivariate techniques)



Top mass

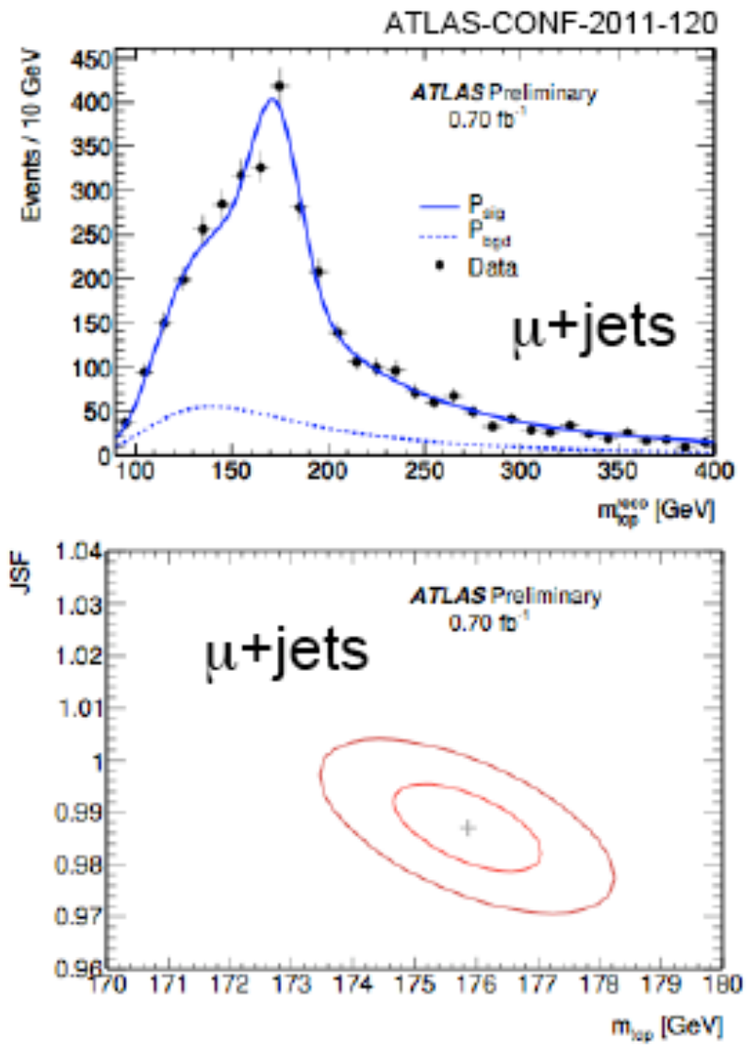


[arXiv:1107.5255v3 [hep-ex]]

- ΔM/M ~ 0.5%!
- half from MC (gen+I/FSR), half from jet energy

- One of the few places where Tevatron still unbeaten
- Why? Precision again!
- This is **THE** rococo measurement par excellence: reduce the uncert. MeV-by-MeV at every round
  - Tevatron expts. have had time to know their jets better than ATLAS/CMS
  - and develop finer techniques (e.g. evt-by-evt Matrix Element)

At LHC: 2-D mass fit



	e+jets	μ+jets
Statistics	1.2	1.0
Method calibration	< 0.05	0.1
Signal MC generator	1.2	1.2
Hadronization	< 0.05	0.4
Pileup	< 0.05	< 0.05
Color reconnection	0.6	0.9
ISR and FSR (signal only)	1.6	0.7
Proton PDF	0.1	0.1
W+jets background normalization	0.2	0.1
W+jets background shape	< 0.05	0.1
QCD background normalization	0.4	0.4
QCD background shape	0.2	0.3
Jet Scale Factor	1.0	0.7
Jet energy scale	0.7	0.8
b-jet energy scale	2.0	1.7
b-tagging efficiency and mistag rate	0.1	0.3
Jet energy resolution	0.3	0.2
Jet reconstruction efficiency	< 0.05	< 0.05
Missing transverse energy	0.1	0.1
Total systematic uncertainty (in GeV)	3.1	2.7

JES calibration "in situ": constrain M_{jj} to M_W

Simultaneous fit to m_{top} and JSF

$\Rightarrow m_{top}$=175.9 ±0.9(stat)±2.7(syst) GeV

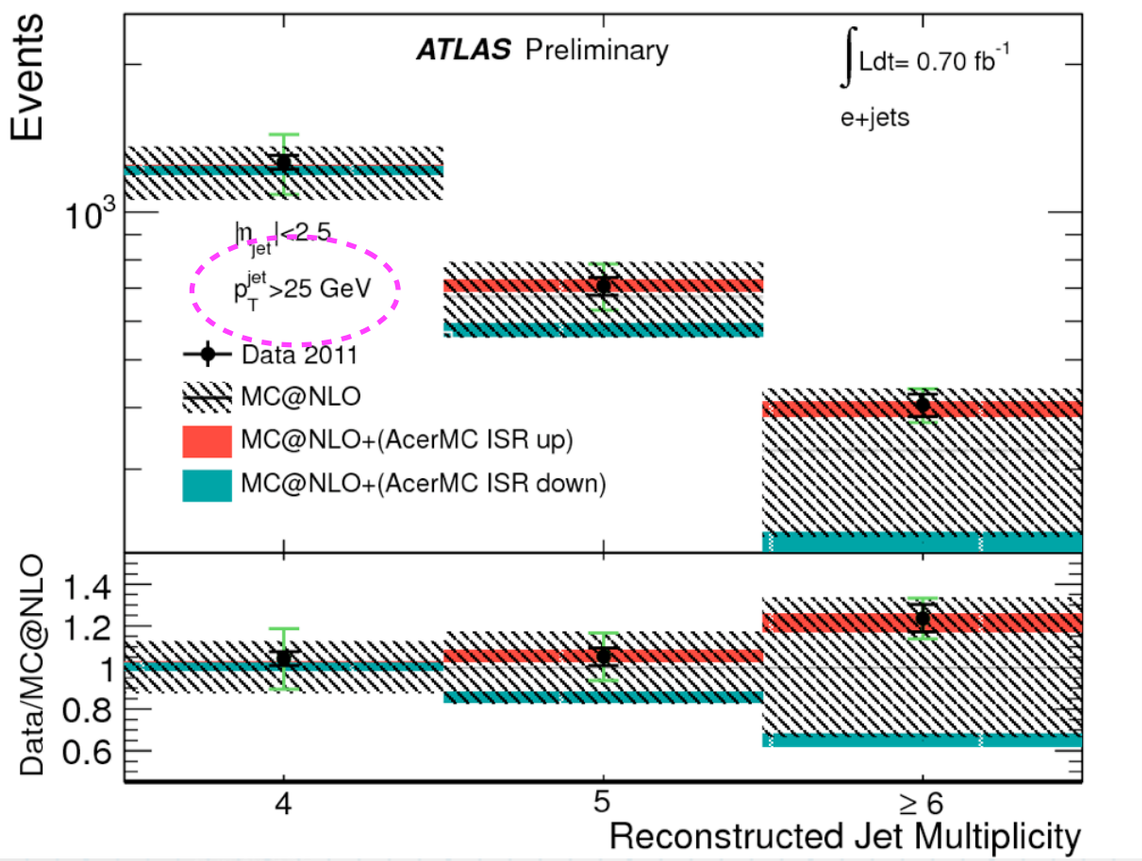
(combination of 2010-2011 ATLAS measurements)

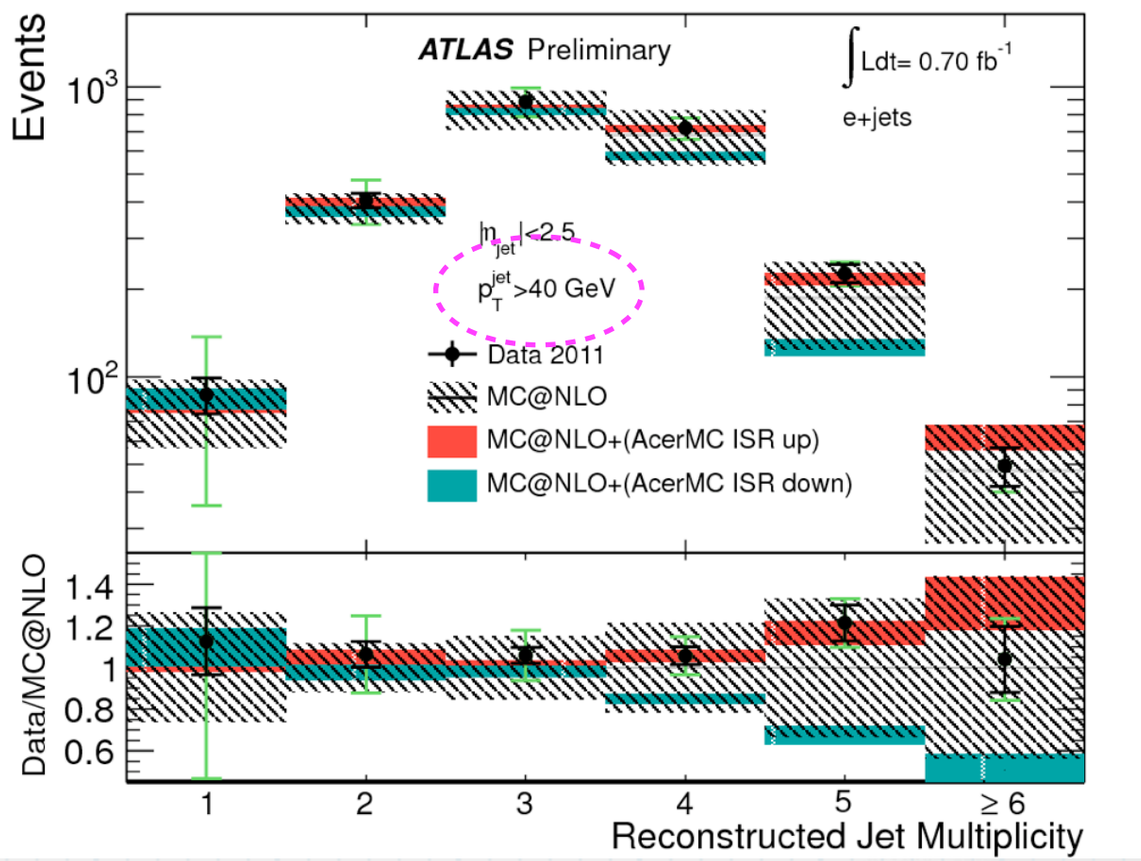
Michele Gallinaro - "Top quark mass measurement at the LHC" - Top2011 - Sep. 28, 2011 8

- Fits MC templates of reco'd mass shape for different top mass values
- Jet Energy as parameter in fit, measured directly in situ using W mass info (well known, Γ (W) = 2.2. GeV)
  - CMS has very similar syst uncertainties with different techniques
- also here: after (b) Jet uncert., next is signal MC generator!
- Ideas at QM to use W lepton + SMT to build mass templates (no Jet dependence!)

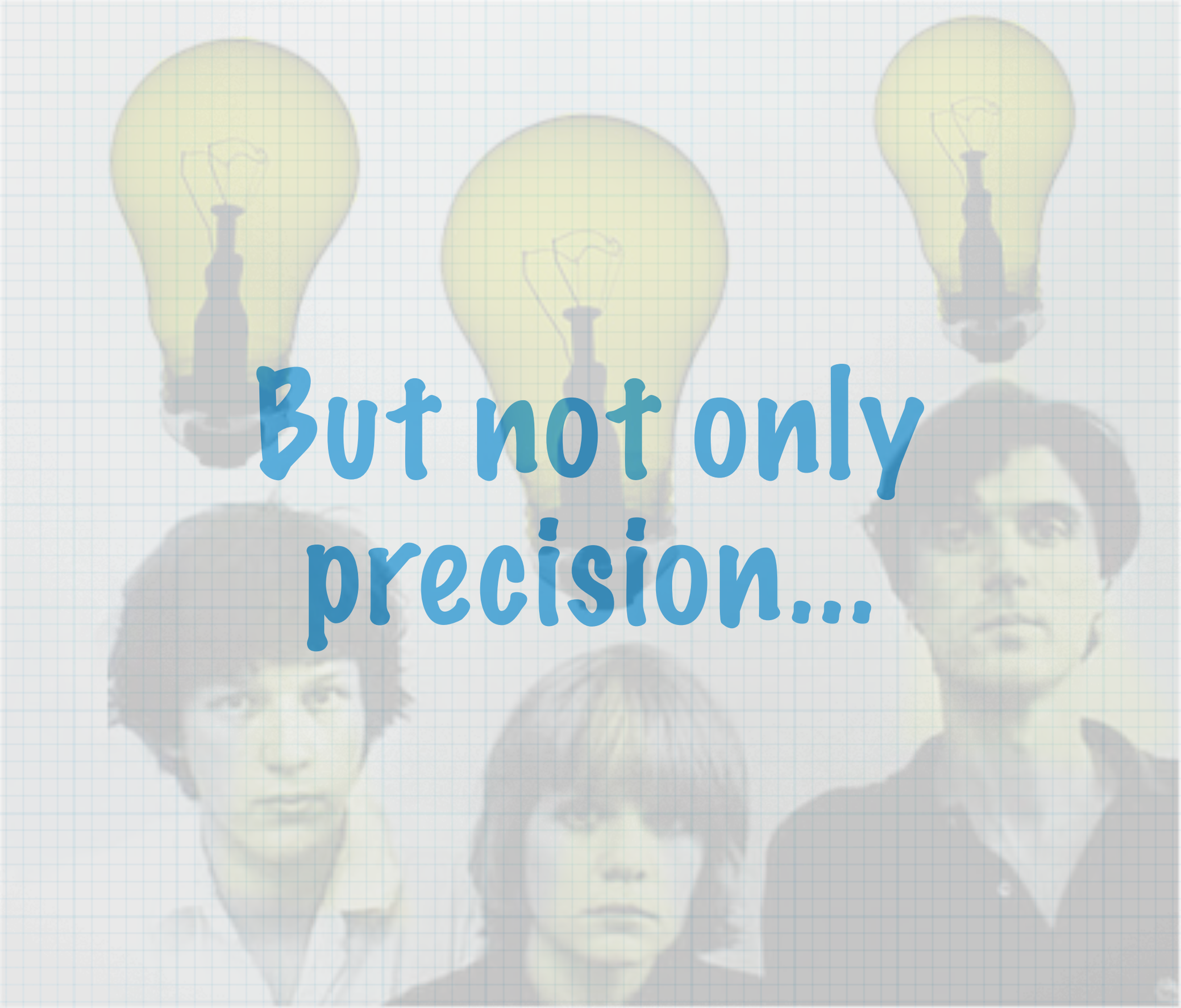
ISR/FSR expt constraints..

- ...may come from tt+jets at high jet multi
- start to compare NLO+PS predictions with data differentially
  - aim: d σ /dN(j): activities of Royal Holloway here
  - unfolding is the tricky part - input from theorists welcome



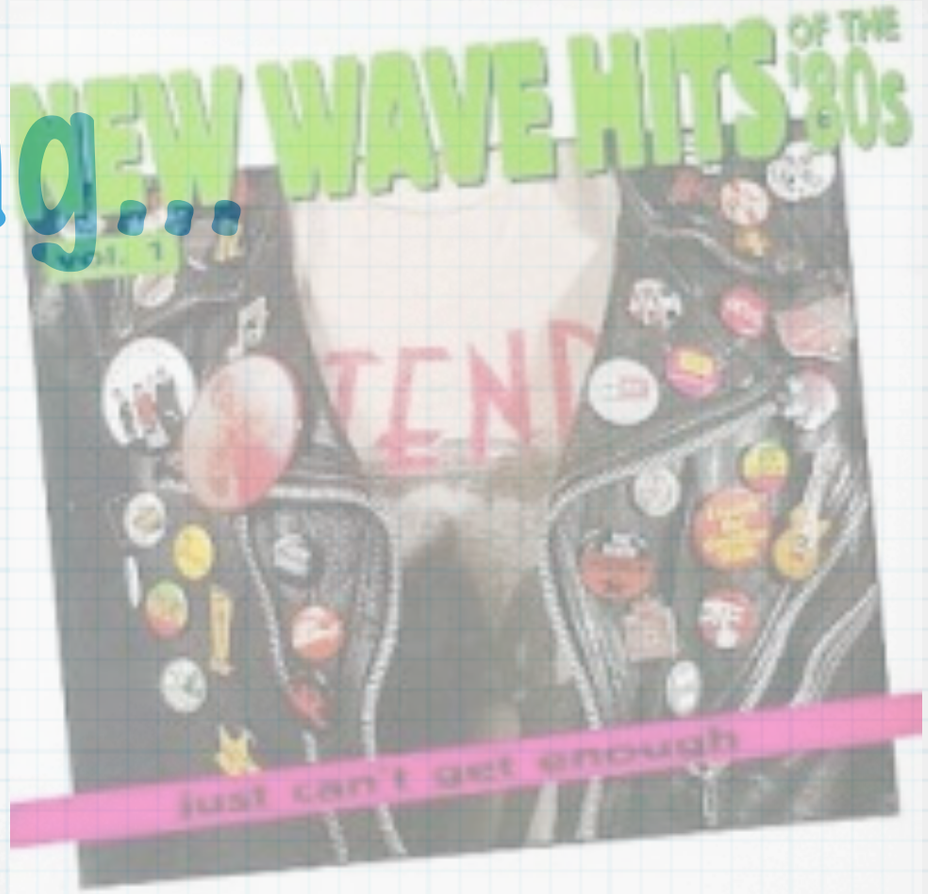


MC@NLO does good job, but need better expt. sensitivity to be conclusive



But not only precision...

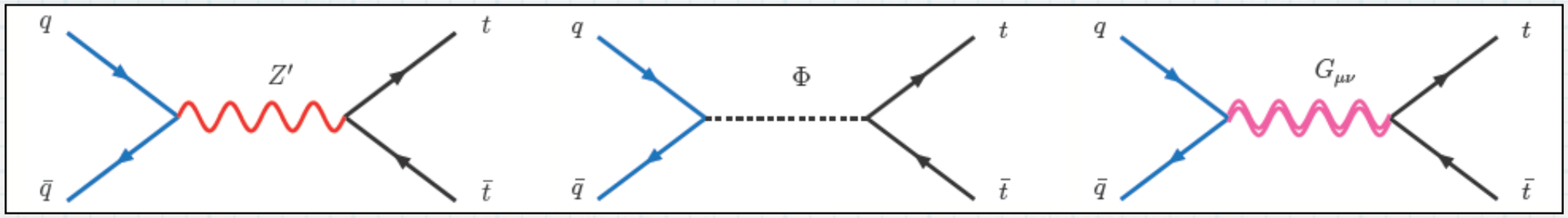
New Wave coming...



- A large number of inclusive, more or less signature-driven, searches already carried out with 1-2 fb^{-1} (summer or in preparation..)
  - e.g. ttbar asymmetry
  - searches for 4th gen quarks into tW
  - searches for heavy bottom-like fermions coupling to top
  - initial look for resonances in M(tt) at mid-masses
  - .... (many many more non mentioned here)
- I'll just provide a list of measurements considered by experimentalists in the NExT-London area
  - theorists interested in proposing new ideas should speak up!

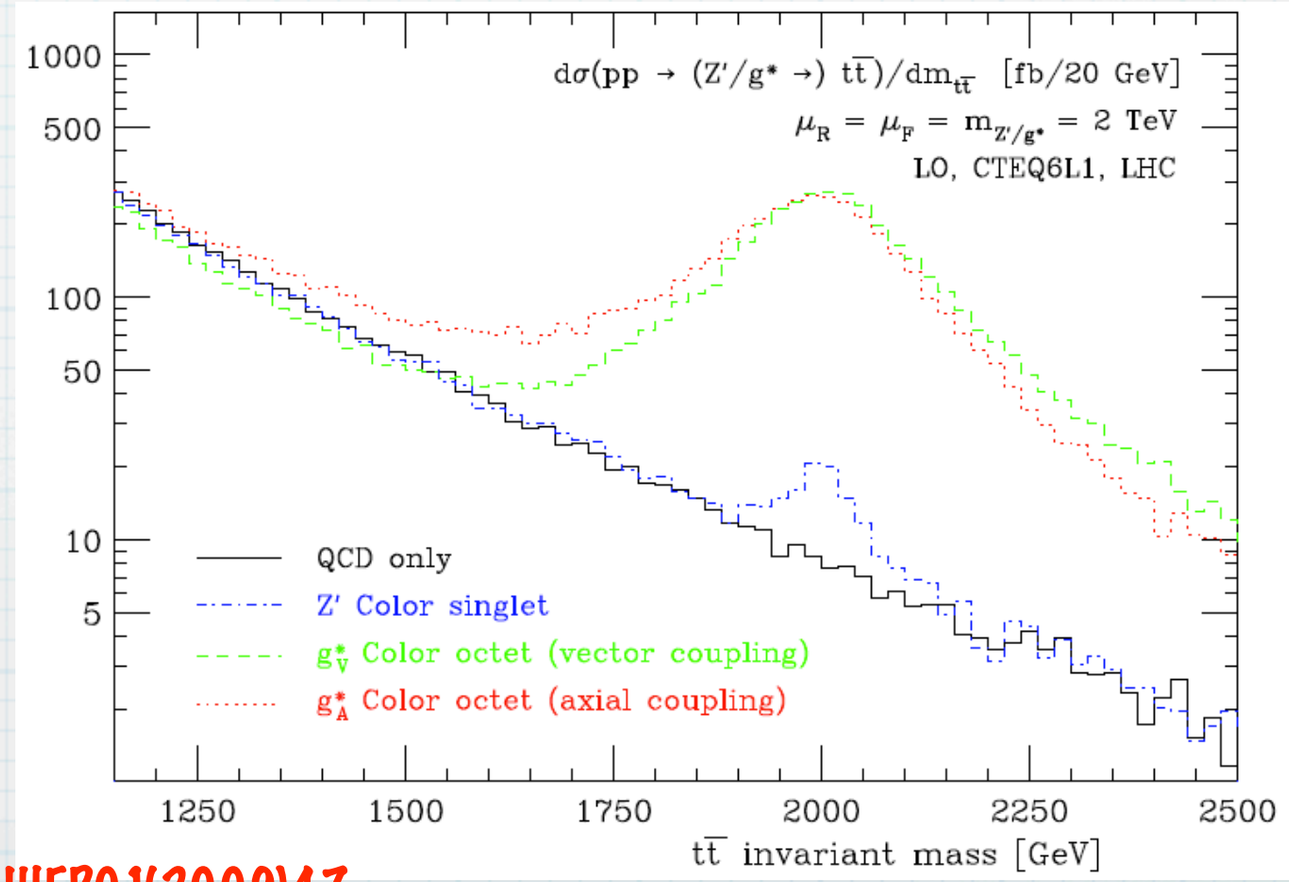
M_{tt} (boosted topo)

- VERY Easy: Resonant/smoking gun/You look for a peak
- VERY Difficult: if M(X) > 1.5-2 TeV, then jets merge into fat jet



- attempt to resolve t and $\bar{t}$ jets: here modeling of additional close-by radiation important

- It's NO top mass: special algos to resolve constituent jets (e.g. M.Seymour Z. Phys., C62:127-138)
- QM/RH: presence of high pt W muon in fat jet: use of Muon b-Tagger as a W-tagger from top could enhance sensitivity?



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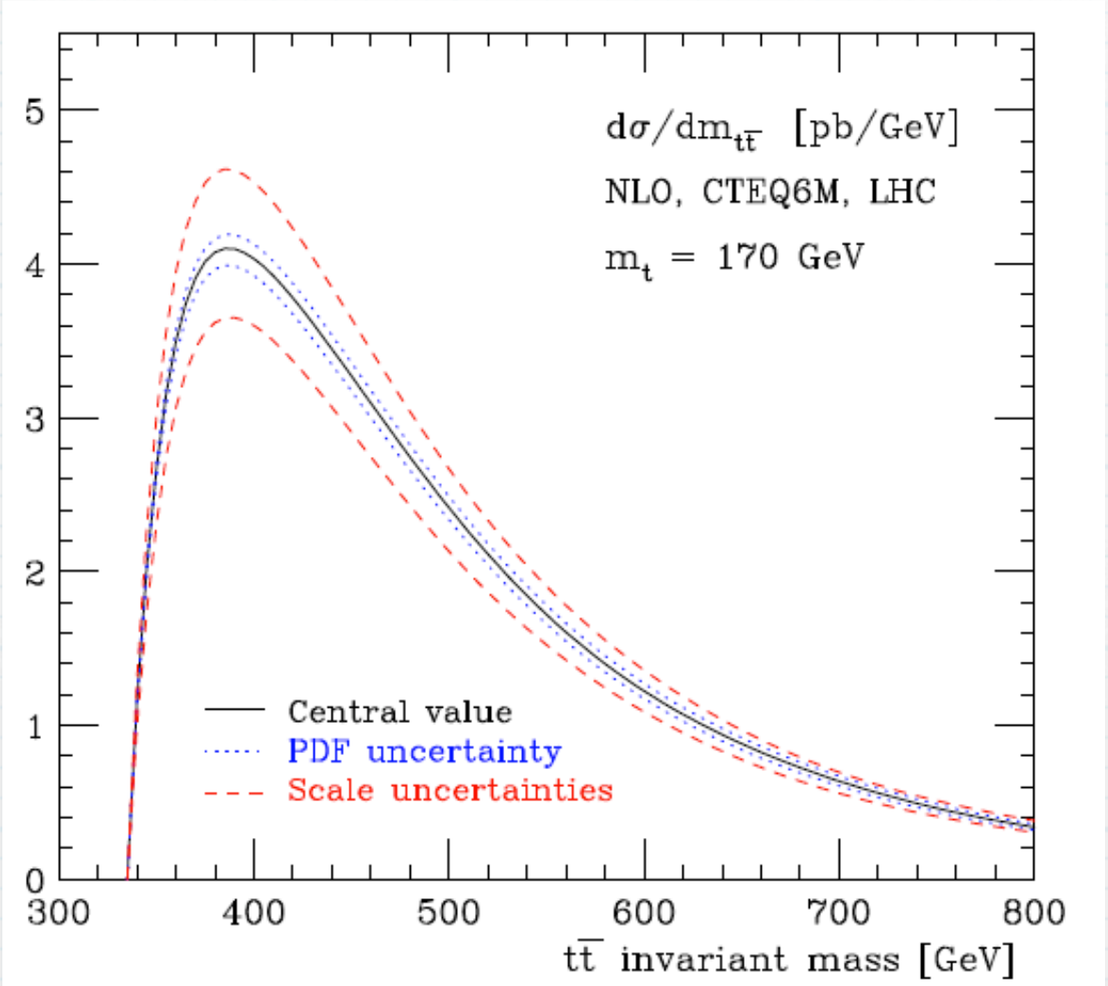
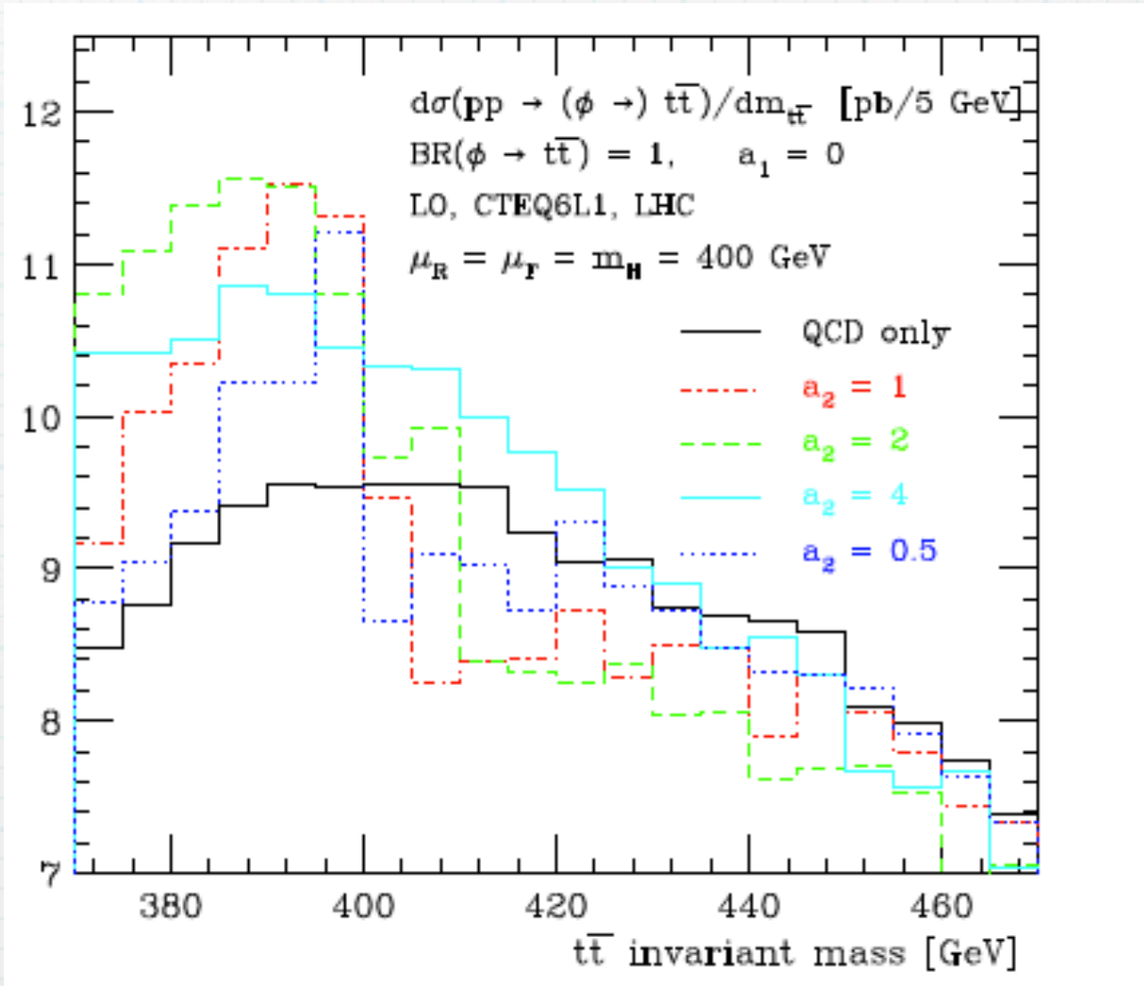
If there's a bump then what?

- Angular analysis of tops required to pinpoint kind of coupling
- Top reconstruction (at least the hadronic leg) is needed
  - if high mass, then it gets even trickier with jet assignment...

d σ /dp$_T$(tt) and d σ /dM$_{tt}$

* theory predictions are quite accurate (approx NNLO, 13%)
  * if deviations, either bad experimental work or NP in non-resonant way ;-)
  * discussion o unfolding of detector effects to meet theo predictions: input welcome!



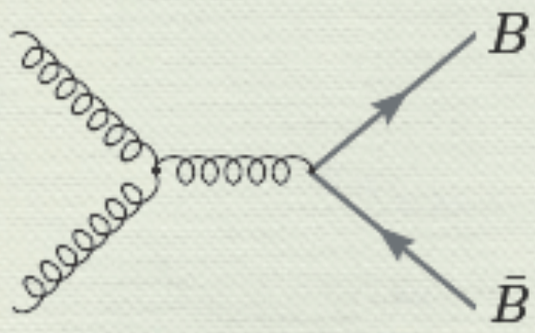


Strong EWSB: top heavy partners

* Hierarchy problem serious limitation in Higgs mechanism
  * SUSY can compensate with s-top destructive interference
* Alternative: strong EWSB (like chiral symmetry in QCD)
  * Higgs composite state of new heavy fermions arising from broken sector ➡ M_H naturally limited
  * fermions are visible because they couple to.....Top!

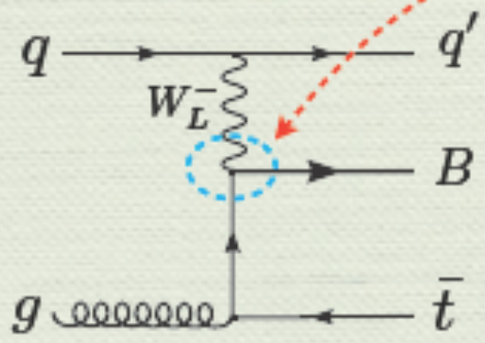
Production mechanisms

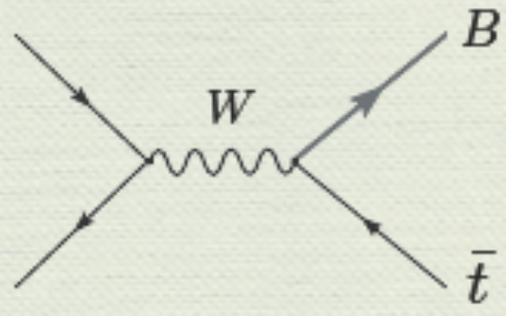
- Pair production



- Single production

gives a measure of the coupling strength $\bar{\lambda}$





$$\sigma^{soft}_{single} \propto \bar{\lambda}^2$$

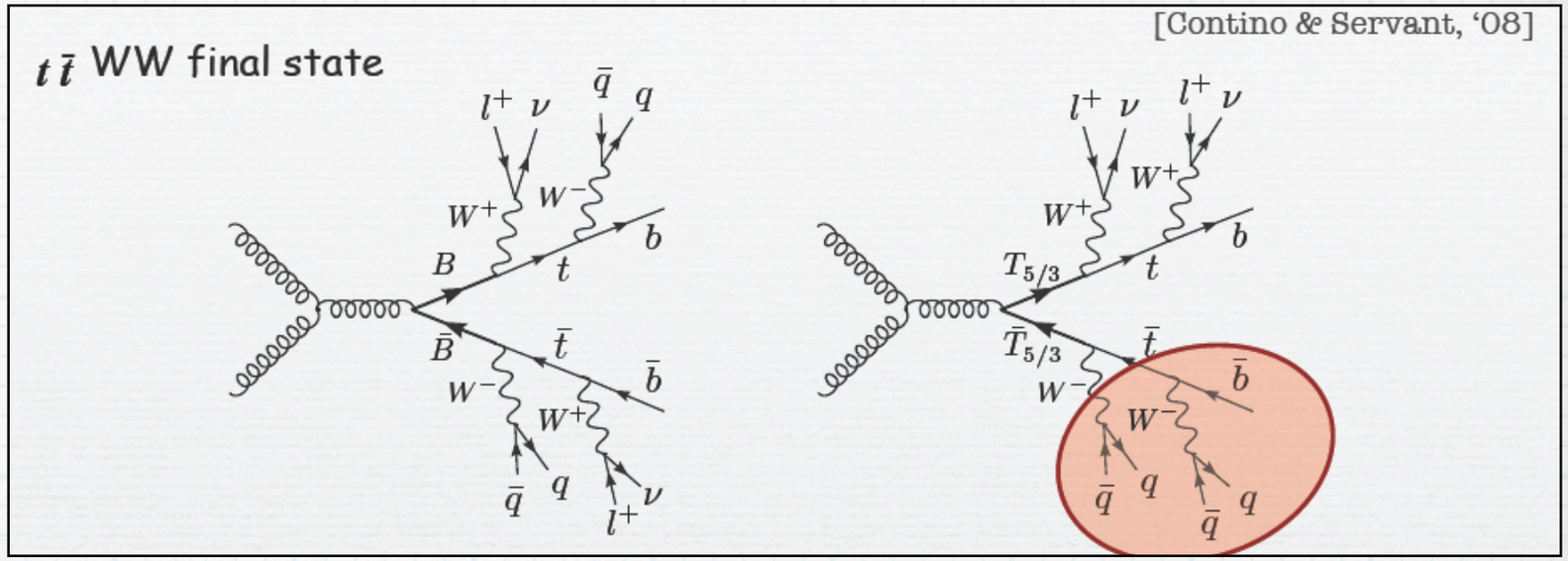
$$\bar{\lambda} \equiv \frac{g}{\sqrt{2}} \sin\theta \left(\frac{m_B}{m_W}\right)$$

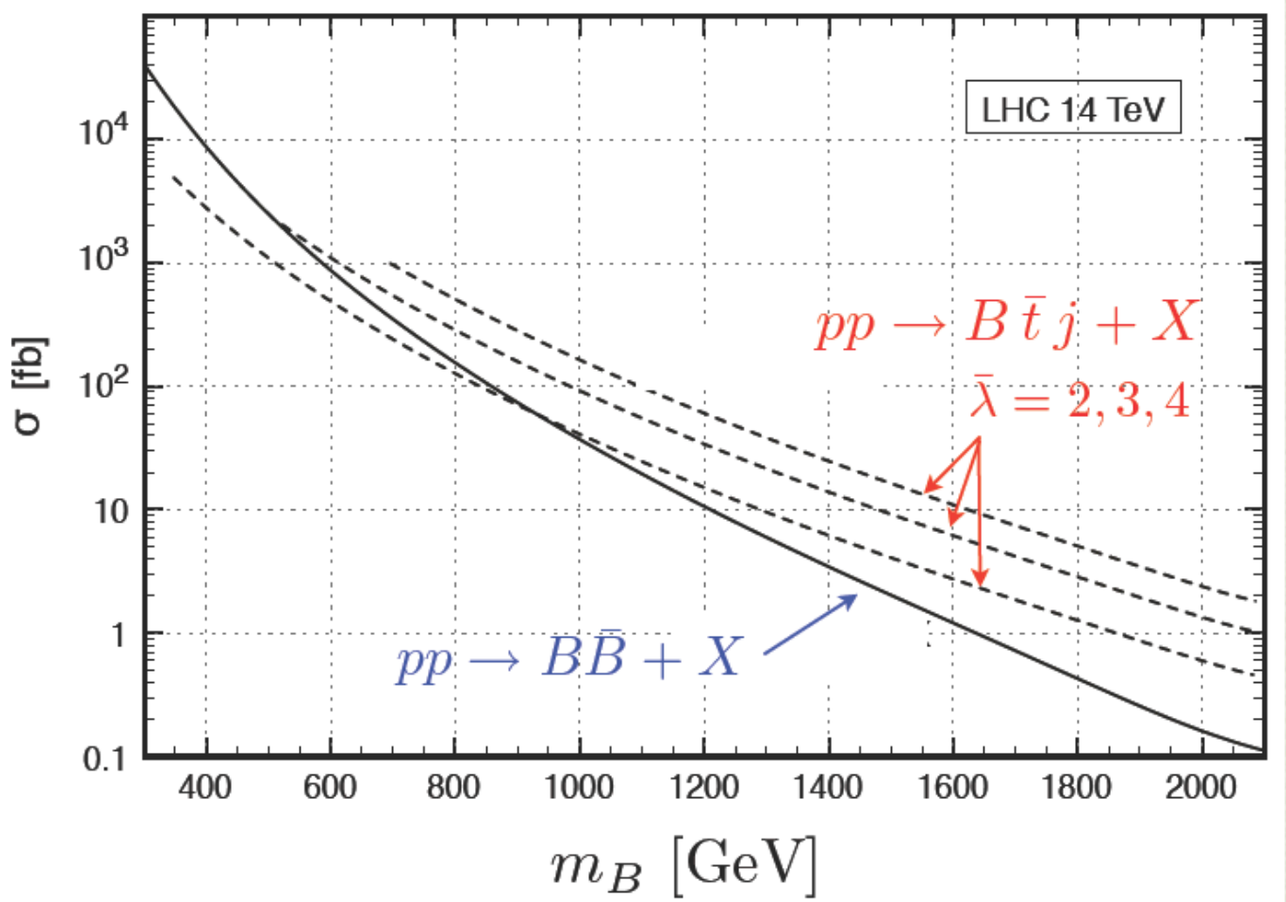
http://arxiv.org/abs/0801.1679

SS tops reveal strong sector

- Search for events with
  - 2 leptons of same sign electric charge
  - many jets+MET+2 btags
- mass measurement!

[Contino & Servant, '08]





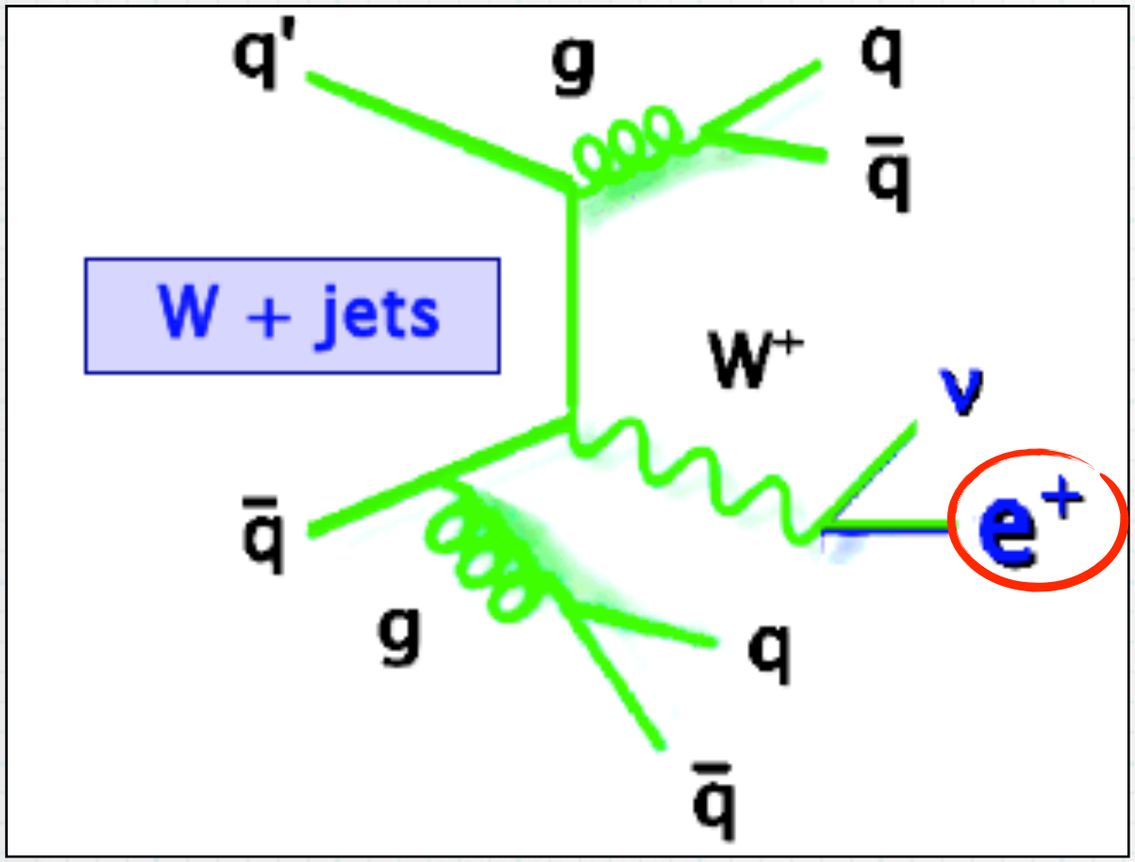
- @ 7 TeV: single production for masses 650 to 800 now-ish!
- Main experimental challenges are:
  - detector effects like mis-measurement of lepton Q
  - backgrounds: WW, ttW, ttWW, tt +jets

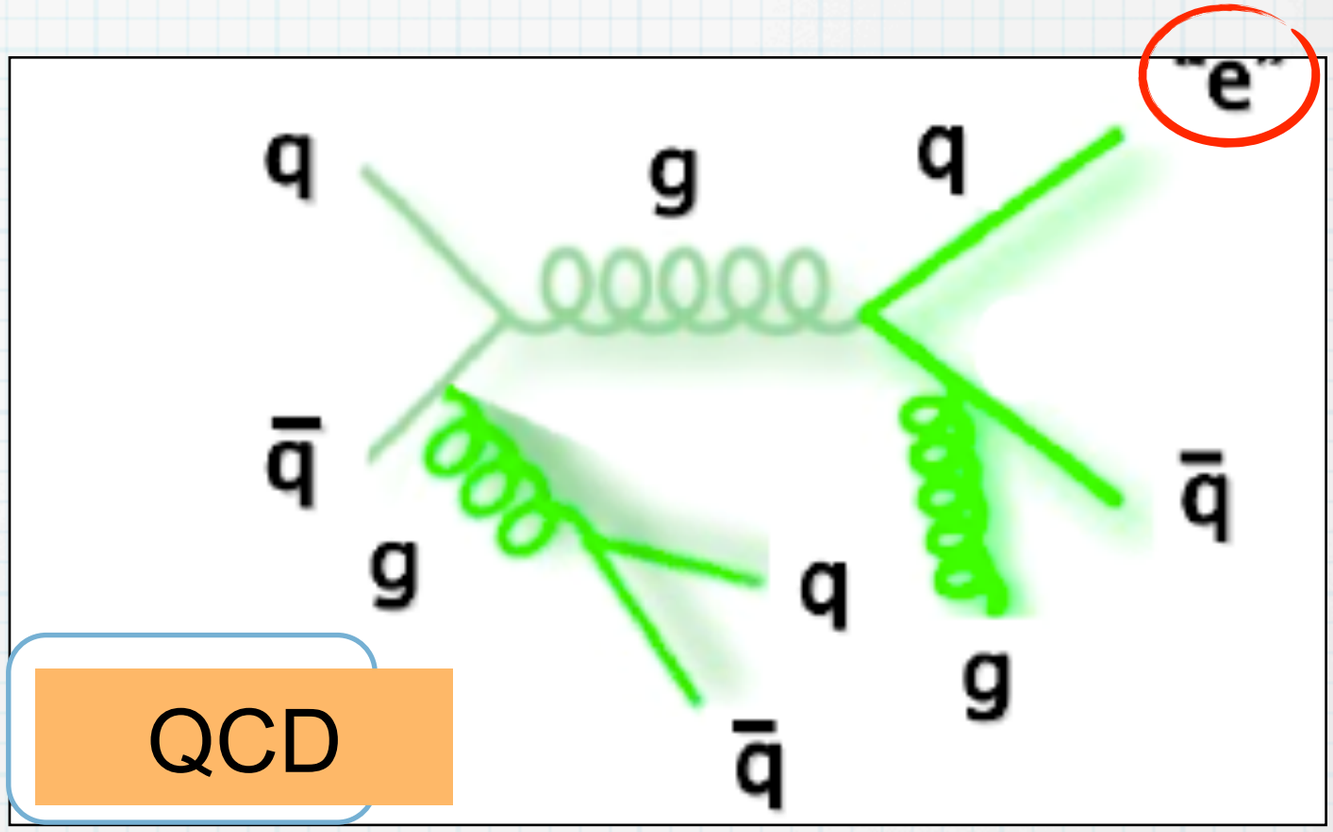
Final messages...

- Experimentally, in top sector we are in challenging time: in between important 'tail' of SM precision and definitely a New Wave of searches....
- NExT uni active in both, as it should be:
  - accurate modeling of multiplicities and kinematics in simulation is vital for searches and limit setting
  - SM precision measurements (DIFFERENTIAL ONES) are the way to constrain MC and a way to look for news
  - Inclusive searches for smoking guns involving leptons considered

Back-up

What "fakes" a $t\bar{t}$?





- *~120 times tt̄*

✓ Lower N(energetic jets)

✓ Asymmetric ±Q production

✓ Includes both W+light flavour and Wc,Wcc,Wbb

- *>1 M times tt̄*

✓ No Missing energy

✓ No isolated Lepton

✓ Lower energy jets

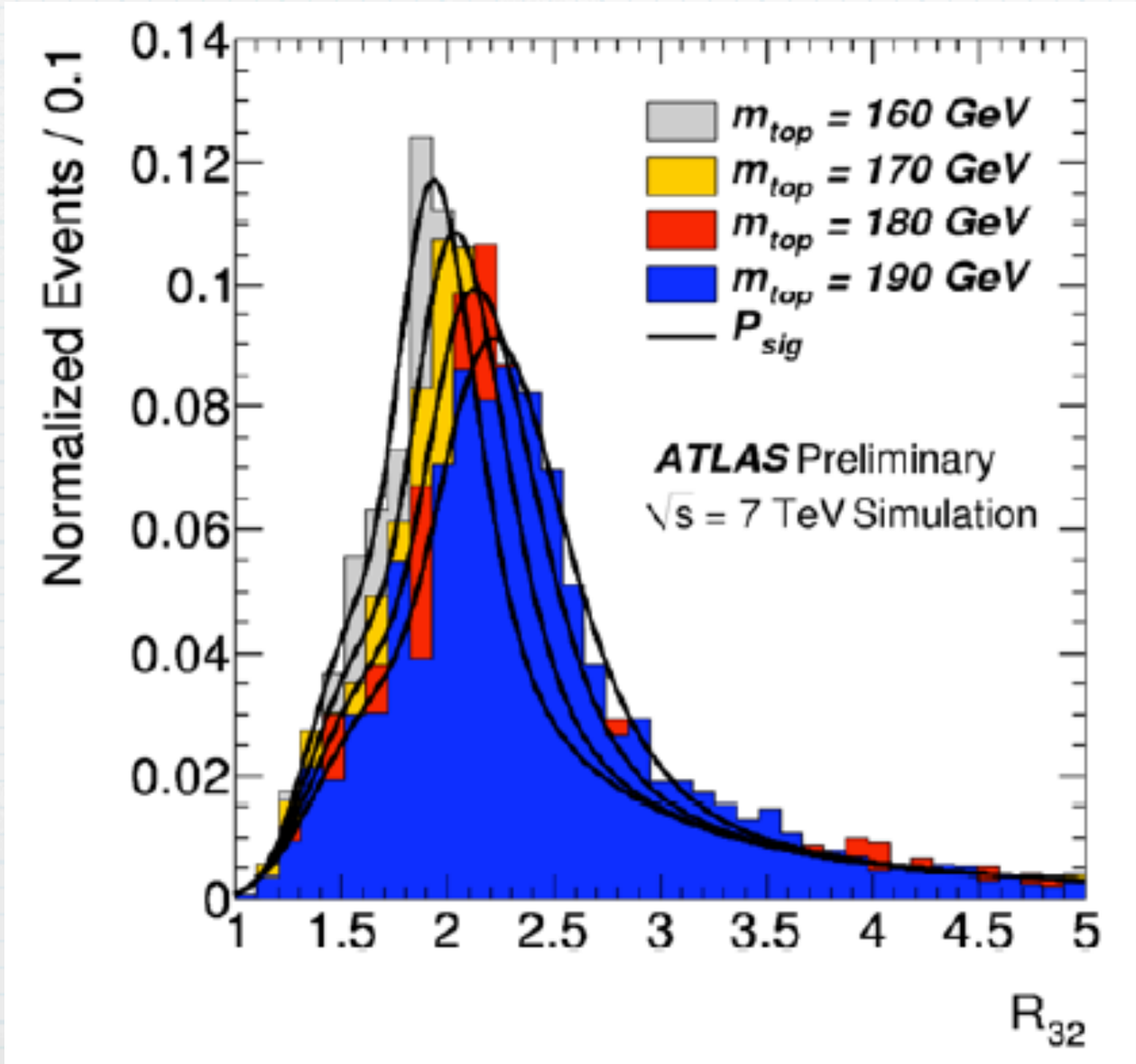
Background estimations

- QCD multi-jet events produce a 'fake' lepton
  - this is less 'good' than a real lepton from the top W
  - can't rely on MC to reproduce all effects, additional interactions at high instantaneous lumi, etc: extract bkg from control regions in data
  - estimate efficiency of sample of leptons from 'side-bands' with "good" leptons BUT surrounded by hadronic activity in calorimeters

- W+j rates from W^+/W^- asymmetry in pp collisions because of valence quarks
  - shapes are from MC, rescaling LO pdf in Alpgen to LO*

At LHC: 2-D fit

* Template method: test which MC template fits better the invariant mass of 3 jets (hadronic leg of top decay)
  * Triplet with max pt is chosen as top candidate



Divided by dijet mass to take away expt syst