Top and ElectroWeak physics
Part II: experimental results

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Taller de Altas Energías

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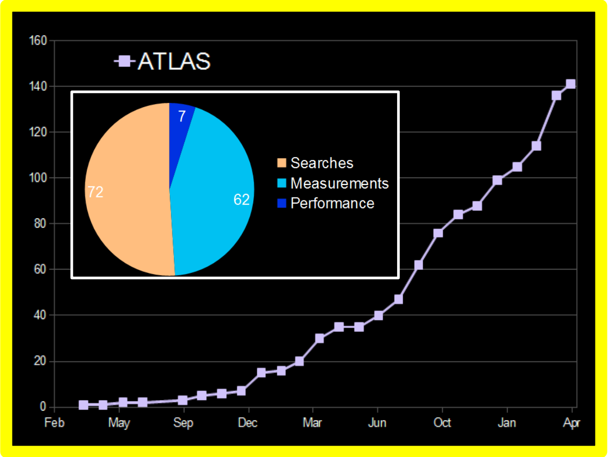
Centro de Ciencias Pedro Pascual,

Benasque

Background and scope

I'll assume you're familiar with the basics.
You'll need some background on:
the Standard Model,
the Large Hadron Collider,
the ATLAS and CMS experiments
(please, ask whenever I go too fast)

The scope of this lecture is limited to:
The physics of top quarks and weak gauge bosons
(roughly everything to come out of the top and SM-electroweak groups in CMS and ATLAS)



Intersparsed with intermezzos on important experimental techniques
Discussing lepton collider prospects along with LHC status

Recommended literature

Bernreuther on LHC top quark physics (before the start of the LHC)

http://arxiv.org/abs/arXiv:0805.1333

An experimentalist's review of the first two years at the LHC:

http://arxiv.org/abs/arXiv:0805.1333

Outline

- Motivation (that should mostly be covered in Juan Antonio's talk)
- Top quark reconstruction (with a bias towards new techniques)
- Some key measurements with top quarks:
  - Top quark pair production cross-section
  - Top quark charge asymmetry
  - Top quark couplings to electro-weak gauge bosons
  - Top quark mass
  - Top quark decay: W helicity
- Searches involving top quarks
  - Top and Higgs
  - Top and new physics
- Electroweak physics
  - W/Z + jets production
  - Gauge boson pair production
- Not a complete review. No mention of top quark polarization, single top, and many other interesting subjects.

Searches vs. SM measurements

A large fraction of ATLAS and CMS papers report the result of

searches:

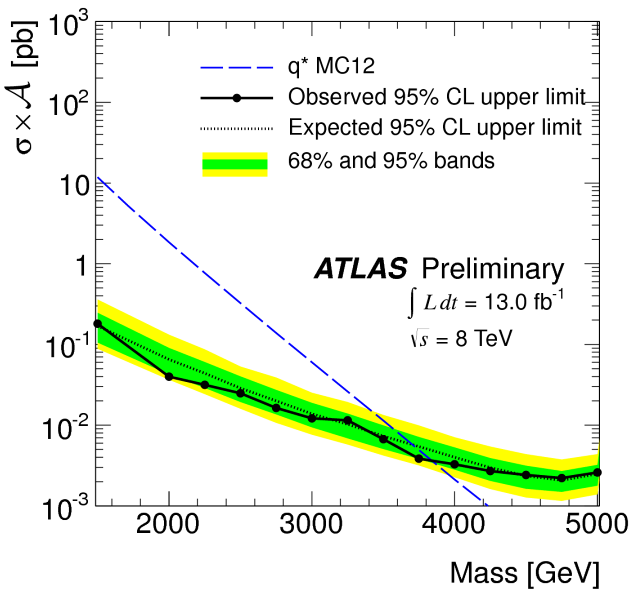
Define a signal region, predict the background, count events

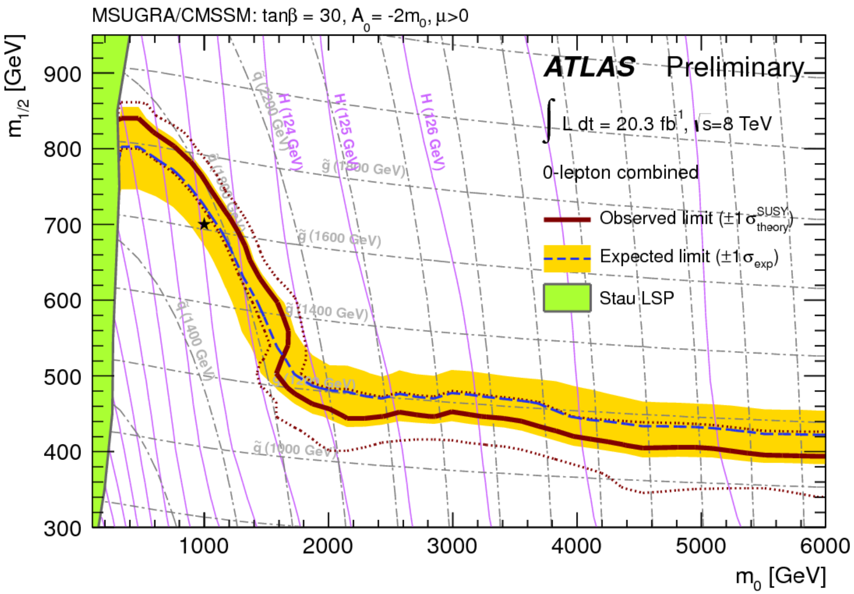
Typical outcome: limit on a (more or less plausible) benchmark scenario for the physics that might lie beyond the Standard Model (BSM physics)

Leave no stone unturned, but expect few searches are successful...

(discussed extensively in other lectures)

Derive bounds on excited quarks from characteristics of di-jet production, or on SUSY





Searches vs. SM measurements

A different approach to study the same data:

SM measurements

No prejudice on what new physics should be like

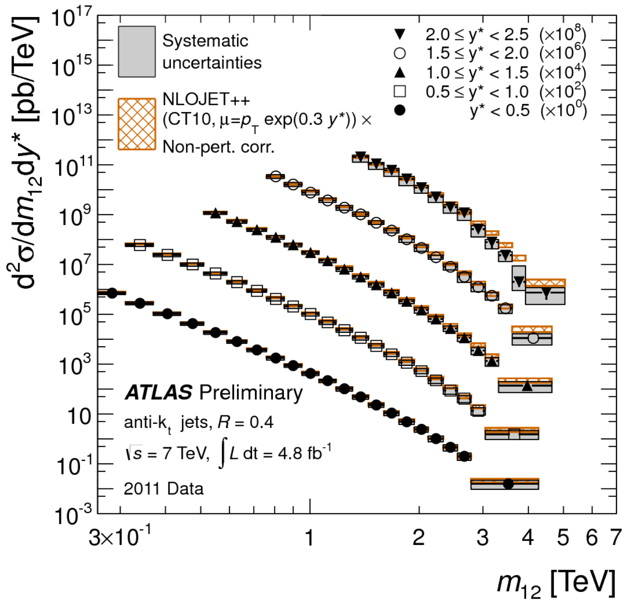
Assume the Standard Model describes kinematics adequately

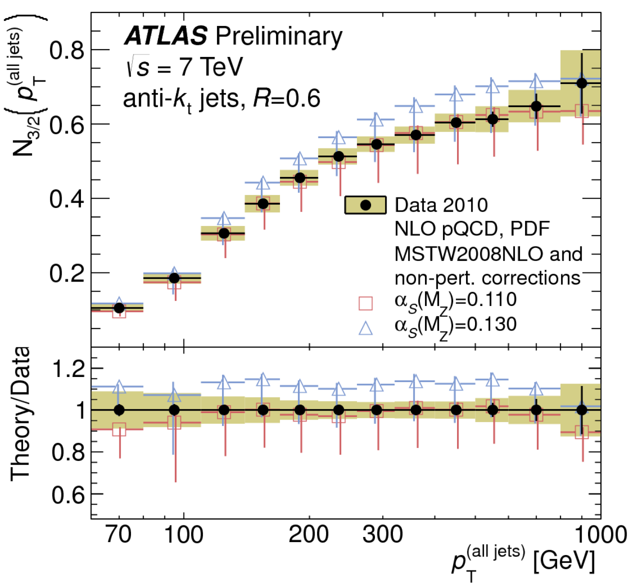
Produce numbers that can be compared to predictions

(i.e. apply corrections for acceptance, detector response)

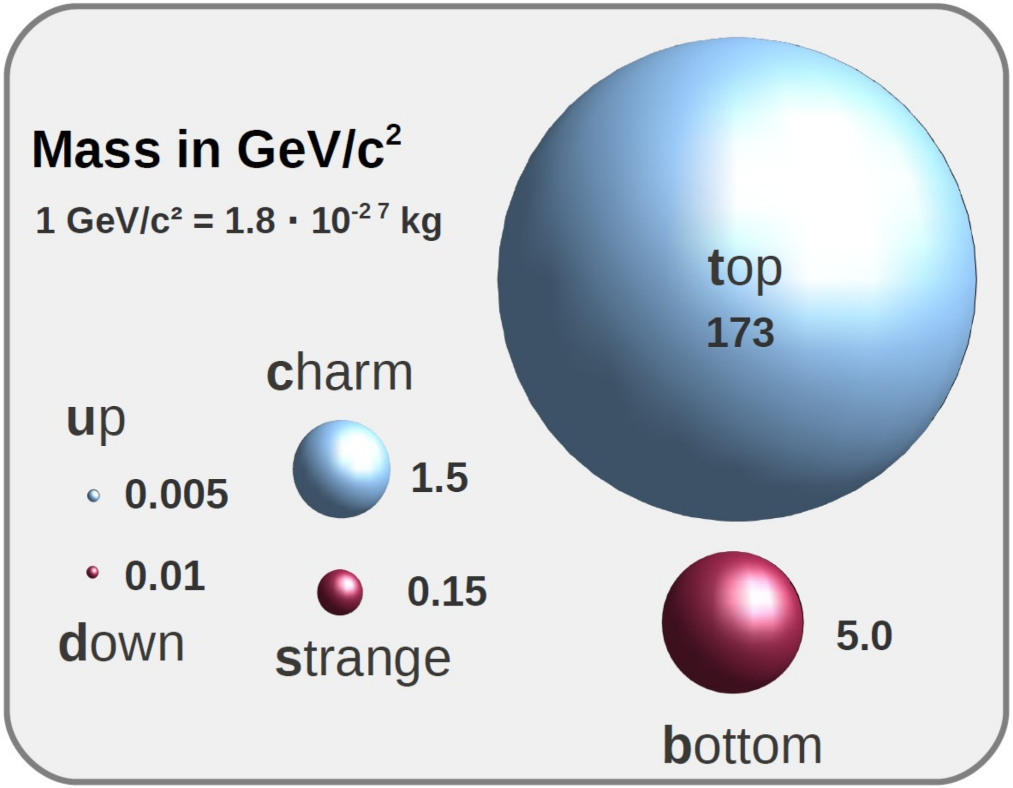
Expose the result to the entire community to interpret the result

Unfolded di-jet mass spectrum and ratio of three-jet to two-jet events





The top quark

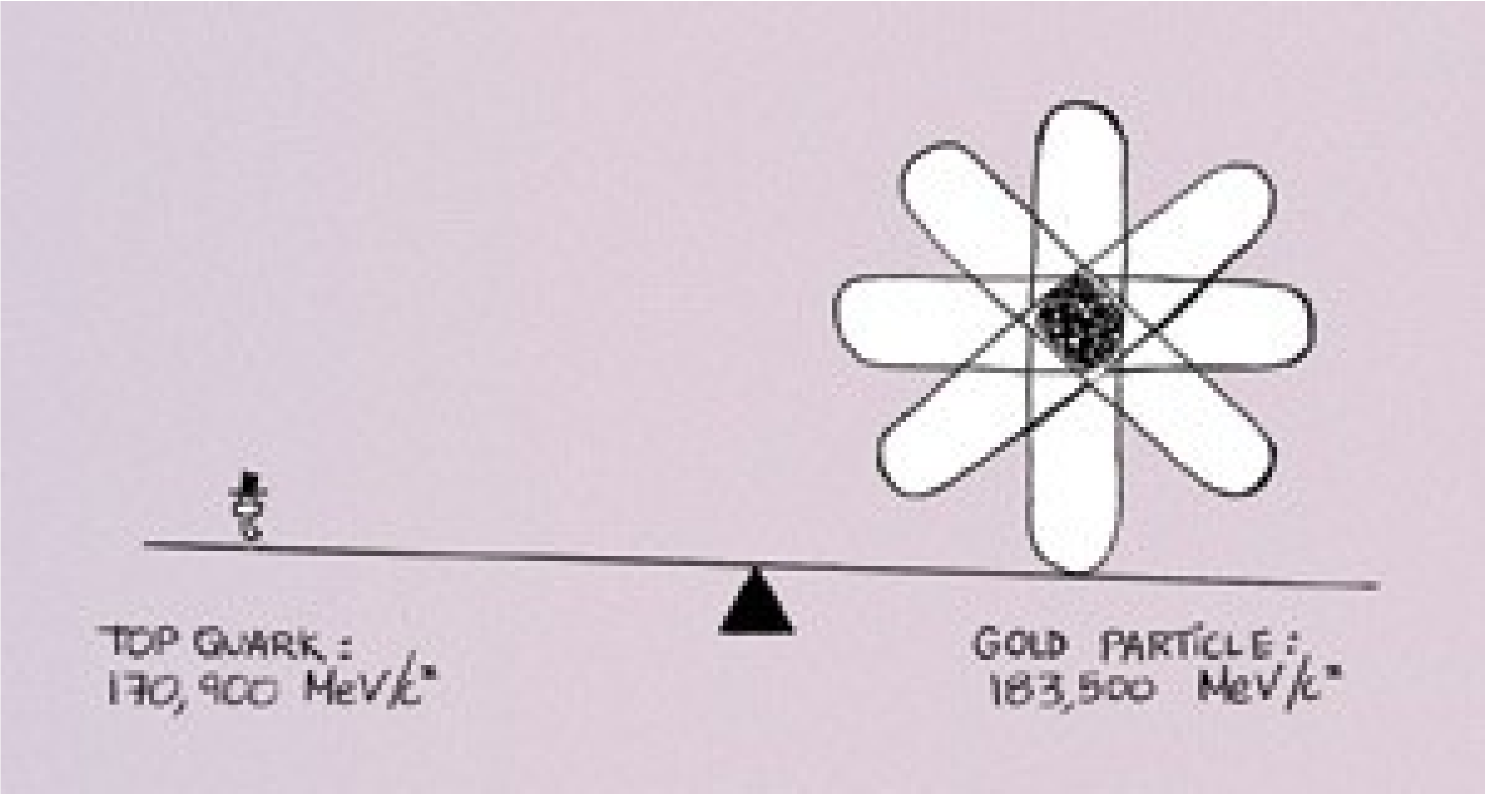


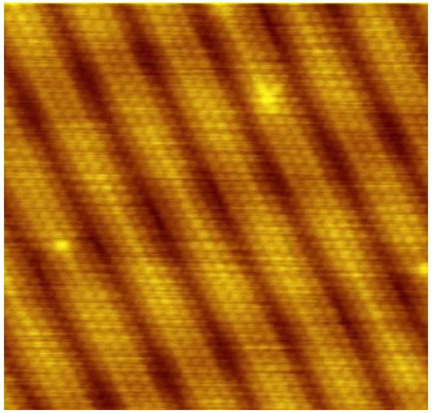
The heaviest particle in the Standard Model

We don't know why the SM fermions have the masses they have. The top quark has a mass of ~173 GeV. What does that number come from? In the SM it's the result of the Yukawa coupling of the top quark to the Higgs boson. But what does the number come from? We have been worrying about this for 45 years and we haven't made any progress!

Steve Weinberg, public lecture UTA, 24/10/2012

The top quark





A single top quark is as heavy as a Gold atom.

Gold atoms are composite *(quite so, indeed: 79 protons, 118 neutrons)* and of finite size *(so large we can "see" them).*

The top quark: structure

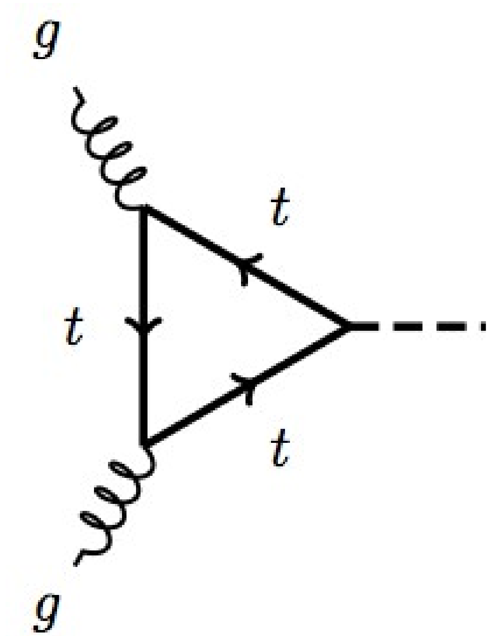
What do we really know about the internal structure of the top quark?

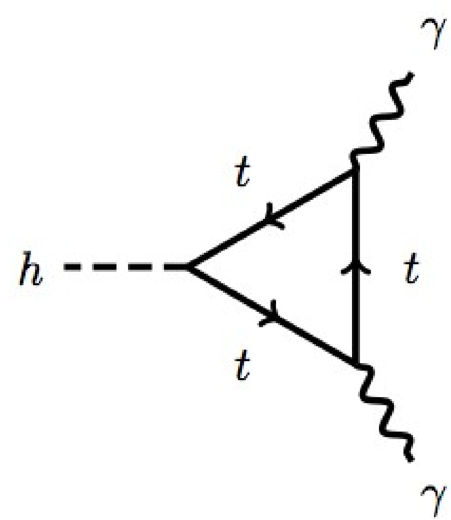
observable	Compositeness scale reached [TeV]
L (eeee)	O(10) (LEP)
L (eeqq)	O(10) (LEP)
L (qqqq)	2.9 (D0) 3.4 (ATLAS) 5.6 (CMS)
$e^* \rightarrow e \gamma$	1 (CMS)
$q^* \rightarrow q g$	2.5 TeV (CMS), 1.3 TeV (ATLAS 2010)

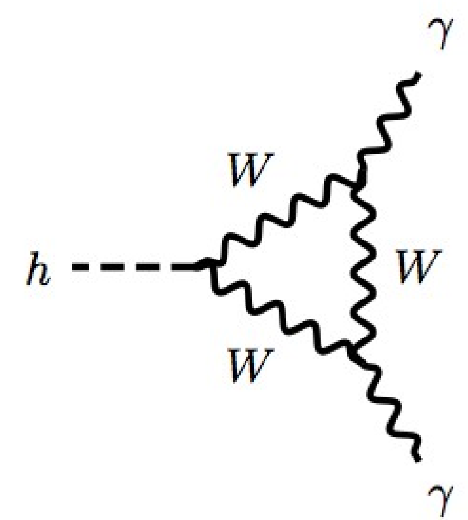
Searches for contact interaction or exicted states of quarks and leptons yield limits on compositeness (from PDG2012)

Tops, gauge bosons and loops

The top quark loves loops and loops love the top quark. Our favourite Higgs decay wouldn't work without heavy objects, nor would the dominant production mode.





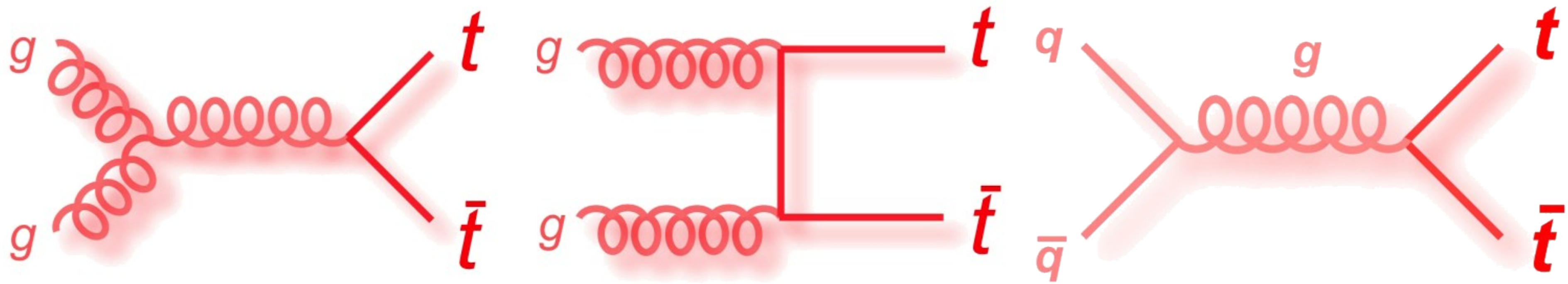


Top quark production at hadron colliders

Collider (energy)	process	approx σ	lumi (deliv/on tape)	# of ev
Tevatron $p\bar{p}$ (run II 1.96 TeV)	$t\bar{t}$	~7 pb	12/10 fb^{-1}	~70 K
LHC pp (7 TeV)	$t\bar{t}$	~165 pb	5.7/5 fb^{-1}	~800 K
LHC pp (8 TeV)	$t\bar{t}$	~235 pb	23/22 fb^{-1}	~5 M

$t\bar{t}$: strong interaction

Electroweak pair production is present, but not accessible as it's rate is several orders of magnitude below QCD pair production

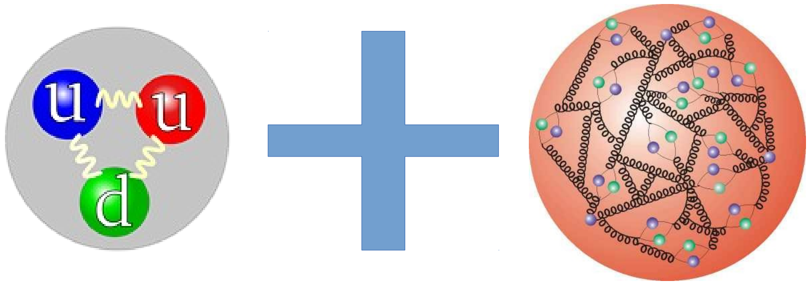


Relation between gluon gluon-initiated and quark anti-quark initiated processes is inverted between LHC and Tevatron

Collider	$q\bar{q}$	gg
Tevatron $p\bar{p}$ (1.96 TeV)	~85%	~15%
LHC pp (7 TeV)	~20%	~80%

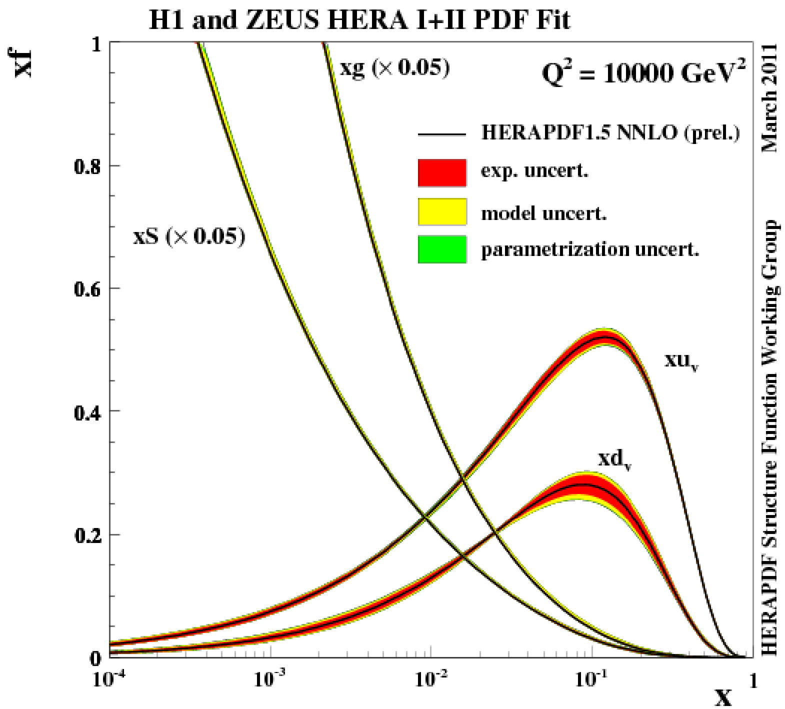
5 million top quark pairs produced at the LHC

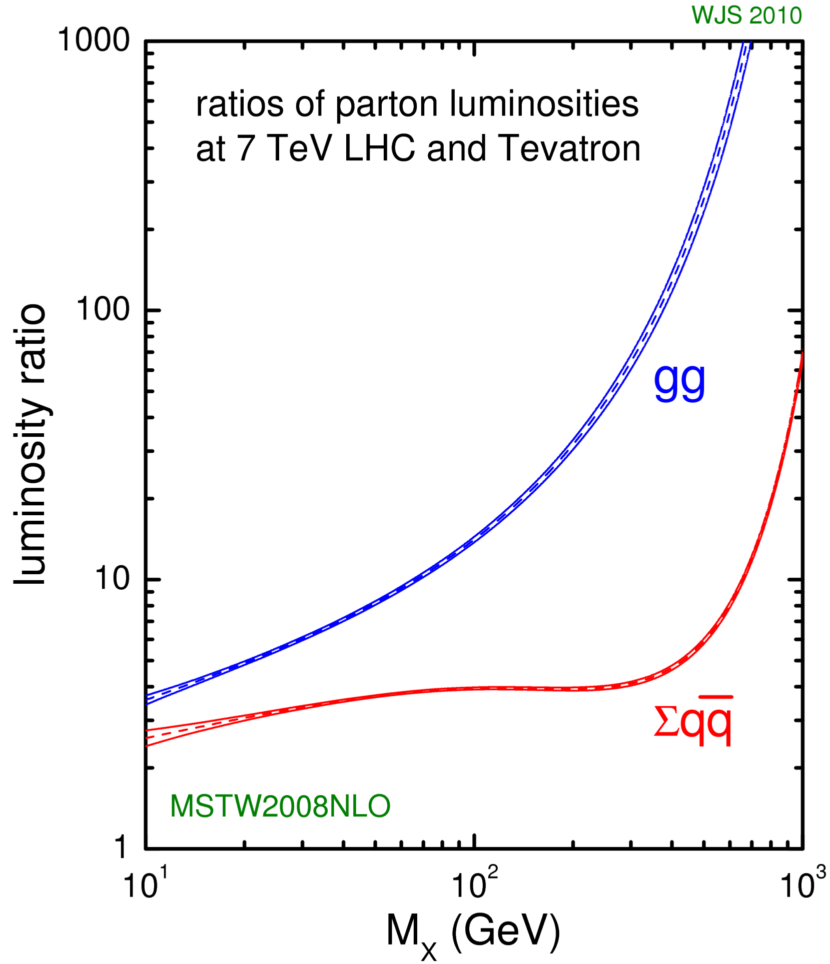
Intermezzo: sea quark, valence quark, gluon



Higher center-of-mass energy allows to take advantage of relatively low-x partons. Parton luminosity increases very strongly from Tevatron to LHC.

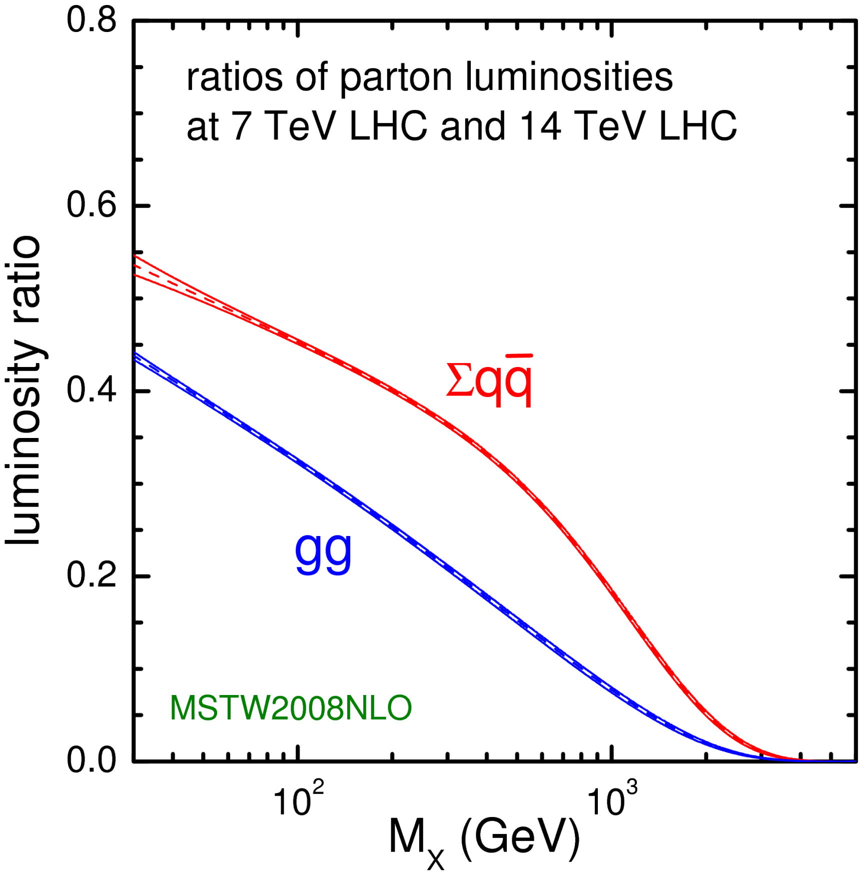
Parton density function: probability to find a quark or gluon with a fraction x of the proton momentum





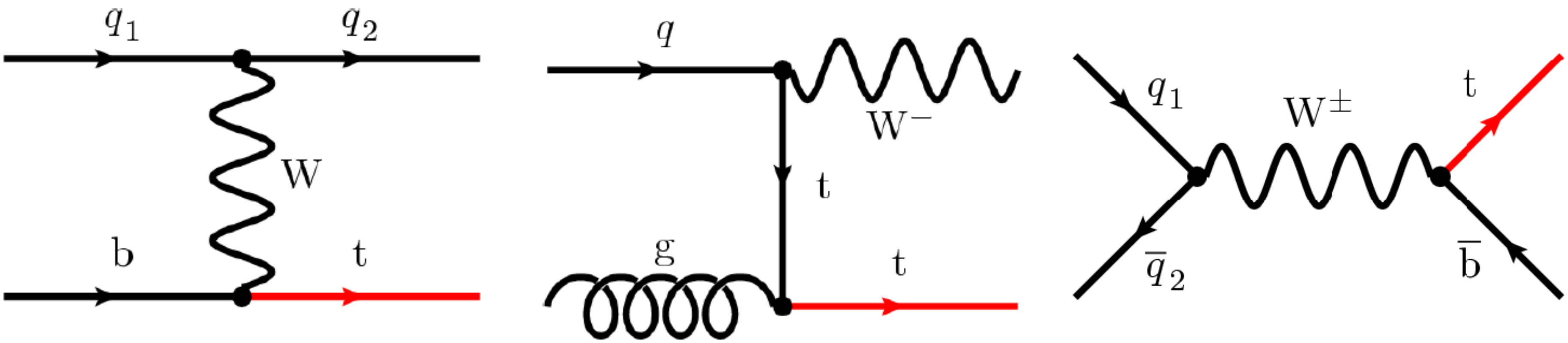
Intermezzo: ½ LHC → LHC

That begs the question:
what can we expect
with 14 TeV (or 13)
running
Another big leap!



Top quark production at hadron colliders

single t: weak interaction



Collider	s-channel σ_{tb}	t-channel σ_{tqb}	tW-channel σ_{tW}
Tevatron $p\bar{p}$ (1.96 TeV)	1.05 pb	2.08 pb	0.22 pb
LHC pp (7 TeV)	4.63 pb	64.6 pb	15.7 pb
LHC pp (8 TeV)	5.55 pb	87.1 pb	22.2 pb

1 million top quarks from single-top production

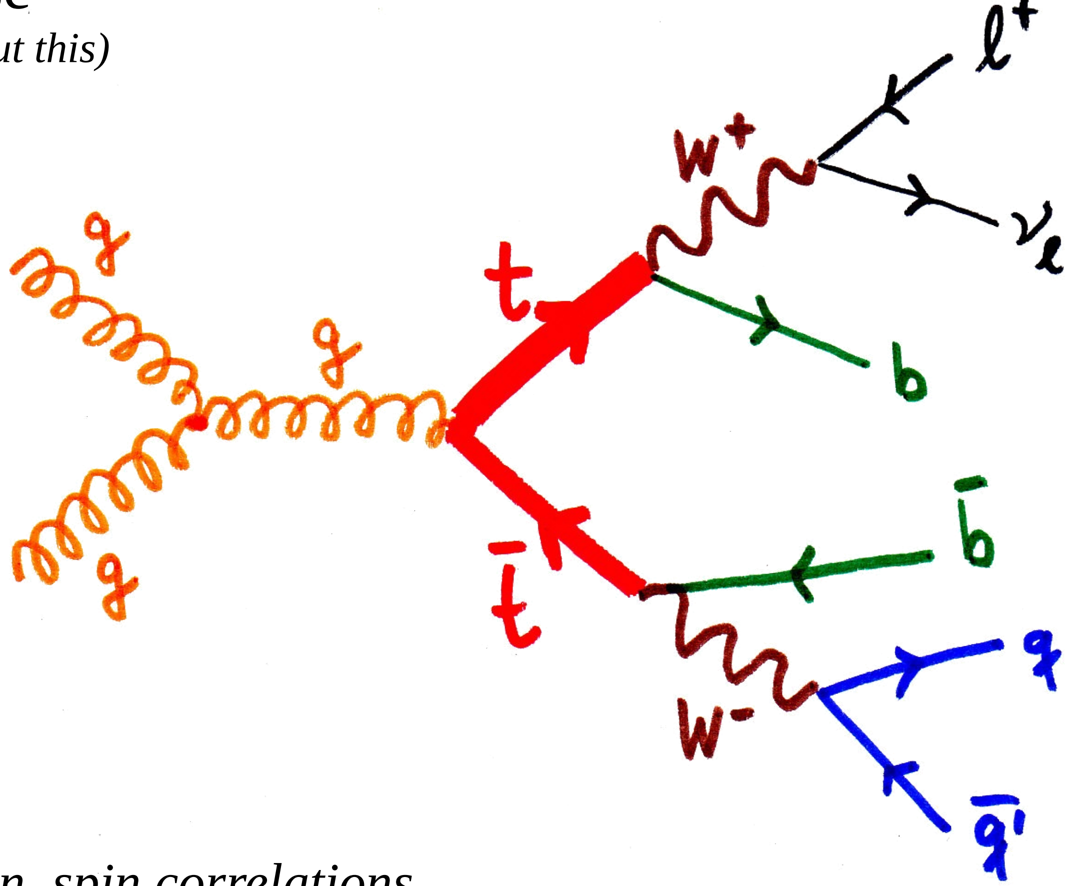
Top decay

The top quark decays to quickly to hadronize

(no top jets in the true sense of the word, but wait and see)

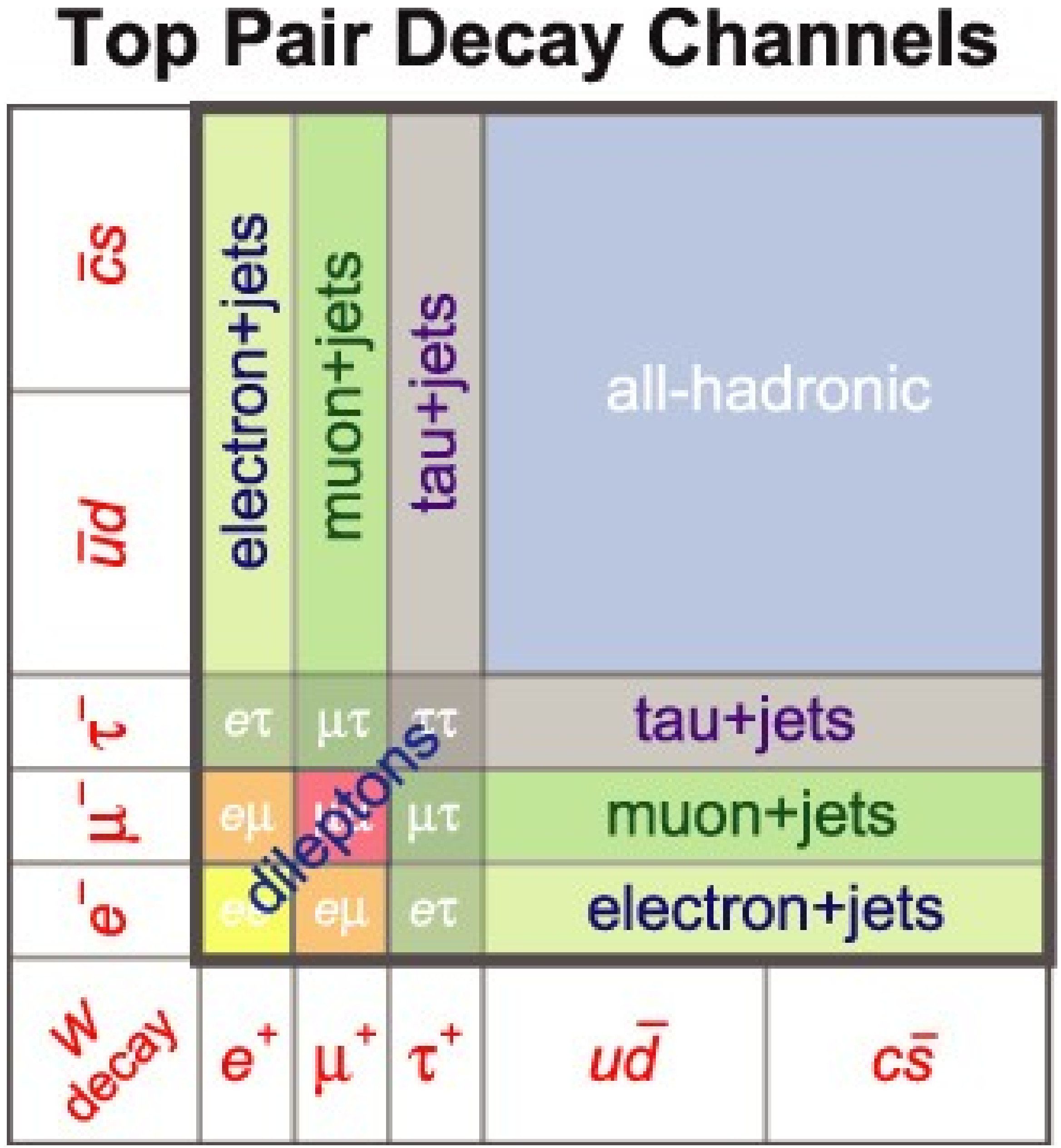
t → Wb and little else

(Juan Antonio told you all about this)



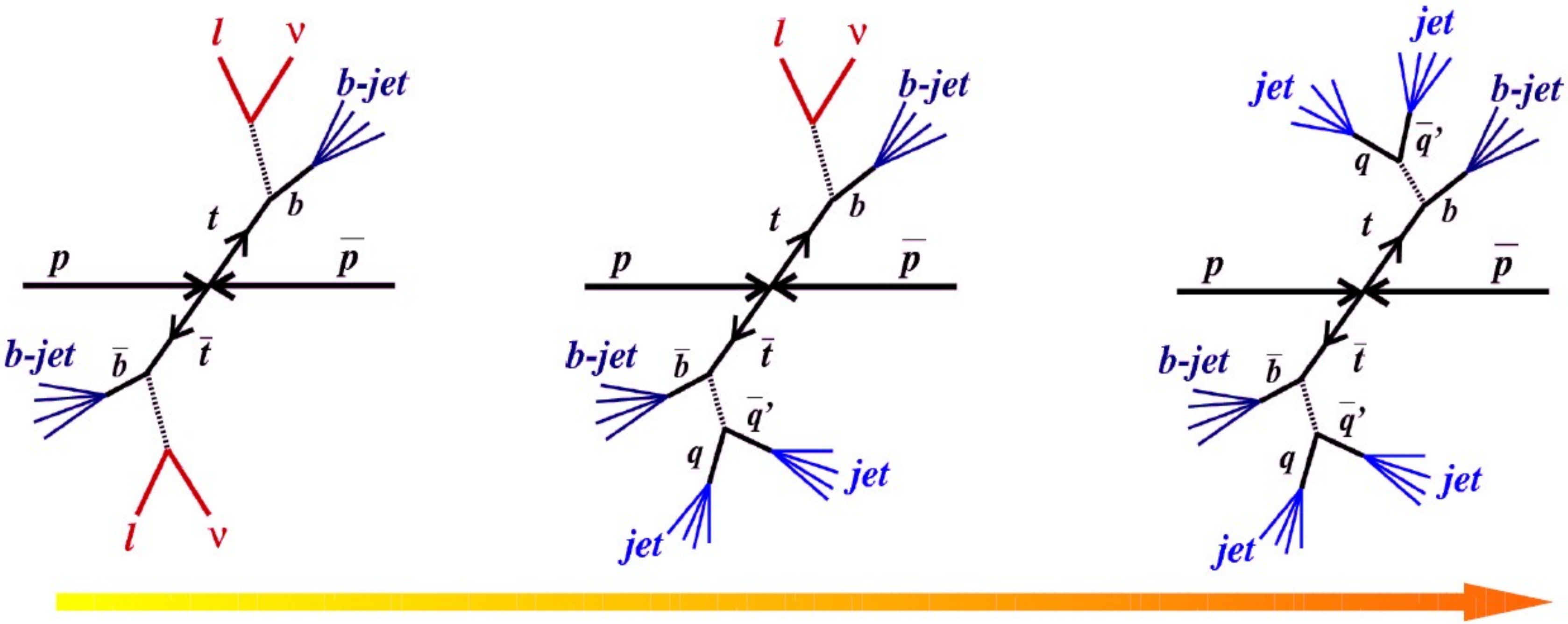
Access to top polarization, spin correlations

Top decay

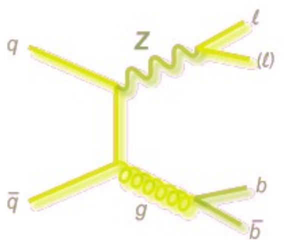


5% di-lepton
20% e,μ + jets
44% six jets

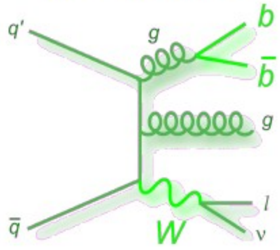
Top quark pairs: final states and background



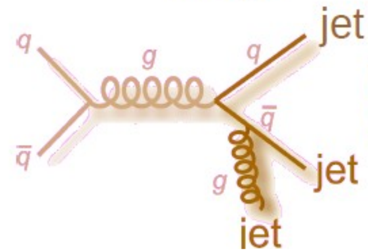
BR:	≈ 5 %	≈ 30 %	≈ 44 %
BG:	few	moderate	huge



Mainly Z+jets



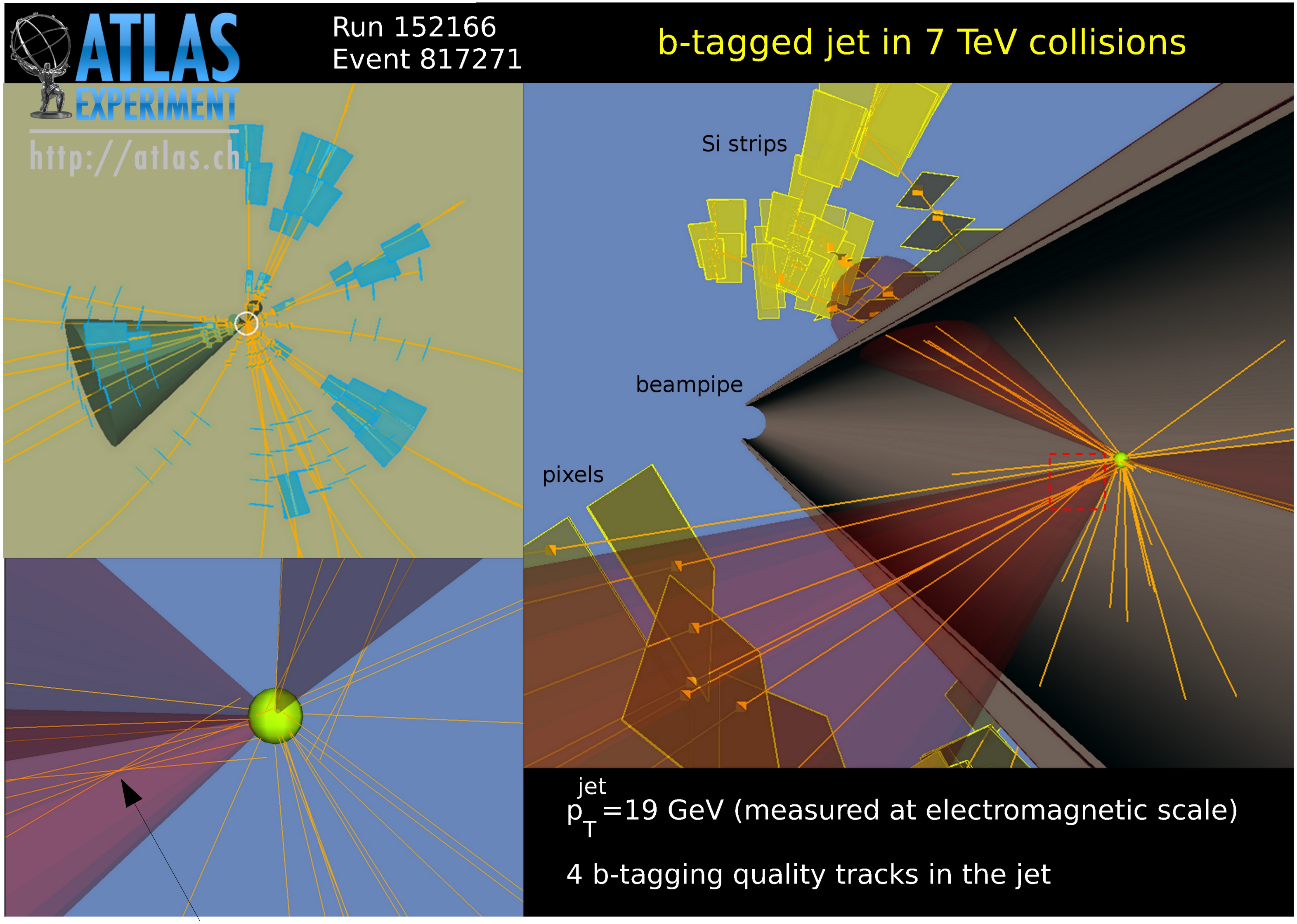
Mainly W+jets



Mainly multijet

Bottom line: charged leptons are useful at a hadron collider

Intermezzo experimental tools: b-tagging



B-hadrons are relatively long-lived
Vertices are displaced by $\gamma c\tau$, where $c\tau$~450 μm

Intermezzo experimental tools: p_T balance

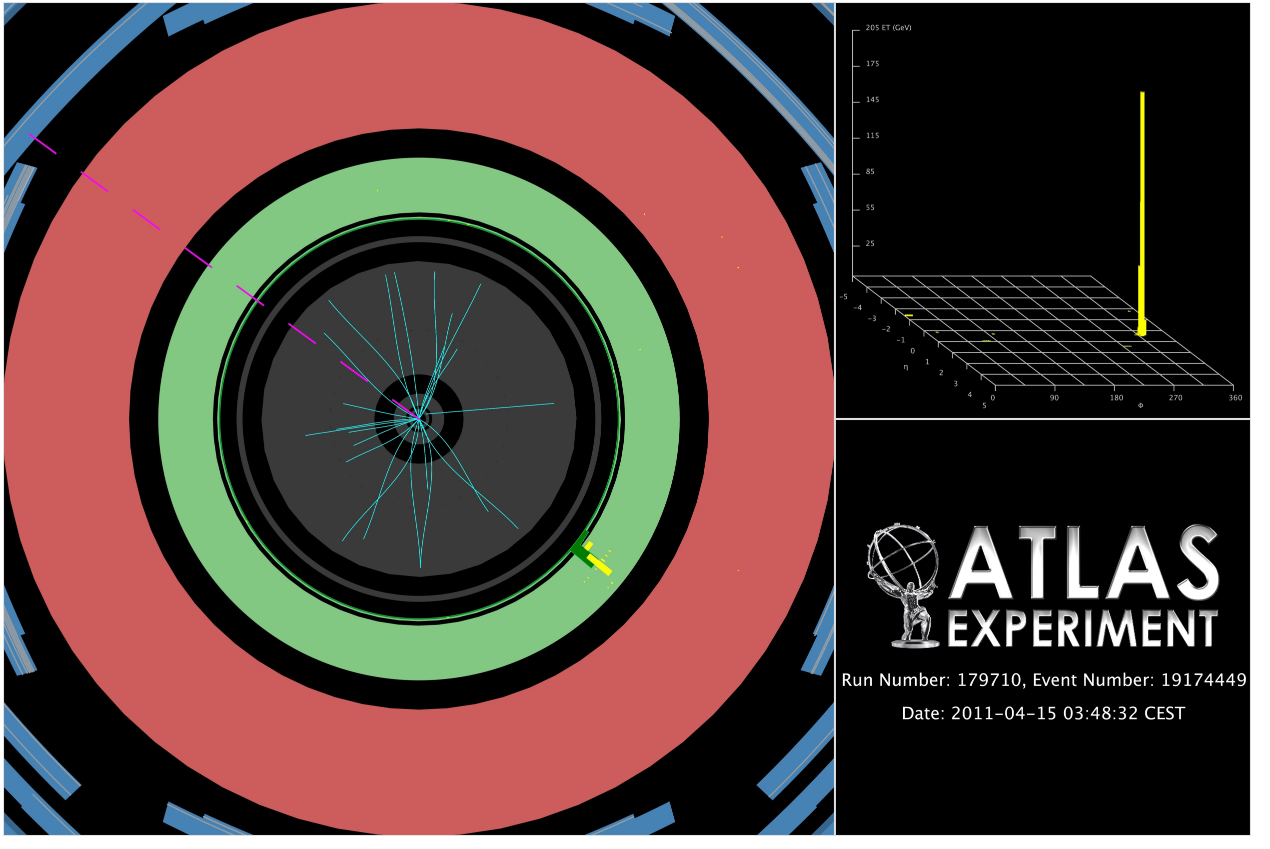
Construct four vector sum of all reconstructed objects

p_z is not balanced (qq or gg initial state is not at rest in the detector)

p_T imbalance can be identified with the p_T of an object escaping detection

There must be only one such ghost particles!

A photon recoiling against a ghost particle (dark matter questions after the lecture)



Top quark pairs: reconstruction

A puzzle with 6 pieces: combine two b-jets, a charged lepton, a neutrino and two “light jets” into two top candidates using the following information:

Two non b-jets must yield W mass

Top and anti-top candidate must have equal mass

...

Main ambiguities; swapped b-jets,
gluon jet mistaken for W-daughter

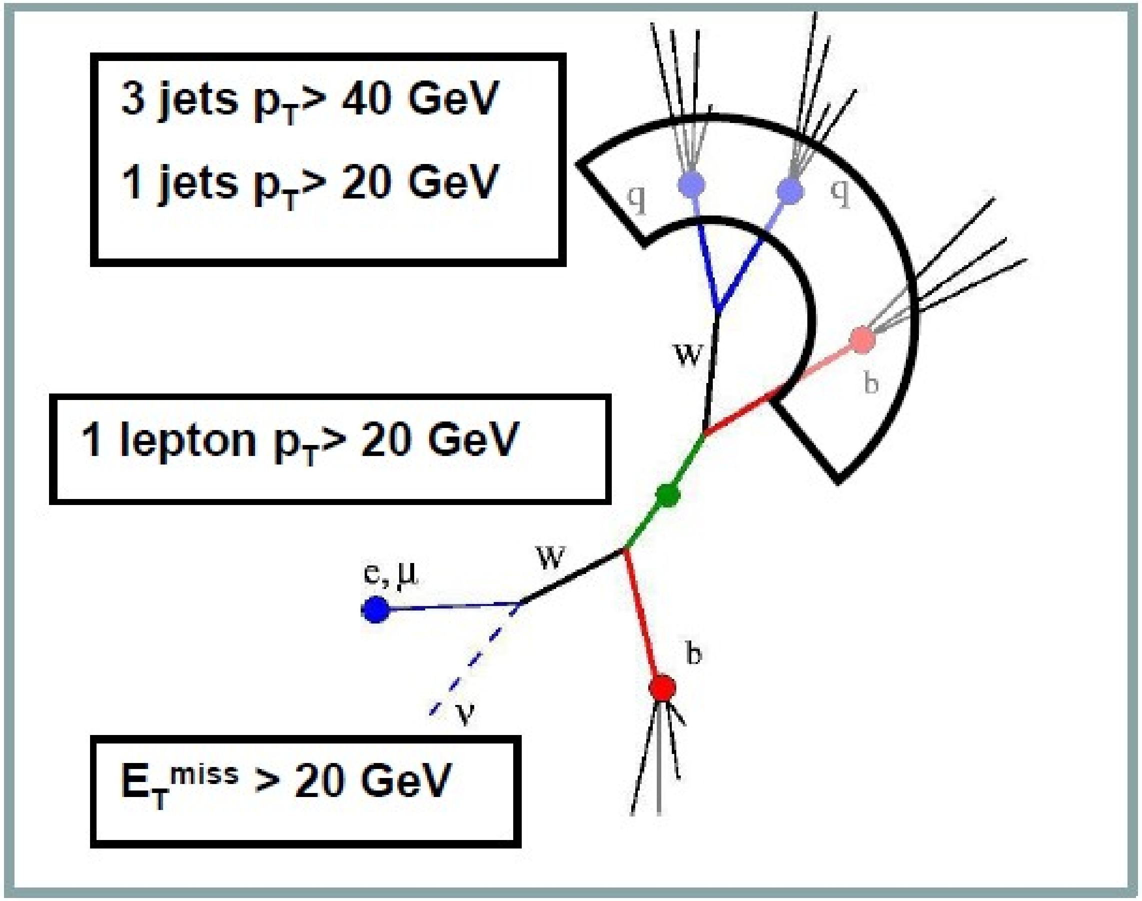
(Can you think of a method to distinguish b-jets from $\bar{b}$-jets. Will it work at the LHC?)

Top quark pairs: reconstruction

B-tagging distinguishes **b-jets** from W-decay jets and gluon radiation

The **neutrino:** $\mathbf{p_T} = - \mathbf{p_T}^{miss}$, p_z from W-mass constraint, resolve 2-fold ambiguity in some ad hoc way

Pick the two with highest $\mathbf{p_T}$ among the **remaining jets**



tt -> Wb Wb -> ℓνb qqb

e + 4 jet event

40758_44414

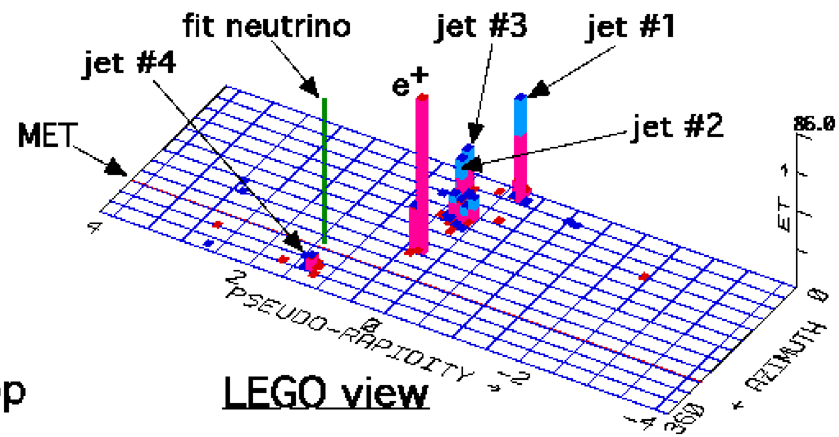
24-September, 1992

TWO jets tagged by SVX

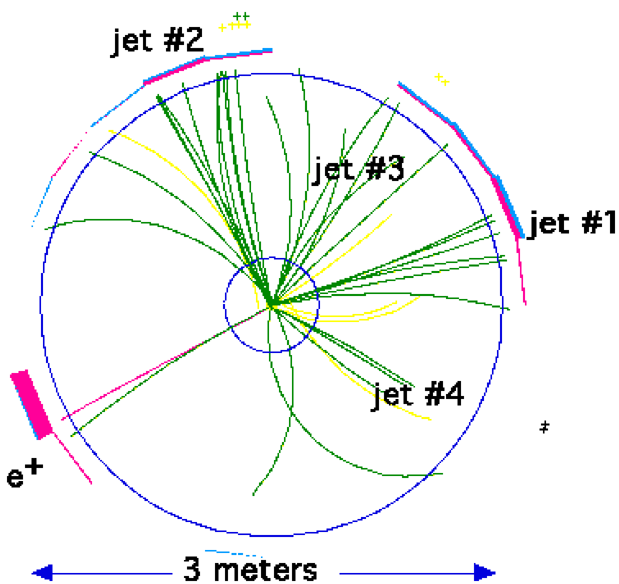
fit top mass is 170 +- 10 GeV

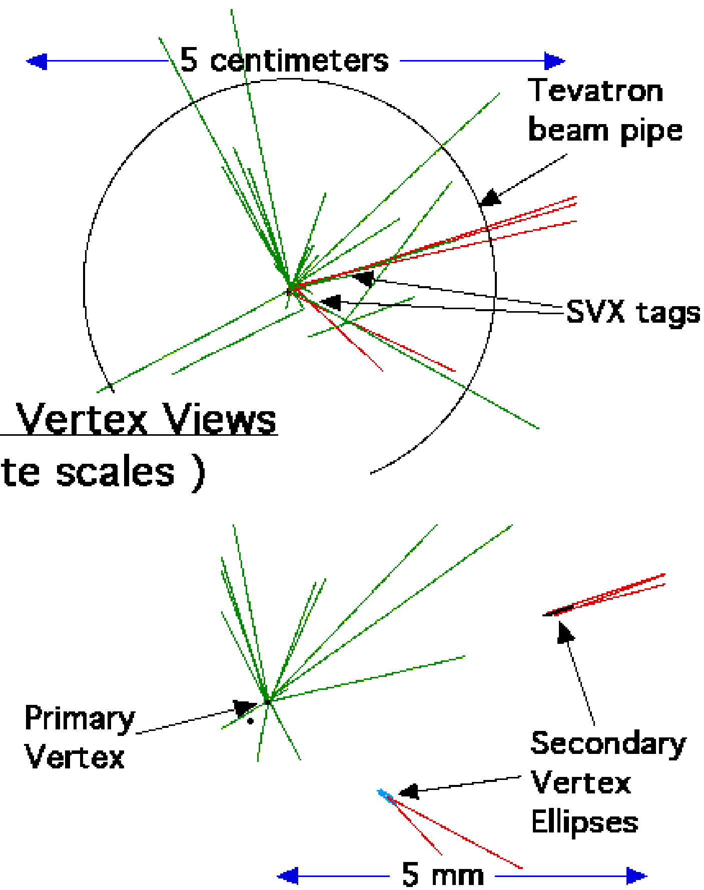
e^+, Missing E_t, jet #4 from top

jets 1,2,3 from top (2&3 from W)



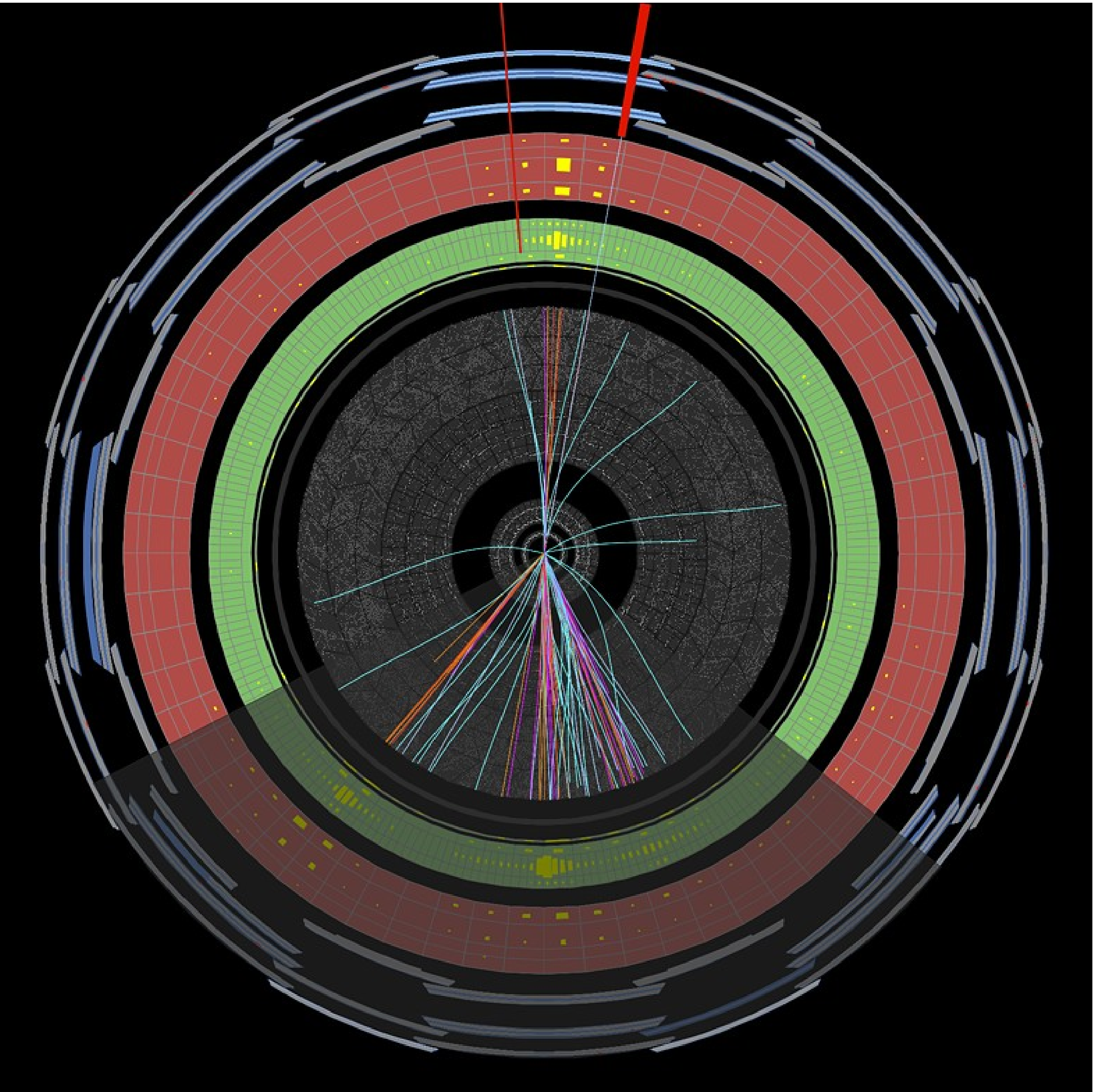
An old example from CDF





Two Vertex Views
(note scales)

????



Now apply the strategy to this (real) event.

What's going on here?

What information is no longer resolved?

What bit of information didn't we use?

Answers in an hour...

Some preparatory work...

Some preparatory work...

tt + no jets

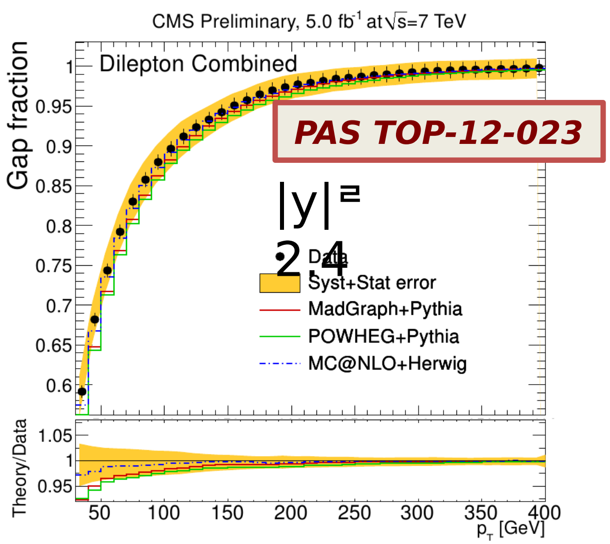
tt → ℓℓbbνν with veto on extra jets

Gap fraction

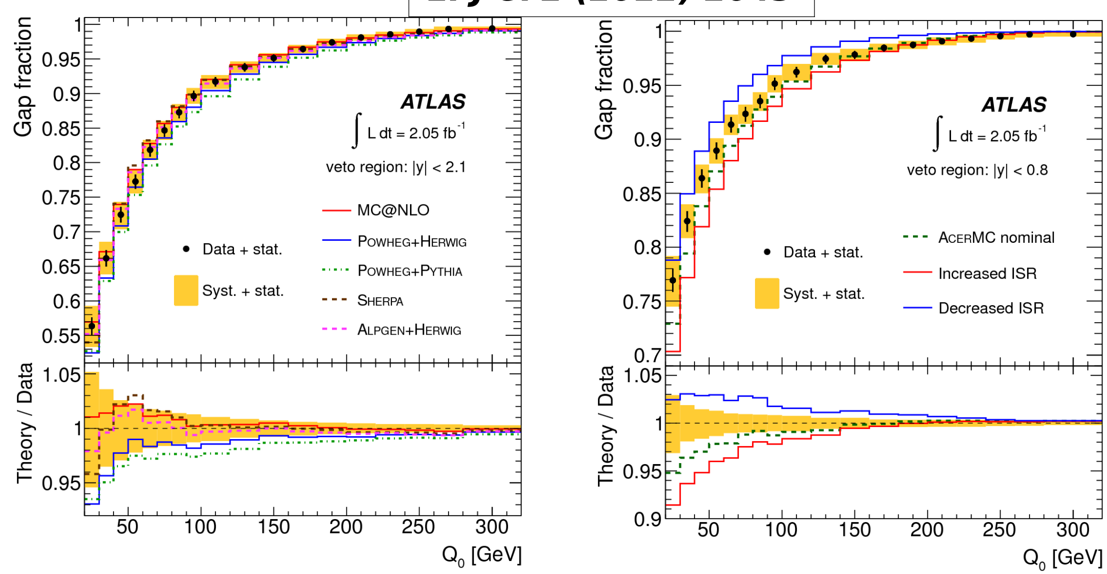
- fraction of events ***without*** an additional jet above threshold

Result

- reasonable description of data, except for MC@NLO in central region; helps reducing allowed radiation variation



EPJ C72 (2012) 2043



Intermezzo on HEPDATA/RIVET

The gap fraction measurement enables other measurements, as it yields an improved understanding of the limitations of NLO MC (MC@NLO, POWHEG) and allows to sharpen the ISR/FSR prescriptions (which then benefit the x-sec and mass measurement)

We need some way to make the corrected results public, so that they can be compared to generators and tunes efficiently

Useful things to look up:
HEPDATA, RIVET

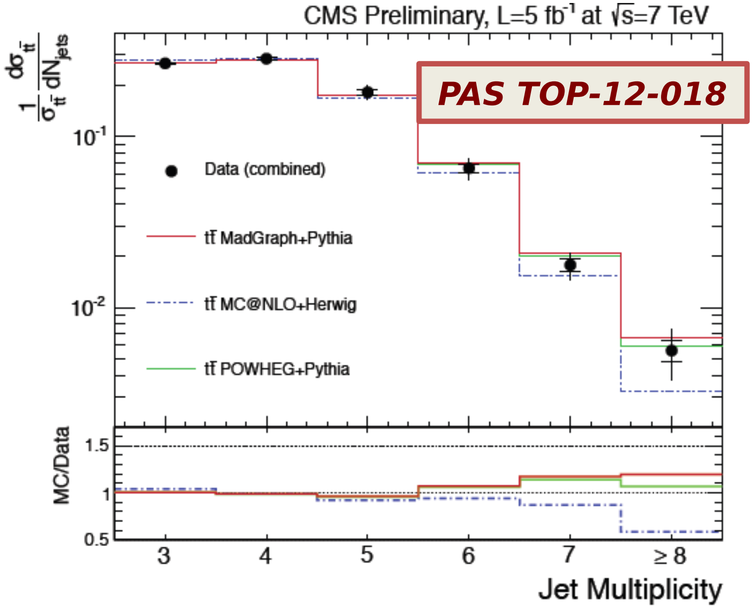
http://arxiv.org/pdf/1003.0694.pdf

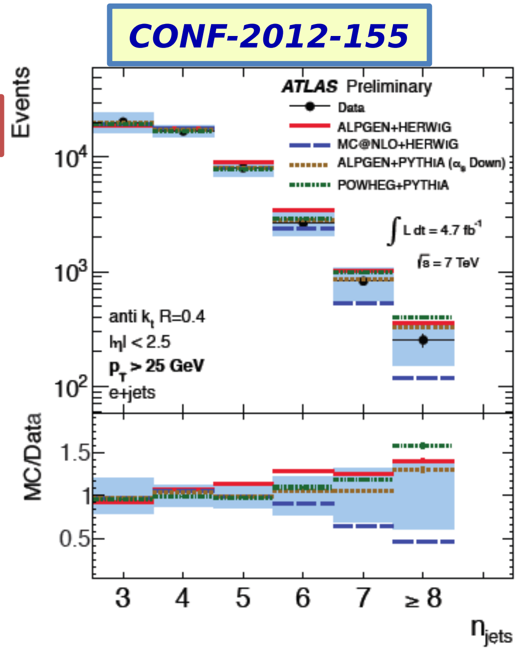
http://hepdata.cedar.ac.uk/view/ins1094568

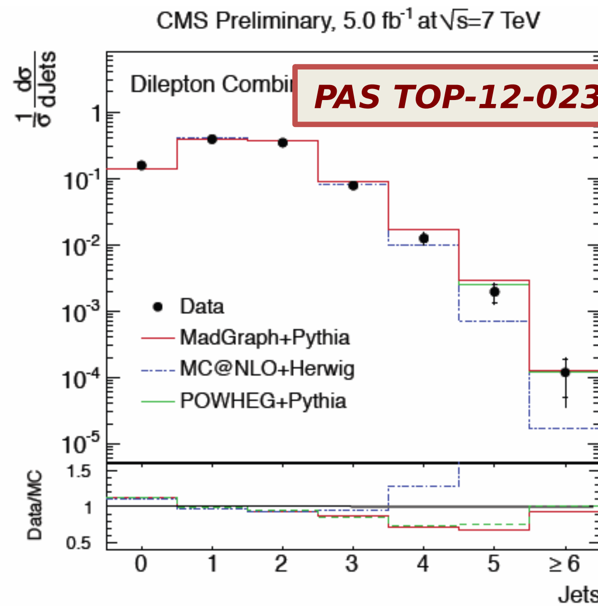
Tt + extra jets

Allows to check modeling at high #jets at top quark scale

- important for top, Higgs, BSM
- unfold spectrum in visible experimental phase space

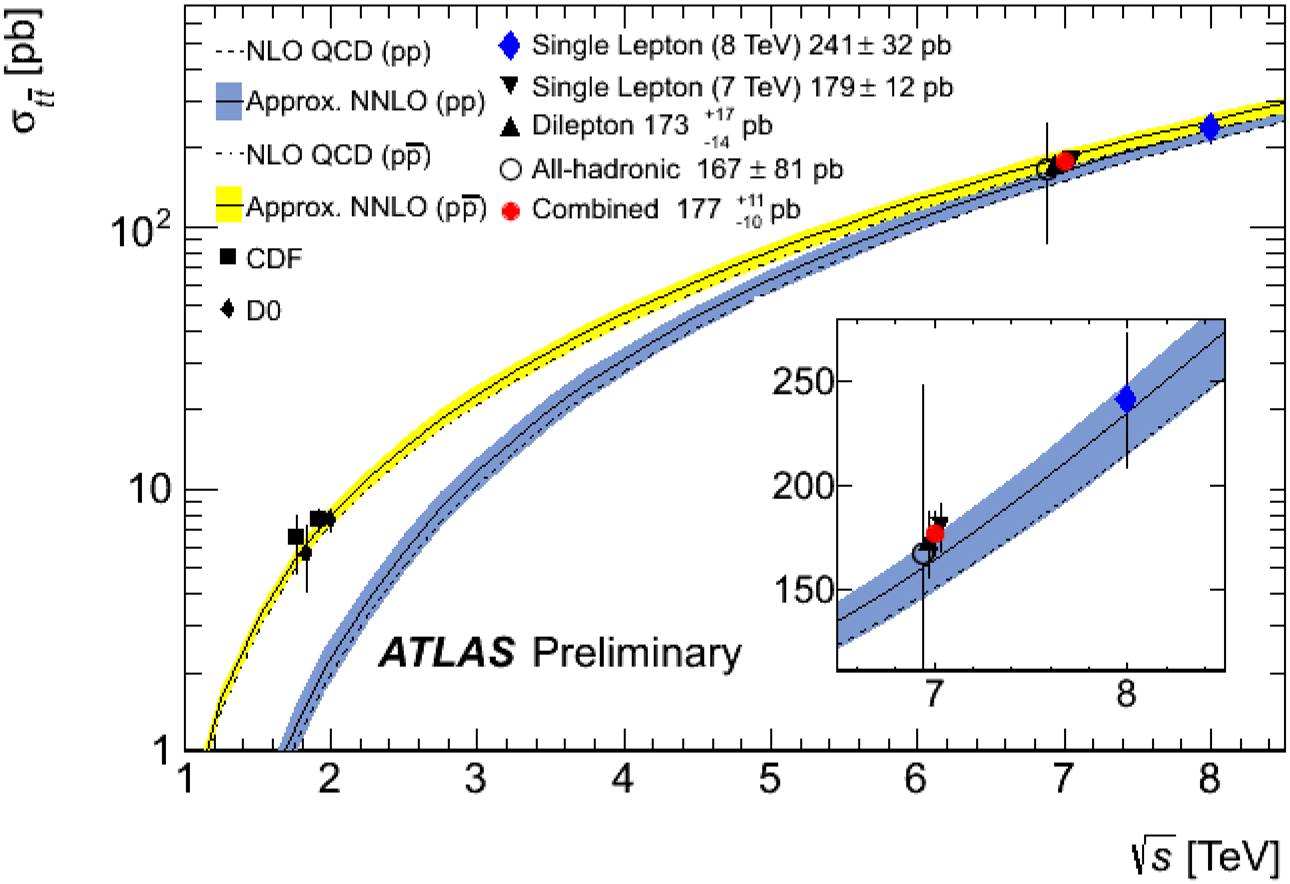




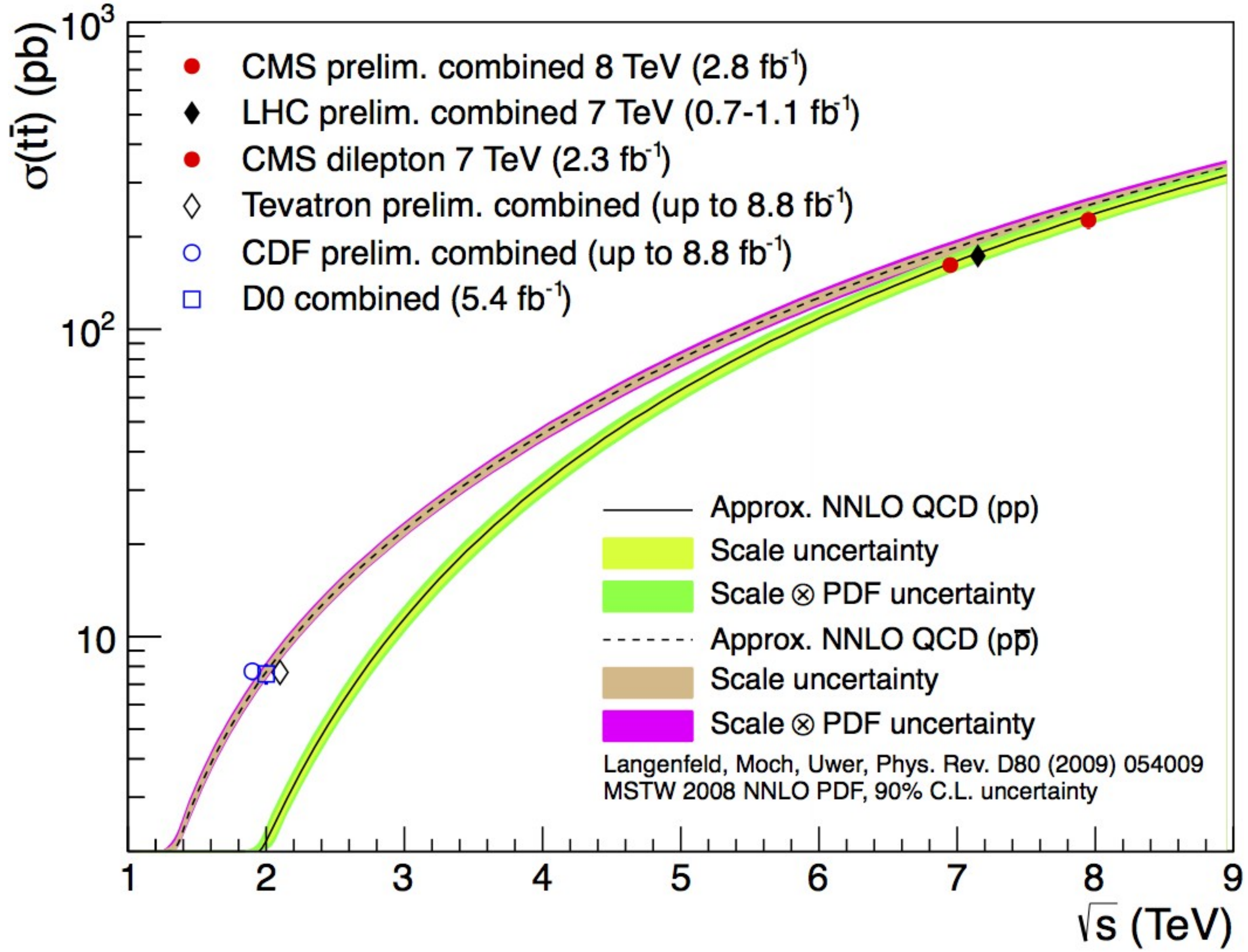


- High #jets is not well modeled by MC@NLO

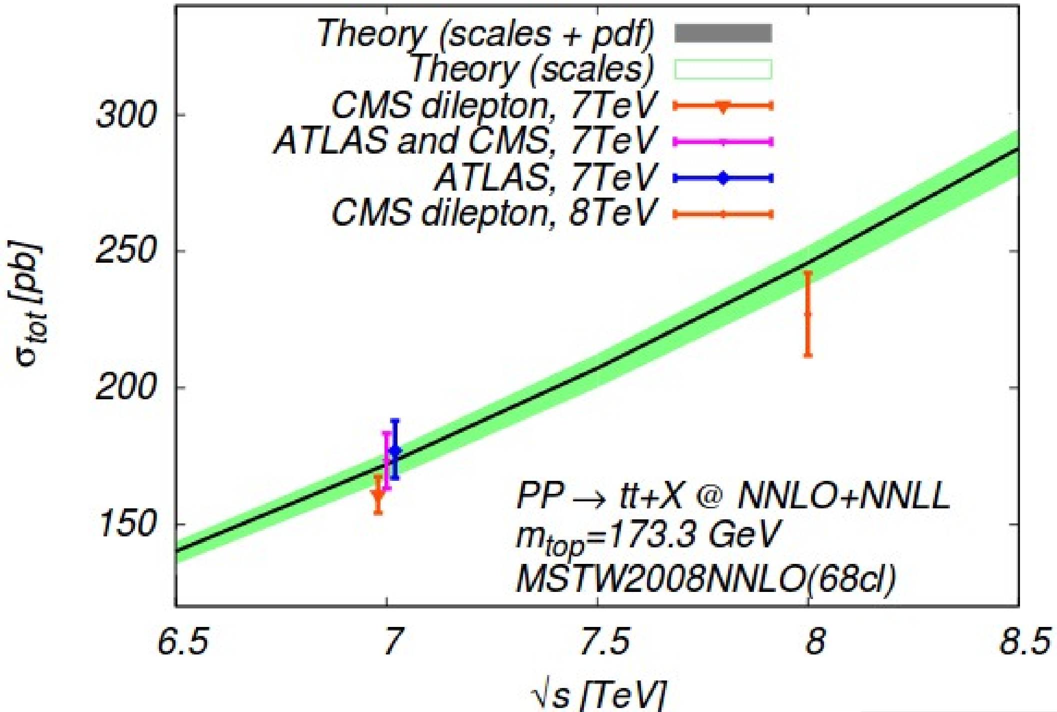
Cross-section



Cross-section



Theory intermezzo: calculability



Theory milestone:
full NNLO and NNLL result for top quark pair production at hadron colliders

K-factor (NLO → NNLO) ~ 10%
Scale stability ~ 5 %

Collider	σ_{tot} [pb]	scales [pb]	pdf [pb]
Tevatron	7.009	+0.259(3.7%) −0.374(5.3%)	+0.169(2.4%) −0.121(1.7%)
LHC 7 TeV	167.0	+6.7(4.0%) −10.7(6.4%)	+4.6(2.8%) −4.7(2.8%)
LHC 8 TeV	239.1	+9.2(3.9%) −14.8(6.2%)	+6.1(2.5%) −6.2(2.6%)
LHC 14 TeV	933.0	+31.8(3.4%) −51.0(5.5%)	+16.1(1.7%) −17.6(1.9%)

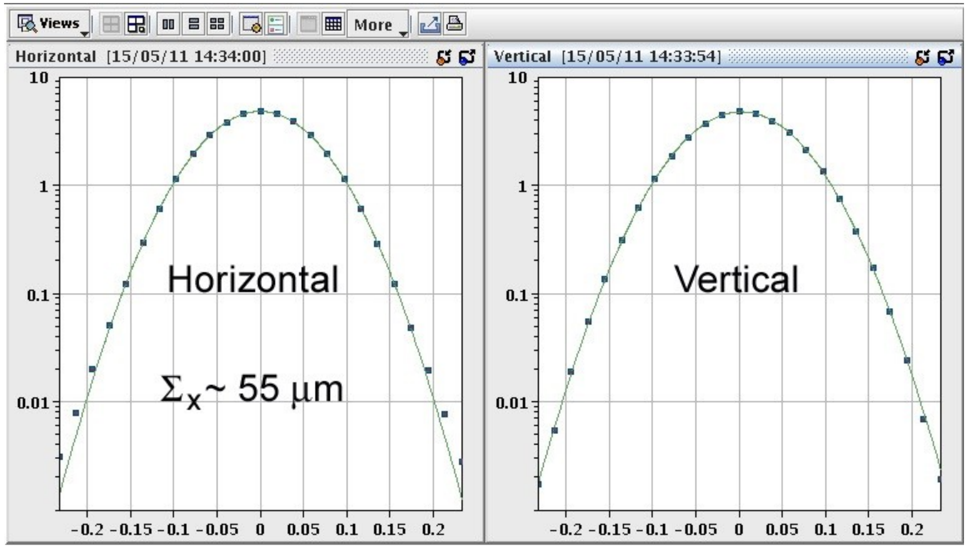
Luminosity & beam energy

The luminosity at the LHC is measured to approximately 3%

Determined from:

- number of particles in the bunches (beam current)
- revolution frequency (precisely known)
- beam size (Vandermeer scan)

The beam energy must be accurately known: a few % error translates into a cross-section that is similar to the current uncertainty on the tt production rate

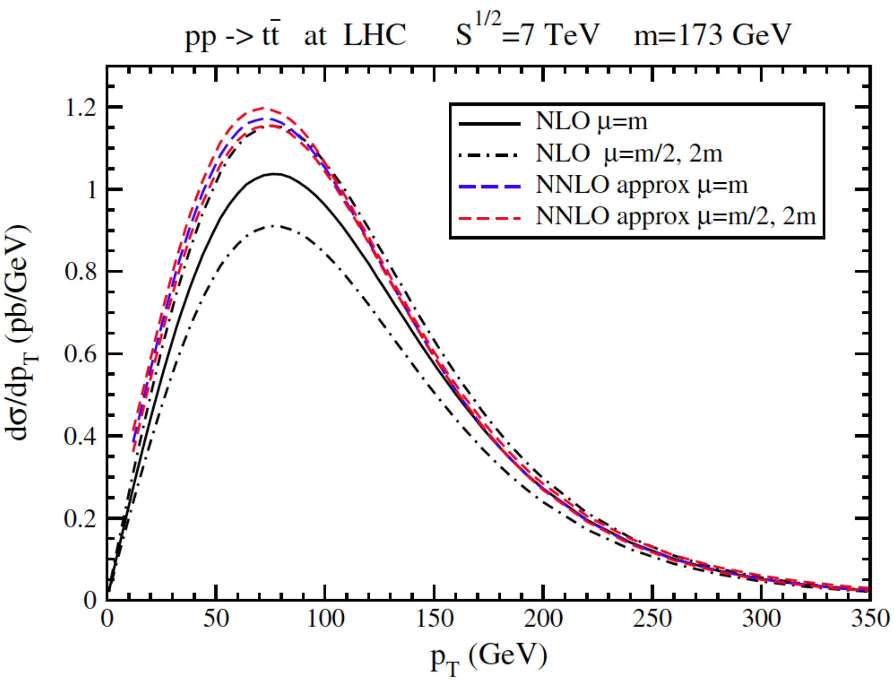


Differential cross-section

Test of pQCD in dσ/dx ℓ+jets, dilepton @ 7 and 8 TeV

- check dependence on QCD scales, ME-PS matching, generators
- enhance sensitivity to new physics

Differential in pT, η (and m) for ℓ, ℓℓ, b, bℓ, t, tt

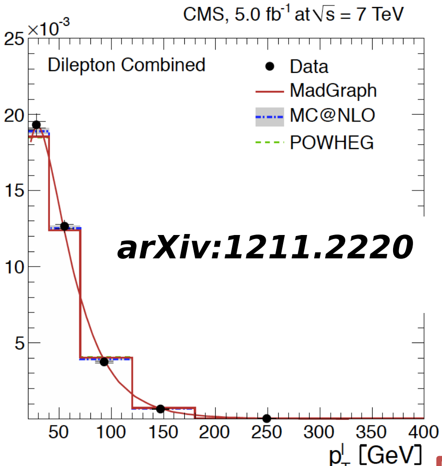


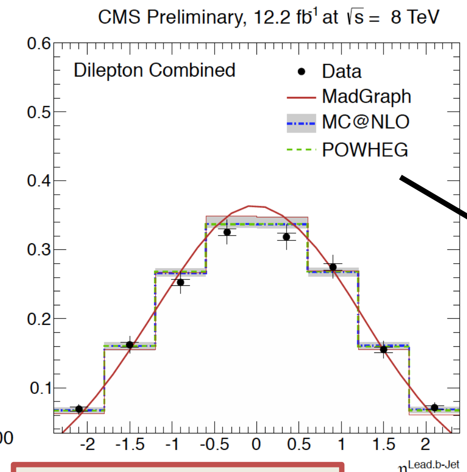
Kidonakis
PR D82 (2010) 114030

Differential cross-section

Provide results that can be compared to predictions “directly”
Differential in pT, η (and m) for ℓ, ℓℓ, b, bℓ, t, tt

Good description in general
aNNLO describes softer pT(top)





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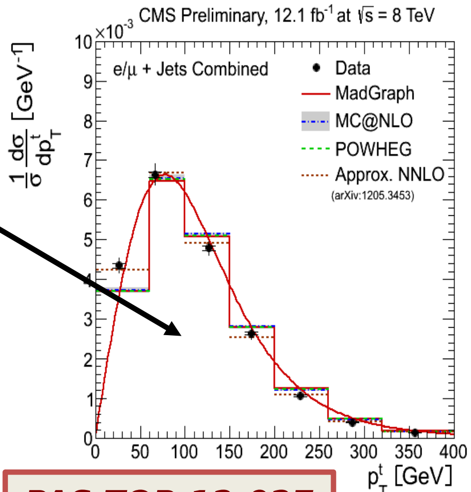

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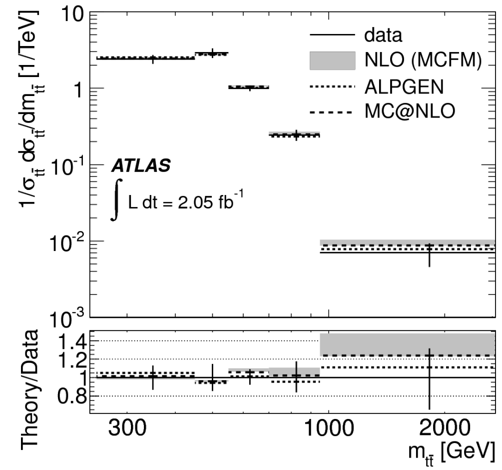

Intermezzo: pseudo-top & fiducial regions

The measurement of the cross-section is prone to modeling uncertainties

Example:

- result depends on lepton p_T spectrum (acceptance correction)
- this uncertainty is estimated by comparing different generators

A more precise comparison of data and theory is possible by "getting closer to the measurement":

- define the cross-section for a fiducial region
- in our example, the tt production with p_T (l) > 25 GeV
- requires theory work: top decay must be included

Tevatron charge asymmetry

Tevatron legacy: evidence for larger charge asymmetry than predicted by Standard Model, especially at large tt invariant mass

Papers with “evidence” in the title, followed by something not predicted by the SM are rare

http://arxiv.org/abs/arXiv:0910.5472

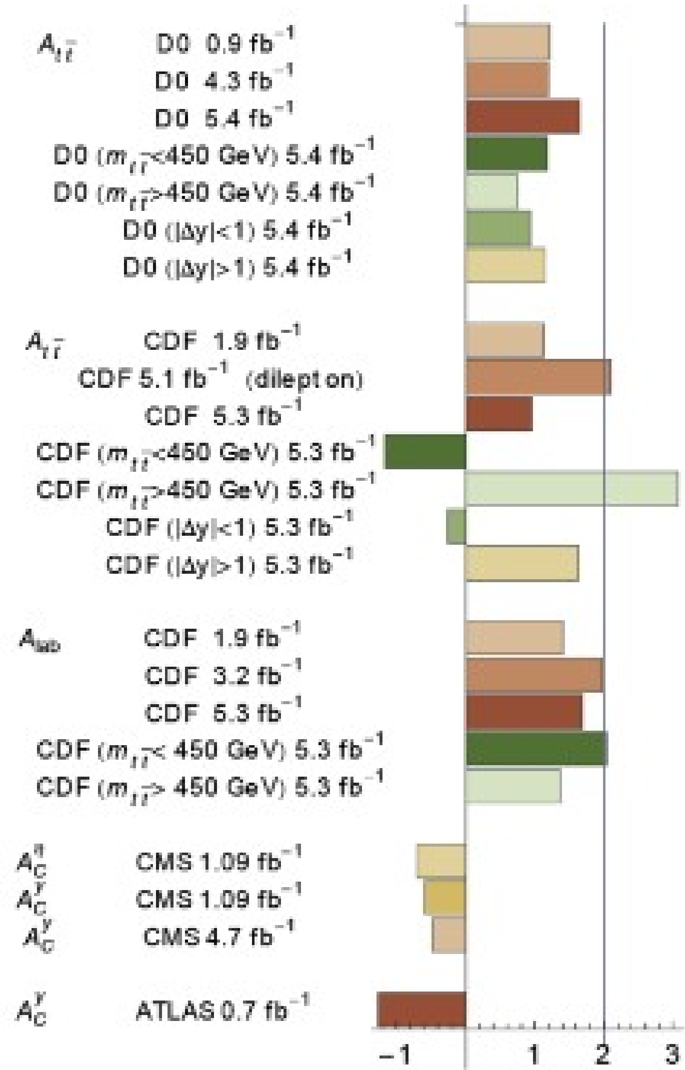

Figure by German Rodrigo
See also: http://ific.uv.es/~rodrigo/talks/2012_03_rodrigo_top_Moriond.pdf

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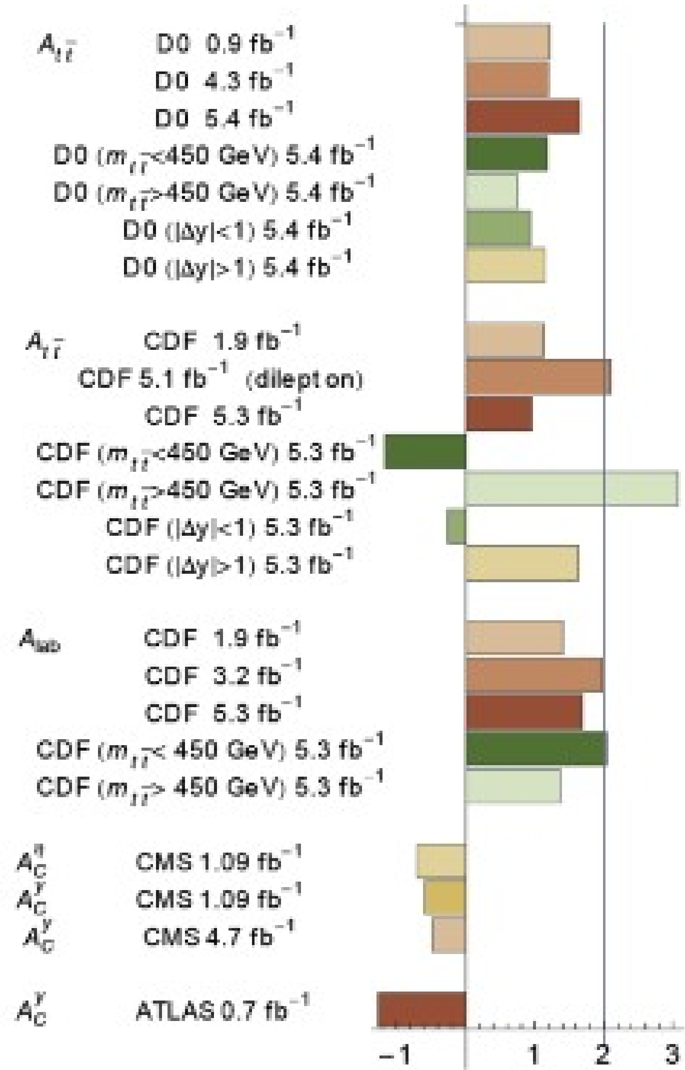
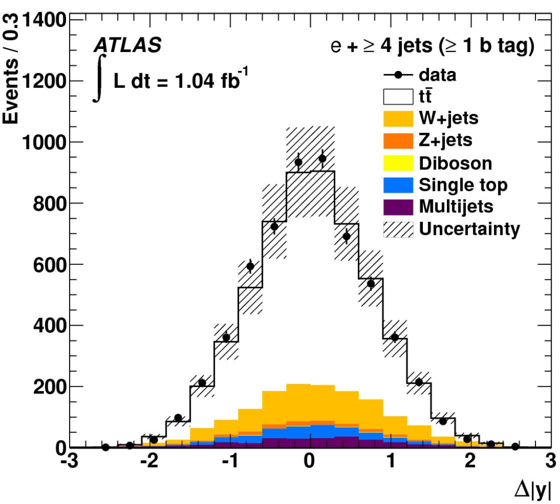
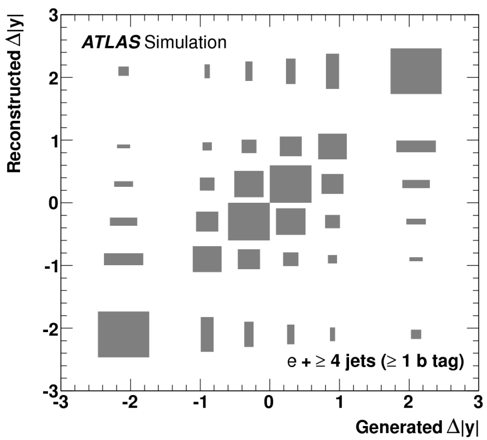
Figure by German Rodrigo
See also: http://ific.uv.es/~rodrigo/talks/2012_03_rodrigo_top_Moriond.pdf

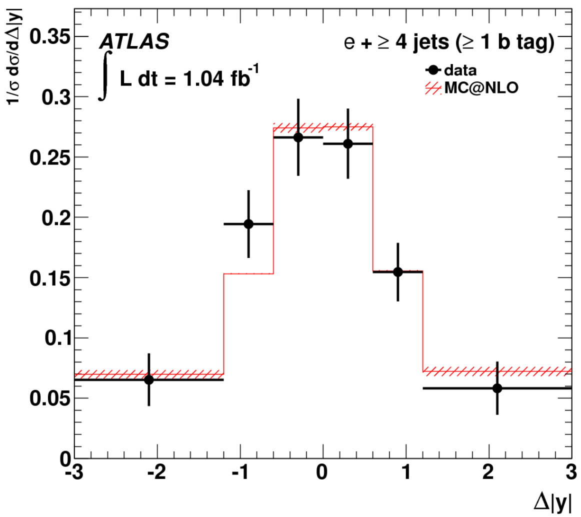


Charge asymmetry

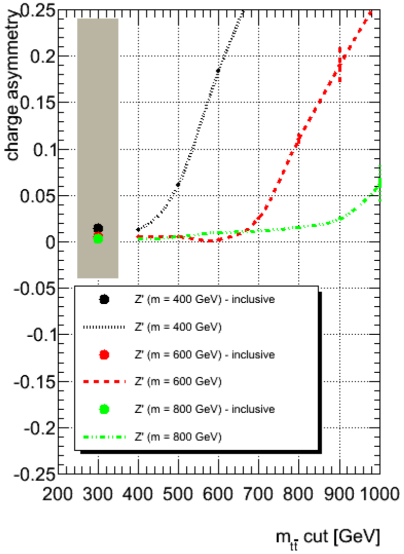
Unfolding → correction for acceptance & migrations due to limited resolution
Reconstruced distr. x acceptance correction x migration matrix^{-1} = corrected result





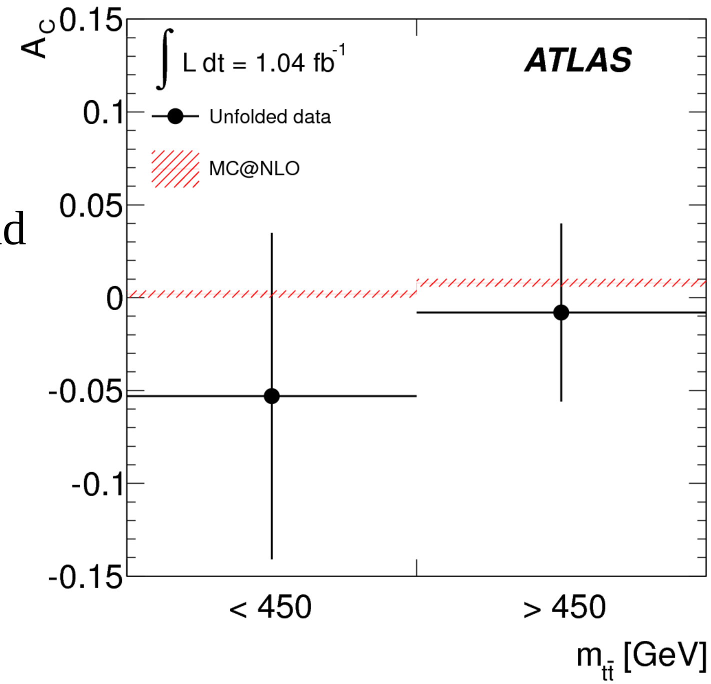


Charge asymmetry



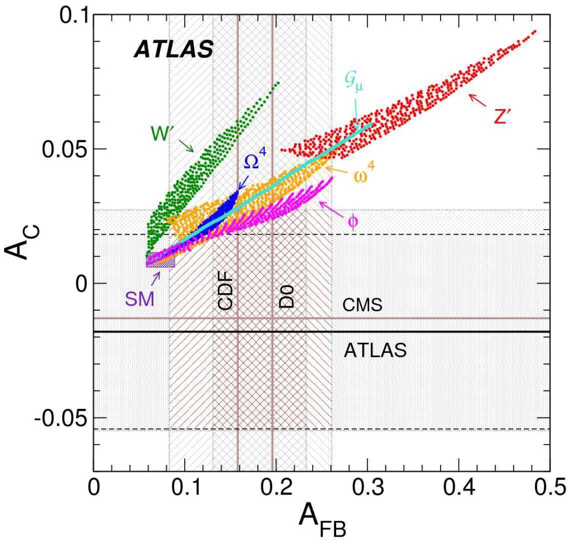
Inclusive measurement and two mass bins <450 GeV, >450 GeV

A_C vs. mass for Z' model (V. Sanchez, A. Hyaya)

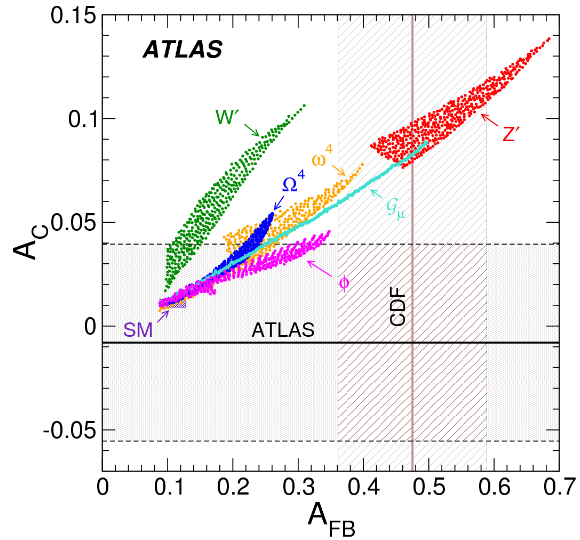


Impact on model zoo

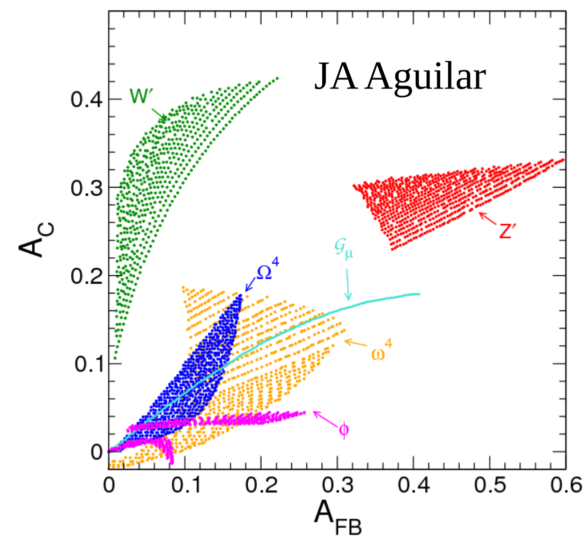
inclusive



m_{tt} > 450 GeV (Tevatron and LHC)

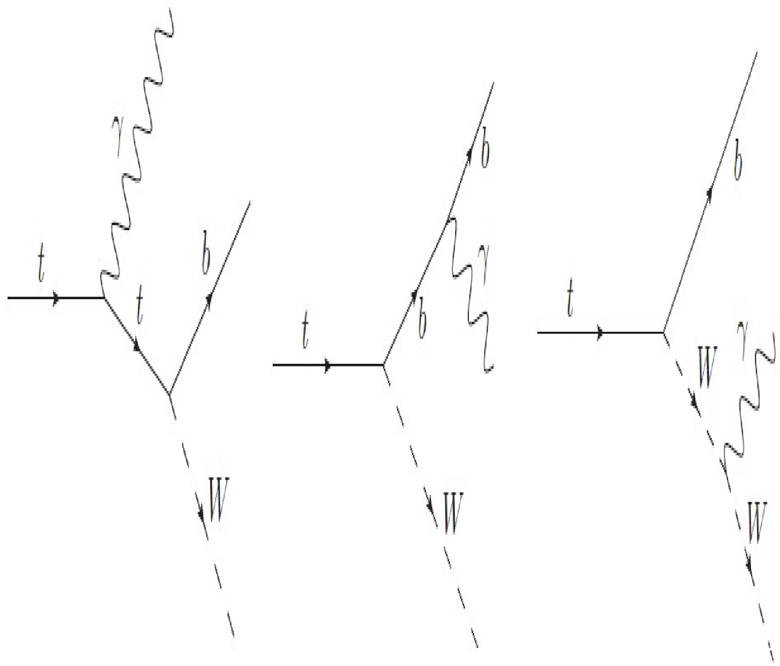


M_{tt} > 800 GeV (LHC only)



Associated production: Top quark pair + photon

- Production rate sensitive to $t\bar{t}$-photon vertex
  - → pair production measures $t\bar{t}$-gluon
  - → top decay and single top production probe tWb
- Require pT(γ) > 8 GeV, SM $\sigma_{t\bar{t}\gamma}$ = 2.1±0.4 pb

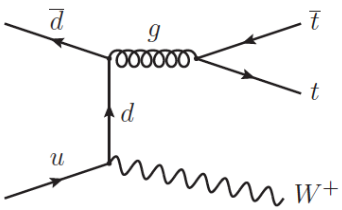


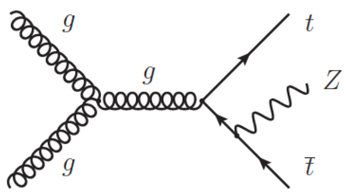
BR*σttγ = 2.0±0.5stat±0.7syst±0.1lumi pb

Significance 2.7σ
Expected 3.0σ

Associated production: Top quark pair + Z boson

- also important background to SUSY and BSM searches
- analysis also designed to measure ttW (not coupling)





- same-sign dilepton (ttV) or trilepton events (ttZ)
- now with updated generator unc. (Powheg-BOX, +50% syst.)

$$\sigma_{t\bar{t}Z} = 0.28^{+0.14}_{-0.11}\,(\text{stat.})\,^{+0.06}_{-0.03}\,(\text{syst.})\,\text{pb}$$ 3.3σ NLO: $0.137^{+0.012}_{-0.016}$ pb

$$\sigma_{t\bar{t}V} = 0.43^{+0.17}_{-0.15}\,(\text{stat.})\,^{+0.09}_{-0.07}\,(\text{syst.})\,\text{pb}$$ 3.0σ NLO: $0.306^{+0.031}_{-0.053}$ pb

CMS establishes $t\bar{t}V$ signal at 4.7 σ (V=W,Z)
σ($t\bar{t}Z$) = 0.28 +0.14 -0.11 (stat) +0.06 -0.03 (syst)
PRL 110 (2013) 172002

Garzelli et al., JHEP 11 (2012) 056
Campbell, Ellis, JHEP 07 (2012) 052

CONF-2012-126

	SR
$t\bar{t}Z$	0.85 ± 0.04
WZ+jets	0.06 ± 0.04
ZZ+jets	0.014 ± 0.014
$t\bar{t}W$	0.011 ± 0.008
$(t\bar{b}Z + \bar{t}bZ) + X(= jj, l\nu)$	0.125 ± 0.013
$WZbbjj$	0.065 ± 0.016
MC Total	1.13 ± 0.06
Fake lepton background	$0.0^{+1.6}_{-0.0}$
Observed	1

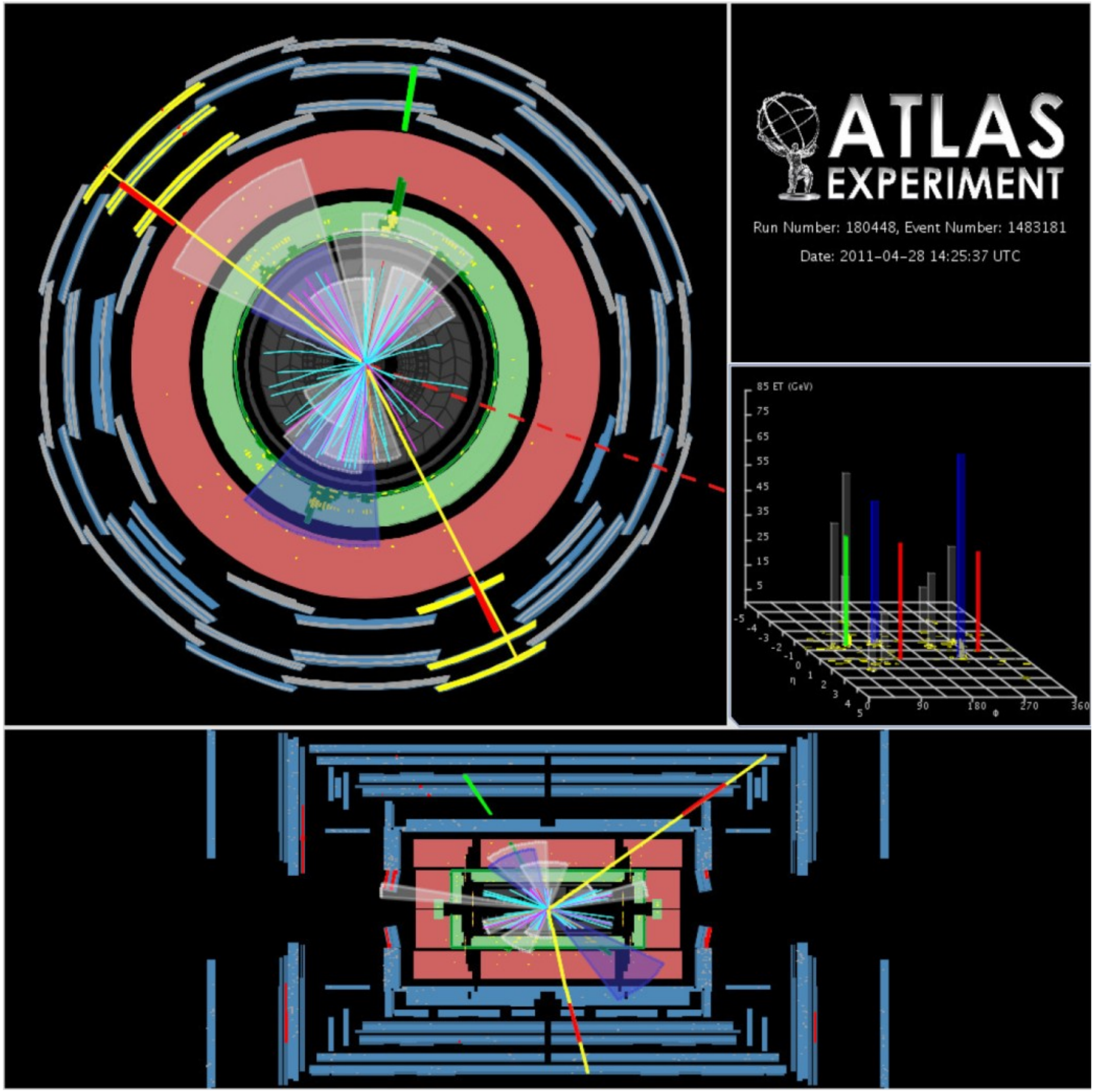
Candidate event (eμμ)

$E_T$miss = 78 GeV

m_{ll}= 91 GeV

m_T(l,ETmiss) = 67 GeV

4 jets (2 b-tagged)

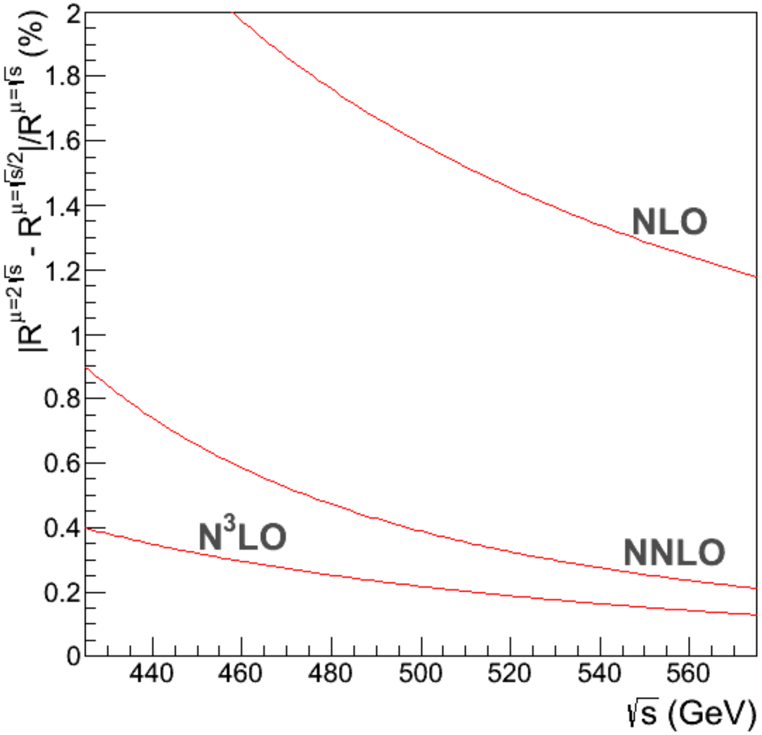


Top quark pair production in the continuum

tt production at ILC:
σ~0.6 pb
at √s = 500 GeV
~0.2 pb
at √s = 1000 GeV

300.000 $t\bar{t}$ events in 4 years @ 500 GeV

Variation in predicted x-section due to scale variations



Unique features of e+e- colliders: calculability and control over initial state

- **Per-mil level uncertainty on inclusive cross-section**
- **Luminosity measured to similar level**
- **Beam energy to 10^{-4}**

Compare to 5% uncertainty in the cross-section prediction at the LHC

Electroweak couplings

LHC expected to reach ~10% precision on form factors governing tt-photon and tt-Z vertices

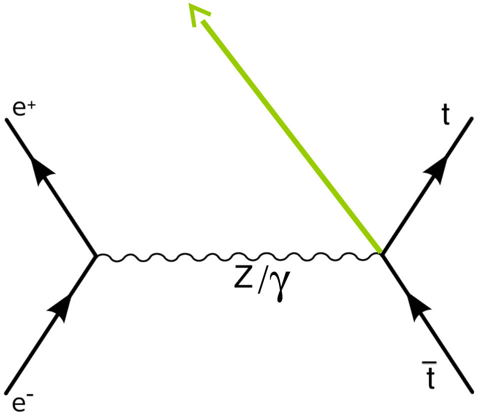
Long-term LHC prospects by Baur, Juste et al. (Snowmass 2005) Phys.Rev. D71 (2005) 054013

Top Couplings: pre-Snowmass Energy Frontier 2013 Overview arXiv:1309.1947

Electroweak couplings

The current at the $t\bar{t}X$ vertex:

$$\Gamma_\mu^{ttX}(k^2, q, \overline{q}) = ie\left\{\gamma_\mu\left(\widetilde{F}_{1V}^X(k^2)+\gamma_5\widetilde{F}_{1A}^X(k^2)\right)+\frac{(q-\overline{q})_\mu}{2m_t}\left(\widetilde{F}_{2V}^X(k^2)+\gamma_5\widetilde{F}_{2A}^X(k^2)\right)\right\}$$



See talk by Nacho García

Electroweak couplings at LC

Measure 6 observables, extract 5 form factors

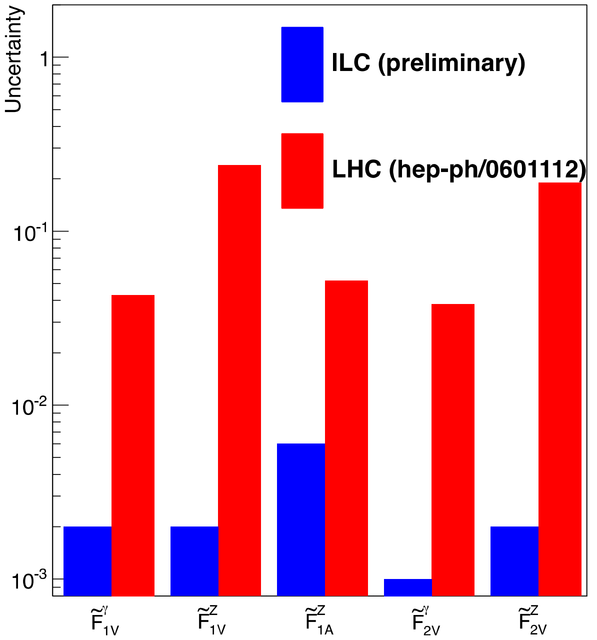
$$\left.\begin{matrix} \sigma(+) & A_{FB}(+) & \lambda_{hel}(+) & (+=e^-_R) \\ \sigma(-) & A_{FB}(-) & \lambda_{hel}(-) & (-=e^-_L) \end{matrix}\right\} \Rightarrow \left\{\begin{matrix} F^{\gamma}_{1V} & * & F^{\gamma}_{2V} \\ F^{Z}_{1V} & F^{Z}_{1A} & F^{Z}_{2V} \end{matrix}\right\}$$

The cross section can be measured to 0.5% (stat. + lumi)

The forward-backward asymmetry to 2% (stat. + syst.)

The slope of helicity distribution to ~4% (stat. + syst.)

LC-REP-2013-007



500/fb at 500 GeV yields 1-2 orders of magnitude better sensitivity than the LHC (300/fb at 14 TeV)

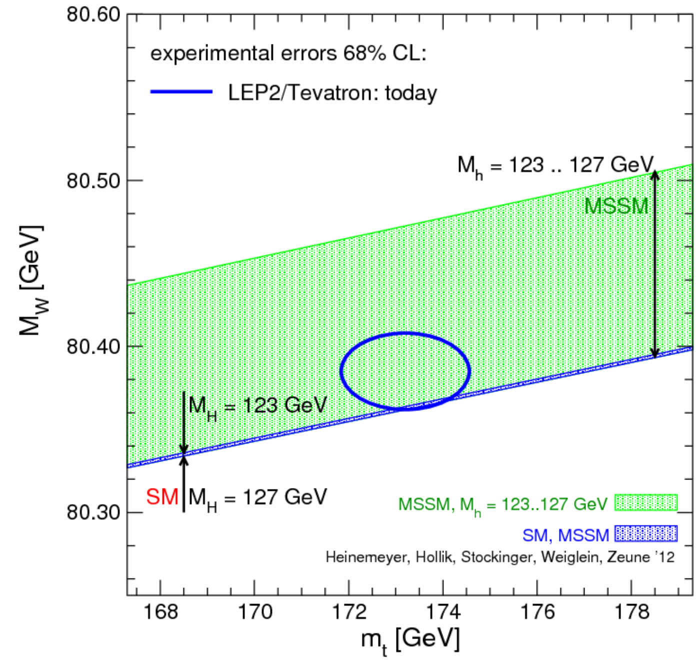
Adding to previous studies in TESLA TDR:
- simultaneous extraction of photon and Z form factors
- full simulation & reconstruction
- discussion of systematic effects
  (knowledge of polarization, energy, ...)

Top quark mass: motivation

Precision test of the SM

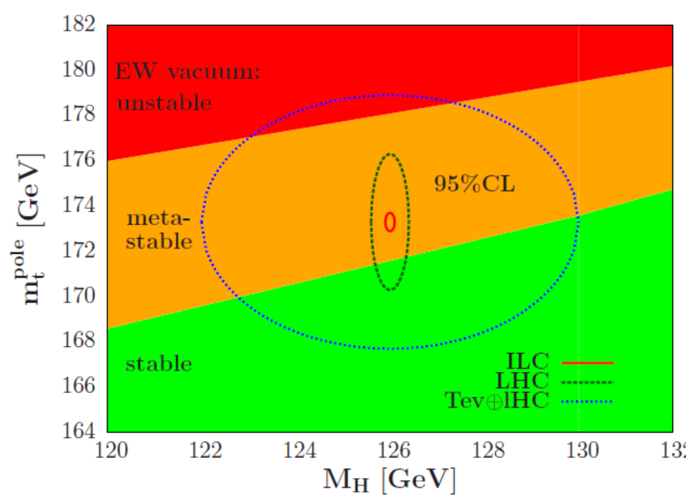
- SM EW fit yields relations between m_H, m_t and m_W

- Currently limited by m_W, must improve also ㅅ $_s$, sin^2 ㅓ, m_Z



Fate of the universe

- Depending on the value of the top quark mass the Higgs potential may go negative somewhere between EW and Planck scale (in the SM)



Degrassi, Di Vita, Elias-Miro, Espinosa, Giudice et al. '12; Alekhin, Djouadi, S.M. '12; Masina '12

Top quark mass

A “philosophical” question: how can we measure a quark mass?

Top quark mass

Quark mass is not an observable.

Extract mass from an analysis that counts events:

- Total rate vs. differential
- Inclusive vs. Exclusive

Differential, exclusive

→ invariant mass distribution of top decay products

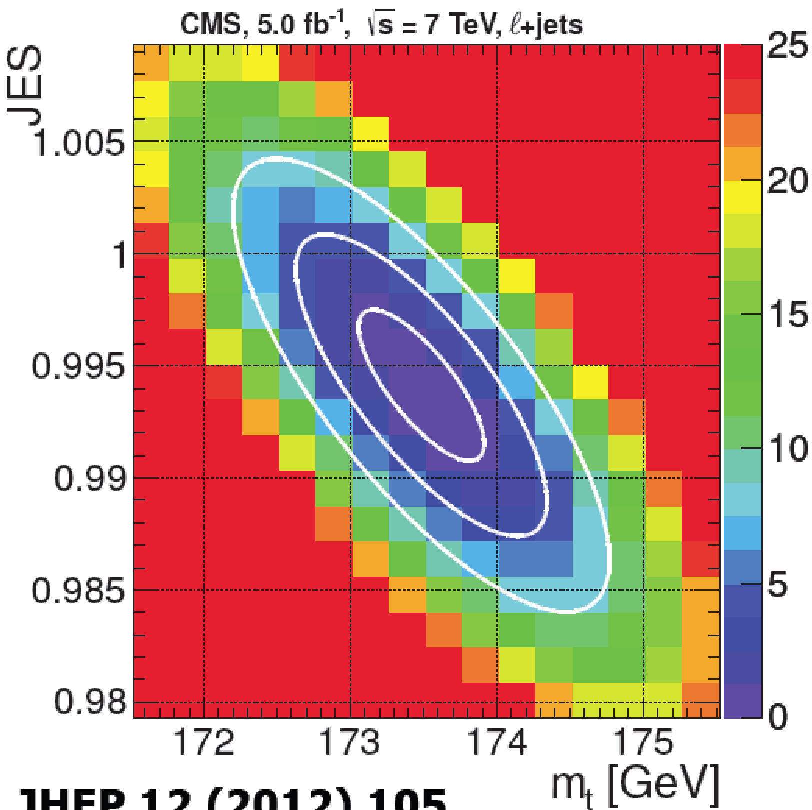
Total, inclusive

→ extract mass from inclusive cross-section

Top quark mass from l+jets events

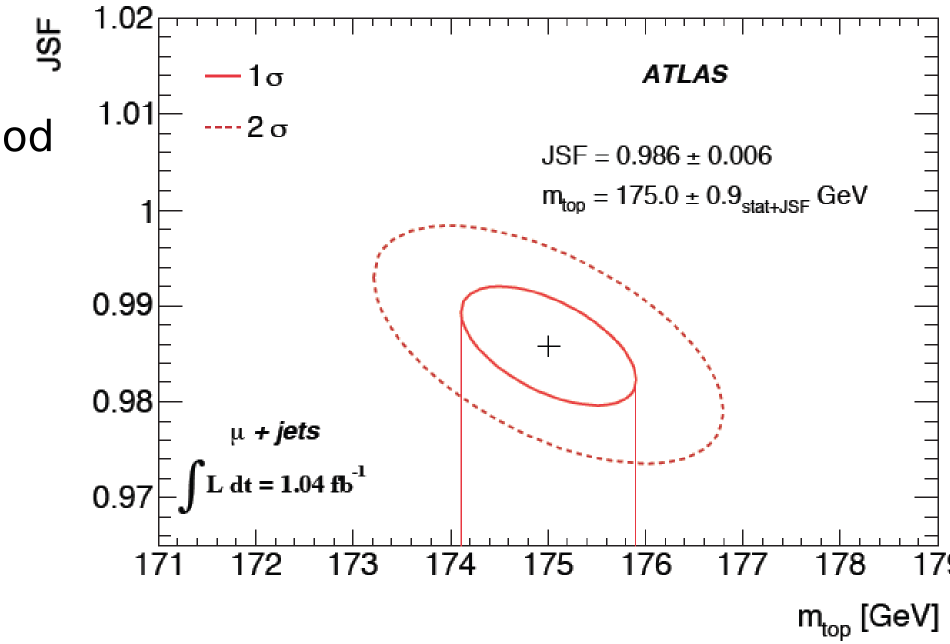
CMS: ideogram method

- JES correction evaluated from the method



JHEP 12 (2012) 105

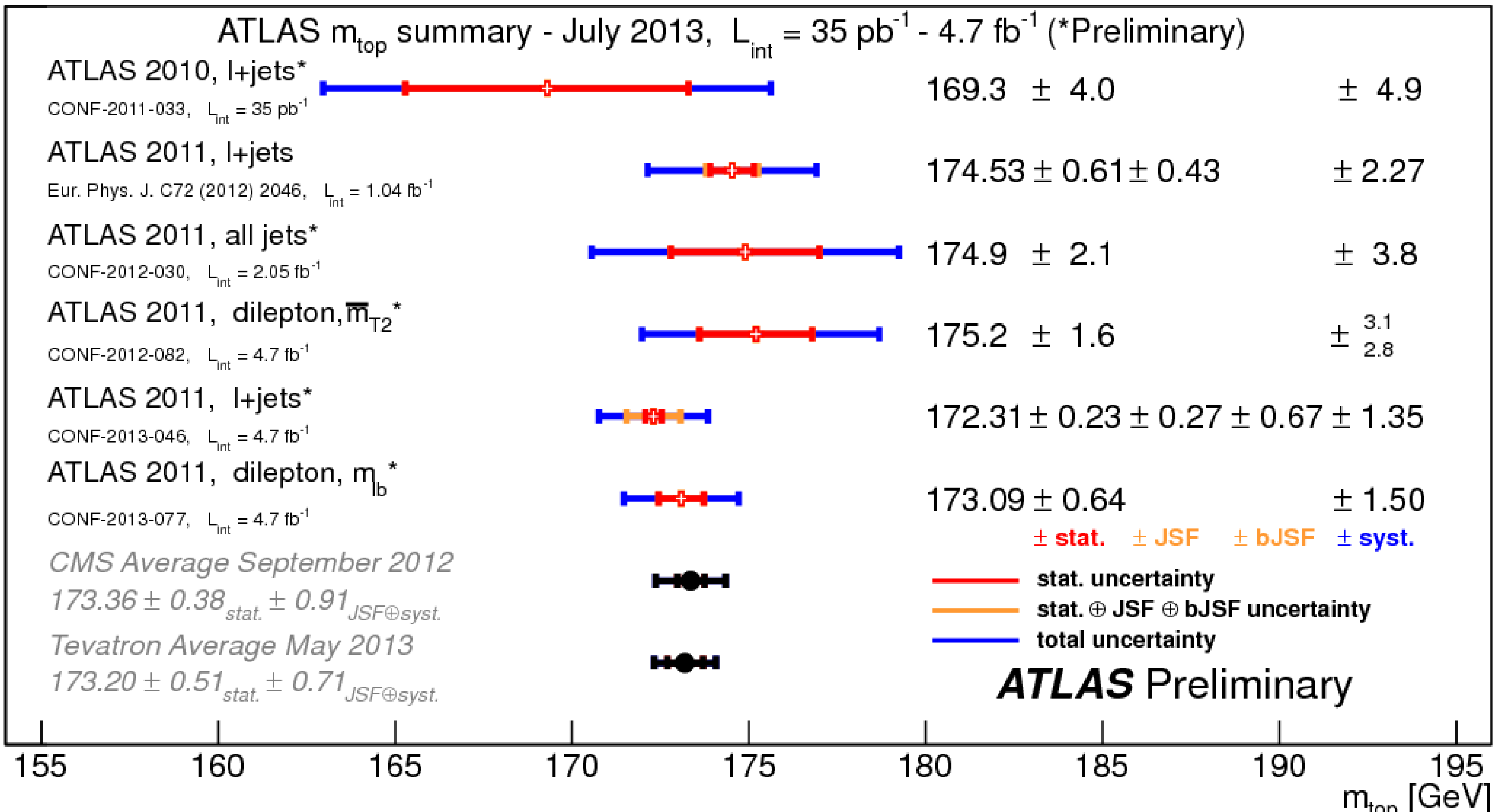
Eur. Phys. J C72 (2012) 2046



ATLAS: template fit

- uses reco mt and mW as input to fit
- JSF impact evaluated in situ from mW
- 3D fit → b-jet JES fixed on data

ATLAS top mass summary



Experimental intermezzo: jet energy scale

Many analyses are limited by the uncertainty on the Jet Energy Scale? What is it?

An estimate of the uncertainty on the calibration of jets.

Could the jet energy be 3% lower than we think?

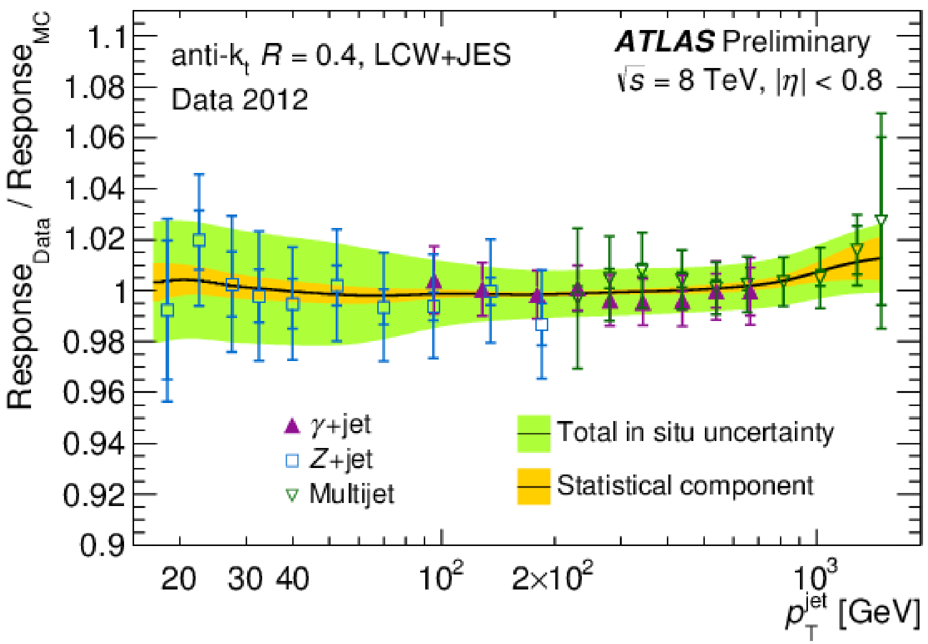
How can we estimate/measure this uncertainty? How can we reduce it?

MC-based: variations in response when we vary:

- Hadronic shower model (swap nominal with one that's not too far off)
- Material budget (within conservative, but reasonable range)
- …

Data-driven methods take over:

- Calorimeter/tracker ratio
- photon + jet events

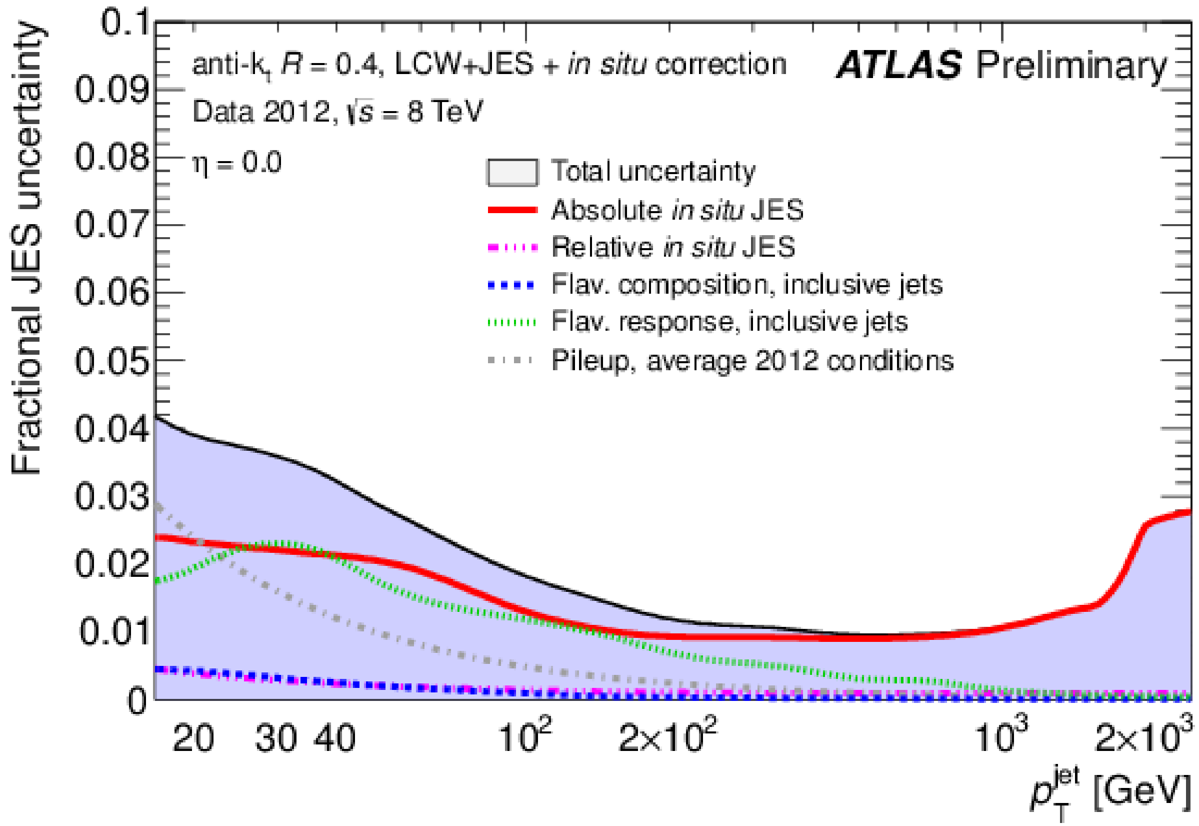


Constrain in data/kinematic fit

- W mass constraint

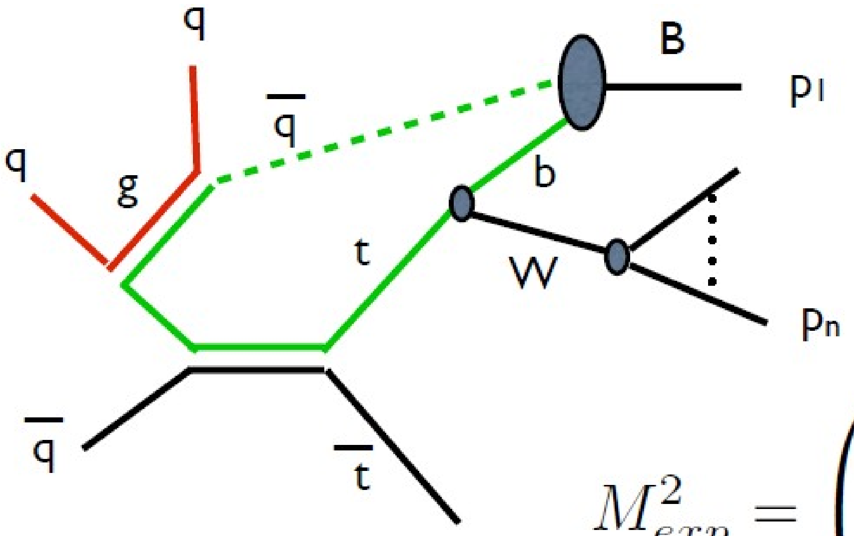
JES

Typical uncertainty between 1 and 2% for intermediate energy
Jets close to others are typically more uncertain
Flavour-dependence (quark vs. gluon, c-jets, b-jets)



Theory uncertainties

- top quark is a colored object, final state is color neutral
- Can estimate colour reconnection uncertainty from MC studies
- Many (precise) measurements in different kinematic regimes give confidence that this is under control



$$M_{exp}^2 = \left(\sum_{i=1,\ldots,n} p_i \right)^2$$

Interpretation

Measured mass (~MC mass) is identified with pole mass
This introduces an uncertainty of XXXX MeV

A long debate follows...

Top quark mass

Alternative methods:

Endpoint measurement

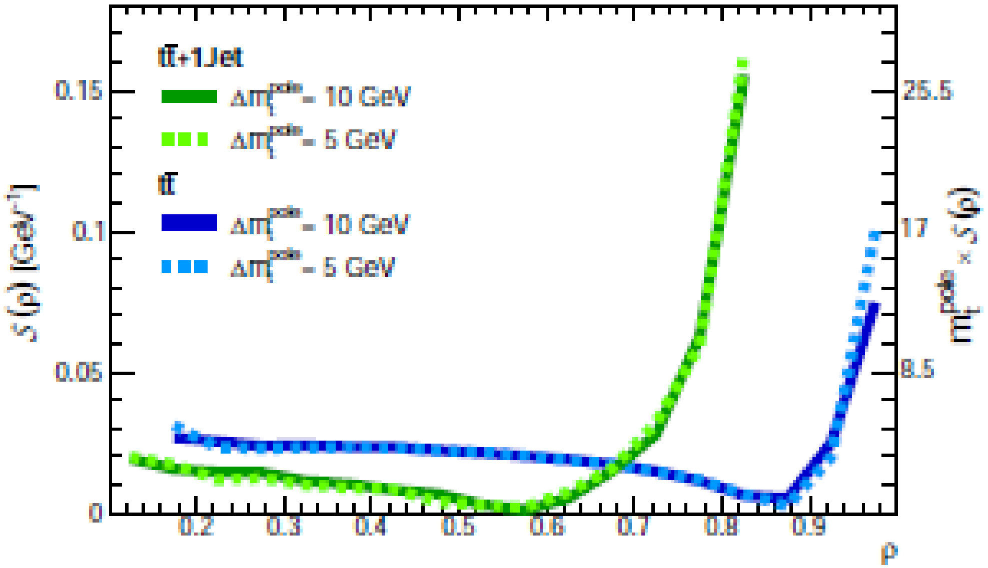
(CMS, arXiv:1304.5783, currently 2 GeV uncertainty)

Extraction from J/psi spectra, m_{bl}

Extracted from total cross section

– $\Delta m/m \sim 0.2\ \Delta\sigma/\sigma$ (currently > 5 GeV uncertainty)

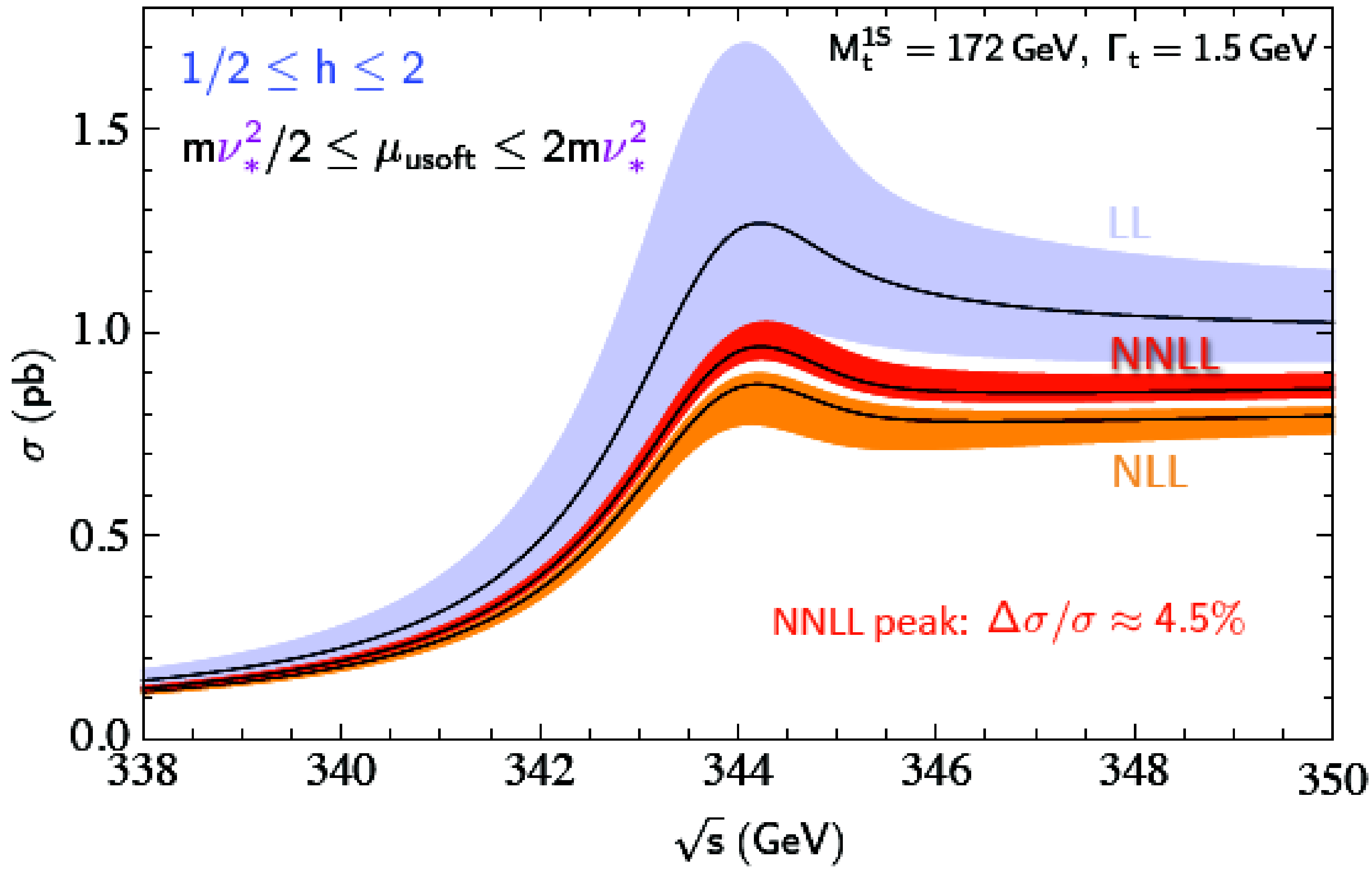
$t\bar{t}g$ cross-section (arXiv:1303.6415)



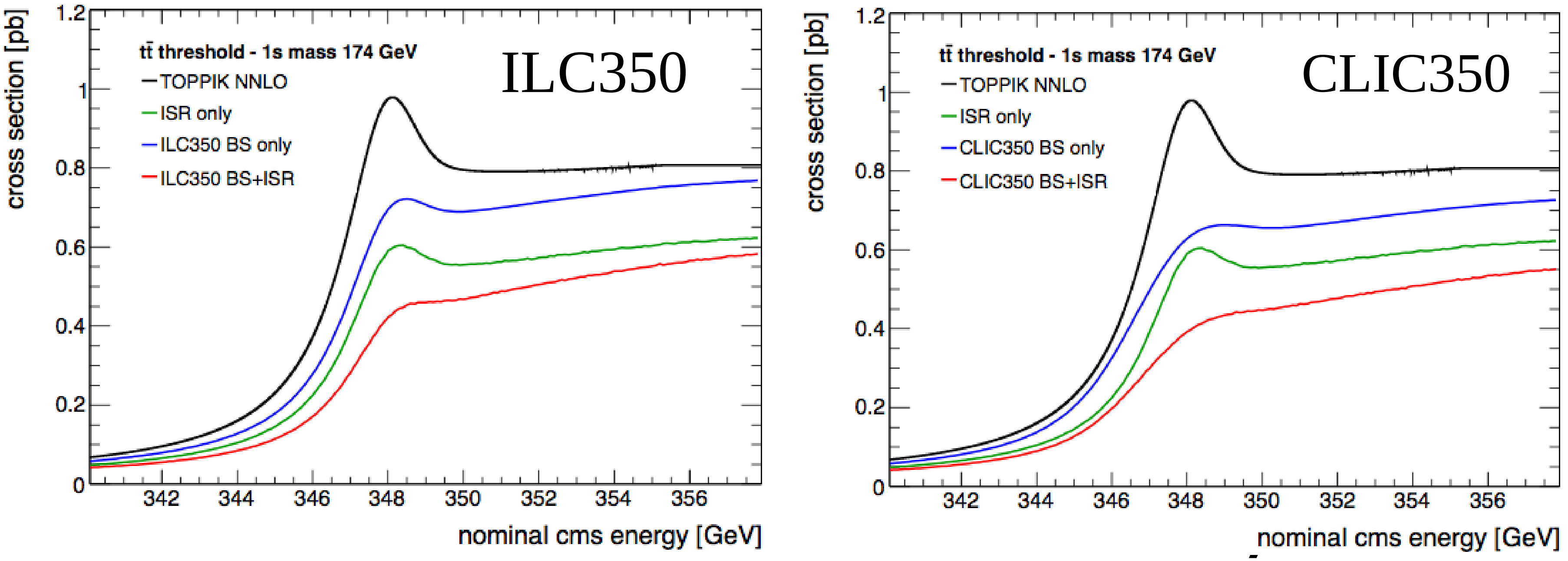
Threshold scan at a future lepton collider

A scan of the beam energy through the $t\bar{t}$ production threshold

(nominally: 10 points of 10/fb each)



Threshold scan at the LC

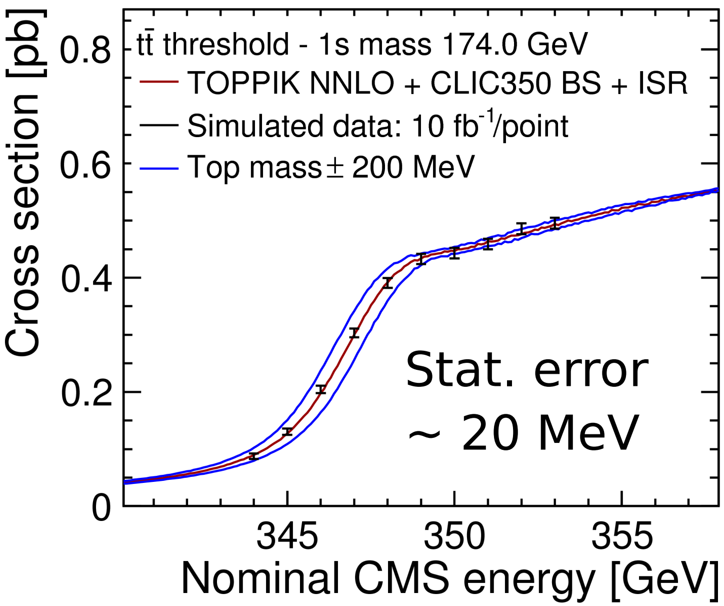


Luminosity spectrum changes shape (ILC & CLIC)

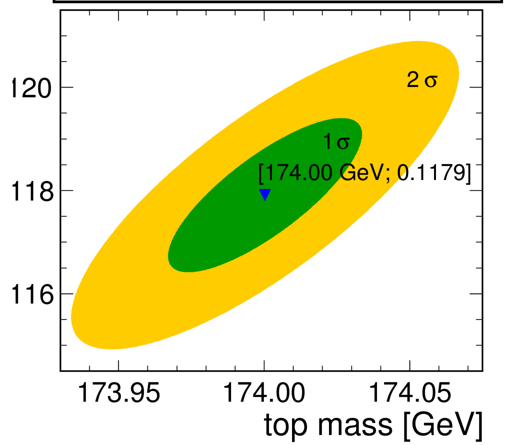
Full simulation & reconstruction, including background

Evaluation/discussion of systematics

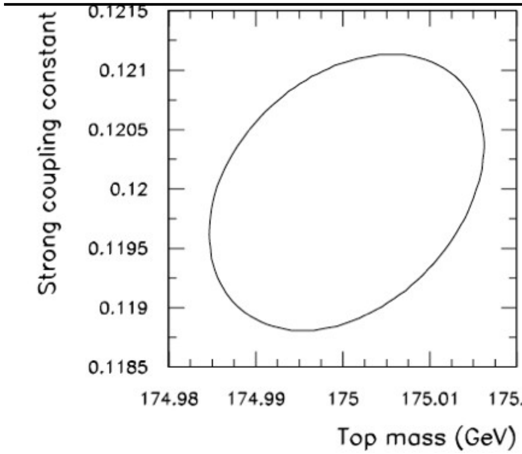
Top quark mass at an LC



Seidel, Simon, Tesar, Poss



Martinez, Miquel, EPJ C27, 49 (2003)



No dependence on location of scan energy
5% uncertainty non-tt bkg → 18 MeV
10^{-4} precision on √s → 30 MeV
20% uncertainty on lumi-spectrum → 75 MeV

1S top mass and α_s combined 2D fit	
m_t stat. error	34 MeV
m_t theory syst. (1%/3%)	5 MeV / 8 MeV
α_s stat. error	0.0009
α_s theory syst. (1%/3%)	0.0008 / 0.0022

A precise measurement (Δ m_t < 100 MeV) can be achieved

+ Δ αs < 0.001 (+ Δ Γ_t < 30 MeV) (+ Δ y_t/y_t ~ 35% *)

Top quark mass: a program for 3 decades

Tevatron: discovery (1995) and develop full characterization

- legacy m_t = 173.18 ± 0.56 ± 0.75 GeV

LHC: continue conventional approach

- Statistical error no longer an issue
- Jet Energy Scale (and b-JES) are tough, but can be treated*
- Major drawback: theory interpretation (see JA this morning)

LHC: extract top mass from measured cross-section

- *Achieved 3% precision, with a rigorous interpretation*
- *Refine to increase sensitivity**

LHC: new methods based on kinematical observables

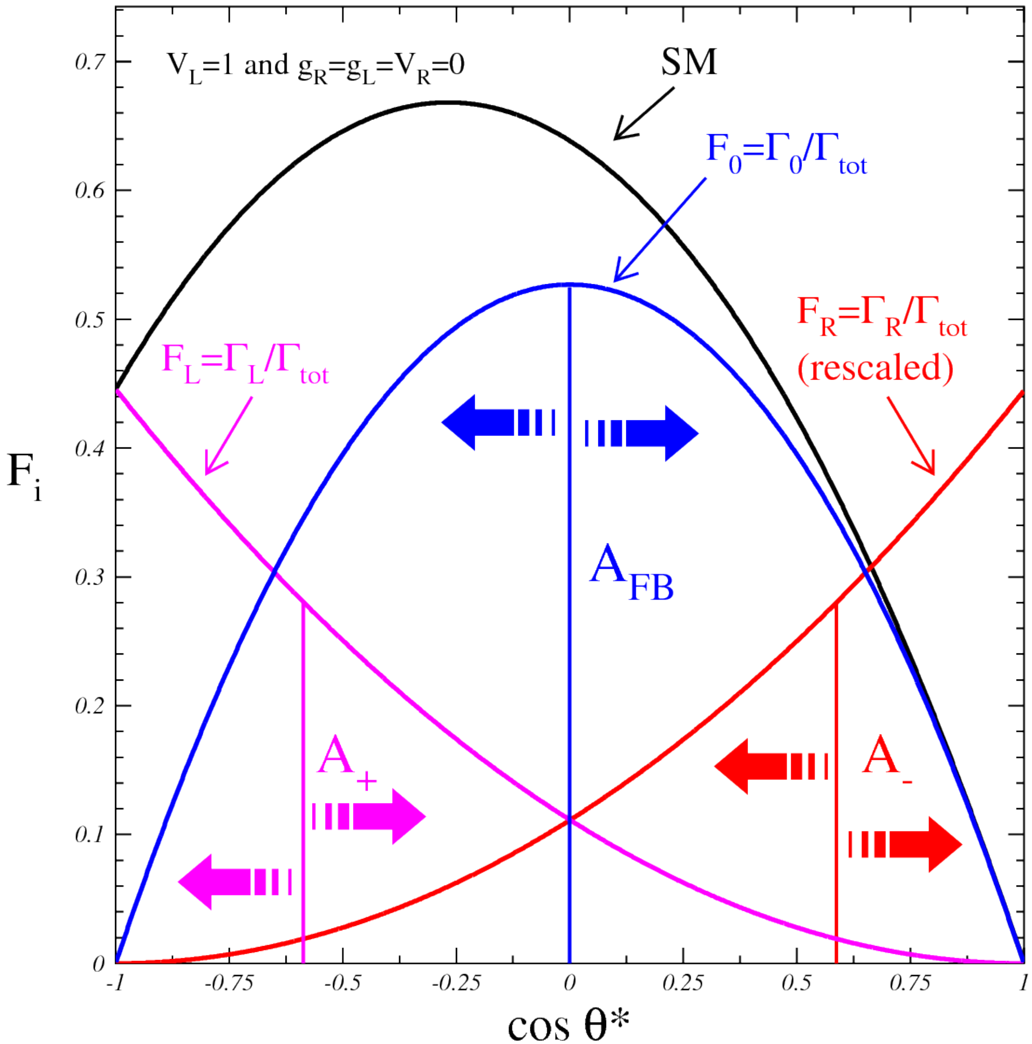
- *B hadron decay length*
- *lepton p_T*
- *J/ψ+lepton from W*
- *Endpoints*

Future LC: threshold scan

- *100 MeV precision!**

W polarization in top quark decays

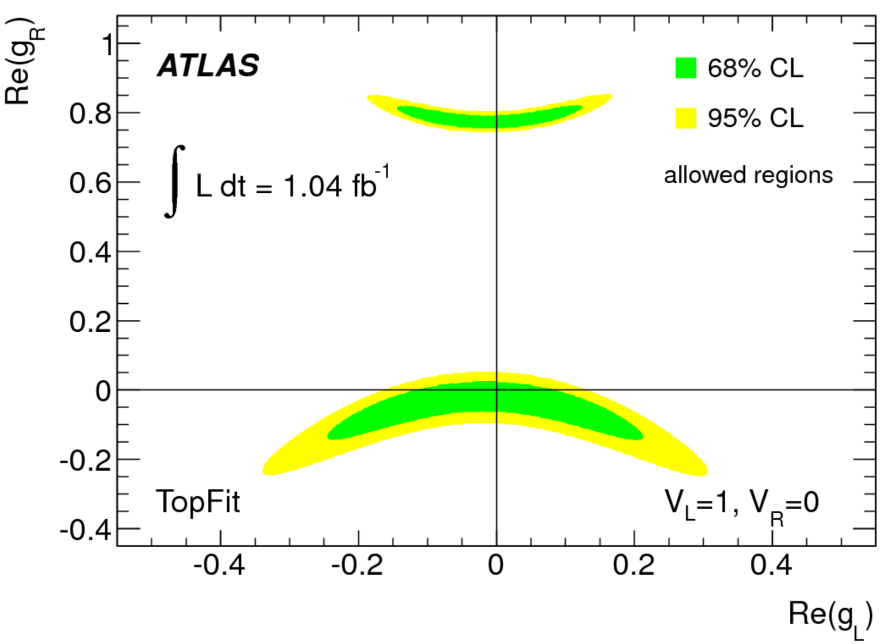
Juan Antonio certainly explained how W polarization (helicity fractions) can be extracted from the distribution of cos θ*

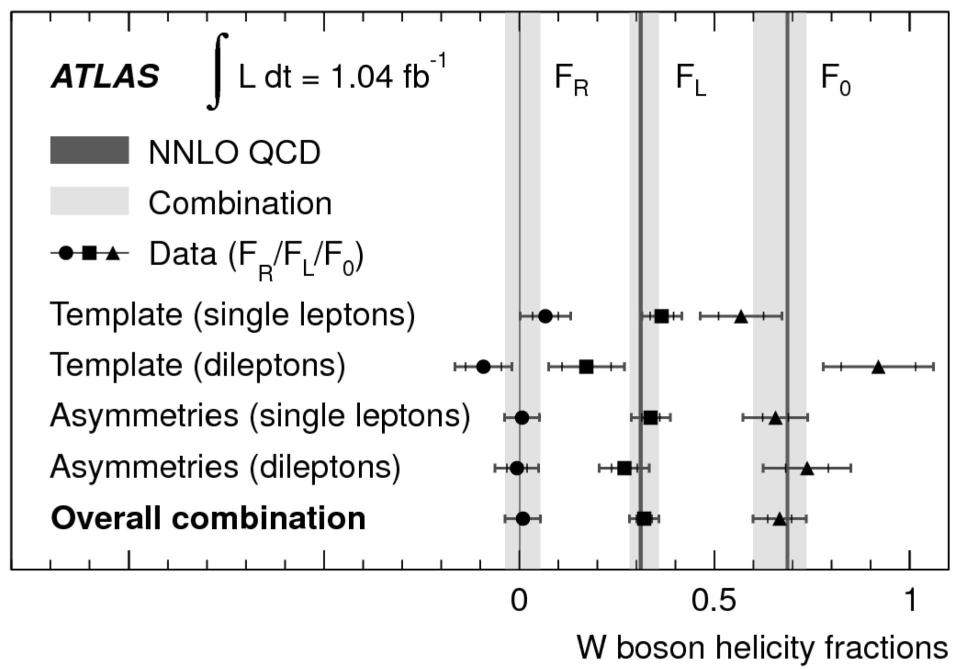


W polarization in top quark decays

http://inspirehep.net/record/1114314

Source	Uncertainties		
	F_0	F_L	F_R
Signal and background modelling			
Generator choice	0.012	0.009	0.004
ISR/FSR	0.015	0.008	0.007
PDF	0.011	0.006	0.006
Top quark mass	0.016	0.009	0.008
Misidentified leptons	0.020	0.013	0.007
W+jets	0.016	0.008	0.008
Other backgrounds	0.006	0.003	0.003
Method-specific uncertainties	0.031	0.016	0.035
Detector modelling			
Lepton reconstruction	0.013	0.006	0.007
Jet energy scale	0.026	0.014	0.012
Jet reconstruction	0.012	0.005	0.007
b-tagging	0.007	0.003	0.004
Calorimeter readout	0.009	0.005	0.004
Luminosity and pileup	0.009	0.004	0.005
Total systematic uncertainty	0.06	0.03	0.04





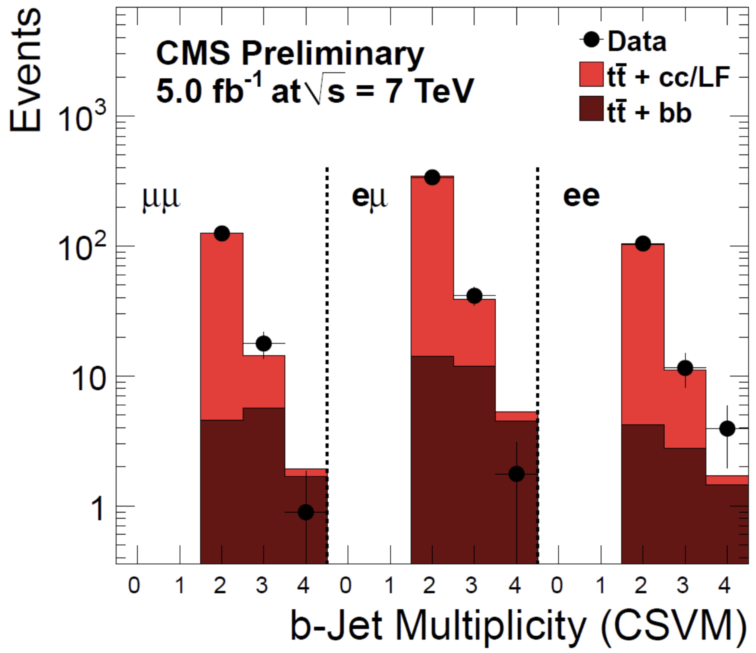
Searches with top quarks

Associated produciton with bottom quarks

Important background to ttH(→bb) channel
Interested in fraction of events with b-flavour

- in σ(ttbb)/σ(ttjj) many systematics cancel

PAS TOP-12-024



Theory

- Madgraph 1.2%, Powheg 1.3%
- NLO calculations predict 4.7% (parton level, can't be compared)

$$\sigma(t\bar{t}b\bar{b})/\sigma(t\bar{t}jj) = 3.6 \pm 1.1(stat.) \pm 0.9(sys.)\%$$

Bevilacqua, Czakon, Papadopoulos et al., PR D84 (2011) 114017

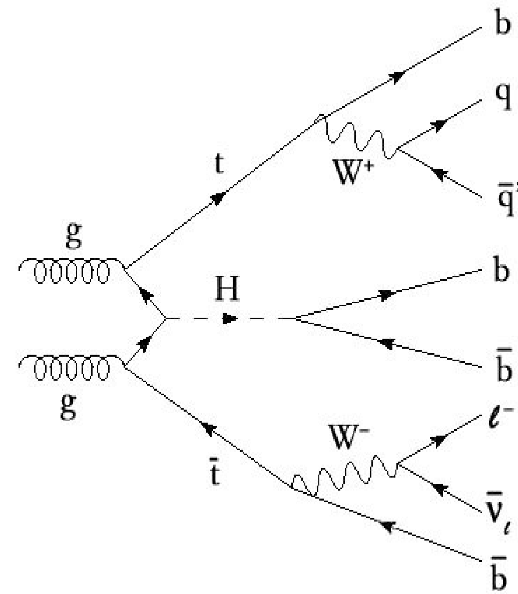
Associated production with Higgs bosons

Can access top-Higgs Yukawa coupling

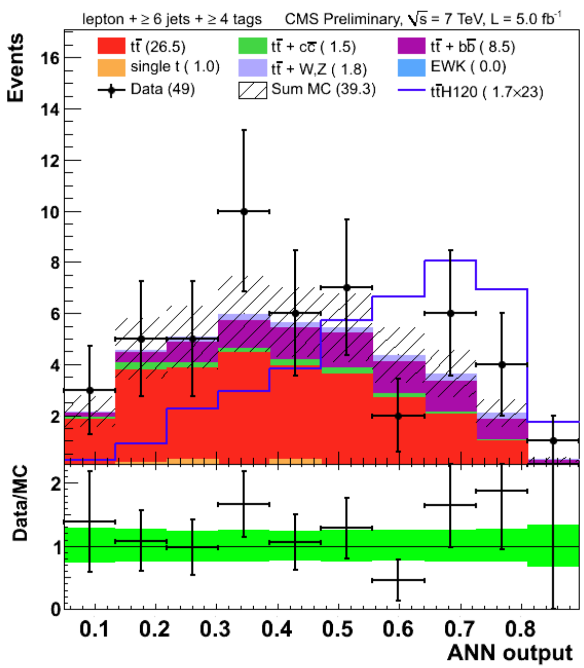
- given enough luminosity

In 2011 looked at ttH (H → bb)

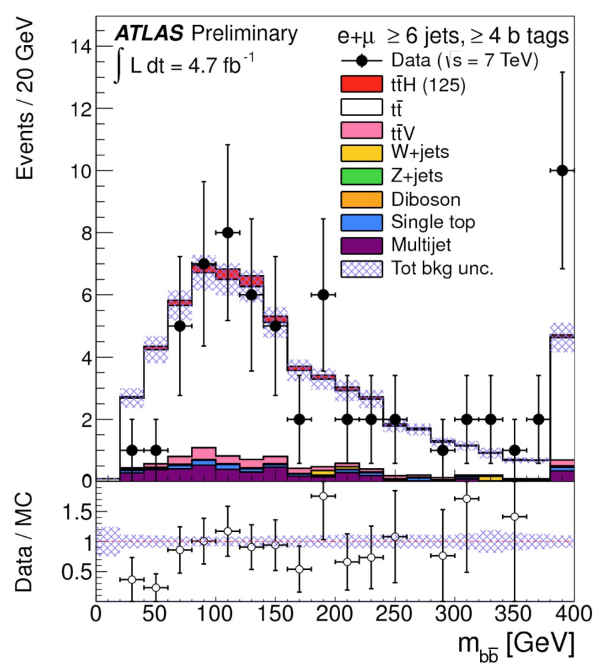
- divide sample in categories #jets #b-jets
- construct likelihood (ATLAS) or neural network (CMS)



PAS HIG-12-025



CONF-2012-135



Not yet sensitive

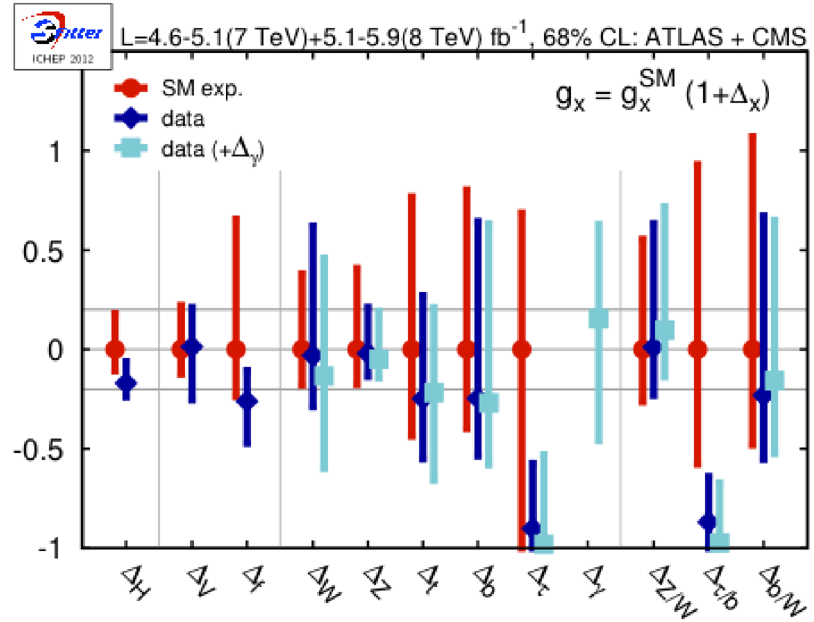
- analysing 2012 data

Limits for mH=125GeV

- CMS 4.6 x SM (3.8)
- ATLAS 13.1 x SM (10.5)

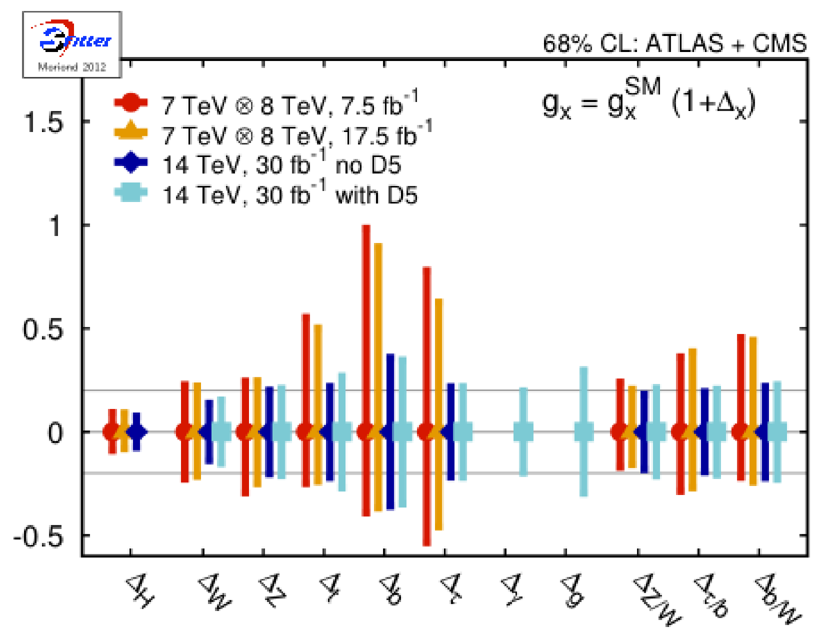
The H boson

Direct determination of couplings to 3rd-generation quarks; a crucial piece of the puzzle



Difficult...

http://arxiv.org/abs/arXiv:0910.5472



A process that is going to be very important in phase II of the LHC

Further searches with (boosted) top quarks

The "boosted production" threshold

$\sqrt{s} \gg E_{EW}$

Even the heaviest SM particles often acquire $p_T > m$

→ abundant production of "boosted objects"

A top factory, our first sample of boosted top quarks

Expected number of tt events in three different kinematical remies	*Tevatron run II* 10 fb^{-1} @ 1.96 TeV	*LHC 2012* 20 fb^{-1} @ 8 TeV	*LHC design* 300 fb^{-1} @ 13 TeV	*Very LHC* 300 fb^{-1} @ 33 TeV
Inclusive tt production	57.000	2.600.000	155.000.000	1.000.000.000
Boosted production: M_{tt} > 1 TeV	25	30.000	3.000.000	46.000.000
Highly boosted: M_{tt} > 2 TeV	0	300	47.000	2.300.000

Enough to discover the top quark, no boosted production

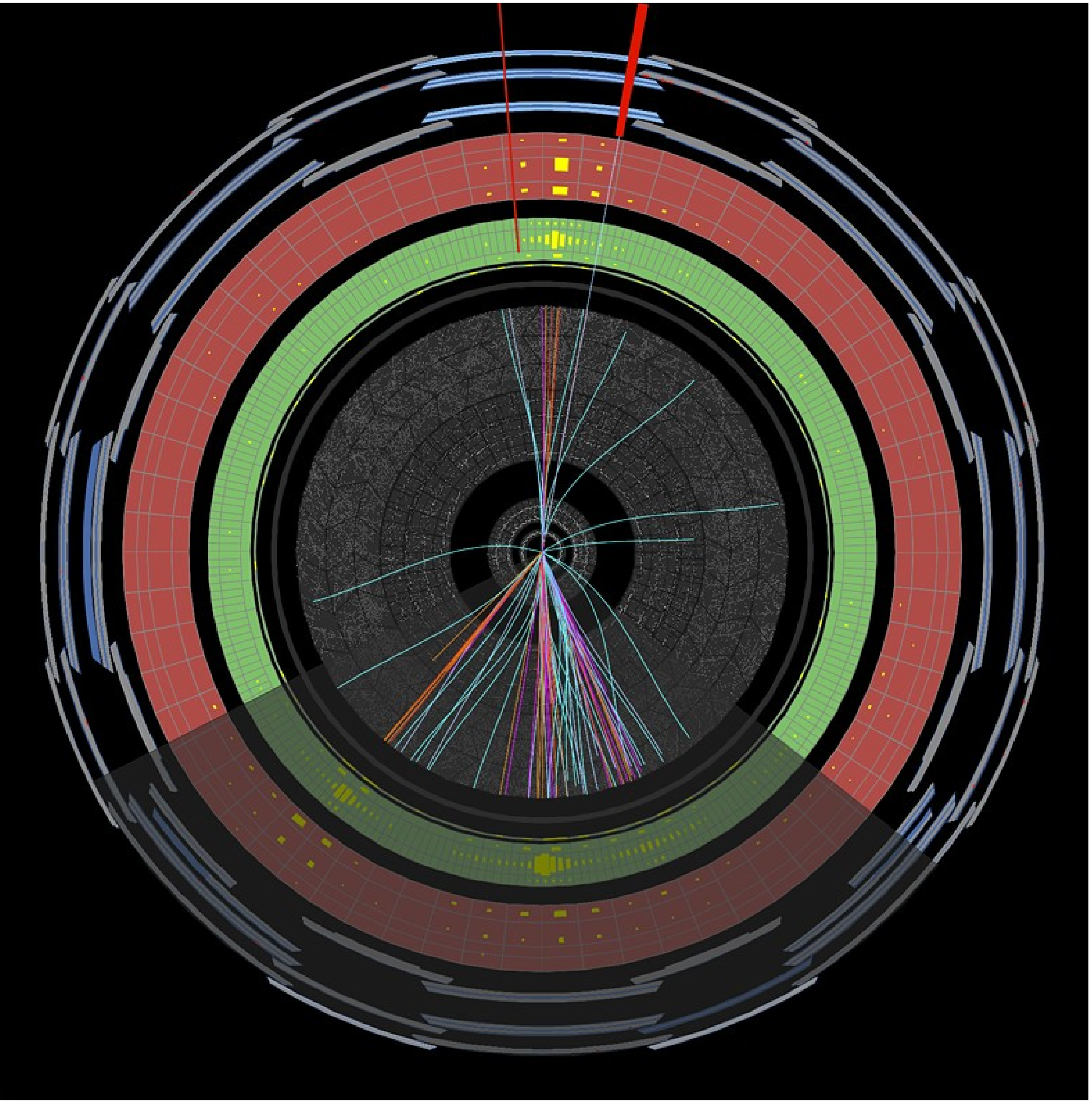
Millions of boosted top quarks, 50.000 extremely boosted events

M.V., Boosting sensitivity to new physics, CERN Courier, Oct 2012

Results obtained with MCFM, J. M. Campbell and R. K. Ellis, arXiv:1204.1513 [hep-ph] MSTW2008NLO PDFs

marcel.vos@ific.uv.es

The boosted regime



Now apply the classical strategy to this event.

It won't work

What's going on here?

Top quark $p_T >> m_t$

What information is no longer resolved?

Jets merge

Lepton not isolated

What bit of information didn't we use?

Back-to-back t and $\bar{t}$

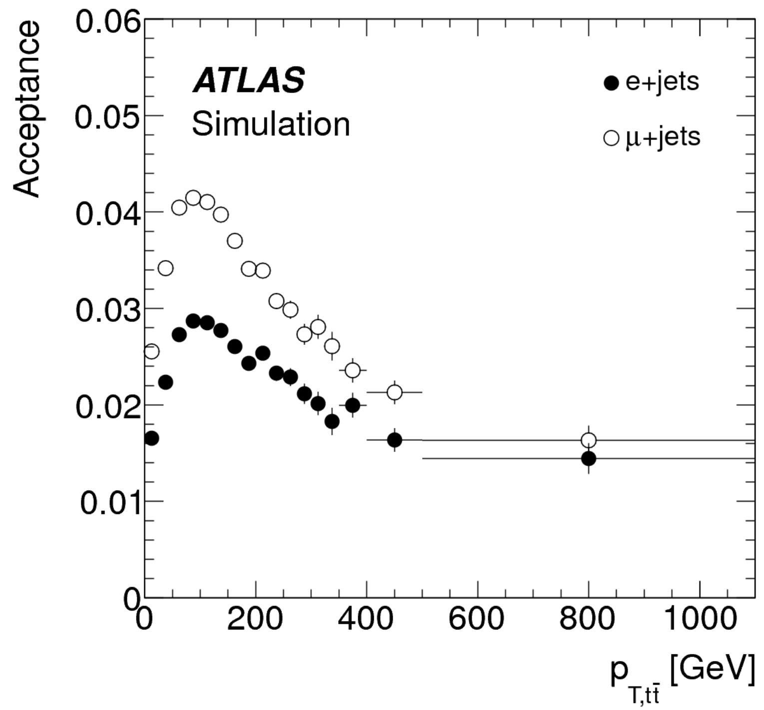
Boosted top quarks

Classical algorithm is great for top quarks at rest, but is not adequate for boosted top quarks

Problem: merging jets, lepton isolation, missing p_T resolution

Missed opportunity: reconstruction of top quark is easier in boosted regime

arXiv:1207.5644



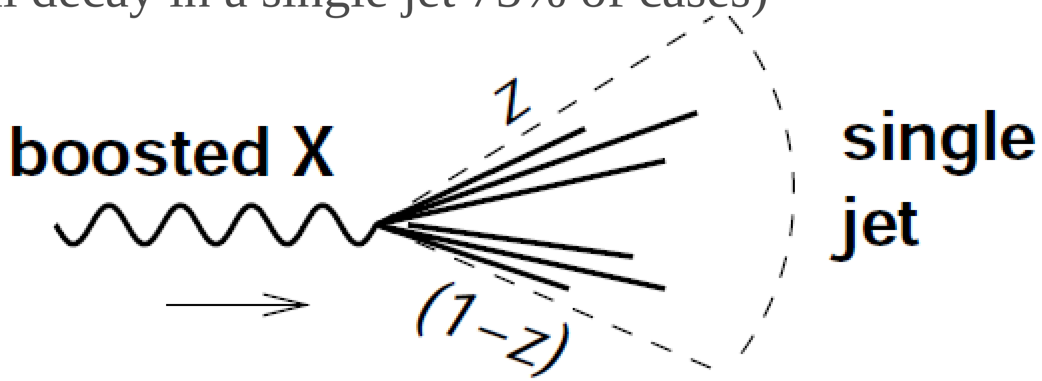
Boosting BSM sensitivity

Let's define "boosted object" by comparing the standard approach (reconstruct components and combine) **to Mike Seymour's alternative** (find composite object and decompose).

Rules of thumb for maximum jet radius parameter for 2-body decay:

$R < 2m/p_T$ (always resolve two jets)

$R > 3m/p_T$ (capture full decay in a single jet 75% of cases)



W boson at rest → use resolved approach

$p_T \sim 240$ GeV → coexisting algorithms,

can resolve with R=0.4, or contain in R=1

$p_T \sim 400$ GeV → boosted regime

cannot always resolve with R=0.4

Boosted objects and fat jets

✓ Boosted objects must be caught in fat jets

Fat jet, according to Colin G.

Boosted objects: a probe of beyond the standard model physics

Report of the hadronic working group of the BOOST2010 workshop, held at Oxford University, from the 22^{nd} to the 25^{th} of June, 2010.

The participants of BOOST2010:
A. Abdesselam[1], E. Bergeaas Kuutmann[2], U. Bitenc[3], G. Brooijmans[4], J. Butterworth[5], P. Bruckman de Renstrom[6], D. Buarque Franzosi[7], R. Buckingham[1], B. Chapleau[8], M. Dasgupta[9], A. Davison[5], J. Dolen[10], S. Ellis[11], F. Fassi[12], J. Ferrando[1], M.T. Frandsen[1], J. Frost[13], T. Gadfort[14], N. Glover[15], A. Haas[16], E. Halkiadakis[17], K. Hamilton[18], C. Hays[1], C. Hill[19], J. Jackson[20], C. Issever[1], M. Karagoz[1], A. Katz[21], L. Kreczko[22], D. Krohn[23], A. Lewis[1], S. Livermore[1], P. Loch[24], P. Maksimovic[25], J. March-Russell[26], A. Martin[27], N. McCubbin[20], D. Newbold[22], J. Ott[28], G. Perez[29], A. Policchio[11], S. Rappoccio[25], A.R. Raklev[30,31], P. Richardson[15], G.P. Salam[23,32,33], F. Sannino[34], J. Santiago[35], A. Schwartzman[16], C. Shepherd-Themistocleous[20], P. Sinervo[36], J. Sjoelin[37], M. Son[38], M. Spannowsky[39], E. Strauss[16], M. Takeuchi[40], J. Tseng[1], B. Tweedie[25,41], C. Vermillion[11,42,43], J. Voigt[28], M. Vos[44], J. Wacker[16], J. Wagner-Kuhr[28], and M.G. Wilson[16]

(arXiv:1012.5412 [hep-ph])

Tools & Technniques: reconstruction

"clustering" jet algorithms use a distance or metric:

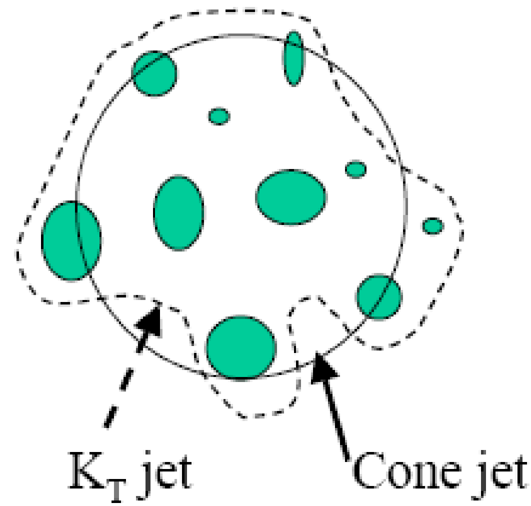
$$d_{ij} = \min(p_{Ti}^{2p}, p_{Tj}^{2p}) * R_{ij}^2/R^2$$

$$d_{iB} = \min(p_{Ti}^{2p}, p_{Tj}^{2p})$$

p=0 → Cambridge Aachen (C/A)

p=1 → k_t

p=-1 → anti-k_t



- Anti-kt is infra-red safe and with nearly circular footprint
- k_t yields clustering that is intrinsically ordered in p_T scale
- C/A clustering sequence is ordered by angle

Anti-k_t = default jet algorithm for ATLAS/CMS is anti-k_t

R=0.4, 0.6, or 0.5, 0.7, with some support for large-R jets

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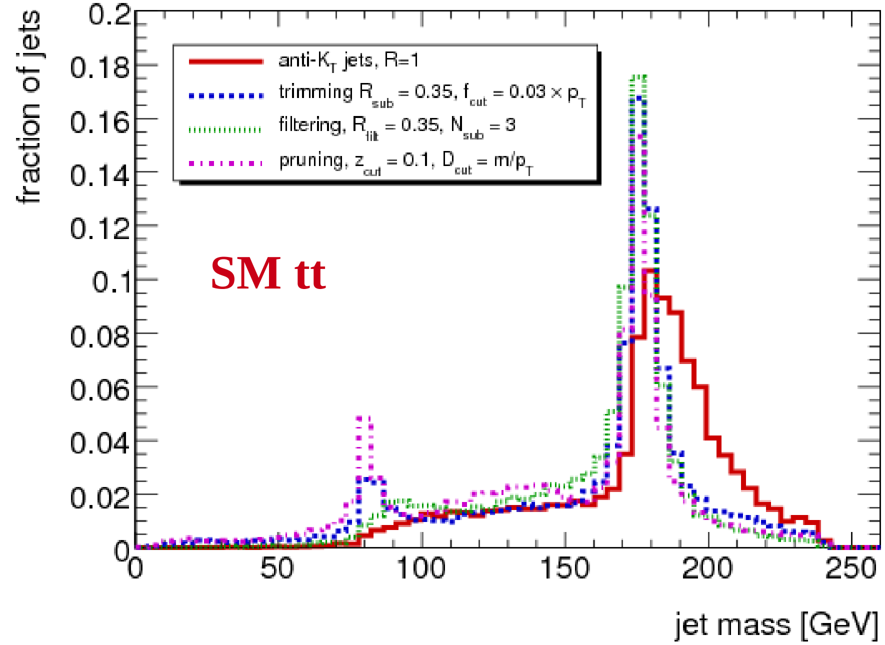
Jet mass

Pythia: 500 < p_T < 600 GeV
Anti k_T (R=1.0) particle-level

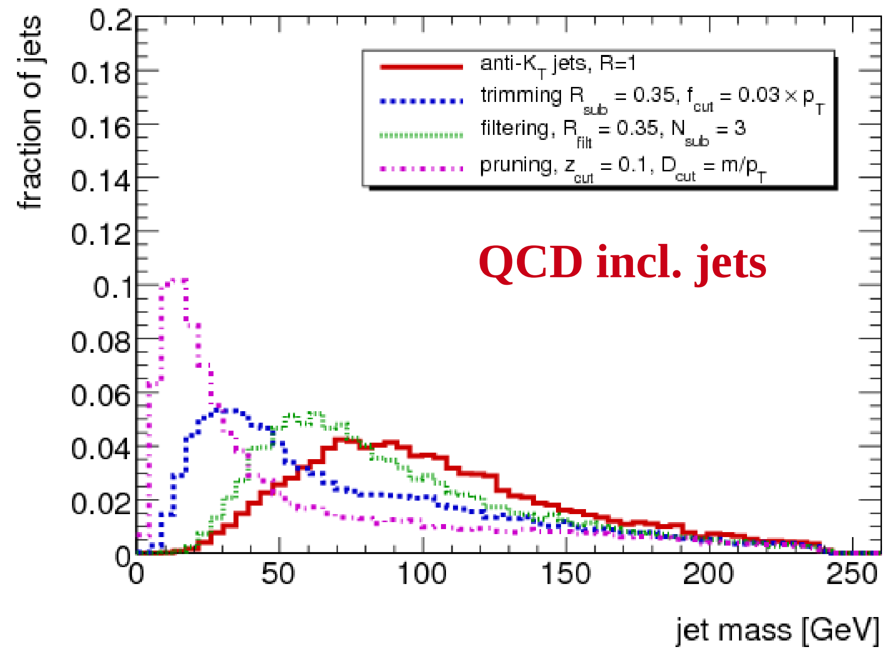
Top jet → $m_j \sim m_t$

Background → m_j µ α_s p_T R

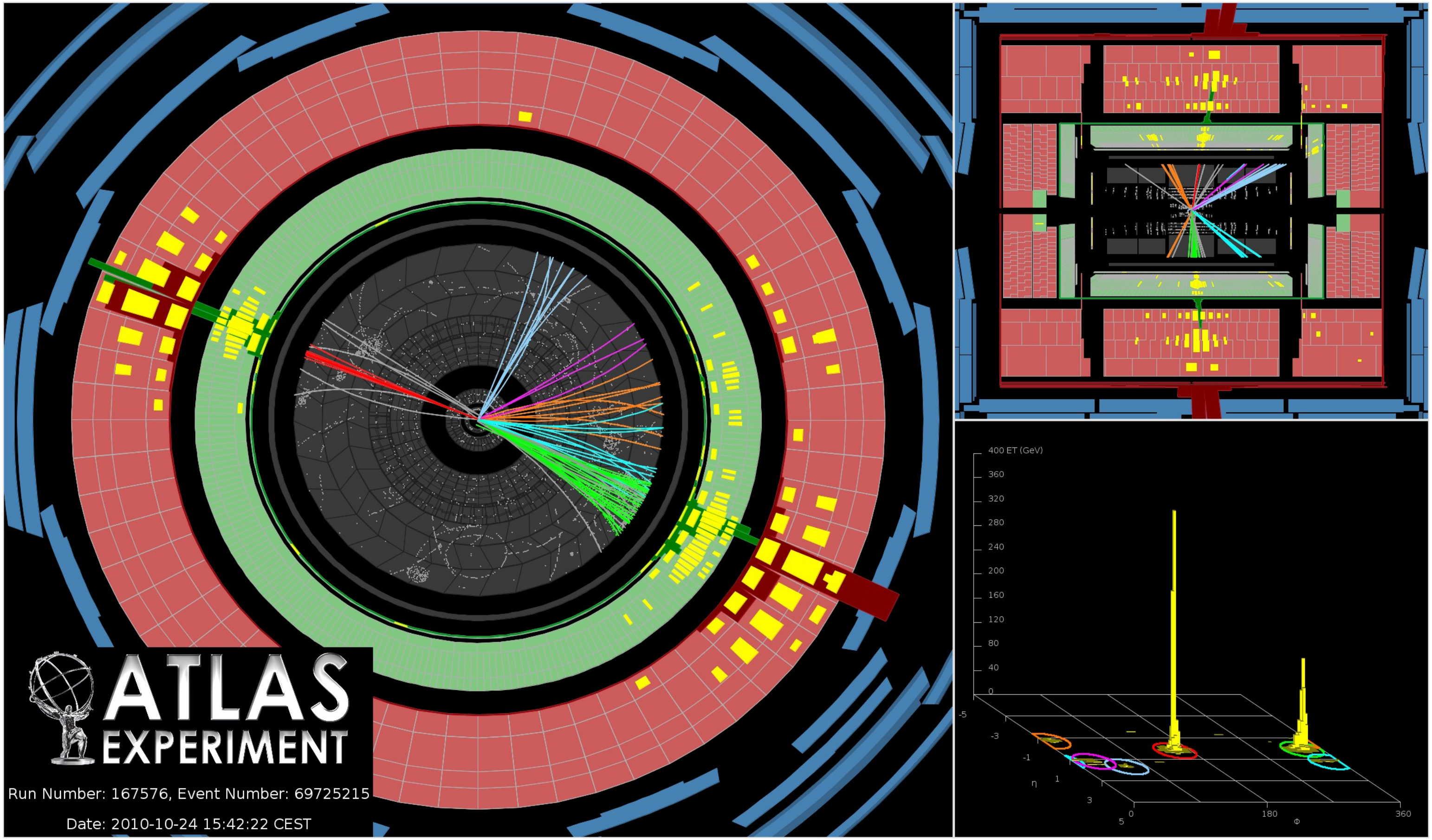


Jet grooming improves performance:

- **resolution**
- **background rejection**
- **Pile-up resilience**



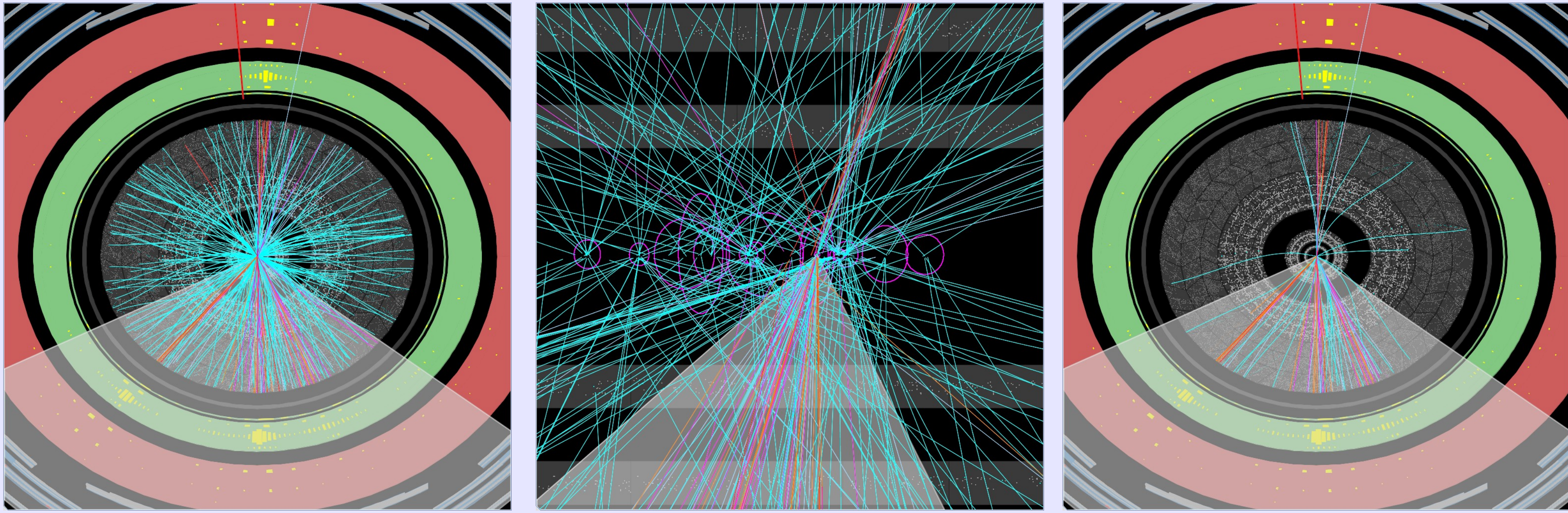
Jet substructure



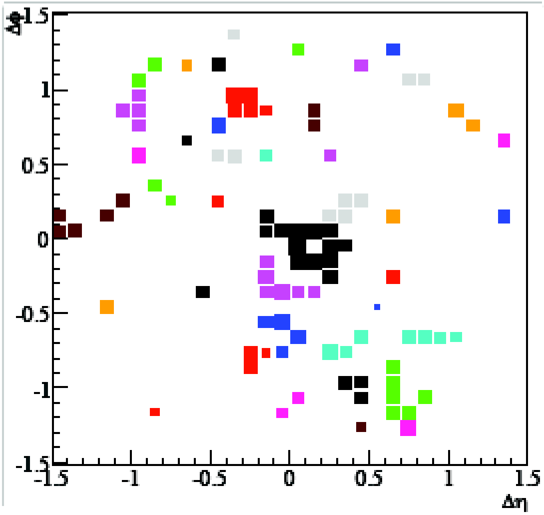
There is more to a jet than a three-vector

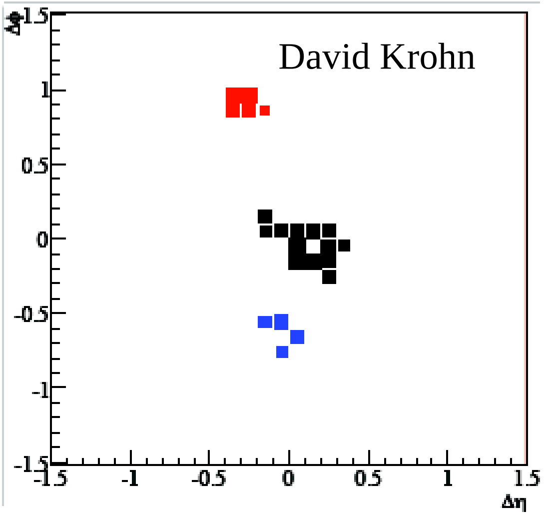
Detector response

Can we measure jet substructure precisely and reliably?



Tools and Techniques: grooming





Jet substructure is often hidden:

- ✓ **Soft emissions inside the jet**
- ✓ **Underlying event**
- ✓ **Pile-up* (identified by associating jets/clusters to tracks/vertices)**

Jet grooming techniques **to remove the "softest" parts (at large angle) of the jet:**

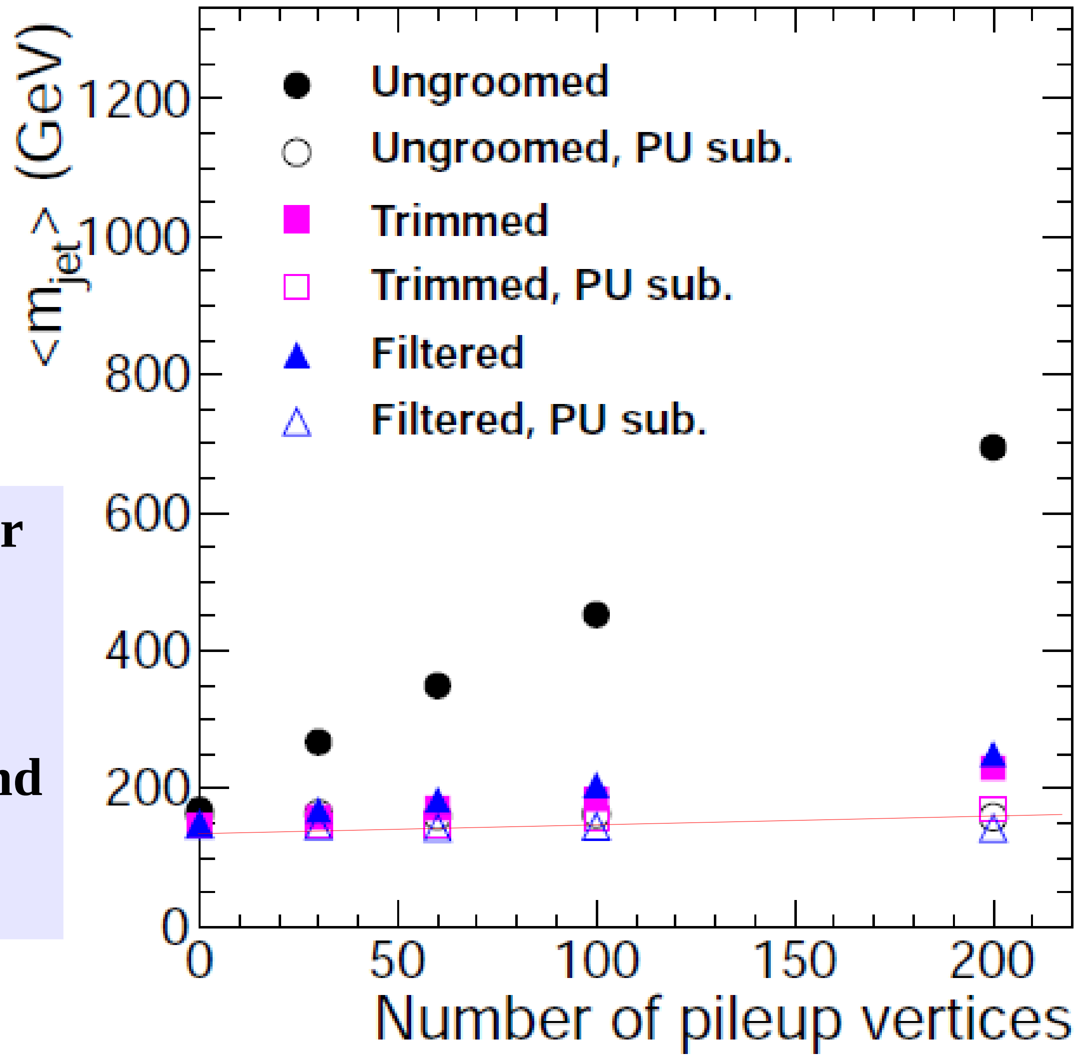
- ✓ **Filtering:** break jet into subjets on angular scale R_{filt} , take n_{filt} hardest subjets Butterworth, Davison, Rubin & Salam '08
- ✓ **Trimming:** break jet into subjets on angular scale R_{trim}, take all subjets with $p_{T,sub} > \varepsilon_{trim} p_{T,jjet}$ Krohn, Thaler & Wang '09
- ✓ **Pruning:** as you build up the jet, if the two subjets about to be recombined have $R > R_{prune}$ and min(pt1, pt2) < ε_{prune} ($p_{T1} + p_{T2}$), discard the softer one. Ellis, Vermilion & Walsh '09

Now, after seeing with our own eyes what pile-up can do to jet, is a good time to convince your experiment to support these

Revisit/reoptimize based on experience on data

Boost2010 report ignored the variable R option...

Measuring jet mass

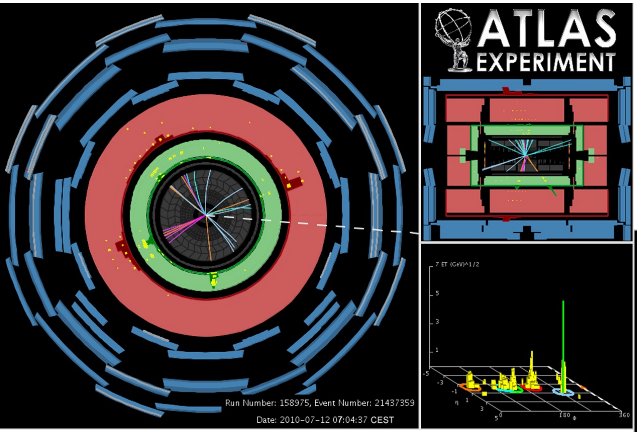


Simulation: jet mass scale for boosted top quarks verus number of pile-up vertices

Combination of grooming and pile-up subtraction restores the scale

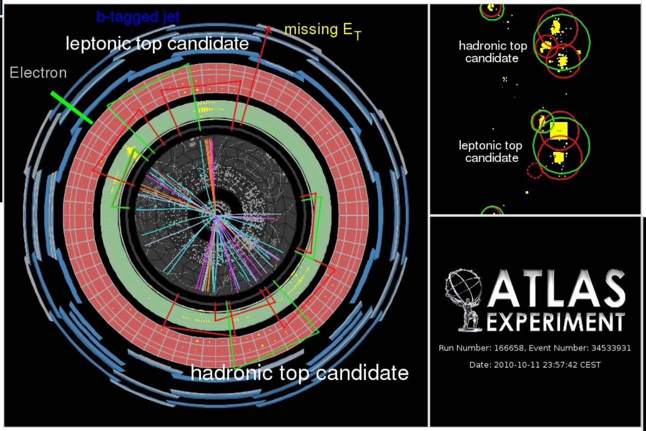
OK! This works for foreseeable future

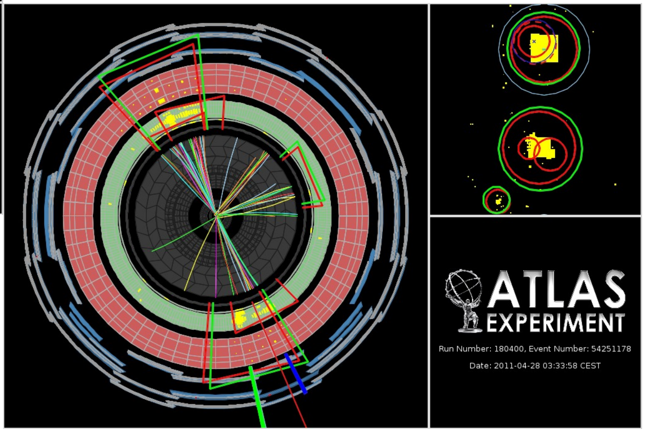
Boosted top quarks (II)



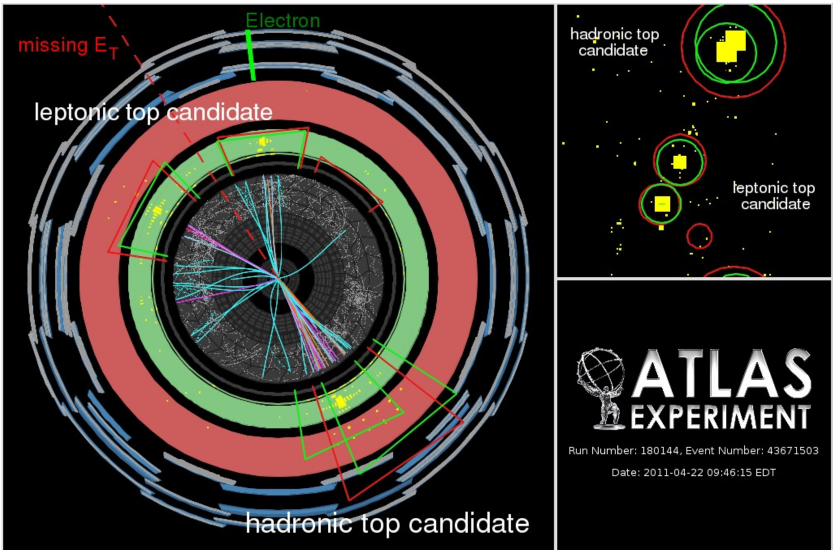
Early “l+jets” candidate
ATLAS-CONF-2010-063

First boosted top quark
Mtt ~ 800 GeV
ATLAS-CONF-2011-073





m_{tt} > 1 TeV
ATLAS-CONF-2011-083



M_{tt} ~ 2.5 TeV
arXiv:1207.2409

A graphical account of the same argument, with real events

Boosted top quarks (III)

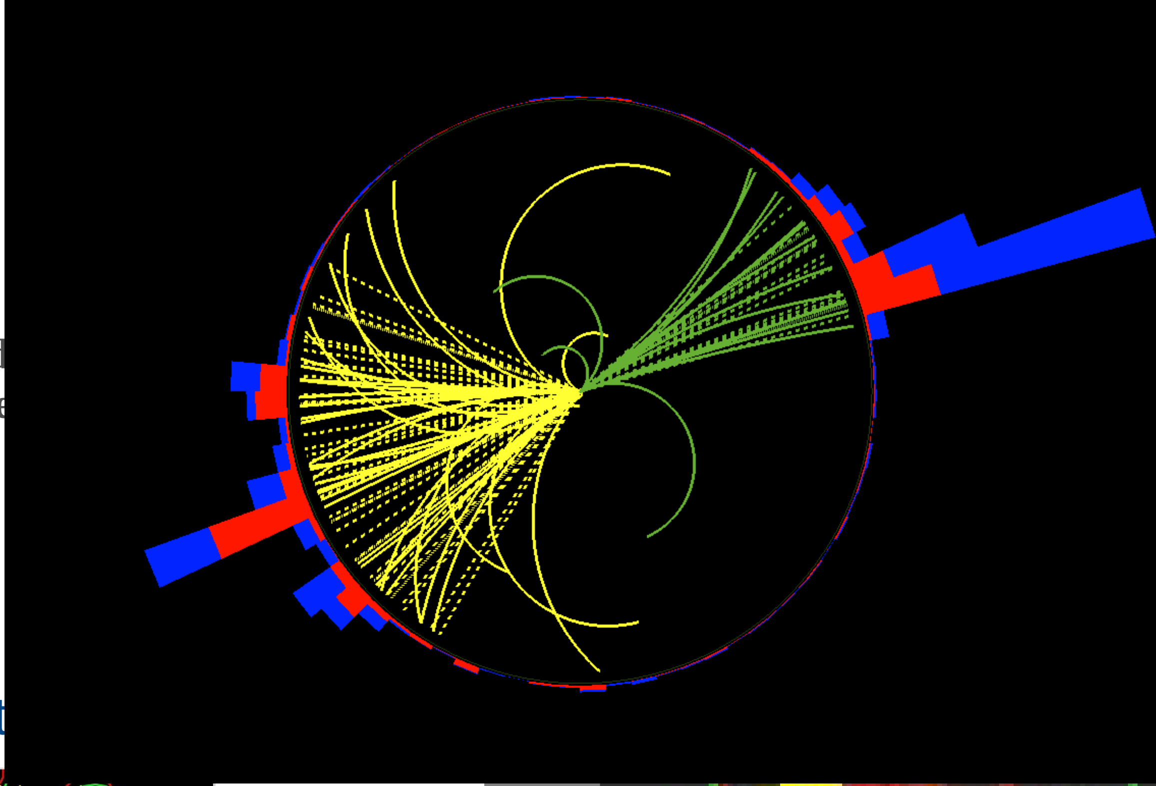
2010 data: the first five events of control sample

High-mass (> 700 GeV) pairs in the stand when reclustered with R = 1.0 the three je single jet with:

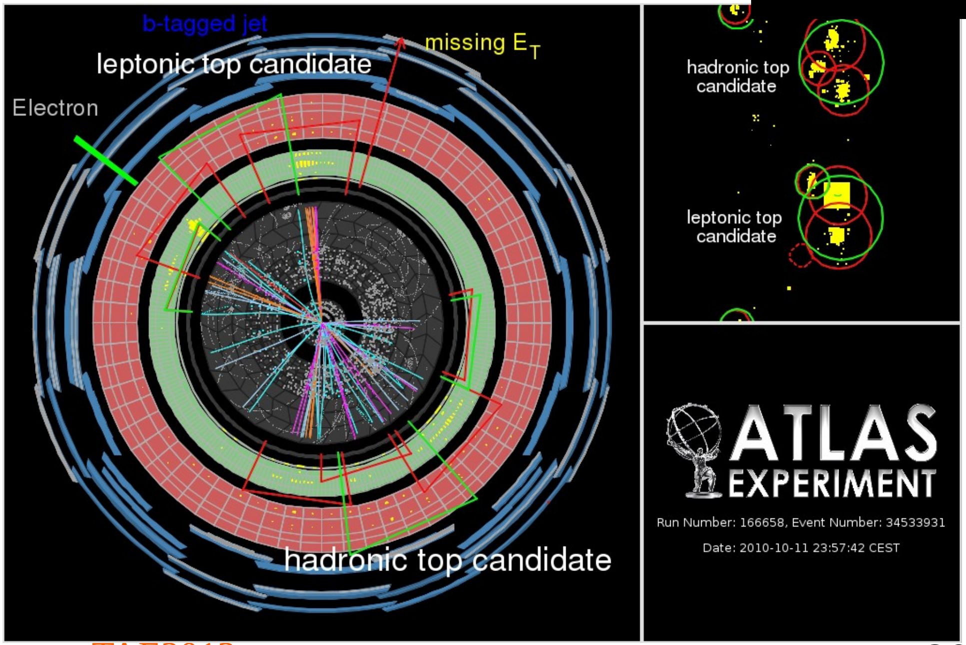
m_j = 197 GeV (expected: m_t)

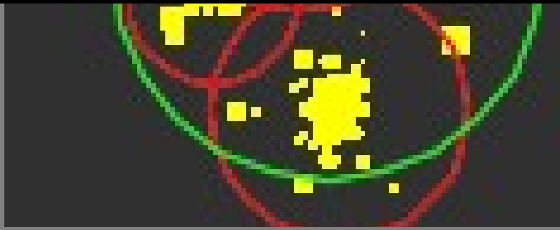
sqrt(d_{12}) = 110 GeV (expected ~m_W)

sqrt(d_{23}) = 40 GeV (expected …)



The world's first "boosted object





Recluster @ R=1
First observation of a
"boosted object"

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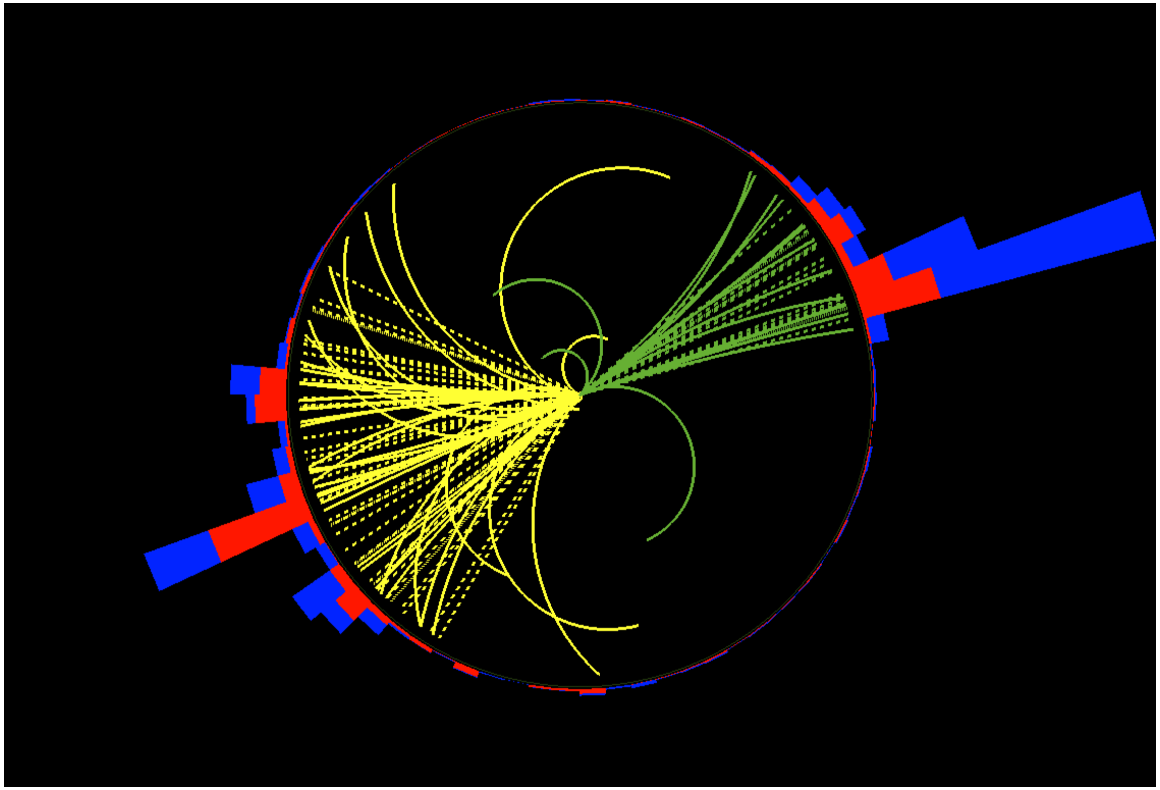
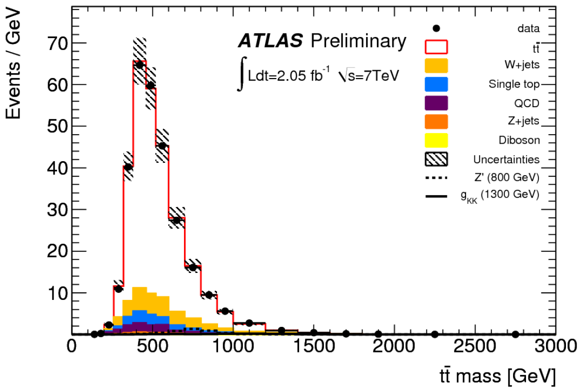
Boosted top quarks

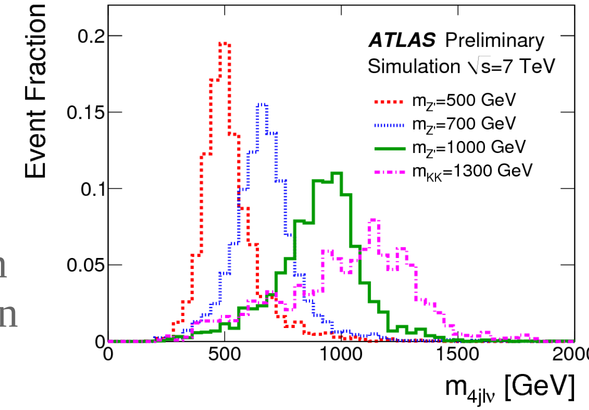


tt resonances

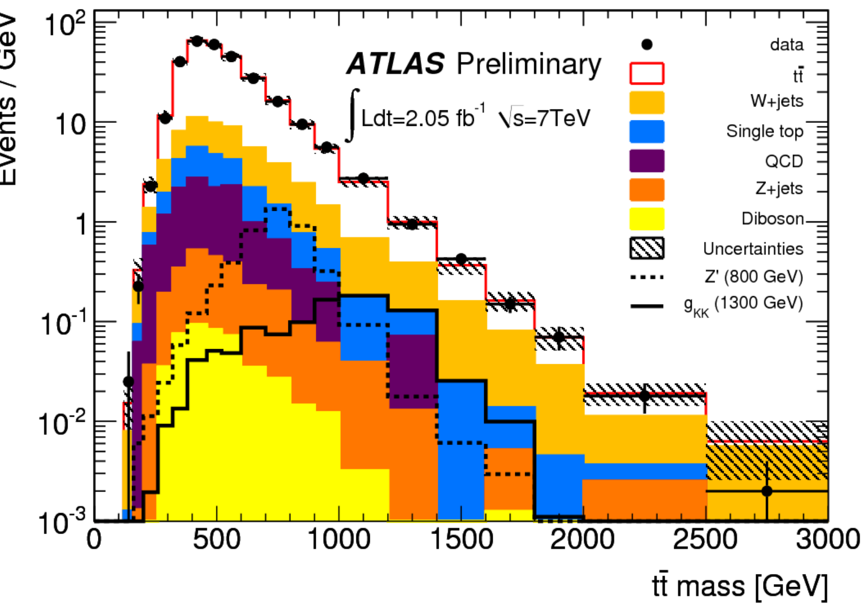


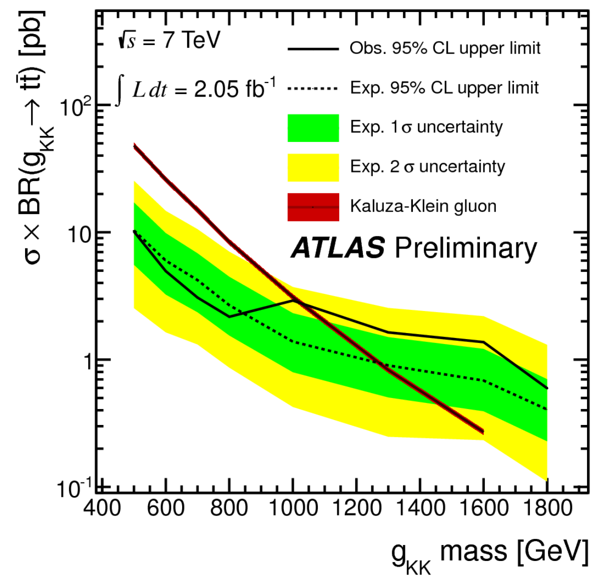
Expect 80% SM population of the Signal Region is due to tt pair production

tt system reconstruction
10% mass resolution



Full Signal Region



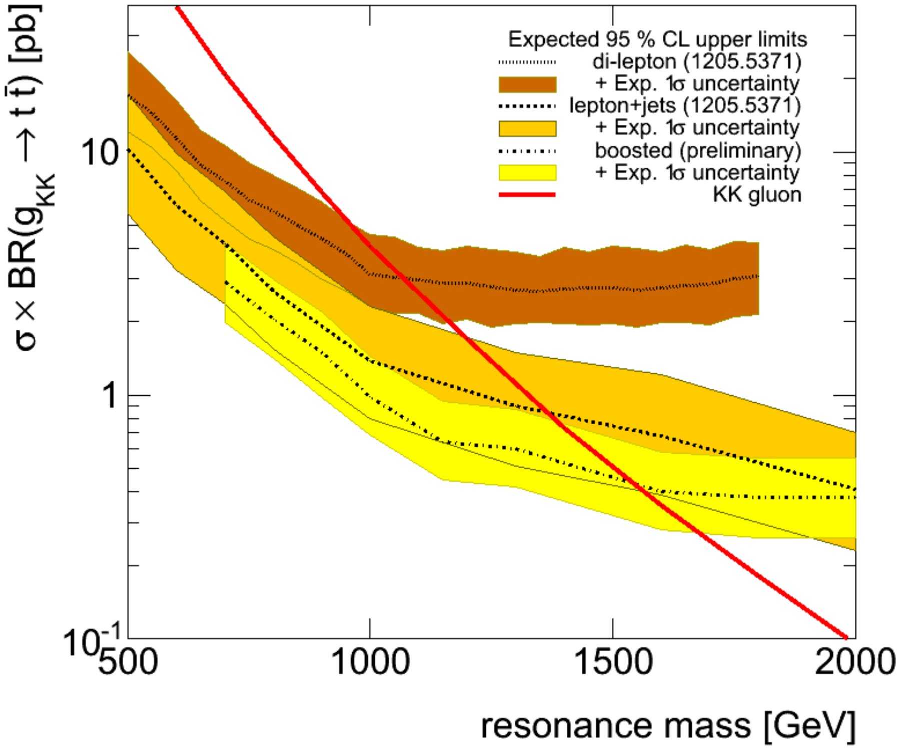


Depending on what you're looking for, the differential) cross-section, the charge asymmetry, same-sign top quark search, tt + missing energy, ... may be more relevant

If you're still here on Saturday, come to the BSM new phenomena discussion

ATLAS resonance searches

Better (more specialized) algorithms allow us to achieve better sensitivity on the same data set!
This is only possible with a sufficiently granular detector system



Summary post-ICHEP2012: Classical and boosted algorithms have complementary low and high mass sensitivity.

Final state	di-lepton	lepton+jets	boosted l+jets	Boosted fully had	combined l+jets
Preprint/publication	EPJC72	EPJC72	JHEP1209	2012-102	2012-136
Data set	2 fb^{-1}	2 fb^{-1}	2 fb^{-1}	4.7 fb^{-1}	4.7 fb^{-1}
Z' limits [TeV]	-	0.55 - 0.88	0.6 - 1.15	0.7 – 1.3	0.7 – 1.7
g_{KK} limits [TeV]	0.5 - 1.08	0.5 - 1.13	0.6 - 1.5	0.7 – 1.5	0.7 – 1.9

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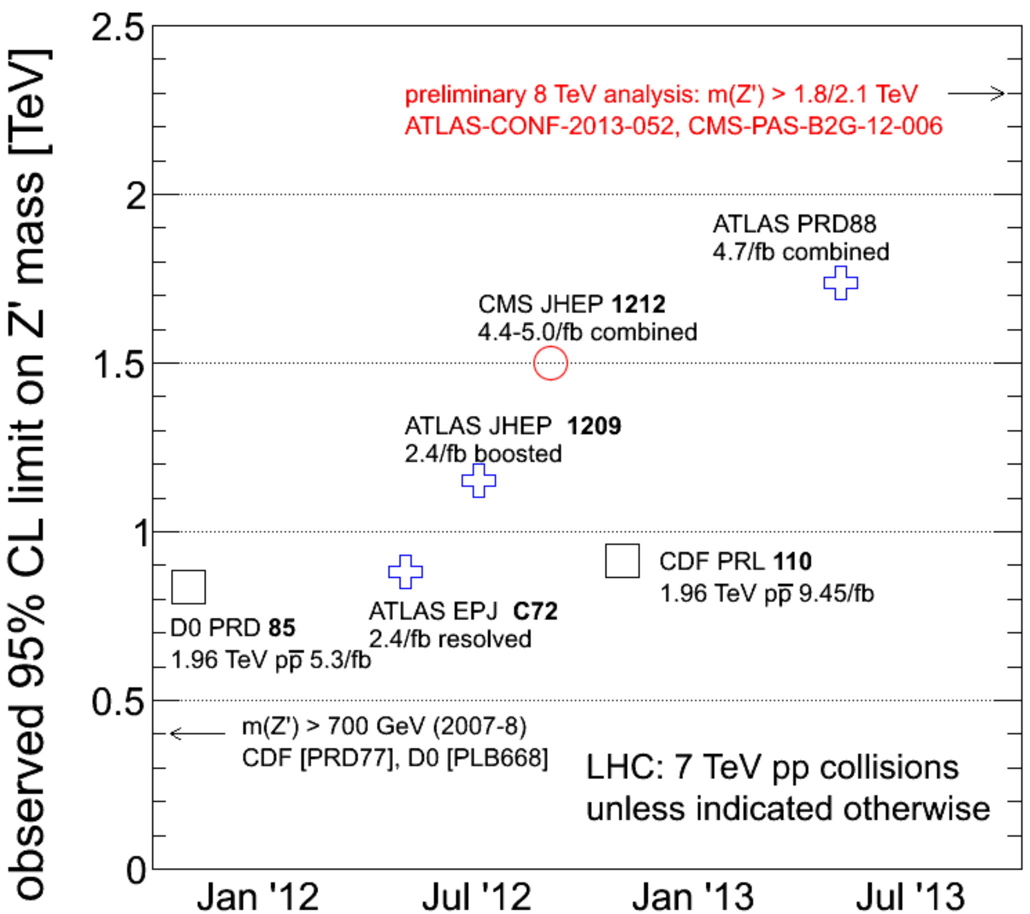
Resonance searches

Use Z' limits as a benchmark to monitor progress

l+jets analyses only. Searches in fully hadronic events are close behind!



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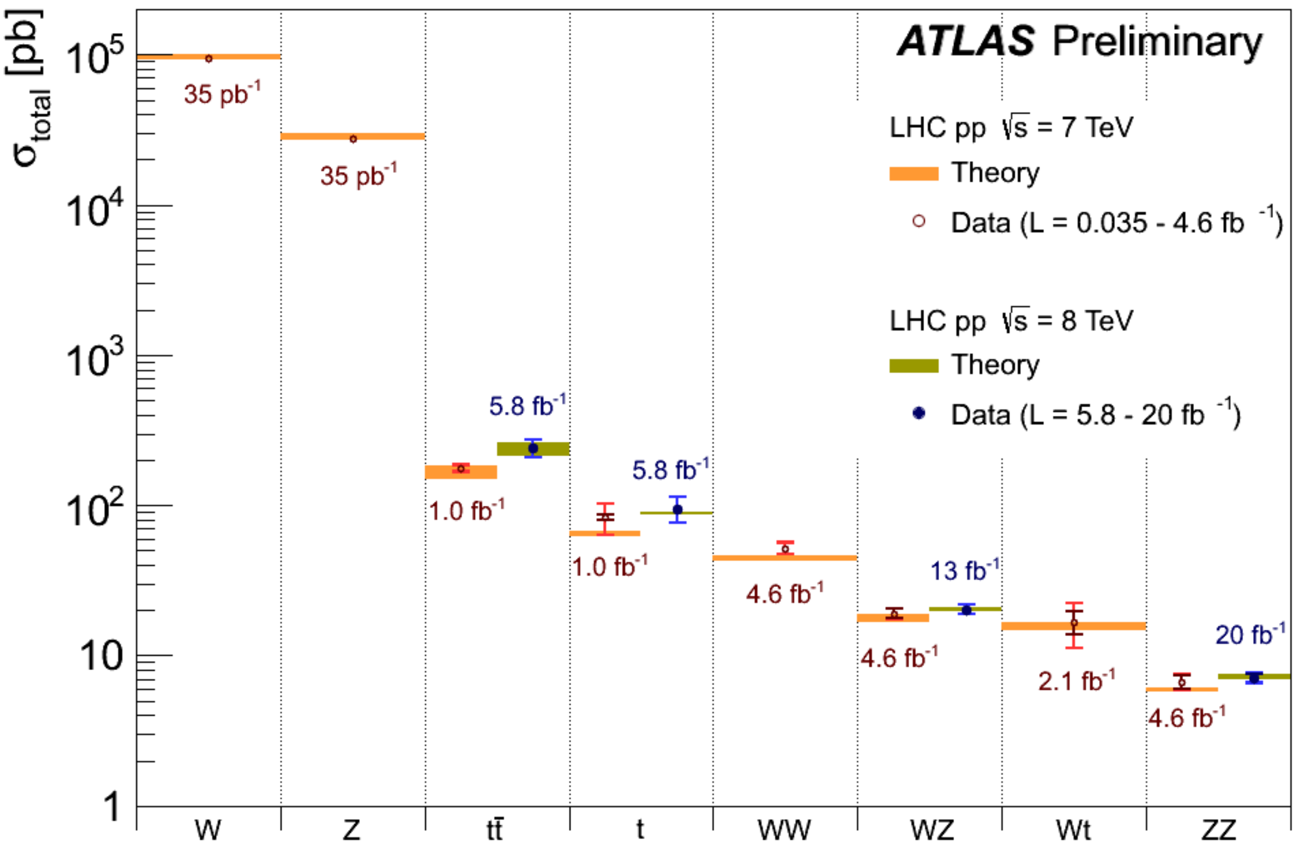
Electro-weak physics

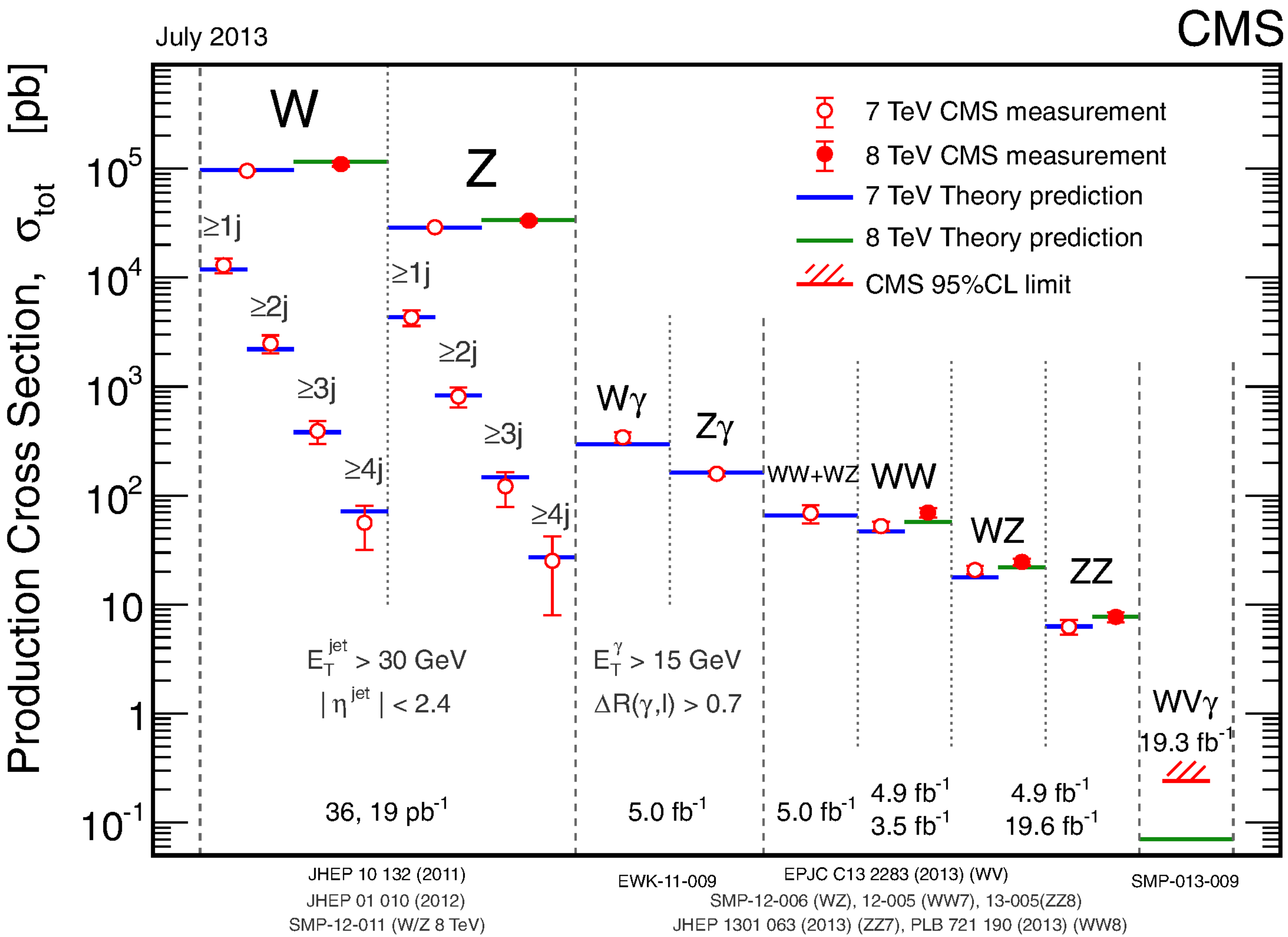
Study of W and Z production:

- test of the Standard Model predictions
- related to Higgs boson production through vector-boson fusion
- important backgrounds for searches with leptons
- access to Parton Density Functions (strange)
- vector-boson scattering

Grand summary



An even grander summary

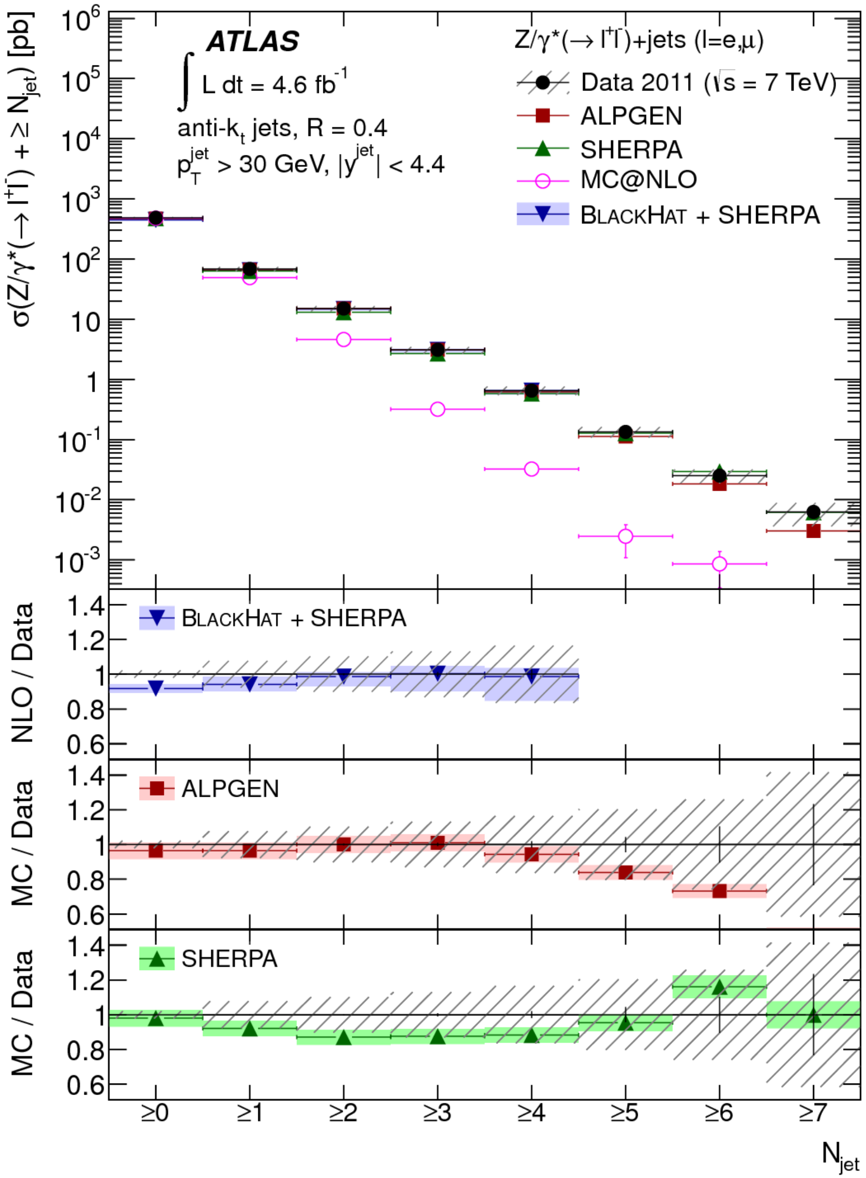


Z+jets

A very good laboratory to study the emission of additional jets

Vector boson + N jets definitely requires specialized tools (multi-leg Monte Carlo) beyond N=1,2

http://arxiv.org/abs/1304.7098

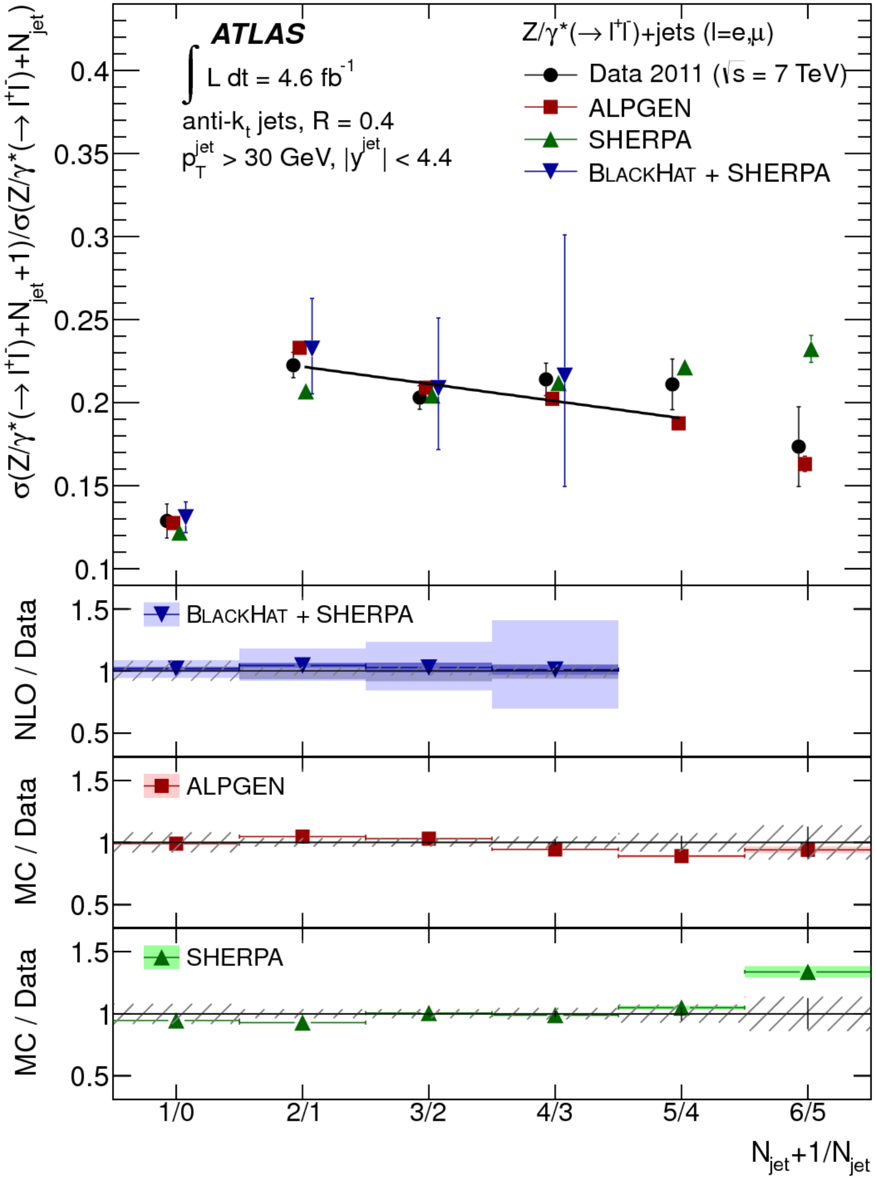


Z+jet ratios

Measuring ratios some of the uncertainties come down considerably

http://benasque.org/2012imfp/talks_contr/319_Mangano.pdf

Measurements are also available for W+b, W+c production

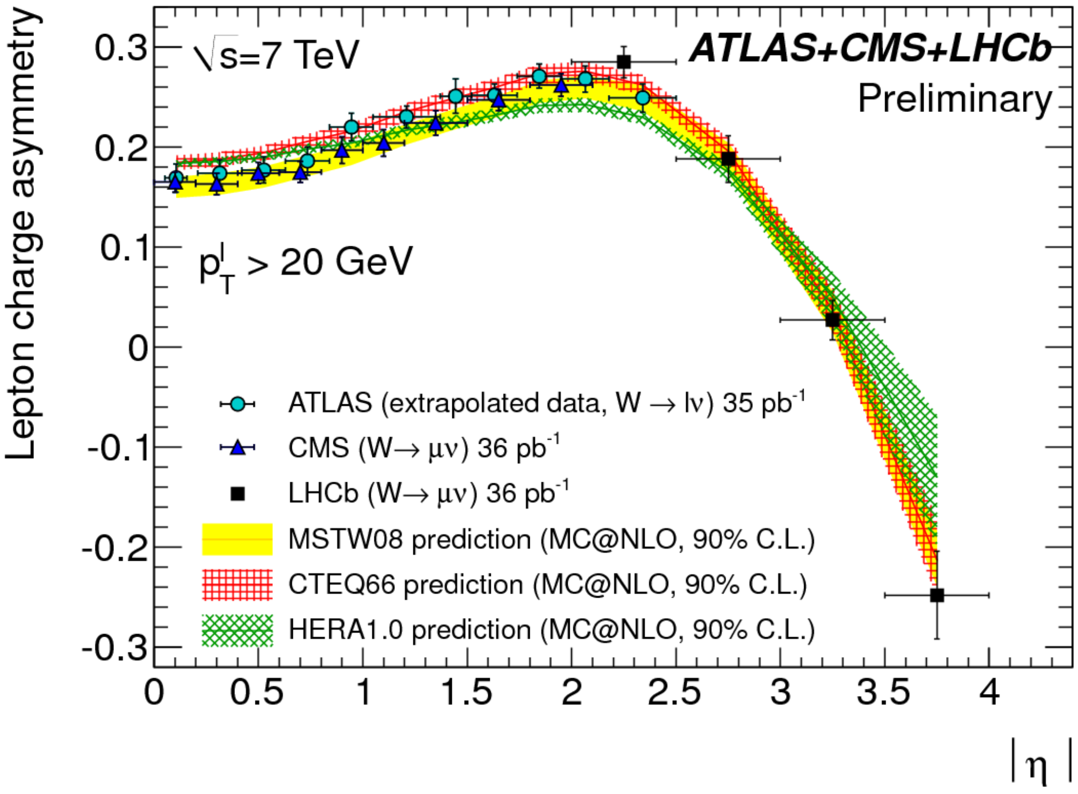


W production is asymmetric

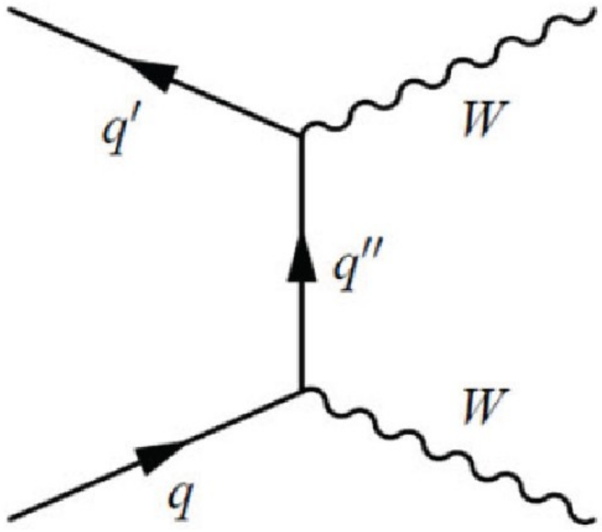
W production has a distinctive charge asymmetry

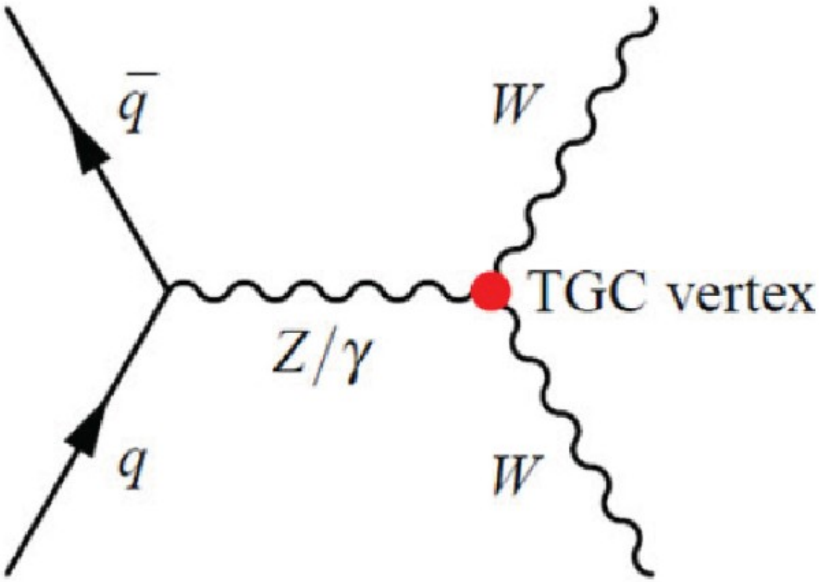
Used, for instance, to determine the background level in studies of top pair production

Proof of the sensitivity to the proton make-up



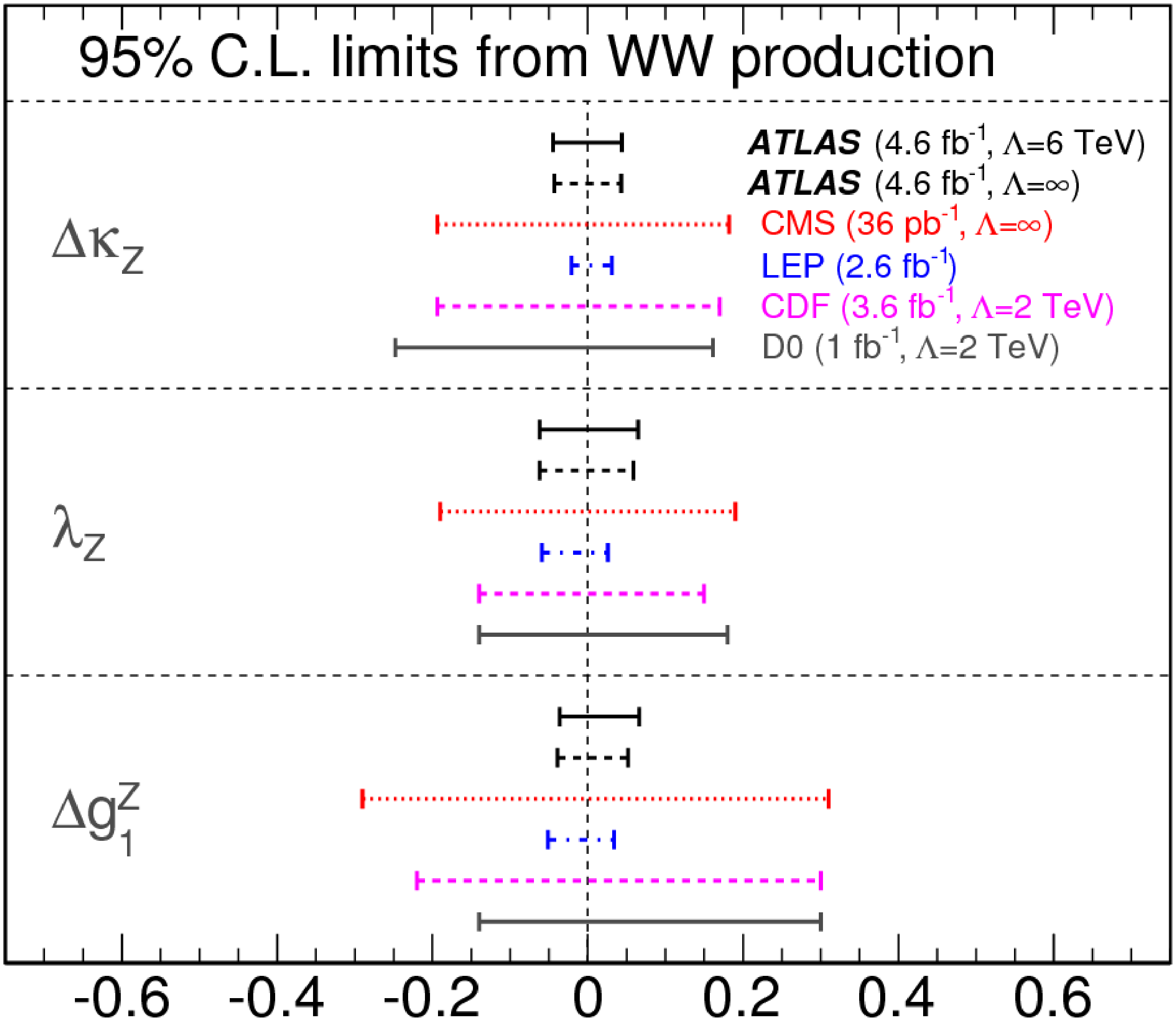
WW cross-section



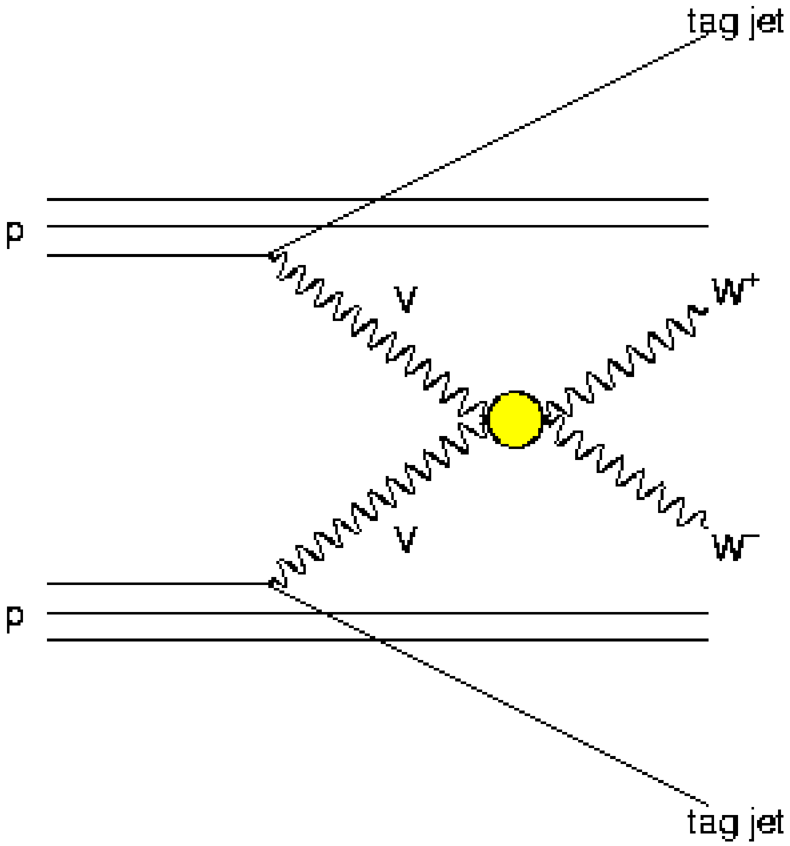


Pairs of vector bosons: SM production + possible BSM contributions

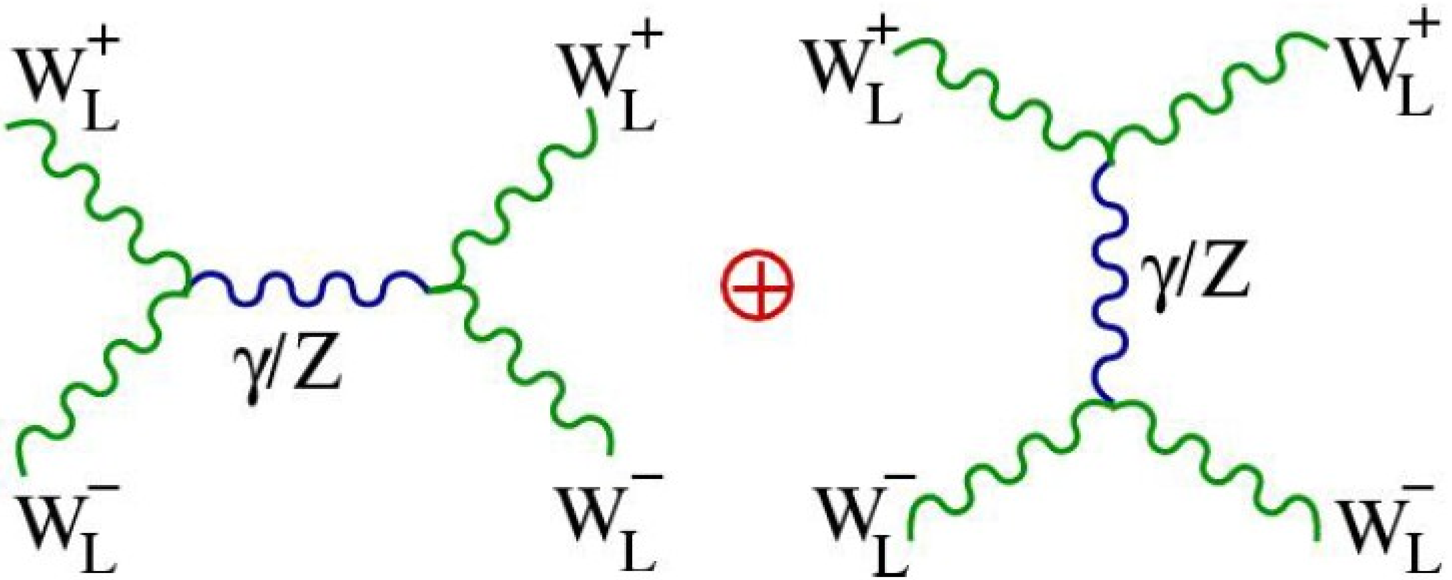
No new physics, so far!



Vector boson scattering



Vector-boson scattering



Vector boson scattering amplitude expectedt to go crazy at ~ 1 TeV if there were no Higgs boson

Study might shed some light on the exact nature of the electro-weak symmetry breaking mechanism

Requires very large integrated luminosity... a good benchmark for a hi-lumi LHC

The end

I hope you enjoyed this tour of the LHC ...