Precision measurements of top pair production from Tevatron to LHC

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- Why study top?
- Top pair production
- Top mass
- Associated top production
- Summary and prospect

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Why study top physics?

The Discovery of the top quark in 1995 was no big surprise. What was surprising is that its mass is 40 times b quark mass, close to the scale of EWSB. Many basic things to know!!!

- Why is top so heavy ? (really SM-like particle?)
- Is top involved with EWSB ?
- Is it connected to new physics ?

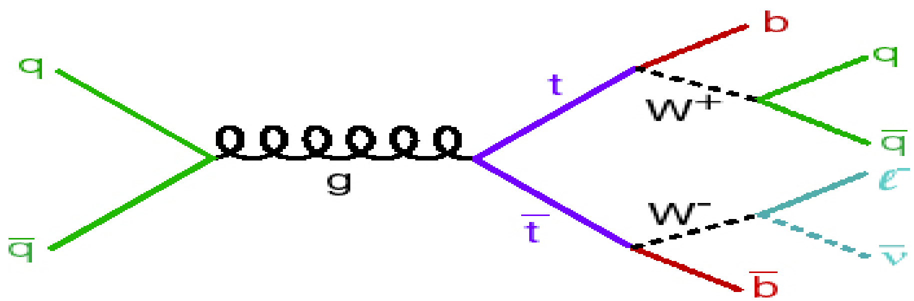
SM only says "top is just a heavy.", even with great success for last three decade.

- Many exotic models are available, just waiting for savior…
- Tevatron has taken a leading role in top until LHC turns on.
  - Tevatron RunIIa (2fb^{-1}): 30 times more top events (~2k)
  - LHC: top factory (~8M with 10fb^{-1}), now, important bckgs

Production and decay of the Top Quark

At the Tevtron, top quarks are primarily produced in pairs, dominated by qq annihilation (85%). LHC by gg (90%)

- $□_{top}$ ~ 4 x 10 $^{-25}$ s (due to large mass)
- Top decays as free quark ($□^{-1}$ ~ (200MeV) $^{-1}$ ~10 $^{-23}$ s)



3 classes of signal (multi-objects)

Dilepton: 2 high-P_T leptons, 2 bjets, large Missing E_T (5%)

Lepton + Jets: 1 high-P_T lepton, 4 jets (2 b's), large E_T (30%)

All-hadronic: 6 jets (44%)

- Top pair production rates
- Kinematic distributions
- Top decays (W helicity)
  (see C. Florentia's talk)
- Top mass
- Rare decays

Cross sections at Tevatron

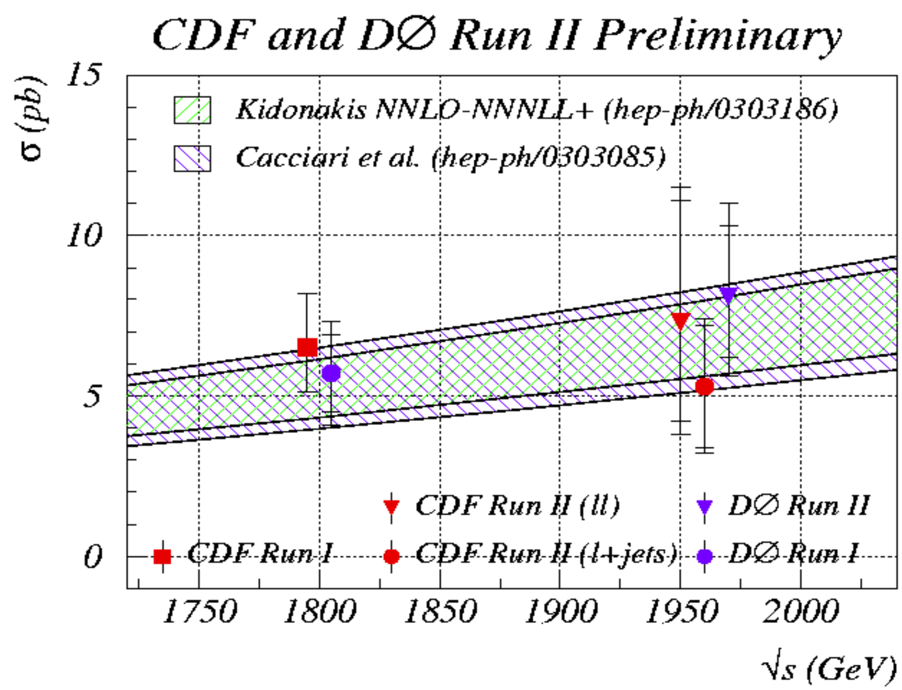
- Discrepancy from QCD is an indication of non-SM physics, SUSY, top-color objects.
  - precisise studies of Pt of top, inv. mass (ttbar)

- Tevatron: currently limited by statistics.

  □□/□ <10% at RunII(2fb-1)

- At LHC, stat. uncertainty <1%

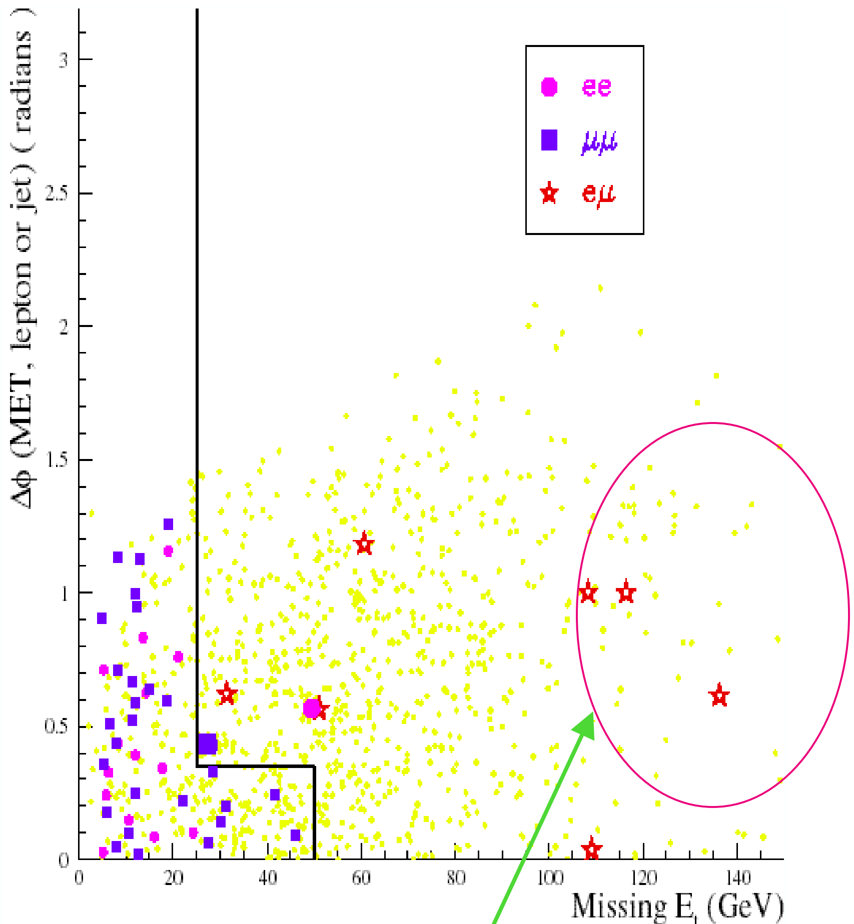
  Accurate understanding of the QCD dynamics is crucial to explore beyond SM.



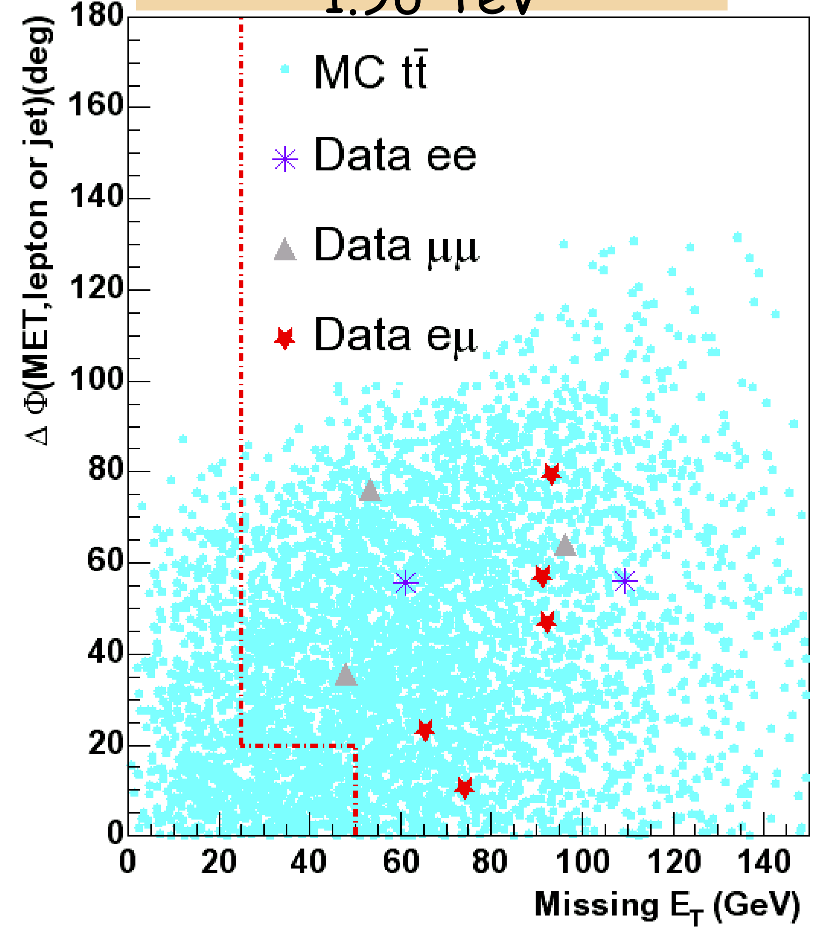
- Dilepton: 2 CDFs, 1D0
- Lepton-jet: 2 CDFs, 4 D0s

Kinematic distributions

RunI L = 109 pb^{-1}
1.8 TeV



RunII L = 126 pb^{-1}
1.96 TeV

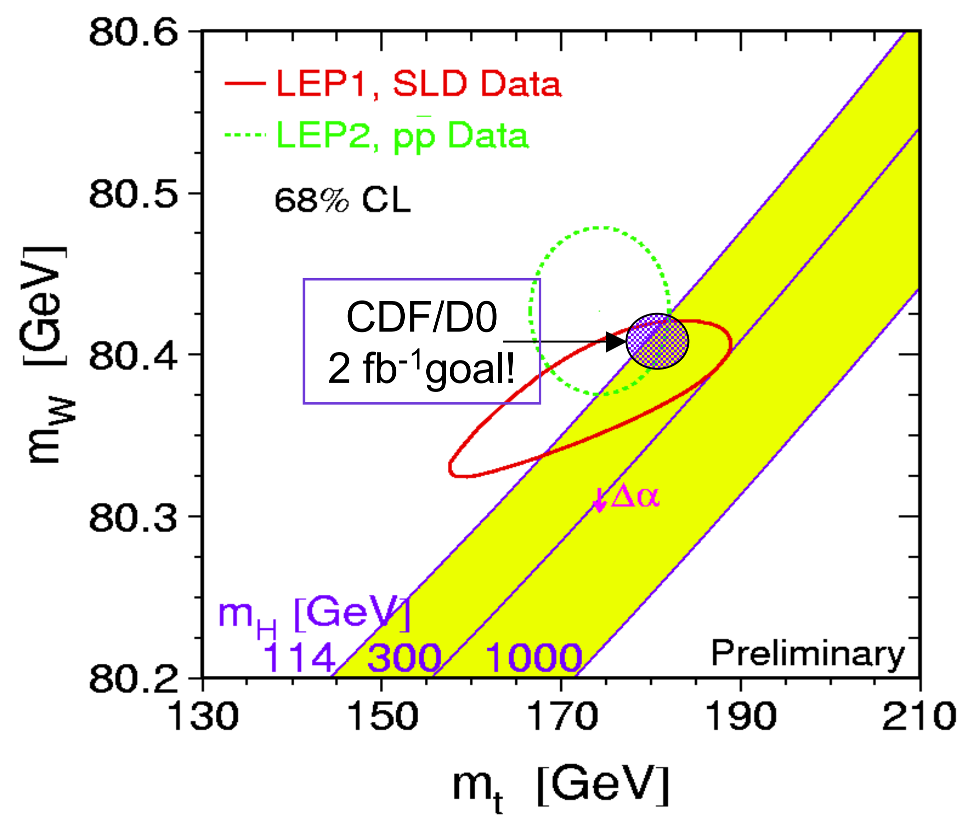


- Events with very large missing E_T in Run 1

Top Mass

- Top Mass: Fundamental SM parameter
  - needed to determine ttH coupling
  - important in radiative corrections: constrain □M_h/M_h to 35% in RunII

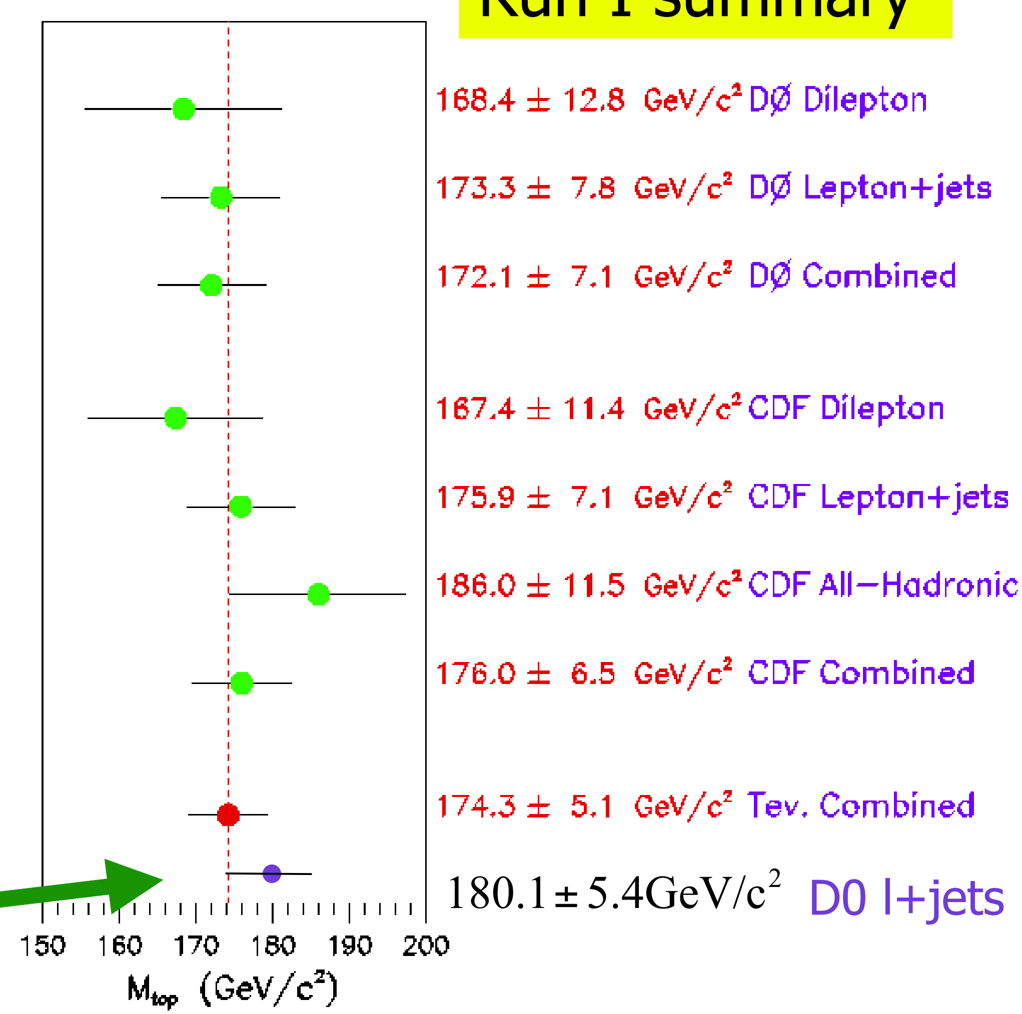
- Experimental handles:
  - B tagging: reduce background & combinatorial
  - Data driven systematics scale with 1/ N (energy scale, gluon radiation)



Top Mass Measurement

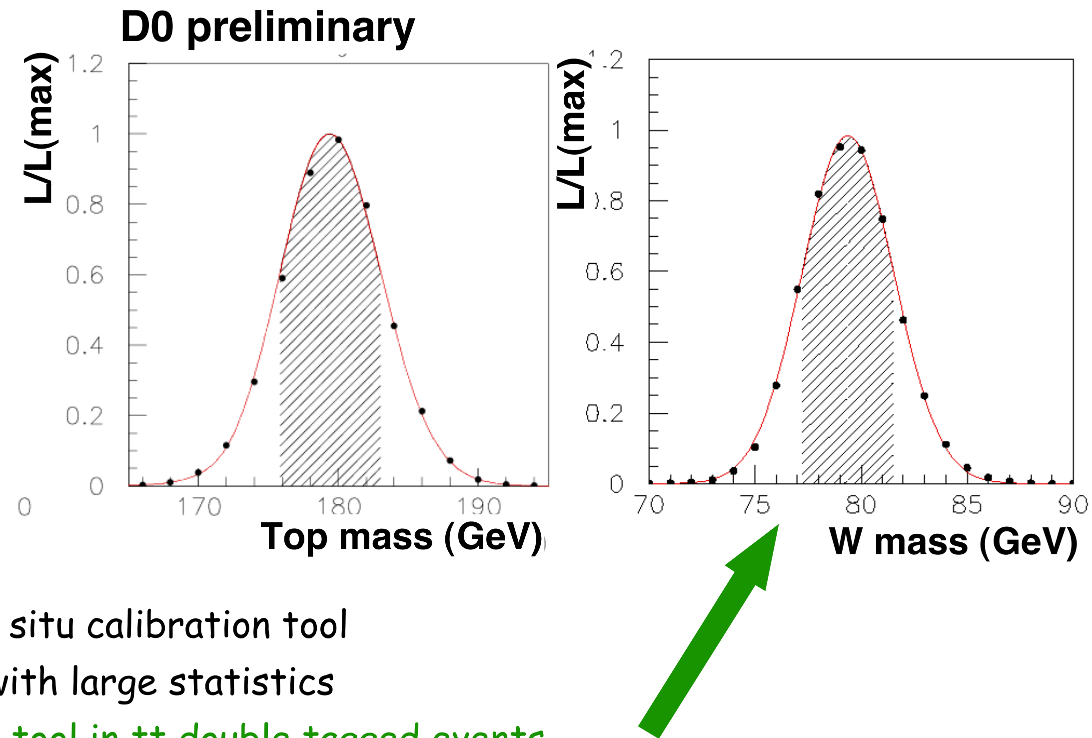
- Template method:
  - Kinematic fit under the tt hypotesis
  - Combinatorial issues
  - best χ^2 combination chosen
  - Likelihood fit
- Dynamical method:
  - Event probability of being signal or background as a function of m(t)
  - Better use of event information → increase statistical power
  - Well measured events contribute more
    - New D0 Run I result: factor 2.5 improvement on the statistical

Run I summary



Handles for a precision measurement

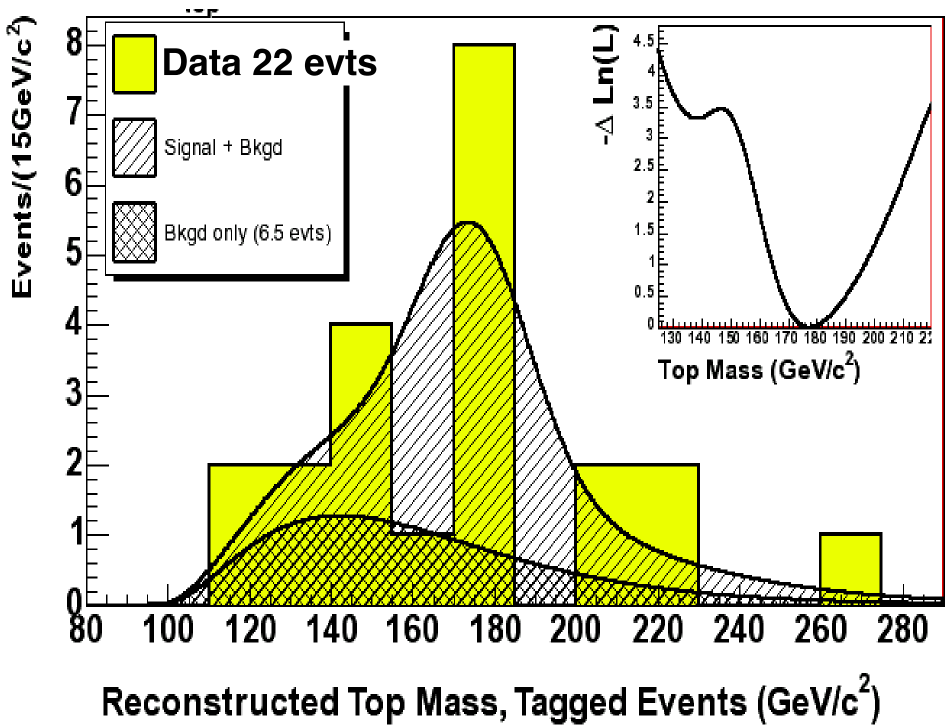
A precise measurement of the top mass combines cutting edge theoretical knowledge with state of the art detector calibration



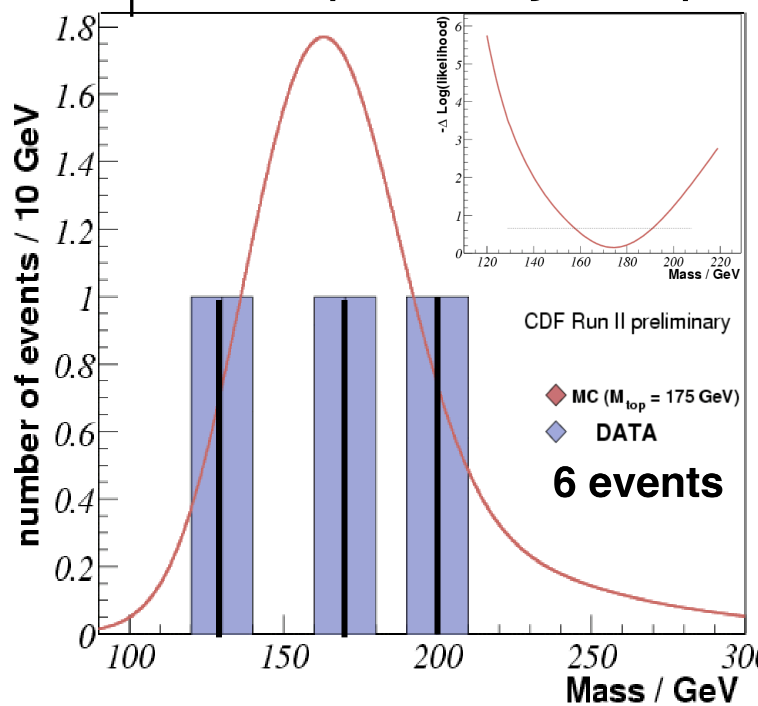
- Jet energy scale
  - gamma-jet balancing: basic in situ calibration tool
  - Z+jet balancing: interesting with large statistics
  - Hadronic W mass: calibration tool in tt double tagged events
  - Z→bb mass: calibration line for b-jets, dedicated trigger
- Theory/MC Generators: understand ISR/FSR, PDF's
- Simulation: accurate detector modeling
- Fit methodology: how to optimally use event information
- Event selection: large statistic will allow to pick best measured events

First look at top mass in Run II

CDF RunII preliminary, 108 pb^{-1}



CDF RunII preliminary, 126 pb^{-1}



Mass in lepton+jets channel with a b-tagged jet

$$177.5^{+12.7}_{-9.4}\,(\mathrm{stat}) \pm 7.1(\mathrm{syst})\ \ \mathrm{GeV/c^2}$$

Mass in dilepton channel

$$175.0^{+17.4}_{-16.9}\,(\mathrm{stat}) \pm 7.9(\mathrm{syst})\ \mathrm{GeV/c^2}$$

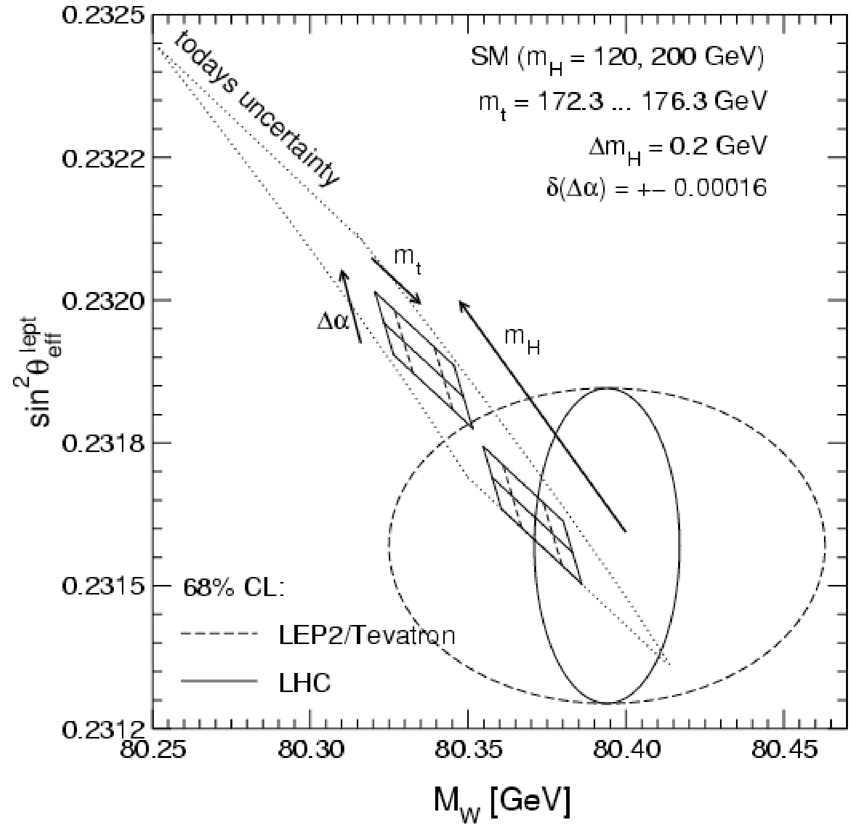
... Top mass measurement

- what is the interest in going from Δm_t = 2 GeV to Δm_t = 1 GeV (<1%)?

present theoretical uncertainty from unknown higher order corrections

$\Delta m_W / m_W$ (MeV) 63.0126.1

- the 1 GeV error in m_t induces an uncertainty about the same as today's theoretical error
- if m_H is known (Tevatron or LHC) the improved accuracy in m_t and m_W leads to a stringent consistency test of the theory

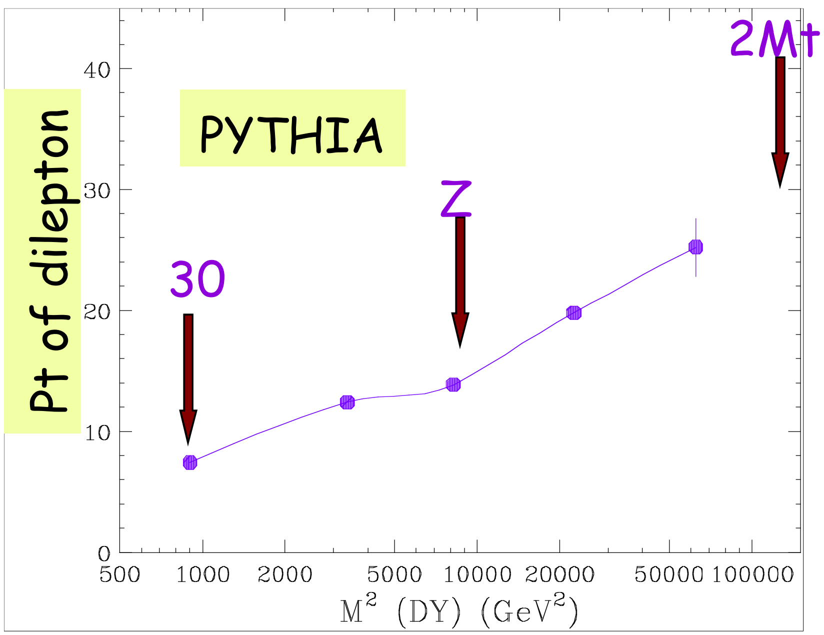


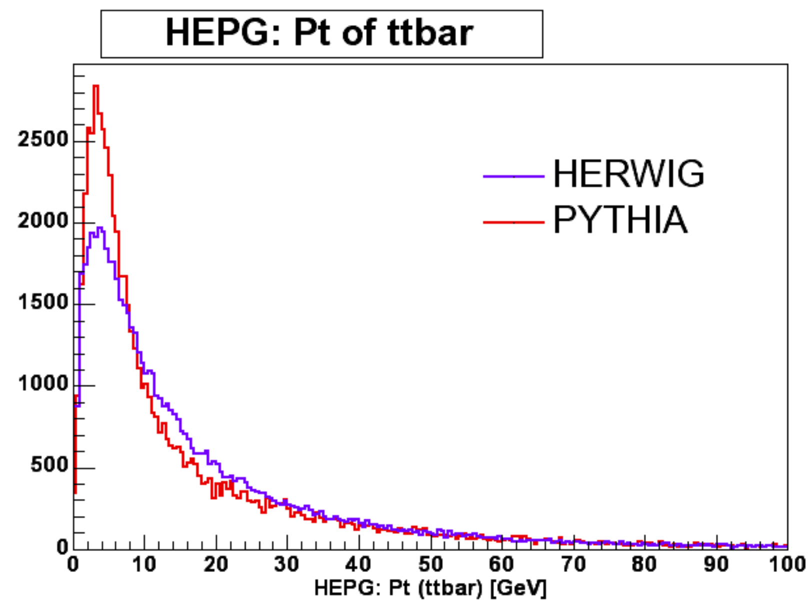
LEP2/Tevatron: $\Delta m_W = \pm 30$MeV, $\sin^2\theta_{eff}^{lept}$ = $1.7 \cdot 10^{-4}$

LHC: $\Delta m_W = \pm 15$MeV, $\sin^2\theta_{eff}^{lept}$ = $1.7 \cdot 10^{-4}$

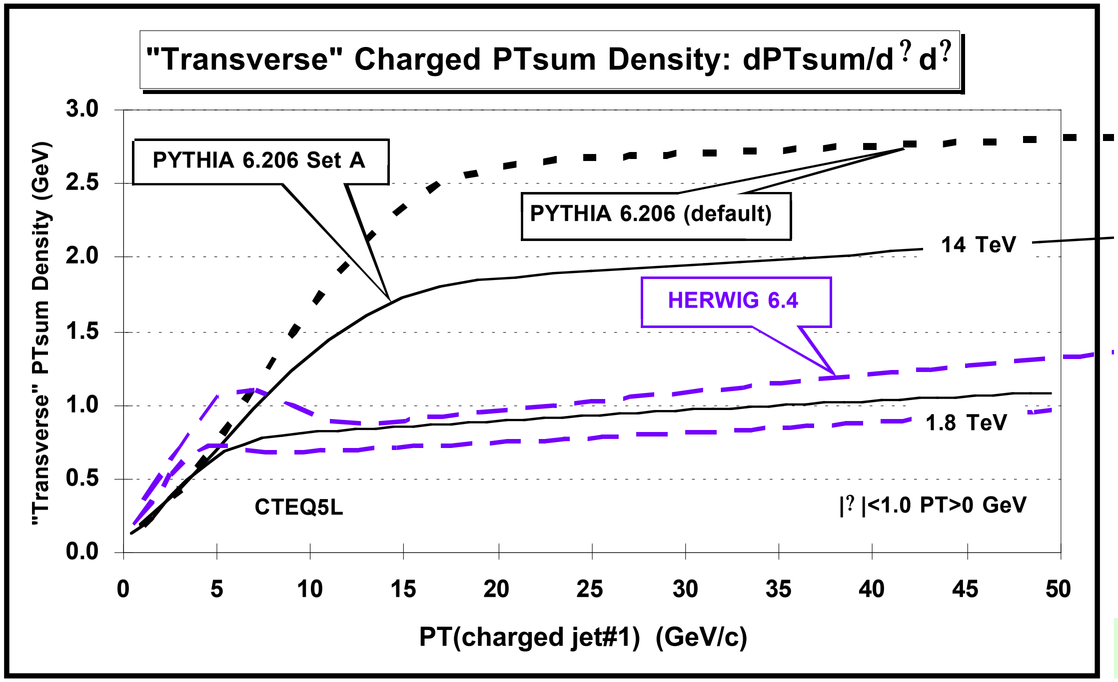
Initial state radiation effect

- ISR/FSR effects are not isolated problems.
- ISR/FSR are controlled by DGLAP evolution eq.
  (Q^2, pdf, Lambda QCD, splitting functions)
  □(Q^2)*Pq->qg(x/y) x fpdf (y, Q^2)
  - ISR: compare DY data with MC at different DY mass region (different Q^2) , Pt(DY), Njet, jet flow at high-eta etc





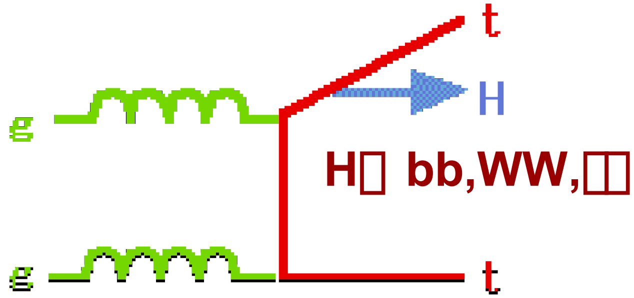
Underlying events from Tevatron to LHC



by R. Field

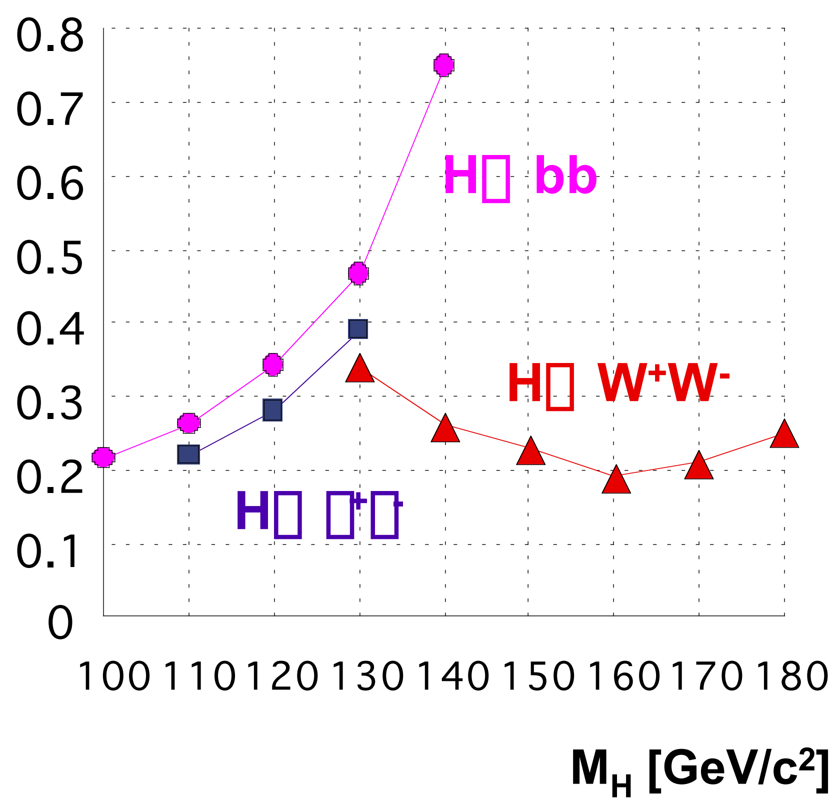
- The tuned PYTHIA with CDF data predicts 200% increase at the LHC in charged Pt density of the "underlying event".
- HERWIG 6.4, and default PYTHIA show big difference.
  - Tunning with Tevatron data at diff. energy (0.6, 1.8, and 1.96 TeV).
  - Eventually with LHC data

Associated production, ttH at LHC



- Complementary to Higgs discovery at low Higgs mass.
- Direct probe of top Yukawa coupling, 20-30% precision possible at early stage.
- ✓ Crucial to understand bckgs

$\Delta g_{ttH}/g_{ttH}$ (L = 30 fb-1)

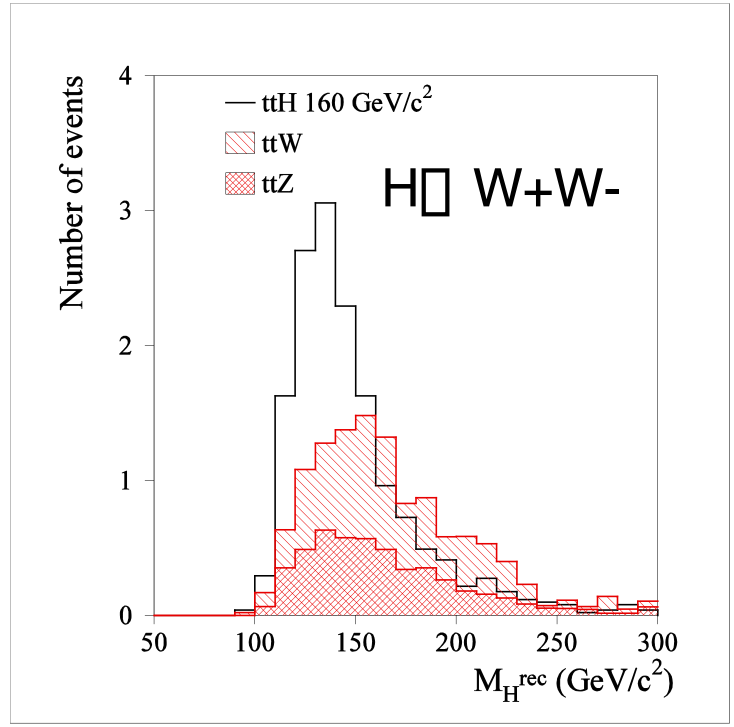


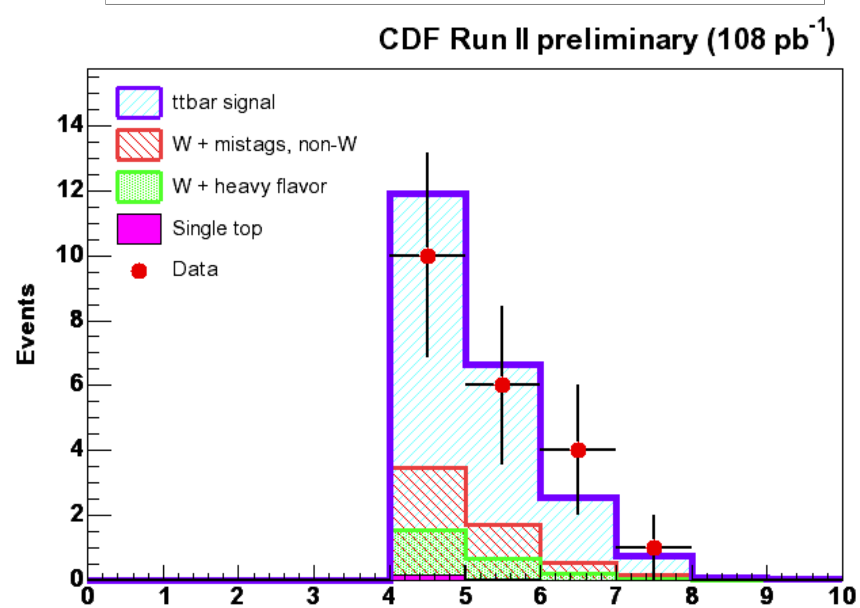
R. TANAKA et al.

Top Yukawa coupling

- Precision measurement of Yukawa coupling is crucial to obtain direct evidence of physics beyond SM.
- ✓ Understanding of heavy flavors (□,b,t) contents.
- ✓ Understanding of QCD/EW bckgs (tt+n-jets, ttW, ttZ etc.)

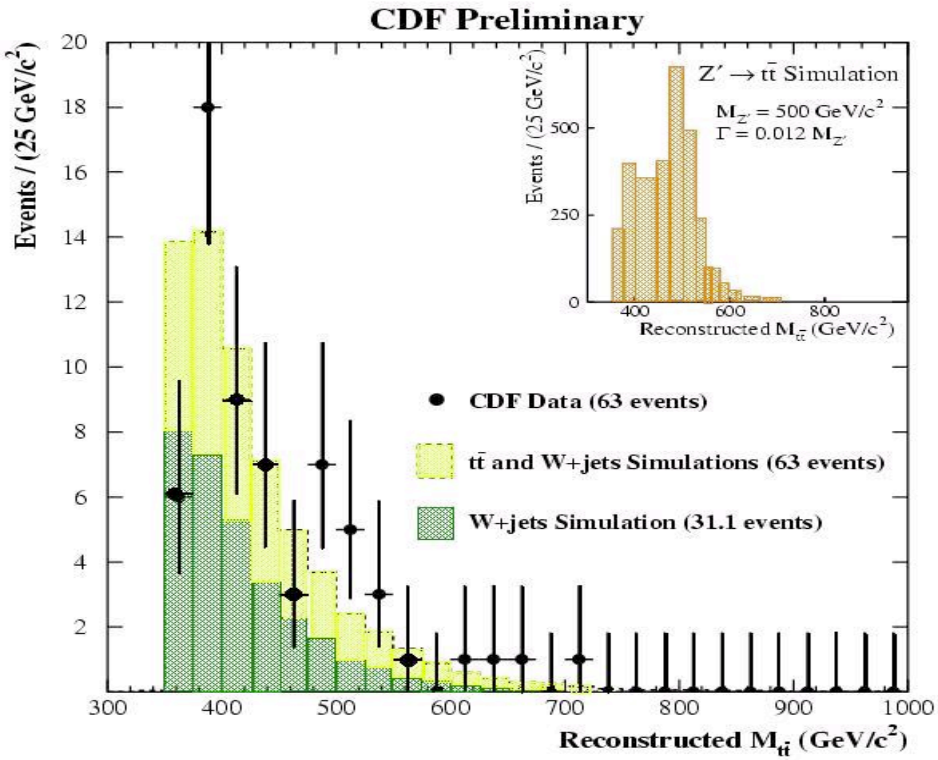
- All of knowledge on top productions from Tevatron and coherent work with theorists.

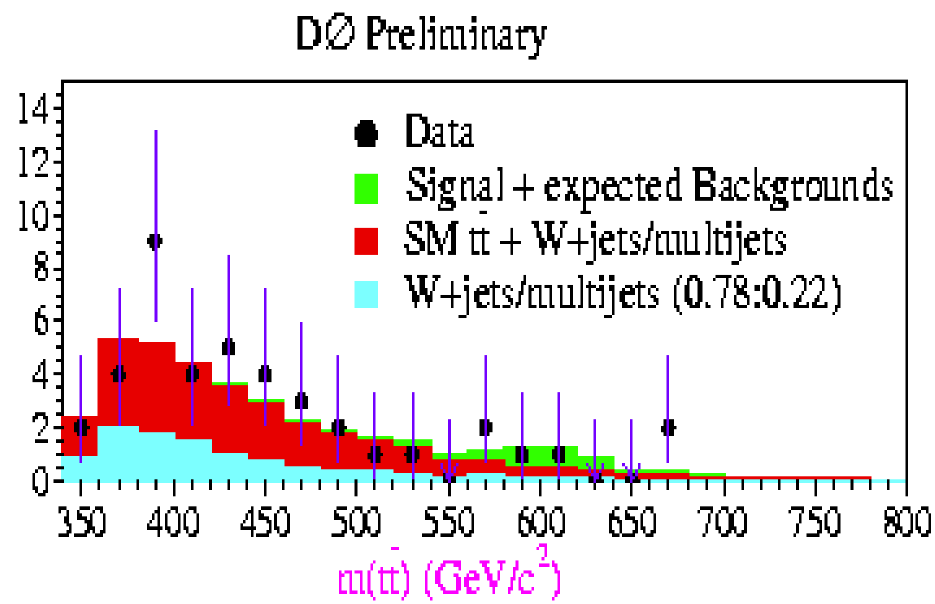




Njets in ttbar(l-jet)

Nnew physics in top pair production





Model independent search for a narrow resonance X→tt exclude a narrow, leptophobic X boson with $m_X < 560$ GeV/c^2 (CDF) and $m_X < 585$ GeV/c^2 (D0)

Conclusions

- Top quark existence established at the Tevatron in 1995
- Several top properties studied using Run I data
  - limited statistic
- The Tevatron is the top quark factory until LHC:
  - Run II ~50 times Run I statistics → precision measurements
  - Constraints on the SM Higgs boson mass and SM consistency
  - ...or surprises?
  - First Run II results cover a variety of channels and topics
  - CDF and D0 are exploiting their upgraded detector features

A very rich top physics program is underway:

let's see what the top quark can do for us!

Event rates at ATLAS

Early results: 1 year of operation at low luminosity
integrated luminosity 10 fb^{-1}

All results and plots correspond to this luminosity

Luminosity $L = 2 \times 10^{33}\ cm^{-2}\ s^{-1}$

Process	Events/s	Events for 10 fb^{-1}	Total statistics collected at previous machines by 2007
$W \to e\nu$	30	10^8	10^4 LEP / 10^7 Tevatron
$Z \to ee$	3	10^7	10^7 LEP
$t\bar{t}$	2	10^7	10^4 Tevatron
$b\bar{b}$	10^6	$10^{12} - 10^{13}$	10^9 Belle/BaBar ?
H m=130 GeV	0.04	10^5	?
$\tilde{g}\tilde{g}$ m= 1 TeV	0.002	10^4	---

Commissioning

Several steps:

- Test beams
- Mapping of detector material and magnetic field
- Alignment
- Electronic calibration
- Cosmic running
- One proton beam
- Proton proton collisions

Precision of detector understanding is given by desired precision of physics results

Equal error on Higgs mass from W- and top mass measurement:

$$\Delta m_W \approx 0.7 \times 10^{-2} \Delta m_{top}$$

Error on top mass: 2 GeV
Error on W mass: 15 MeV
this puts severe constraints on detector understanding

QCD

- QCD processes represent major background to most analyses

- Production cross-sections for most processes are controlled by QCD

Need detailed understanding of QCD before any other analyses

Parton distribution functions need to be known (from HERA and Tevatron) with great precision

Evolution in Q^2 with DGLAP equations, but uncertainties in F_2 (several %) from uncertainty in a_s

measurement of pdf at LHC via Drell-Yan (for quark distribution) and direct photon and jet production (gluon distribution)
→check agreement with previous measurements

Most important at LHC is gluon distribution
Global fits needed for final check

Higgs

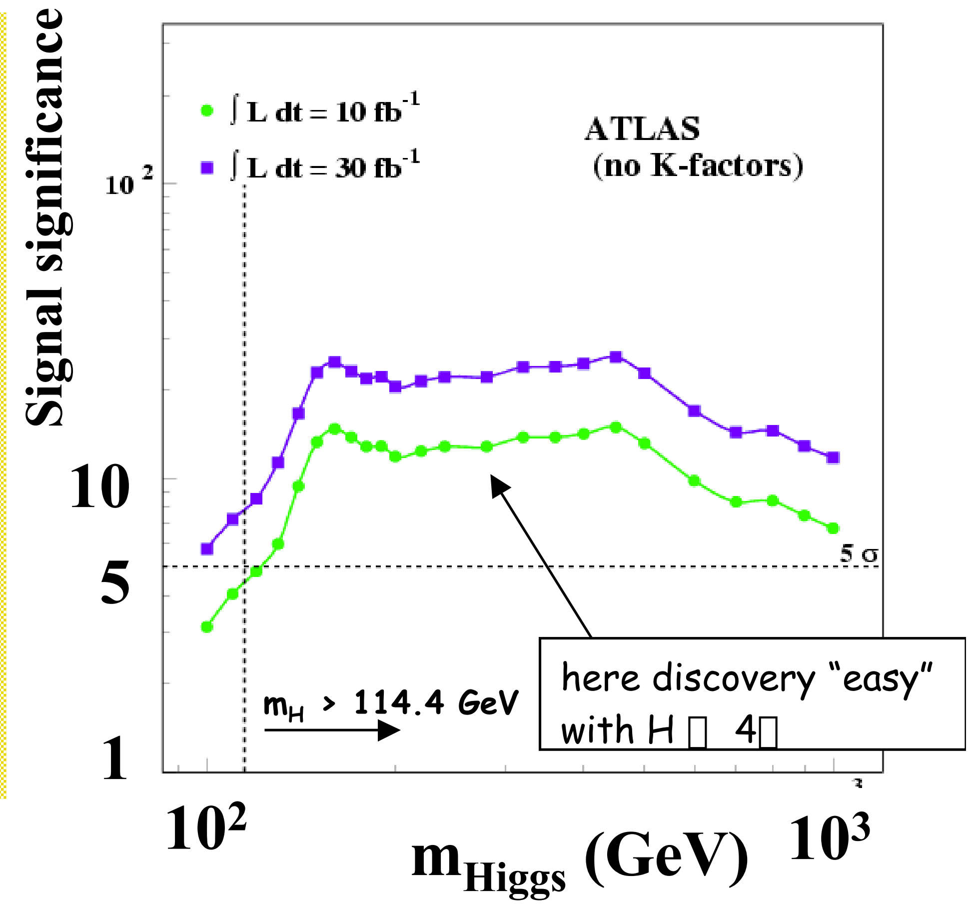
Most wanted particle in Standard model

One or several Higgs bosons may exist

Theoretical limits:
M(Higgs) < 1 TeV

Experimental limits:
M(Higgs) > 114.4 GeV

Indirect constraints:
M(Higgs) < 211 GeV



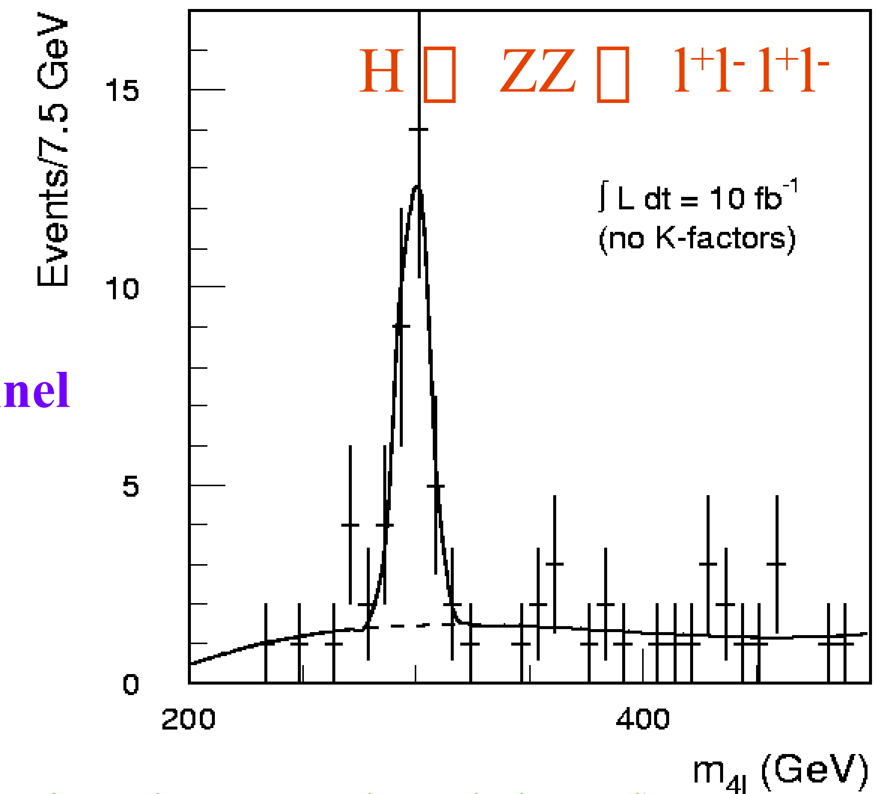
Large mass region

200 GeV < m(Higgs) < 600 GeV:

- discovery in H ZZ $l^+l^-l^+l^-$

background smaller than signal,
Higgs natural width larger than
experimental resolution (m_{Higgs} > 300 GeV)

- confirmation in H ZZ l^+l^- jj channel



m(Higgs) > 600 GeV:

4 lepton channel statistically limited

H ZZ l^+l^- nn

H ZZ l^+l^- jj , H WW ln jj (150 times larger BR than 4l channel)

Event signature: high p_T lepton, two high p_T jets

Combination of analyses allows Higgs discovery in full mass range

Low mass Higgs

M(Higgs) ~ 115 GeV, favored from LEP

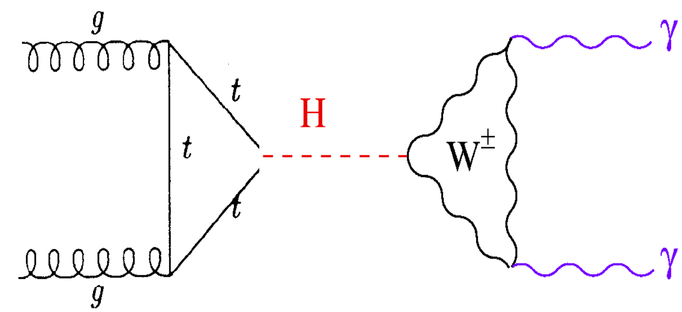
Several channels give ~ 2 s significance
□ observation of all channels important to extract convincing signal in first year

H □ □□ relies only on electromagnetic calorimeter, constant term < 0.7 % needed for observation

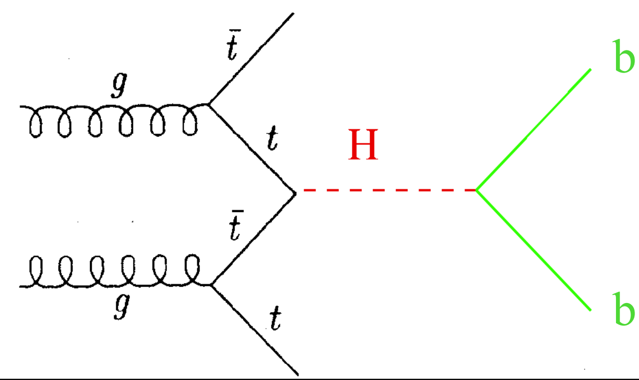
	H □ □□	ttH □ ttbb	qqH □ qq□□ (□□ + □-had)
S	130	15	~ 10
B	4300	45	~ 10
S/ B	2.0	2.2	~ 2.7

K □ factor ≡ $\frac{ó_{NLO}}{ó_{LO}}$ □ 2 not included

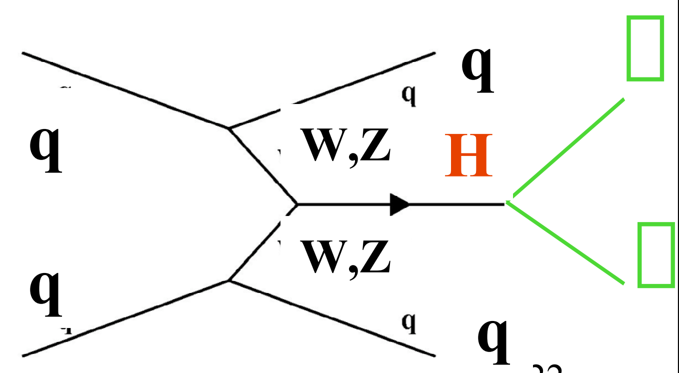
H □ □□



ttH □ tt bb □ b□□ bjj bb



qqH □ qq□□

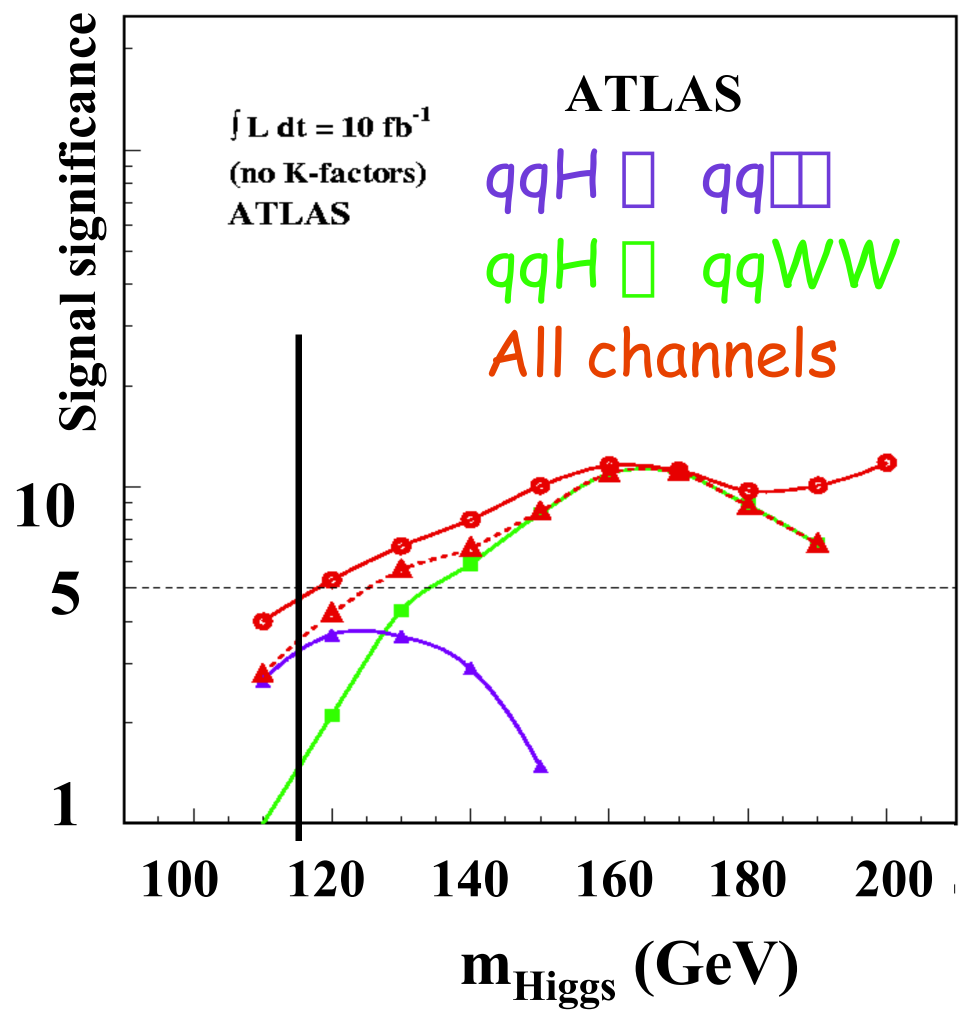


Vector Boson Fusion

Recent studies demonstrate that vector boson fusion channels may be accessible in the low mass region already in the first year.

Several studies to improve performance

For m(Higgs) = 115 GeV combined significance ~ 5s



Results are conservative:

- K-factor not included
- very simple analyses used

Low mass remarks

The 3 channels are complementary □ robustness:

- different production and decay modes
- different backgrounds
- different detector/performance

requirements:

-- ECAL crucial for H □ □□
(in particular response uniformity) :
□/m ~ 1% needed

-- b-tagging crucial for ttH :
4 b-tagged jets needed to reduce combinatorics

-- efficient jet reconstruction over |□| < 5
crucial for qqH □ qq□□:
forward jet tag and central jet veto needed against background

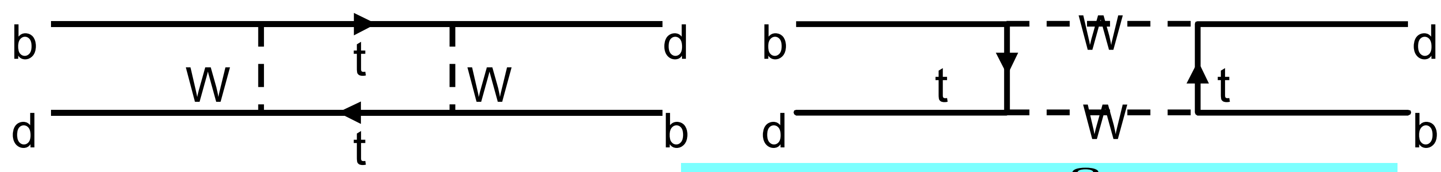
Note :
all require "low" trigger thresholds.
e.g. ttH analysis cuts :
p_T (□) > 20 GeV,
p_T (jets) > 15-30 GeV

Interest in dilepton channel

- In Run I we expected: 6.0 ± 0.5 events,
  observed 9 events
  - Run I cross-section: $\sigma_{t\bar{t}} = 8.2^{+4.4}_{-3.4}$ pb
  - Anomalous events with very large missing energy or very high lepton momenta
- Many new physics processes which may generate a dilepton-like signal:
  - SUSY models
  - leptoquarks
  - $t\bar{t}$ resonances
  - Higgs production (ZH)

Top Quark Mass

- Fundamental parameter of Standard Model (SM)
- Affects predictions of SM via radiative corrections
  - BB mixing



$\Delta M_W \propto m_t^2, \ln(M_H)$

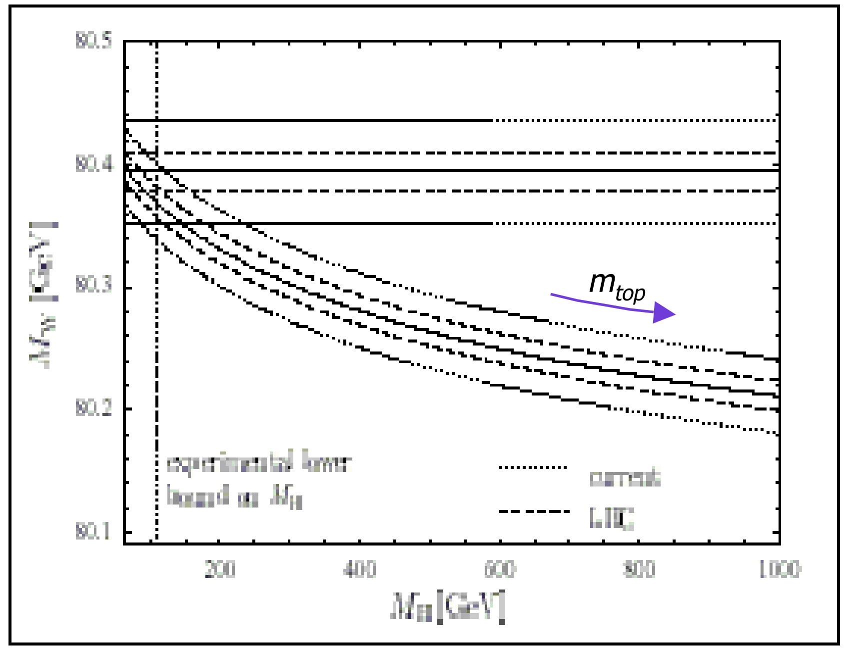
  - W and Z mass
  - measurements of M_W, m_t constrain M_H
- Large mass of top quark
  - Yukawa coupling 1
  - may provide clues about electroweak symmetry breaking

Why study top physics at LHC

- the top quark exists and will be copiously produced at LHC
- it's properties can be studied with good accuracy due to large statistics available
- several questions to answer:
  - why m_t so different from other quarks?
    - is it really a SM-like particle?
  - study it's production, couplings and decays

  any deviation from SM values will be a sign of new physics
- in the SM, the m_t, m_W and m_H are coupled:

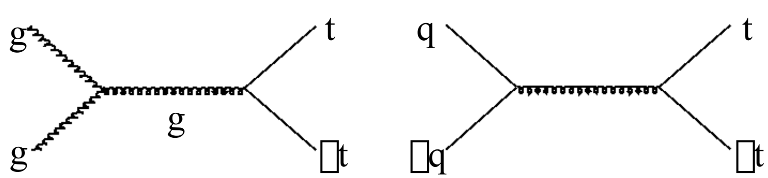
  $\Delta m_W \approx 0.7 \times 10^{-2} \Delta m_t$ to get similar errors
- top quark events are a major source of background for many physics searches
- important sample for absolute jet energy calibration



- Δm_W=±0.042GeV(current), ±0.015GeV(LHC)

Top production & tagging at LHC

- *t*-pair production mainly through *gg*-fusion



~90% 10%

- The LHC machine is a real **top factory!!!**
- NLO: σ(t̄t) ~830 pb

low luminosity 10 fb^{-1} (≈ 1 year at 10^{33} cm^{-2} s^{-1})

–~ 8 million t̄t pairs

in addition:

–~ 3 million single top events

1 top event per second at LHC startup!

- no problem with statistics
- background can be kept small in most of the cases

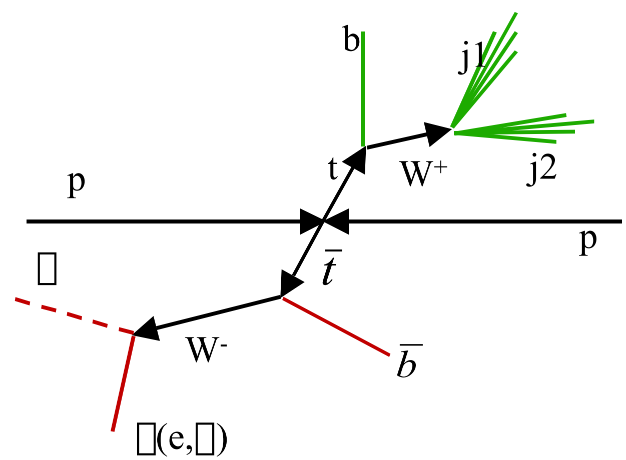
...Top production & tagging at LHC

top events can be easily reconstructed in single/double lepton channels with good statistics and small background contamination

single lepton + jets channel

- ~29.6% Br, ~2.5M events/year
- isolated lepton for trigger (p_T>20 GeV)
- selection cuts:
  - –lepton: p_T> 20 GeV, $|\eta|$< 2.5
  - –E_T^{miss} > 20 GeV
  - –jets: ≥ 4, p_T> 20 GeV, $|\eta|$< 5, ΔR=0.7
  - –b-tag jets: ≥ 1

⇒ 33.3% efficiency, ~ 820 000 events/year, S/B(mainly W+jets) ~ 18.6

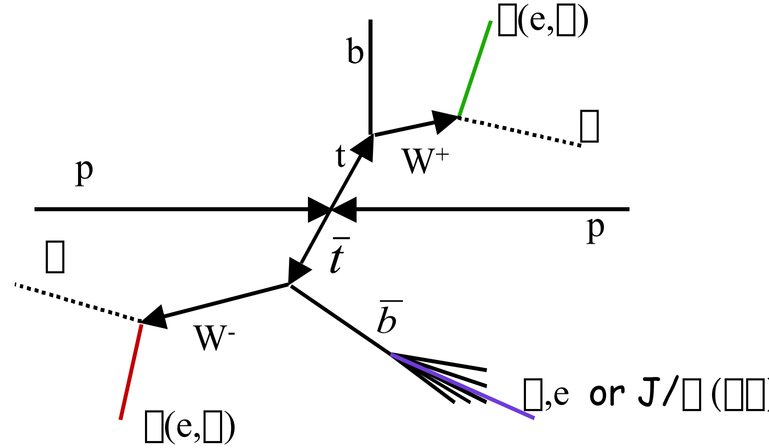


- sub-samples can also be exploited for specific studies
  - –e.g. high p_T sample for top mass measurement (see later...)

...Top production & tagging at LHC

di-lepton channel

- ~4.9% Br, ~400 000 events/year
- selection cuts:
  - –two opposite sign leptons:
    - •p_T> 35(20) GeV, |□|< 2.5
  - –E_T^{miss} > 40 GeV
  - –jets: ≥ 2, p_T> 25 GeV, |□|< 5, □R=0.7
  - –like-flavour case (e^+e^-, $□^+□^-$)
    - •|$m_{□□}$ - M_Z| > 10 GeV
  - □ ~ 80 000 □events/year, S/B~10
  - –b-tag jets: ≥ 1
  - □ ~ 58 000 □events/year, S/B~50



- again sub-samples can also be exploited for specific studies
  - –e.g. J/□ sample for top mass measurement (see later...)

...Top production & tagging at LHC

multi-jet channel

- ~44.4% Br, ~3.7M events/year
- but huge background
  - –QCD multi-jet
  - –not easy to have an efficient trigger
    - •multi-jet + total E_T threshold
- selection cuts:
  - –jets: ≥ 6, p_T> 15 GeV, |□|< 3, □R=0.7
  - –b-tag jets: ≥ 2, |□|< 2.5
  - –sum P_T^{jets} >200 GeV
  - □ 19.3% signal efficiency, only 0.29% of QCD multi-jets remaining
- S/B ~ 1/57 assuming:
  - □(QCD multi-jet) = 1.4□10^{-3} mb for P_T^{hp} >100 GeV

- further improvement possible using event topology and kinematic cuts
  - –W reconstruction
  - –both *t* & □reconstruction
  - □ S/B improved to ~ 1/8 in m_t [130, 200] GeV
  - –harder jet cuts: p_T> 25 GeV
  - □ S/B improves to ~ 1/6 in m_t [130, 200] GeV

□ it might be possible to extract the signal from the background,

but

□ it will suffer from the uncertainties

...□ event reconstruction - □H associated production

- combine the two remaining b-jets to reconstruct the H□ □ decay

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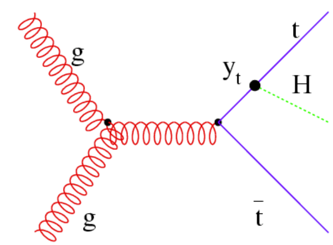
m_H=100 GeV

100 fb^{-1}

top Yukawa coupling y_t



- for 30 fb^{-1}
  - N_{signal} = 61 events
  - $N_{bcckground}$ = 150 events
  - □ □y_t(stat) = 12%
- for 100 fb^{-1}
  - □ □y_t(stat) = 5% for m_H = 100 GeV
  - □ □y_t(stat) = 10% for m_H = 120 GeV
- systematics can be controlled by comparing to the standard □production

Summary

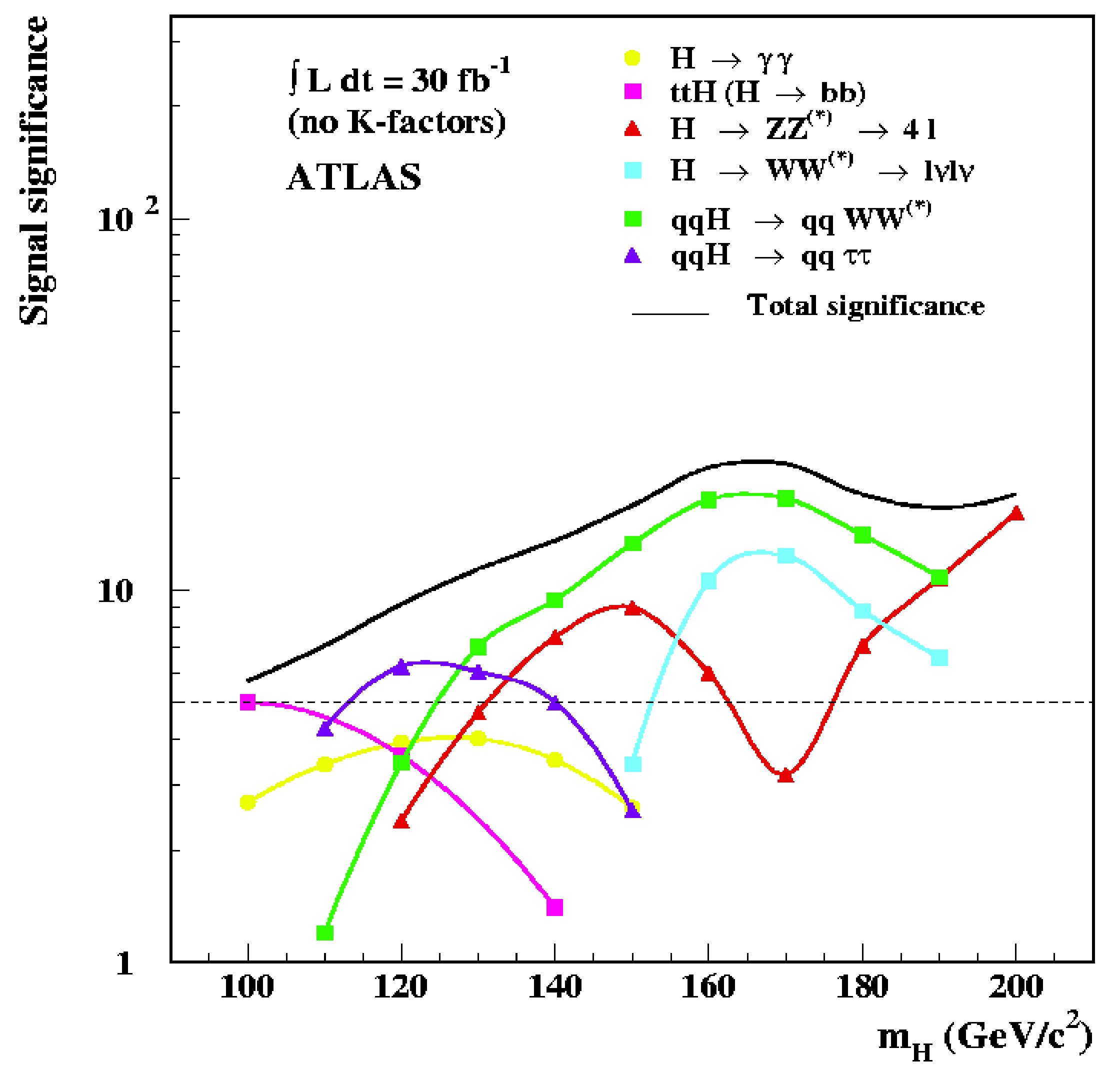
- An overview of the top studies performed by both experiments ATLAS and CMS has been presented here
- A broad spectrum of top physics has been studied so far in the context of the TDR (ATLAS) and of the LHCC SM Workshop (ATLAS+CMS)
- The importance of top physics at LHC is very much acknowledged
  - top is a critical tool in both to understand the SM physics but also as an important background for many new physics searches beyond that
  - in addition, it is an important tool to understand and tune the detector performance and in particular the jet E-scale calibration
- Before LHC turns on, results from the Tevatron Run-II will be available which will be an important guide
- we are looking very forward for the LHC startup at] 2005

new exciting physics might be just about to show up ...

Summary

- Run 2a is well underway and most of anlysis tools are in Place for precision measurements and search.
- With larger samples, we will be able to explore top properties and new phenomena, and we hope to answer heart-beating questions from lack of SM.

All channel plot



Pt of top and ttbar