CMS

Issues in Standard Model Physics and Higgs Searches as seen by an experimentalist

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KTIP, Collider Physics Workshop
Santa Barbara, CA
Jan 12, 2004

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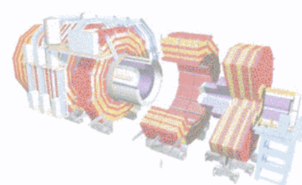

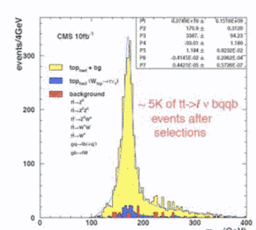

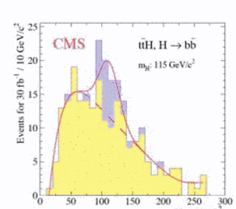

- **Note** : Tomorrow Ian Hinchliffe (ATLAS) will talk about SUSY and other searches….

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Introduction

- The richness of the LHC/CMS physics program is outstanding
- I cannot cover all, will show a few examples
- Main aim : to point out where I see a further need for combined efforts by **theoretical AND experimental** particle physicists

CMS Construction Status

The CMS Detector

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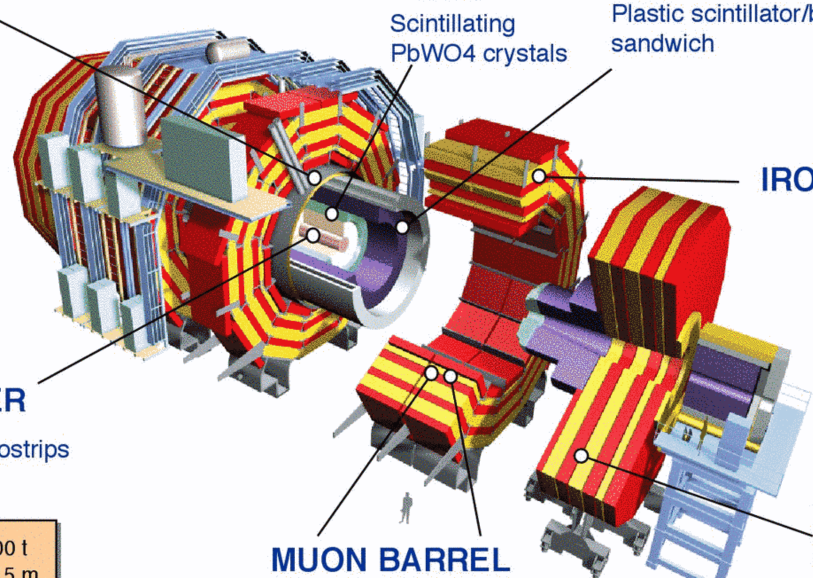

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

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Trial Test of Coil Insertion

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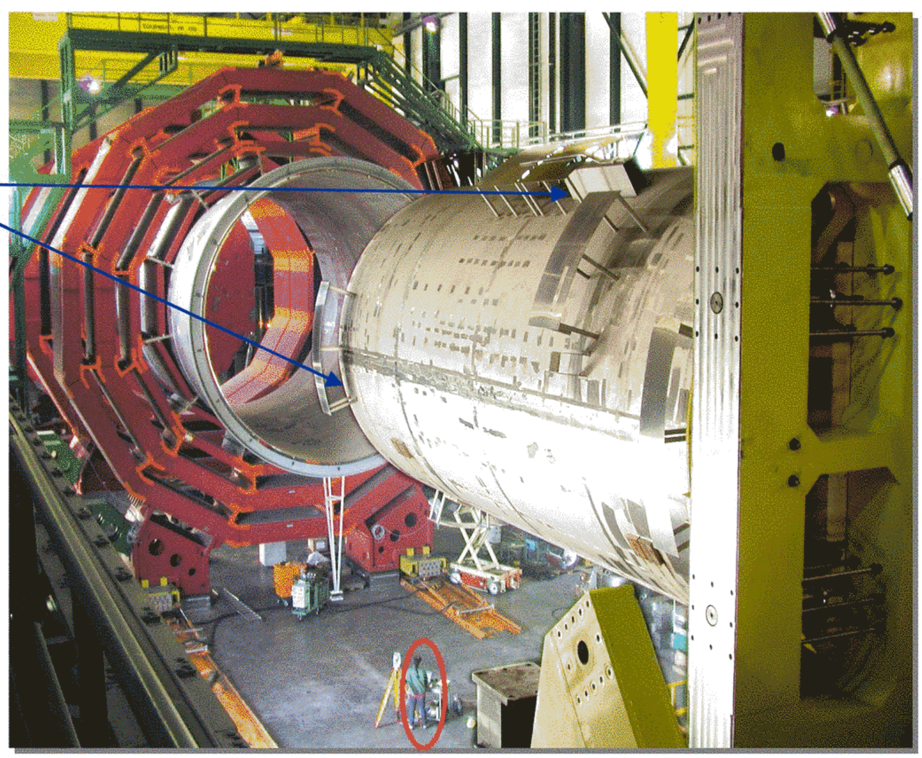
Simulation of coil radial extent



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COMPACT Muon Solenoid
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ATLAS
CMS
Bld. 40
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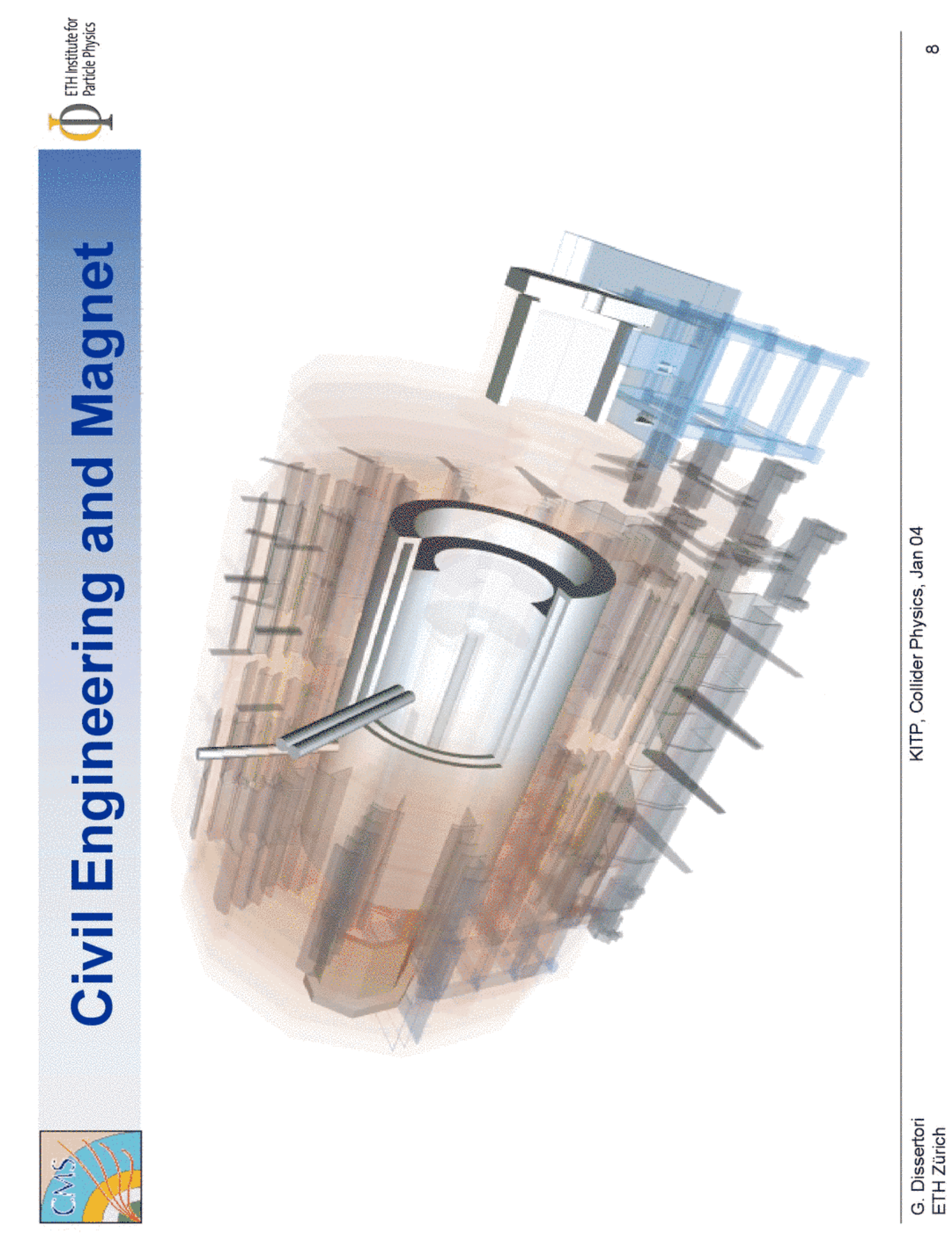
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Experimental area : Point 5

Experimental Caverns

Service Cavern
to be delivered to CMS in March 04

Experiment Cavern
to be delivered to CMS in July 04

Magnet Coil : ~ 50% done

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- Expect the 5 coil modules at CERN by 1.6.04
- Start cooling on 1.3.05
- Complete magnet test on 15.8.05

The CMS Conductor

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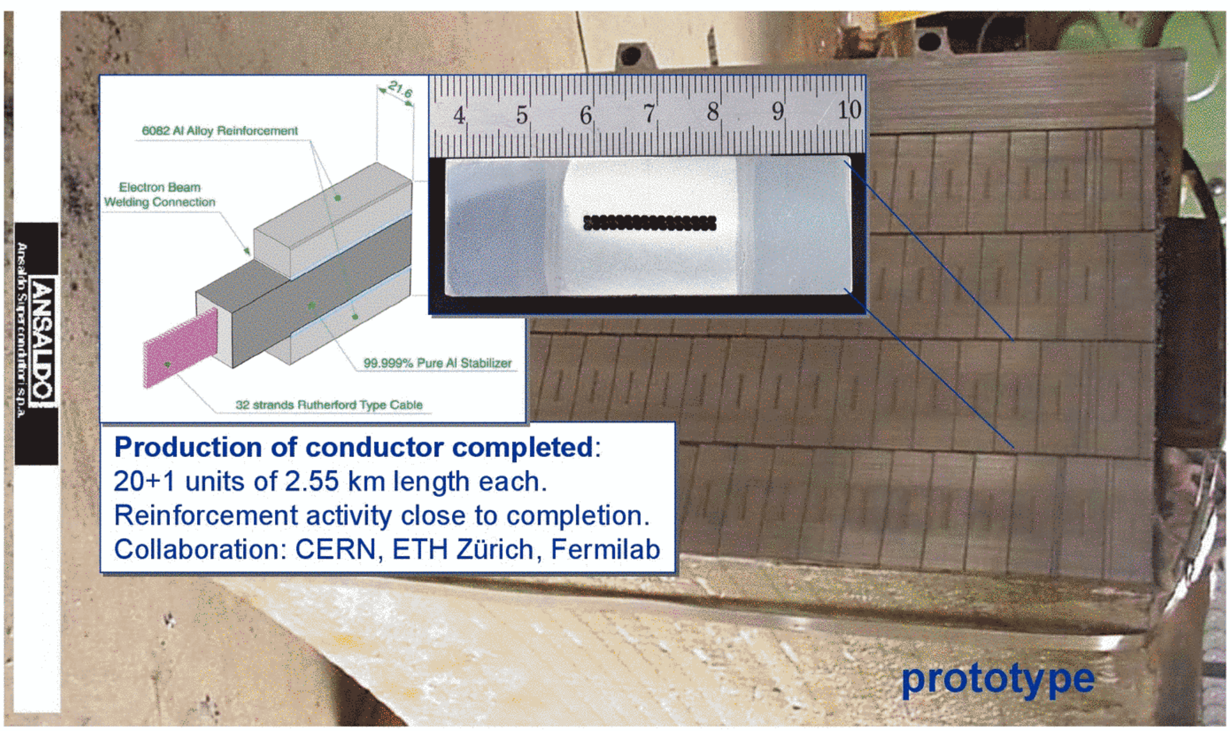

Production of conductor completed:
20+1 units of 2.55 km length each.
Reinforcement activity close to completion.
Collaboration: CERN, ETH Zürich, Fermilab

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Magnet Yoke

Metallic structures have been completed

Subdetectors

Tracker

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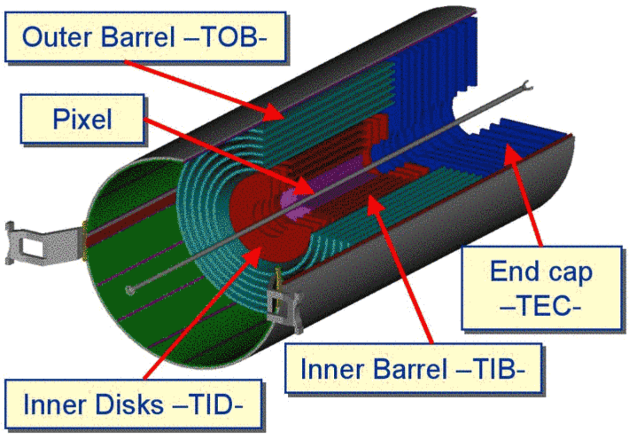

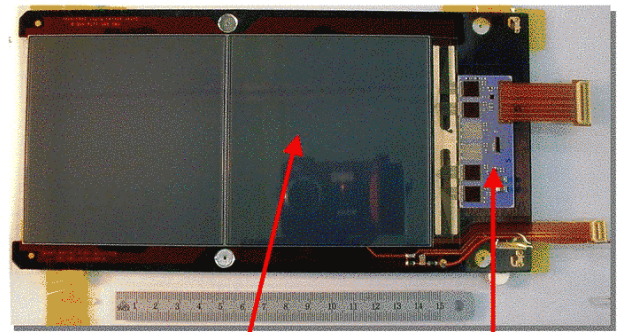

210 m² of silicon sensors **9,648,128 electronics channels**

- All-Silicon Tracking
- Good progress on mechanics, electronics and associated system tests
- difficulties in startup of module production due to hybrids, now started
- Hamamatsu sensors OK, problems with quality of ST sensors

Electromagnetic Calorimeter

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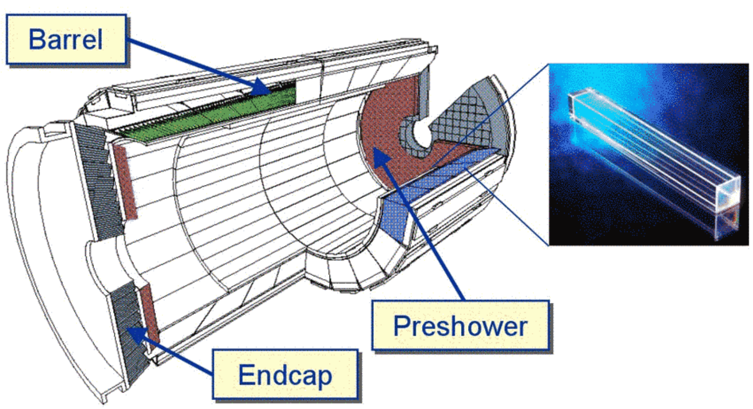
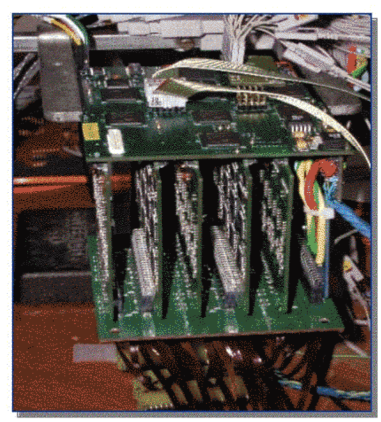


~ 76000 Lead-Tungstate Crystals



Trigger Tower, 5x5 ch.

- Excellent results from tests of new 0.25 μm electronics
- Electronics mass production and integration starting
- ~22000 crystals delivered (35%), Supermodule production ongoing
- > 50% of photodetectors (APDs) ready

Hadronic Calorimeter

Half Barrel

Endcap HE-1

Plastic scintillator tiles between brass absorber

- Both half barrels (HB) and end-caps (HE) completed
- On-board electronics installation in Q2-04, then start comissioning
- **HF (very forward)** : All 36 wedges complete in Jan 04 (instead of Apr 04 target); mount them on final support structure in 2004.

Muon System

- Four stations
- Three types of chambers:
  - Drift tubes (barrel)
  - Cathode strip chambes (endcap)
  - Resistive plate chambers (barrel+endcap)
- Chamber production well on track
  - CSC : ~ 90% complete
  - DTs : ~ 40% assembled
  - RPCs : ~ 23% assembled for barrel
- Installation started

YE-2, 45 CSCs mounted

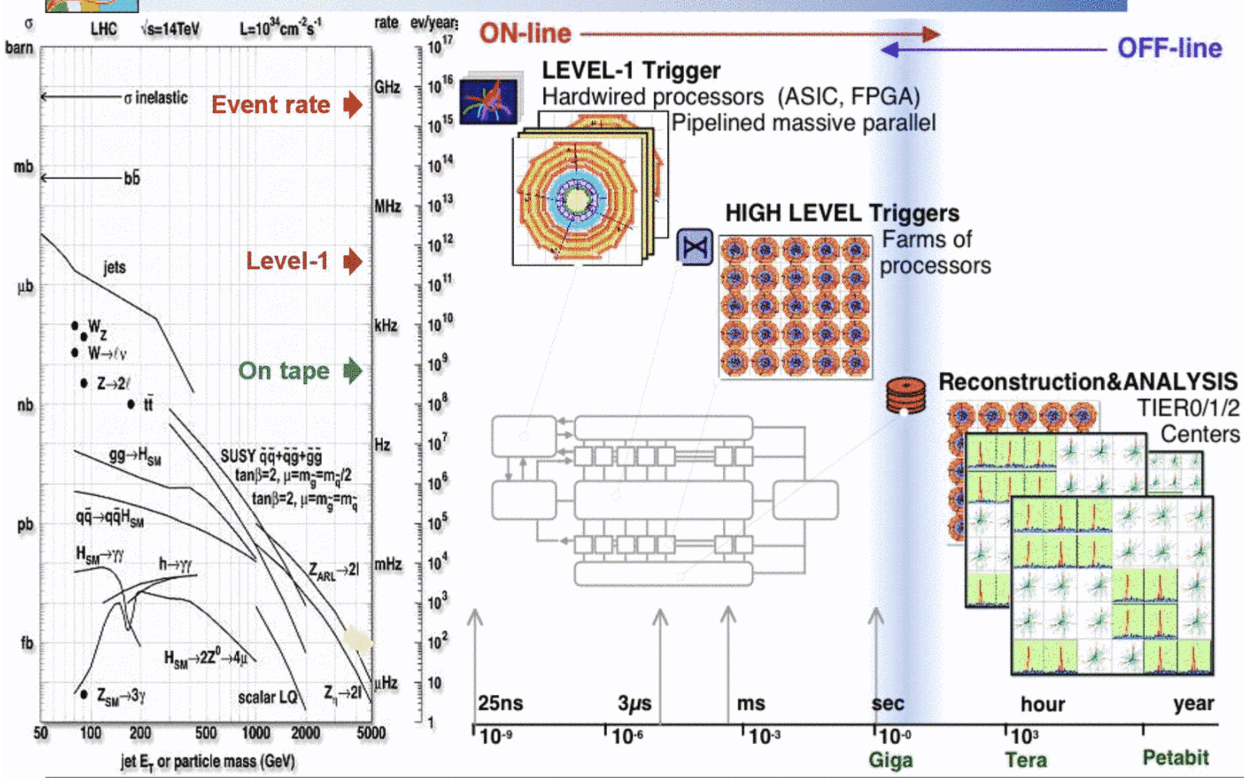
CMS Schedule

Objective: Complete Initial CMS for April 2007

Pixel detector ready but not installed for machine commissioning run ('pilot run')

US and UX area delivered to CMS	Mar 04, Jul 04
Magnet test on surface	Mid 2005
ECAL barrel (EB) installation (partial)	Q3 2005
Lowering CMS	2nd Half 2005
Tracker installation + cabling	by mid-2006
ECAL: EB- installation + EB cabling	Q3 2006
EE installation	Q1 2007
Det/Trig/DAQ Integration and Commissioning	Apr 06-Apr 07
CMS closed ready for beam	Apr 07
Collisions	mid – 2007
Start Physics Run	Q3 2007

Trigger/DAQ



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Event rates

Event production rates at $L=10^{33}\,cm^{-2}\,s^{-1}$ and statistics to tape

Process	Events/s	Evts on tape, 10 fb^{-1}
$W\rightarrow e\nu$	15	10^8
$Z\rightarrow ee$	1	10^7
$t\bar{t}$	1	10^6
gluinos, m=1 TeV	0.001	10^3
Higgs, m=130 GeV	0.02	10^4
Minimum bias	10^8	10^7
$b\bar{b}\rightarrow\mu X$	10^3	10^7
QCD jets p_T>150 GeV/c	10^2	10^7

(The last three entries: assuming 1% of trigger bandwidth)

⇒ statistical error negligible after few days!

⇒ dominated by systematic errors (detector understanding, luminosity, theory)

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HLT performance : signal efficiency

- Efficiency of the Higher Level Trigger selection for some typical physics channels:

Channel	Efficiency
$W\rightarrow e\nu$	67%
$W\rightarrow\mu\nu$	69%
$Top\rightarrow\mu X$	72%
$H(115\ GeV)\rightarrow\gamma\gamma$	77%
$H(160\ GeV)\rightarrow WW^*\rightarrow 2\mu$	92%
$H(150\ GeV)\rightarrow ZZ\rightarrow 4\mu$	98%
$A/H(200\ GeV)\rightarrow 2\tau$	45%
SUSY (~0.5 TeV sparticles)	~60%

Issues to be addressed

Our Master Equation

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Stat vs syst errors, backgrounds from data or MC? Signal Significance

$$\sigma_{\mathrm{meas}} = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{\varepsilon \, L}$$

Reduce error?

Understand isolation, jet veto; p_T distributions at NLO; need calculations for detectable acceptance.

$$\sigma_{\mathrm{theo}} = PDF(x_1, x_2, Q^2) \otimes \sigma_{\mathrm{hard}}$$

constrain, define uncertainties

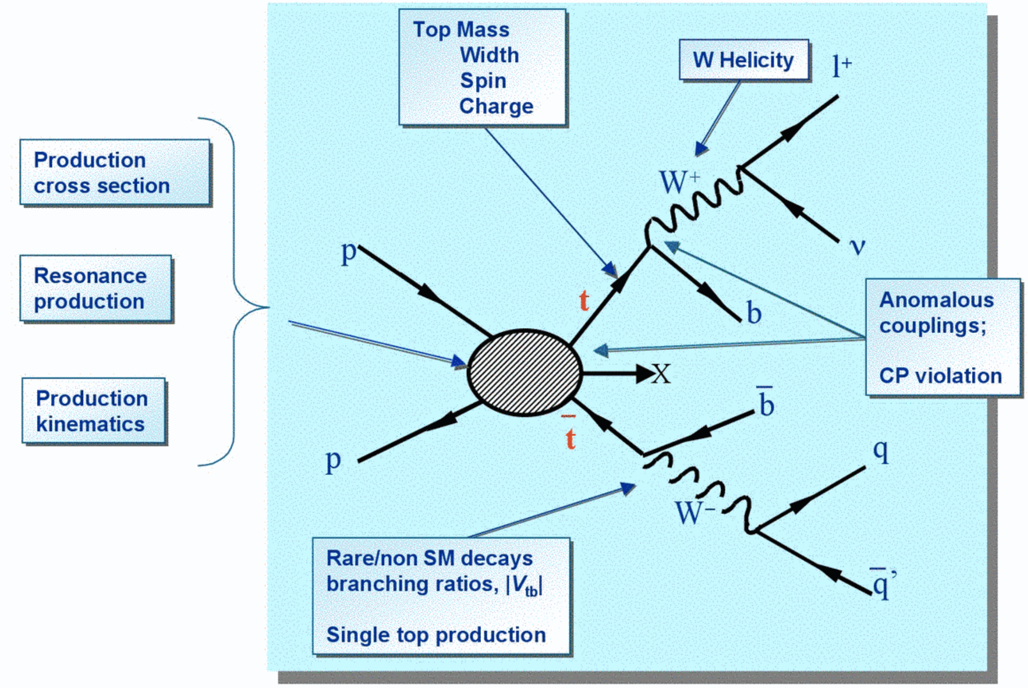
HO calculations, implement in MC

Standard Model Physics

Why SM physics

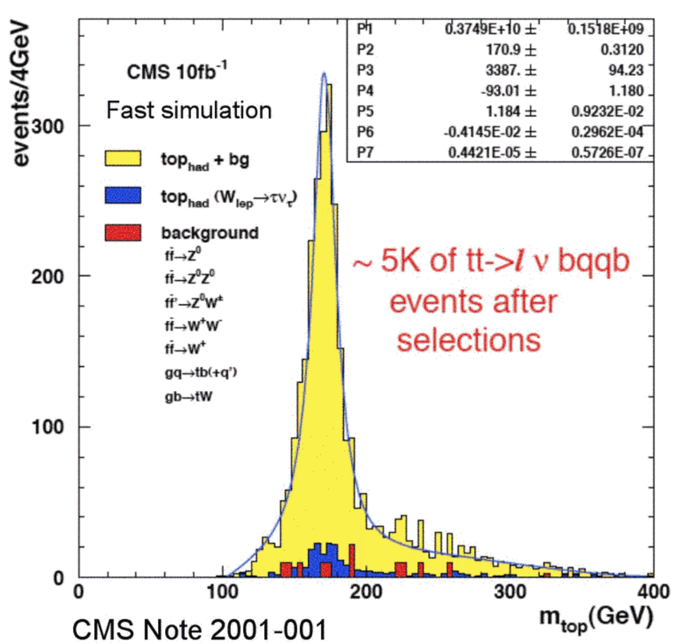
- Interesting in its own right
  - measure (calculable) event rates, cross sections (relative, differential, absolute)
  - establish (dis)agreement with SM, constrain SM
  - challenge theoretical calculations at high Q^2
  - **demonstrate "working" experiment with well known processes**
- Understanding of **detector**, calibration
- **Backgrounds** to many searches
- Constrain (relative) **PDFs**
- Alternative measurements of **luminosity**

Top Quark Physics



Top Mass Measurement

- Require : isolated lepton + E_{Tmiss}, $M_{JJ}=M_W$, two b-tag jets $\Rightarrow \delta_{stat} \approx 250$ MeV



CMS Note 2001-001

Main systematics:

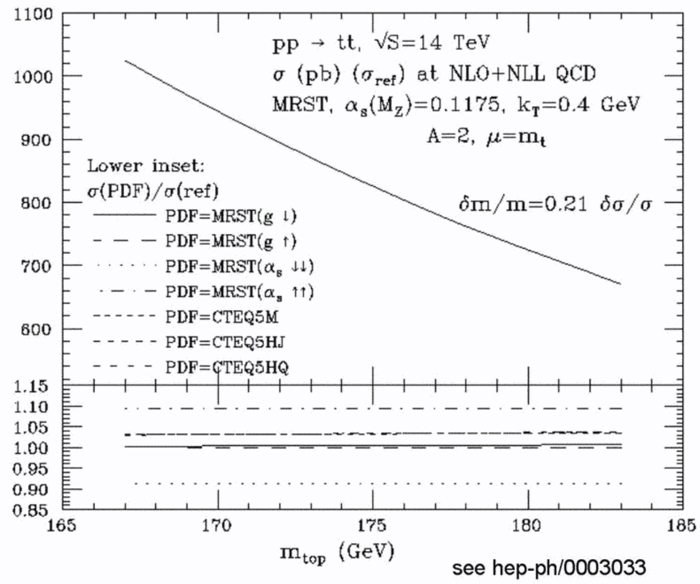
- knowledge of light- and b-jet energy scale
  - ➔ fragmentation, radiation, non-linearities, UE
  - ➔ need good E-flow
- b-fragmentation
- gluon radiation (ISR, FSR)
- backgrounds

$\delta m_{top} \approx 1$ GeV achievable?

Top Mass Measurement

- Why not from cross section?
  - huge statistics
  - totally different systematics
- Uncertainty on PDFs
  - ΔPDF of 10% translates into $\Delta m_{top} \approx 4$ GeV
  - need to constrain PDFs
- Luminosity
  - $\Delta L \approx 5\%$
  - can we do better?

$\Delta\sigma/\sigma \sim 5\Delta m_t/m_t$



see hep-ph/0003033

Luminosity Measurement

- Expected uncertainty from luminosity monitors ≈ **5%**
- Alternative : use W/Z counting as luminosity monitor Dittmar et al, Phys. Rev. D56 (1997) 7248

$$N_{pp\to Z} = L_{pp} \cdot PDF(x_1, x_2, Q^2) \cdot \sigma_{q,\bar{q}\to Z}(+\mathrm{HO})$$

count extract from theory

- **or better** : normalize processes to number of Zs (parton-parton luminosity)

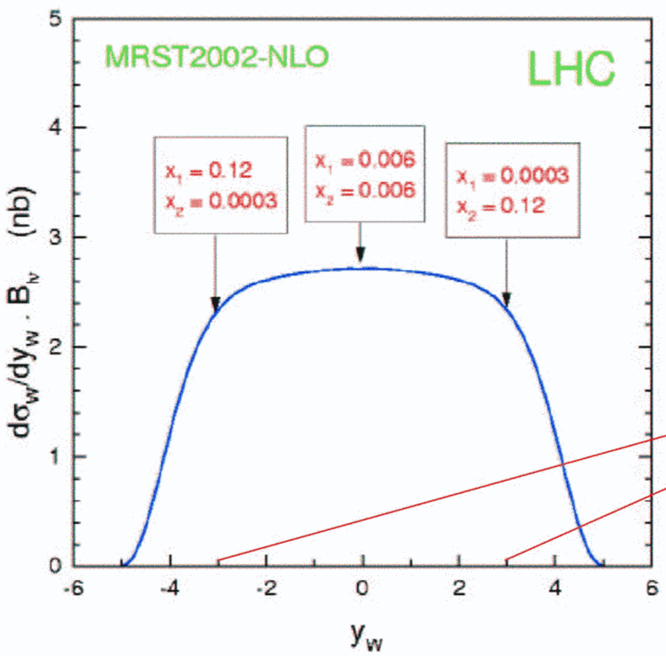
$$N_{pp\to WW} = N_{pp\to Z} \cdot \frac{\sigma_{q,\bar{q}\to WW}}{\sigma_{q,\bar{q}\to Z}} \cdot \frac{PDF(x_1', x_2', Q'^2)}{PDF(x_1, x_2, Q^2)}$$

$\Delta L_{pp} = 0!$

Calculate ratios.
Reduced uncertainties(?)

Constraining PDFs

- at the same time : precise PDFs from $W^+/W^-/Z$ rapidities



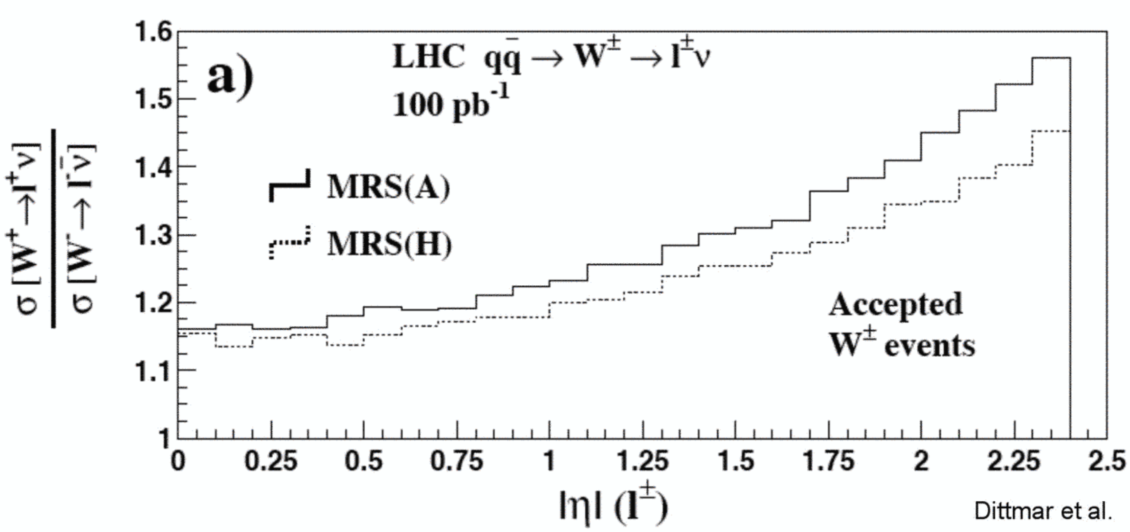
Note:

if we want **precise measurement** of Luminosity or some parameter in hard-interaction cross section, it is essential to have HO calculation restricted to measurable acceptance

$\Rightarrow$ avoid **extrapolation errors** (extrapolation to large y_W)

Constraining PDFs

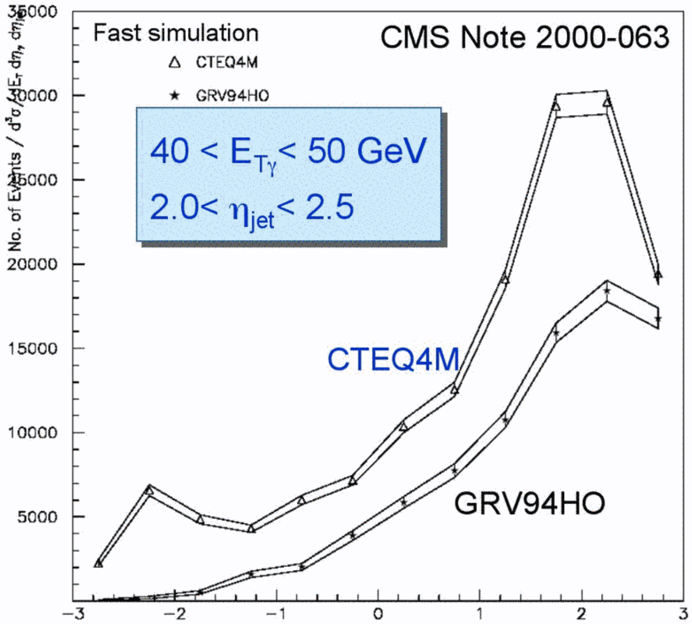
- particularly well suited : W^+/W^- cross section ratio ~u(x)/d(x)
- even small PDF differences observable



Dittmar et al.

Direct photons

δ_{stat} after 10 days at L=10^{32}



η_γ for direct photons and background

Very useful tool:

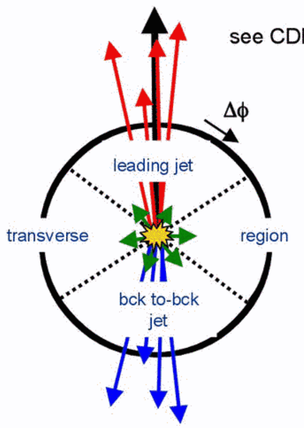
- energy scale calibration
- understanding of photon isolation
- constrain gluon and
- test SM predictions

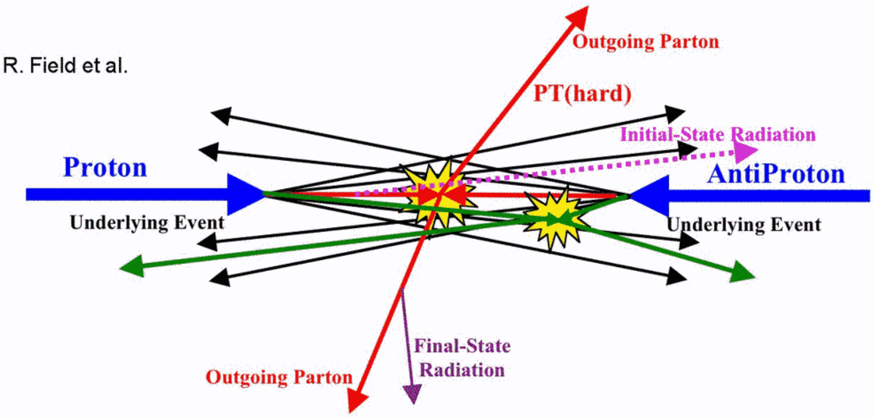
Messages 1

- compute ratios of cross sections
- have new ideas/proposals for such ratios
- normalize processes to the well known W/Z production, and
- extend this method to **gluon-initiated** processes
- get (N)NLO predictions for measureable acceptance, **or better**, differential predictions
- direct photons : get best possible theoretical input (isolation criteria, higher order predictions) and constrain the gluon

The Underlying Event

see CDF study, R. Field et al.



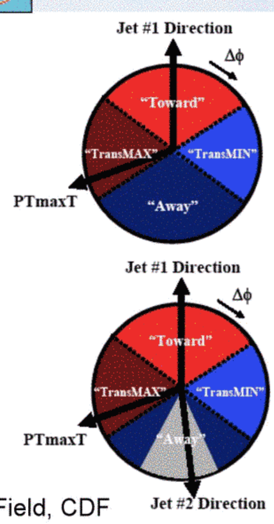


The Underlying Event:

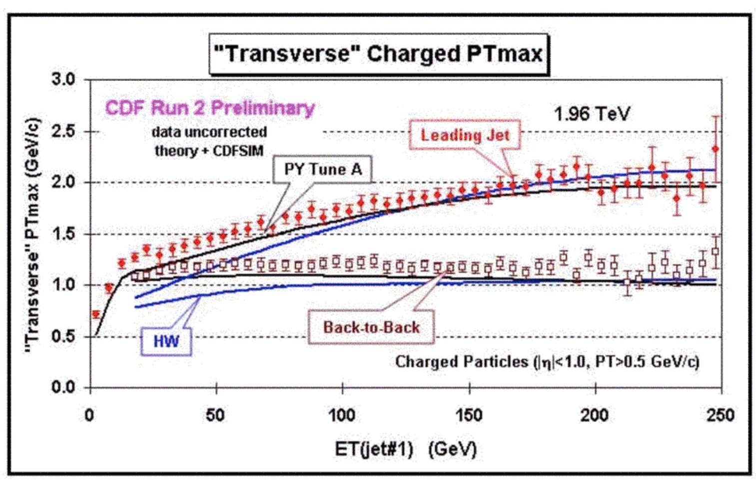
beam-beam remnants
initial-state radiation
multiple-parton interactions

- Issues:
  - modelling (min bias, multiple interactions)
  - extrapolation to LHC energies
  - impact on selection efficiencies ?

The Underlying Event



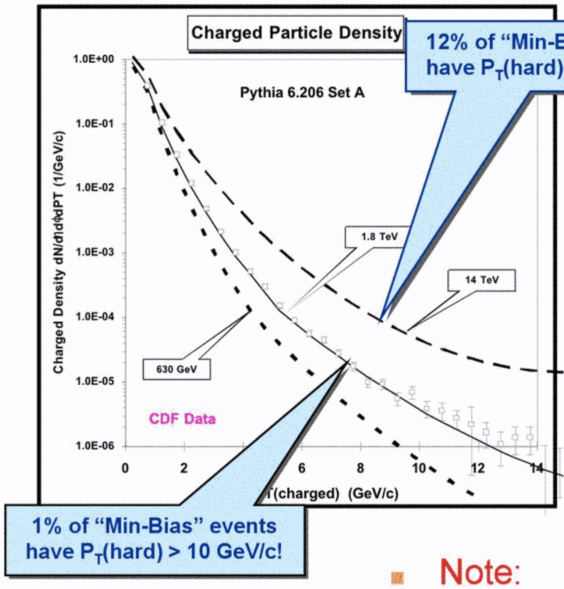
by R. Field, CDF

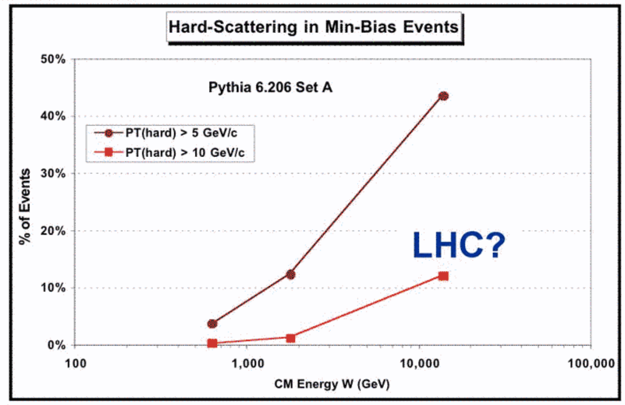


- **TransMax region** defined event-by-event: contains highest p_T charged particle
- In this comparison : PYTHIA has **multiple interactions**, HERWIG not
- **CDF data show** "jet structure" in UE : more activity in TransMax region (without p_{Tmax} track) than on average in transverse region
- **Correlations** between the two transverse regions, described by 'PY Tune A'.

UE : Extrapolation to LHC

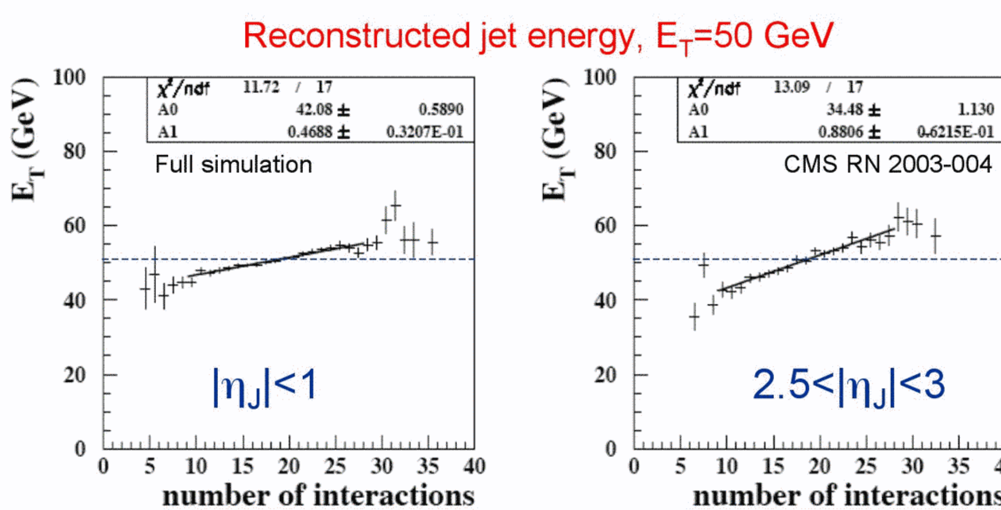
by R. Field, see LHC MC WS





- Note:
  - will have 10-20 "minimum bias" events per beam crossing at high luminosity
  - PY Tune A describes well the "underlying event", but not so well the properties of the leading jets!

Example : Impact on jet studies



- To get good jet energy resolution, such an effect has to be corrected for
- algorithms try to obtain corrections from the data
- however, calibration/testing of algorithms will be done using MC

→ **have to understand well MB + UE**

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Messages 2

- need models and data for understanding of underlying event
- try to learn as much as possible at the TEVATRON
- understand impact on “other” physics, such as isolation efficiencies for searches, jet resolution, MET resolution
- further issue : fragmentation (in particular b-fragmentation): we need not only N(N)LO calculations, but also progress on fragmentation side

Higgs Searches

Searches : general remarks

- as significance (number of 'sigmas') one usually sees the definition (σ_{stat}(background) = $\sqrt{n_b}$ for large enough statistics)

$$n_\sigma = \frac{n_s}{\sqrt{n_b}}$$

- Adding a relative systematic uncertainty ***f***, σ_{syst}(background) = $f\, n_b$, in quadrature to the statistical uncertainty, this becomes:

$$\tilde{n}_\sigma = \frac{n_s}{\sqrt{n_b + f^2 n_b^2}}$$

Searches : general remarks...

- this can be rewritten as

$$\tilde{n}_\sigma = n_\sigma \cdot \left[1 + \left(\frac{f \cdot n_\sigma}{n_s / n_b} \right)^2 \right]^{-\frac{1}{2}}$$

- limiting cases:

$$n_s / n_b << f \cdot n_\sigma \quad \Rightarrow \quad \tilde{n}_\sigma \approx \frac{n_s / n_b}{f}$$

dominated by systematics

$$n_s / n_b >> f \cdot n_\sigma \quad \Rightarrow \quad \tilde{n}_\sigma \approx n_\sigma$$

dominated by statistics

Searches : general remarks...

- a concrete example (10% background uncertainty)

n_s	n_b	n_s/n_b	n_σ	$\tilde{n}_\sigma$
50	100	0.5	5	**3.5**
500	10000	0.05	5	**0.5**

- in the second case, more luminosity will not improve the significance! (unless more data help to better understand the background)

SM Higgs

(see CMS Note 2003/033, Nov 03)

Production and Decay

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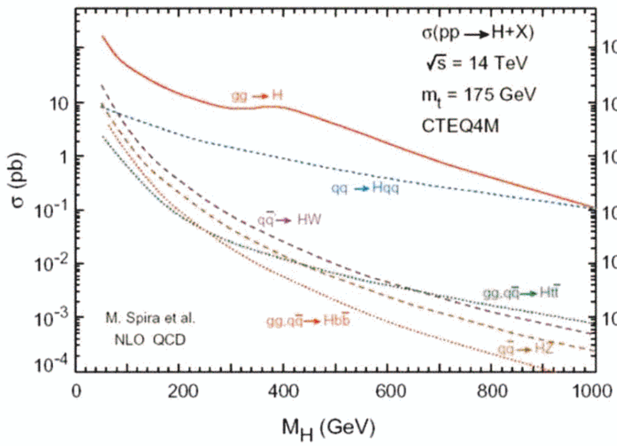

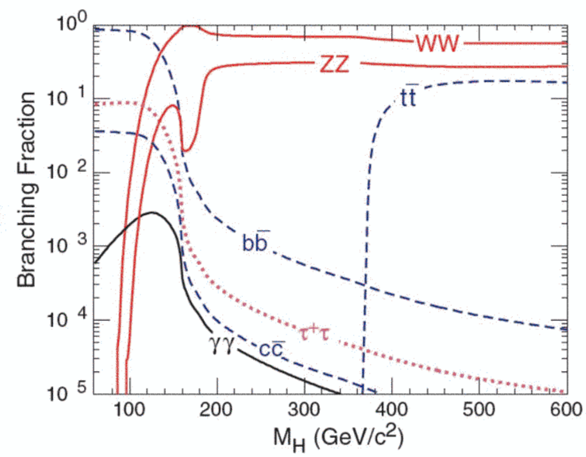

Signatures/Channels

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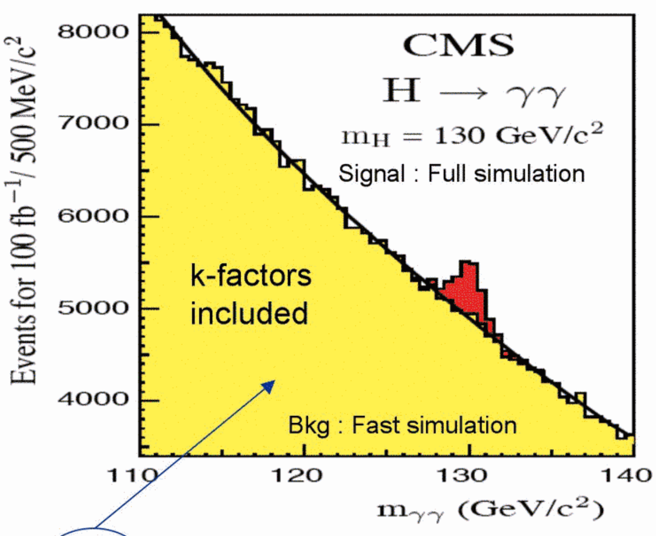
- 2-photon final states (gg→ H, qqH, WH, ttH)
  - excellent detector resolution, isolation, QCD jets rejection
- lepton final states (4ℓ, μ, e or τ)
  - isolation, momentum resolution, tau identification
- lepton + neutrino final states
  - lepton identification, WW and tt background rejection, MET resolution
- associated Higgs production (bbH, ttH)
  - b-tagging, ttjj backgrounds
- Higgs production via Vector Boson Fusion
  - very forward jet tagging, tt(j) background

Classes of Final States

- Mass can be fully reconstructed ($\gamma\gamma$, 4 leptons, $b\bar{b}$)
  - background from sidebands
  - for hadronic final state: need excellent jet E_T resolution
- Neutrinos in final state, no exact mass reconstruction possible (eg. **H → WW→$\ell\nu\ell\nu$** or **H/A→ $\tau\tau$**)
  - Jacobian peaks
  - background from 'sidebands' if possible
  - background from MC
  - extrapolation of background from non-signal region using data and MC (shape)
  - extrapolation of background using data and theory (ratio of cross section)

H → γγ

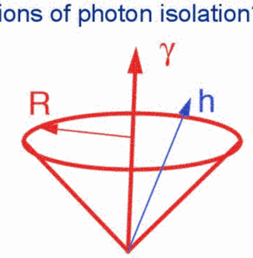
S/B ~ 1/10
(for inclusive search)



in bckg: irreducible pp → $\gamma\gamma$+X, pp → γ jet with FSR

not in : QCD multi-jet, pp → γ jet →isol. π^0 (~20-30% of irred.bckg)

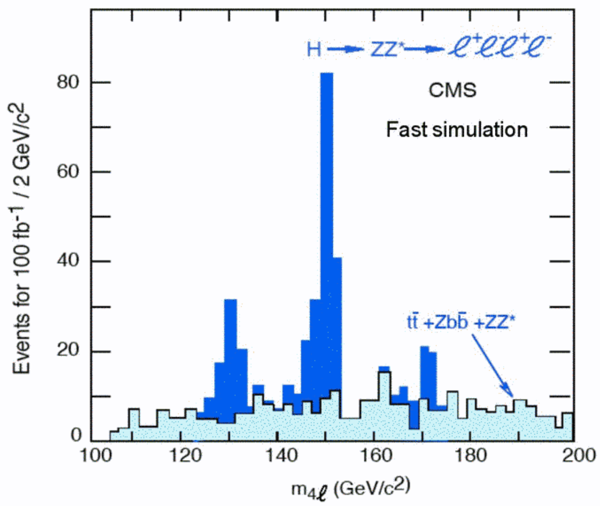
- enormous background, but smooth sidebands (need **excellent resolution** and **high efficiency**)
- Important issue: Isolation criterion
  - how to match theoretical and experimental definitions of photon isolation?

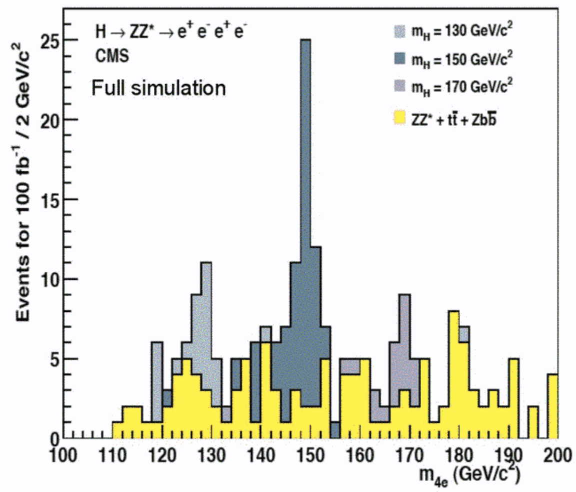


1. smooth cone isolation (S. Frixione)
   $E_T < p_T(\gamma)\ \varepsilon\ [(1-\cos r)/(1-\cos R)]^n$, $r < R$
2. "standard" theor. cone isolation (L. Dixon)
   $E_T < E_T^{cut}$ inside cone R
3. "standard" exp. cone isolation (CMS / ATLAS)
   no tracks p_T < 1-2 GeV/c inside cone R
   E_T in calorimeter inside cone $R < E_T^{cut}$

$H \to ZZ^{(*)} \to 4$ leptons

S/B > 1 (~ **4** for M_H=130 GeV, ~ **3** for M_H=200 GeV)

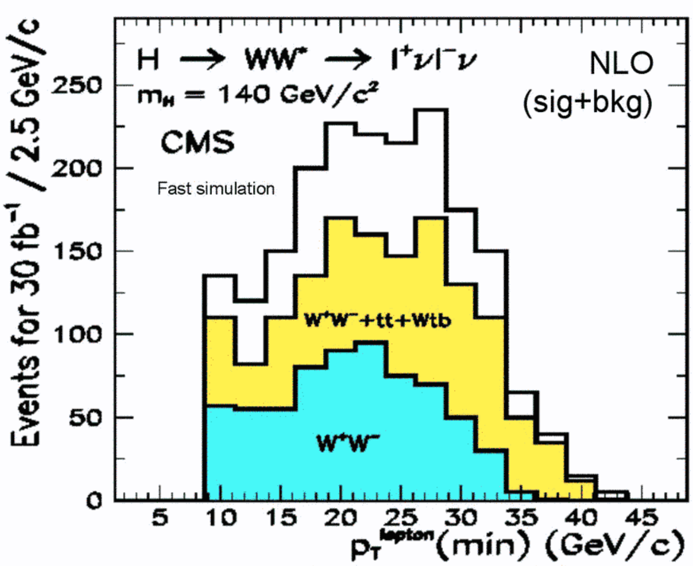




- Backgrounds : ZZ(*), Zbb, ttbar
- Issues: lepton isolation; tracking ('no' impact parameter); uncertainties from UE regarding efficiencies, thresholds?

$H \to WW^{(*)} \to \ell\nu\ell\nu$

S/B < 1 (~0.3 for M_H=130 GeV)



for 30 GeV/c < P_T^{lepton} (max) < 45 GeV/c

Issues :

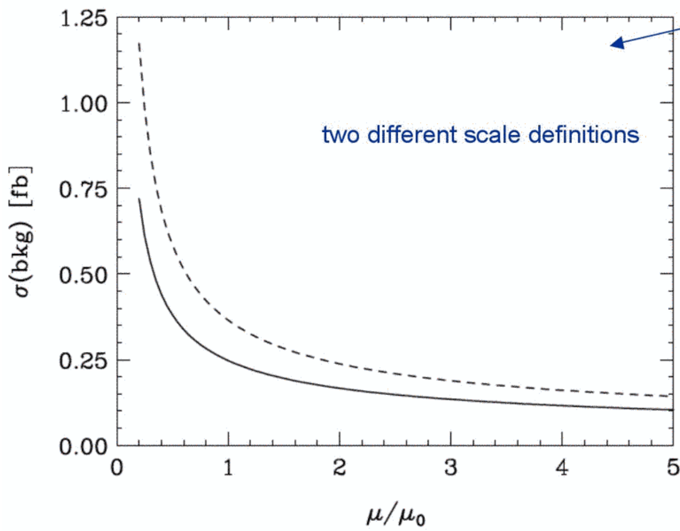
- Backgrounds : WW, tt (WbWb)
- central jet veto (suppresses WbWb)
- lepton isolation
- use different dynamics of signal and background, eg. lepton angles → good MCs needed!
- differential NNLO Higgs cross section as function of Higgs p_T would be nice

Note :

- best channel for M_H~160-170 GeV. 10 fb^{-1} enough

Background extrapolation

Backgrounds to H→WW →ℓνℓν : $t\bar{t}$ for gluon fusion, $t\bar{t}j$ for qqH



40-50% scale uncertainty at LO

Idea of extrapolation:
Cavelli, Kauer, Zeppenfeld

$$\sigma_{bkg} \approx \underbrace{\left(\frac{\sigma_{bkg,\,LO}}{\sigma_{ref,\,LO}}\right)}_{\text{low theoret. uncertainty}} \cdot \underbrace{\sigma_{ref}}_{\text{low experim. uncertainty}}$$

Background extrapolation...

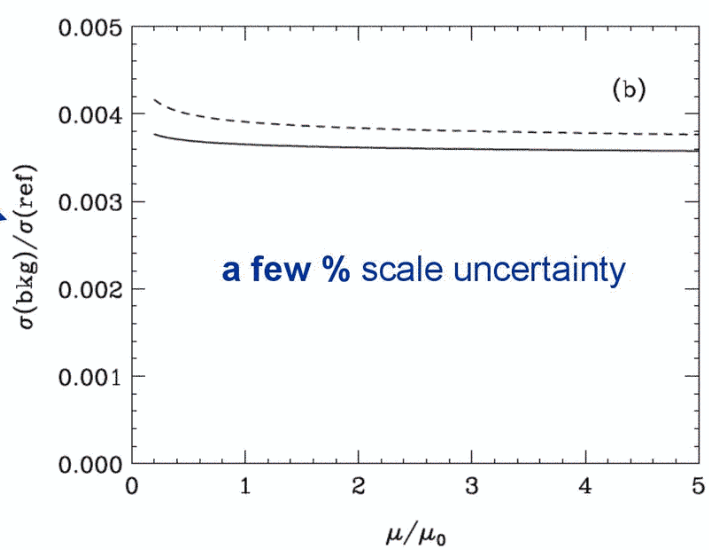
Backgrounds to H→WW →ℓνℓν : $t\bar{t}$ for gluon fusion, $t\bar{t}j$ for qqH

Idea of extrapolation:
Cavelli, Kauer, Zeppenfeld

$$\sigma_{bkg} \approx \underbrace{\left(\frac{\sigma_{bkg,\,LO}}{\sigma_{ref,\,LO}}\right)}_{\text{low theoret. uncertainty}} \cdot \underbrace{\sigma_{ref}}_{\text{low experim. uncertainty}}$$

Reference selection :
- like background, **but**
- no central jet veto
- no lepton pair cuts
- require b-tag

⇒ gives expt. stat. uncertainty of 1-2%

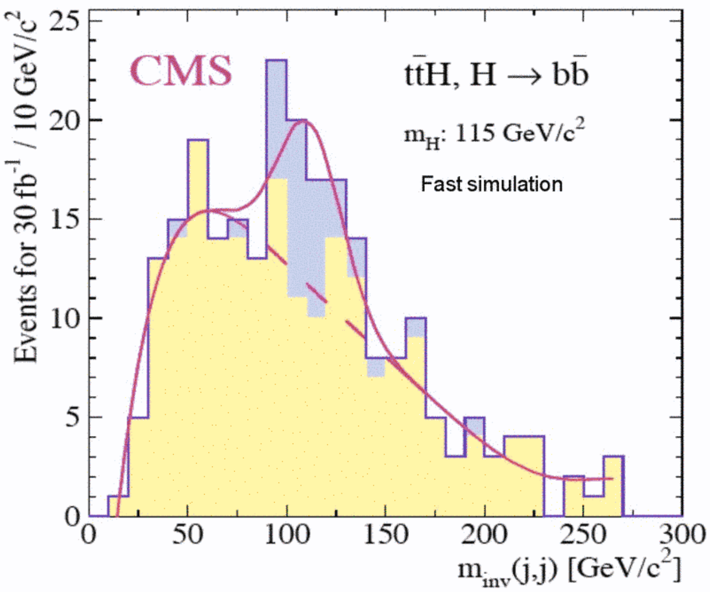


a few % scale uncertainty

☛ **~ 5%** background uncertainty

Associated Higgs production

S/B < 1 (~ 0.6-0.8)



one leptonic + one hadronic top decay

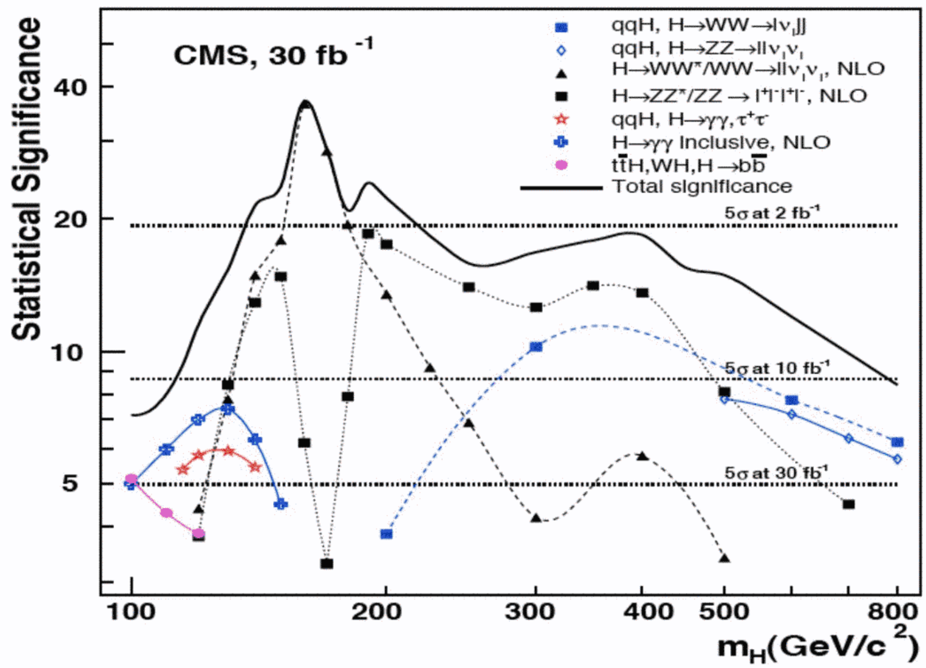
Issues (very challenging):

- Backgrounds : ttbb, ttjj, Ztt, W+jets (from LO CompHEP)
  - sidebands-method not safe
- ttbb : dominant bckg. after selection. Very large **scale uncertainties**.
- additional jets (at NLO) can change the shape
- background extrapolation applicable (a' la Kauer et al.)?

ttjj background

- Another approach: learn from TEVATRON (recent CMS talk by R. Demina)
  - production and ISR different, but
  - FSR very similar, jet E_T spectrum very similar
  - eg. CDF RUN1 : ttj gives a 5% contribution to W+njets (>= 1b-tag) data
  - note : ttbb rate too small at TEVATRON
- Proposal for TEVATRON contribution
  - **Monte Carlo** verification and tuning for ttjj production
  - Study initial state radiation on gluon fusion dominated processes, e.g. bb prod.
  - Separation can be done with invariant mass selection:
    - M(bWj)=~M(t) – b-jet radiation
    - M(jjj)=~M(W) – W decay products radiation
    - Forward jets – ISR
  - **Analyses methods** development and verification

SM Higgs sensitivity



BUT NOTE : no systematic errors included!

MSSM Higgs

(one example of recent studies)

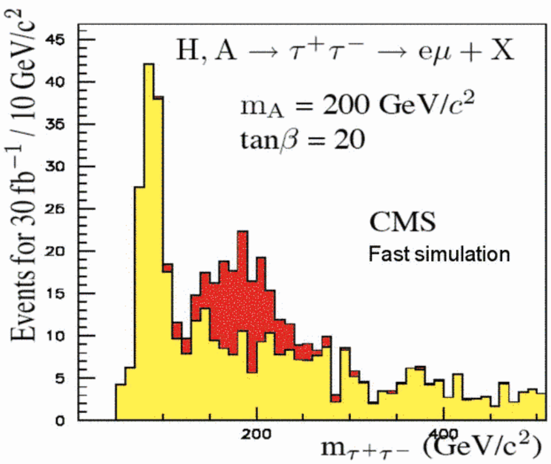
(see CMS Note 2003/033, Nov 03)

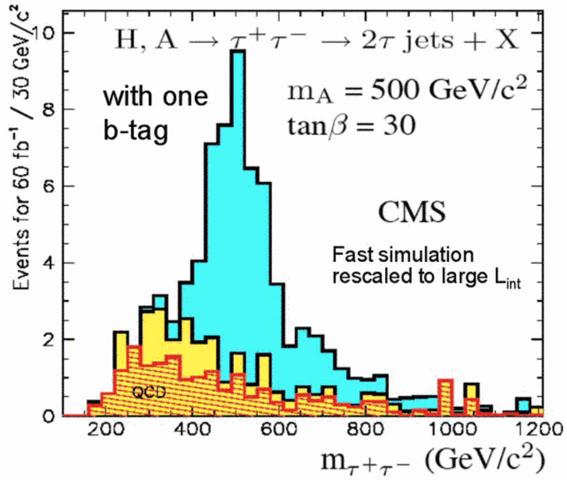
$pp \to b\bar{b}$ H/A, H/A $\to \tau\tau$

looked for in τ decays : **e+μ, ℓ+jet** and **jet+jet**

Very challenging : **hadronic τ-decays (isolation); S/B ~ 1.7-2.7** (large tanβ)

↪ full trigger simulation performed





- Backgrounds : Z decays, QCD multijet. ttbar and Wt → veto 2. central jet
- Note : use this channel to precisely measure tanβ, with Δstat < Δtheo ~ 20% ?

Roadmap

- 10 fb^{-1} :
  - SM-like Higgs discovery in $H \to ZZ^{(*)}$, $H \to WW^{(*)}$
- 30-60 fb^{-1} at low luminosity:
  - observation of other Higgs channels, such as $H \to \gamma\gamma$
  - first measurements of Higgs properties
- 100-300 fb^{-1} at high luminosity:
  - observation of more Higgs channels
  - precise measurements of Higgs properties
  - in what model are we?

Messages

ETH Institute for Particle Physics

- same isolation criterion in experiment and theory
- differential (N)NLO cross sections needed (signal + backgr)
  - eg. as function of Higgs p_T or rapidity
  - in particular, need more theory-input for important channel $H \rightarrow WW^{(*)} \rightarrow \ell\nu\ell\nu$
- very important and difficult background:
  - ttbb, ttj(j), WW
  - need NLO, associated systematic uncertainties, **and/or**
- clever background estimations, such as
  - extrapolation via ratios of cross sections from theory
  - use TEVATRON: understand **where useful, where NOT** **(eg. different colour structure)**
- CMS Physics TDR to come out in 2005
  - if you theorists do a good job, you will get a lot of citations .... d;-)

Further Remarks

Further remarks

- Try from the very beginning
  - to establish an excellent collaboration theorists - experimentalists
  - in order to avoid (to have for years) , eg.

  - improper usage of MCs
  - different definitions of systematic uncertainties

  - **example** : only about 12 years after LEP startup there has been an agreement between experiments (and theorists) on the theoretical uncertainty of α_s from event shapes….

Summary

- CMS is getting ready for exciting and challenging data taking at the LHC
  - detector construction at full steam, will be ready in April 07
  - see WEBCAM : http://cmsinfo.cern.ch/Welcome.html/cmseye/index.html
  - many (stat. only) studies have shown that CMS is well designed for addressing the very rich LHC program
- Now entering new period of analyses preparation
  - Physics TDR by 2005 : write/debug/learn necessary software tools
  - concentrate carefully on ALL aspects of the analyses, such as
  - calibrations, systematic uncertainties due to detector
  - theoretical uncertainties
- Need good collaboration between experimentalists and theorists in order to
  - improve predictions
  - validate MCs
  - invent new/clever approaches where ‘standard’ methods appear hopeless

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