Top pair production at CMS

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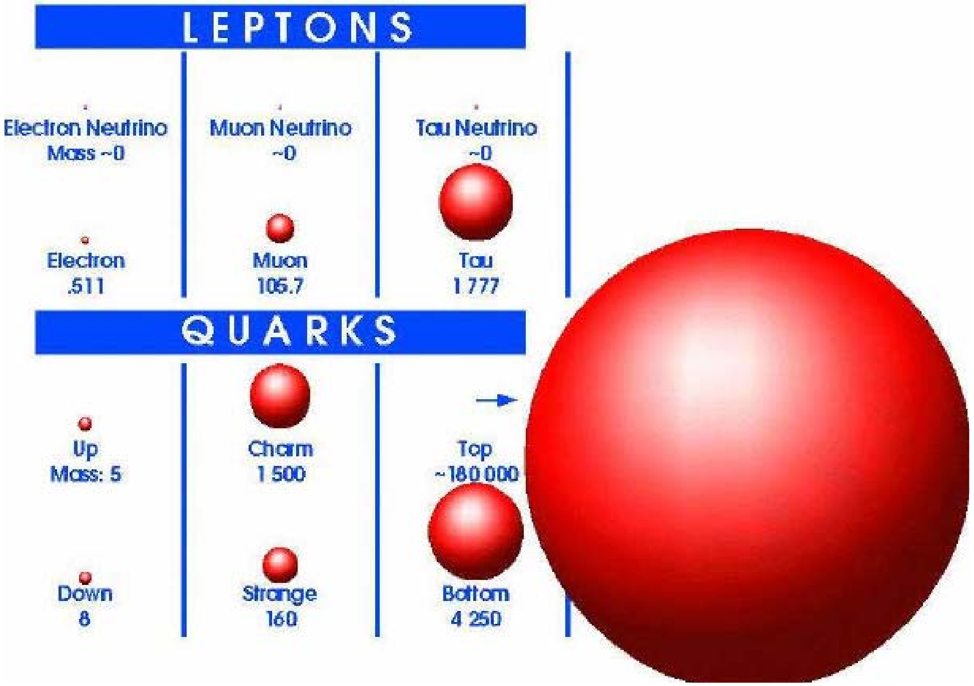
On behalf of the CMS Collaboration

- The importance of the top quark
- What the top pair production can tell us
  - precision measurements
  - Higgs and new physics
- How is CMS getting ready?

Coimbra, January 2006

Studying the top



Is it 'standard' physics?

- The top turns ten years, but still so little known about it…
- Its large mass gives unique features for the investigation of EW symmetry breaking and physics beyond the SM
- Hope it will be the key for revealing new physics at the LHC.

The LHC will be a top-factory

The NLO production cross-section is about 830 pb. At L=2•10^{33}:

$\rightarrow$ 2 tt events per second !

$\rightarrow$ more than 10 million tt events expected per year: perfect place for precision physics

Many good reasons

1. Precision physics measurements:

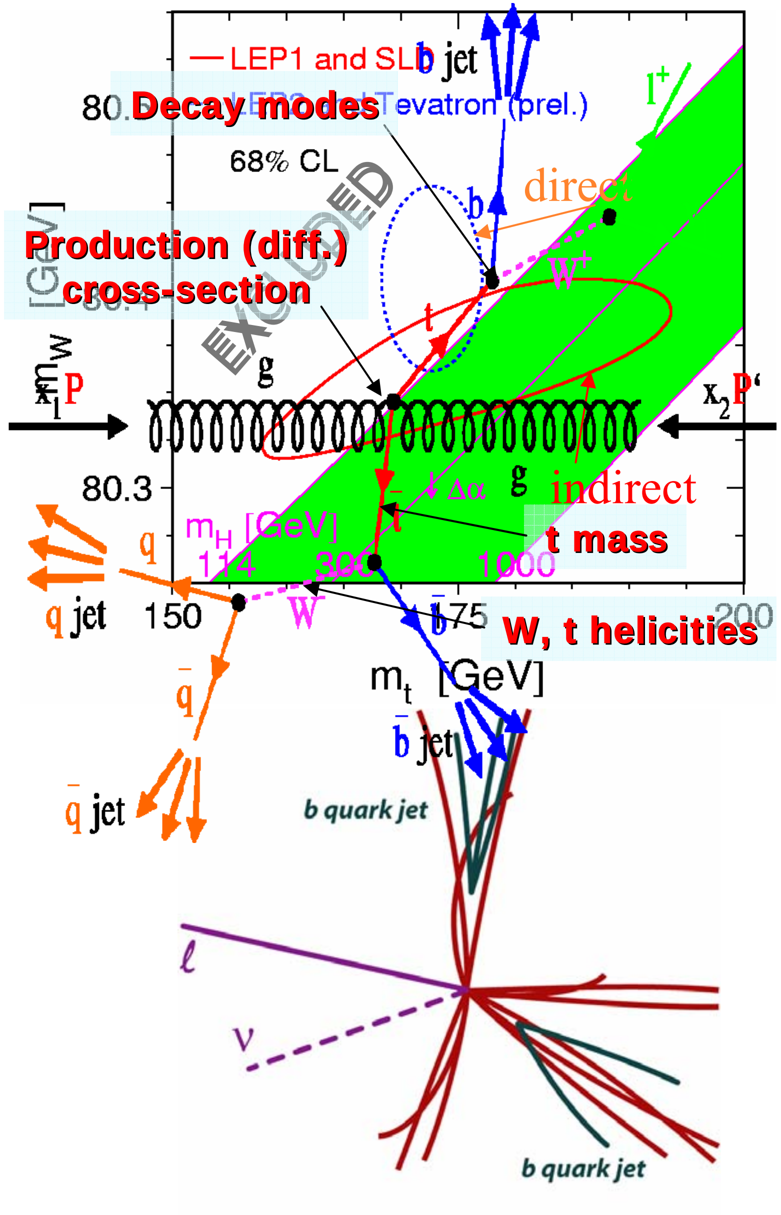
- many measurements in the production and the decay phase
- place where to best constrain the SM ! EW radiative corrections ∝ m_t^2

2. New physics potential:

- enormous mass, close to the EW scale
- larger coupling with Higgs
- perfect place where new physics could manifest itself (in production and decay)

3. Essential tool for calibration:

- jet energy scale (b, light jets)
- b-tagging calibration



- excellent understanding of standard physics is essential to search for new physics and for any claim of discovery !

Getting ready

In preparation for data taking, CMS is also completing its Physics TDR. This has been the time to refine/prepare software, tools and analysis techniques to be ready when the first data will arrive.

Main focus on:

☞ Robust software architecture for event simulation and reconstruction
- aim to have first results with full detector simulation in the Physics TDR

☞ Sound and complete event generation, or know how to do it
- massive event generation and simulation with up-to-date generation tools
- getting experience on the needs (tools/computation) for real analyses.

☞ Sound strategies for assessing systematics from theory and detector
- common (between analyses and eventually experiments for theory) determination of systematics is highly desirable. Work ongoing.

→ Many results are being completed in these months, still it is possible to give an overview of what we have been doing and what we should expect.

Generation/simulation setup

The event generation setup in CMS is steadily moving towards a more complete and realistic data simulation.

- From PYTHIA to Toprex for top spin correlation.
- Define a common set-up for input parameter and 'environmental' settings in PYTHIA:
  - radiation and hadronization/fragmentation
    - → **use LEP tuning**
  - minimum bias and underlying event
    - → **PYTHIA tuning to Tevatron and lower energy data from UA5**
  - PDF description
    - → **CTEQ6L/M for central value and study of systematics**
- Use a better ME description where needed –CompHEP, ALPGEN- (next slide)

Full simulation is entirely GEANT 4 based.

→ **validated on test beam data and with previous simulation GEANT 3 based**

→ More than 10M SM events produced in the last months

Hard process description

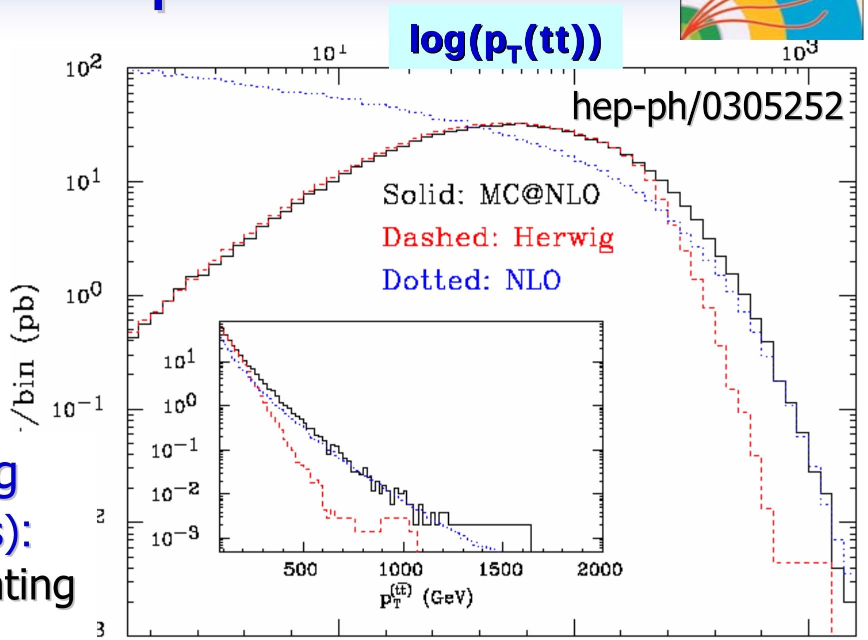
The study of top production involves final states with many jets/partons.

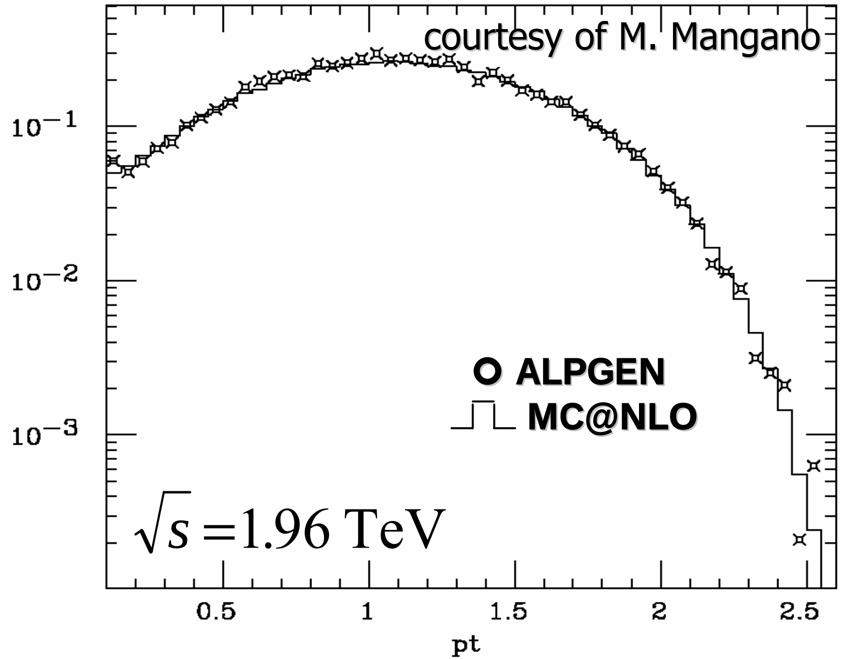
- → better to describe the processes with the highest matrix elements (ME) possible order.
- → this is true for the tt signal, but even more so for the background (esp. W/Z+jets).

In CMS a large production of SM processes using ALPGEN has also been launched O(10-20M events):
(LO ME plus parton-jet matching to avoid double counting in exclusive samples)

W/Z+N jets	(N=0,1,2,3,4,5,6+)
WW/WZ/ZZ+N jets	(N=0,1,2,3,4+)
tt+N jets	(N=0,1,2,3,4+)
N jets	(N>1)
bb+N jets	(N=0,1,2,3,4,5,6+)
Z/W+bb+N jets	(N=0,1,2,3,4+)
Z/W+Mc+N jets	(N=0,1,2+; M=2)
bbbb+N jets	(N=0,1,2,3,4+)
ttbb	
γγ+N jets	(N=0,1,2,3,4,5,6+)

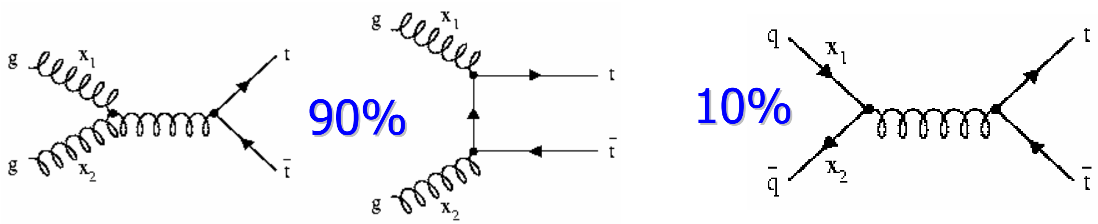
They will be used to validate results, study backgrounds and systematics with more details



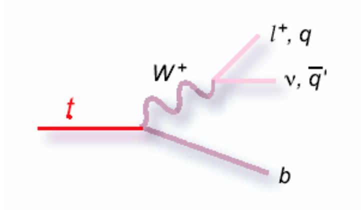


Top production and decay at the LHC

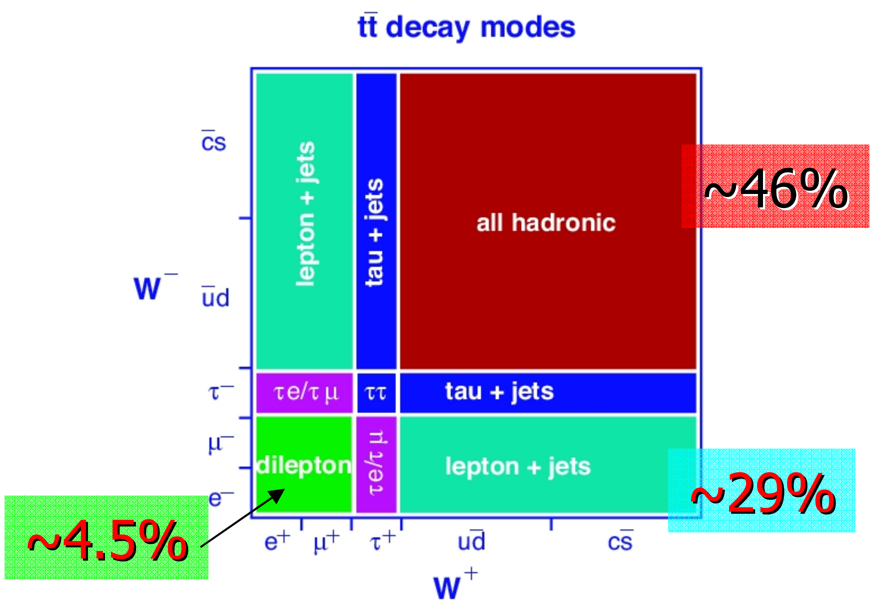
Top production at the LHC happens mainly via gluon fusion:



The top in the SM decays into W+b, leading to different signatures



~100%



☞ need to reconstruct and identify

- electrons
- muons
- b-jets
- light jets
- missing E_T

→ Excellent energy flow is mandatory

Measuring the rates tests production and decay mechanisms at the same time

Triggering on top

Trigger efficiency is an issue at hadronic machines

The inclusive triggers allow to explore as much as possible the wide range of standard physics final states

- isolated leptons, many jets and missing ET, also b/τ tagging possible with the inclusion of tracking devices in the second level trigger

Generally no big problems for top pair production in (semi)leptonic channels.

The most difficult is the fully hadronic final state:

- ☞ Lower the thresholds and make use of a fast pixel b-tagging requiring 2 tracks in a jet with IP significance exceeding 2σ
- ☞ Additionally use the regional full track reconstruction requiring 3 tracks with IP significance of at least 2.5σ
- ☞ Signal efficiency ~15% with S/B~1/160

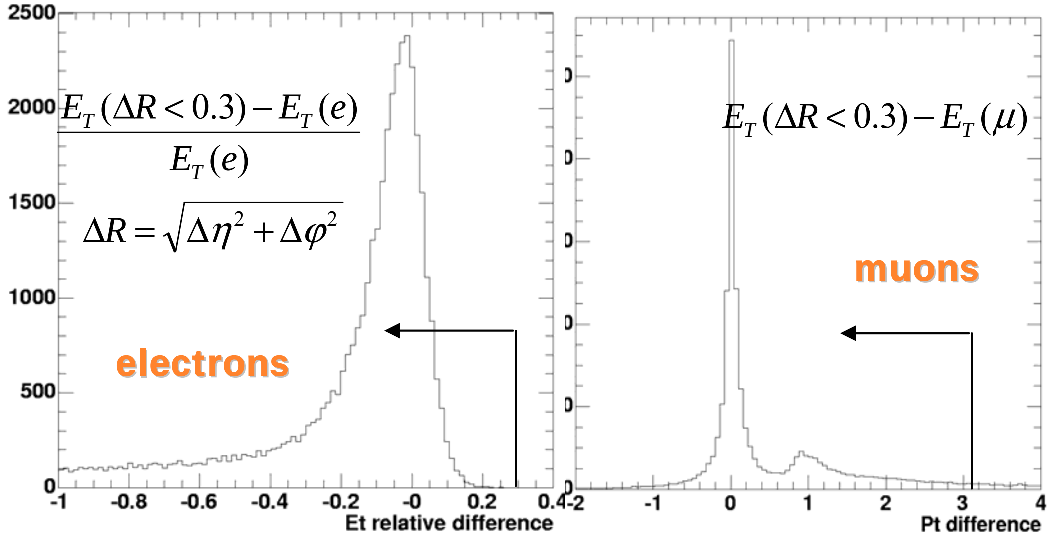
low luminosity HLT trigger table

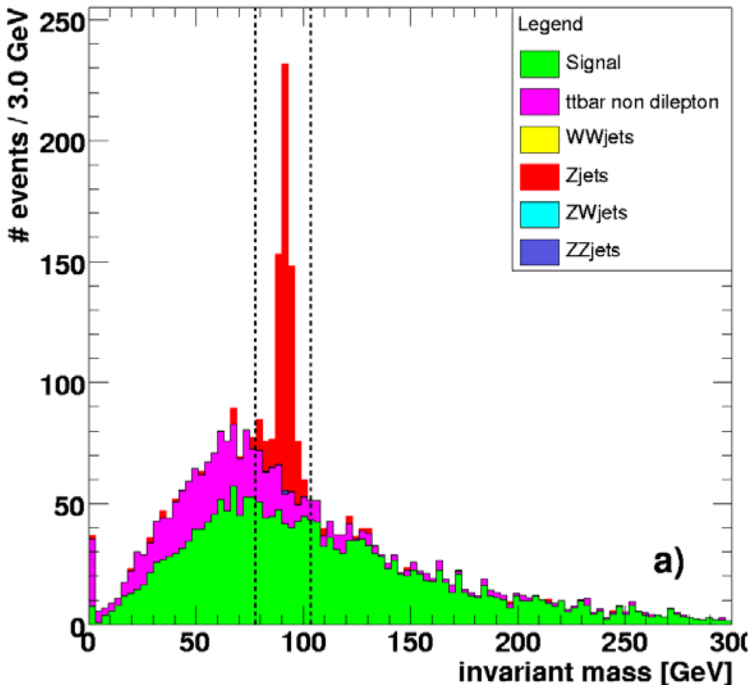
Trigger object	**Threshold** (GeV)	**Rate** (Hz)
Isolated muon	19	25
Isolated electron	29	33
Single Jet, 3 Jet, 4 Jet	657, 247, 113	9
Jet + missing E	180,123	5
Inclusive tau jet	86	3
Electron + jet	19, 45	2
Inclusive b-jets	237	5

Di-lepton event selection

Selection is cut based:

- Single or di-lepton trigger
- Two isolated oppositely charged leptons with E_T>20 GeV and $|\eta|$<2.5
- Missing E_T>40 GeV
- At least two jets with E_T>20 GeV and $|\eta|$<2.5
- Two tightly b-tagged jets





Main background represented by Z+jets when no b-tagging is present.
→ cut the Z peak for leptons of same flavour

With tight b-tagging, efficiency about 5% (15% without b-tagging) with excellent background reduction
→ S/B~5 (B mainly from leptonic τ decays)

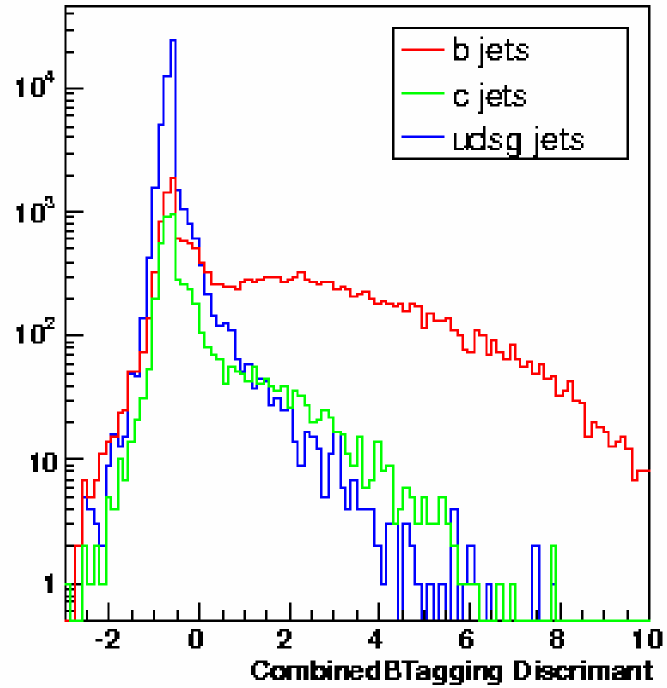
Semileptonic event selection

Selection is cut based:

- Single lepton trigger
- One isolated lepton with $E_T > 20$ GeV and $|\eta| < 2.5$
- Exactly four jets with $E_T > 30$ GeV and $|\eta| < 2.4$
- Exactly two tightly b-tagged jets (P>60%)
- Exactly two anti b-tagged jets (P<30%)

Main background represented by W+jets

(to a minor extent Z+jets and di-bosons)

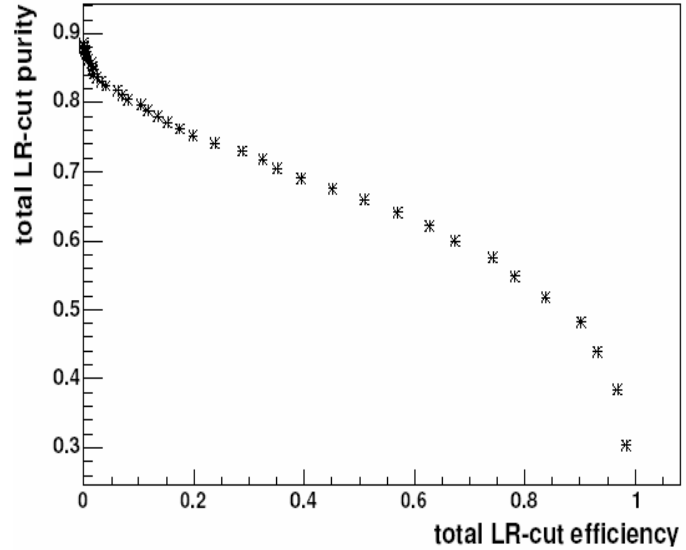


→ Efficiency about 4% with excellent background reduction (S/B~4)

Further improvement can be obtained by a mass cut after the full event reconstruction

Jet pairing via a likelihood ratio technique based on:

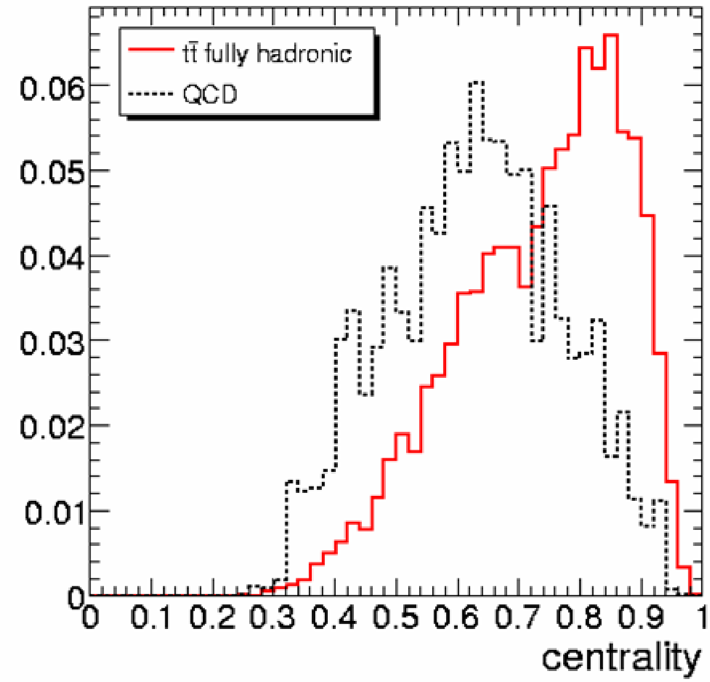
- χ^2 **of the constrained fit imposing the W masses**
- **transverse momentum of the resulting tops**
- **difference between the fitted and the reconstructed W boson masses**
- ΔR **between the lepton and the hadronic b**
- **the b tagging probabilities**



Fully hadronic channel

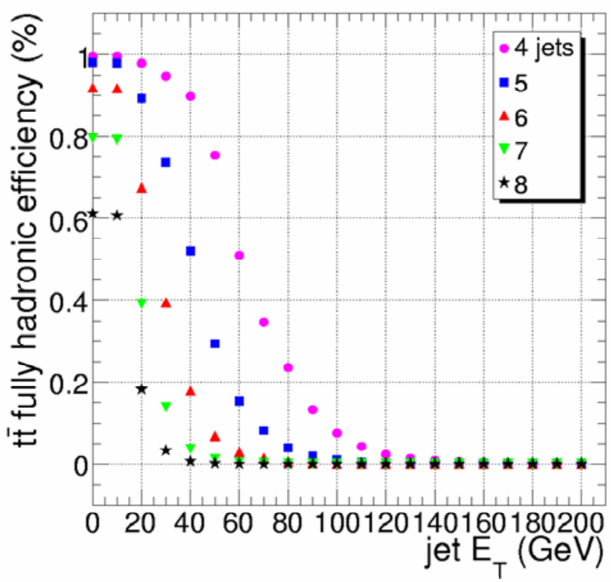
Selection is cut based:

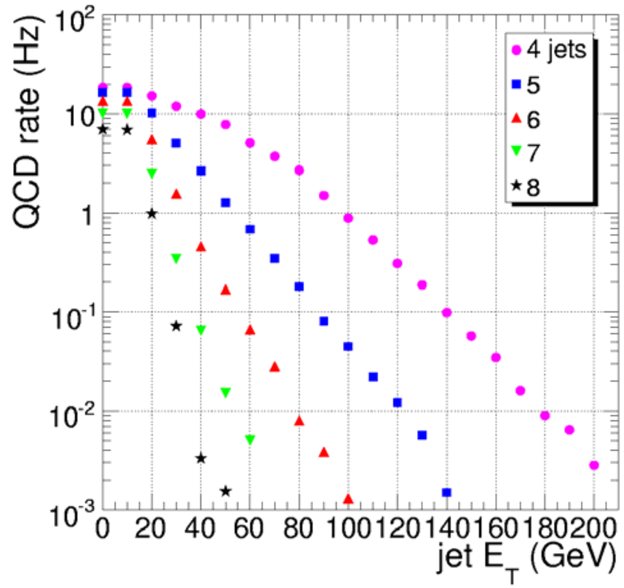
- Any jet trigger with fast b-tag (either with pixels or with regional track finding) on one of the two most energetic jet
- 6 to 8 jets with E_T>30 GeV and $|\eta|$<2.4
- Kinematic selection:
  - centrality of the event
  - non leading jets total E_T
  - aplanarity
- Separately consider singly and doubly b-tagged events



Main background is given by QCD

Efficiency about 2-3% with S/B~0.15-0.25





Systematic uncertainties

In the (not so) long run the determination of total and differential top-pair cross-sections will be dominated by systematic errors.
The most important are expected to be:

Luminosity:

- Reasonable goal is 5%

(→ measure the number of interactions per bunch crossing (HF) and σ(pp) (TOTEM))

Theory related:

- Radiation description **(→ vary Λ_{QCD} and Q^2_{max})**
- Minimum bias and underlying event **(→ extrapolation error from low energy data)**
- PDF parametrization **(→ CTEQ6M)**

Reconstruction related:

- Jet energy scale **(→ ECAL: 0.5%, HCAL: 1-2%, jet energy calibration to a few %)**
- b-tagging efficiency+fake rate **(→ use tt for calibration: to 4-5% with 10/fb)**
- Lepton identification and energy scale

☞ Work is ongoing to provide sound estimates for the Physics TDR.

Challenges at the start-up

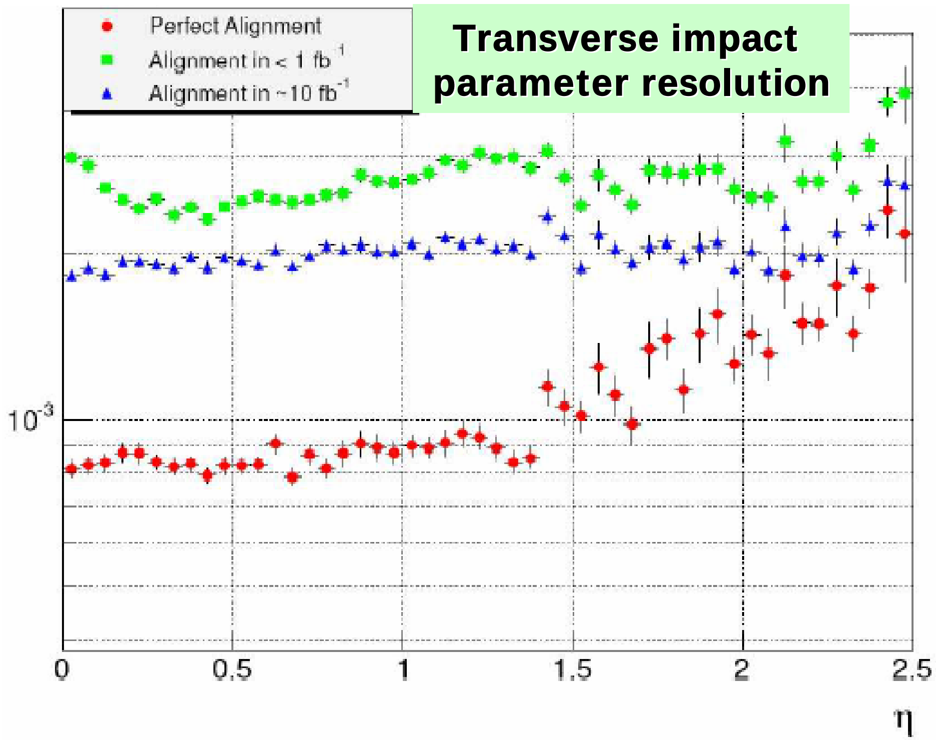
Pilot run in 2007 without ECAL end-caps and pixels.
The first fb^{-1} will be in 2008 with full detector: the main issue for interpreting the first data will come from imperfect alignment:

- first data taking scenario (1 fb^{-1}), opposed to long term data taking (10 fb^{-1}):
  - → alignment of the tracker with data will be incomplete (e.g. isolated μ)

Pixels aligned to a 10 μm level is good enough to have an acceptable degradation of the b-tagging performance.

The systematics, in particular those detector related, will be worse by a factor ~2, but:

→ Selection procedure basically works also for the first fb^{-1}
→ The top mass peak can be reconstructed in matter of days
→ Fast feedback on detector performance.



'Standard' use of top pair production

Top-pair production will be extremely useful for standard precision measurements…

- top quark properties (mass, spin, charge)
  [→ other talks in these sessions]
- constraining of PDFs
- V_{tb} measurement (in addition to single top):
  measured by the ratio of double to single b tag of the selected events
  within the SM $$R(bb/b) = \frac{BR(t \to Wb)}{BR(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2$$
  dominated by systematics on the b-tagging efficiency and fake rate.
- measurement of coupling from ttZ and ttγ production
  Would be the first direct information on top couplings to neutral bosons.

…and a perfect workshop for calibrating reconstruction tools:

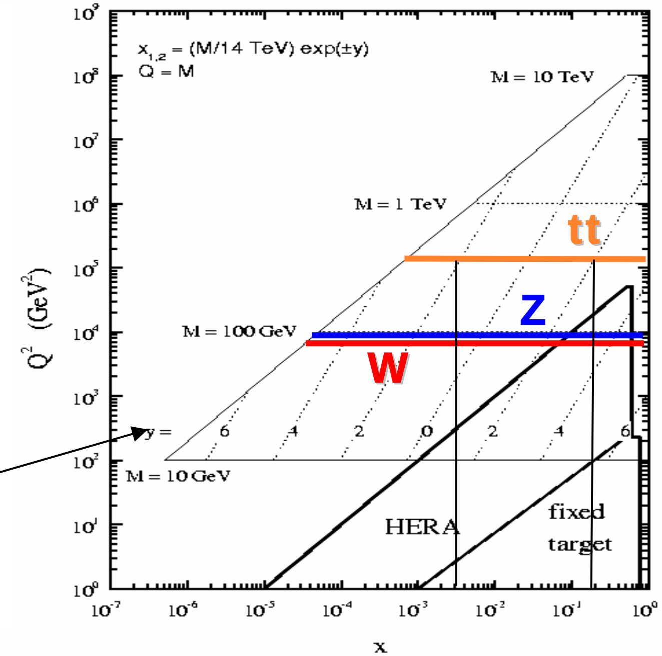
- b-tagging
- jet energy scale

→ see Jan Heyninck's talk

Example: gluon PDFs

With an accurate measurement of the top-pair production cross-section the proton PDF can be further constrained:

$$\frac{dN_X}{dy} = \frac{d\sigma_{qq,gg\to X}}{dy} \bullet L \bullet pdf_{qq,gg}(x_1, x_2; Q^2)$$

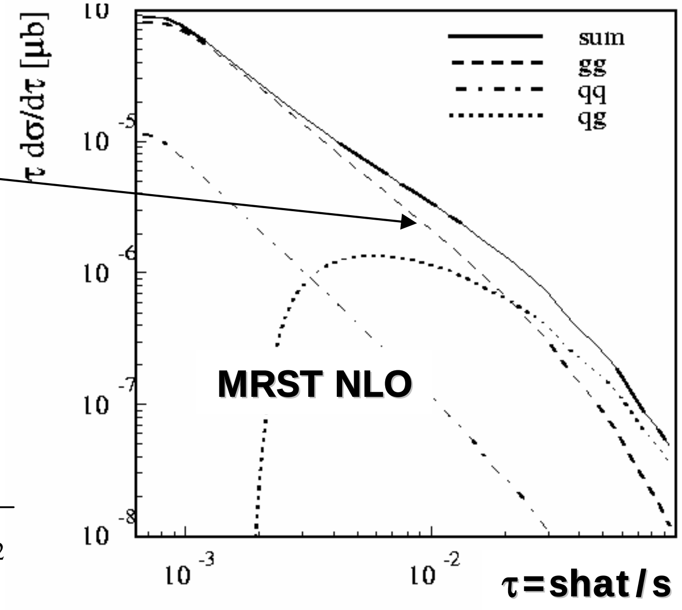


- a large range of x and Q2 can be probed:
  $m^2 = s x_1 x_2$ and $y = 1/2 \ln(x_1/x_2)$
  $\Rightarrow x_{1/2} = e^{\pm y}\, m/\sqrt{s}$

- The dominant production mechanism for heavy quarks (b and t) at the LHC is gluon-gluon fusion

- QCD there needs to be solidly understood

$$\sqrt{\tau} = \sqrt{x_1 x_2}$$

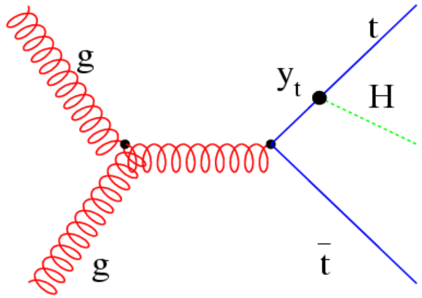


Beyond the SM

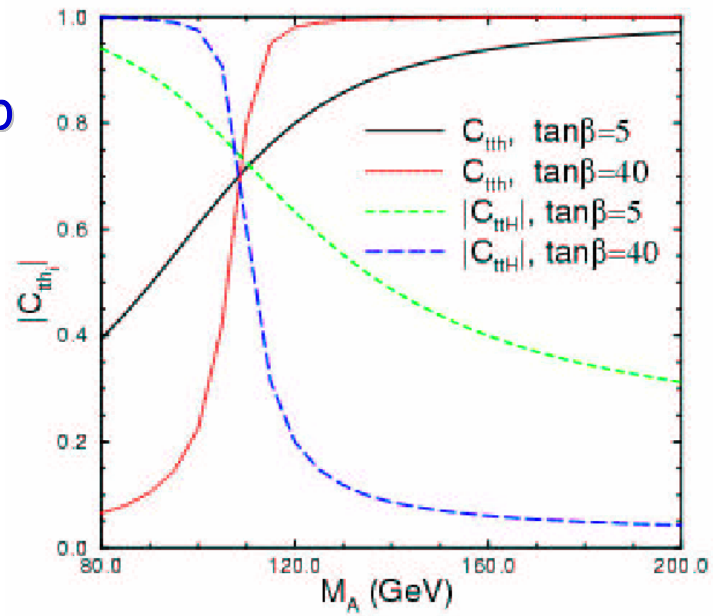
top-pair production will also be a probe for physics beyond the SM:

- non-SM production ($X \to tt$)
  - → resonances in the tt system (SM/MSSM Higgs, technicolour, SEWSB)
  - → MSSM production
    - unique missing E_T signatures from $\tilde{g} \to t\,\tilde{t}$, $\tilde{t} \to \chi^0_{1,2}\,t$, $\tilde{b} \to \chi^+_1\,t$
- non-SM decay ($t \to Xb$, Xq)
  - → charged Higgs
    - change in the top BR, can be investigated via direct evidence or via deviations of $R(\ell\ell/\ell) = BR(W \to \ell\nu)$ from 2/9 ($H^+ \to \tau\nu, cs$).
  - → FCNC t decays: $t \to Zq$ $t \to \gamma q$ $t \to gq$
    - highly suppressed in SM, less in MSSM, enhanced in some sector of SEWSB and in theories with new exotic fermions
    - 5 sigma discoveries possible for BR down to 10^{-4}
- non-SM loop correction
  - → precise measurement of the cross-section
    - $\sigma_{tt}^{NLO}-\sigma_{tt}^{LO}/\ \sigma_{tt}^{LO}$ <10% (SUSY EW), <4% (SUSY QCD) typical values, might be much bigger for certain regions of the parameter space
- associated production of Higgs
  - → ttH (next slide)

ttH



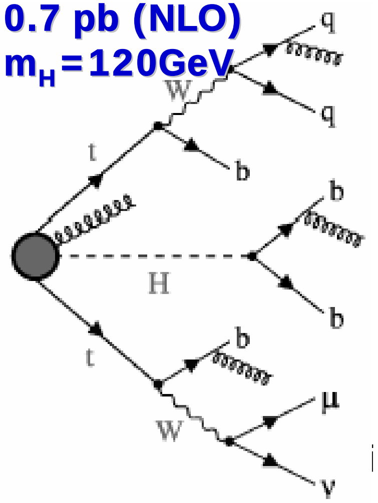
The Yukawa coupling of top to Higgs is the largest.



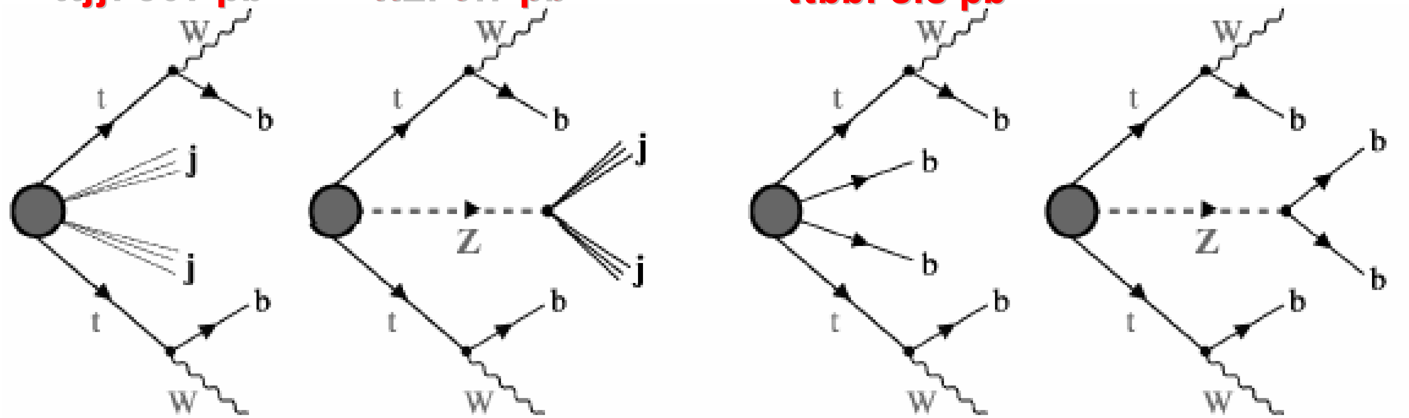
- It is a discovery mode of the Higgs boson for masses less than 130 GeV
- Measuring the coupling of top to Higgs can test the presence of new physics in the Higgs sector

☞ Very demanding selection in a high jet multiplicity final state

0.7 pb (NLO)
m_H=120GeV

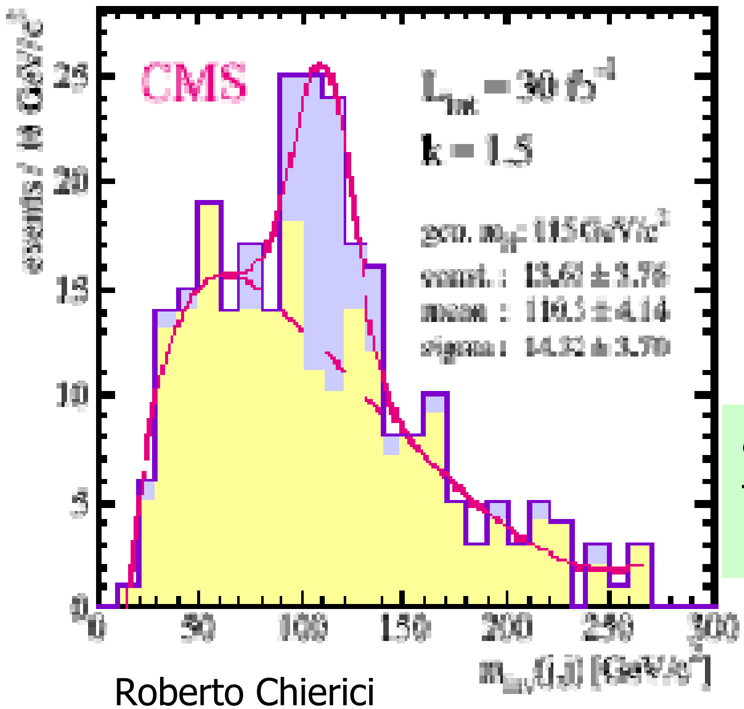


ttjj: 507 pb **ttZ: 0.7 pb** **ttbb: 3.3 pb**



Higgs boson reconstruction

- Reconstruct $ttH(h) \rightarrow WWbbbb \rightarrow (l\nu)(jj)bbbb$
- Isolated lepton selection using a likelihood method
- Jet reconstruction: 6 jets at least, 4 of which b-tagged
- Reconstruct missing E_T from four-momentum conservation in the event
  (+W mass constraint in z)
- Complete kinematic fit to associate the two bs to the Higgs
  (can improve the pairing efficiency to 36%, under investigation)



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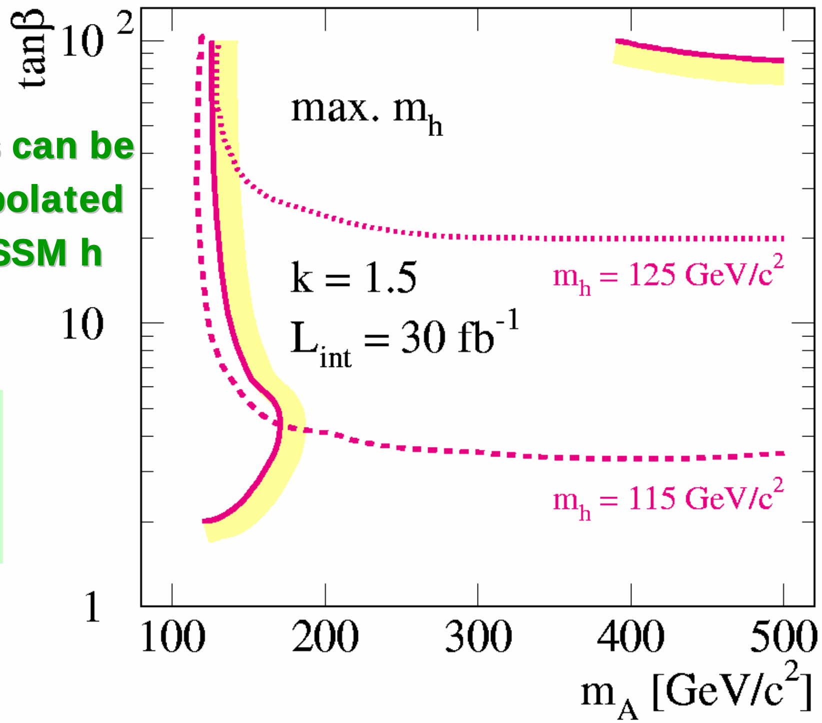
$\delta g_{ttH}/g_{ttH}$~16%
for m_H=120 GeV
hep-ph/0003033

results can be extrapolated to MSSM h



Conclusions

Top production at the CMS/LHC will be an excellent place where to:

1. make precision electroweak measurements and constrain the SM
   (m_t, σ_{tt}, top quantum numbers, PDF)
2. test the presence of new physics and explore beyond the SM
   (ttH, charged H, MSSM)
3. calibrate tools and detector
   (b-tagging, jet energy scale)

Provided that:

- we gather an accurate understanding of detector and backgrounds
- we know how to deal with systematics

At CMS we are working on that…

The physics TDR will be the occasion to show all the CMS potential in terms of both physics results and readiness to take and analyze data

Backup

Resonances

Many theoretical models include the existence of resonances decaying to top-pair

- SM Higgs (but BR smaller with respect to the WW and ZZ decays)
- MSSM Higgs (H/A, if $m_H, m_A > 2m_t$, BR($H/A \rightarrow tt$)≈1 for tanβ≈1)
- Technicolor Models, strong ElectroWeak Symmetry Breaking, Topcolor

Clear experimental signature and ability to reconstruct top also make it a useful "tool" for studying exotica

ATLAS: study of a resonance X once known σ_X, Γ_X and BR($X \rightarrow tt$)

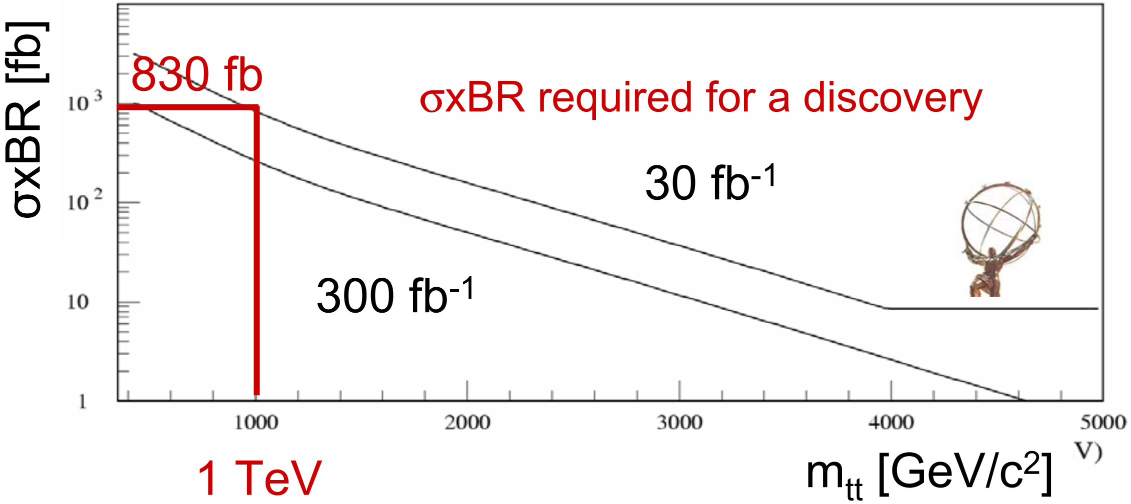
Reconstruction efficiency for semileptonic channel:

- 20% m_{tt}=400 GeV
- 15% m_{tt}=2 TeV

→ Shown sensitivity up to a few TeV

Re-do with full simulation testing:

- sensitivity
- mass resolution



Commissioning

Determination M_{Top} in initial phase

- Use 'Golden plated' lepton+jet

Period	Stat δm_t (GeV)	Stat $\delta\sigma/\sigma$
1 year	0.1	0.2 %
1 month	0.2	0.4 %
1 week	0.4	2.5 %

Selection:

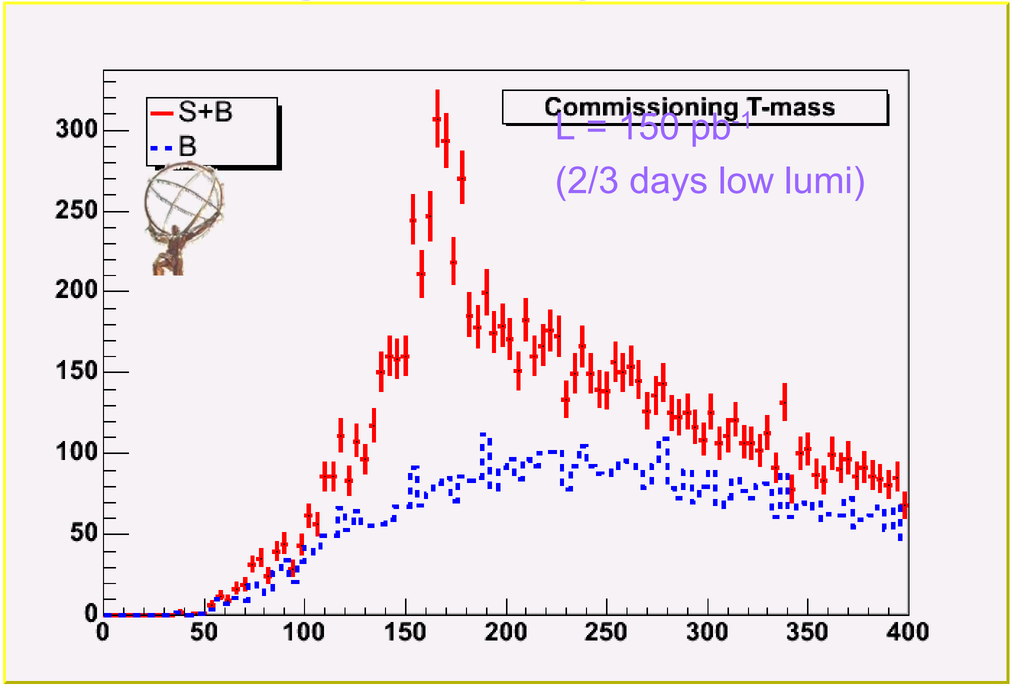
- Isolated lepton with P_T>20 GeV
- Exactly 4 jets (ΔR=0.4) with P_T>40 GeV

Reconstruction:

- Select 3 jets with maximal resulting P_T

With an extremely simple selection and reconstruction the top-peak should be visible at the LHC since the beginning

Main background: W+4jets



measure the top mass to 5-7 GeV

→ give feedback on detector performance

PS vs ME

Fixed order matrix elements: truncated expansion in α_S:

- Full helicity structure to the given order
- To be used for hard (compared to signal scale) jets.

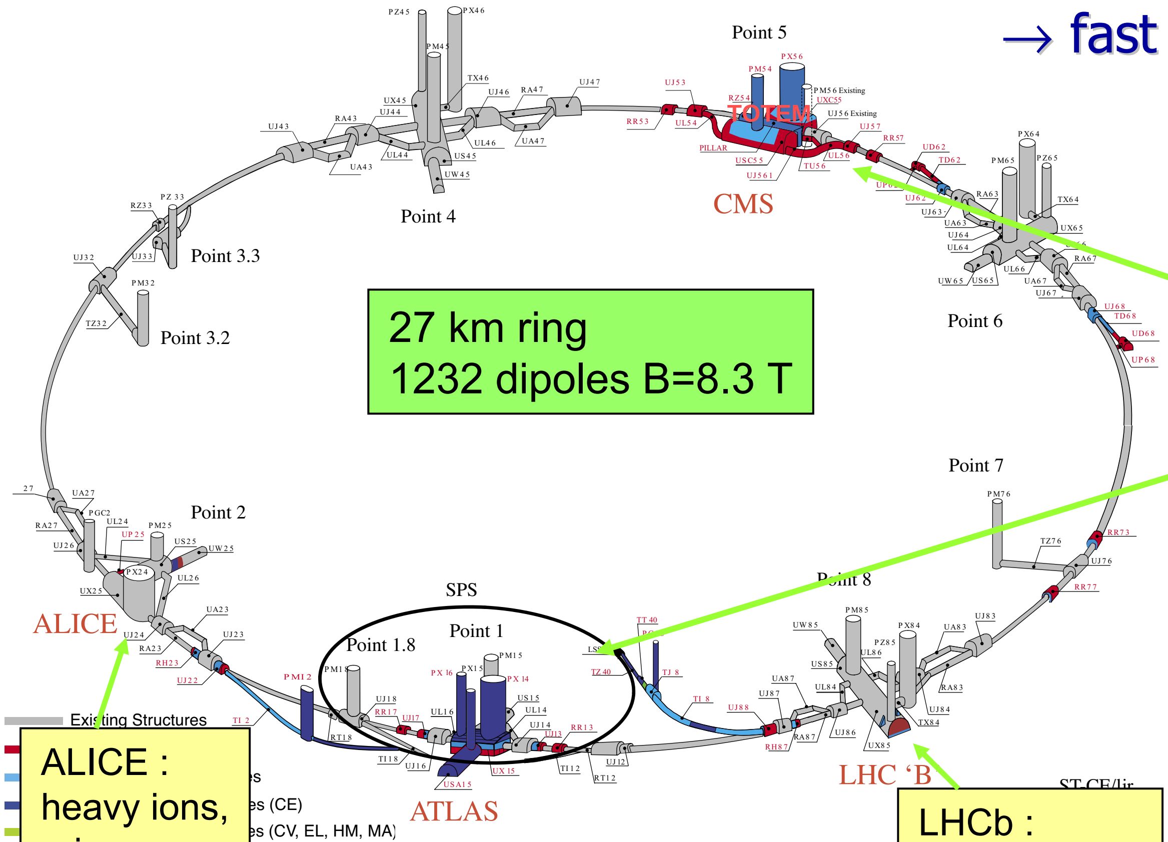
Parton Showers: infinite serie in α_S keeping only singular terms (collinear approximation):

- Excellent approximation at low p_T, with emission at any order and simple interface with hadronization models
- Large uncertainties away from singular regions
- To be used for soft (compared to signal scale) jets.

The LHC

pp (mainly) at $\sqrt{s}$ = 14 TeV
Startup in April 2007

- Initial/low lumi L≤10^{33} cm^{-2} s^{-1}
  a few minimum bias/crossing
- Design/high lumi L=10^{34} cm^{-2} s^{-1}
  after ~ 3 years
  >20 minimum bias/x-ing
  → fast (≤ 50 ns) radhard detect



27 km ring
1232 dipoles B=8.3 T

ATLAS and CMS :
pp, general purpose

ALICE :
heavy ions,
p-ions

LHCb :
pp, B-physics

Precisely constraining the SM

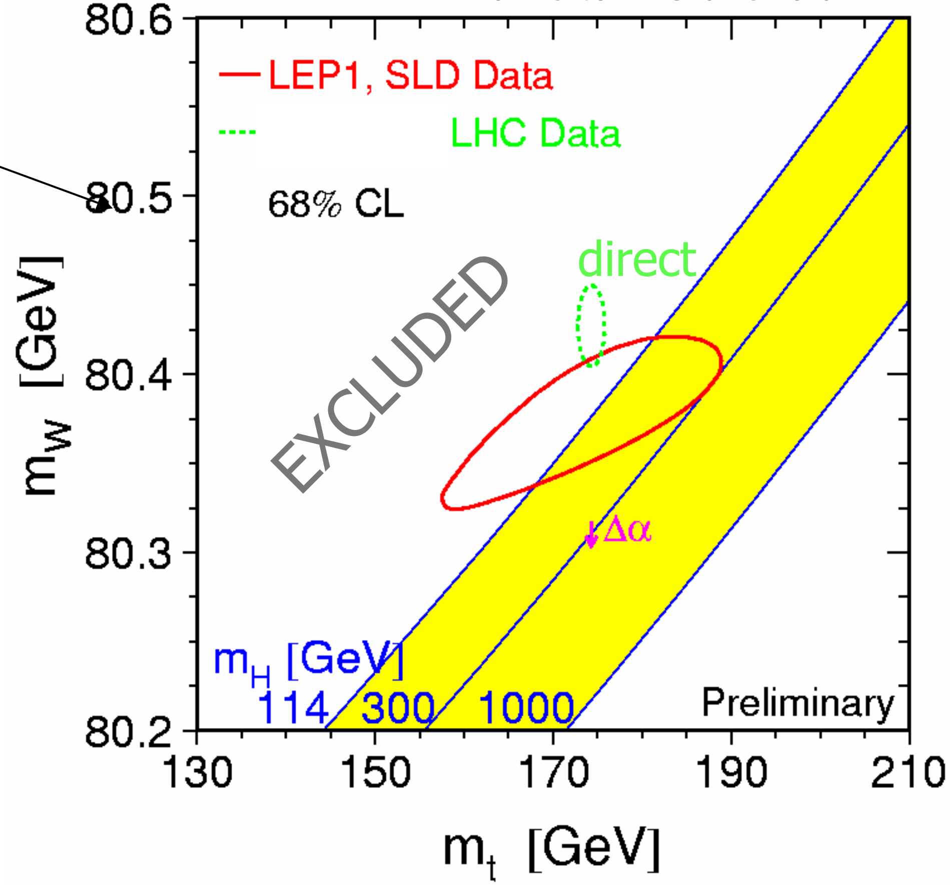
Repeating the electroweak fit only changing the errors on the top and the W masses:

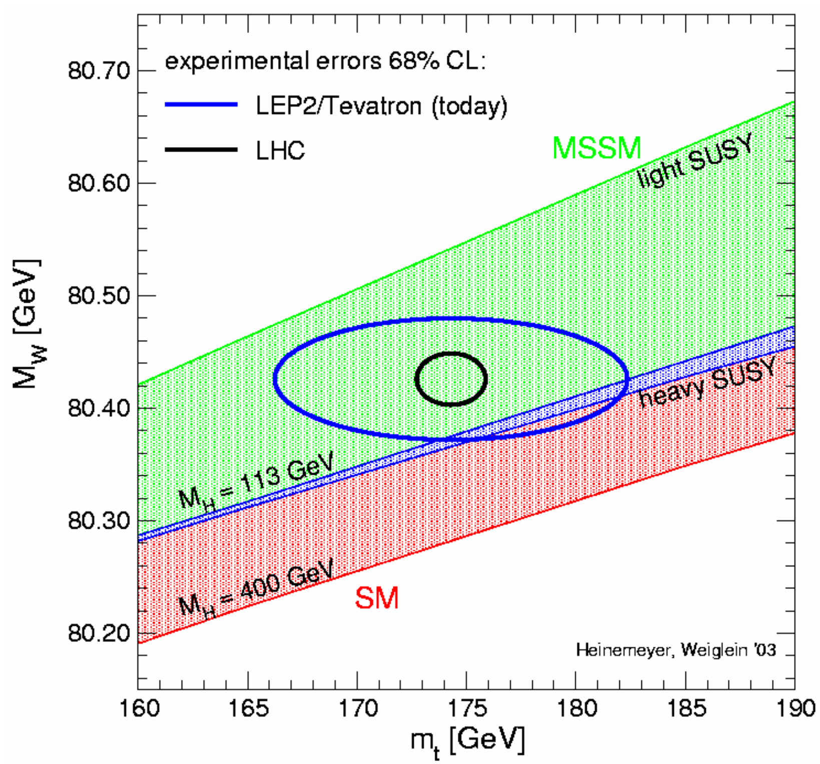
δm_W=15 MeV; δm_t=1 GeV

(world combined will look better than these ! – Tevatron run II, LEP2)

(current central values assumed)

Thanks to M.Grunewald



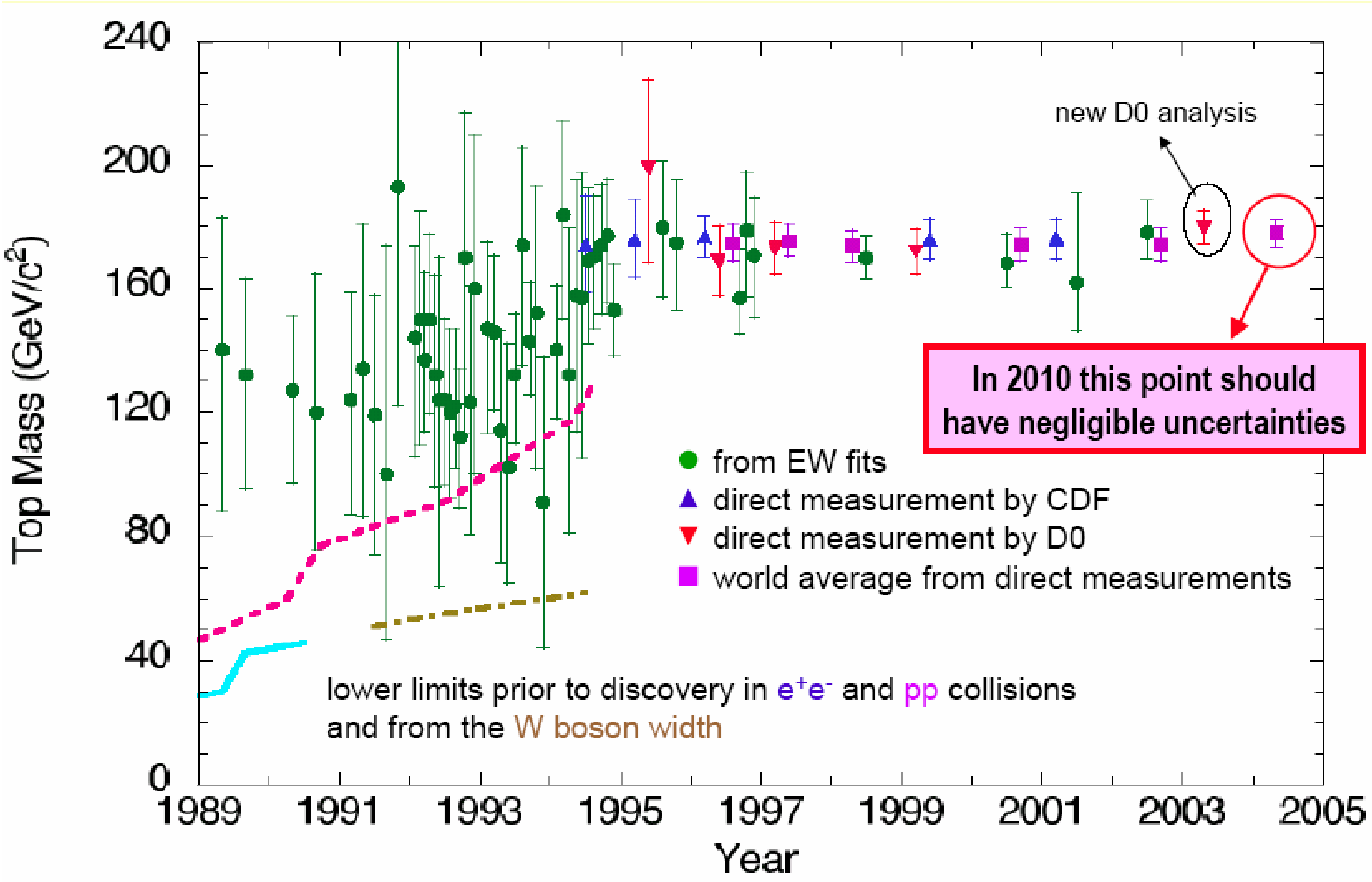


SM constraints on m_H: $\Rightarrow m_H = 73^{+20}_{-16}$

($\delta m_H / m_H \approx 25\%$)

⇒ Chances of ruling out the SM !

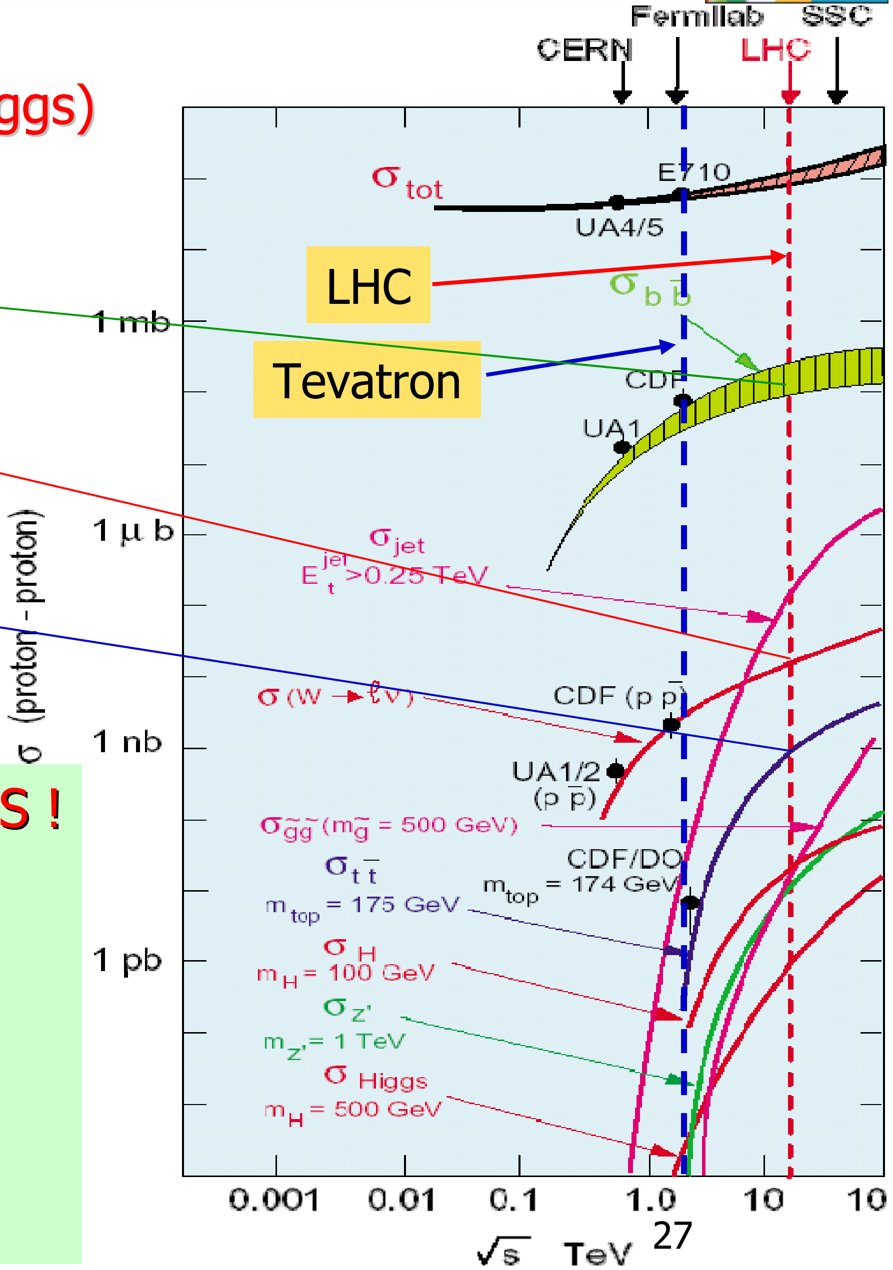
Top mass error evolution



A needle in a million haystacks

Triggering and selection phase typically require reduction factors of 10^{11} ! (i.e. Higgs)

process	σ(pb)	Events/s	Events/y
bb	5×10^{8}	10^{6}	10^{12}
$Z\rightarrow ee$	1.5×10^{3}	~3	10^{7}
$W\rightarrow e\nu$	1.5×10^{4}	~30	10^{8}
$WW\rightarrow e\nu X$	6	10^{-2}	6×10^{3}
tt	830	~2	10^{7}
H(700 GeV)	1	2×10^{-3}	10^{4}



Need of an excellent understanding of CMS !

- calibrated calorimetry
  - ECAL: use MB, $Z\rightarrow ee$, $W\rightarrow e\nu$, E/p
  - HCAL: Z+j, γ+j, $W\rightarrow jj$
- aligned detector
  - laser system
  - cosmic μ
  - beam halo

Generation tools

	Pythia	Herwig	ME	MC@NLO
Hard scattering	LO $t\bar{t}$	LO $t\bar{t}$	LO $t\bar{t}$+n	NLO $t\bar{t}$ (hard gluon)
PS shower (ISR/FSR)	**coherent branching (LO DGLAP)**	**coherent branching (LO DGLAP)**	Pythia or Herwig interface (double counting problem, can be fixed by the CKKW)	Herwig
Hadronization	LUND string	cluster model		
beam-beam remants, MPI	all	No MPI (Yes, v605)		
Spin corr	NO	Yes	Yes	No
Comments	Good for inclusive tt but poor in tt+njets		Good for multi-jets, but still LO	Good for tt multi jets

- ME: ALPGEN/MadGraph/ComHep/TopRex etc (Γ_t=0)

HLT performance

Event selection is conditioned by efficiency, bandwidth, CPU power

Different classes of selections:

- Inclusive triggers to cover the large part of the standard physics program
- Exclusive triggers to extend the physics program to specific sectors
- Calibration and monitor triggers to understand the status and performance of the detector

Each trigger receives part of the bandwidth. Thresholds will be changed according to new physics scenarios or detector needs

Process	ε (L1)	ε (L1+HLT)
$W \to e\nu$	87%, 90%	77%, 69%
$H \to \gamma\gamma$	91%	78%
$Z \to \mu\mu$	99%	92%
$tt \to \mu X$	94%	72%
$A/H \to \tau\tau \to 2$ jets	78%	45%
$H^{+} \to \tau\nu \to jet+E_{miss}$	81%	58%

(acceptance inefficiency not included)

low luminosity HLT trigger table

Trigger object	Threshold (GeV)	Rate (Hz)
Isolated muon	19	25
Double muon	7	4
Isolated electron	29	33
Double electron	17	1
Isolated photon	80	4
Double photon	40, 25	5
Single Jet, 3 Jet, 4 Jet	657, 247, 113	9
Jet + missing E	180,123	5
Inclusive tau jet	86	3
Di-tau-jet	59	1
Electron + jet	19, 45	2
Inclusive b-jets	237	5
Other (calibration...)		10
Total		**105**

Resolution comparison

	ATLAS	CMS
Single π resolution with ECAL + HCAL (E in GeV)	$\frac{\sigma}{E} = \frac{42\%}{\sqrt{E}} \oplus \frac{2\%}{E} \oplus 1.8\%$	$\frac{\sigma}{E} = \frac{127\%}{\sqrt{E}} \oplus 6.5\%$
100 GeV π	4.6%	14.3%
Jet resolution with calorimetry (E in GeV)	$\frac{\sigma}{E} = \frac{54\%}{\sqrt{E}} \oplus 1.3\%$	$\frac{\sigma}{E} = \frac{118\%}{\sqrt{E}} \oplus 7\%$
100 GeV jet	5.6%	13.7%
1 TeV jet	2.2%	7.2%
Resolution from inner tracking (p_T in TeV)	$\frac{\sigma}{p_T} = 60\% \cdot p_T + 1.8\%$	$\frac{\sigma}{p_T} = 15\% \cdot p_T + 0.5\%$
100 GeV p_T μ	6.3%	1.6%
500 GeV p_T μ	30%	7%

Trigger CPU, rate, speed

HLT trigger table

HLT trigger table	Threshold (GeV or GeV/c)	Rate (Hz)	Cumulative Rate (Hz)
Inclusive electron	29	33	33
Di-electrons	17	1	34
Inclusive photons	80	4	38
Di-photons	40, 25	5	43
Inclusive muon	19	25	68
Di-muons	7	4	72
Inclusive τ-jets	86	3	75
Di-τ-jets	59	1	76
1-jet * E_T^{miss}	180 * 123	5	81
1-jet OR 3-jets OR 4-jets	657, 247, 113	9	89
Electron * Jet	19 * 45	2	90
Inclusive *b*-jets	237	5	95
Calibration and other events (10%)		10	105
TOTAL			105

Physics Object	CPU time per Level-1 event (ms)	Level-1 Trigger rate (kHz)	Total CPU time (s)
Electrons/photons	160	4.3	688
Muons	710	3.6	2556
Taus	130	3.0	390
Jets and E_T^{miss}	50	3.4	170
Electron + Jet	165	0.8	132
B-jets	300	0.5	150

X =

How to plan a L1 trigger:
100(50) KHz @ high(low) lumi
⇓
33(15) KHz safety factor 3
⇓
8(4) KHz per physics object

CPU per physics object at L1:
1 GHz Intel PIII CPU (=41 SpecInt95)

- 4092 CPU seconds to cover the full 15 KHz of L1 @ low lumi
- on average ~300ms/event
- considering full 100KHz one needs 30000 PIII
  ⇒ 1.2 10^6 SI95

At the start of LHC (50 KHz+a factor 8 from Moore's law) 2000 CPUs should be enough

Early physics with CMS

Possible from April 2008, after the pilot run is over…

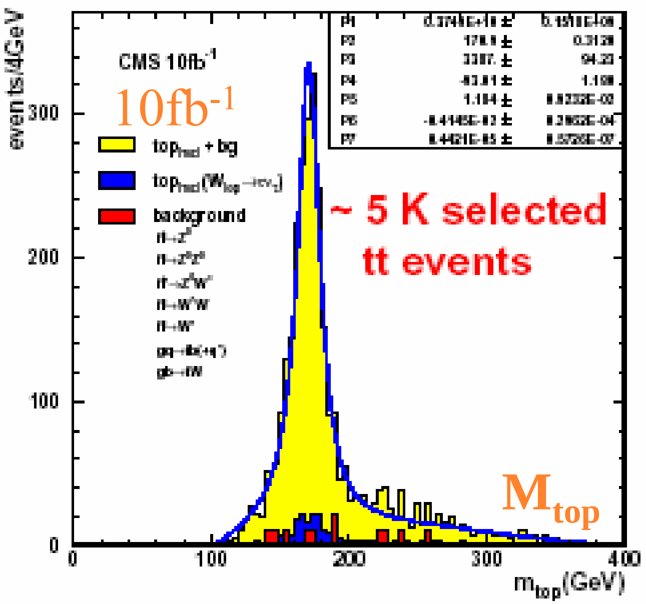
⇒ The first thing we need to understand/measure …

channel, NLO σ x Br	Level-1 + HLT efficiency	events for10 fb^{-1}
W->e ν, 20.3 nb	0.25	5.1×10^7
W->μν, 20.3 nb	0.35	7.1×10^7
Z->ee, 1.87 nb	0.53	1.0×10^7
Z->μμ, 1.87 nb	0.65	1.2×10^7
tt~->μ+X, 187 pb	0.62	1.2×10^6

Basic rates for W, Z, tt, …

Important for:

- calorimeter calibration, alignment, …
- the understanding of the major background sources for Higgs and SUSY searches such as Z+nj, W+nj, tt, …



Yet, there are also very exciting SM measurements!

Example: M_{top} from tt→WbWb→ bbqqlν

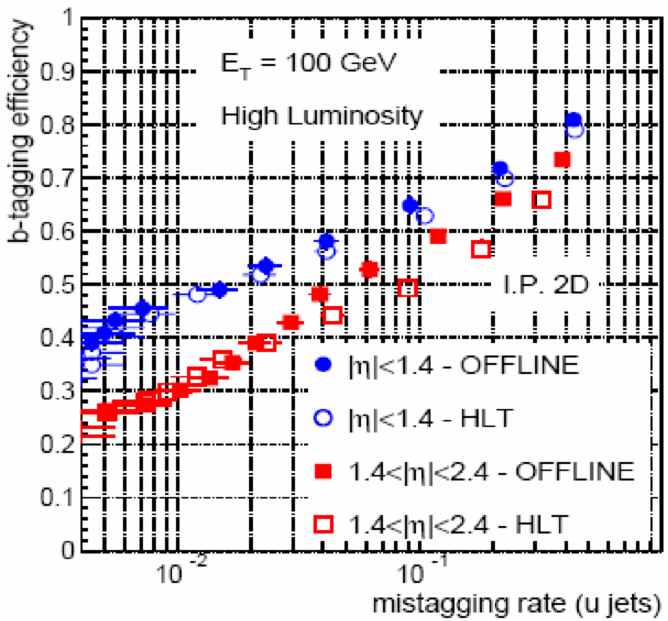
Ingredients:

- full kinematic reconstruction (utilize all constraints)
- b-tagging of jets
- isolated lepton + jet reconstruction + E_T^{miss}

⇒Target **ΔM_{top}~1GeV**
A clear challenge because this measurement is completely limited by systematic!
… looks like a perfect learn exercise …

The b-tagging

It is performed exploiting the b decay characteristics:
→ IP of decay tracks, vertex displacement, high p_T lepton

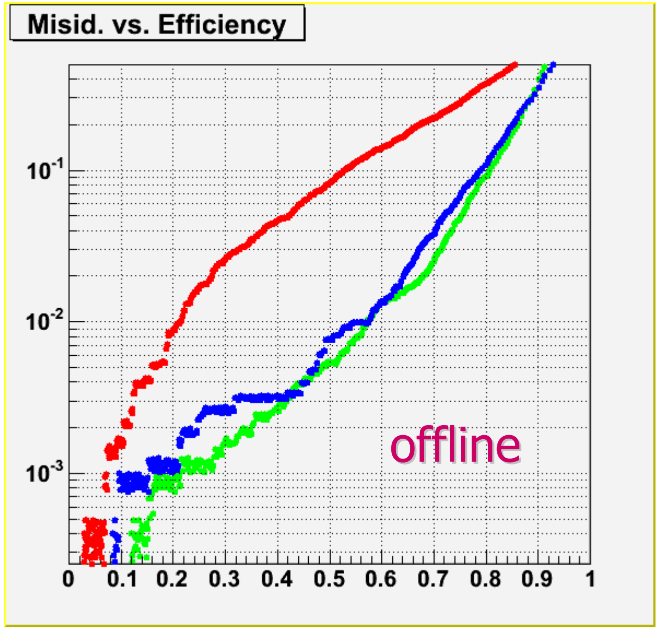


60% b tag => ~ 6% u jet mis-tag
1% u jet mis-tag => ~ 45% b jet tag

u jet rejection
- limited by vertex detector quality
- 60% b tag => ~ 1% u jet mis-tag

c jet rejection
- limited by c lifetime

g jet rejection
- limited by g splitting to bb (4%) or cc (6%)



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A

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner cavity Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels+ strips TRD $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 5x10^{-4}\ p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5x10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow$ σ/p_T < 10 % at 1 TeV standalone; larger acceptance	Fe $\rightarrow$ $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker