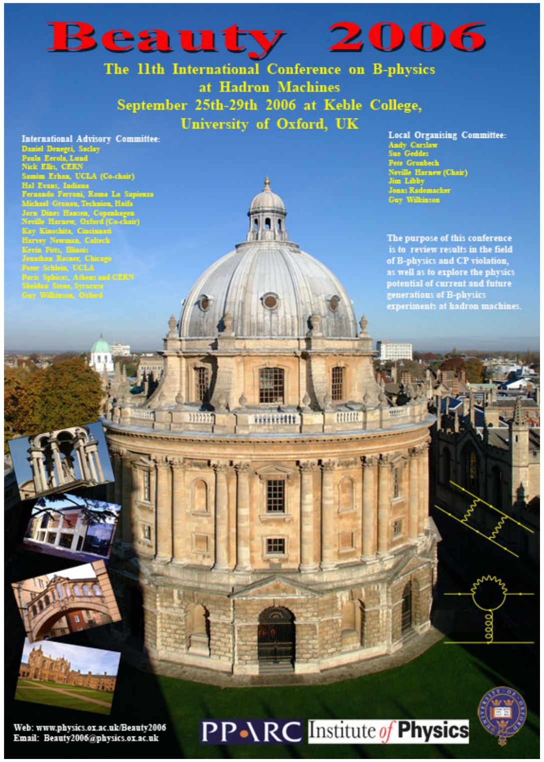
CMS Commissioning and Early Physics

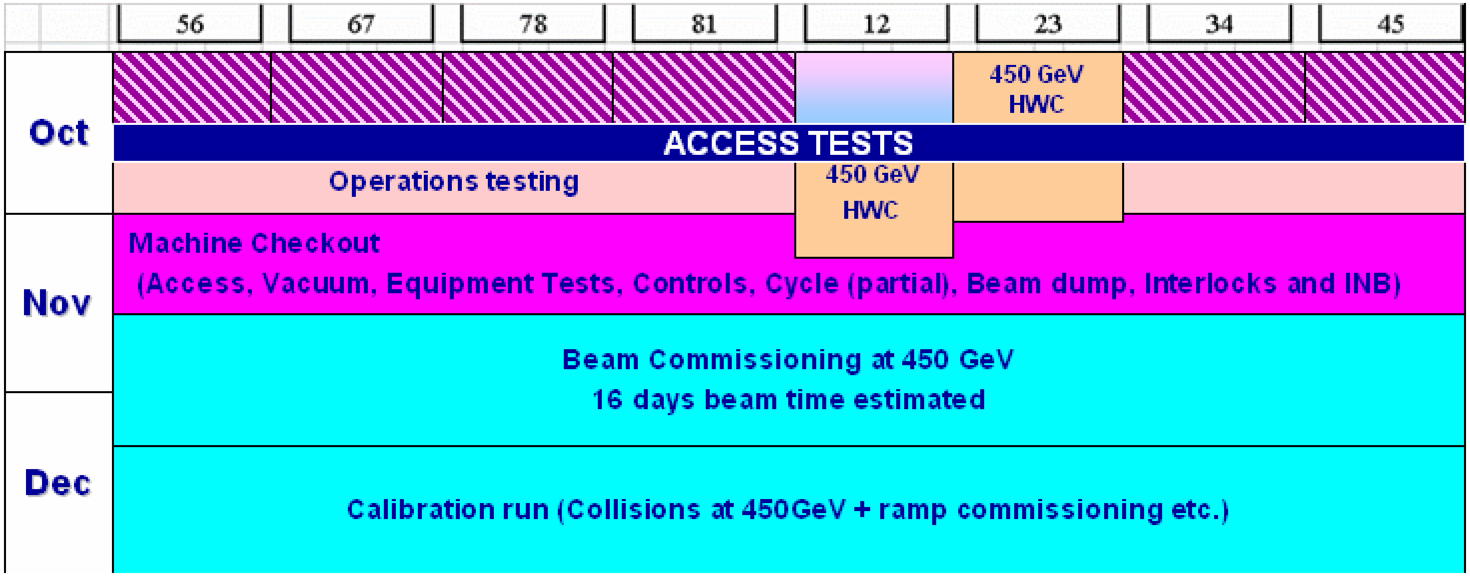
Frank-Peter Schilling (CERN)

BEAUTY 2006, Oxford, September 2006



- LHC startup schedule
- Commissioning overview and data sets
- Commissioning tasks
  - Trigger
  - Alignment
  - Calibration
  - b-tagging
- Examples for early physics and discovery potential in 2008-9

LHC startup schedule in 2007



- 1st September 2007: Experiments closed: Startup LHC machine
- Beam commissioning with single beams
- December 2007: ~3 weeks collisions ("calibration run")
  - E_p=450 GeV (injection energy)
  - L~10^{29} $cm^{-2}s^{-1}$

			Reasonable	Maximum
k_b	43	43	156	156
i_b (10^{10})	2	4	4	10
β* (m)	11	11	11	11
intensity per beam	8.6 10^{11}	1.7 10^{12}	6.2 10^{12}	1.6 10^{13}
beam energy (MJ)	.06	.12	.45	1.1
Luminosity ($cm^{-2}s^{-1}$)	2 10^{28}	7.2 10^{28}	2.6 10^{29}	1.6 10^{30}
event rate [1](kHz)	0.4	2.8	10.3	64
W rate [2] (per 24h)	0.5	3	11	70
Z rate [3] (per 24h)	0.05	0.3	1.1	7

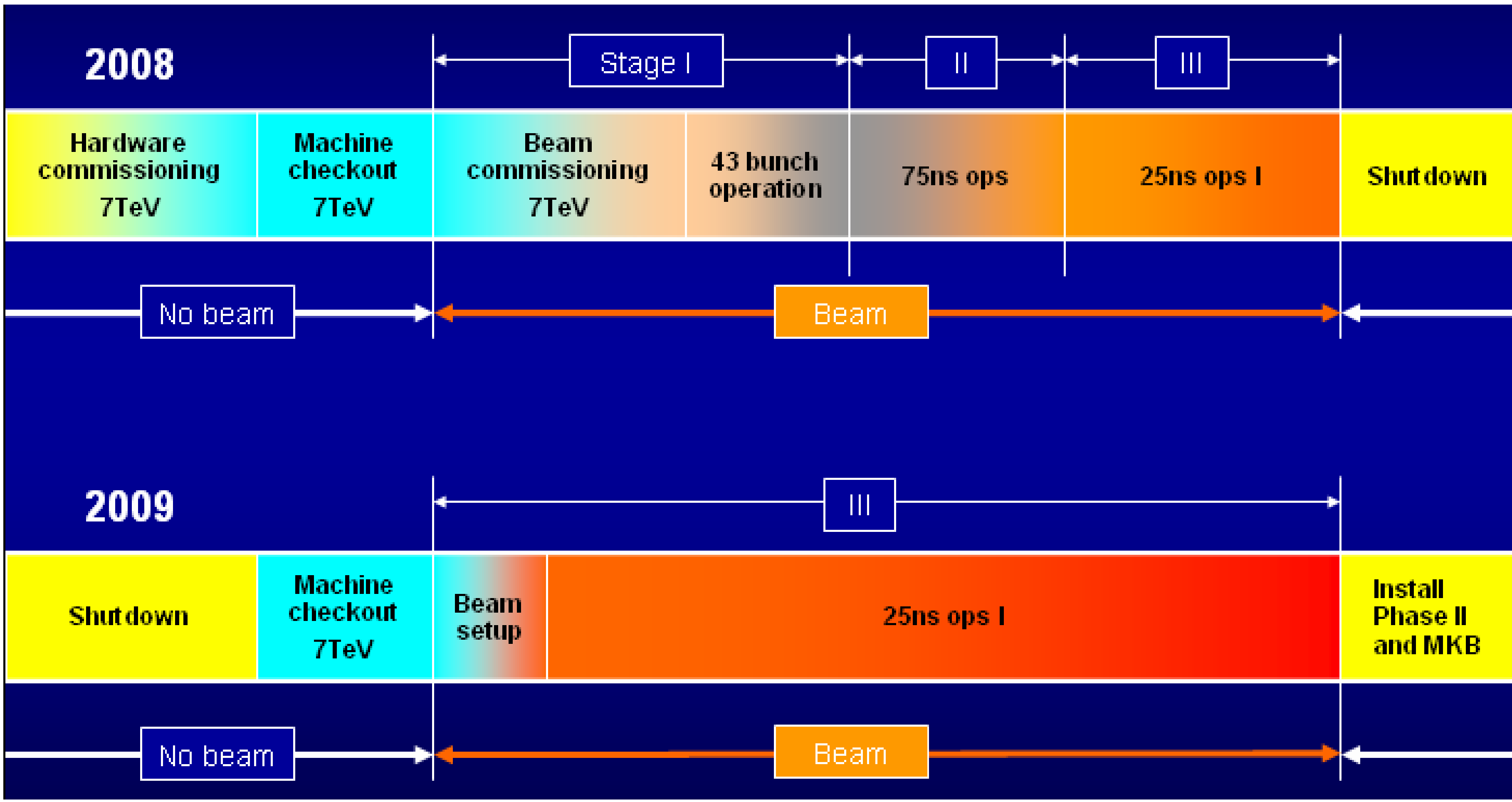
Several days →

Staged commissioning plan for protons at 7 TeV

Stage I: "Pilot physics" ~1 month, 43 bunches, no crossing angle, $L<10^{32}\ cm^{-2}s^{-1}$

Stage II: 75ns operation, push crossing angle and squeeze, $L<10^{33}$

Stage III: 25ns operation, nominal crossing angle, $L<2*10^{33}$



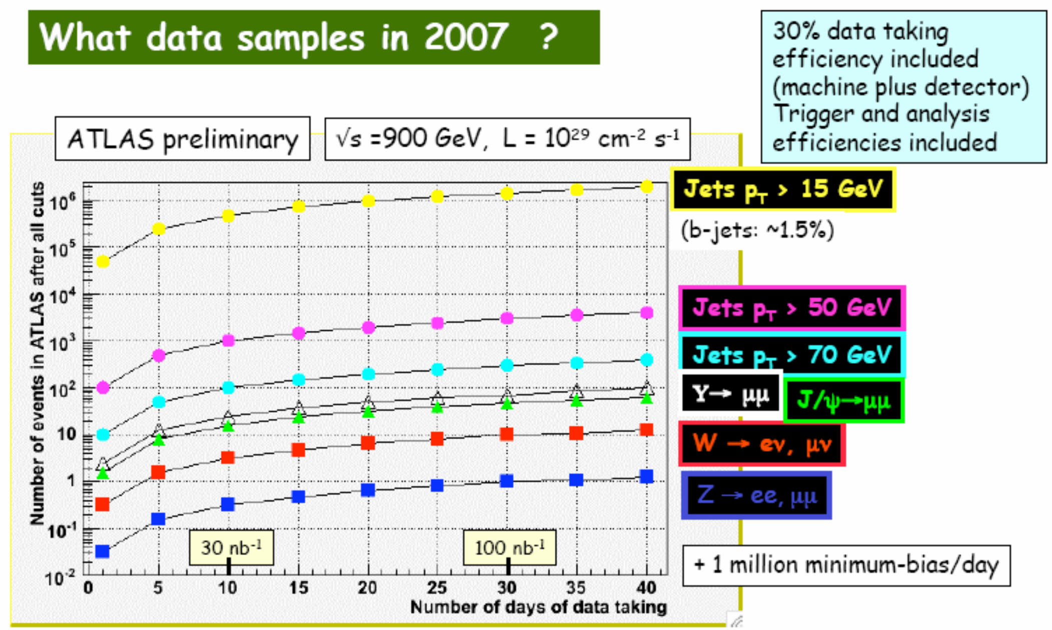
Data scenarios for CMS Commissioning

- **No beams (Sept-Nov 2007)**
  - Cosmic Muons
- **Single beam commissioning (Nov-Dec 2007)**
  - Beam halo muons
  - Beam gas interactions
- **Calibration Run (Dec 2007)**
  - 3 weeks, 2*450 GeV, L~10^{29}
  - Millions of min. bias
  - QCD jets
- **Pilot physics Run (2008)**
  - 2*7 TeV, L=$10^{32...33}$
  - Signficiant W,Z rates
  - Top becoming accessible

For efficient commissioning of the experiment all of these datasets must be fully exploited

- **Evemt Rates in Calibration Run 2007**

F. Gianotti (ATLAS, ICHEP 2006)



- **Rates for Z,W in 2008**

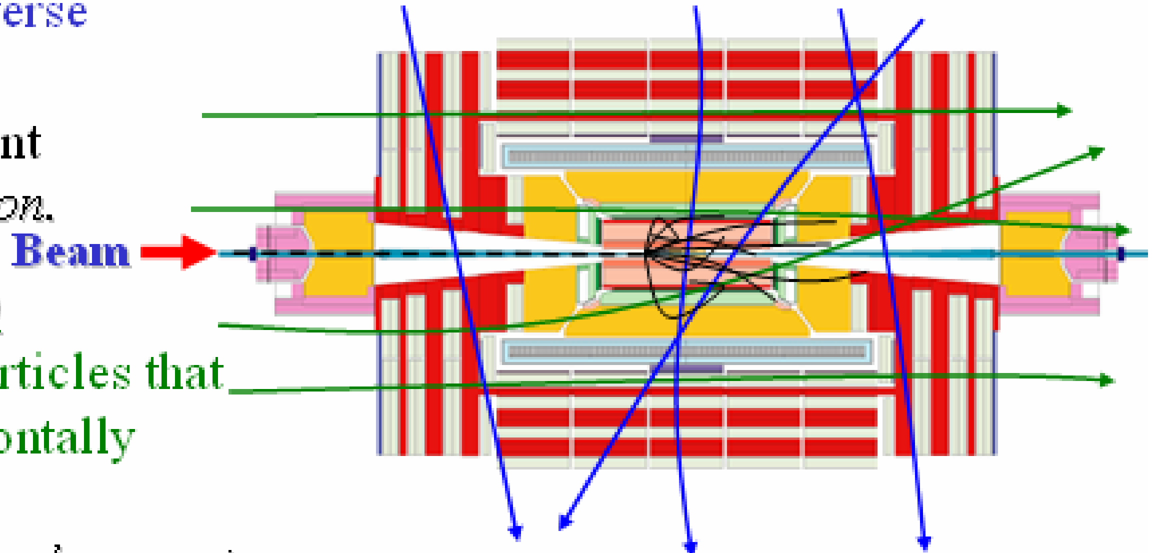
Luminosity	10^{32} cm^{-2}s^{-1}		$2*10^{33}$ cm^{-2}s^{-1}		
Time	few weeks	6 months	1 day	few weeks	one year
Int. Luminosity	100 pb^{-1}	1 fb^{-1}		1 fb^{-1}	10 fb^{-1}
$W^\pm \to \mu^\pm \nu$	700K	7M	100K	7M	70M
$Z^0 \to \mu^+ \mu^-$	100K	1M	20K	1M	10M

Pre-Collision Data

Cosmic Muons

High energetic muons that traverse the detector vertically

→particular useful for alignment and calibration - *barrel region.*



Beam Halo Muons (Hadrons)

Machine induced secondary particles that cross the detector almost horizontally

→particular useful for alignment and calibration - *endcap region.*

Beam Gas Interactions

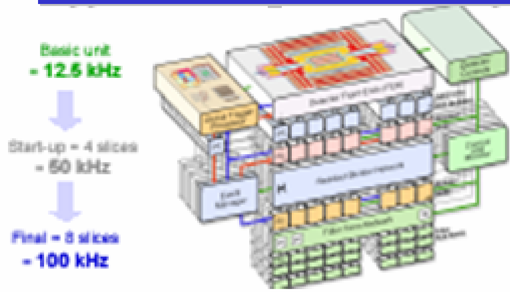
Proton-nucleon interaction in the active detector volume (7TeV→E_{cm}=115 GeV)

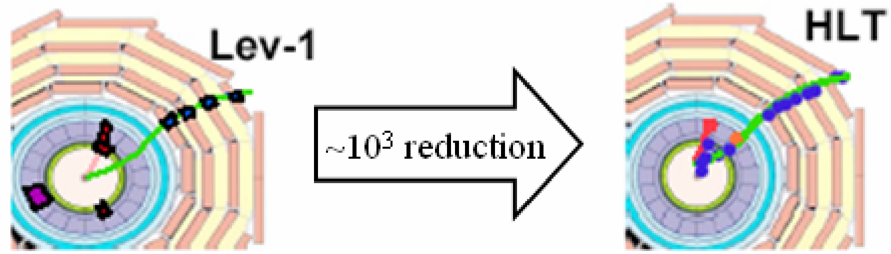
→resemble collision events but with a rather soft p_T spectrum (p_T<2 GeV)

All three physics structures are interesting for alignment, calibration, gain operational experience, dead channels, debug readout, etc …

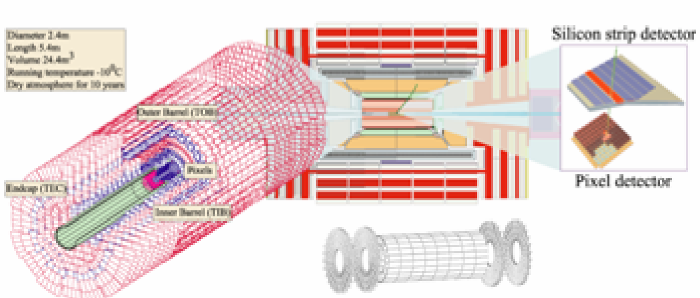
Major Commissioning Challenges

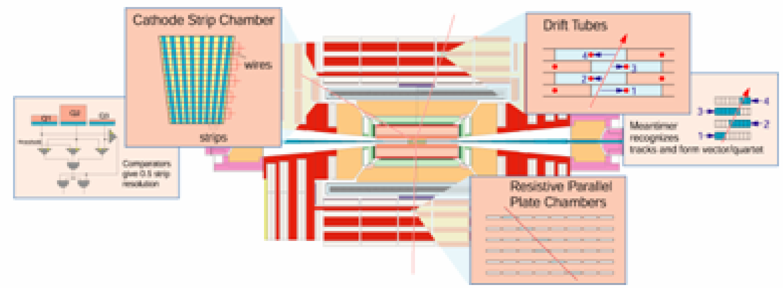
Efficient operation of Trigger (Level1/HLT) and DAQ System



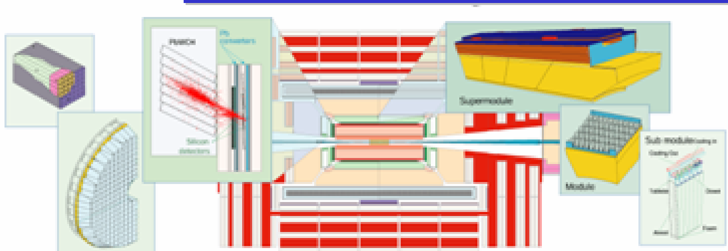


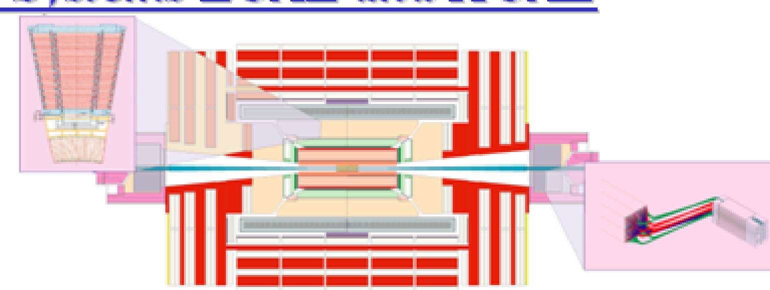
Alignment of the tracking devices Tracker(PIXEL,Strip) and Muon System





Calibration of the Calorimeter Systems ECAL and HCAL





→form the base for the "commissioning of physics tools" like b and τ tagging, jets, missing E_T …

Commissioning at the "2007 Calibration Run"

Assume that we get a reasonable amount of collision data which are completed by significant Cosmic Muon and Beam Gas/Beam Halo Muon datasets.

What can be done ...

LVL1/HLT/DAQ

Timing-in, data coherence, sub-system synchronization, calibration, debug algorithms, …

ECAL and HCAL calibration

Utilize dedicated calibration stream (1kHz) for min.bias events to:

- Intercalibrate barrel crystals - "Phi Symmetry Method" → ~2%
- Cross check and complete source calibration for HCAL channels → ~2%

Tracker and Muon alignment

Utilize tracks from Cosmic and Beam Halo Muons as well as collision tracks to:

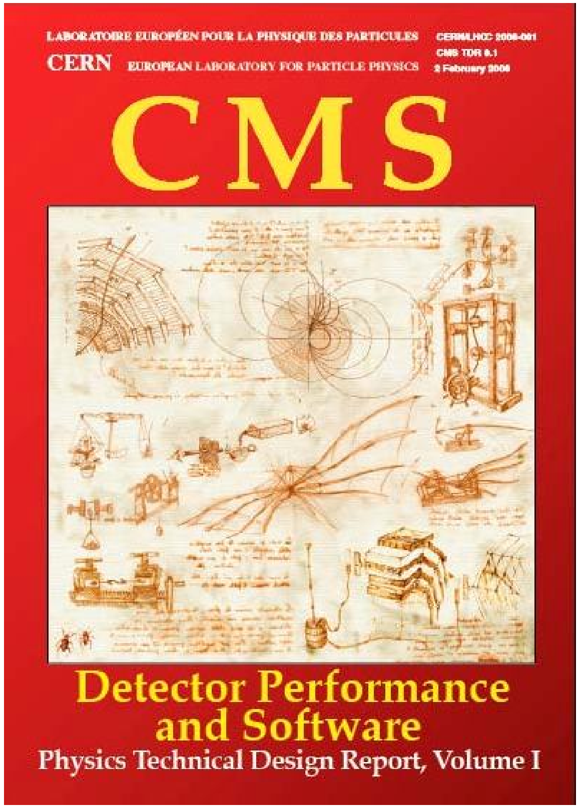
- To align the tracker strip detector significantly below the 100 μm level
- To align the muon chambers at the 100 μm level

What can't be done ... (left over for 2008 Physics Run)

- final HCAL and ECAL barrel calibration (need large $W \to e\nu$ and $Z \to ee$ samples)
- final alignment (not enough statistic and no PIXEL)
- no full E_T^{miss} calibration (not enough statistic)
- no b-tag calibration (no PIXEL detector)

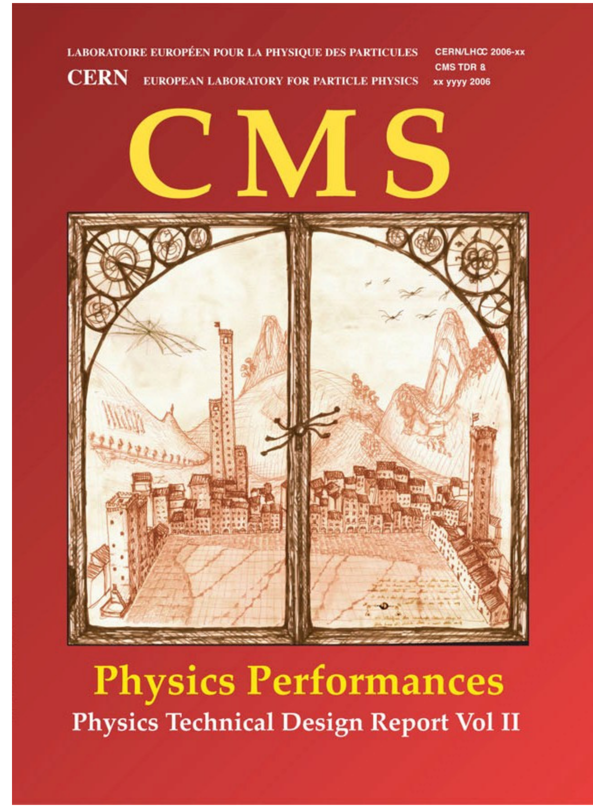
New: CMS Physics TDR

- **Vol.1: CERN/LHCC 2006-001**



- **Detector performance**
- **Alignment & Calibration procedures**
- **Reconstruction algorithms (tracks, e, μ, jets, MET, b, τ…)**

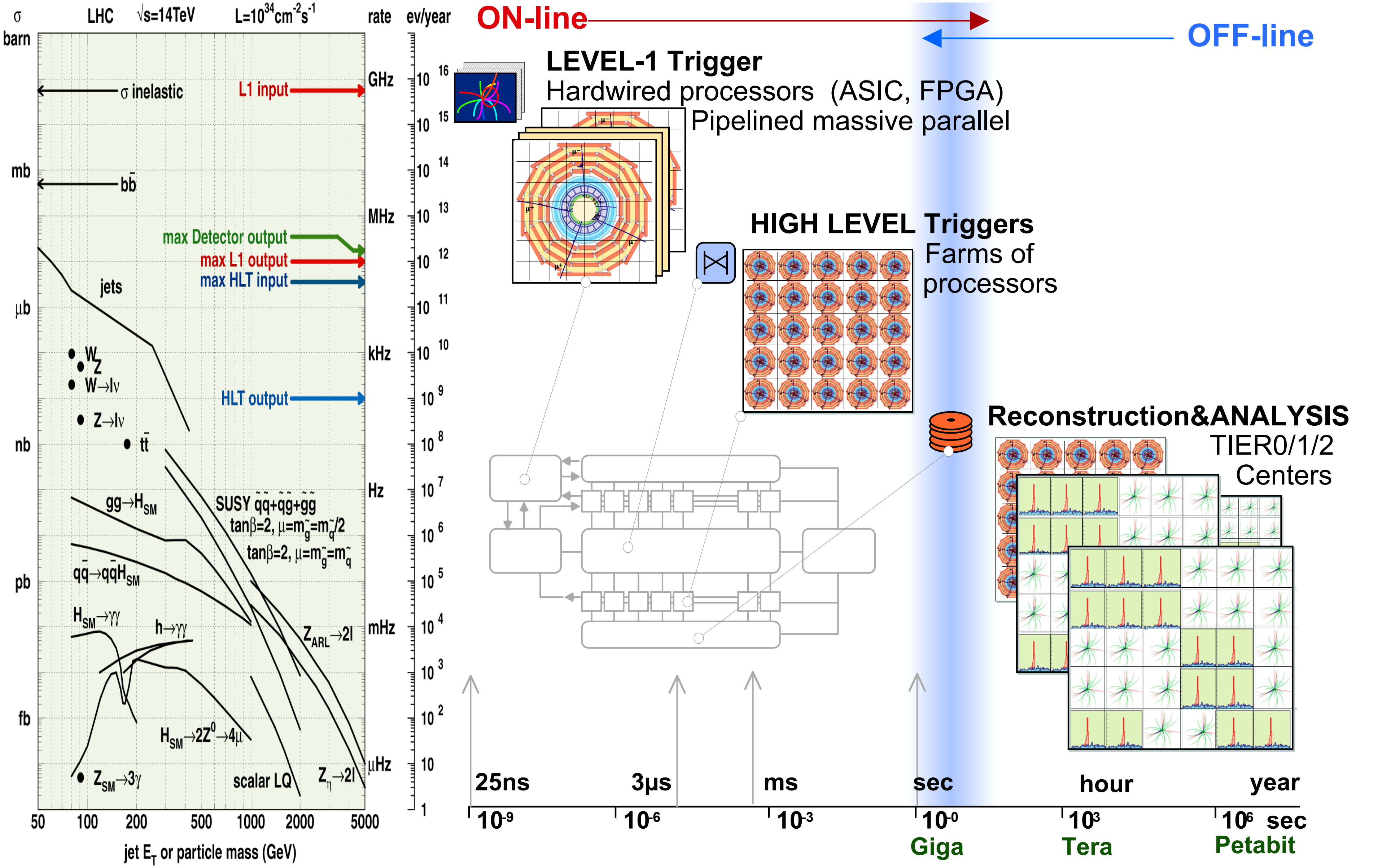
- **Vol.2: CERN/LHCC 2006/021**



- **Physics Performance**
- **Full analyses (incl. systematics, miscalibration etc.)**
- **Physics Reach**

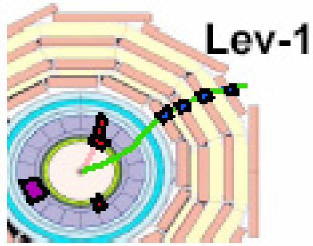
http://cmsdoc.cern.ch/cms/cpt/tdr/

Event Selection & Trigger (L1&HLT)



Level-1&HLT @ low Lumi

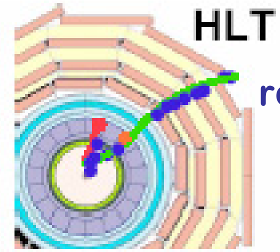
Tot Rate x Safety = Rate
50 kHz x 1/3 ~ 16kHz
~1/4 per class
(e/γ, muon, tau, jet)
+ 1kHz calibration



Channel	Threshold [GeV] ε = 95%	Individual Rate [kHz]
Inclusive isolated e/γ	29	3.3
Di-electrons/di-photons	17	1.3
Inclusive isolated muon	14	2.7
Di-muons	3	0.9
Single tau-jet trigger	86	2.2
Two tau-jets	59	1.0
1-jet, 3-jets, 4-jets	177 , 86 , 70	3.0
Jet * E_T^{miss}	88 * 46	2.3
Electron * jet	21 * 45	0.8
Min-bias (Calibration)		0.9

Sum ~16kHz

Event Selection: ~10^3 reduction from Level-1 to HLT



Utilize dedicated offline reconstruction tools at HLT.
No intermediate level (i.e. Level-2) required.

Channel	Threshold [GeV] ε = 90...95%	Rate [Hz]
1 e, 2 e	29 , 17 + 17	34
1 γ, 2 γ	80 , 40 + 25	9
1 μ, 2 μ	19 , 7 + 7	29
1 τ, 2 τ	86, 59 + 59	4
1-jet OR 3–jet OR 4	657 , 247, 113	9
e * jet	19 + 45	2
Jet * E_T^{miss}	180 + 123	5
Inclusive b-jets	237	5
Calibration,Other		~10
Sum		~105 Hz

Efficient Level1/HLT operation is insured when:

ECAL and HCAL calibrated to ~2%; Muon System aligned ~500 μm, Silicon Strip Detector aligned ~20 μm; PIXEL detector aligned to ~10 μm.

⇒Most of these requirements can already be met during the Pilot Physics Run

Tier-0 Data Streams

- **Prototype data streams created at Tier-0**

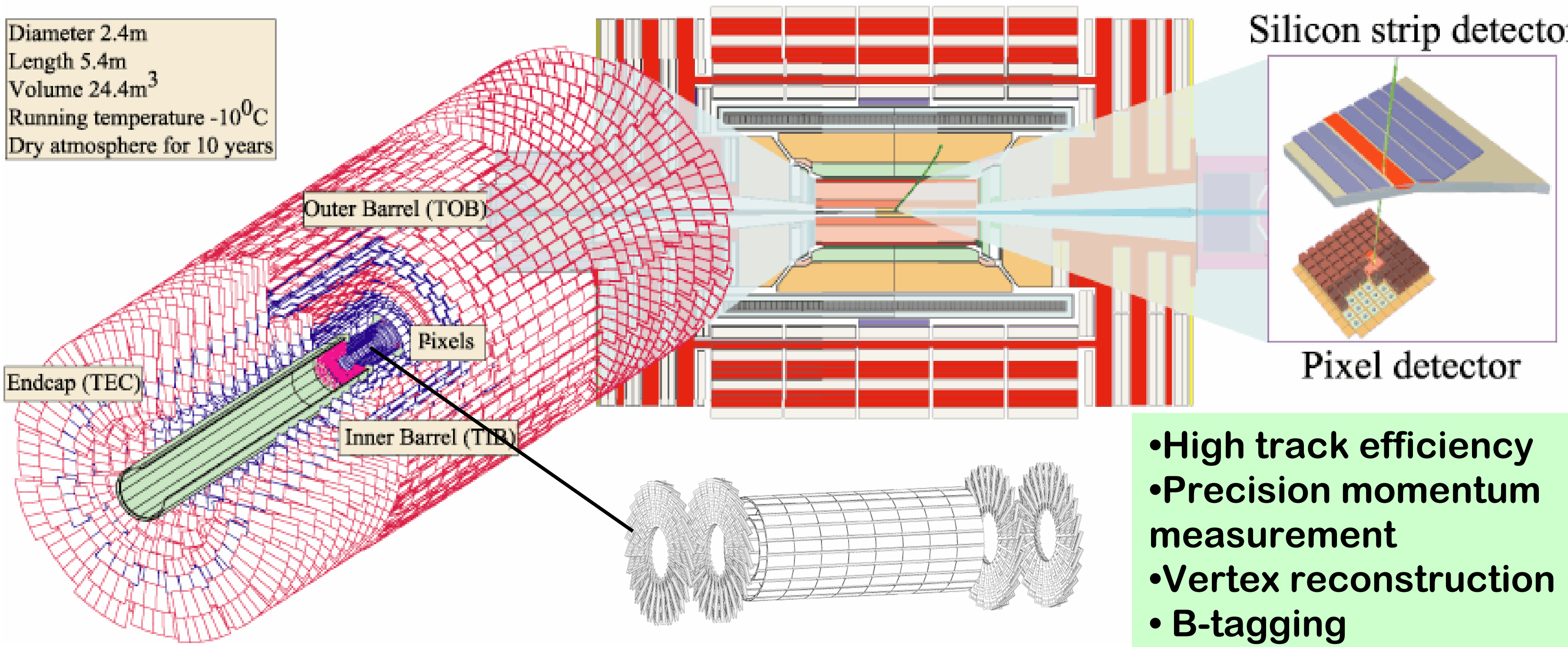
Stream	Dataset	HLT σ	Stream	Dataset	HLT σ
A Express	Selected $J/\Psi \to \mu\mu$		E	Single τ L1 bit 10	
	$W \to e\nu$			Di-τ L1 bit 13	
	$W \to \mu\nu$			3-τ L1 bit 16	
	$Z \to ee$			4-τ L1 bit 19	
	$Z \to \mu\mu$			EM + τ L1 bit 26	
	high-P_T jets			$\mu + \tau$ L1 bit 22	
	diobject mass				
B	Single Iso EM L1 bit 2		F	Jets L1 bits 8,9,11,12,14,15, 17,18	
	Iso di-EM L1 bit 3			SumET L1 bit 6	
	di-EM L1 bit 4				
	Single EM + μ L1 bit 5				
C	Single EM+jet L1 bit 24,25		G	MET inclusive L1 bit 7	
	di-EM L1 bit 4			MET+jet L1 bit 28,29	
	Single EM + μ L1 bit 5			MET + tau L1 bit 30	
				MET + μ L1 bit 23	
D	Single μ L1 bit 0		H	min-bias	
	Single μ+jet L1 bit 20,21			diffractive	
	Di-μ L1 bit 1				

- **Express stream:**
  - **Fast availability (~1h)**
  - **Monitoring (efficiencies)**
  - **calibration and alignment**
  - **High mass signals**

- ECAL response
  - high P_T electron
  - high P_T cluster (no track)
  - $Z \to ee$
  - $J/\Psi, \Upsilon$ to ee
  - diphoton
- Calorimeter response
  - photon+jet
  - Dijet
  - Isolated tracks
- Global Calo Integrity
  - high-P_T jet
  - P_T^{miss}
  - $\sum P_T$
- tracking efficiency / momentun scale/ alignment/ muon efficiency
  - $Z \to \mu\mu$
  - $J/\Psi, \Upsilon$ to $\mu\mu$
  - $W \to \mu\nu$
  - isolated high-P_T track (HLT)
  - 2-isolated high-P_T tracks (HLT) + Z mass window
- vertexing precision/beam monitoring
- b-tagging
  - $Z \to b\bar{b}$
- τ-tagging
  - $Z \to \tau\tau$
- "pandora"
  - very high mass di-EM
  - very high mass di-μ
  - very high mass dijet
  - very high P_T di-object + MET
  - other weird combinations (small rates)

Tier-0 RTAG Report CMS Note 2006/095

Silicon Tracker Alignment



- High track efficiency
- Precision momentum measurement
- Vertex reconstruction
- B-tagging
- ...

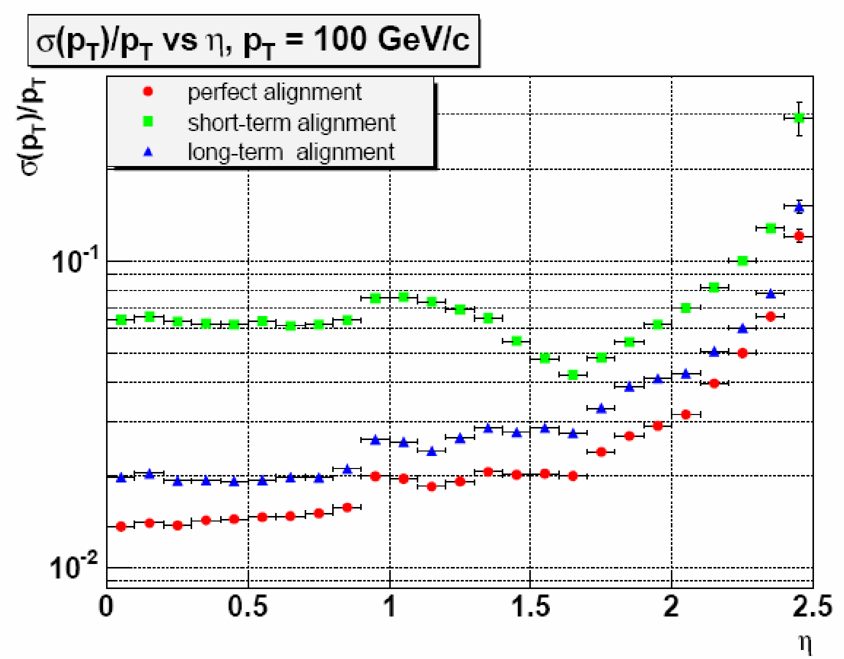
- CMS Tracker: Silicon Strip and PIXEL detectors
- ~16000 sensors with intrinsic resolutions of ~20μm
- Alignment of the CMS tracker is a real challenge!
- Laser Alignment + Track-based Alignment

⇒Need to align ~200m² of silicon (16000 modules) at the 10μm level!

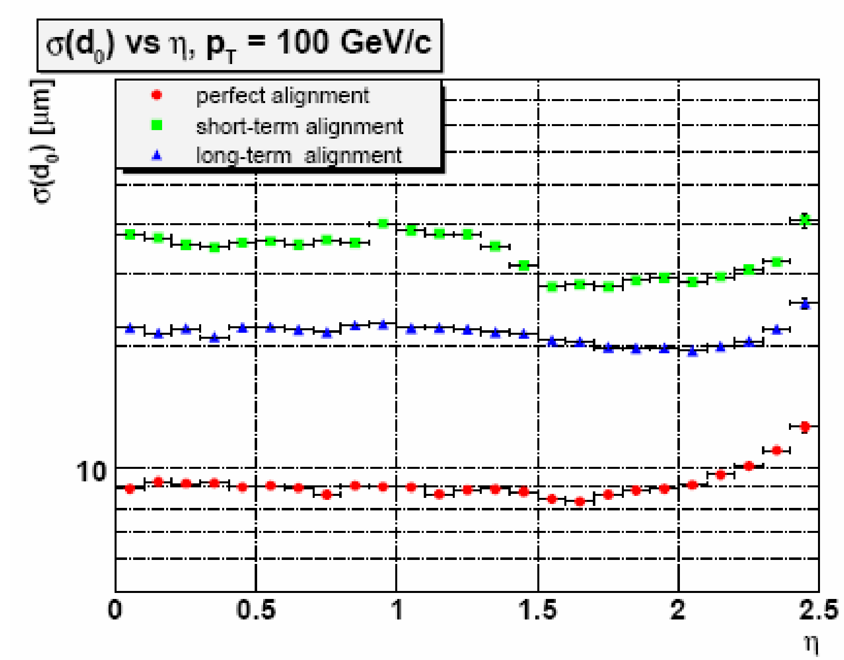
Impact of Misalignment

- **Single muons with Pt=100 GeV (typical scale for LHC physics, resolutions not dominated by multiple scattering)**

- **Transverse Momentum Resolution**

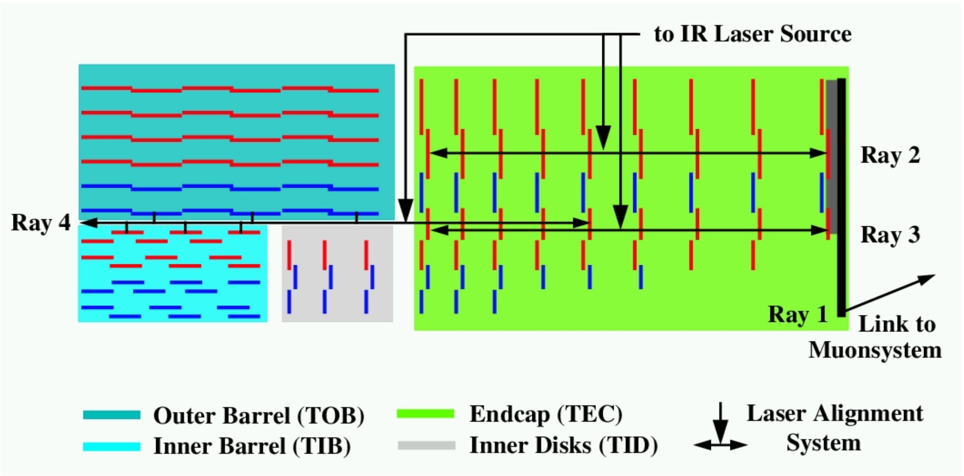


- **Transverse Impact Parameter resolution**



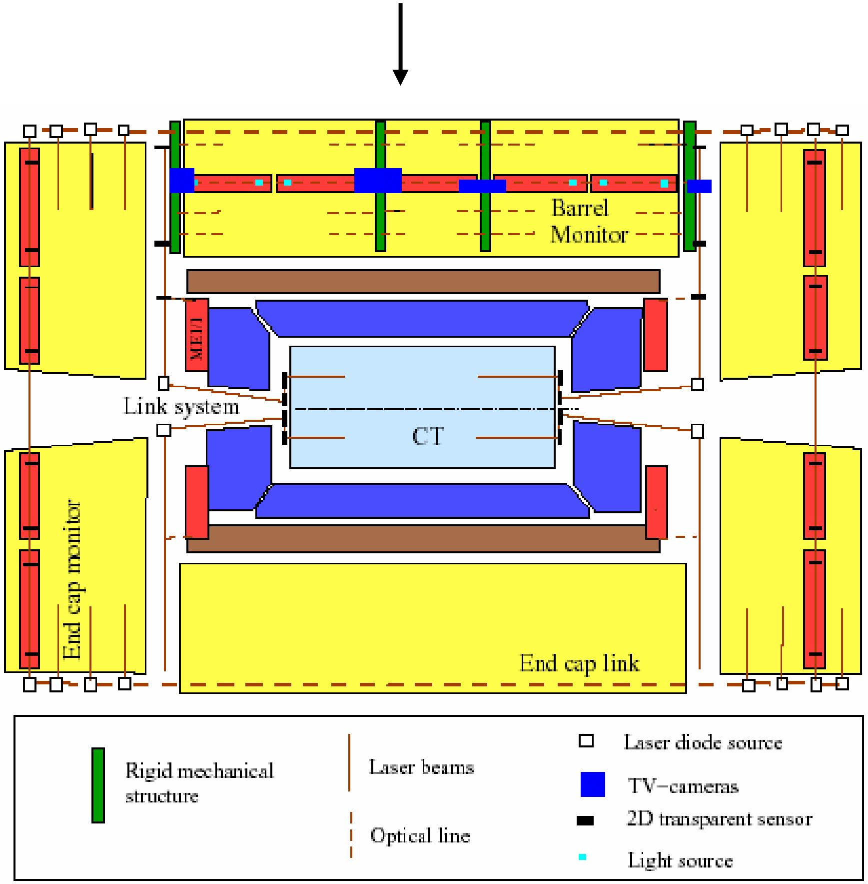
- **Pt resolution (2-3% in barrel) initially degraded by factor ~5**

- **d0 resolution degraded from 9 up to ~35 μm**
- **But: assumes fast alignment of Pixel detector**



Alignment Monitoring System for global Tracker strip detector parts

Comprehensive Muon Hardware Alignment System



Track Based Alignment

Three algorithms being studied in CMS (using common software):

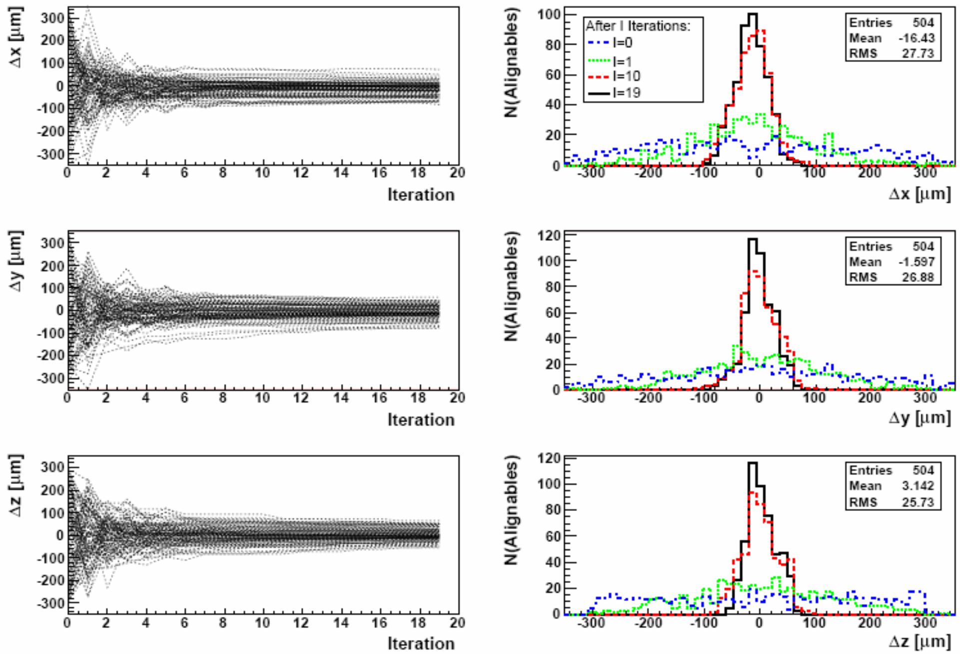
- **Kalman filter CMS-Note-2006/022**
  - Parameters and correlations updated after each track
  - No large matrix inversions, but book-keeping of relevant correlations
- **Millepede CMS-Note-2006/011**
  - Used successfully in other experiments (e.g. CDF, H1)
  - New version Millepede-II, expected to be scaleable to CMS problem (see next slides)
- **HIP Algorithm CMS-Note-2006/018**
  - Robust approach, no large matrices (ignores module correlations)
  - Pixel alignment

Alignment Strategy

- 2007 before collisions: Alignment with Cosmics and Beam Halo Muons
- 2007 Calibration Run: use high p_T tracks (if possible)
- 2008: Alignment with muons from Z,W
  - Standalone alignment of pixel detector
  - Alignment of strip tracker (pixel as reference)

Alignment Studies

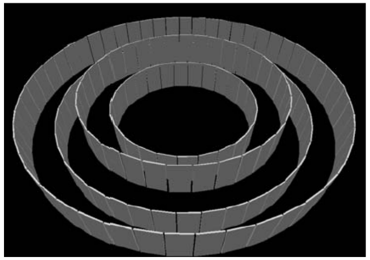
- **HIP Algorithm:**
- **Standalone Pixel alignment**
  - ❑ **Refit only pixel hits**
  - ❑ **Momentum from full tracks**

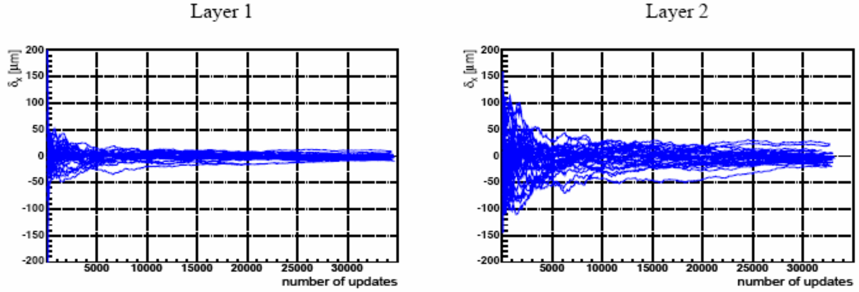


- **500K $Z \rightarrow \mu\mu$ events**
- **RMS ~25μ m in x,y,z**

CMS Note 2006/018

- **Kalman Filter Alignment:**
- **Extension of Kalman track fitter to alignment**
- **Global update, but avoids inversion of large matrices**
- **Studied in wheel-like setup of TIB modules (pixel as reference)**



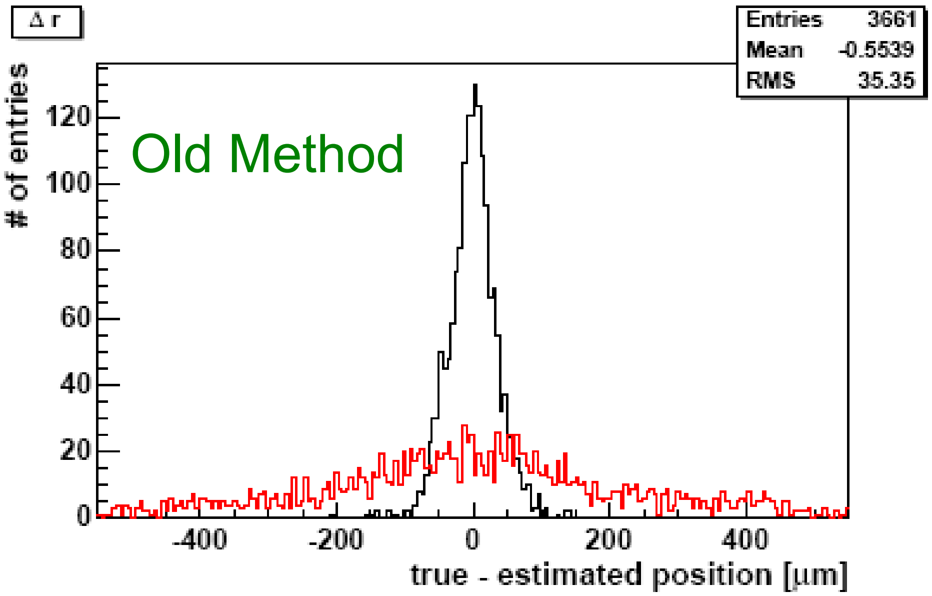


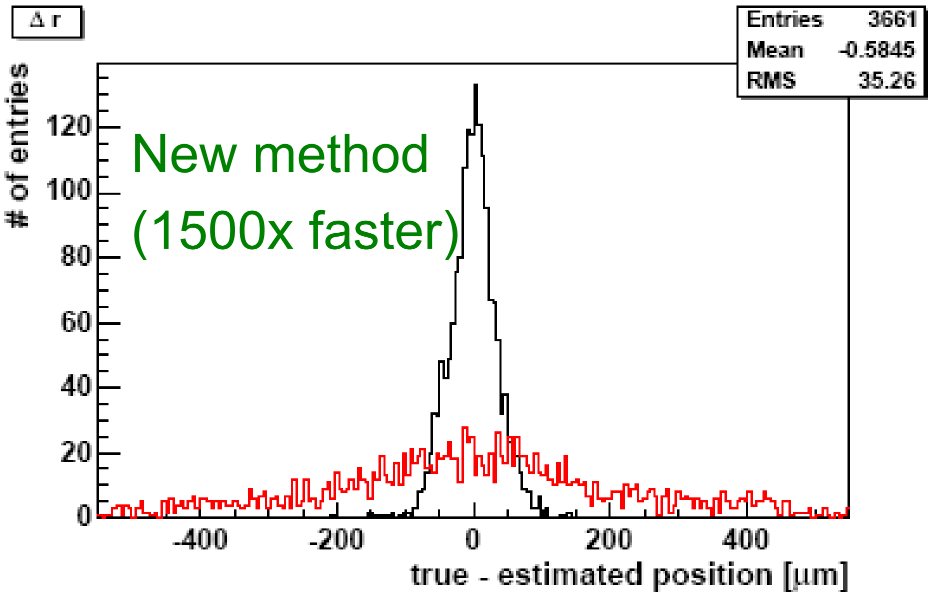
- **Good convergence**

CMS Note 2006/022

Alignment with Millepede-II

- **Original Millepede method solves matrix eqn. Ax = B, by inverting huge matrix A. Can only be done for <12000 alignment parameters**
- **New Millepede II method instead minimises |A x – B|. Expected to work for ~100000 alignment parameters (i.e. for full CMS at sensor level)**
- **Both successfully aligned ~12% of tracker modules using 2M $Z \to \mu\mu$ events. Results identical, but new method 1500 times faster!**

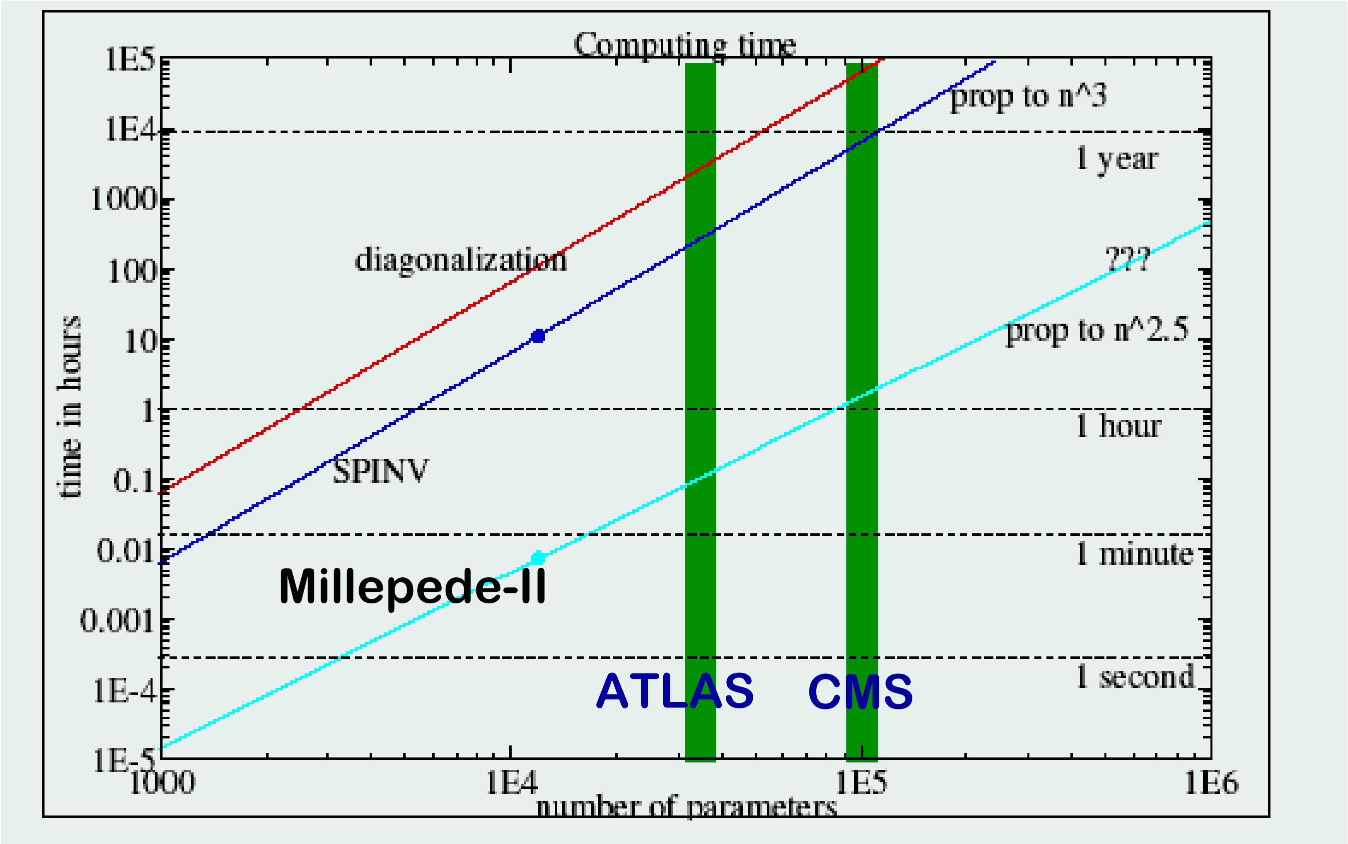




CMS Note 2006/011

Millepede-II: CPU Requirements

CPU time in hours as a function of number of parameters



CPU Time for CMS (100k parameters):

- **Diagonalization**
  ~10 year at one CPU
- **Inversion:**
  ~1 year at one CPU
- **Iteration:**
  ~1 h at one CPU

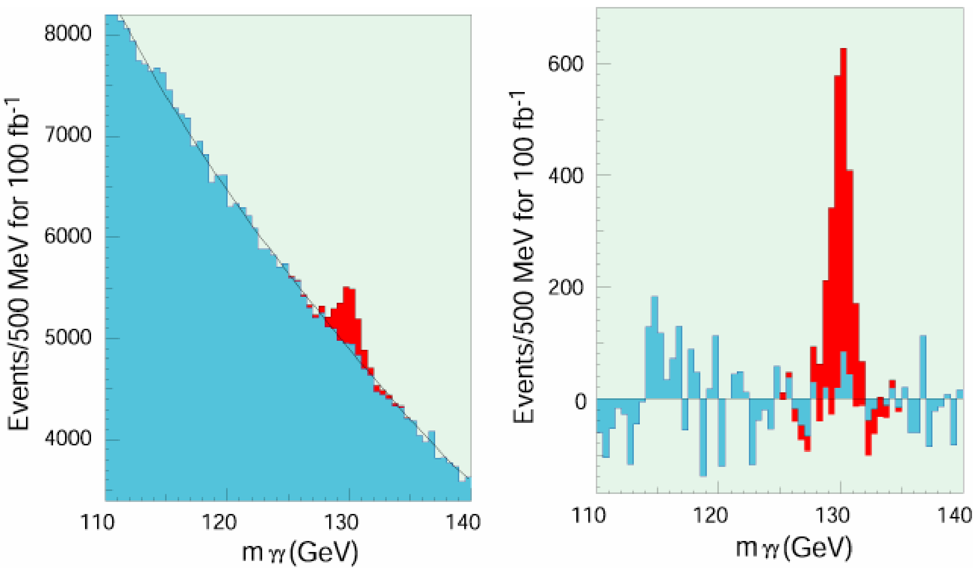
- **Only the new Millepede-II (iterative method) scaleable to full CMS problem**
- **Alternative: massively parallel algorithm (difficult to implement)**
- **Memory needs (dep. on sparseness of matrix) under study…**

ECAL and HCAL Calibration

⇒ **Key ingredient for precision measurements of γ, e, hadrons, jets, E_t^{miss}…**

ECAL

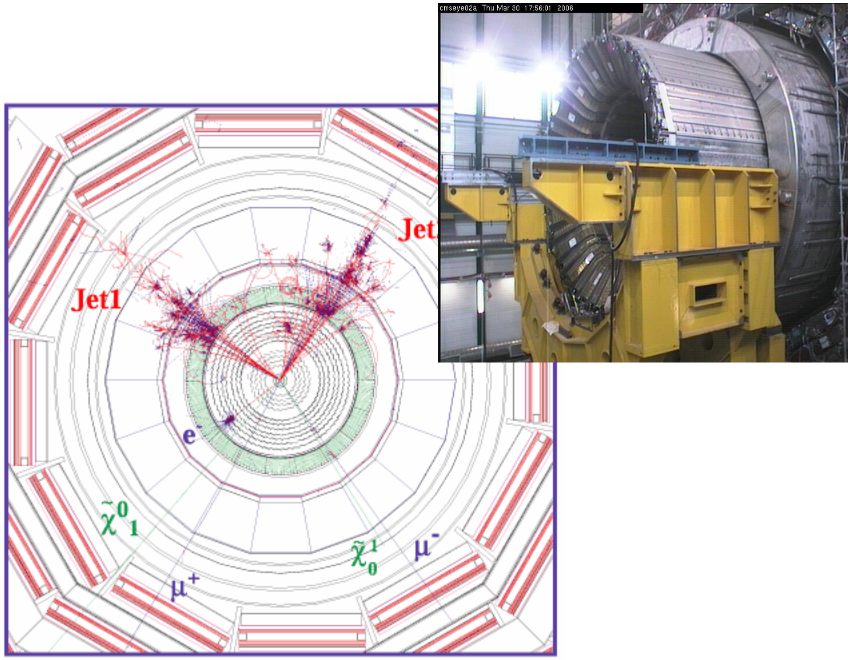
- Physics processes (e.g. $H \to \gamma\gamma$) impose very tight requirements on ECAL performance



- Need E calibration ~0.5%

HCAL

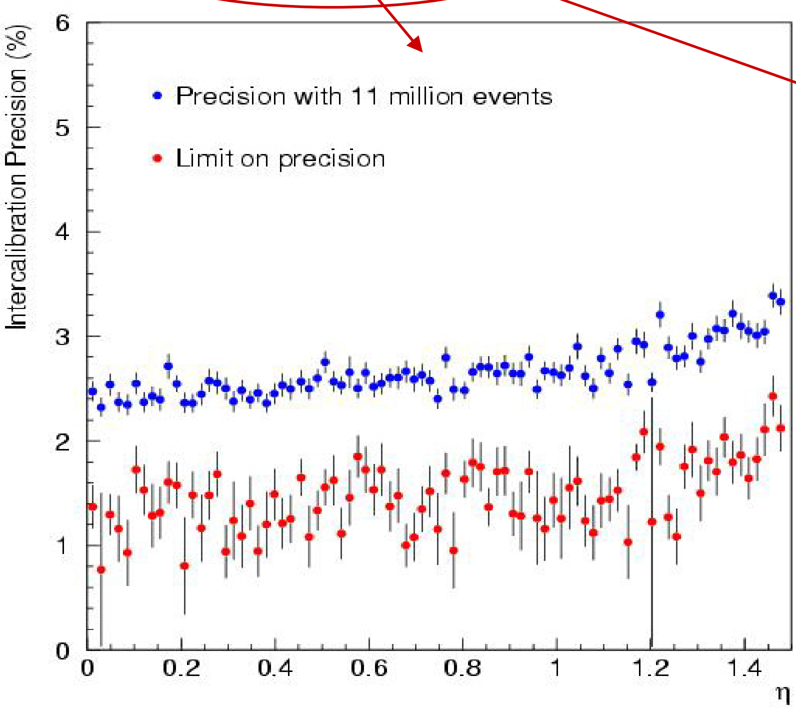
- Typical SUSY signatures involve jets and missing E_T
- B-jet energy scale cruical for top

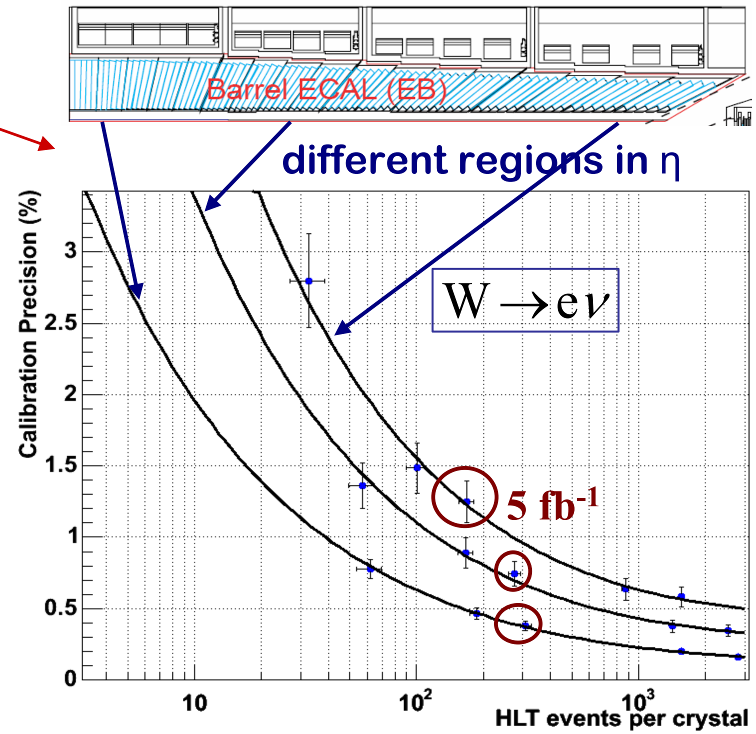


- HCAL pre-calibration to 4% using radioactive source
- Improvement with physics

ECAL Calibration

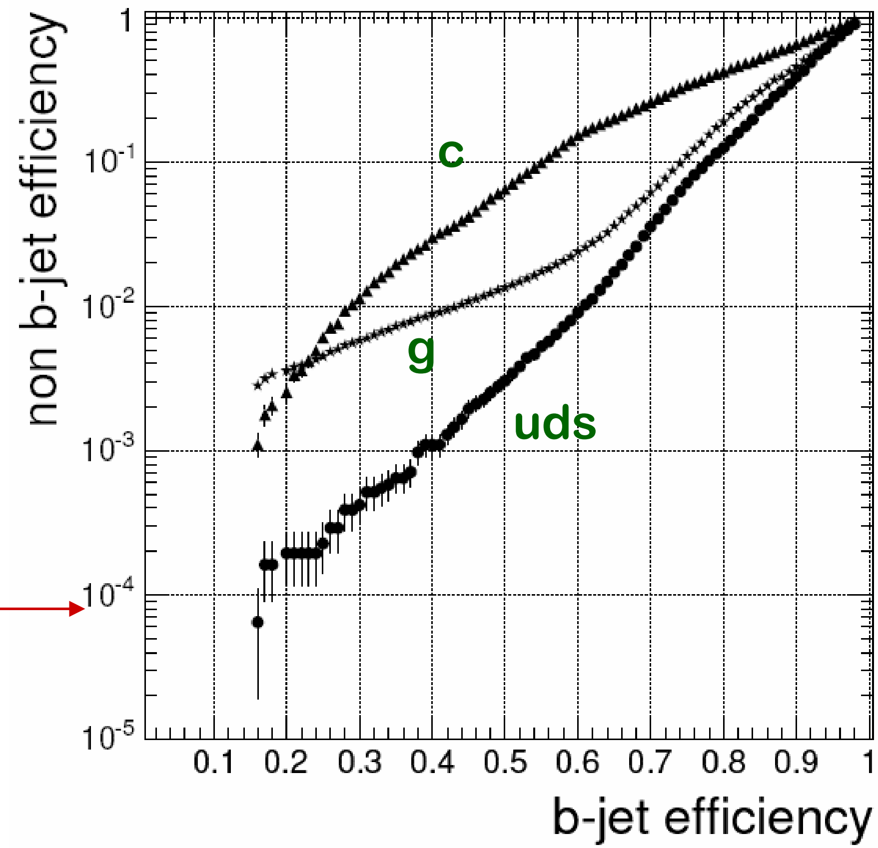
- **Before data taking:**
  - Pre-calibration using test beam, light yield meas., cosmics: ~4%
- **Calibration run 2007:**
  - Few hours of min.bias events (1kHz calib. Stream): 1..2%
  - Phi symmetry, $\pi^0 \to \gamma\gamma$
- **From 2008 Pilot run onwards:**
  - Isolated electrons from W,Z: trackerE/p $\to$ 0.5%





b-Tagging

- **Various b-tagging algorithms have been implemented and studied in detail for PTDR Vol. 1**
- **Lifetime based tags**
  - ❑ **Track counting**
    - o **Robust, Count number oftracks with impact parameter above thresholds**
  - ❑ **Probability**
    - o **Compatibility with primary vertex**
  - ❑ **Combined secondary vtx tag**
- **Soft lepton tags**
  - ❑ **Soft Muon**
  - ❑ **Soft Electron**



- **HLT b-tagging techniques**
  - ❑ **Pixel-only tracking (fast!) + vertex**
  - ❑ **Full trackereco only as 2nd stage and only in ROI's**

Requirement: Pixel Detector Aligned with tracks!

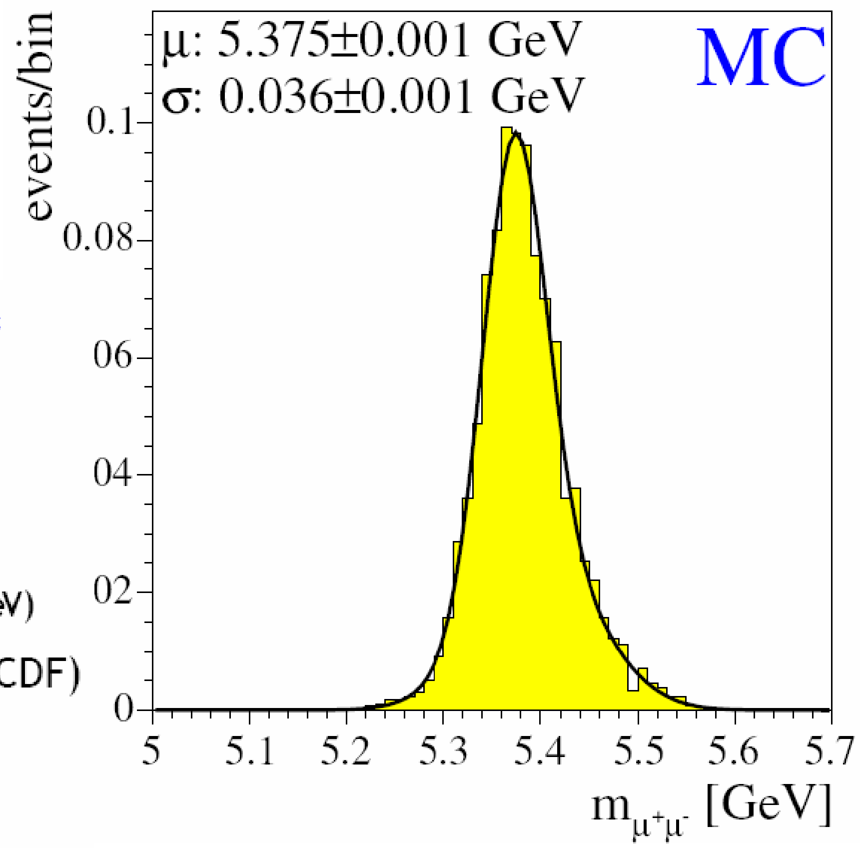
New CMS Limit on $B_s \to \mu\mu$

- **Dedicated HLT trigger**
  - Accept rate ~1.7Hz
- **Cut-based offline analysis**
  - Flight length significance
  - Muon separation
  - Isolation
  - Secondary vertex
- Signal selection efficiency $\varepsilon = 0.019 \pm 0.002_{stat}$
  where the efficiency $\varepsilon = \varepsilon_{cuts}\, \varepsilon_I\, \varepsilon_{\chi^2}$ is factorized
  - In $10\,\text{fb}^{-1}$: $N_S = 6.1 \pm 0.1$ signal events
- Background rejection $\eta = 2.6 \times 10^{-7}$
  - In $10\,\text{fb}^{-1}$: $N_B = 13.8^{+22.0}_{-13.8}$ background events
  (one remaining background event in $5 < m_{\mu\mu} < 6\,\text{GeV}$)
- Extract upper limit with Bayesian procedure (CDF)

$$\mathcal{B}(B_s^0 \to \mu^+\mu^-) \le \frac{N(n_{obs}, n_B, n_S)}{\varepsilon_{\text{gen}}\, \varepsilon_{\text{total}}\, N_{B_s}}$$
$$\le 1.4 \times 10^{-8}\ (90\%\ \text{C.L.})$$

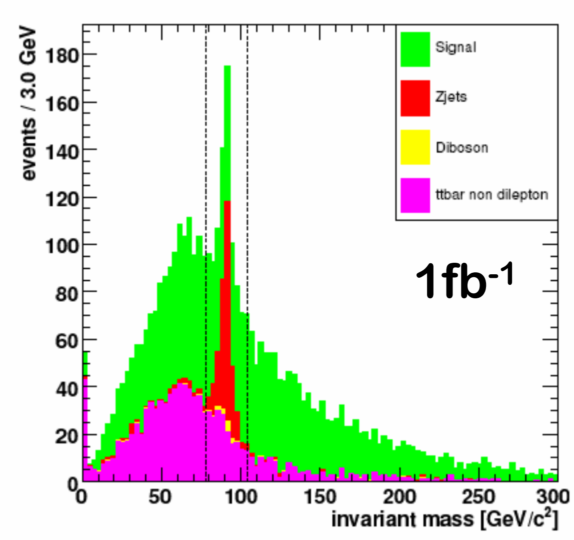
including statistical and systematic error

- **Impact of tracker misalignment on mass resolution 10…20%**



Early Physics: Top Quarks

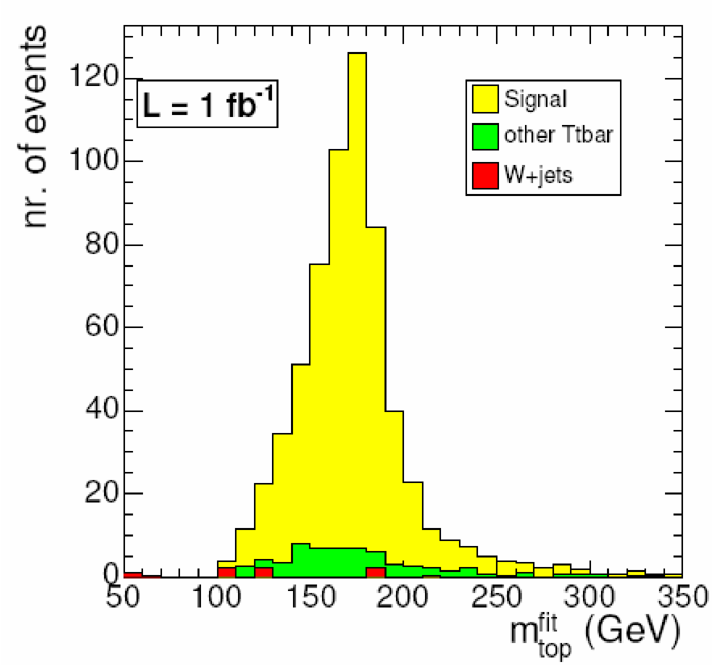
- **Top pair-production $\sigma \sim 830$ pb**
- **Cross section and mass measurements in all 3 channels (dilepton, semileptonic, hadronic)**



- **Selection dilepton channel**

- **1fb-1: 700 events in dilepton channel (large S/B~12)**
- **Δm_t~4.2 GeV (1fb^{-1}): b-jet energy scale 15%**
- **x-section measurement at ~10% possible**

- **Mass measurement in semileptonic channel:**



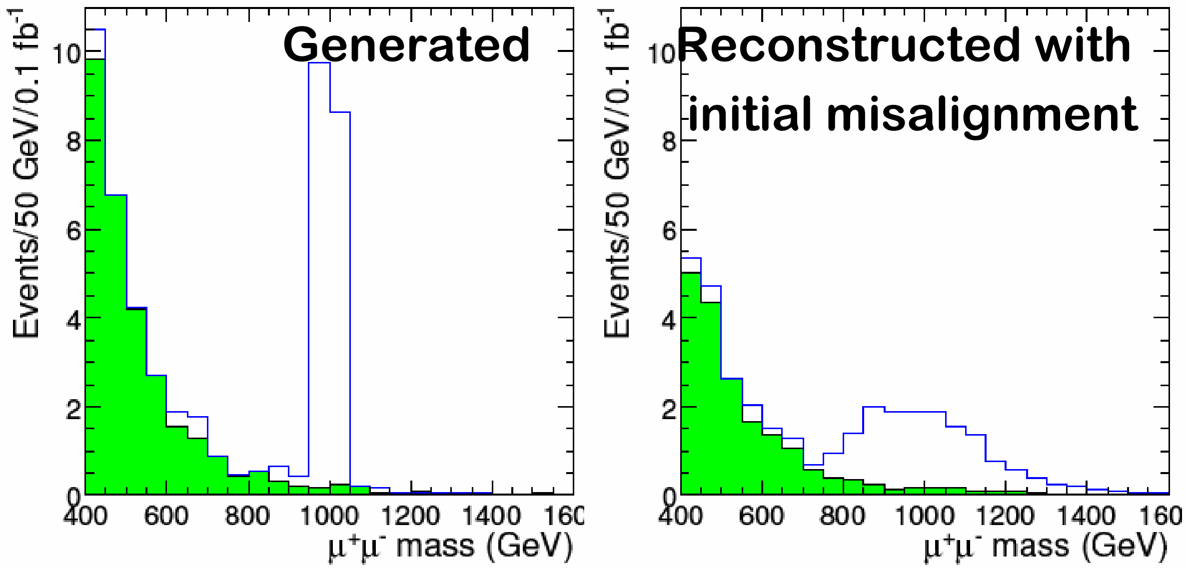
- **Potential for Δm_t~1.2 GeV (10 fb^{-1})**
- **Requires b-jet energy scale known to 1.5%**

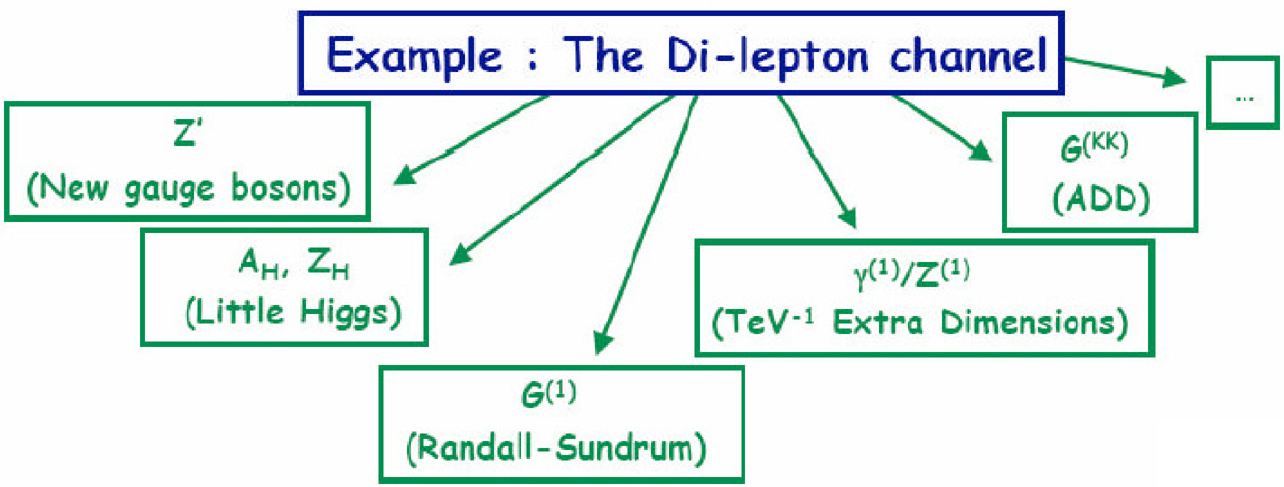
B-jets energy scale calibration crucial for top mass!

Early Discoveries: Di-lepton Resonances

- **$Z' \to \mu\mu$ ($0.1 fb^{-1}$)**

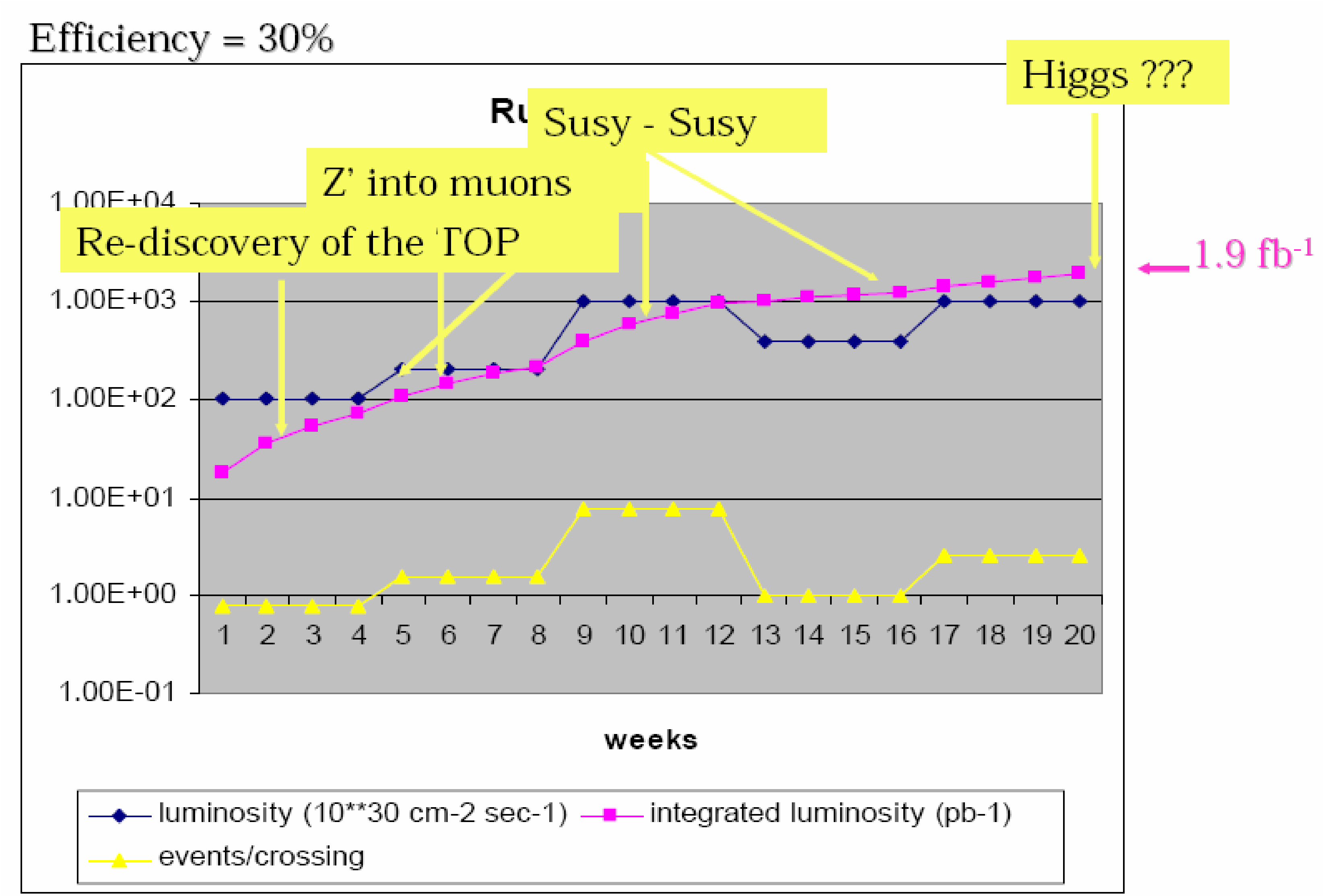
May be seen very early: first weeks





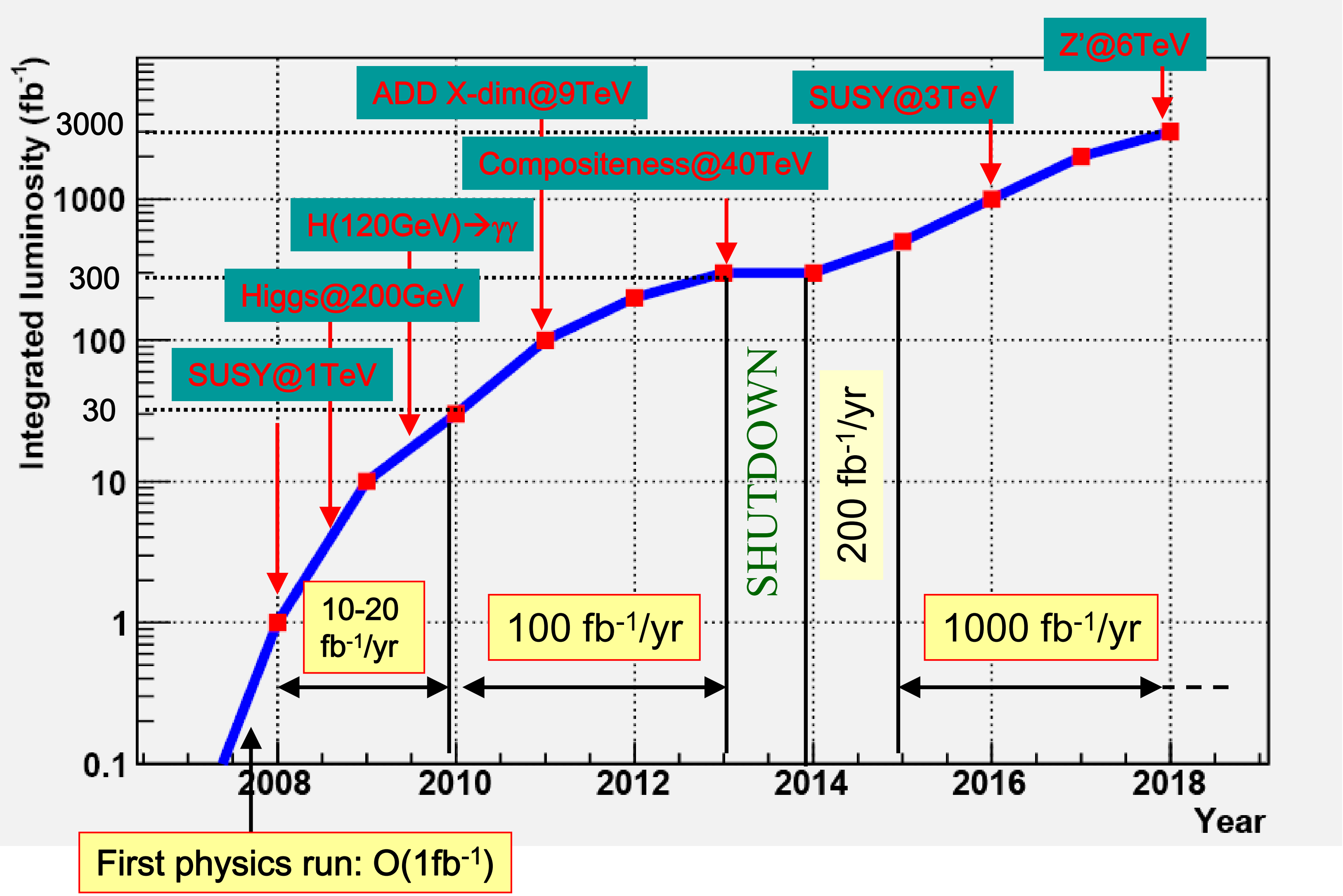
Early discovery (~weeks), but alignment cruical!

CMS Early Physics in 2008-9



- **N.B. plot to be updated with revised LHC schedule**

CMS Road Map to Discoveries



Conclusions

- Revised LHC schedule impacts CMS commissioning plans
  - ❑ Commissioning with Cosmics and beam halo muons
  - ❑ 2007 Calibration Run (3 weeks @ 450 GeV): mainly minimum bias
  - ❑ 2008 Pilot Run: Accumulate large Z,W samples for cal./ali., physics
- Major Commissioning Challenges
  - ❑ Trigger, Calorimeter Calibration, Tracker Alignment
- CMS Physics TDR's Vol. 1+2
  - ❑ Significant progress on calibration and alignment procedures, reconstruction algorithms, understanding of physics performance (incl. systematic errors e.g. misalignment)
- Early physics and discoveries in 2008 possible, e.g.
  - ❑ Top quark (+QCD, W,Z, b-physics etc.)
  - ❑ Dilepton resonances (+light SUSY, Higgs, etc.)
  - ❑ All depending on commissioning success

Further talks with ATLAS/CMS b physics studies:

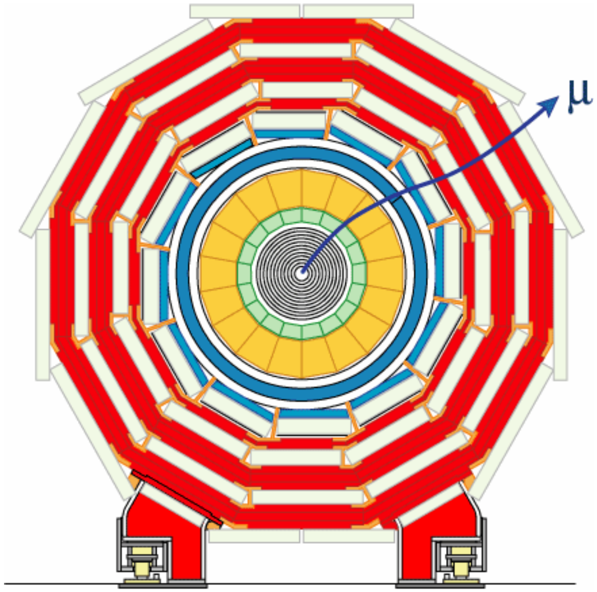
Julie Kirk: B triggers in ATLAS and CMS

Maria Smizanska: Searches and leptonic rare B decays @LHC

Nicolo Magni: J/ΨΦ LHC review

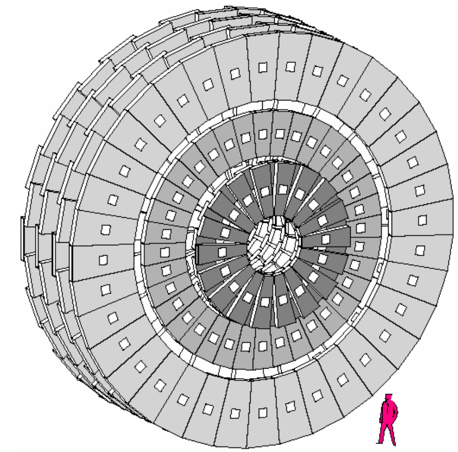
Backup

Alignment of Muon Chambers



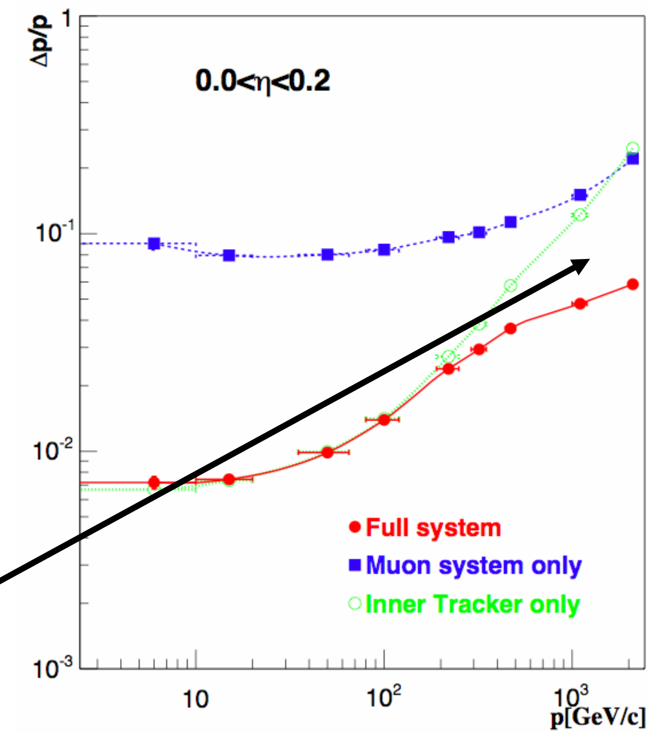
Muon Barrel
- 5 wheels
- 4 layers/wheel
- 250 chambers

Muon Endcaps
- 6000m² sensitive area
- 540 chambers



Intrinsic resolution:
DT and RPC (Barrel): ~100μm
CSC and RPC (Endcap): ~100-75μm
⇒ Need to align large structures to less then 100μm

Precision alignment especially important for high p_T muon tracks (TeV region) and for efficient muon triggering



Alignment Strategy

Basic scetch:

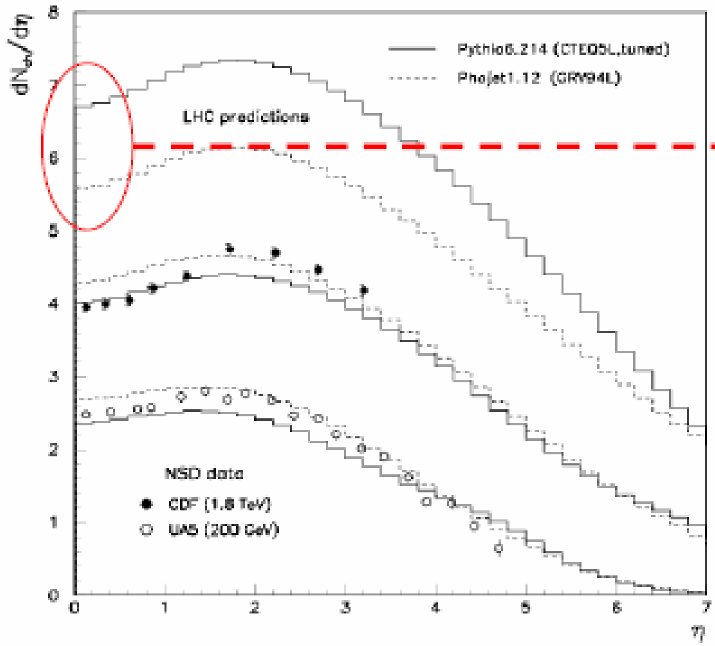
- **2007: Before beams:**
  - Cosmics (+laser alignment and survey measurements)
- **2007: single beams**
  - add beam halo muons
- **2007: Pilot run, pixel detector not installed (except few test modules)**
  - Cosmics, beam halo muons
  - add available high pt muons, tracks
  - Initial alignment of high level strip tracker structurs (layers, rods)?

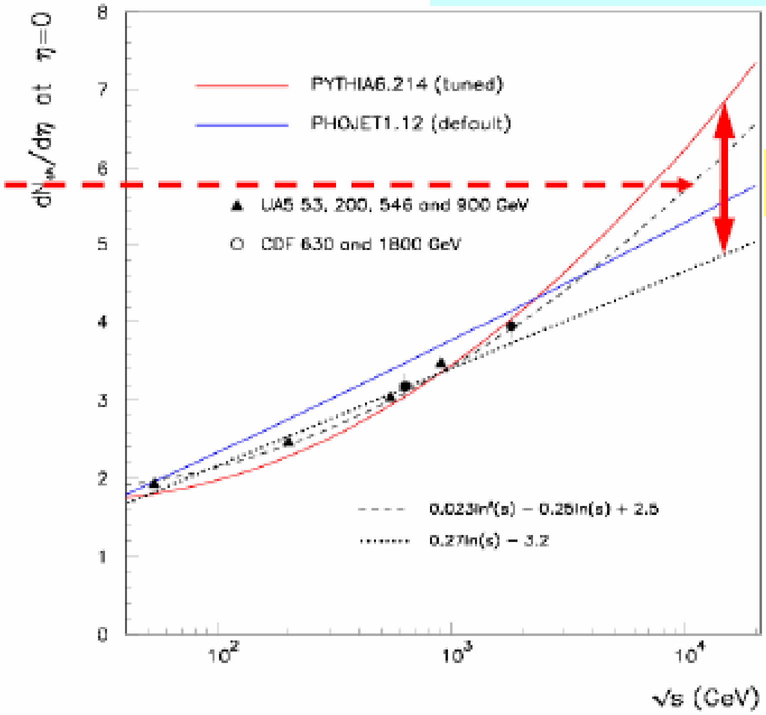
- **2008:Two-step approach:**
  - Add Larger statistics of muons from Z,W
  - 1. Standalone alignment of pixel detector
  - 2. Alignment of strip tracker, using pixel as reference
- **To be laid out in more detail …**

Early Minimum Bias Measurements

Charged particle density

The pile-up for the future





LHC?

- Energy dependence of dN/dη ?
- Vital for tuning UE model (see later)
- Only requires a few thousand events.

- PYTHIA models favour $\ln^2(s)$;
- PHOJET suggests a $\ln(s)$ dependence.

Commissioning Shopping List

To-Do List:

- General Hardware Commissioning; Debug readout
- Timing-in, data coherence, sub-system synchronization
- Establish L1 muon and calorimeter trigger
- Map of dead-noisy channel
- Pre-alignment of tracker and muons using optical alignment systems and pre-collision data
- Commission muon system
- Measure noise in the calorimeter
- Set calorimeter readout thresholds
- Look at calorimeters inter-calibration using pre-collision data

⇒ Establish conditions for efficient collisions data taking of CMS

Strategy at Start-up

Goal # 1

Understand and calibrate detector and trigger in situ using well-known physics samples

e.g. - $Z \rightarrow ee, \mu\mu$ — tracker, ECAL, Muon chambers calibration and alignment, etc.

- $t\bar{t} \rightarrow bl\nu\, bjj$ — 10^3 evts/day after cuts → jet scale from W→jj, b-tag perf., etc.

Understand basic SM physics at $\sqrt{s}$ = 14 TeV → first checks of Monte Carlos (hopefully well understood at Tevatron and HERA)

e.g. - measure cross-sections for e.g. minimum bias, W, Z, $t\bar{t}$, QCD jets (to ~ 10-20 %), look at basic event features, first constraints of PDFs, etc.

- measure top mass (to 5-7 GeV) → give feedback on detector performance

Note : statistical error negligible after few weeks run

Goal # 2

Prepare the road to discovery:

-- measure backgrounds to New Physics : e.g. $t\bar{t}$ and W/Z+ jets (omnipresent …)

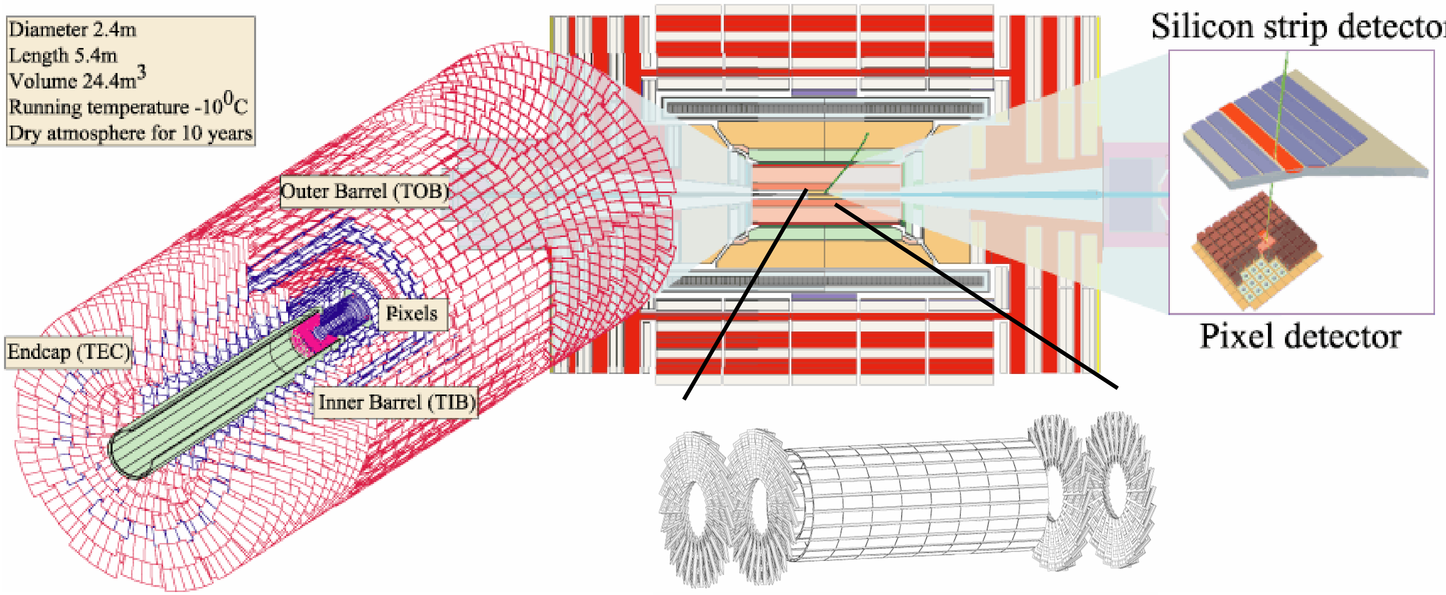
-- look at specific "control samples" for the individual channels:

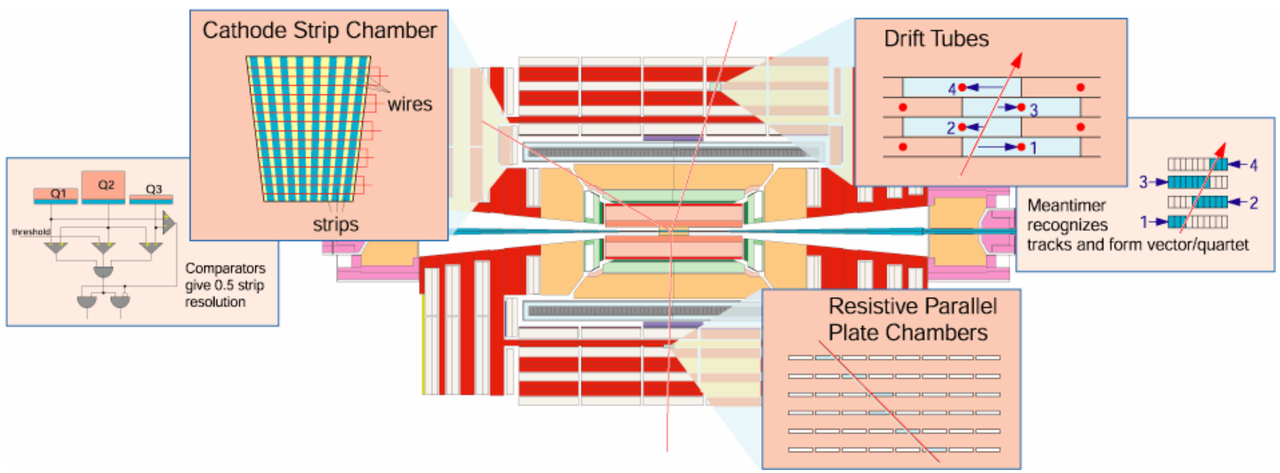
e.g. $t\bar{t}jj$ with $j \neq b$ "calibrates" $t\bar{t}bb$ irreducible background to $t\bar{t}H \rightarrow t\bar{t}bb$

Goal # 3

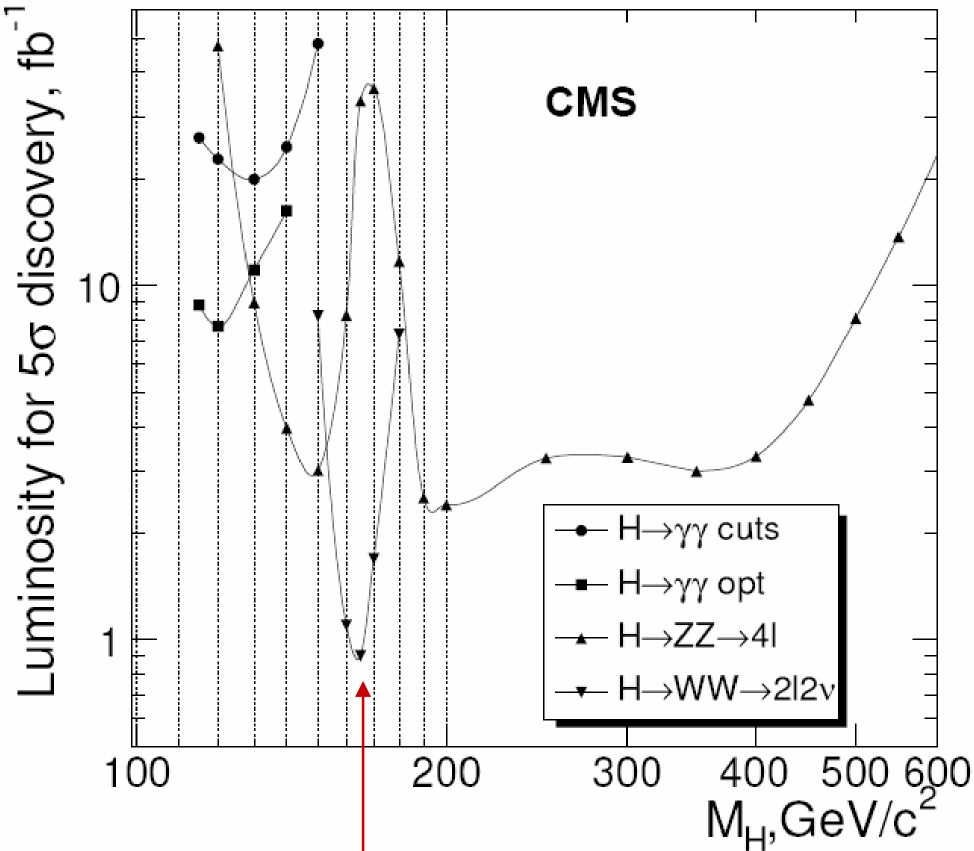
Look for New Physics potentially accessible in first year (e.g. SUSY, some Higgs ? …)

Alignment of the CMS tracking devices is a crucial task for CMS



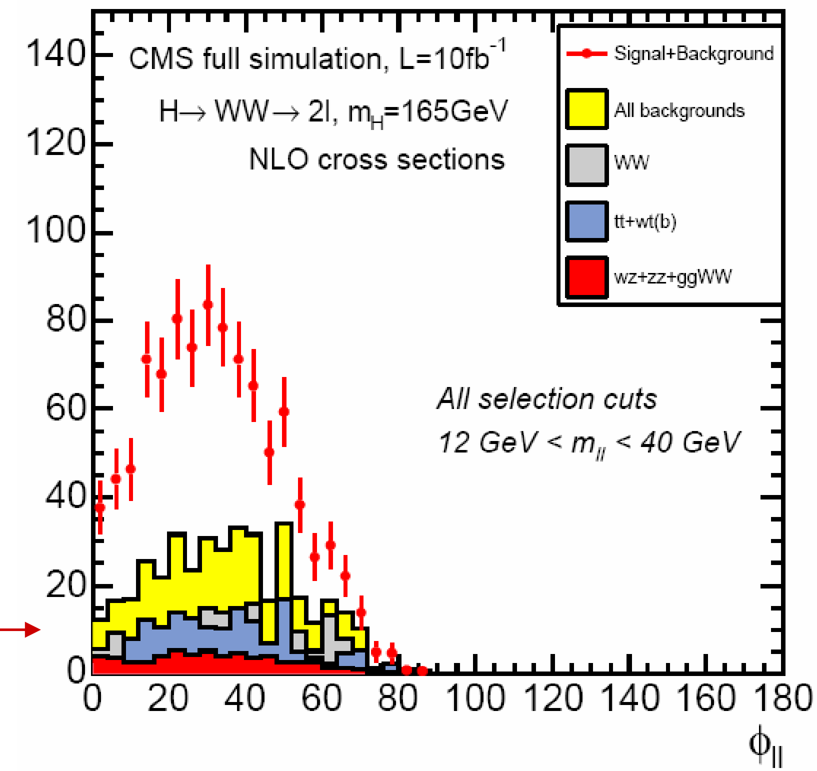


Higgs

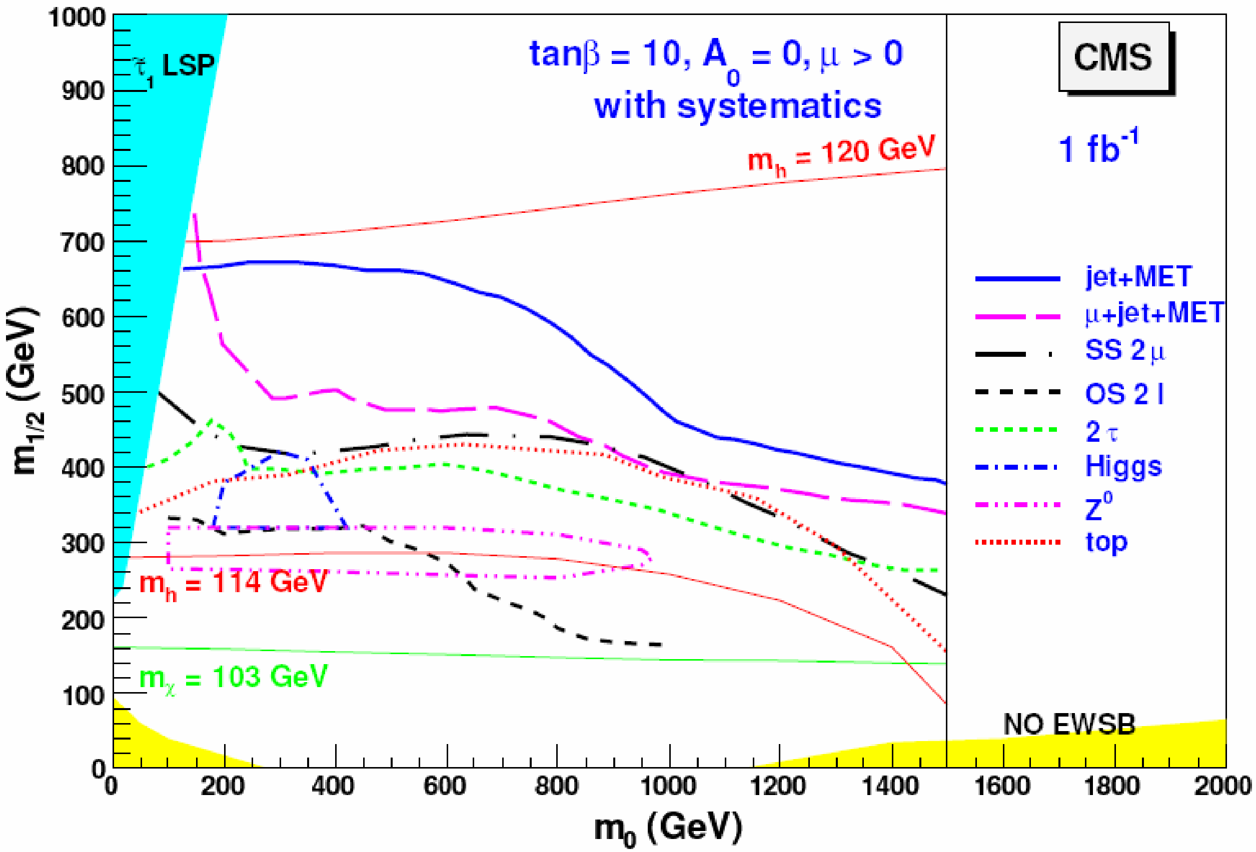


Discovery with <1fb^{-1} possible

- **$H \rightarrow WW \rightarrow l\nu l\nu$**



- **SUSY 5σ discovery reach with L=1fb^{-1} including systematics**
- **Inclusive signature based searches**
  - ❑ **Canonical channels (include jets, leptons, MET)**
  - ❑ **Channels with reconstructed Z, Higgs, MET**



Low-mass SUSY can be discovered in many channels with L<1fb^{-1}

Alignment: Typical Numbers

	Muon	Tracker: Strip	Tracker: Pixel
Assembly:	O(mm)	0.1-0.5mm	…0 μm
+ Hardware Alignment:	~<100μm	~<100μm	50-100 μm (no HA foreseen)
+ Track Based Alignment	~100μm (perhaps below)	~10μm	~5 μm
Remarks:	Hardware Alignment will provide the operational alignment level. Track based alignment will be a cross check and eventually a completion	Hardware Alignment will insure pattern recognition. Track Based Alignment must provide the final alignment	Only Track based Alignment. Nothing else!

Importance of Hardware Alignment

Importance of T… Based Alignment