2004 LHC DAYS IN SPLIT

Diocletian's Palace/Palazzo Milesi,
Split, Croatia
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Physics with the CMS Tracker

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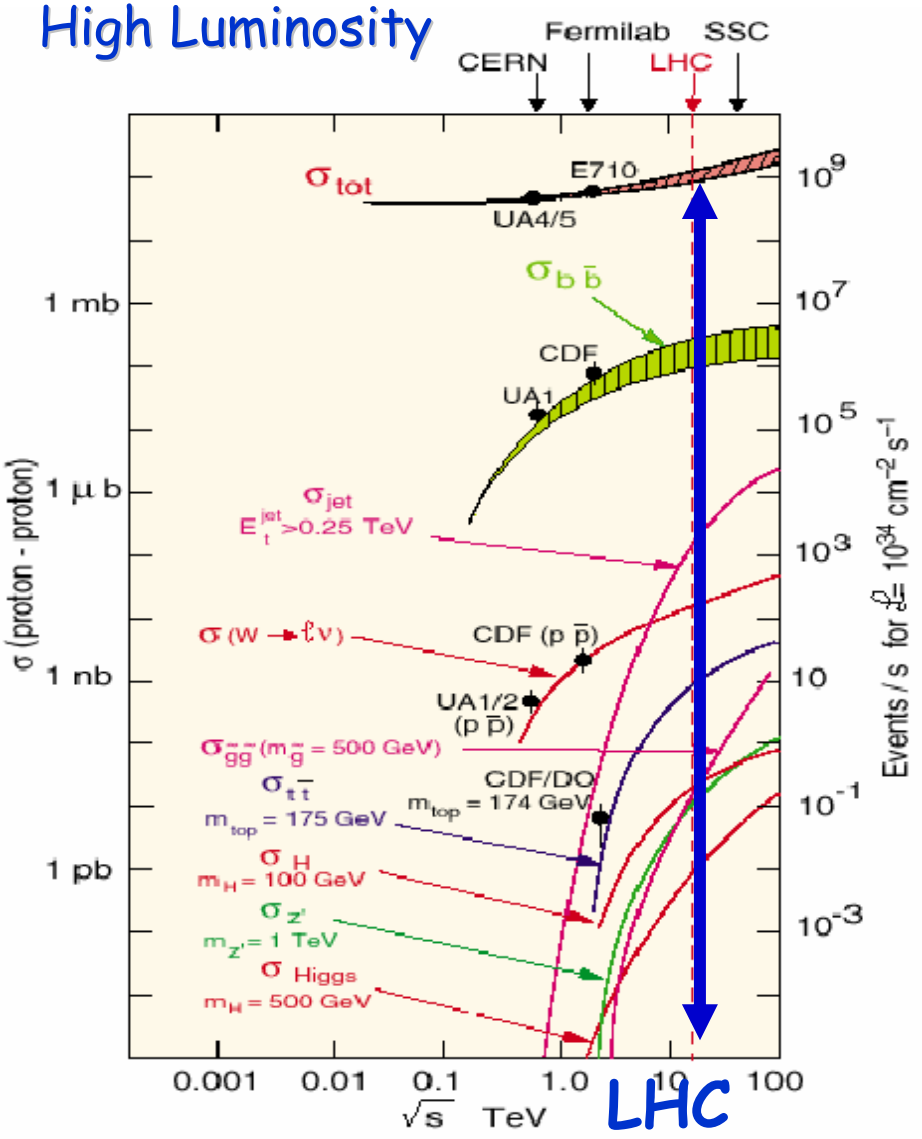
Selectivity: The Physics

Cross-sections of physics processes vary over many orders of magnitude:

- inelastic: 10^9 Hz
- b b production: 10^6-10^7 Hz
- W $\rightarrow$ /ν: 10^2 Hz
- t t production: 10 Hz
- Higgs (100 GeV/c^2): 0.1 Hz
- Higgs (600 GeV/c^2): 10^{-2} Hz

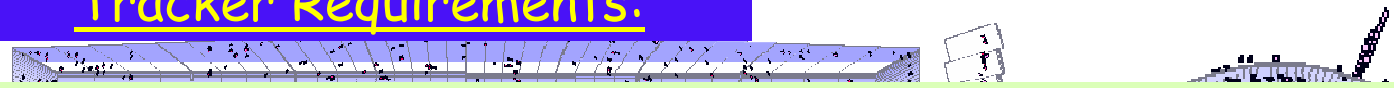
Tracker plays an essential role on:

- Triggering
- particle identification μ and e,
- b and τ tagging
- Jet reconstruction (Energy Flow)
- Missing E_T



High Luminosity Physics at the LHC

Tracker Requirements:



$H \rightarrow ZZ^* \rightarrow 2e2\mu$

Efficient & robust Pattern Recognition algorithm

⇒ Fine granularity to resolve nearby tracks
⇒ Fast response time to resolve bunch crossings

Ability to reconstruct narrow heavy object

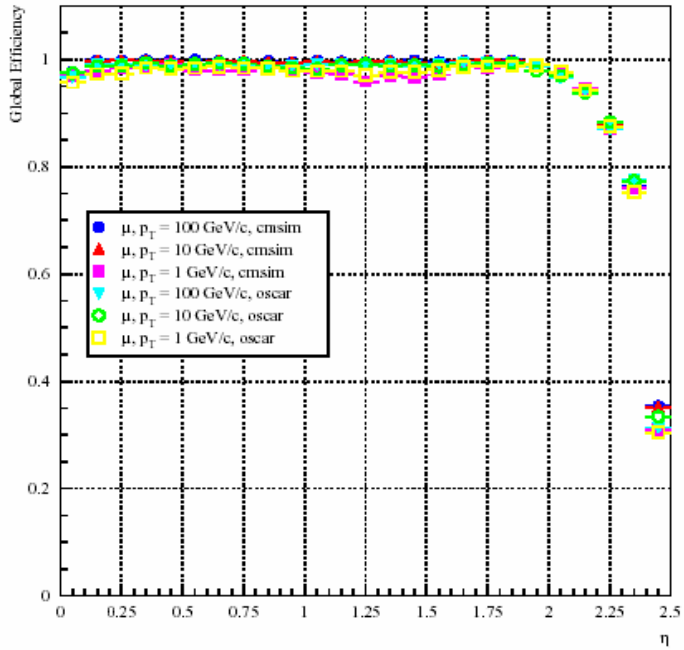
⇒1~2% Pt resolution at ~ 100GeV

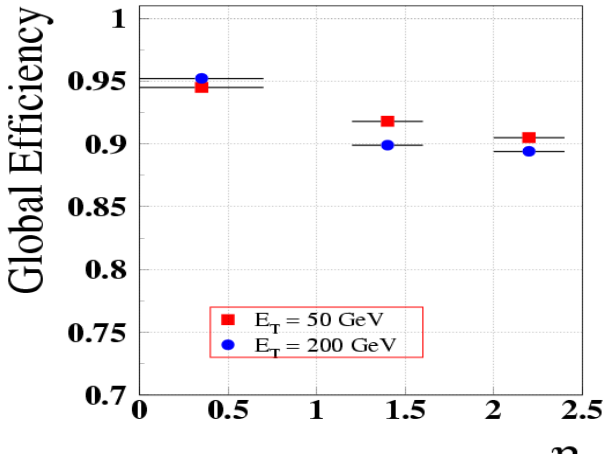
Ability to operate in a crowded environment
⇒ Nch/(cm^2*25ns) = 1.0 at 10 cm from PV

Ability to tag b/τ through secondary vertex
⇒Good impact parameter resolution

Ability to operate in a very high radiation environment
⇒ Silicon detectors will operate at -7°C ÷ -10°C to contain reverse annealing and limit leakage current

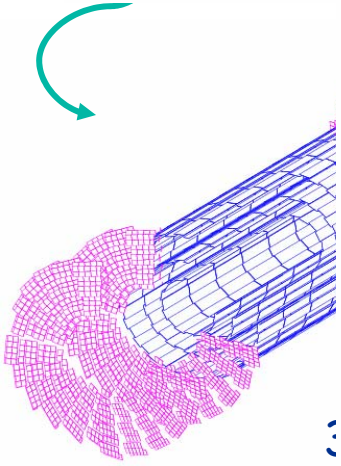
CMS Tracker Strategy

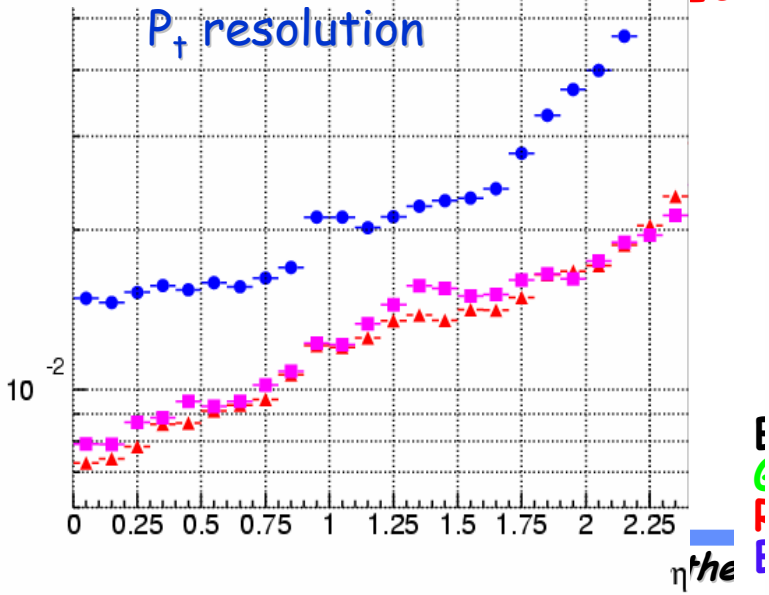


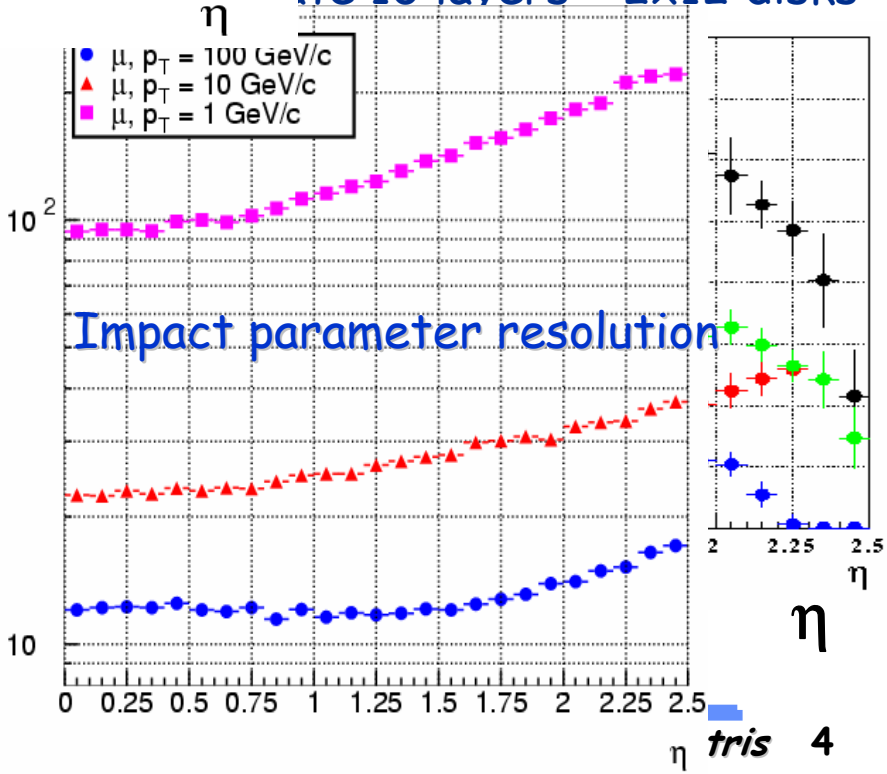


Jets E_T = 50-200 GeV
Fake Rate < 1 %

ite 10 layers + 2x12 disks



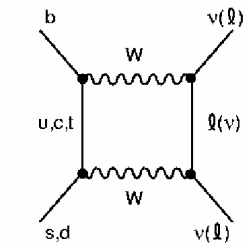




Physics Program: Exclusive B decay channels

Few decay channels chosen as benchmark

- $B_s \rightarrow \mu^- \mu^+$



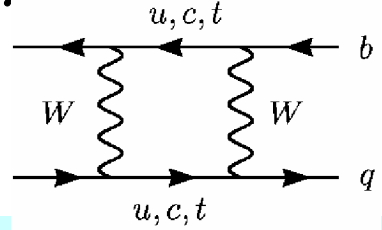
  - FCNC b→ s, loop-level process in SM
  - Indicator of possible new physics
  - Observable before LHC only if drastically enhanced
  - Unique signature…….but BR ~ O (10^{-9})

- $B_s \rightarrow J/\psi\ \varphi \rightarrow \mu^- \mu^+\ K^- K^+$

  - Gold-plated decay mode for CP-violation
  - Sensitive to new physics
  - Won't be studied with big accuracy before LHC

Triggered @ L1 by the presence of 2μ

- $B_s \rightarrow D_s \pi^+ \rightarrow \varphi \pi^- \pi^+ \rightarrow K^- K^+\ \pi^- \pi^+$



  - B_s-B_s Mixing
  - B_s flavour @ decay time unambiguously tagged by D_s sign

Triggered @ L1 by the presence of 1μ (from the semileptonic decay of the other b hadron in the event)

High Level Trigger & Tracker

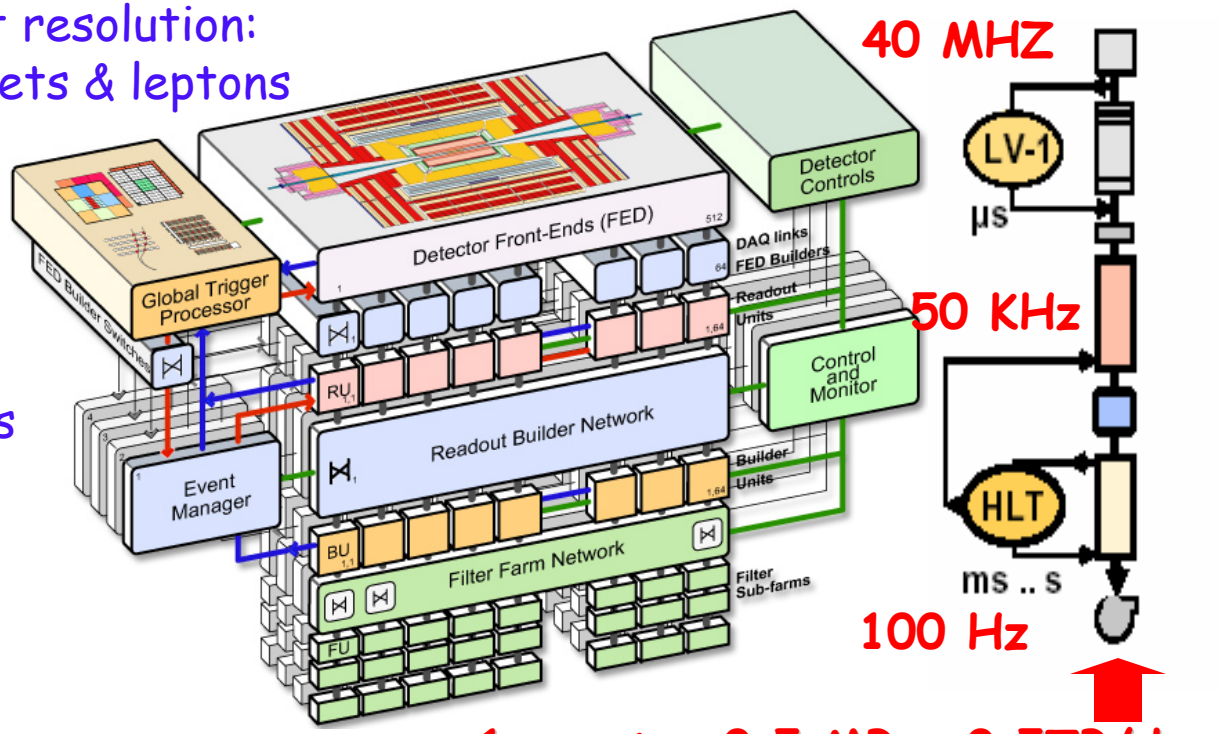
Lvl-1 = "crude" granularity and Pt resolution:
Rate dominated by mis-measured jets & leptons

HLT task: reduce rate by ~ 1000
Exploit much better granularity and Pt resolution to correctly tag and retain only interesting physics events

Filter Farm 2000 CPUs

Foreseen mean CPU time

[PentiumIII 1 GHz]: 300ms/ev



1 event ~ 0.5 MB ~0.5TB/day

4 DAQ slices in 2007
=> 50 KHZ into HLT, 100 Hz out

"How can I kill these events using the least CPU time?"

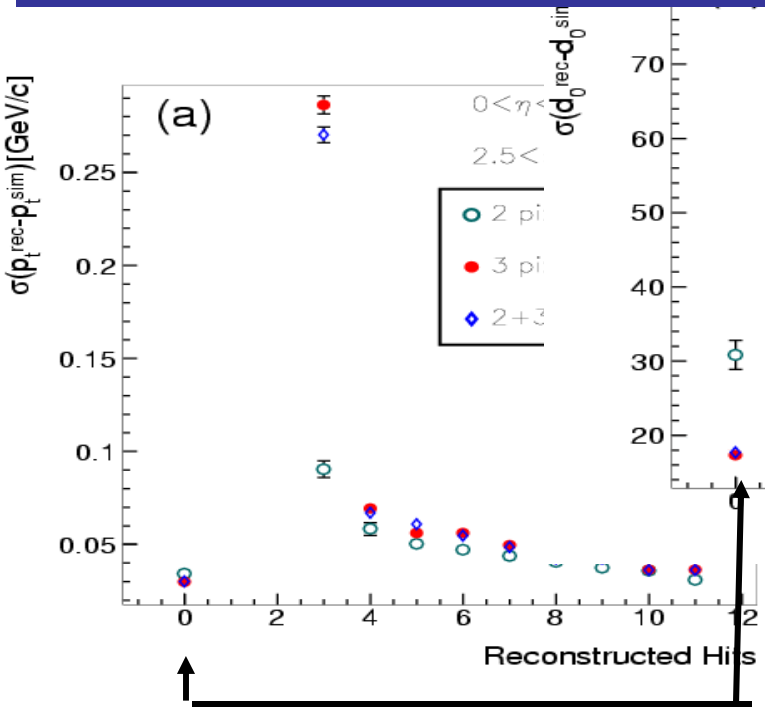
- The fastest (most approx.) reconstruction
- The minimal amount of precise reconstruction
- A mixture of the two

HLT Tracker Strategy

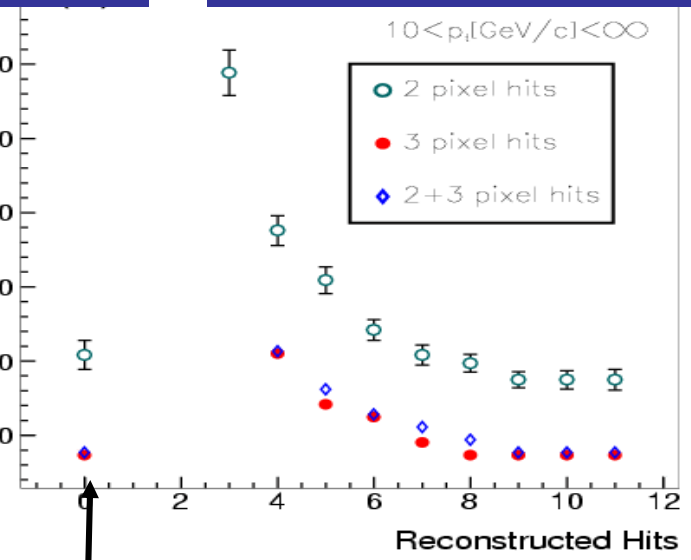
HLT Tracking

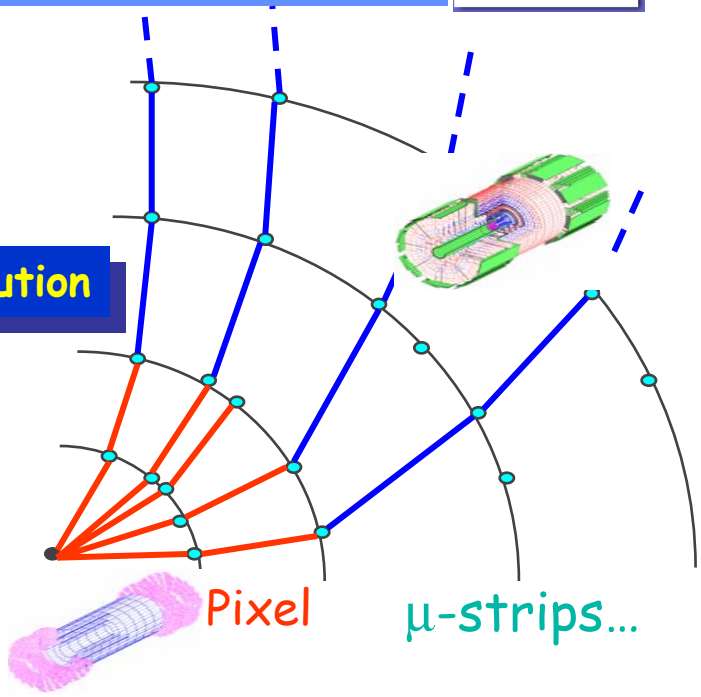
Reconstruction of charged tracks with Tracker (trajectory=helix) from inside (pixel) out (μ-strip detectors). Pixel Occupancy ~ 10^{-4}

Transverse Momentum Resolution



Impact parameter Resolution



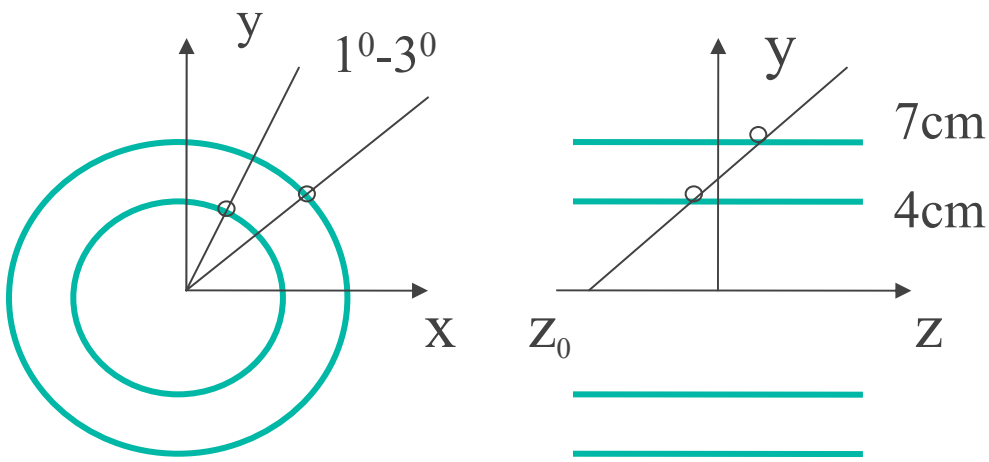


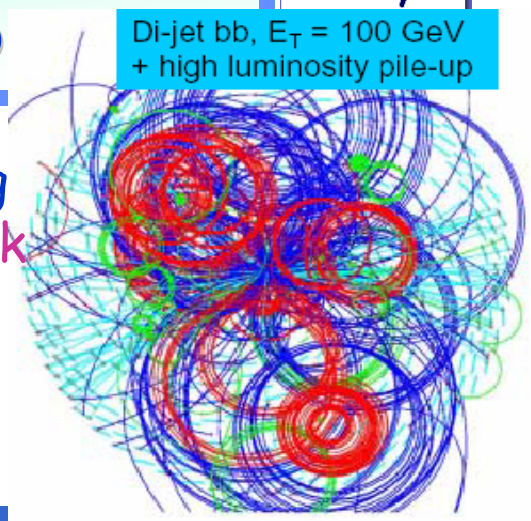
Full tracker performance

At HLT we are not necessarily interested in ultimate resolution.
Good track parameter resolution for moderate Pt tracks is obtained already with 4 or more hits

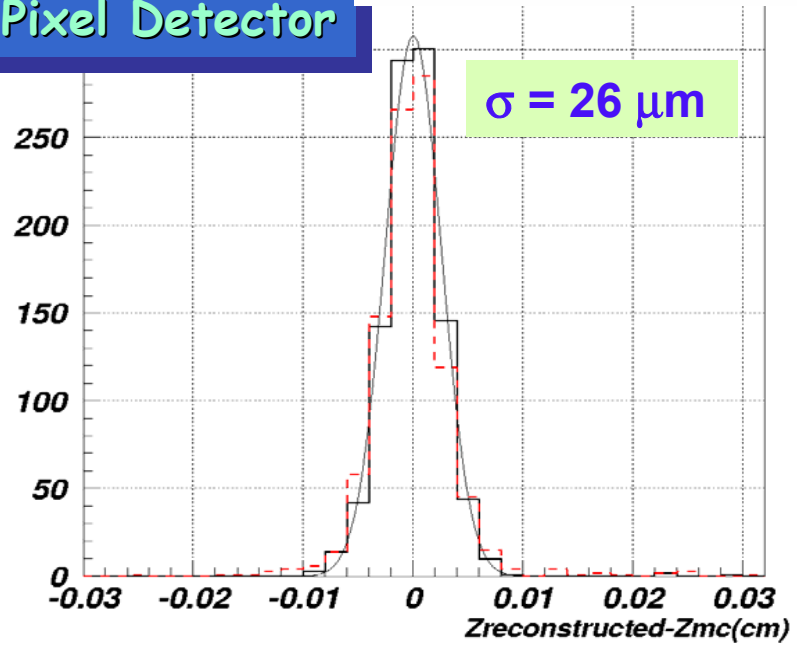
HLT Primary vertex reconstructio

At LHC design luminosity ~ 20 interaction per beam crossing spread out by σ(z)=5.6 cm: primary vertex is an essential task





Only Pixel Detector



- Hit pairing with a straight line in rz
  - IP≤1 mm
  - P_T>1 GeV
- Matching with 3rd layer → track candidate
- PV candidate if ≥ 3 track cross z-axis
- Signal vertex from ΣP_T and N_{tracks}

Average time:50msec/1 GHz

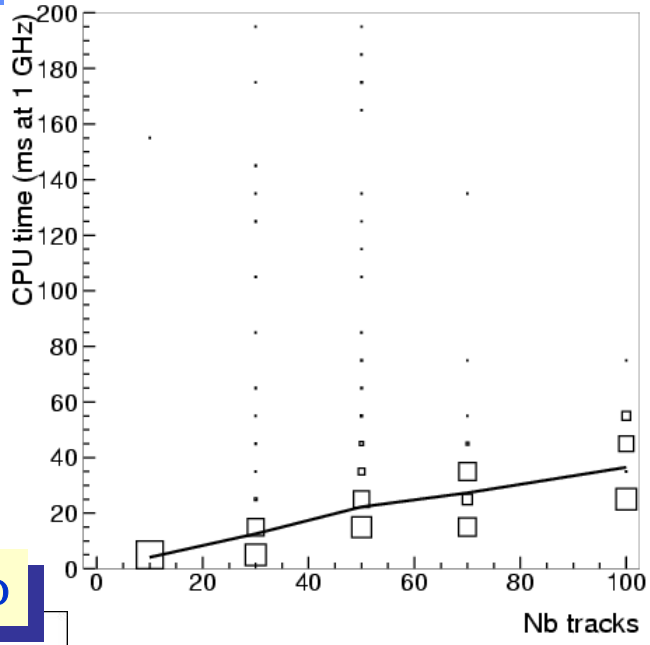
PV efficiency >95% in high luminosity events

HLT Secondary Vertices Reconstruction

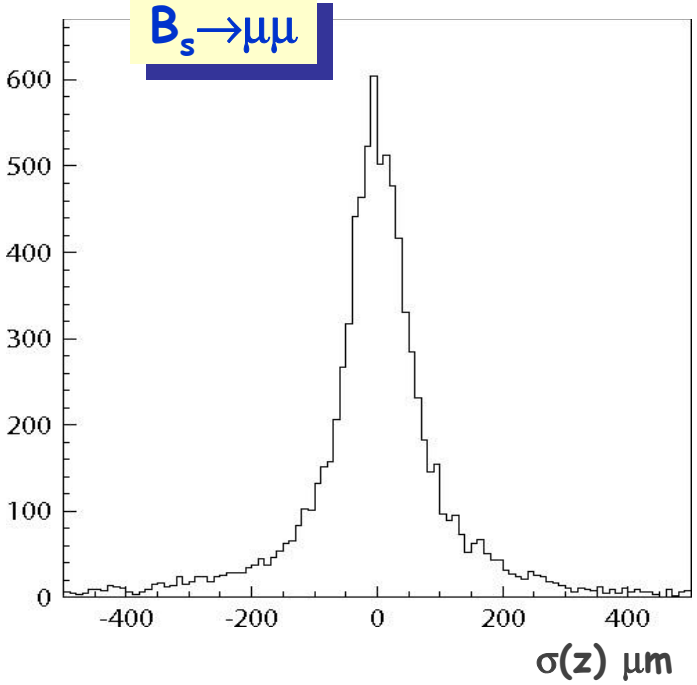
Exclusive Vertices

Secondary vertex resolution using Kalman Filter

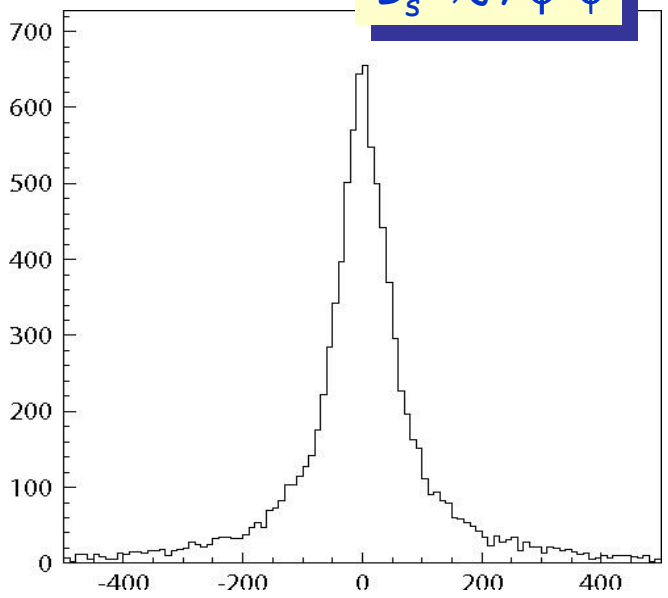
	H^0 (130)->4 μ	$B_s \to \mu\mu$	$B_s \to J/\psi\ \phi$
σ(x) μm	12.12 ± 0.13	47.5 ± 3.63	55.3 ±0.95
σ(z) μm	19.18 ± 0.23	71.5 ± 1.3	72.7 ±1.4
CPU time msec	2.5	1.9	3



$B_s \to \mu\mu$



$B_s \to J/\psi\ \phi$

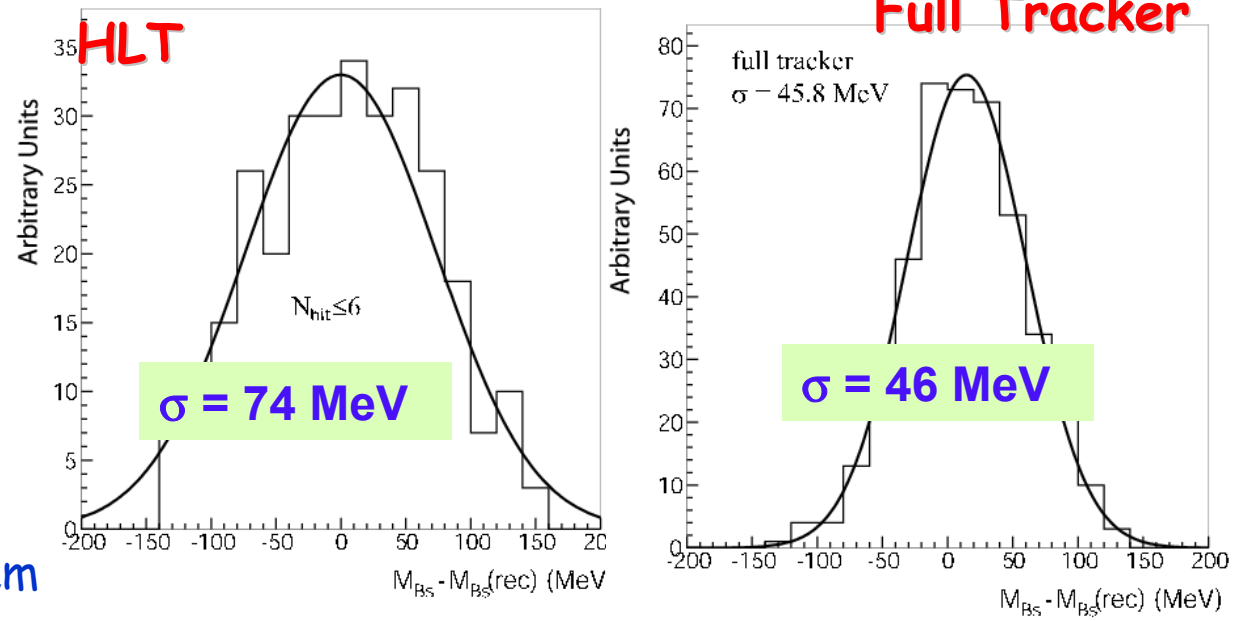


Key component for B Physics program

HLT and Offline Exclusive $B_s \to \mu\mu$

- Lvl-1: 2μ P_T>3GeV, ε=15.2%
- HLT strategy:
  - Select pixel seeds with P_T > 4 GeV in η-φ region around trigger μ's
  - Conditional tracking:
    - stop if p_t<4 GeV/c @ 5σ or N_{hit}=6 or $\sigma(p_t)/p_t$<0.02
  - B_s reconstruction if only 2 track candidates with opposite charge in $\pm$150 MeV window
  - Vertex: χ^2 < 20 and $d_{r\phi}$ > 150 μm

B_s Mass resolution



Aver

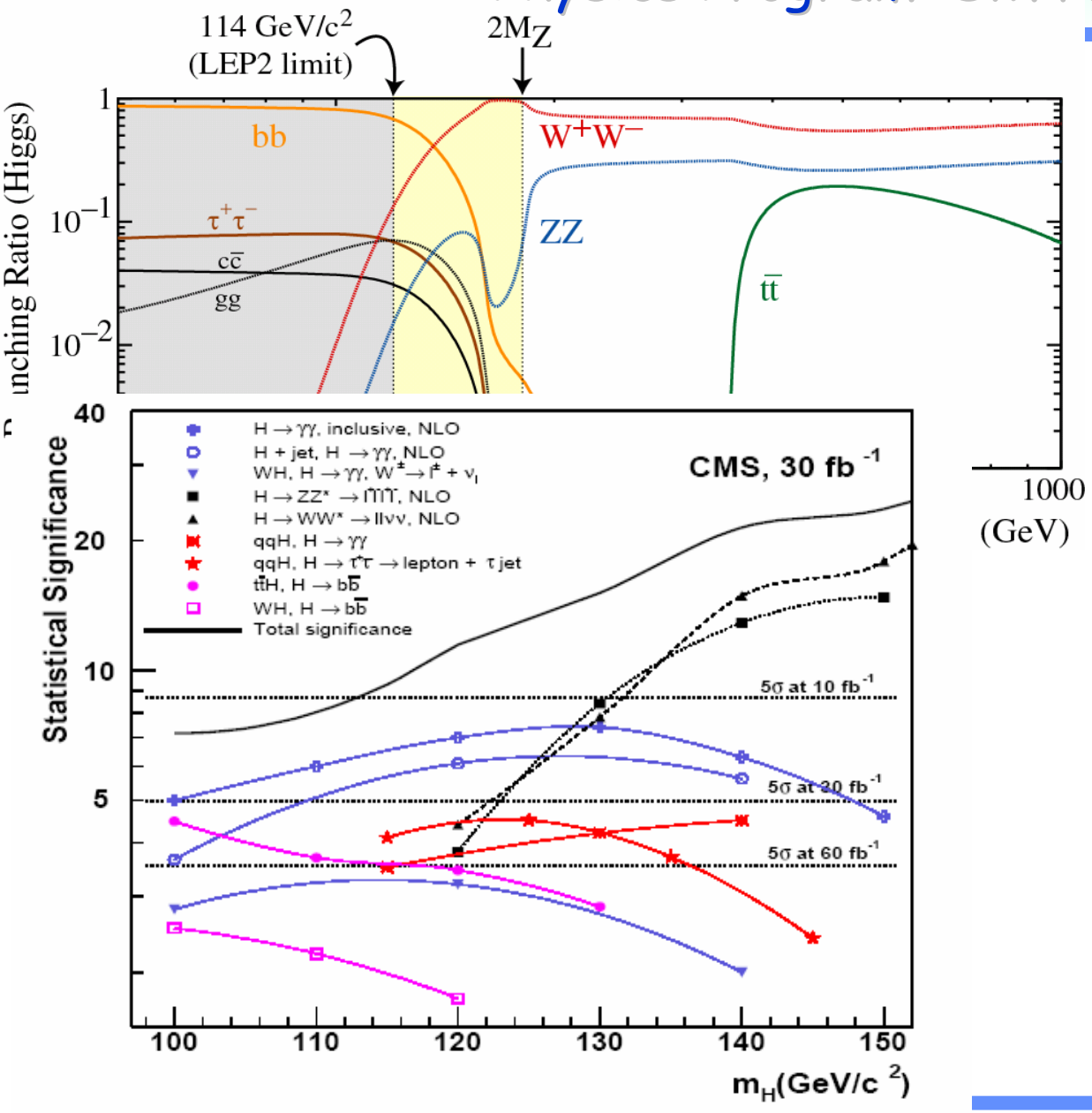
Old offline analysis (hep-ph/9907256 Jul 1999) predicts:

- ✓ 14 evts $\pm$ 2 bkg @ 90 C.L. with 20fb^{-1} (1 year @ 2x10^{33} cm^{-2}s^{-1})
- ✓ 5σ observation with 40fb^{-1} and feasibility @ high lumi too

…… But L1 is in $|\eta| < 2.4$ + slightly different kinematics cut

Update foreseen for the CMS Physics TDR

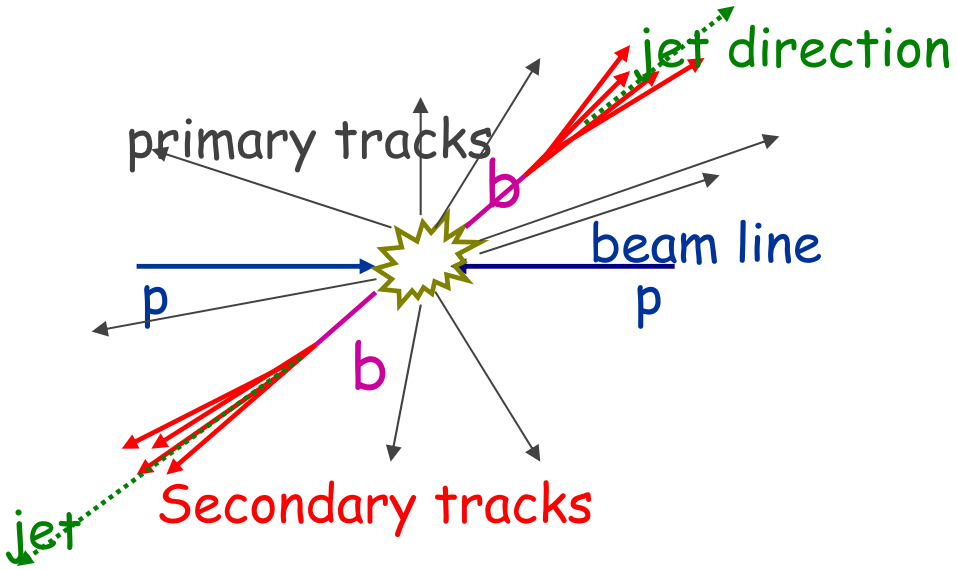
Physics Program: SM Higgs Boson

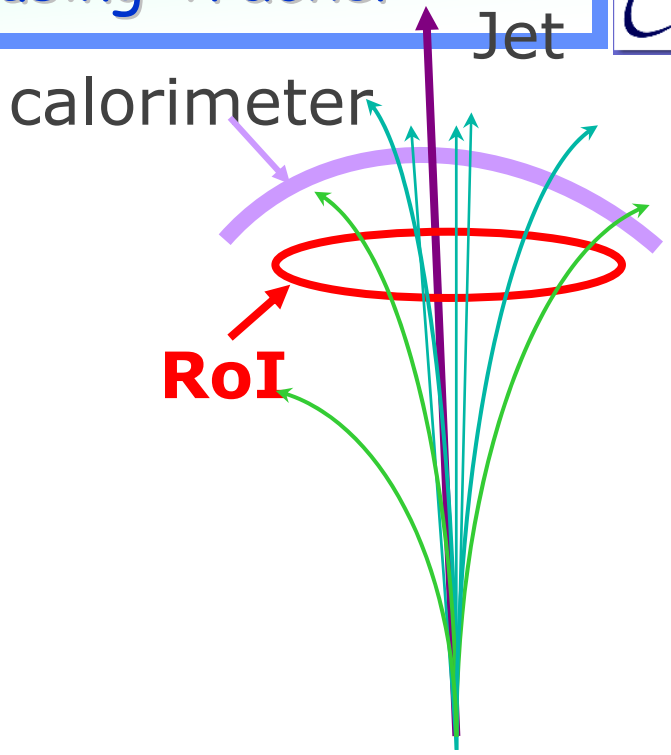


Explore the full mass range from 0.1-1 TeV, search signatures depend on Higgs mass.

- $H \rightarrow \gamma\gamma$, $H \rightarrow bb$ channels used to probe the low mass region close to the LEP limit
- Golden channel $H \rightarrow ZZ \rightarrow 4l$, excellent e/μ momentum resolution allows for a distinct mass peak, extended mass reach.
- $H \rightarrow WW^* \rightarrow 2l2\nu$ fills the gap around $m_H \sim 2M_W$
- WBF channels used for high Higgs masses. Recently turned out to be quite effective also in the very low mass region

Trigger a b Jet at HLT using Tracker





From pixel hits and calorimeters:

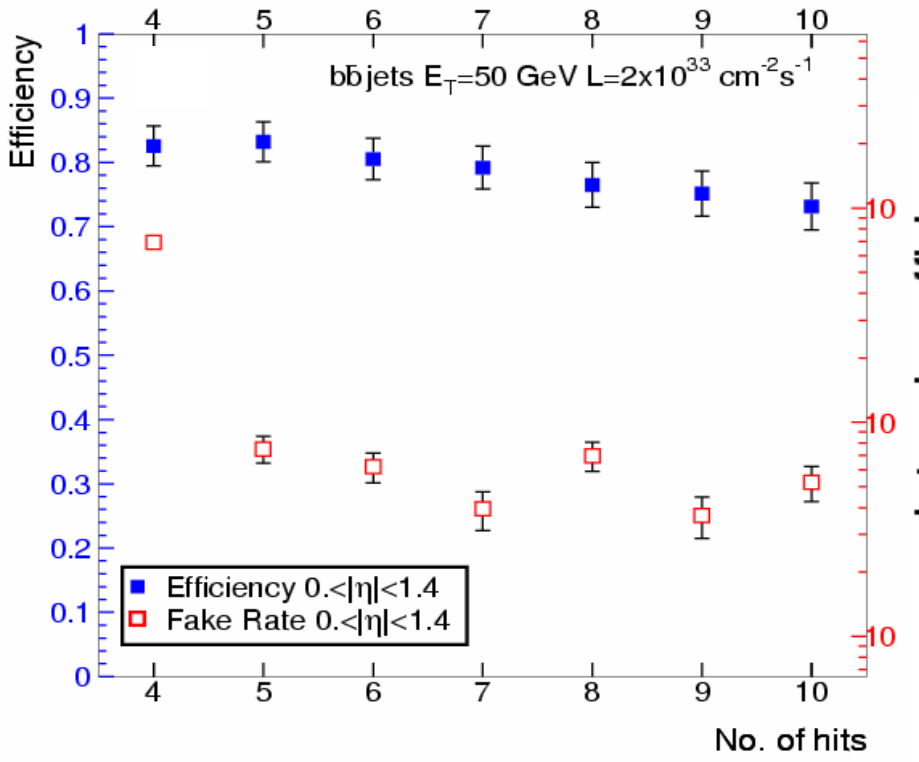
- The seed for tracks reconstruction is created around the LVL1 jet direction
- Primary vertex is calculated

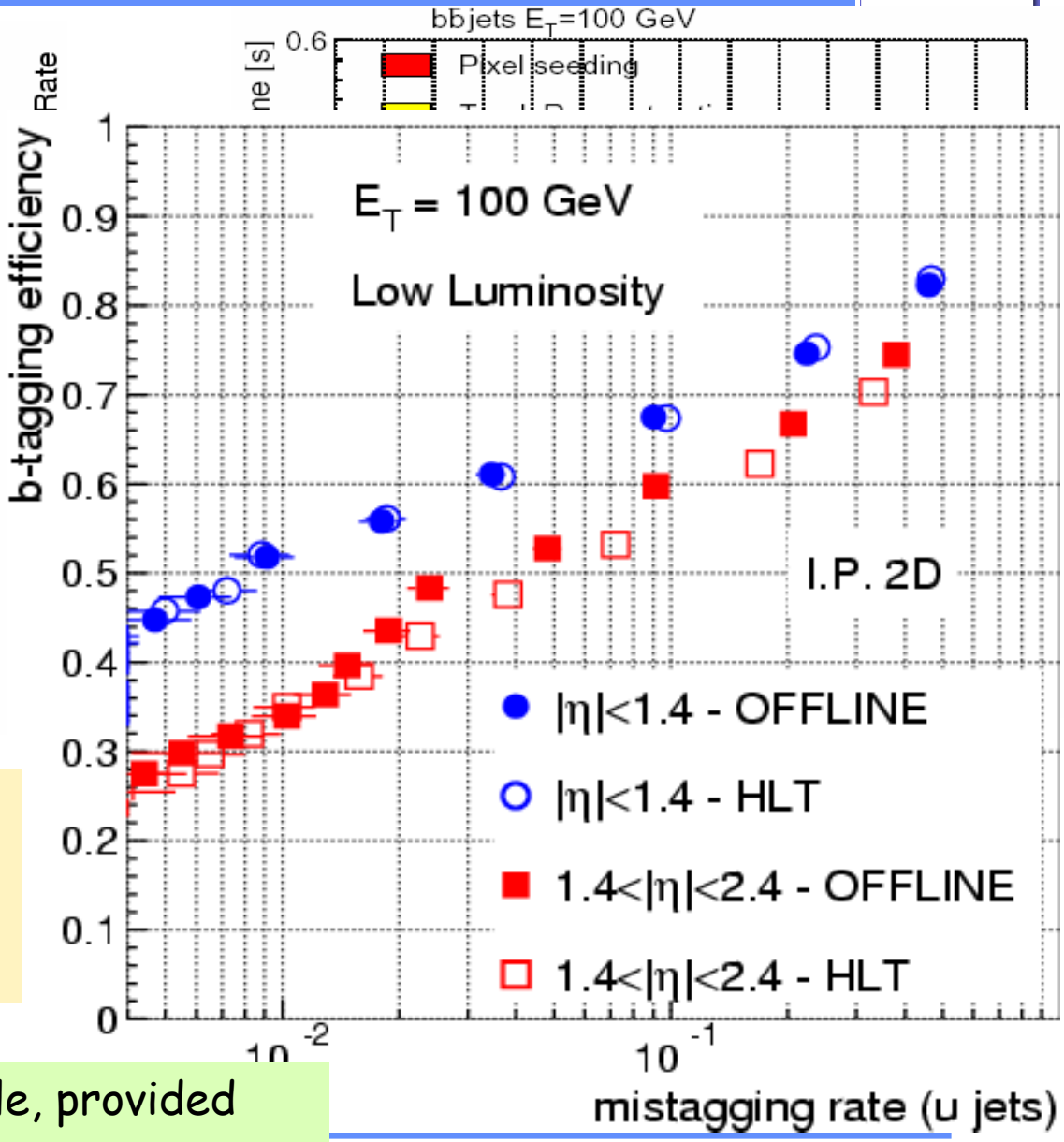
Tracks are reconstructed in a cone of $\Delta R>0.15$ around the jet direction

Tracks are conditionally reconstructed

The Jet direction is refined using the reconstructed tracks

HLT Inclusive b tagging





b-tag efficiency vs bkg efficiency @ low lumi; offline and HLT.
The difference offline-HLT is negligible

Online inclusive b tag at HLT possible, provided alignment under control …

Higgs searches: ttH -> ttbb (M_H < 130 GeV)

σ.Br=300 fb

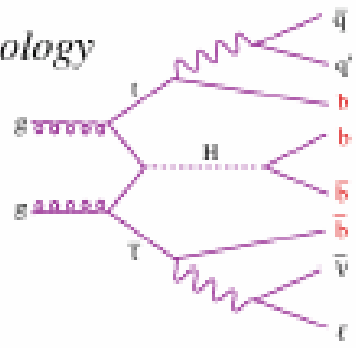
Challenging and complex topology

4 b-jets, 2 jets, 1 lepton

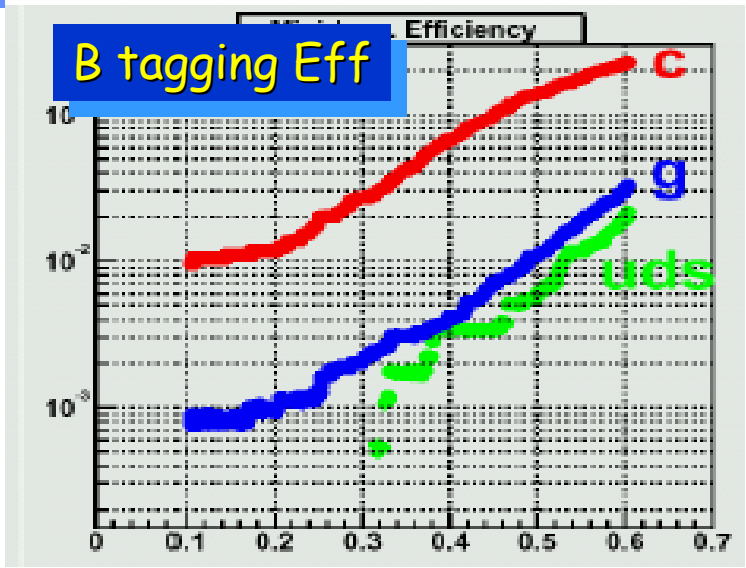
$H \to b\bar{b}$

$t \to bqq'$

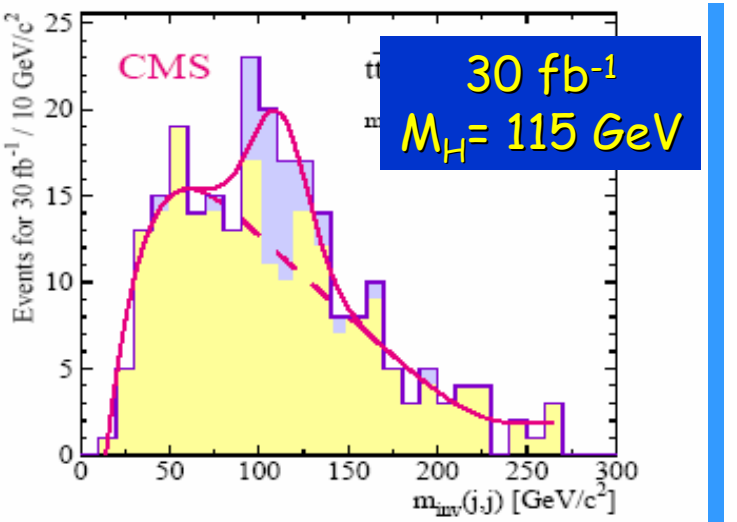
$\bar{t} \to \bar{b}\ell\nu$



B tagging Eff



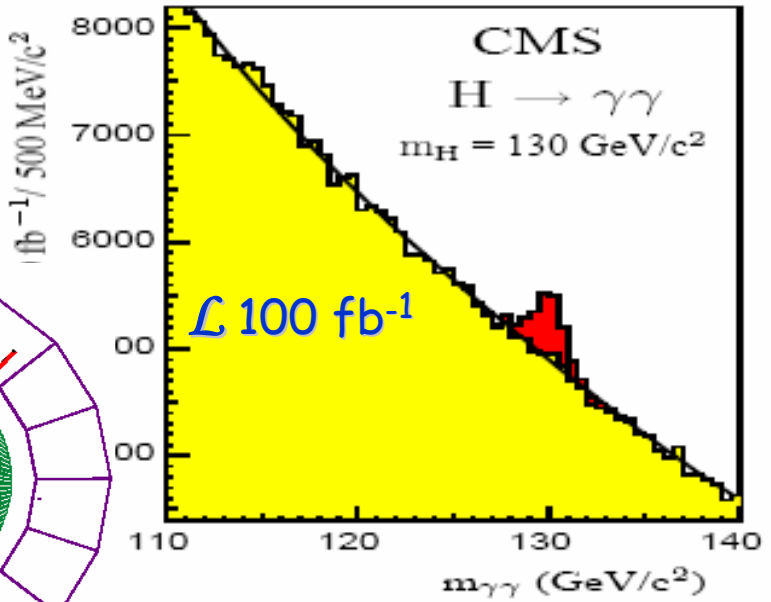
- Fully reconstructed final state- expect ν
- Required good b tagging and t tagging
  - Trigger: $t \to b(e/\mu)\nu$
  - Reconstruct both t quarks
- Backgrounds
  - Combinatorial from signal
  - Irreducible ttbb (ttjb, ttjj)
- Signal significance (5σ) :
  - M_H < 120 GeV needs 100 fb^{-1}
  - M_H < 130 GeV needs 300 fb^{-1}
- More studies on going in preparation for Physics TDR.



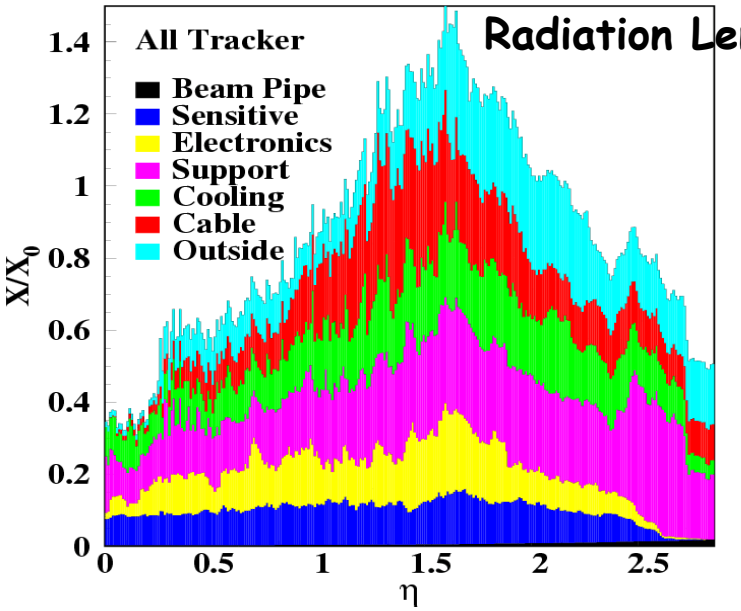
Higgs searches: H->γγ (M_H < 140 GeV)

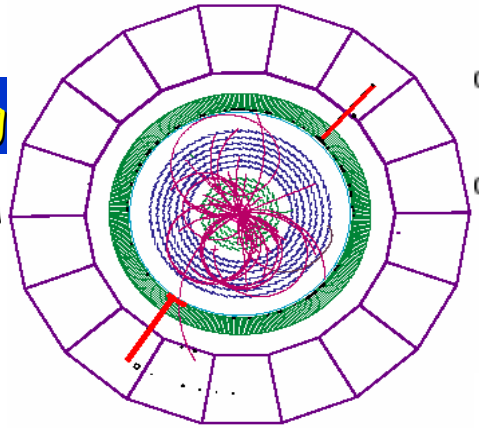
$H \rightarrow \gamma\gamma$: decay is rare (B~$10^{-3}$)

- Motivation for $PbWO_4$ calorimeter.
- EM Cal to achieve ≈1% resolution on M_H



The dark side: tracker material budg

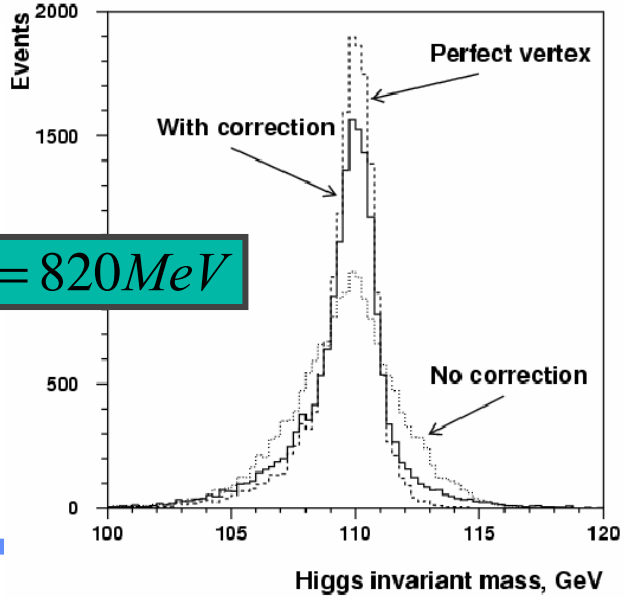




Reduces (somewhat) efficiency for usefully reconstructing H → γγ

How Tracker helps in this analysis:

- Find vertex for H->γγ signal
- Photon convertion reconstruction in Tracker



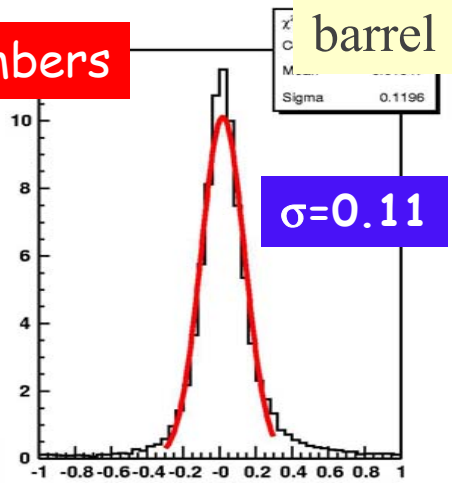
$\sigma = 820 MeV$

Higgs searches: $H \to ZZ \to \ell^+\ell^- \ell^+\ell^-$ (ℓ =e,μ)

$H \to ZZ \to \ell^+\ell^- \ell^+\ell^-$ (ℓ =e,μ)

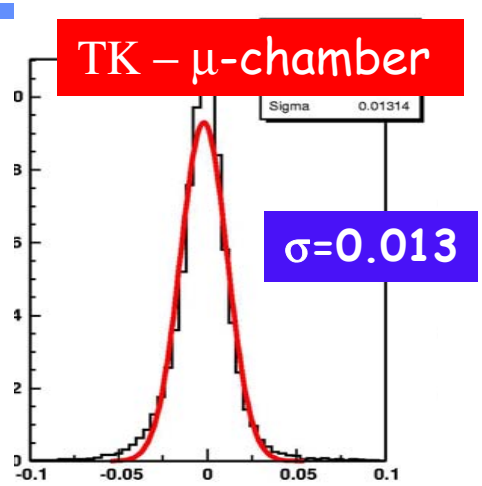
- Very clean
  - Resolution: better than 1 GeV (around 100 GeV M_H)
- Valid for the mass range $130 < M_H < 500$ GeV/c^2

μ-chambers



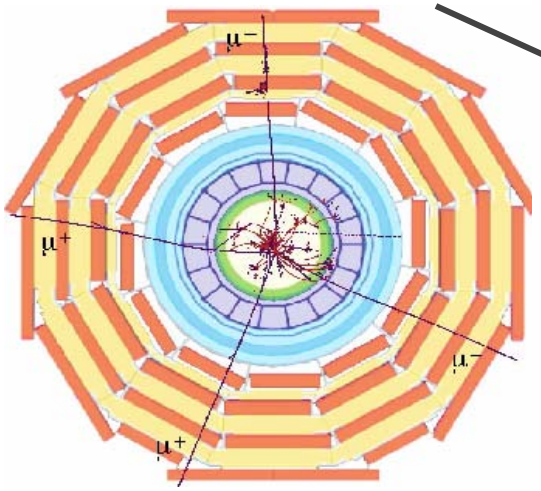
σ=0.11

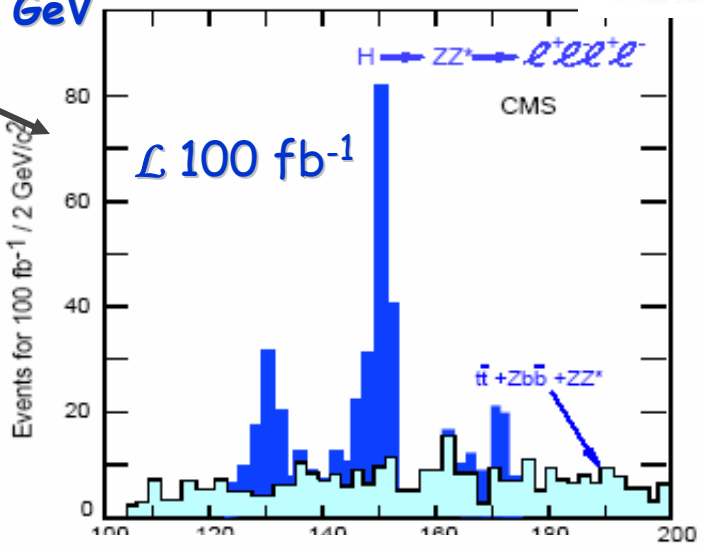
TK – μ-chamber



σ=0.013

M_H = 130, 150, 170 GeV

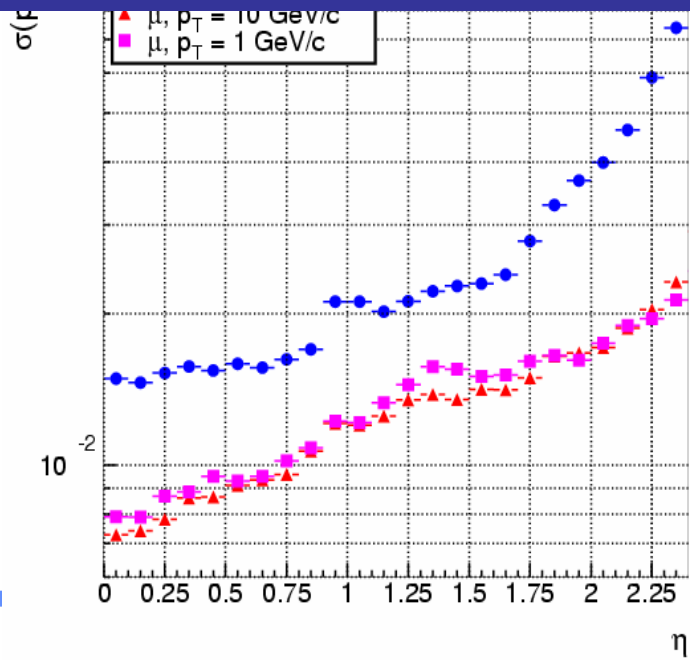




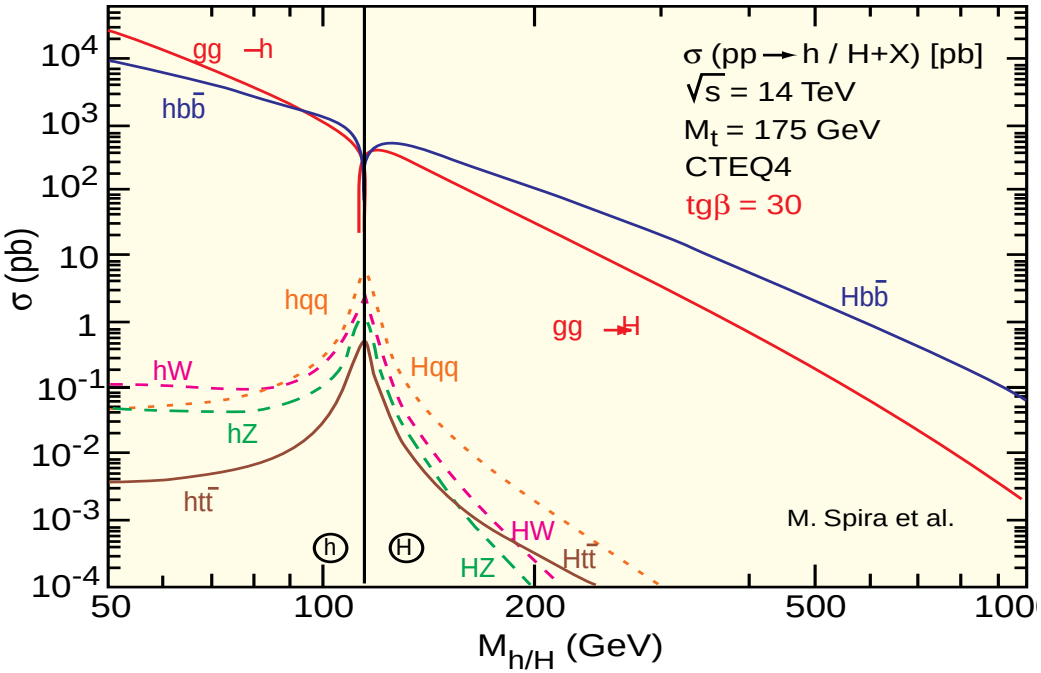
Higgs Mass, GeV	120	130	140
4e; L for 5 σ discovery, fb^{-1}	351	106	31
4μ; L for 5 σ discovery, fb^{-1}	152	35	15

MS Tracker

Transverse Momentum Resolution



Physics Program: MSSM Higgs A,H



Most promising channels:

- $A/H \to \tau\tau$, BR ~10%
- $A/H \to \mu\mu$, BR ~0.03%

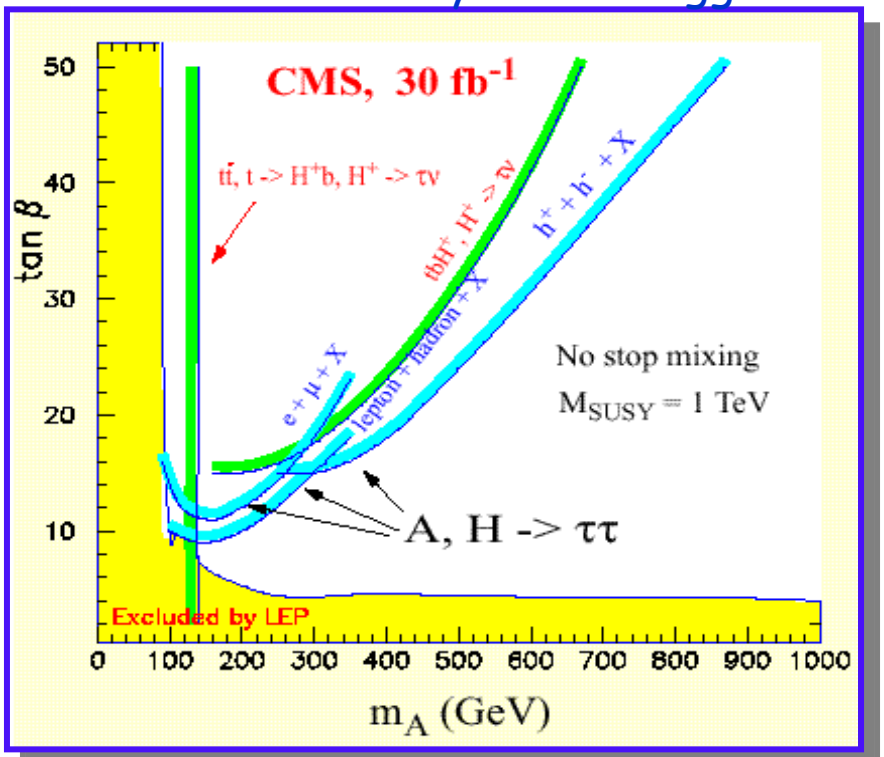
(Insensitive to stop mixing)

B and τ tagging play a key role

Production predominantly via gluon fusion and bbH

Associated bbH,A production enhanced by $tg^2\beta$ in the MSSM wrt SM

Heavy SUSY Higgs



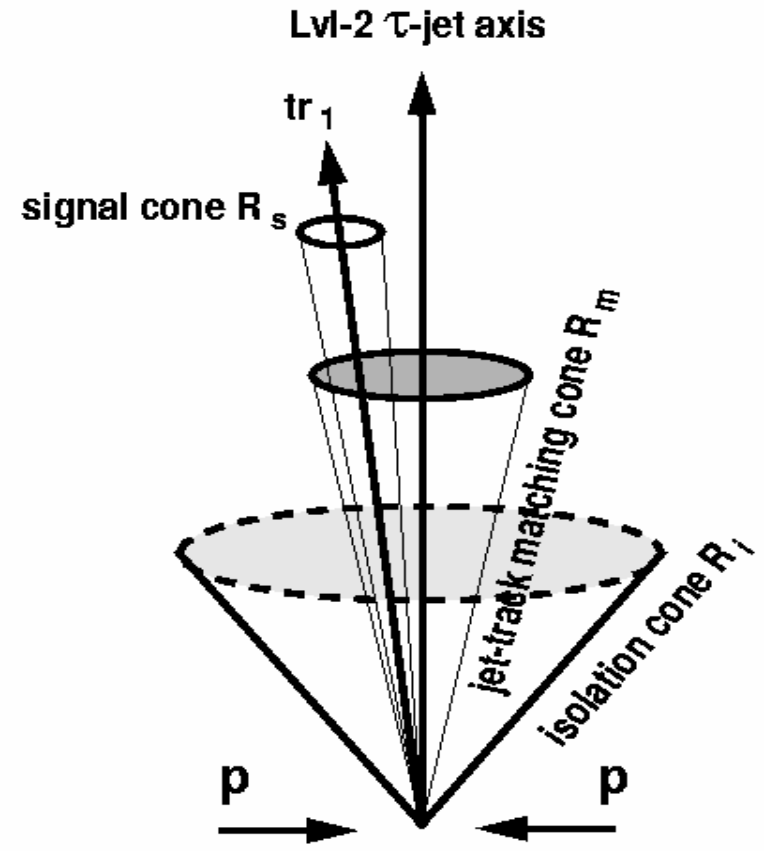
Trigger a τ Jet at HLT using Tracker

Regional Tracking: Look only in
Jet-track matching cone
Loose Primary Vertex association

$A^0/H^0 \rightarrow 2\tau \rightarrow 2\tau$ jets

Conditional Tracking: Stop track as soon as
Pixel seed found (PXL) / 6 hits found (Trk)
If Pt<1 GeV with high C.L.

Reject event if no "leading track" found



Regional Tracking: Look only inside
Isolation cone
Loose Primary Vertex association

Conditional Tracking: Stop track as soon as
Pixel seed found (PXL) / 6 hits found (Trk)
If Pt<1 GeV with high C.L.

Reject event as soon as additional track found

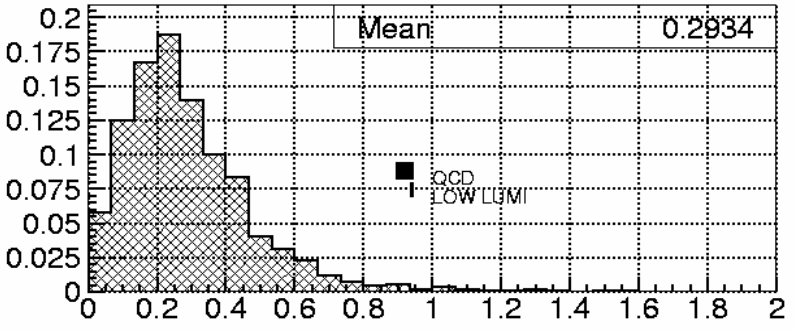
Trigger a τ Jet at HLT using Tracker

By adding a few Tracker hits, can measure track momentum:
Cut on leading track Pt (>6,7 GeV) allows to reduce isolation cone size => higher signal efficiency and less sensitivity to pile-up

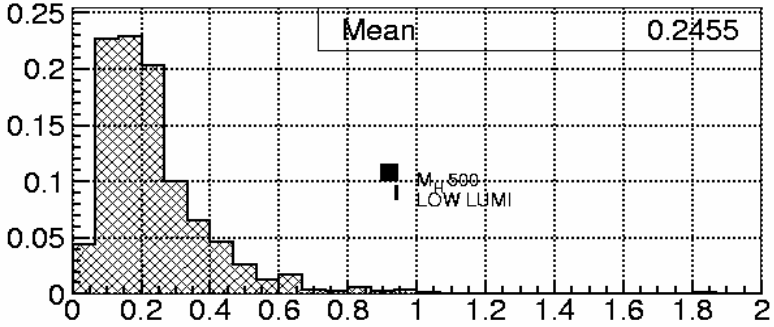
$A^0/H^0 \to 2\tau \to 2\tau$ jets

	Luminosity	Configuration/Trigger	M_H = 200 GeV/c²	M_H = 500 GeV/c²	QCD
	$2\times10^{33}cm^{-2}s^{-1}$	Staged pixels, Track Tau	0.355±0.006	0.375±0.005	$(8.6\pm1.6)\times10^{-4}$
Low $\mathcal{L}$	$2\times10^{33}cm^{-2}s^{-1}$	Full pixels, Track Tau	0.433±0.006	0.489±0.005	$(8.3\pm1.6)\times10^{-4}$
	$2\times10^{33}cm^{-2}s^{-1}$	Full pixels, Calo+Track Tau	0.446±0.00 **0.47**	0.486±0.005	$(1.0\pm0.2)\times10^{-3}$
High $\mathcal{L}$	$10^{34}cm^{-2}s^{-1}$	Track Tau	0.346±0.006	0.420±0.005	$(1.13\pm0.4)\times10^{-3}$
	$10^{34}cm^{-2}s^{-1}$	Calo + Track Tau	0.361±0.00 **0.40**	0.427±0.005	$(9.4\pm3.0)\times10^{-4}$

Trk tau fast enough at low luminosity for full L1 rate
At high luminosity currently need a moderate Calo pre-selection factor to reduce time



Trk τ timing @ low lumi: QCD events



Trk τ timing @ low lumi: signal events

MSSM Higgs Searches: H,A→ττ

Main search channel for heavy MSSM Higgs, three final states studied:

- 2 leptons + ν 's, 12 % B.R.
- 1 lepton + τ jet + ν 's, 35 % B.R.

} Low MA region, lepton signature necessary to kill the background

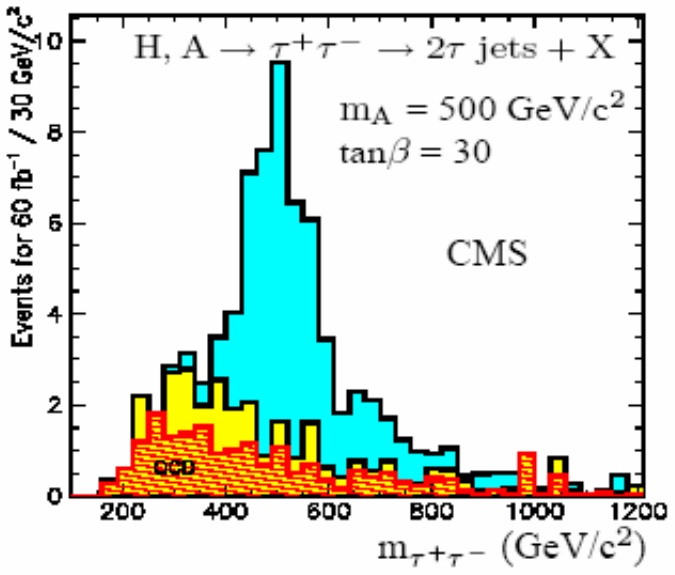
- 2 τ jets + ν 's, 25% 1-1 prong, 44% 1-3 prong

} Extends reach at larger MA

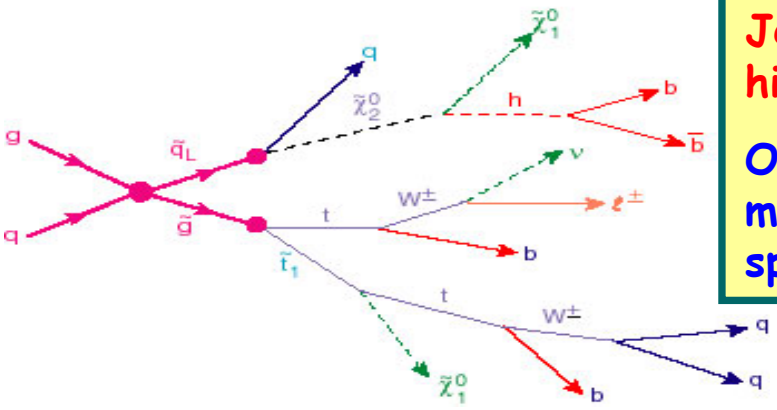
Main backgrounds from $Z/\gamma^* \rightarrow \tau\tau$, tt, QCD for 2-jets final state.

Selection based on:

- b-tagging (this analysis ε_b~40%, purity ~94%)
- E_T^{miss}
- identified leptons (e,μ)
- tracks with high impact parameter
- τ jet tagging: **low multiplicity narrow jets with hard tracks isolated in calorimeters and in tracker**

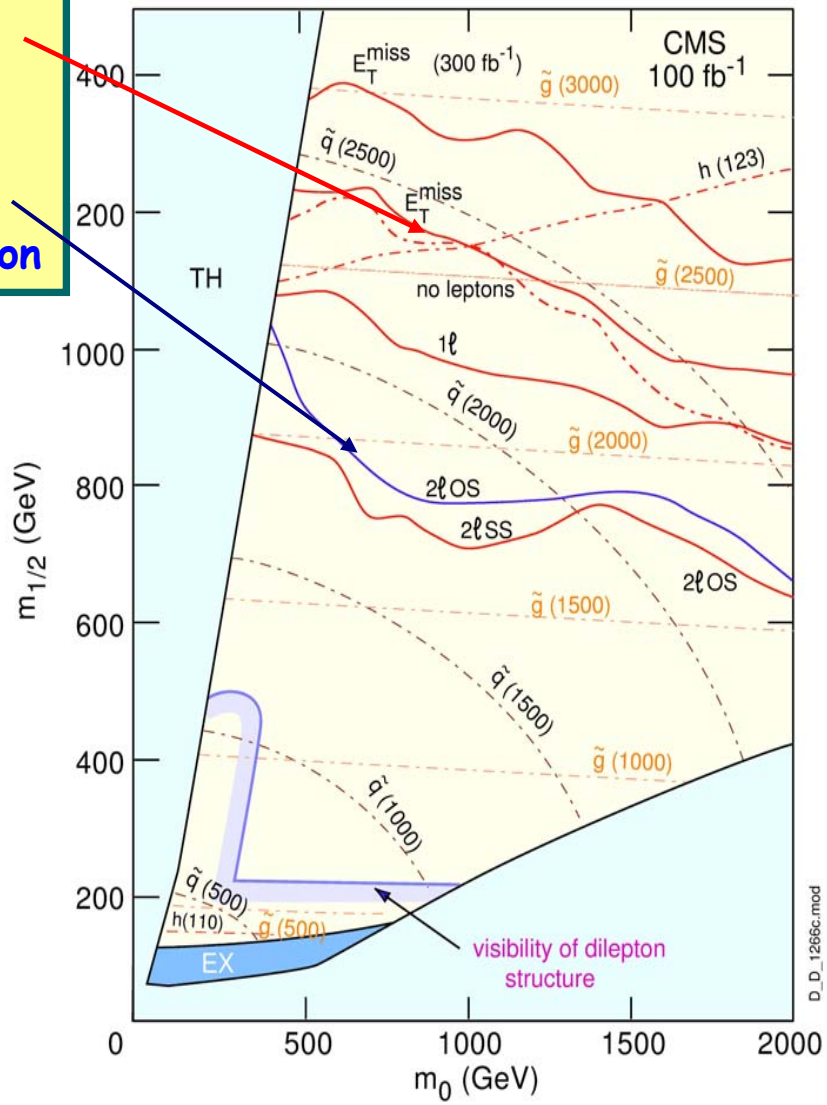


SUSY Signatures



Jets + E_T^{miss} has the highest reach

OS two-leptons are most useful for sparticle reconstruction



Squark, gluino production leads to lepton(s) + E_T^{miss} + jets

Backgrounds: W + jets, Z + jets, tt, Wtb, WW, WZ, …

$\tilde{q}$, $\tilde{g}$ pair production dominates the total cross section

Cross sections don't vary much with m, tan β

Also for this studies Tracker plays a key role!!

Summary

CMS Tracker Detectors expected to play an essential role to address the full range of physics which can plausibly be accessed at the LHC.

- Standard Model Physics, like B Physics, Top Physics
- SM Higgs Searches, MSSM Higgs Searches, SUSY Searches .....

CMS Tracker designed to cope the LHC Physics

- Pixel detector allows fast & efficient track seed generation, as well as excellent 3-D secondary vertex identification
- Pixel and μ-strip sensors, together with the analyzing power of the CMS 4T magnet allow for a ~ 2% or better resolution for 100GeV muons over about 1.7 units of rapidity
- Pixel and μ-strip sensors used in HLT and Offline Studies for e, μ, identification, b and τ tagging, Energy Flow.....

Physics of the LHC will be extremely rich
... just get it running!

Backup slides

Muons in High Level Trigger

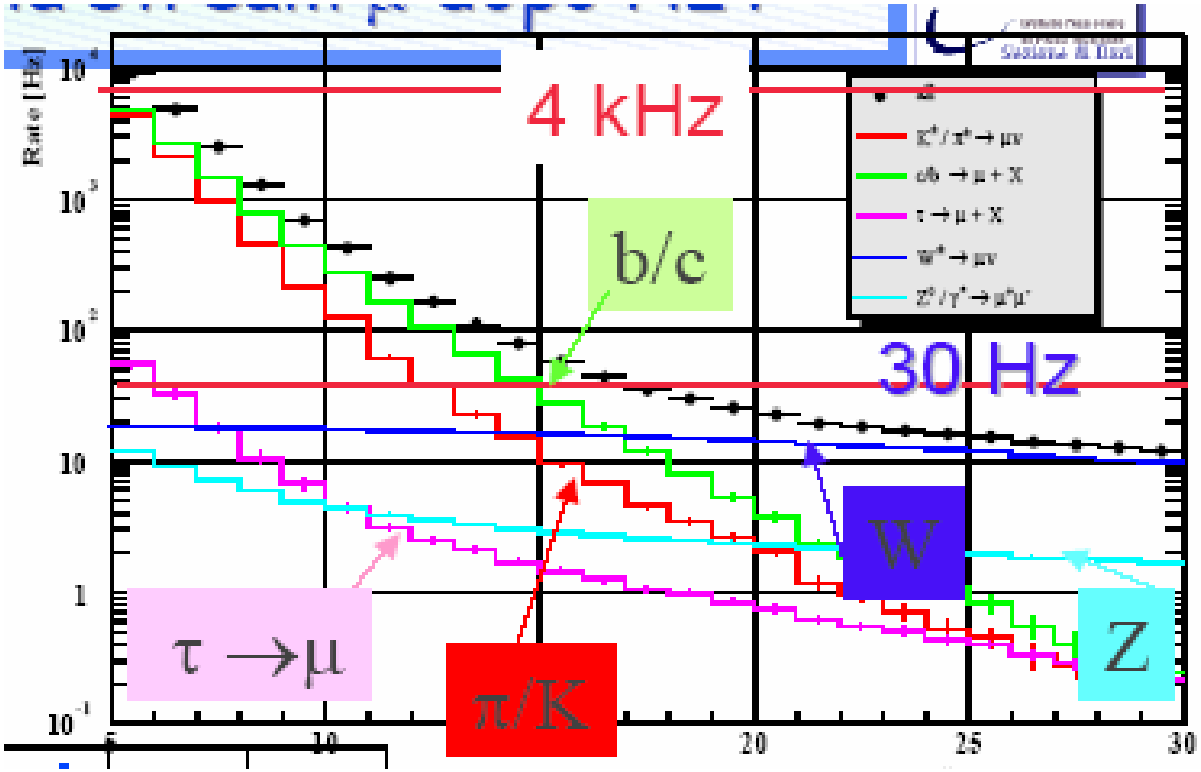
After HLT only 100Hz can be stored on tape

30Hz allocated to 1μ,2μ (25Hz+5Hz)
(P_T > 19GeV, P_T > 7GeV)

The content in b is too little (~ 10 Hz for b/c)

Need to push and select exclusive b events

Exploit the online tracking



1Hz ➡ 10^7 evts/year @ low luminosity
Insufficient for processes with BR < 10^{-4}

Trigger Table Low Luminosity

Low Luminosity L1 Trigger Table (Prototype)

Trigger type	Threshold (ε=95%) (GeV)	Indiv. Rate (kHz)	Cumul rate (kHz)
1e/γ, 2e/γ	29, 17	4.6	4.3
1μ, 2μ	14, 3	3.6	7.9
1τ, 2τ	86, 59	3.2	10.9
1-jet,3-jets, 4-jets	177,86,70	3.0	12.5
Jet * MissE_T	88 * 46	2.3	14.3
e * jet	21 * 45	0.8	15.1
Min-bias		0.9	16.0

Hardwared processors (Asic,FPGA) Using only calorimeters and Muon data

Designed to cover the widest possible range of physics for discovery

Total L1 allocated rate- 50 KHz x 1/3 safety factor

- B Physics selection triggered @ L1 by single or di-muon triggers
- Particles from B decays have relatively soft spectrum
- Important keeping the L1 threshold as low as possible
- Muons are preferred to electron because of the lower trigger threshold

Online Tracking

Limited amount of CPU time available for trigger decision:
500 ms on a 1GHz machine possibly 50 ms in 2007

Regional seed generation

Limited to some region identified by Lvl1 objects (e.g. cone around μ direction)

Reduce

- # of track seeds
- # of operations per seed

Partial/Conditional Tracking

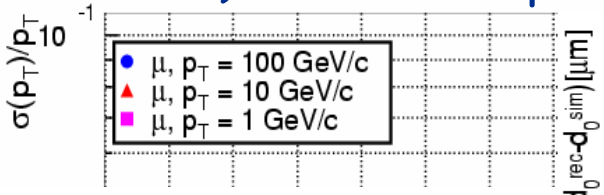
Stopped when:

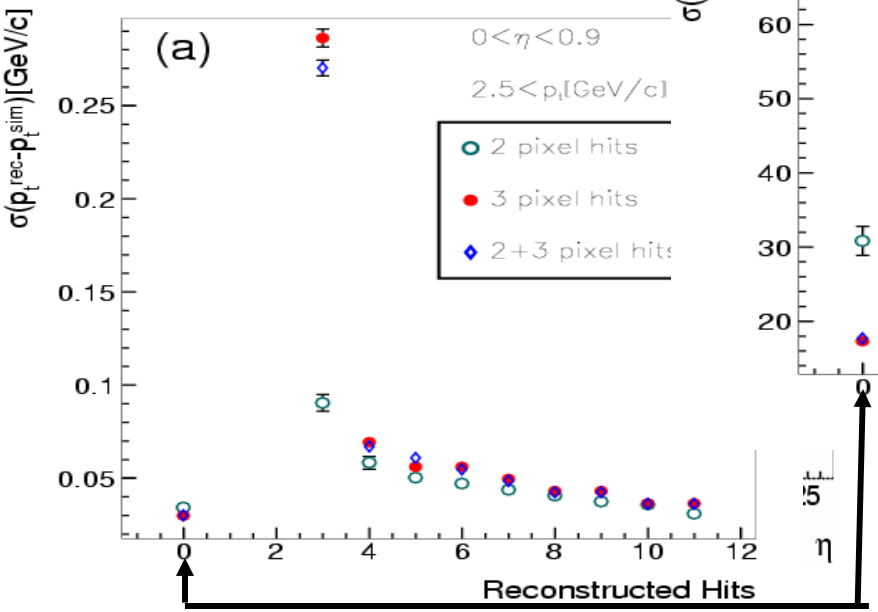
- N hits are reconstructed
- P_T resolution > given threshold
- P_T value < given threshold
- ……..

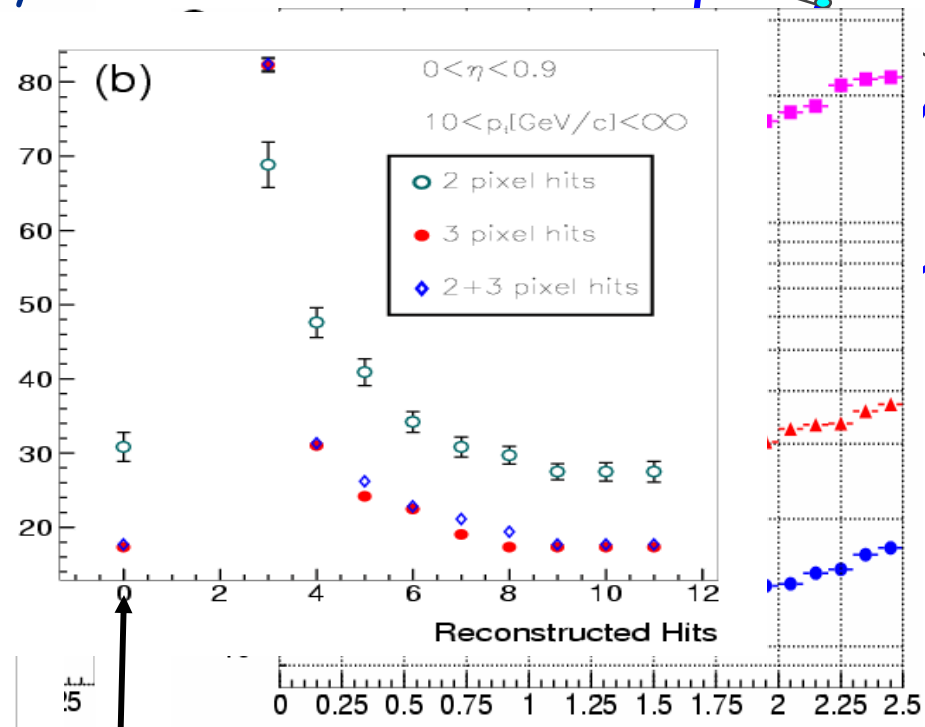
HLT Tracking does not need to be as accurate as in the offline

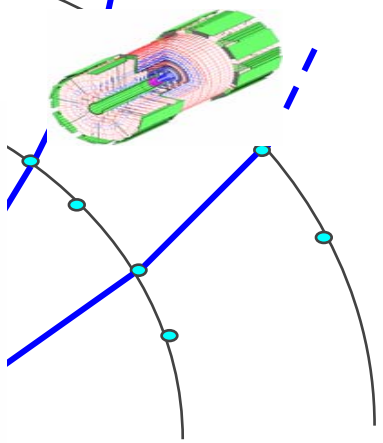
Global and Partial Track Reconstruction Performances

Reconstruction of charged tracks with Tracker (trajectory=helix) from inside (pixel) out (μ-strip detectors). Pixel Occupancy ~ 10^{-4}









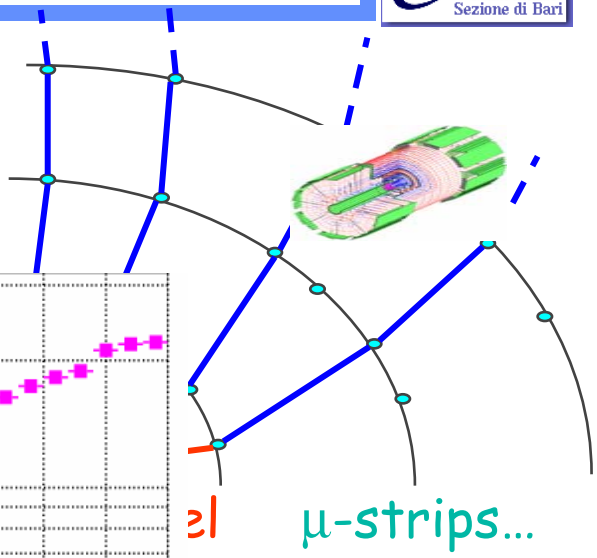
μ-strips…

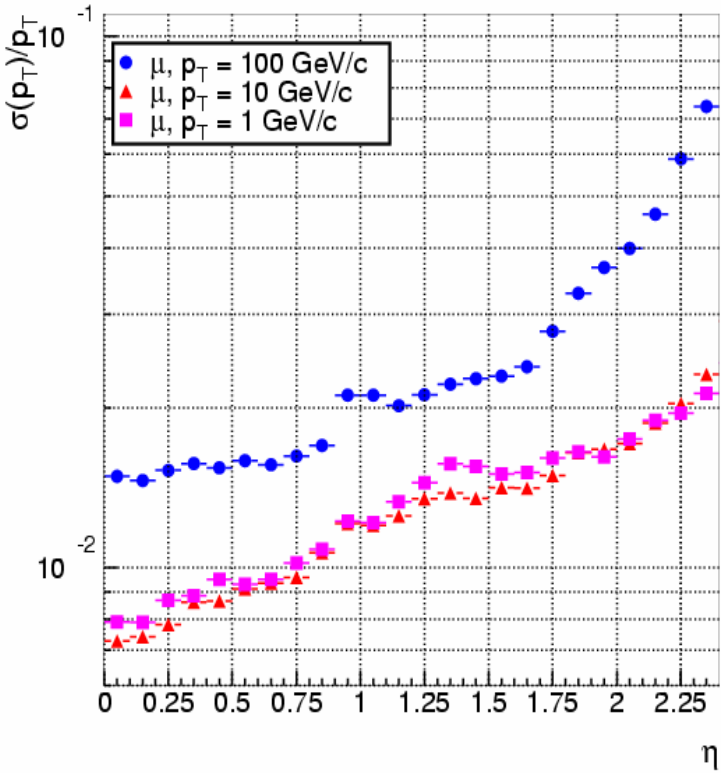
Full tracker performance

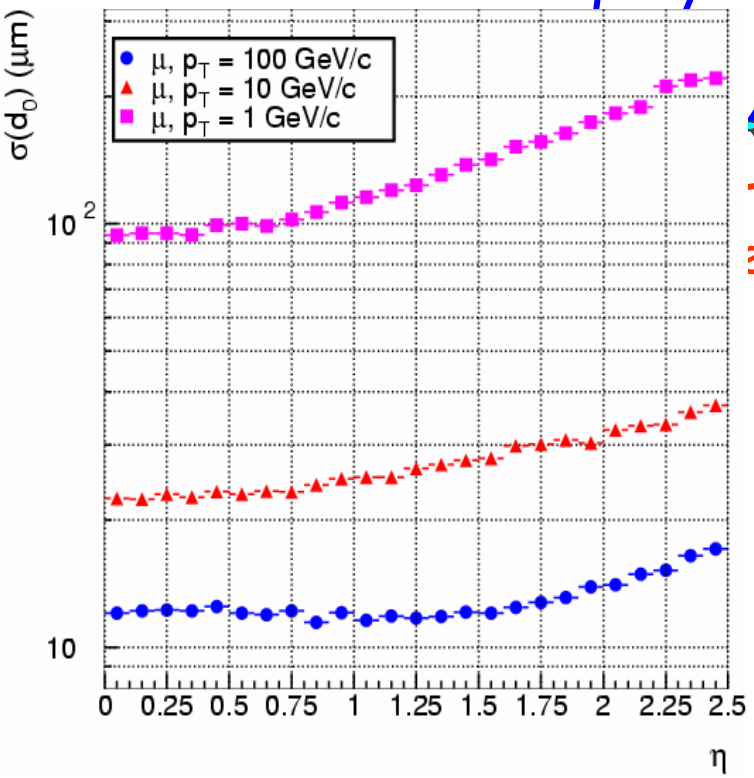
At HLT we are not necessarily interested in ultimate resolution.
Good track parameter resolution for moderate Pt tracks is obtained already with 4 or more hits

Track Reconstruction Performances

Reconstruction of charged tracks with Tracker (trajectory=helix) from inside (pixel) out (μ-strip detectors). Pixel Occupancy ~ 10^{-4}







For lower pt tracks multiple scattering becomes significant and the η dependence reflects the amount of material traversed by tracks and the lever arm effect

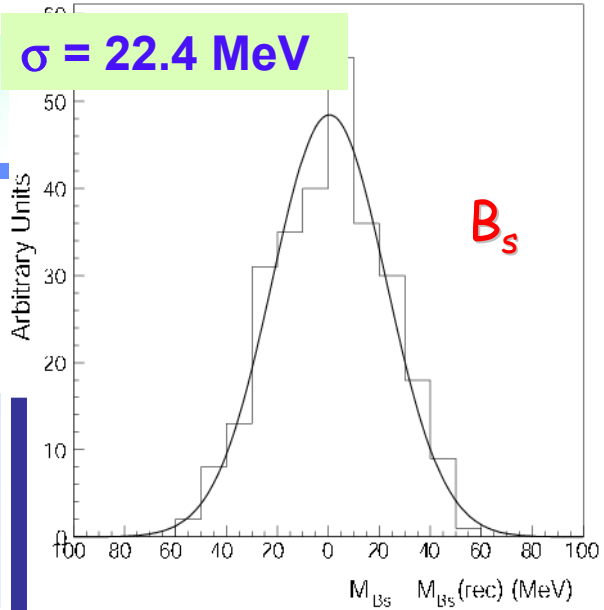
HLT Exclusive $B_s \rightarrow J/\psi\phi$

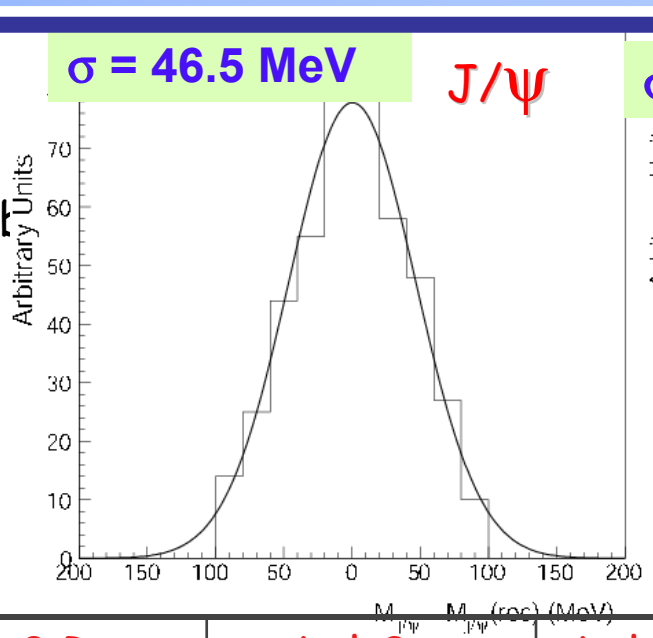
CP violation weak phase
$\phi_s = 2\delta\gamma = 2\lambda^2\eta$
SM predicts tiny CP asymmetry $\phi_s \sim O(0.03)$

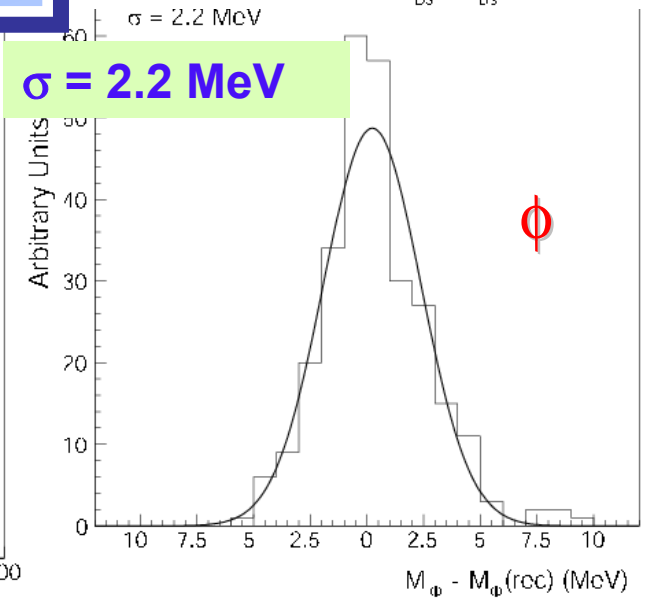
$BR(B_s \rightarrow J/\psi\,\phi) = (9.3 \pm 3.3) \times 10^{-4}$
$BR(J/\psi \rightarrow \ell^+\ell^-) \approx 6\%$
$BR(\phi \rightarrow K^+K^-) \approx 49\%$

HLT strategy:

- Lvl-2: reconstruct mu
  - ±100MeV window around J/ψ mass, $\chi^2 < 20$ and $d_{r\phi} > 200\ \mu m$
  - ⇒ Rate = 15 Hz, <t>~260ms
  - ⇒ 90% of Lvl-2 J/ψ are from b
- Lvl-3: reconstruct ϕ and B_s
  - Regional tracking around J/ψ direction
  - <t>~800ms

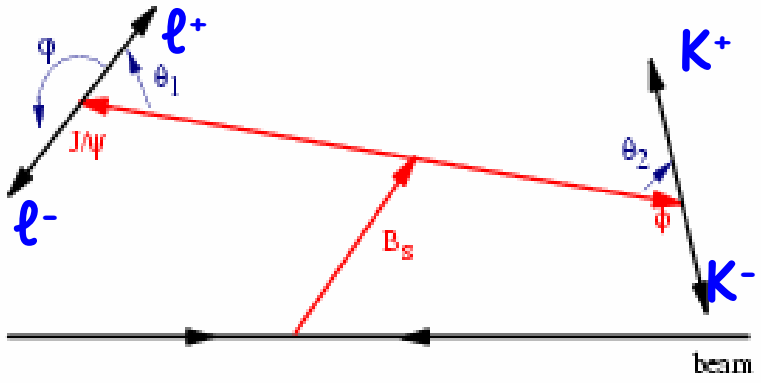






Lvl-1 ε	Lvl-2 ε	Lvl-2 Rate	Lvl-3 ε	Lvl-3 Rate	Events/ 10fb^{-1}
16.5%	13.7%	14.5 Hz	8.7%	<1.7Hz	83800

$B_s \rightarrow J/\psi\varphi \rightarrow \mu\mu$ KK

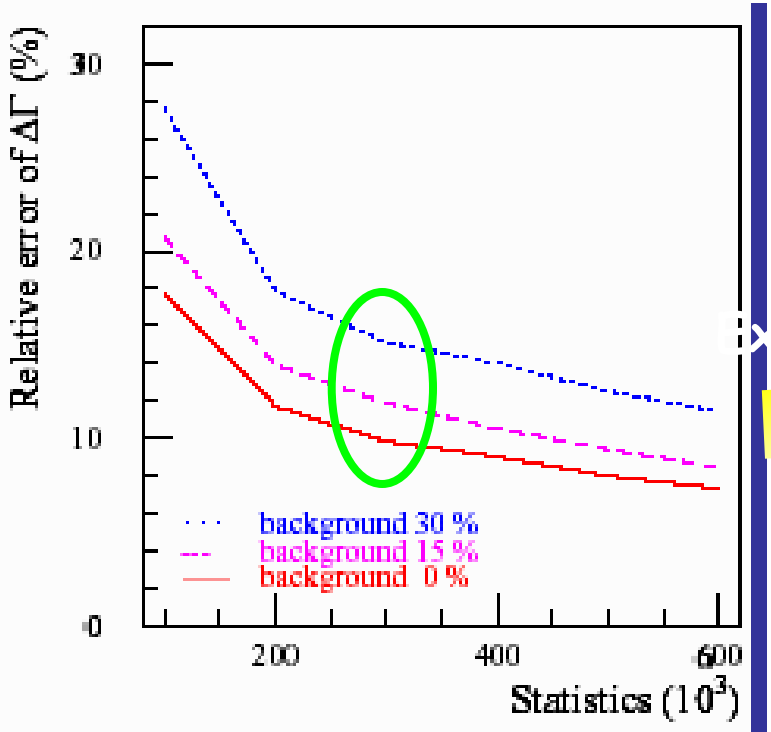


Old CMS analysis (CERN-2000-004)
not updated yet

Angular distribution analysis
Expected number of signal evts ~600K
(yield with 30fb^{-1})

Trigger was NOT optimized

	$\Delta\Gamma_s$	$\phi_s(x_s=20)$	$\phi_s(x_s=40)$
Value	$0.15\times\Gamma_s$	0.04	0.04
Error	8.0%	0.014	0.03



~300K 40fb^{-1}

$\sigma(\Delta\Gamma_s)/\Delta\Gamma_s \sim 12\%$

$\delta\phi_s(x_s=20) \sim 0.02$ rad

$\delta\phi_s(x_s=40) \sim 0.04$ rad