Prospects of measuring

$B_s \to \mu^+\mu^-$ with CMS

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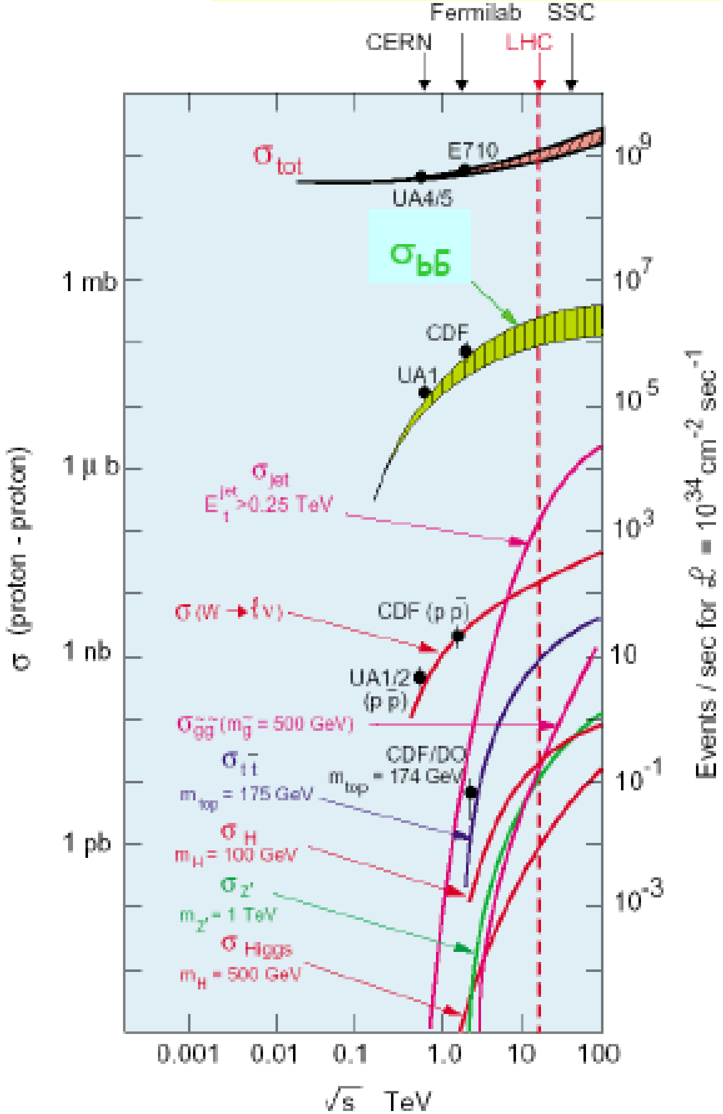
B physics at CMS

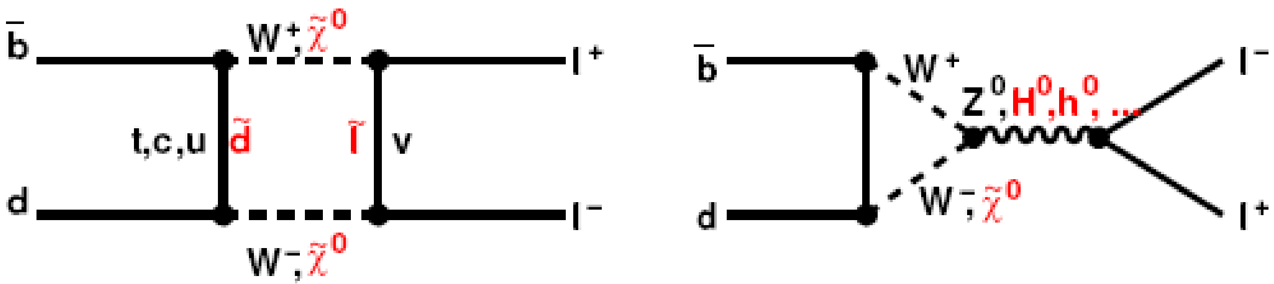


- B production at the LHC:
  - Peak Luminosity: 2×10^{33} … 10^{34} $cm^{-2}s^{-1}$
  - b cross section: σ(bbar) ~ 500 μb
  - O(10^5…10^6) b pairs/sec
  - But: High level trigger output <100Hz!
  - Trigger highly challenging!
- B-Physics program:
  - Rare decays
  - CP Violation
  - B^0_s mixing
- This talk: focus on rare decay $B^0_s \$ \mu^+\mu^-$

$B_s\$\;\mu^+\mu^-$: The Physics Case

- B^0_s highly suppressed in SM: $B=(3.42$ « $0.54)*10^{-9}$ *
  - Forbidden at tree level, Effective FCNC
  - Internal quark annihilation, Helicity suppression
  - In SM, only through higher order loop diagrams

, highly sensitive probe for new physics!



- Sensitivity to BSM parameters
  - tanβ in MSSM and various other models

*) A.J. Buras, PLB566,115

Standard Model Expectation for $B^0_s \to \mu^+\mu^-$ and $B^0_d \to \mu^+\mu^-$

- In SM, $\mathbf{B^0_d} \to \mu^+\mu^-$ suppressed wrt $\mathbf{B^0_s} \to \mu^+\mu^-$
  - Suppression $(|V_{td}|/|V_{ts}|)^2$
  - No $\mathbf{B_s}$ at B factories
- Helicity suppression favours $\mathbf{B_{s(d)}} \to \tau^+\tau^-$
  - Very challenging mode
- All decay channels beyond current reach of presently running experiments:

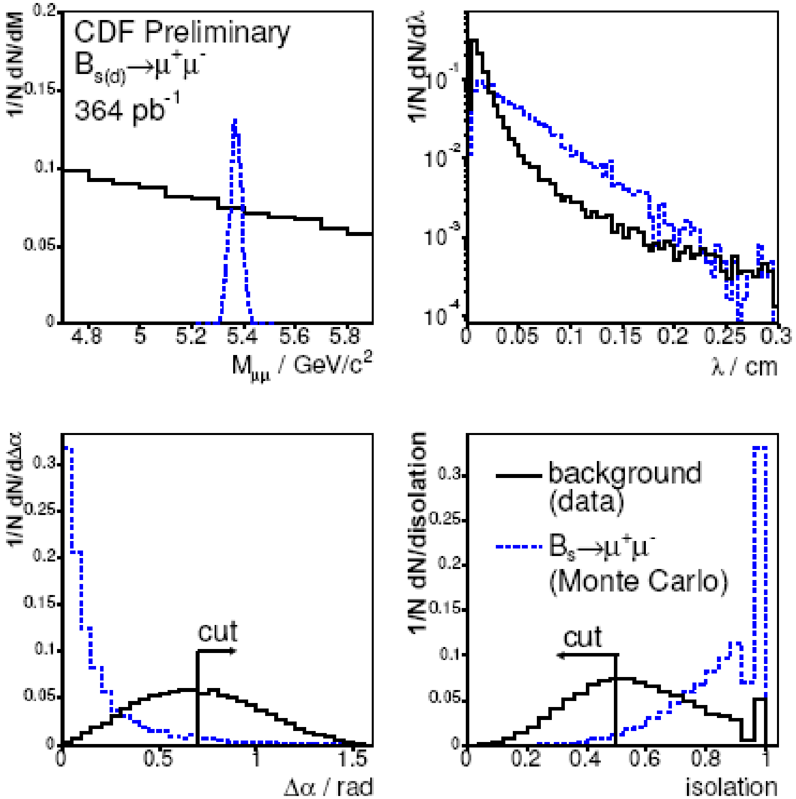
Mode	$B^0_s \to \mu^+\mu^-$	$B^0_d \to \mu^+\mu^-$	$B^0_d \to e^+e^-$	$B^0_d \to e^\pm\mu^\mp$	Reference
SM Expect.	3.5×10^{-9}	1.0×10^{-10}	2.4×10^{-15}	~ 0	PRD68, 111101
CLEO	-	6.1	8.3	15	PRD62, 091102
BELLE	-	1.6	1.9	1.7	PRD68, 111101
CDF	5.8	1.5	-	-	PRL93, 032001
D0	4.1	-	-	-	PRL94, 071802
BABAR	-	0.61	0.83	1.8	PRL94, 221803

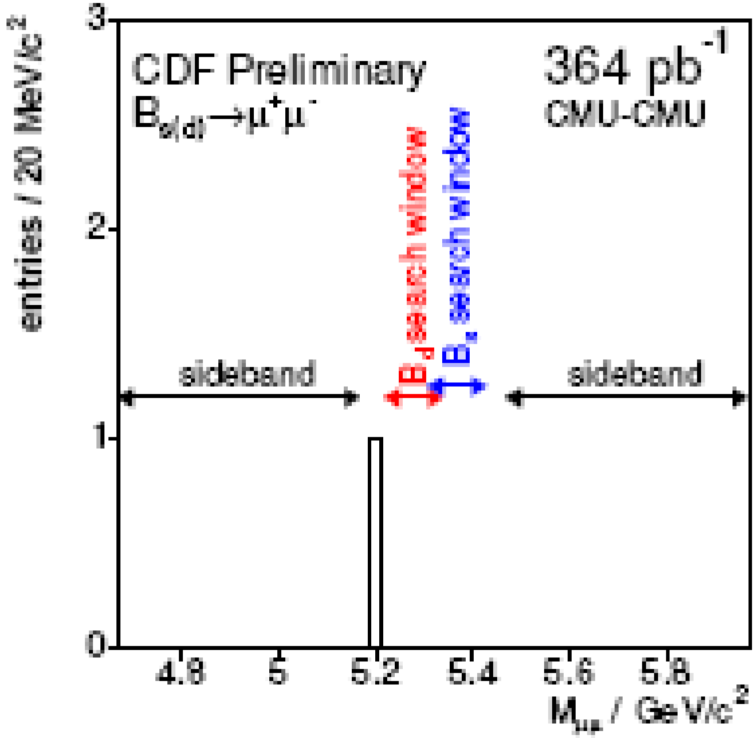
(All experimental results in units of 10^{-7})

CDF Result (best limit so far)

CDF Collaboration, PRL93(2004)032001

NEW Update: CDF-Note 7670 ($L=364 pb^{-1}$)





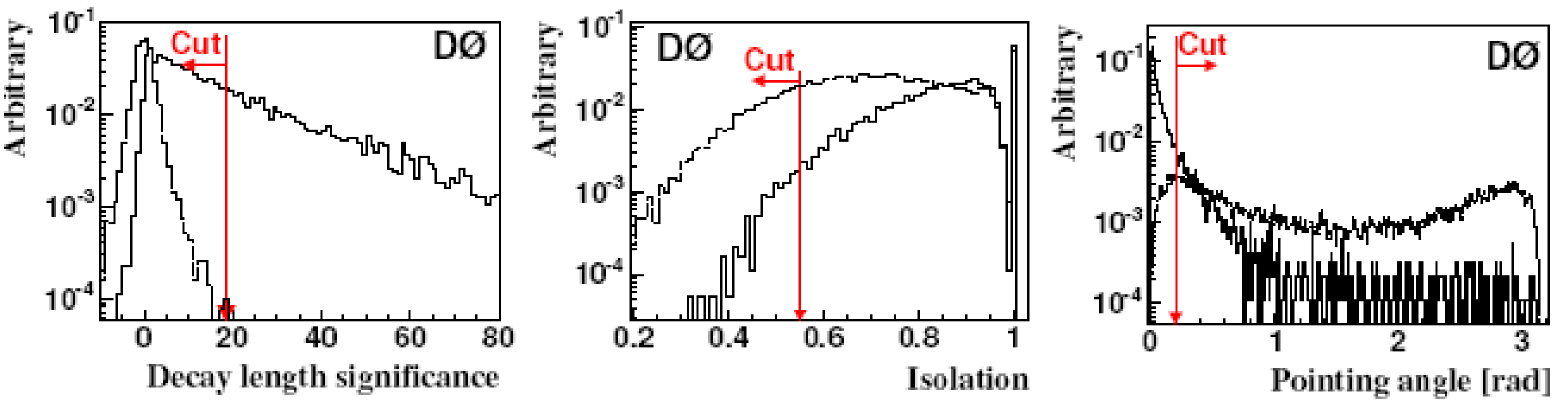
- **Mass resolution σ=25 MeV**
- **closest candidate, M=5.190 GeV**

$\mathbf{\mathit{B}(B^0_s \rightarrow \mu^+\mu^-) < 1.5 \times 10{-}7}$

$\mathbf{\mathit{B}(B^0_d \rightarrow \mu^+\mu^-) < 3.8 \times 10{-}8}$

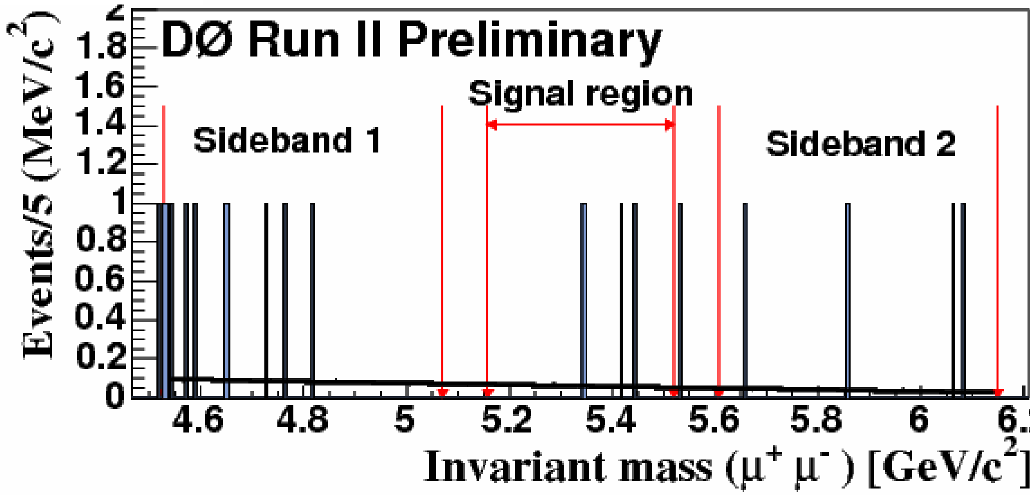
D0 Result

- D0 Collaboration, PRL94(2005)071802, L=240 pb^{-1}
- NEW: Update Moriond 2005, D0Note-4733-Conf, L=300 pb^{-1}



- **Mass resolution σ=90 MeV**
- **4 Candidate events**
- **4.3 ± 1.2 background**

$B(B^0_s \to \mu^+\mu^-)<3.0*10^{-7}$

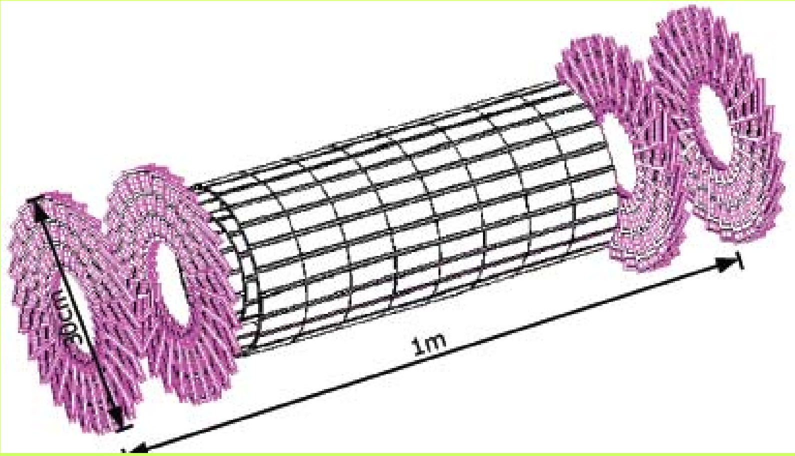


BSM Expectations

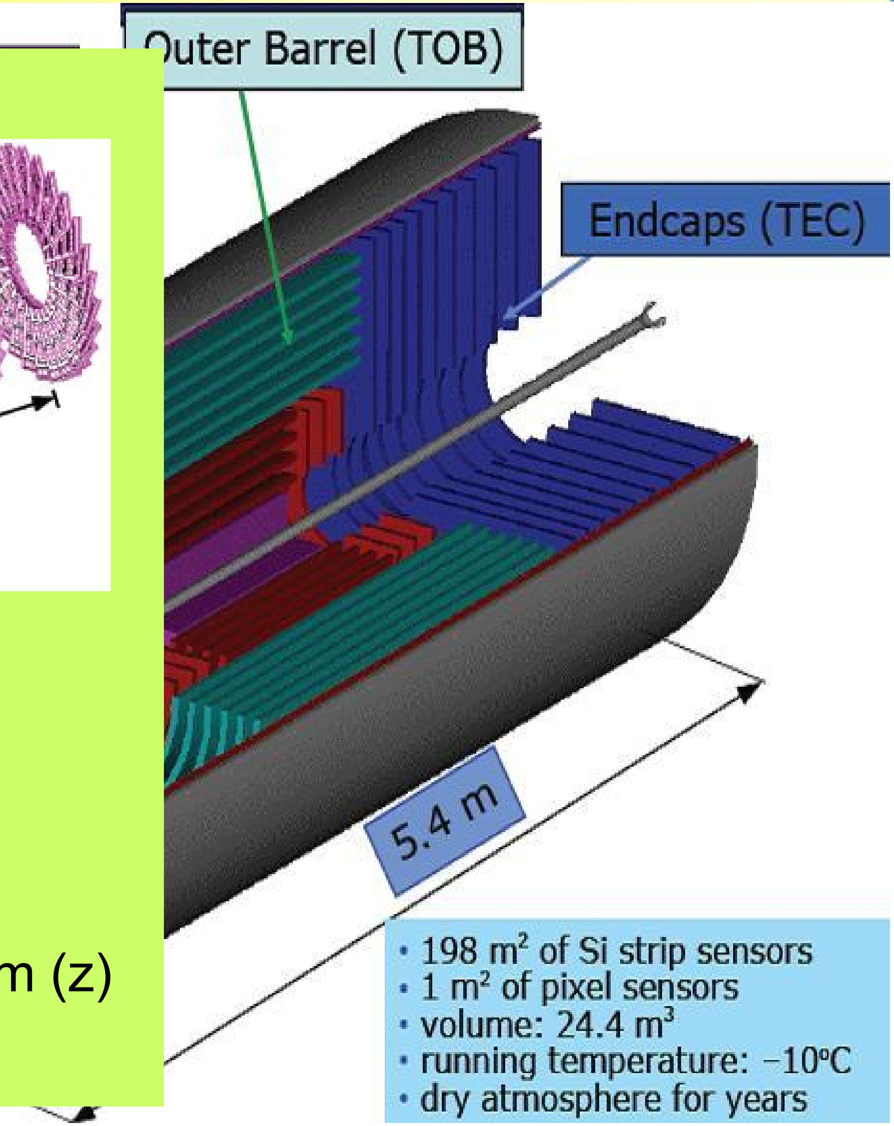
- Significant (~10^4) enhancement possible in SM extensions
  - Potentially interesting even for first LHC data
- In Minimal Supersymmetric Extension of SM
  - $B(B_s \to \mu^+\mu^-) \propto (\tan\beta)^6$
  - With minimal flavour violation (CKM only): observation of $B_s \to \mu^-\mu^+$ yields upper bound on heaviest mass in MSSM Higgs sector
- MSSM with modified minimal flavour violation at large tan β:
  - Increase B by $\times 10^4$ also for $B_d \to \mu^+\mu^-$
- M-Sugra at large tanβ: B~O(10^{-7}) in regions of parameter space consistent with g-2 and CDM
- R-Parity violating SUSY (tree-level sneutrino)
- Possible constraints on
  - tan β, Heaviest mass of (extended) Higgs sector

Introduction to the CMS Tracker

The Pixel detector



- Active area ~$1m^2$
- 3 barrel layers r~4,7,10cm
- 2 endcap disks: r=6…15cm
- $40*10^6$ channels
- Px size: 100 µm (rφ)x150 µm (z)
- Hit Resolution 10µ in rϕ

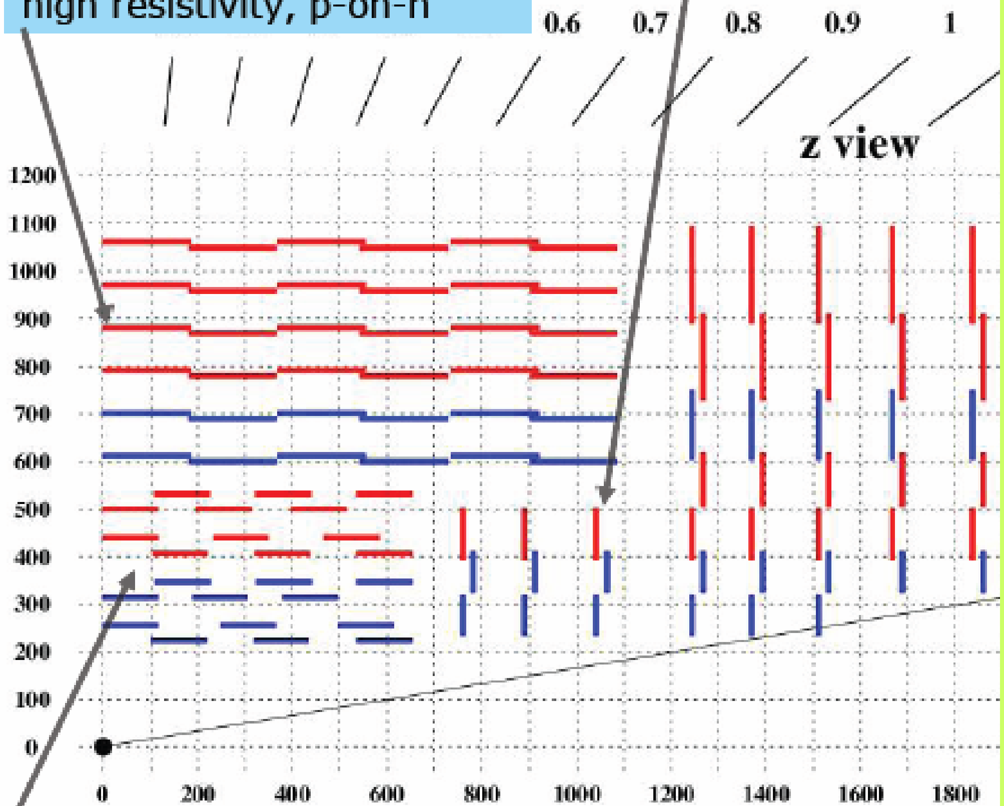


- 198 m^2 of Si strip sensors
- 1 m^2 of pixel sensors
- volume: 24.4 m^3
- running temperature: −10°C
- dry atmosphere for years

The silicon strip tracker

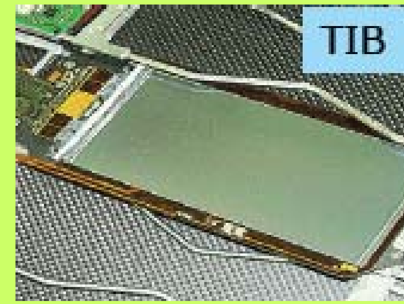
Outer barrel
6 layers of 500 µm sensors
high resistivity, p-on-n

Inner disk
3 disks, 3 rings



Inner barrel
•4 layers of 320 µm sensors
•low resistivity, p-on-n

Strip sensors

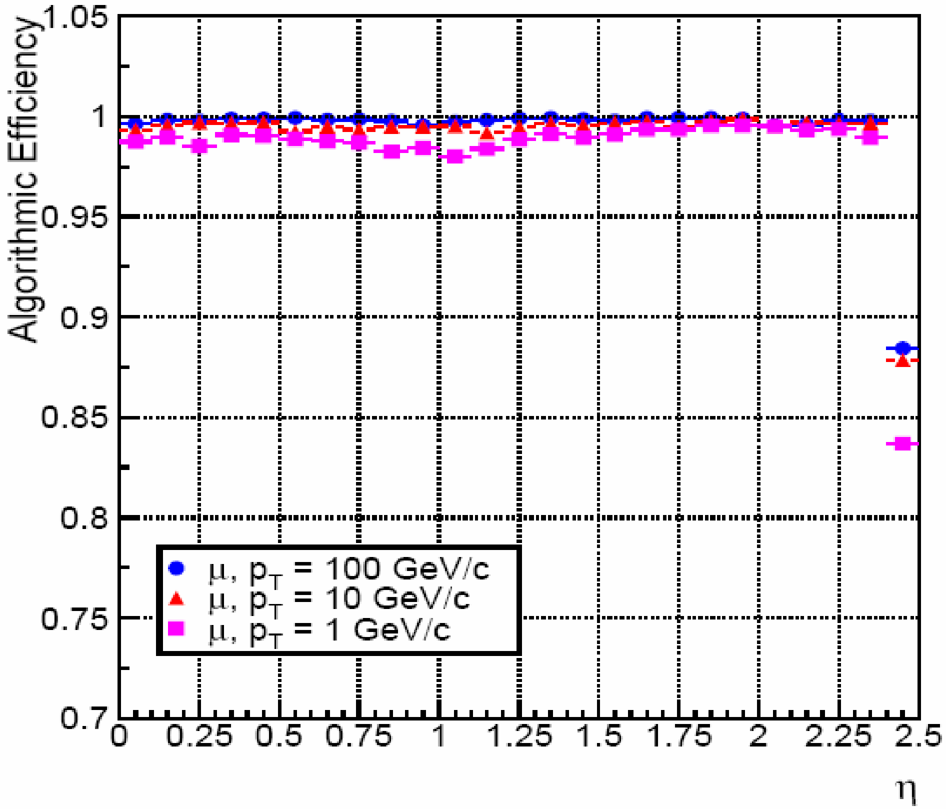


- 10cm length
- 80..200 µm pitch
- 512 or 768 strips

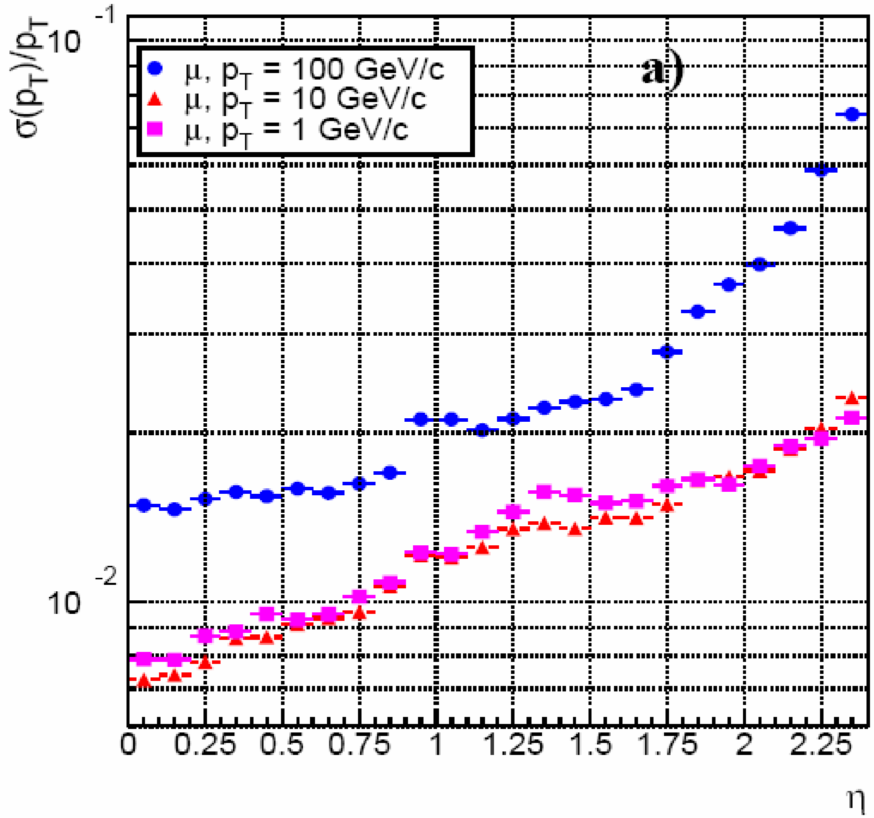
Tracker Performance

Using muons with 1,10,100 GeV:

- Efficiency



- Pt resolution



- Efficiency >98% for η<2.4
- Pt resolution 2…3% for η<1.75

$B_s \rightarrow \mu^+\mu^-$: Offline analysis

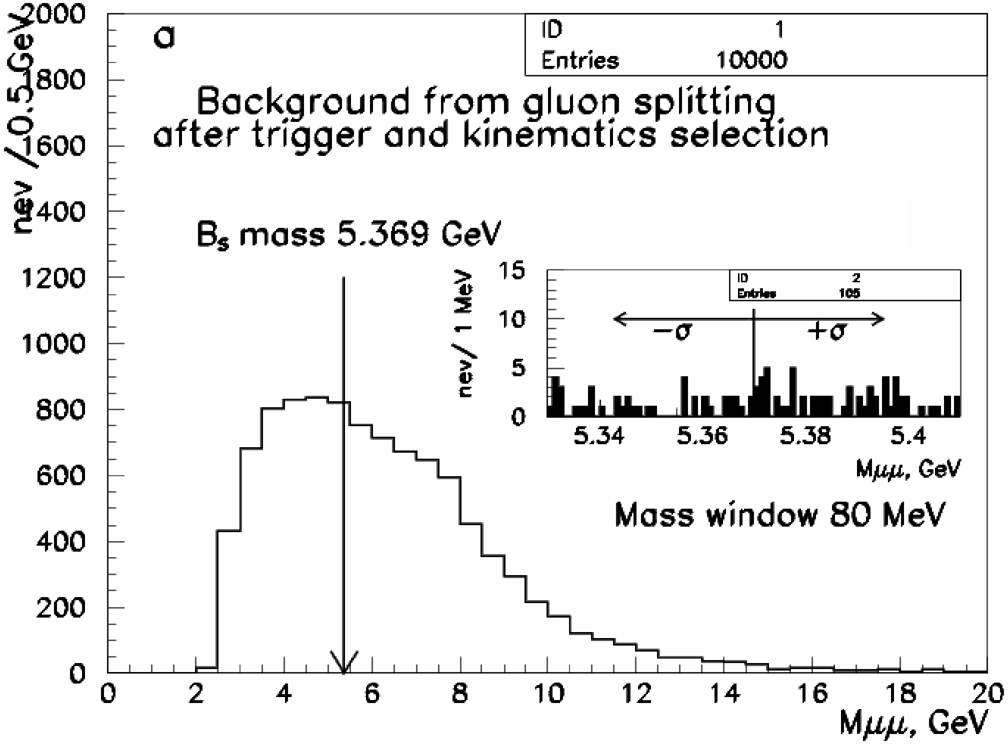
- Full simulation and reconstruction of signal and dominant background (gluon splitting)
- Kinematic selection:

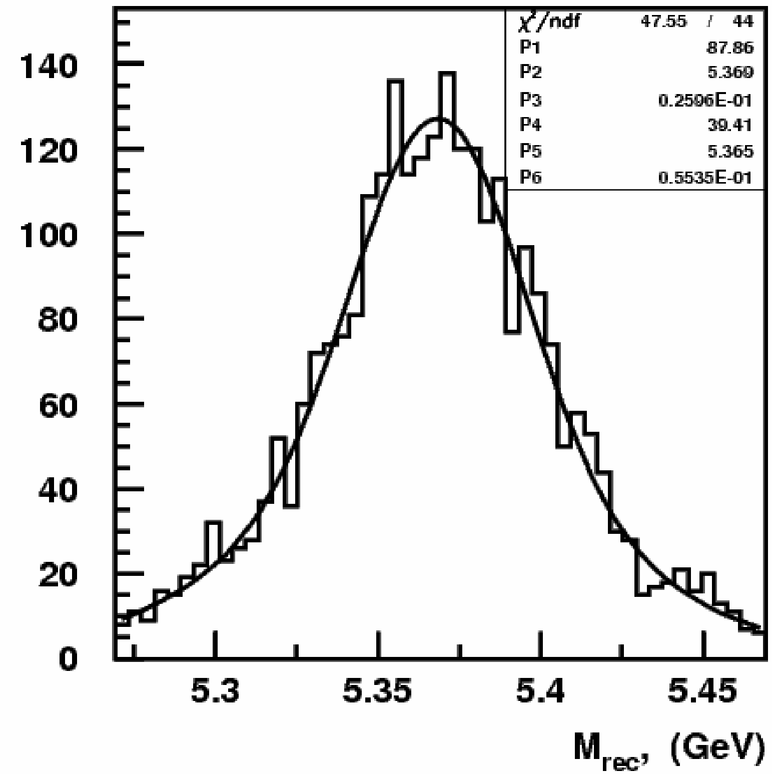
  Pt^{μ} > 4.3 GeV **$|\eta^{\mu}|<2.4$**

  $0.4 < \Delta R_{\mu\mu} < 1.2$ **$Pt^{\mu\mu}>12$ GeV**

- Estimated event numbers for $10fb^{-1}$ (1 year @ $L=10^{33}$ $cm^{-2}s^{-1}$) (without HLT inefficiency)
  - Signal: $N_{signal}=66$
  - Dominant background from $g \rightarrow bb$ splitting: $N_{bkgd} \sim 3*10^7$
- Most important ingredients for analysis:
  - Good invariant mass resolution
  - Muon Isolation in tracker and calorimeter
  - Precise secondary vertex reconstruction

Dimuon mass window



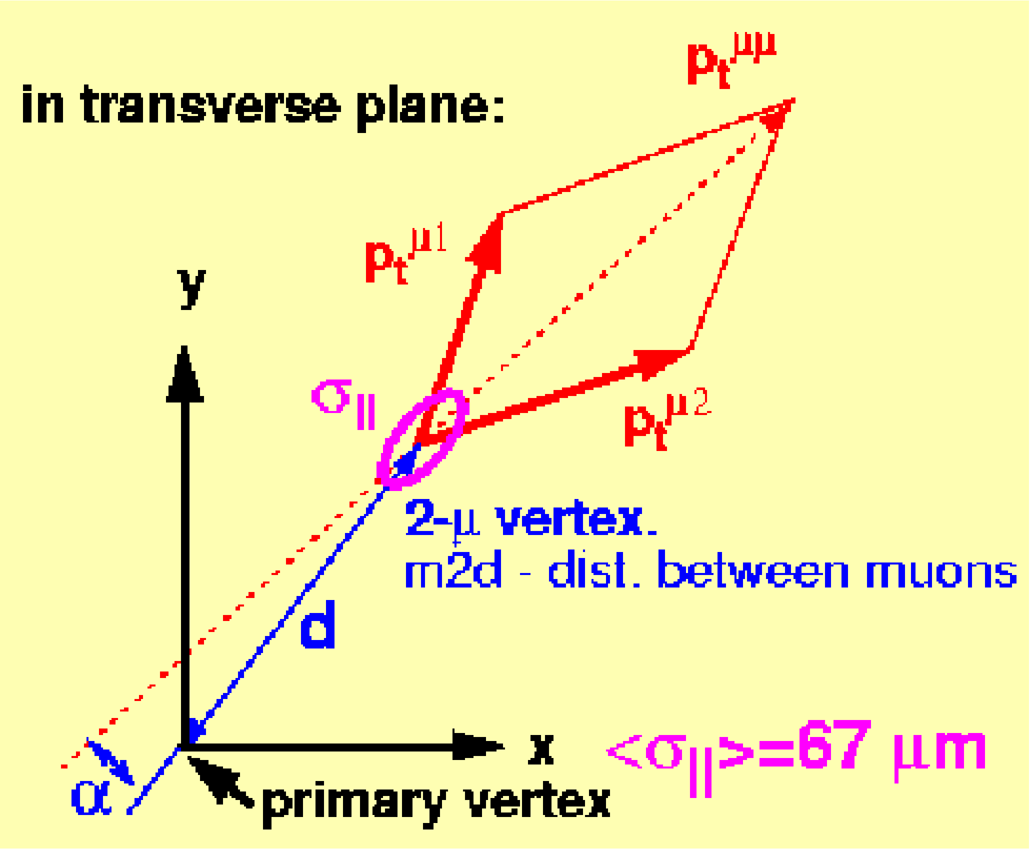


- 80 MeV mass window around $M(B_s)$=5.369 GeV
- Background rejection ~1.1%

Secondary Vertex Selection

Cuts on variables provided by SVX reconstruction algorithm

- m2d < 50μm
  (min transv. dist. between 2μ)
- m2d/σ(m2d) < 2
- d > 820μm
  (transv. vertex dist.)
- $\sigma_{||}$ < 80μm
  (svx err in transv. plane)
- cos(α) > 0.9997
  (2d pointing angle)



Background rejection < $2.3 \cdot 10^{-4}$ / Signal efficiency ~30%

Isolation in tracker and calorimeter

- Tracker isolation

No charged track

Pt>0.9 GeV

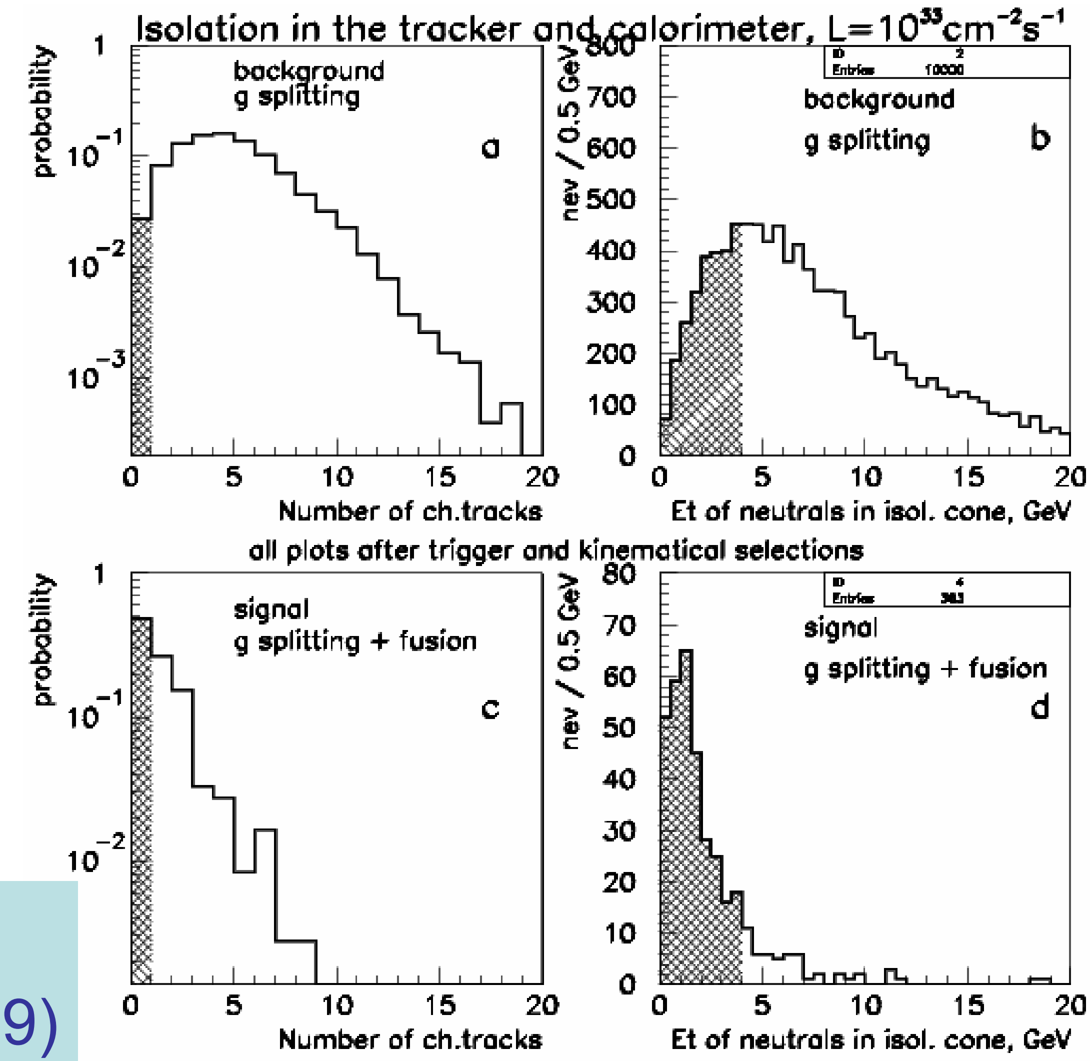
In $\Delta R = 0.5*\Delta R_{\mu\mu}+0.4$

- Calorimeter Isolation

(EM+HAD, same ΔR):

Et < 4GeV (low lumi)

Et < 6GeV (high lumi)



- ε(signal)~0.45 (0.3)
- Bkg. rej. ~0.013 (0.009)

Rate estimates

Efficiencies and event numbers for 10 (100) fb^{-1}:

	Signal	Background
number of events after trigger and kinematics selections	66	2.9×10^7
tracker isolation. Low luminosity	0.49	3.0×10^{-2}
tracker isolation. High luminosity	0.34	2.0×10^{-2}
tracker+calo isolation. Low luminosity	0.46	1.3×10^{-2}
tracker+calo isolation. High luminosity	0.31	0.87×10^{-2}
$2-\mu$ rec. + sec.vertex selections. Low luminosity	0.32	$\leq 2.3 \times 10^{-4}$
$2-\mu$ rec. + sec.vertex selections. High luminosity	0.18	$\leq 2.3 \times 10^{-4}$
mass window 80 MeV	0.72	1.1×10^{-2}
number of events after cuts. Low luminosity	7.0	≤ 1.0 at 90% C.L.
number of events after cuts. High luminosity	26.0	≤ 6.4 at 90% C.L.

- 4σ observation after 3 years at 10fb^{-1} possible!

- BUT: CMS L1+high level trigger must select the events …

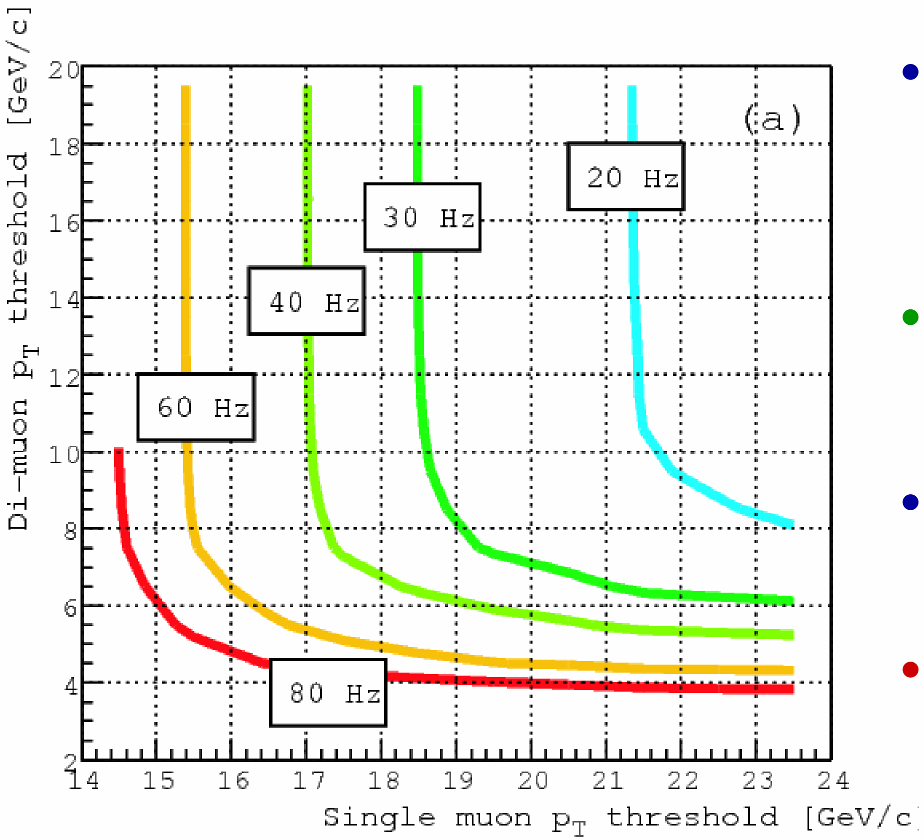
Muons in the CMS L1 Trigger

- Low Luminosity L1 trigger table

Trigger	Threshold (GeV or GeV/c)	Rate (kHz)	Cumulative Rate (kHz)
Inclusive isolated electron/photon	29	3.3	3.3
Di-electrons/di-photons	17	1.3	4.3
Inclusive isolated muon	14	2.7	7.0
Di-muons	3	0.9	7.9
Single tau-jet trigger	86	2.2	10.1
Two tau-jets	59	1.0	10.9
1-jet, 3-jets, 4-jets	177, 86, 70	3.0	12.5
Jet * E_T^{miss}	88 * 46	2.3	14.3

- B physics triggered at L1 by single/dimuon trigger
- Low thresholds mandatory for B physics
  - For $B_s \rightarrow \mu^+\mu^-$ can use dimuon trigger!
- Electron channel disfavoured due to higher threshold

Muons in the High Level Trigger



- 30Hz out of total 100 Hz HLT output rate allocated to single/dimuon trigger
- Thresholds:

  1(2) muons: P_T>19(7) GeV
- b/c contribution in 1μ only ~25%: ~5Hz
- Insufficient for rare decays<10^{-4}

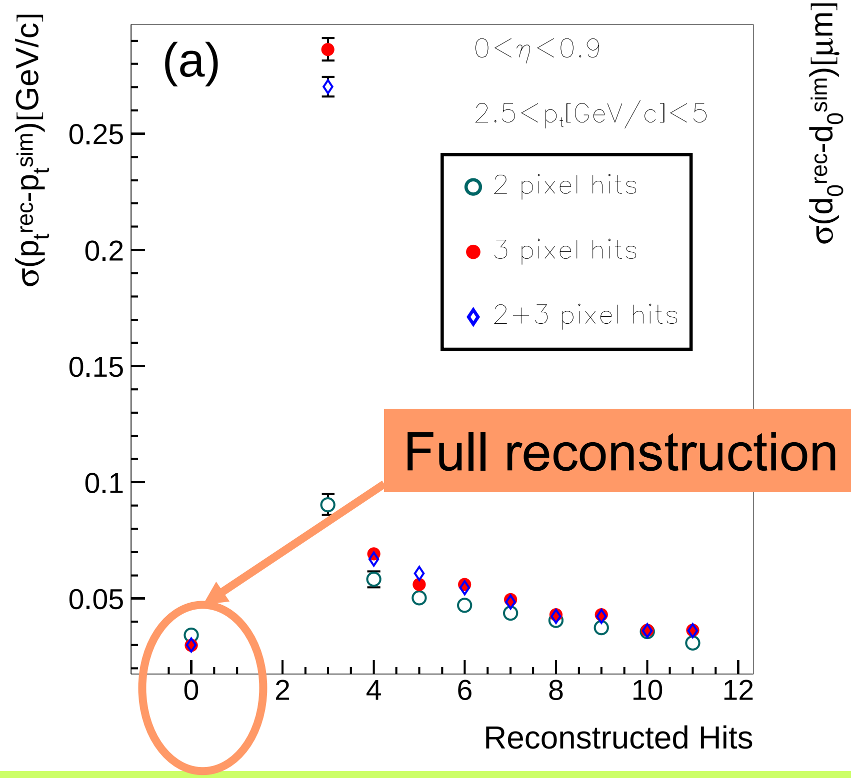
For rare B decays efficient online event reconstruction and selection mandatory!

Tracking at the High Level Trigger

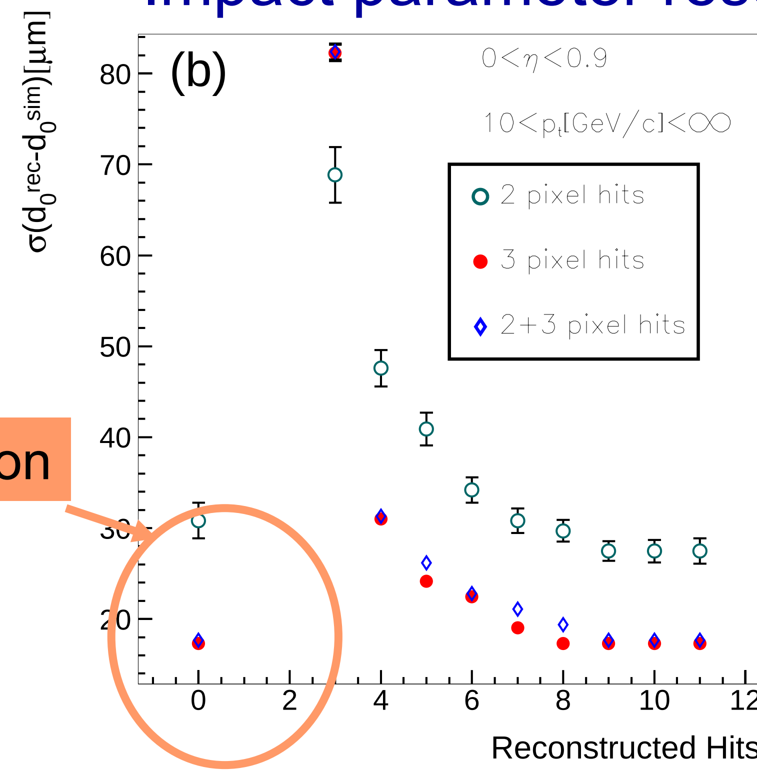
- Limited amount of CPU time available for trigger decision, so need to reduce:
  (a) Number of track seeds
  (b) Number of operations per seed
- Regional seed generation
  - Limited to regions of interest (ROI) identified by L1 objects (e.g. cone around muon direction
- Partial / conditional tracking: Stop reconstruction if
  - N hits are reconstructed
  - Pt resolution > given threshold
  - Pt value < given threshold

Partial Tracking Performance

- Pt Resolution



- Impact parameter resolution



- Reconstruction time ~ number of hits
- Good efficiency, ghost rate, resolution with ~5 hits already

Further Important ingredient at HLT already: Alignment …

A few remarks on CMS Alignment

Requirement:

Misalignments of the silicon and strip trackers must not compromise intrinsic resolution of 10…20μm

Three ingredients

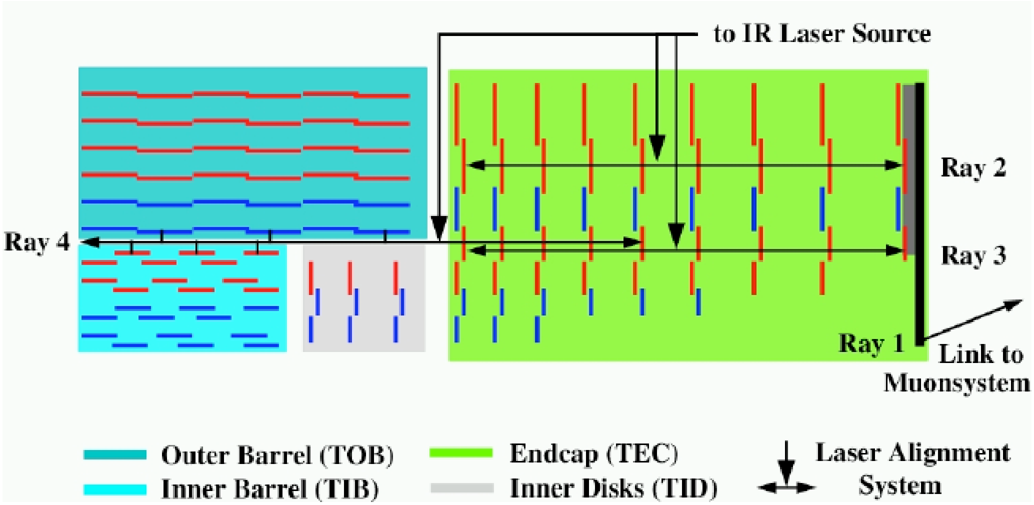
1. Mounting precision
2. Laser alignment
3. Track based alignment

Mounting Precisions:

Sensor vs Module: 10…30 μm

Module vs Layer: 50…500 μm

Laser Alignment system



- **Layer vs layer**
- **Barrel vs endcap**
- **Link to muon system**

CMS Alignment Strategy

- CMS Startup ("day 0"): Laser alignment plus placement constraints: alignment to ~100μ
  - efficient pattern recognition possible for Δ<100-200μ
  - BUT: only true if precise pixel seeds available!
- Laser alignment to monitor movements of TIB,TOB,TEC composite structures to ~10μ
- "Fast" track based alignment: monitor Pixel, TID (and other) composite structures
  - Important for HLT performance
- "Full" track based alignment:
  - alignment at sensor level to ~10μ for full tracker

Track based alignment

- Scale of the problem
  - ~20k Si sensors, i.e. O(100k) parameters
  - Covariance matrix O(100k * 100k)
  - Impossible for standard approaches
- Several Algorithms presently being studied
  - Straightforward LSQ approach (no correlations between sensors)
  - Kalman filter: novel approach, treatment of correlations avoiding large matrix inversions (R. Fruehwirth)
  - "Simulated Annealing"
  - New version of Millepede (V. Blobel)
- Data samples
  - Start-up: Cosmics, Beam-halo μ
  - Physics: $W \rightarrow \mu\nu$, $Z \rightarrow \mu^+\mu^-$

Results expected for

Physics TDR (end 2005)

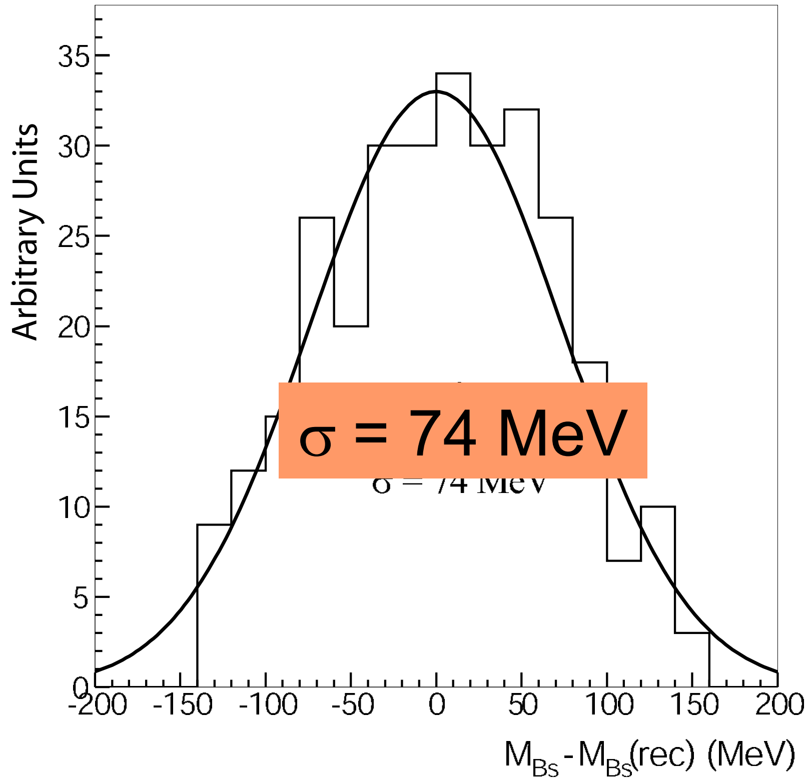
B_s\$ $\mu^+\mu^-$: trigger strategy

- L1 trigger selection
  - Double muon trigger, Pt>3 GeV $|\eta|<2.1$
- High level trigger (HLT) selection
  - Regional tracking: look for pixel seeds only in cones around the muons, Pt>4 GeV, d_0<1mm, compatible with primary vertex
  - Conditional tracking: reconstruct tracks from good seed
    - **Stop reconstruction if Pt<4 @ 5σ**
    - **Keep only tracks with σ(Pt)/Pt<2%, N-hit>=6**
  - If exactly 2 opposite sign tracks found:
    - **Calculate $M_{\mu\mu}$**
    - **Retain pairs with $|M_{\mu\mu}-M_{Bs}|$<150 MeV**
    - **Vertexing: χ^2<20 and d_0>150μm**

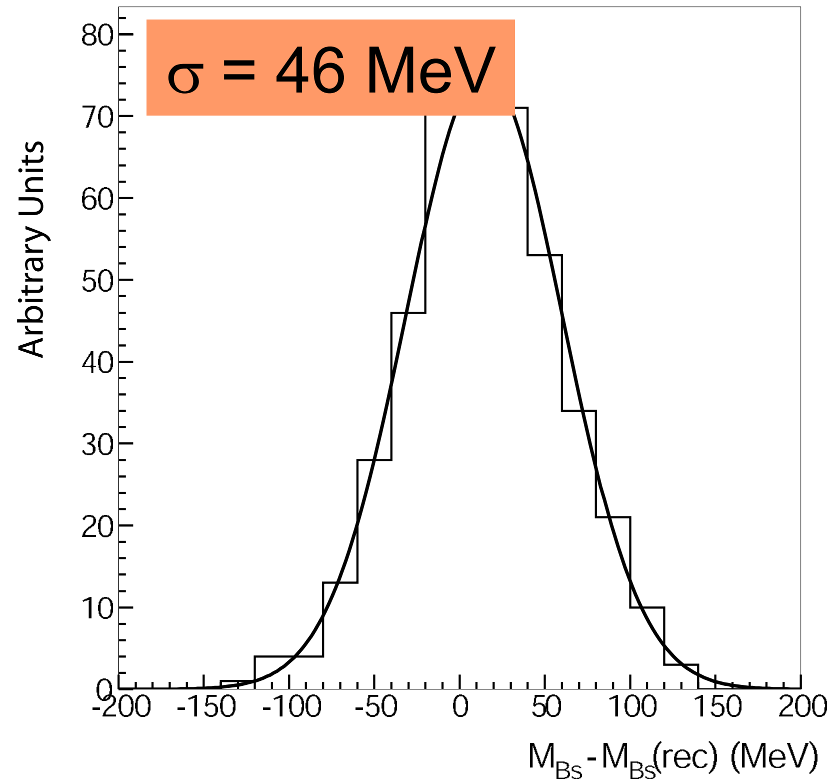
L1 Efficiency	HLT Eff.	Global Eff.	Events / $10fb^{-1}$	Trigger Rate
15.2%	33.5%	5.1%	47	<1.7Hz

B_s mass resolution

- High level trigger



- Offline reconstruction



- N.B.: Invariant mass and vertex reconstruction assume perfectly aligned Pixel and strip tracker already online!

Conclusions

- CMS@LHC well suited for B physics (and rare B decays)
  - High Luminosity $L=10^{34}cm^{-2}s^{-1}$
  - Precise all-Silicon tracking,
  - Powerful Muon system, also providing L1 trigger

- Cruical ingredients: Trigger and Alignment
  - Low Pt L1 muon treshold
  - Efficient online (HLT) reconstruction/selection of final states needed!
  - SVX and inv.Mass reconstruction rely on Alignment @ $10\mu m$ level!

- $B(B_s \to \mu^+\mu^-)$ can place severe constraints on BSM models
  - In reach for LHC experiments
  - Observation with CMS possible