VI symposium on LHC Physics and Detectors

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CMS: Muon System and Physics performance

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on behalf of the CMS collaboration

Outline

- Introduction,
- Muon detectors,
- Muon reconstruction,
  - High Level Trigger,
  - Local reconstruction,
  - Global reconstruction,
  - Muon isolation,
- Physics performance,
- Summary

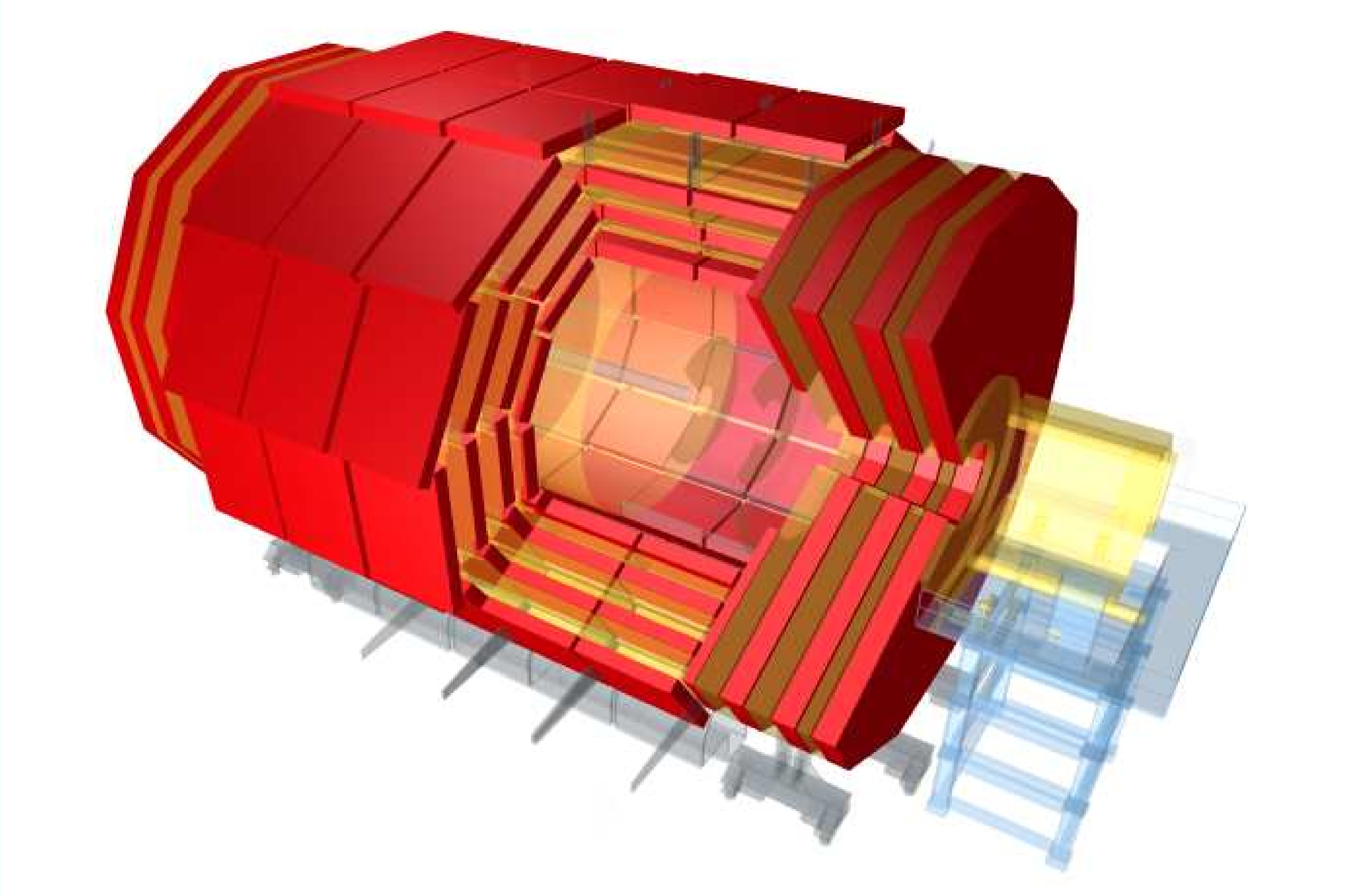
Introduction

- Results presented for two LHC instantaneous luminosities:
  - Low luminosity (LL) first 3 year of data taking:

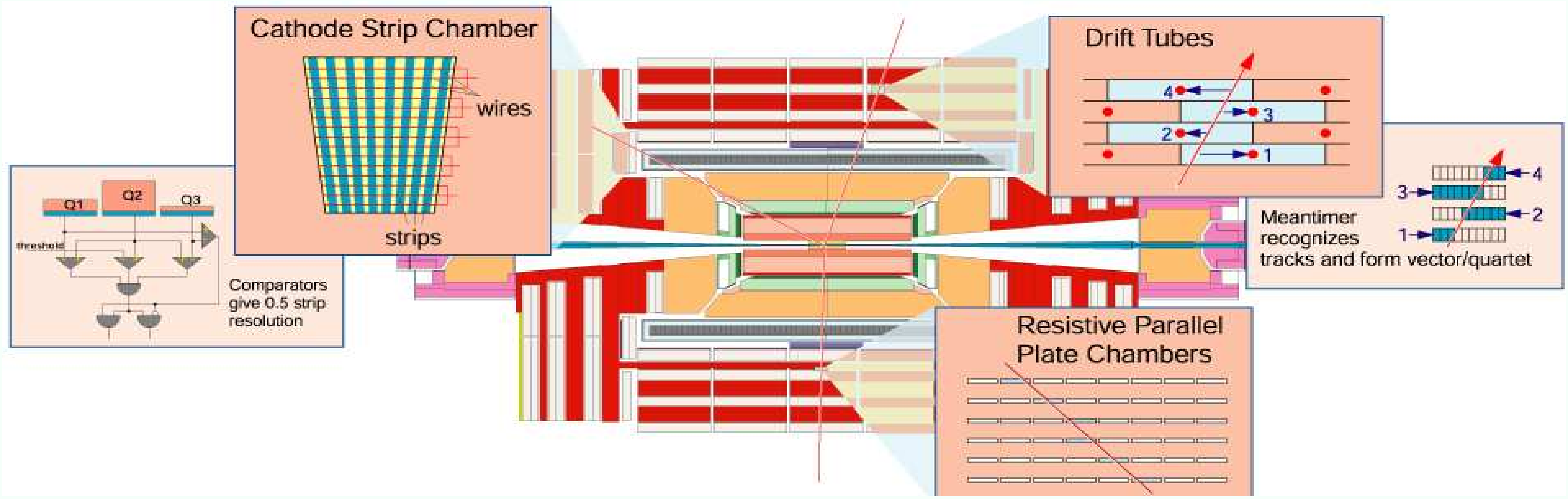
    $\mathcal{L} = 2 \times 10^{33}\, cm^{-2} s^{-1} = 2\, nb^{-1} s^{-1}$
  - High luminosity (HL) after:

    $\mathcal{L} = 10^{34}\, cm^{-2} s^{-1} = 10\, nb^{-1} s^{-1}$
- All results presented with full CMS simulation (`GEANT3`)
- Pile up included for both luminosities,
- OO-reconstruction ORCA (Object-oriented Reconstruction for CMS Analysis)

Muon Detectors in CMS



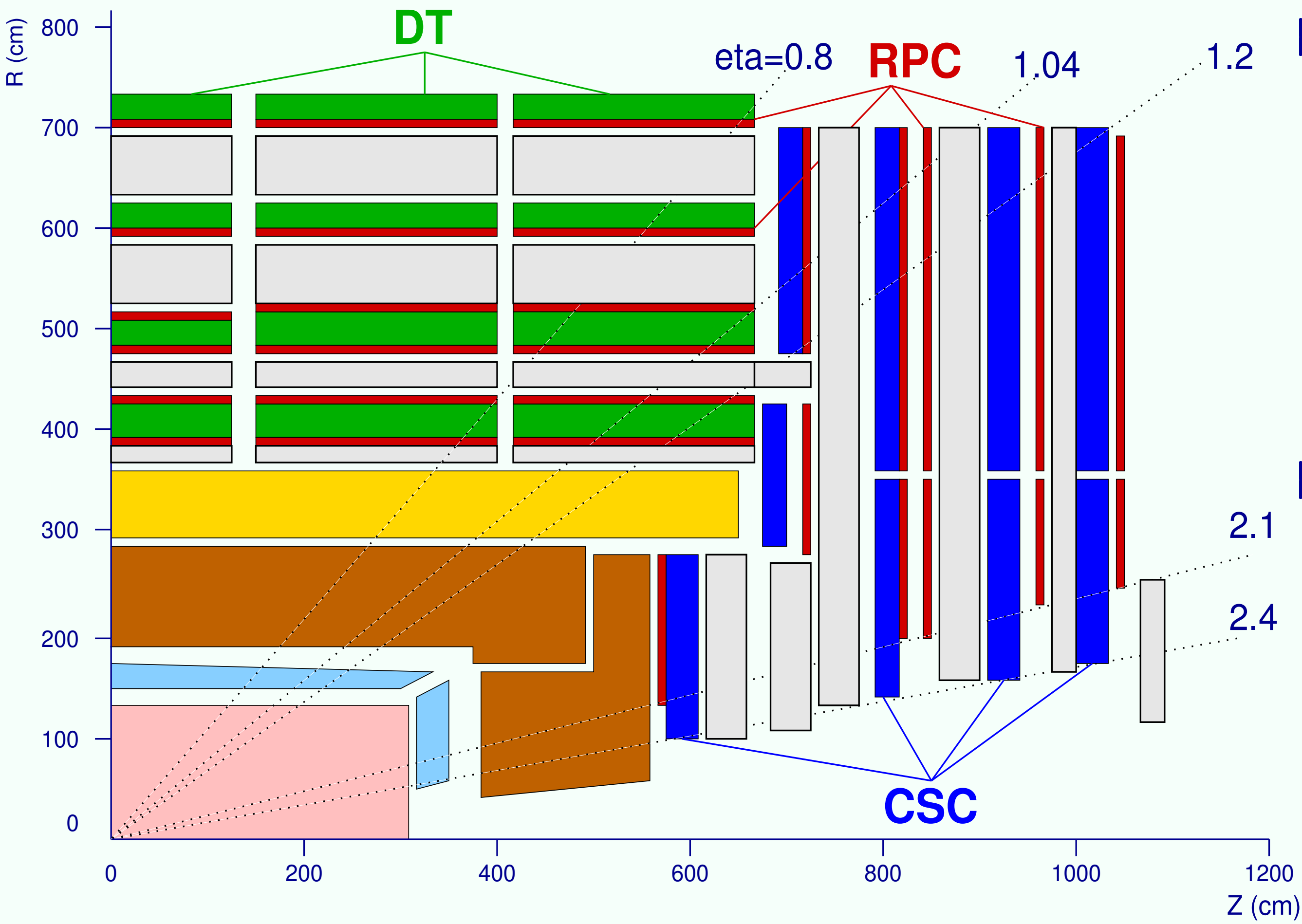
Muon Detectors (2)



Three type of gaseous detectors:

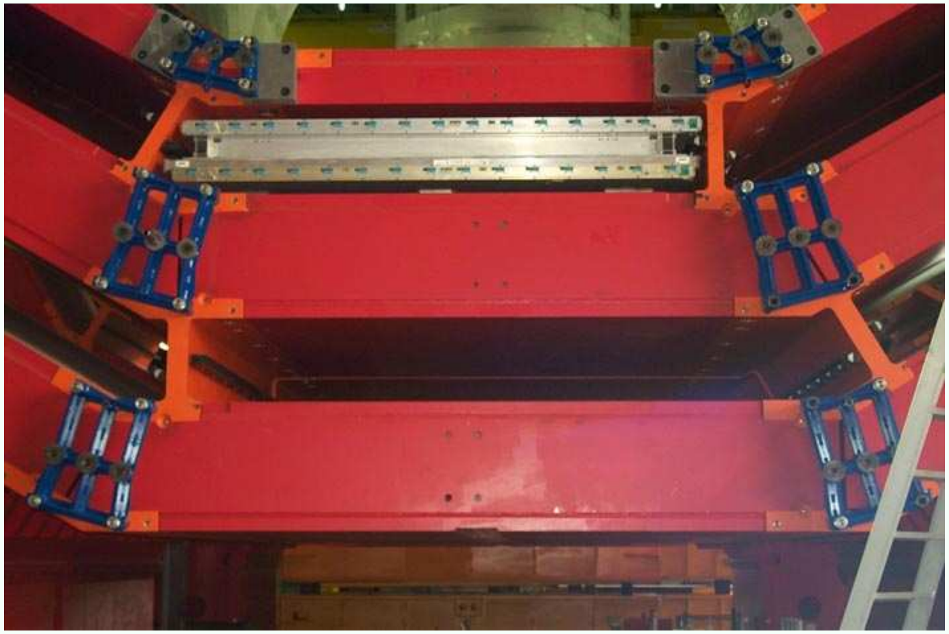
- Drift Tubes in barrel region,
- Cathod Strips Chambers in endcap regions,
  - DT's and CSC's provide precise position measurements, ($\rightarrow\ p_t^{\mu}$),
- Resistive Plate Chambers in both barrel and endcaps.
  - RPC provide precise bunch crossing (bx) id.
  - all the 3 sub-systems contribute to the L1-trigger.

Muon Detectors (3)



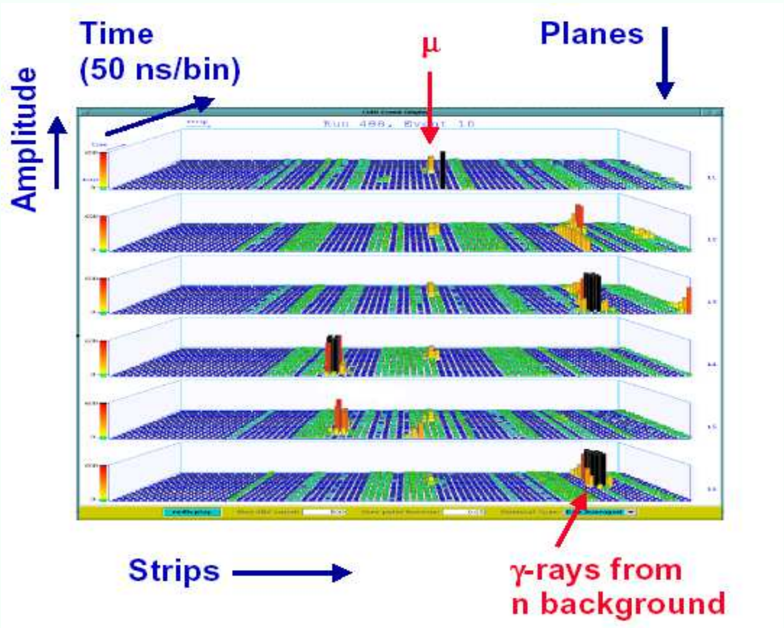
- 4 stations of DT's, interleaved with the iron of magnet yoke, self triggering and bx identification,
- 4 stations of CSC's with same capabilities, interleaved with iron disk yoke, up to $|\eta| < 2.4$,
- 6 –Barrel– or 4 –Endcaps– station of RPC's up to $|\eta| < 2.1$,
- L1 trigger up to $|\eta| < 2.1$
- Start-up staged detector: no ME4 and RPC $|\eta| < 1.6$

Drift Tube chambers



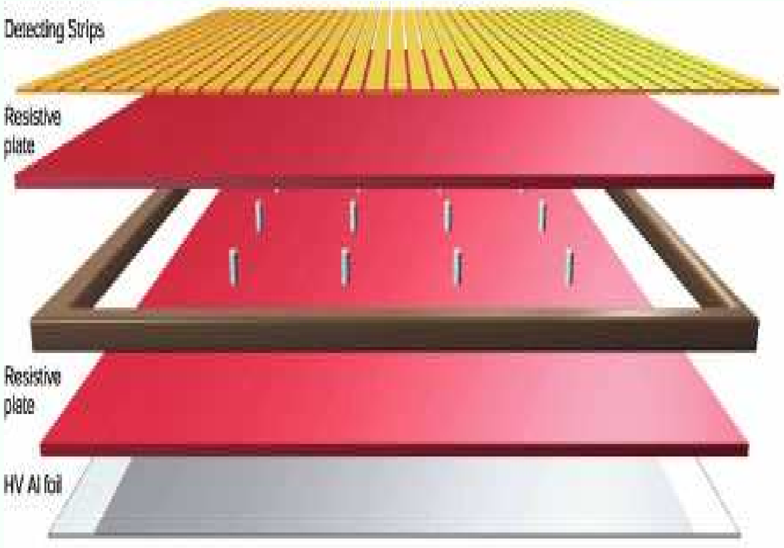
- Made of 3 SuperLayers, 2 in $r-\phi$ and 1 in $r-z$ (not in the 4^{th} station) separated by honeycomb spacer
- Each SL made of 4 layers of –staggered– $4.2\ cm$ wide cells,
- E-field shaped to give maximum linearity,
- Gas mixture: $Ar-CO_2\ 85-15\%$,
- Single point resolution: $\sim 200\ \mu m$,
- Chamber resolution: pos $\sim\ 100\ \mu m$, dir $\sim\ 1\ mrad$,
- Total 250 chambers, $\sim 190\ k$ wires.

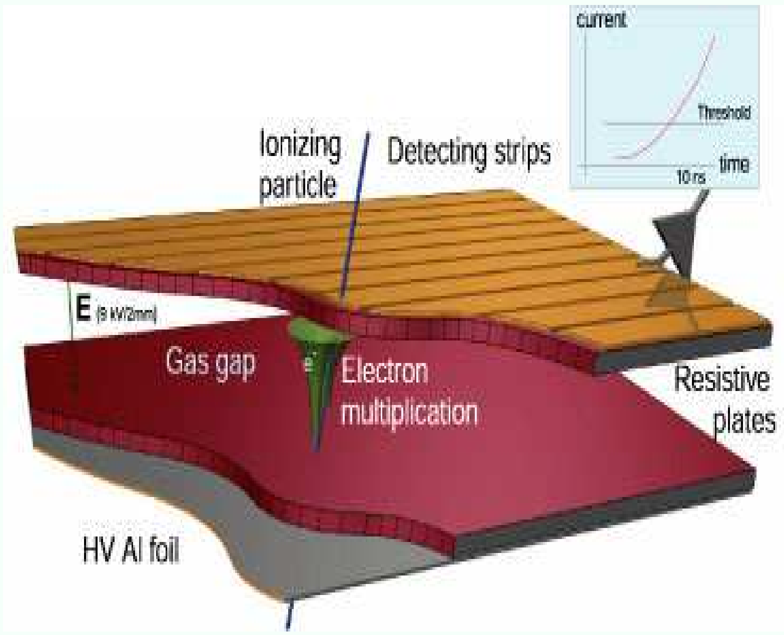
Cathode Strip Chambers



- Arranged in 4 disks,
- Inner ring have 18 CSCs each covering $20°$, outer 36 covering $10°$,
- Made of 6 Layers, trapezoidal shape,
- Radial strips measure precise bending co-ordinate by interpolation of induced charge $\sigma \sim 100 \div 240 \mu m$,
- Orthogonal anode wires readout $\sigma \sim cm$, $3d$ points,
- Gas mixture: $Ar - CO_2 - CF_4$ $30-50-20\%$,
- Total 540 chambers, $\sim 0.5\ M$ channels.

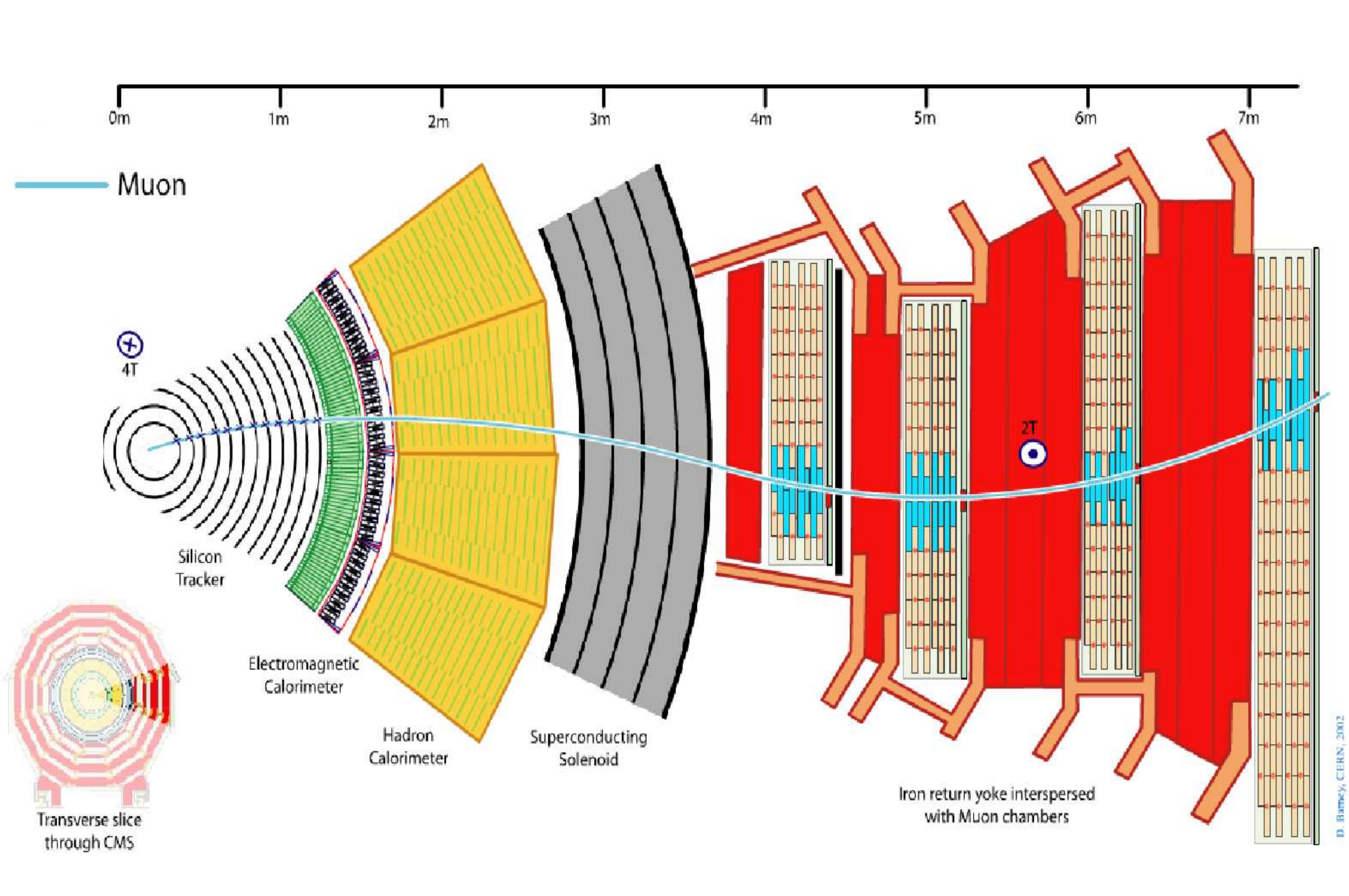
Resistive Plate Chambers





- Double gap, single readout (strips),
- Dedicated trigger detectors,
- Fast timing response, precise identification of bx $\sigma_t \sim 1\,ns$,
- Coarse $\sim cm$ position resolution,
- p_t^μ assignment via Pattern Comparator Trigger,
- Help in identification of μ tracks,
- Total 612 chambers, $\sim 160\,k$ channels.

Muon Reconstruction



Muon Reconstruction

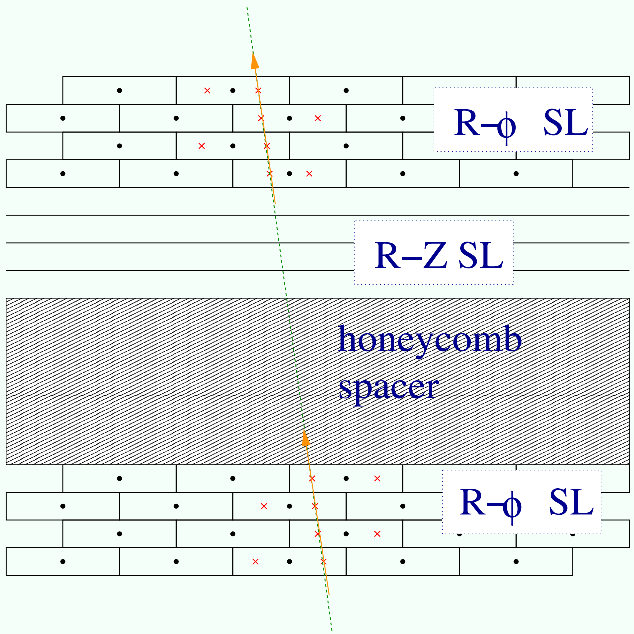
- In CMS the High Level Trigger is performed on a commercial processor farm (Filter Unit) running software algorithm on raw data,
  - Software used will be as much as possible the same used in offline reconstruction
  - Offline reconstruction will make full use of complete calibration, alignment, etc ...
- Robust, high quality reconstruction software
  - Use of a common framework
  - Object-oriented Reconstruction for CMS Analisys: ORCA
- Basic principle: regional reconstruction
  - Reconstruction performed in region only,
  - Need seed to start: for HLT is Level-1 trigger object
- Working prototype of full HLT reconstruction and selection already developed: DAQ & HLT TDR, *CERN/LHCC 2002/26*, 15 december 2002

Local Pattern Recognition

▶ DT's and CSC's are multi-layers detectors:

first step of muon reconstruction is local, i.e. inside chambers

Barrel

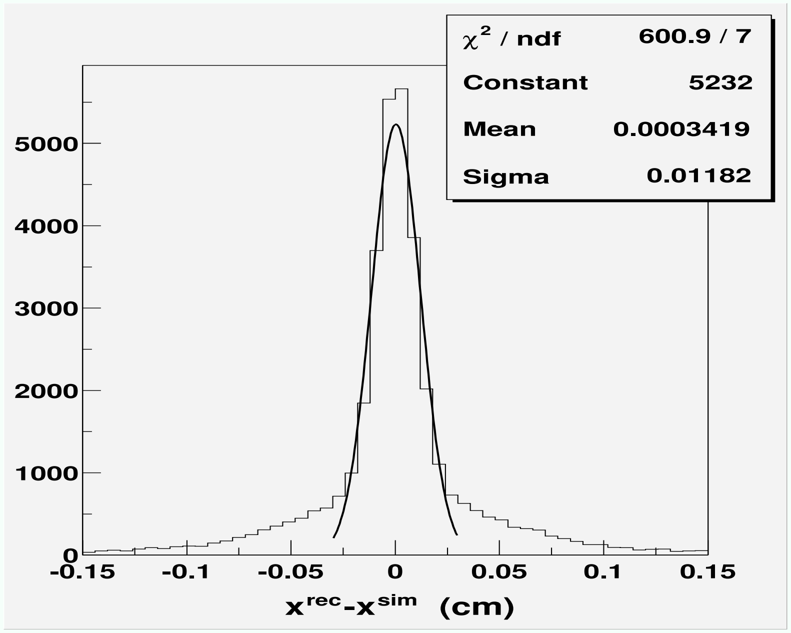


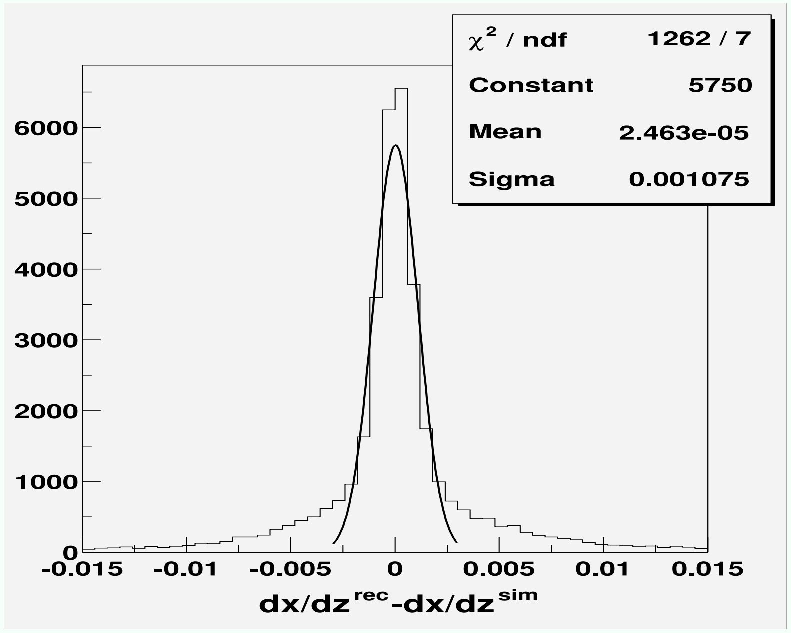
- Reconstruct $r - \phi$ SL hits (time-space conversion), hit error = resolution,
- v_{drift} depends on $\vec{B}$ field and impact angle θ, first approx.: $\vec{B}$ @ center of wire, $\theta = 0$,
- Build segments $2D$ –linear fit–,
- Solve L/R ambiguity by best χ^2 criterion,
- Apply impact angle correction to hits and refit,

- Build segment in $r - z$ SL (where present): initial θ assuming μ from I.P.,
- Associate two projections (if present) to build a $3D$ segment,

Local Pattern Recognition: Barrel (2)

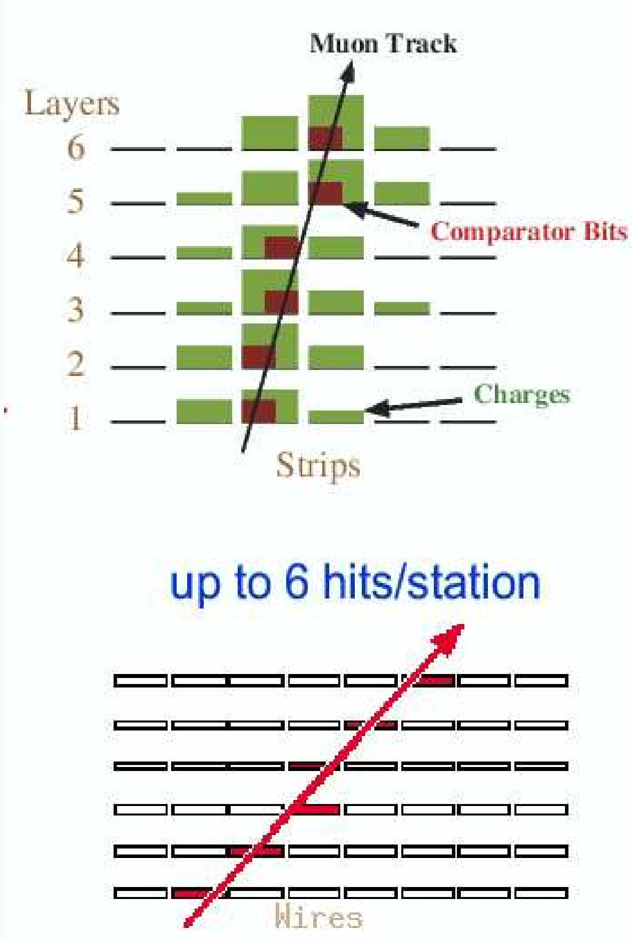
- Apply further correction for $\vec{B}$, using knowledge of hit position along the wire ($\vec{B}$ varies!) and do final refit.
- Position and direction of segment and corresponding error matrices from linear fit,
- Hits error (used in the fit) depends on $\vec{B}$ and θ, apply proper corrections,
- Resolution: $\sigma_{pos} \sim 100\ \mu m$ for bending coordinate, $\sigma_{dir} \sim 1\ mrad$.





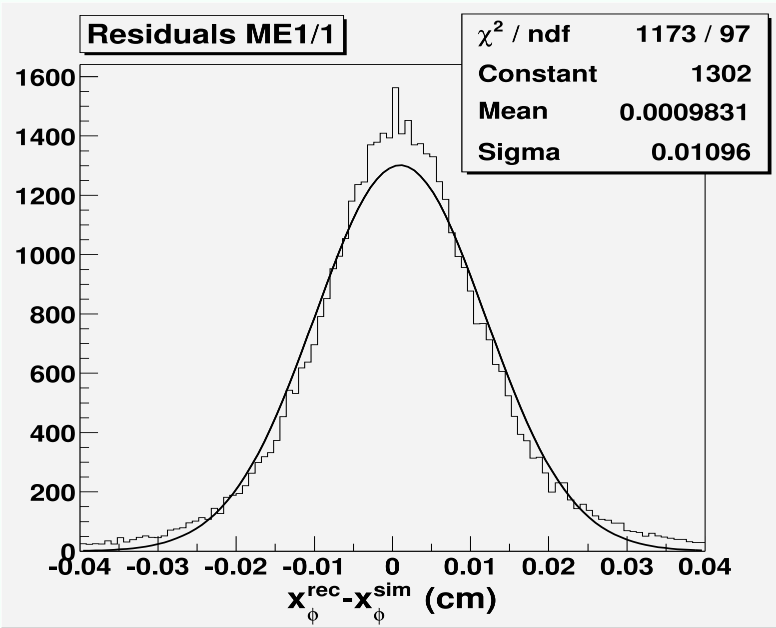
Local Pattern Recognition (2)

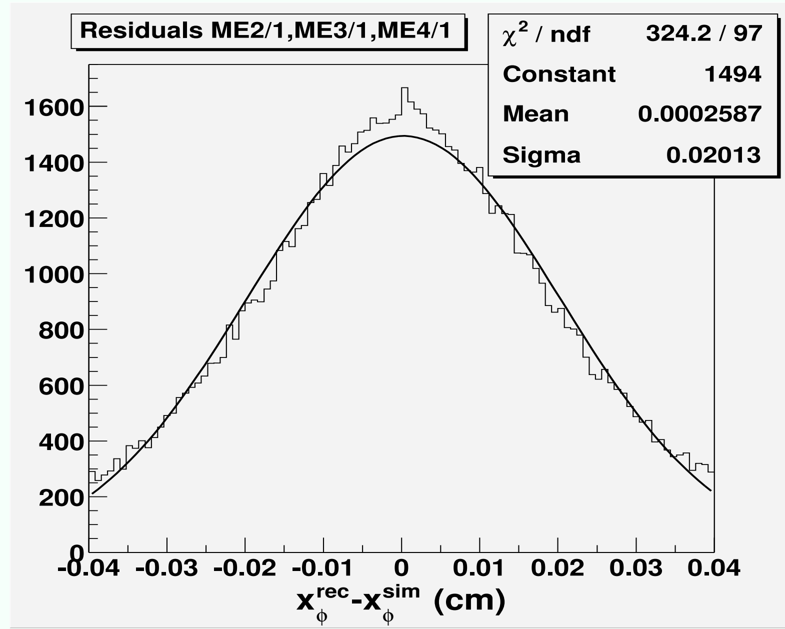
Endcap

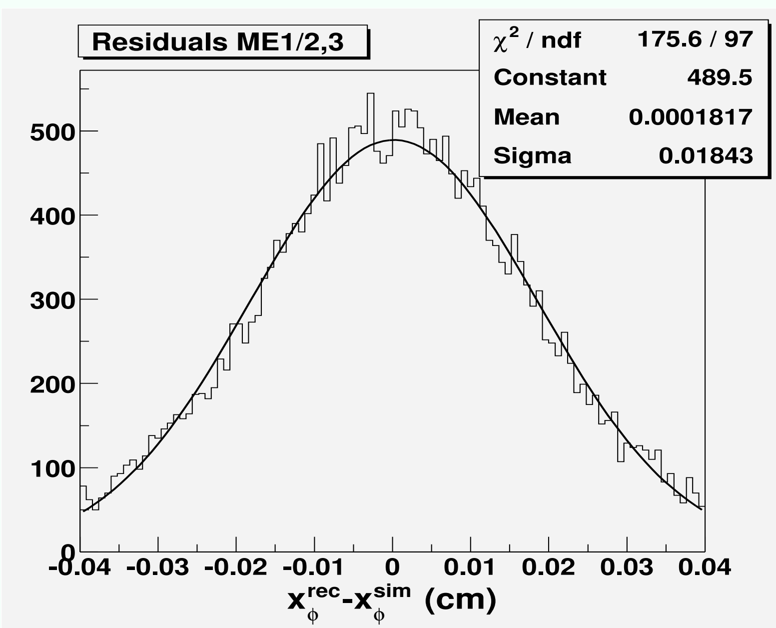


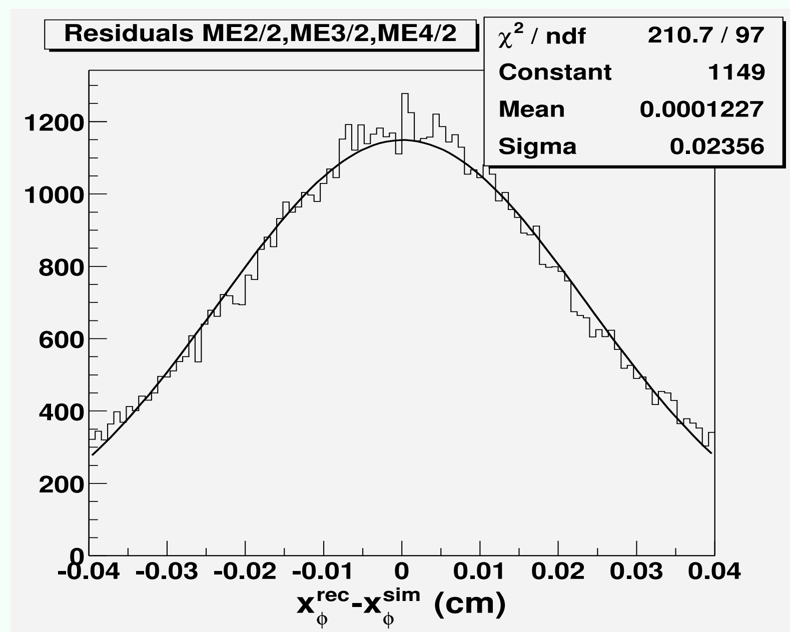
- Reconstruct $3D$ hits,
- Fit ("Gatti" function) charge distribution on nearby strips to get cluster centroid,
- Use discriminated wire-group signal to get non-bending coordinate,
- Associate two projection by time coincidence,
- Fit $3D$ segment using $3D$ hits, linear fit,
- Resolution: $\sigma_{pos} \sim 100 \div 250 \mu m$ for bending coordinate, depending on chamber,

Local Pattern Recognition: Endcap(2)

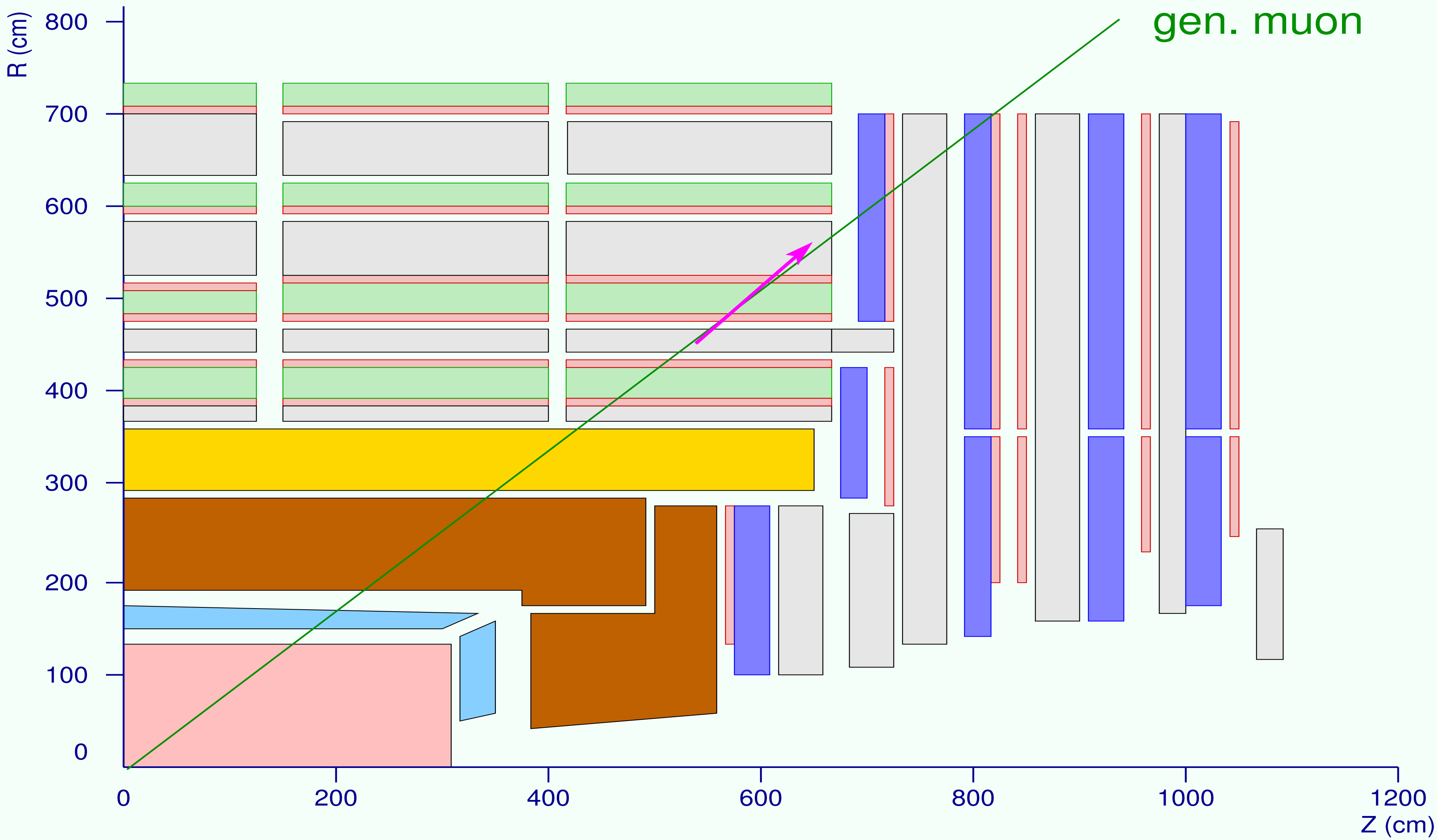




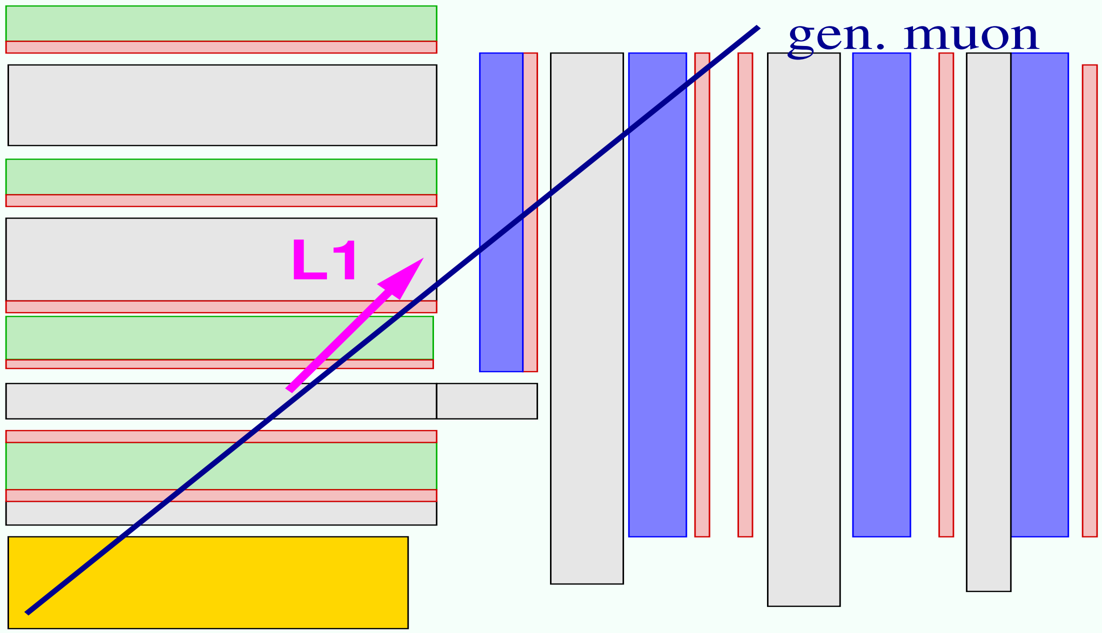




Standalone Muon Reconstruction (1)

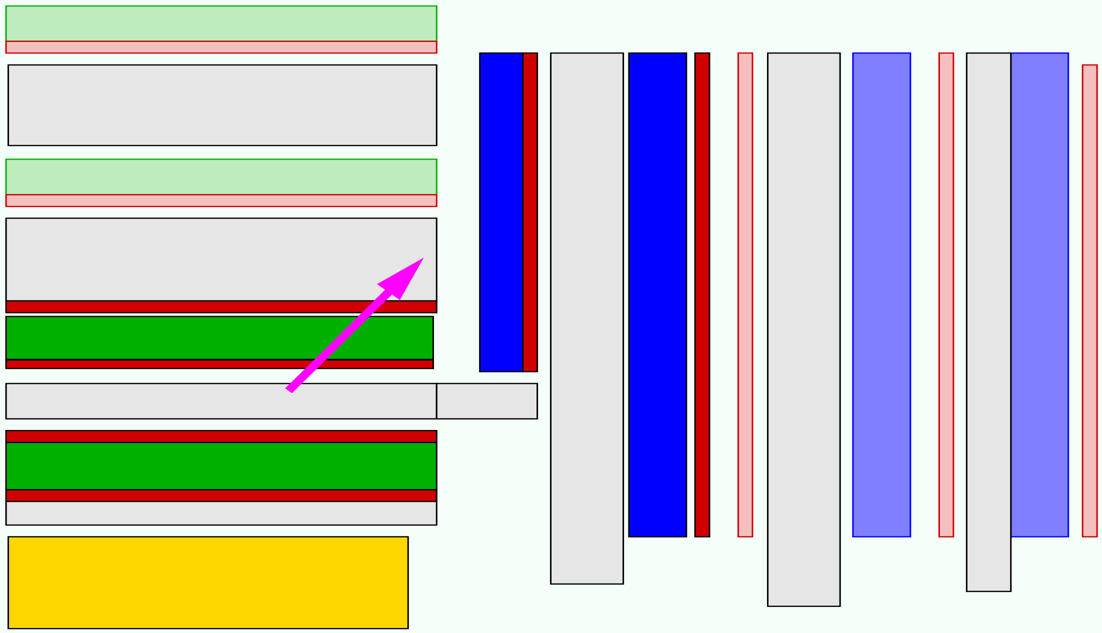


Standalone Muon Reconstruction (2)



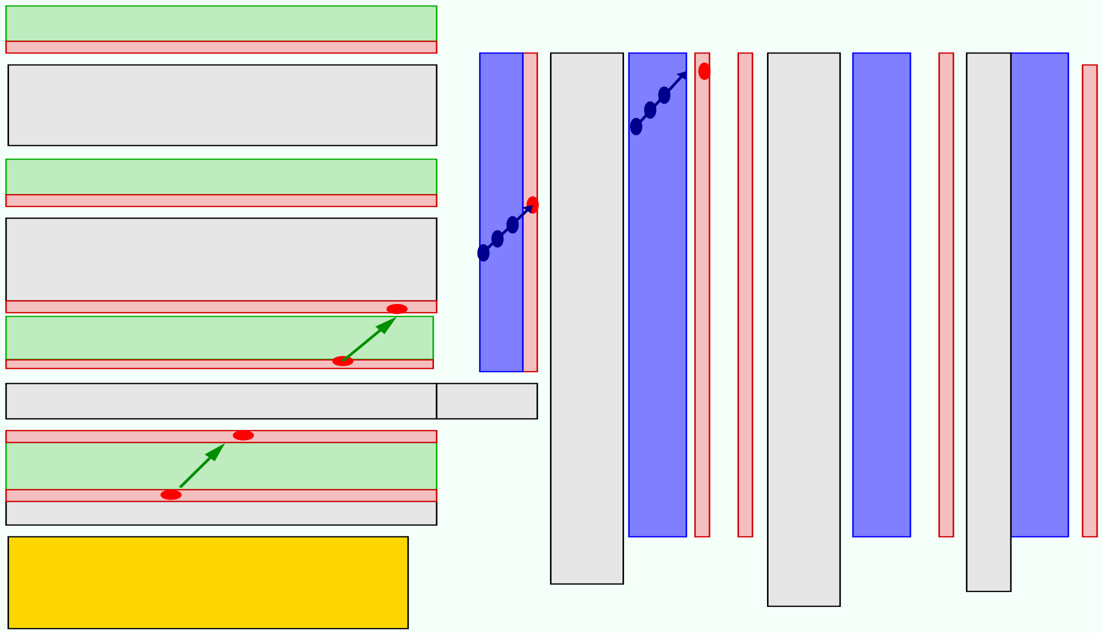
- Based only on Muon detectors: DT, CSC and RPC,
- Seed generation:
  - L1-output for L2 trigger or
  - From track segments from local reconstruction,

Standalone Muon Reconstruction (2)



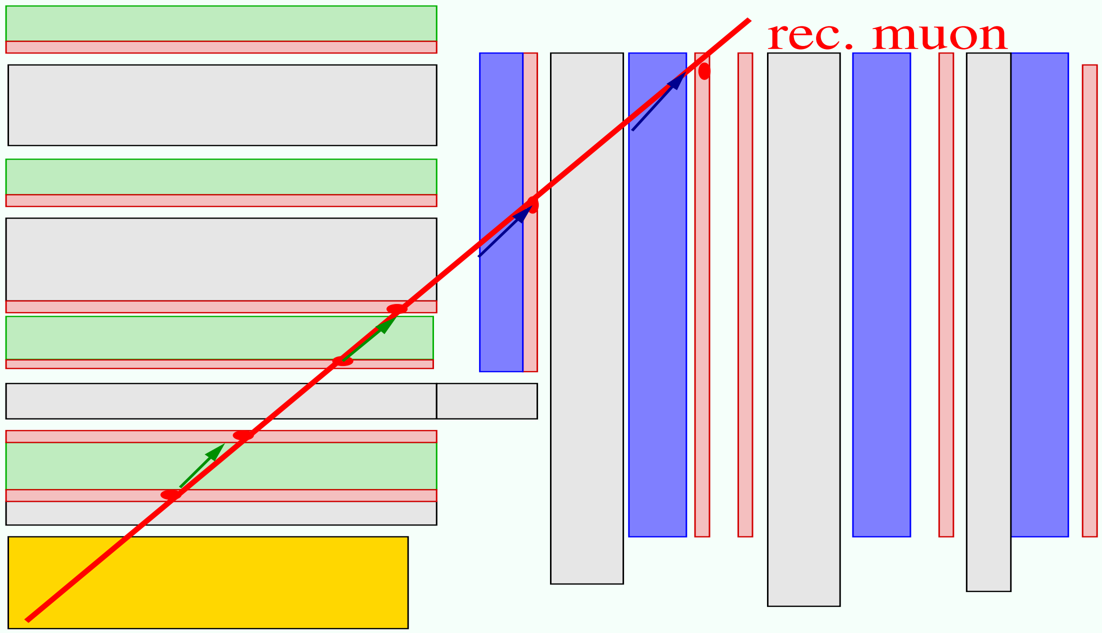
- Search of detectors compatible with seed,

Standalone Muon Reconstruction (2)



- Search of detectors compatible with seed,
- Local pattern reconstruction performed **only** in those detectors: regional reconstruction on demand,
- Use DT 3D segments, CSC 3D hits constituents of segments, and RPC hits,

Standalone Muon Reconstruction (2)



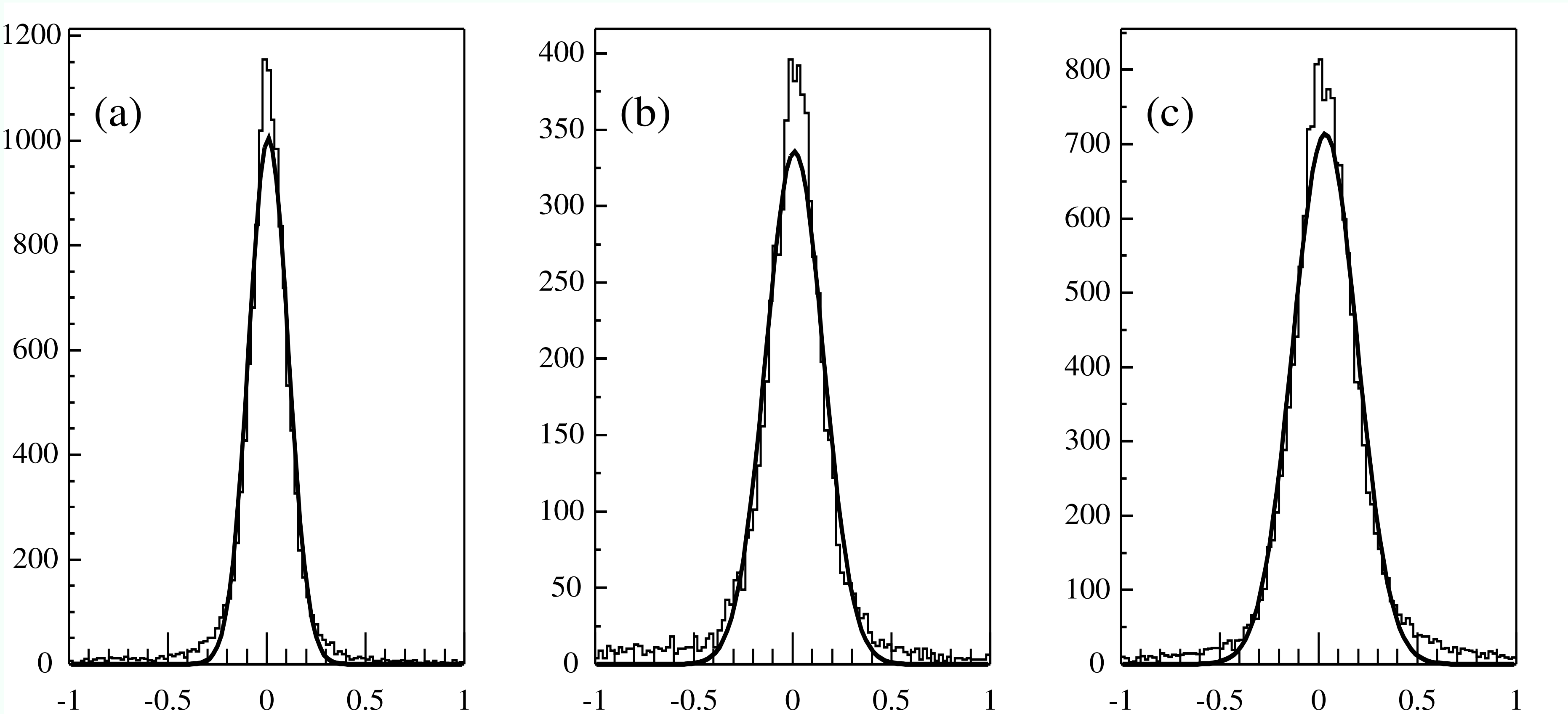
- Trajectory building inside-out to collect hits,
- Kalman filter technique to grow trajectory, χ^2 cuts to reject bad hits,
- State propagation across iron with non-const B field:
  CPU time consuming!
- Track fitting works outside-in,
- Extrapolation to nominal I.P. and refit

Standalone Muon Reconstruction (6)

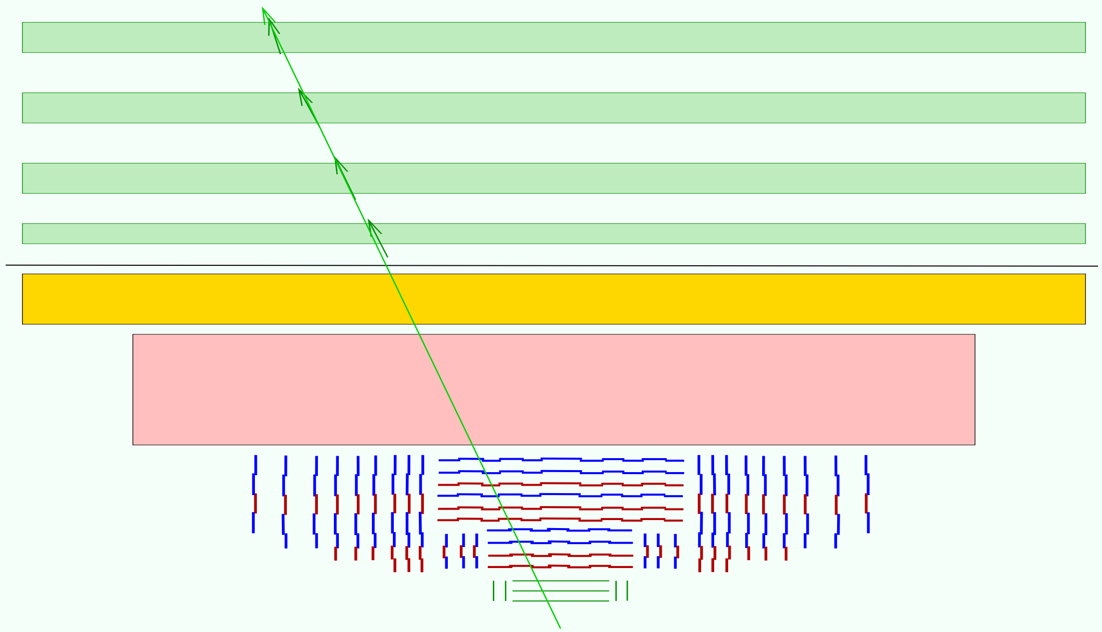
Resolution at L2: $\frac{1/P_t^{rec} - 1/P_t^{gen}}{1/P_t^{gen}}$

a) Barrel $(|\eta| < 0.8)$ b) Overlap $(0.8 < |\eta| < 1.2)$ c) Endcap $(1.2 < |\eta| < 2.1)$

reso $\sim 10\%$ reso $\sim 15\%$ reso $\sim 16\%$

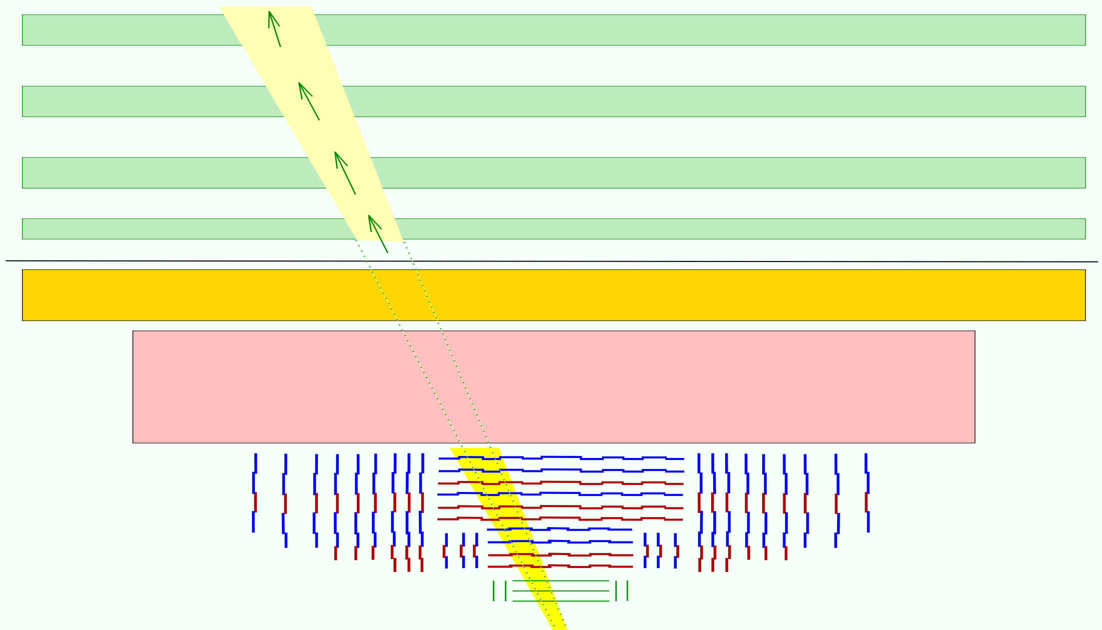


Global Muon Reconstruction (1)



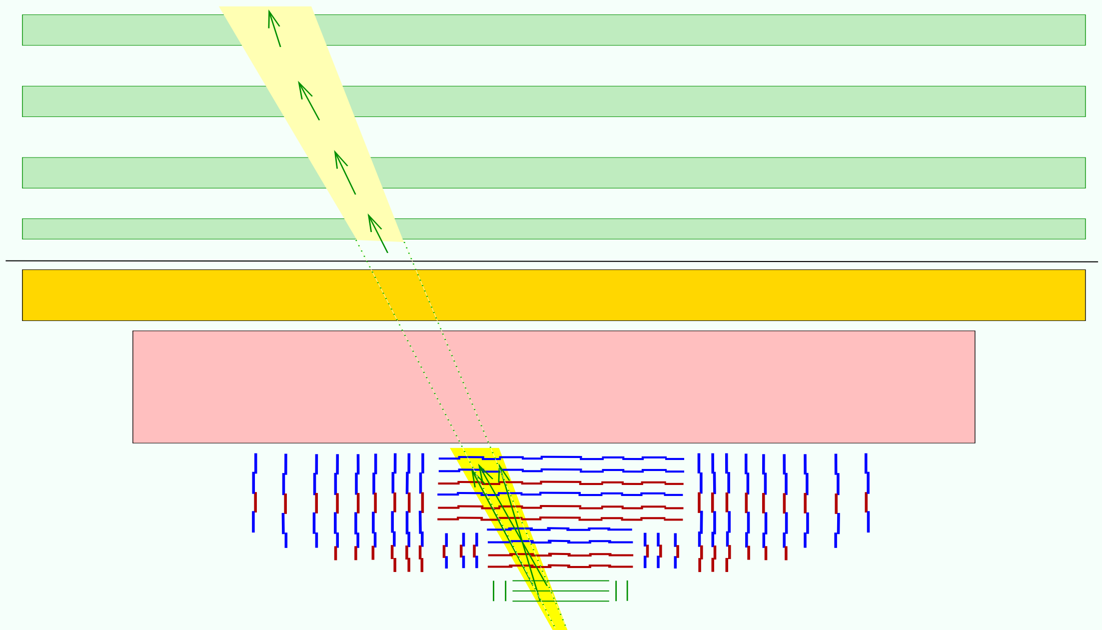
- Inclusion of inner Tracker hits:
- Use L2 reconstructed muons as seed for tracker reconstruction,
- Get muon state at outermost tracker surface and at interaction point,

Global Muon Reconstruction (1)



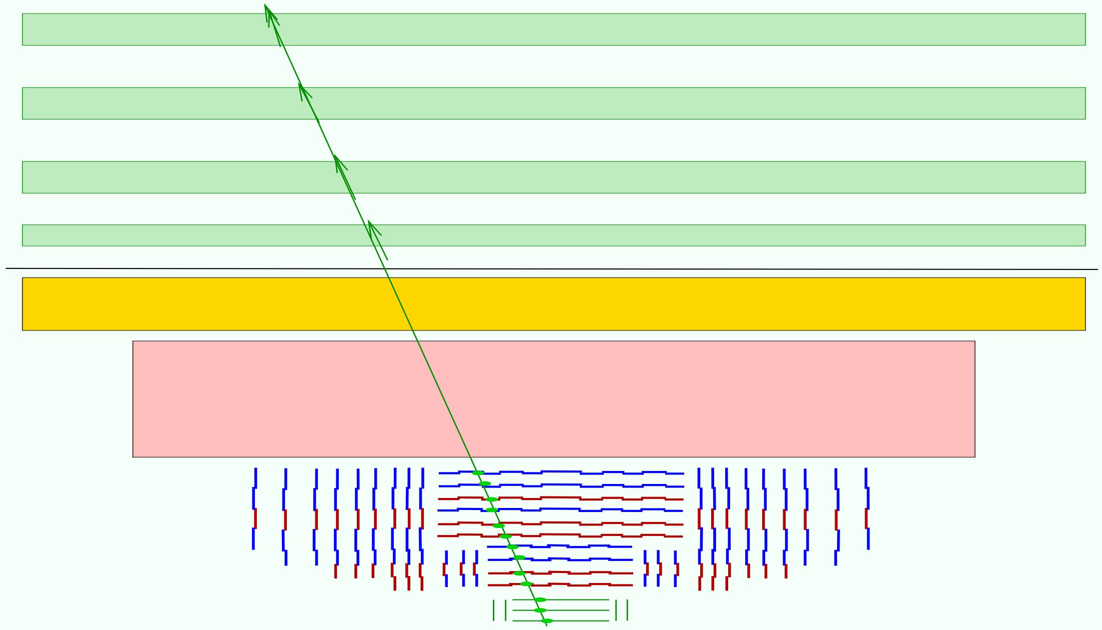
- Inclusion of inner Tracker hits:
- Use L2 reconstructed muons as seed for tracker reconstruction,
- Get muon state at outermost tracker surface and at interaction point,
- Define *region of interest* in the tracker,

Global Muon Reconstruction (1)



- Inclusion of inner Tracker hits:
- Use L2 reconstructed muons as seed for tracker reconstruction,
- Get muon state at outermost tracker surface and at interaction point,
- Define *region of interest* in the tracker,
- Create one or more seeds from pairs of reconstructed hits in different tracker layers,

Global Muon Reconstruction (1)



For a given seed build trajectory:

- ◇ Building inside-out,
- ◇ Kalman filter applied,
- ◇ Uniform B, few material: propagation is much simpler and faster than in the muon system,

Trajectory cleaning and final fit:

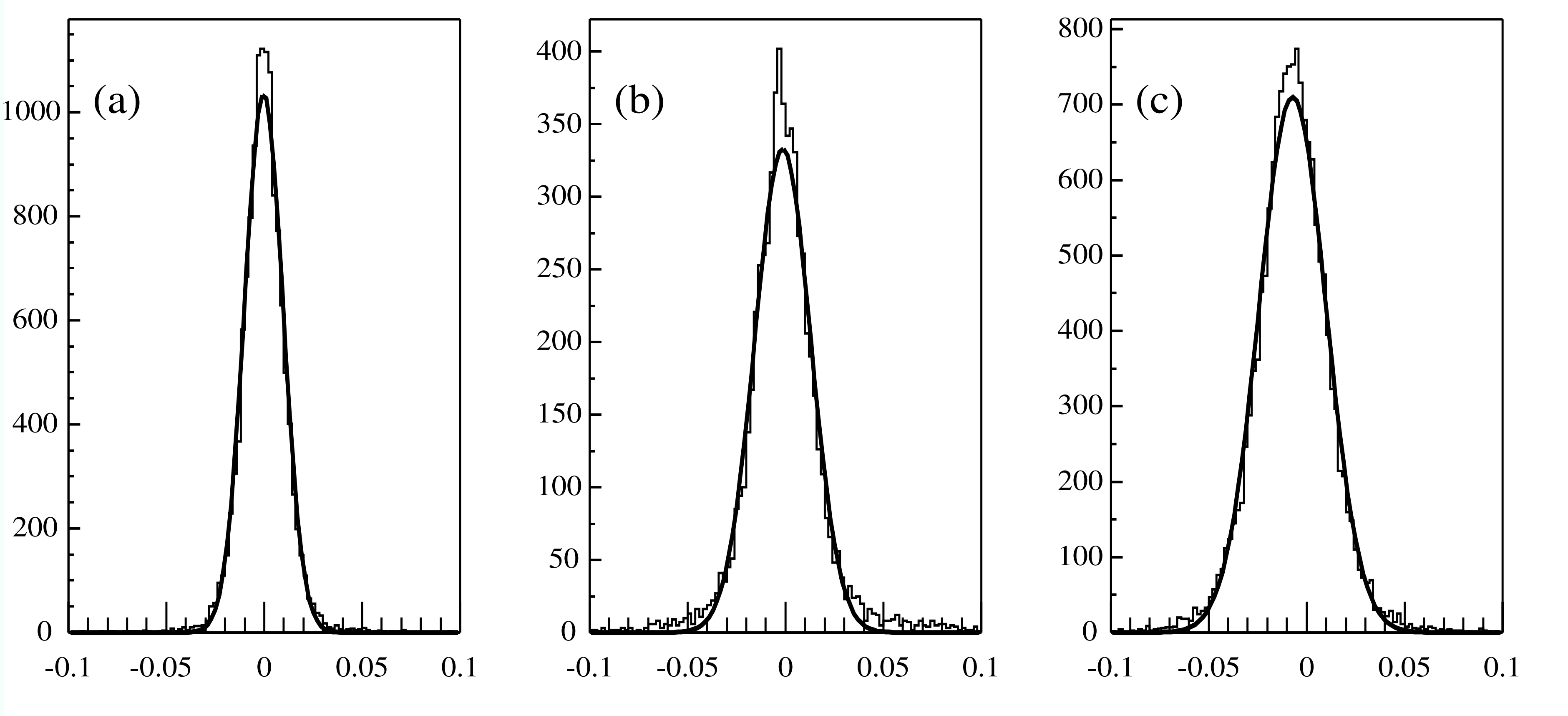
- ◇ Solve ambiguities,
- ◇ Ghosts suppression (# hits and χ^2),
- ◇ Use tracker and muon hits for final fit,
- ◇ Reject bad tracks.

Global Muon Reconstruction (2)

Resolution with Tracker: $\frac{1/P_t^{rec} - 1/P_t^{gen}}{1/P_t^{gen}}$

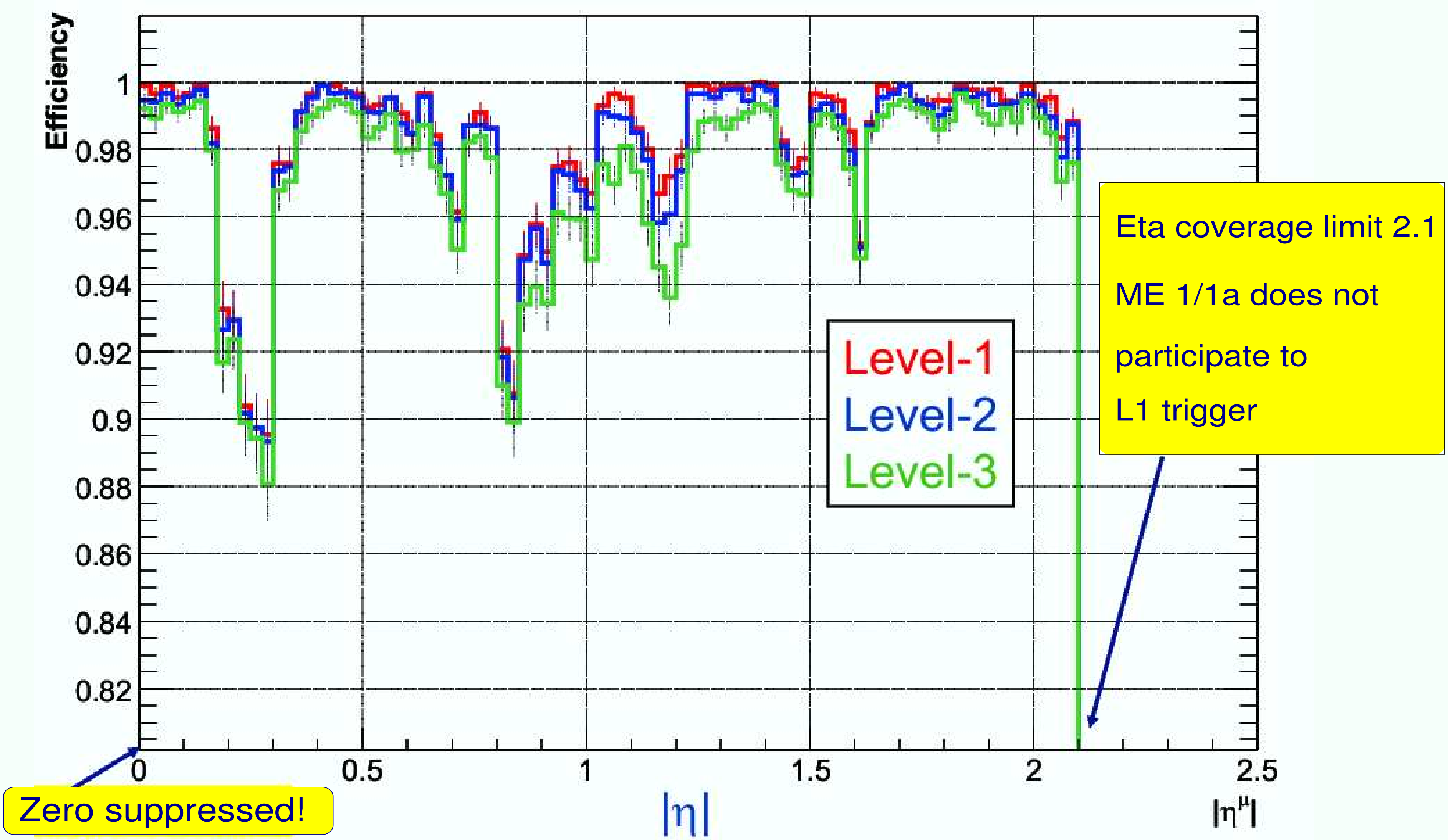
a) Barrel ($|\eta| < 0.8$) b) Overlap ($0.8 < |\eta| < 1.3$) c) Endcap ($1.3 < |\eta| < 2.1$)

reso $\sim 1.0\%$ reso $\sim 1.4\%$ reso $\sim 1.7\%$



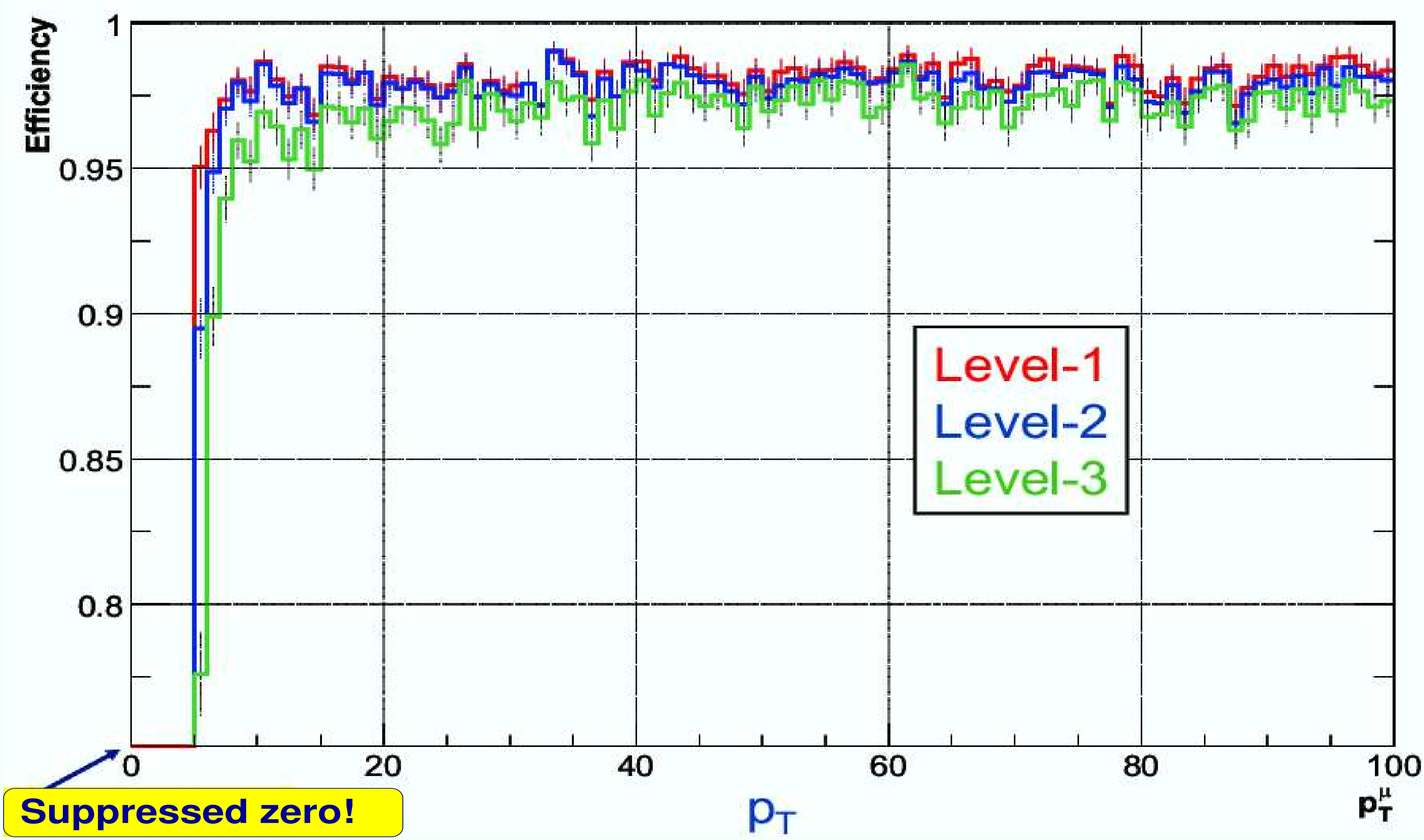
Global Muon Reconstruction (3)

L1, L2, L3 efficiency vs $|\eta|$



Global Muon Reconstruction (4)

L1, L2, L3 efficiency vs $|p_t^\mu|$



Suppressed zero!

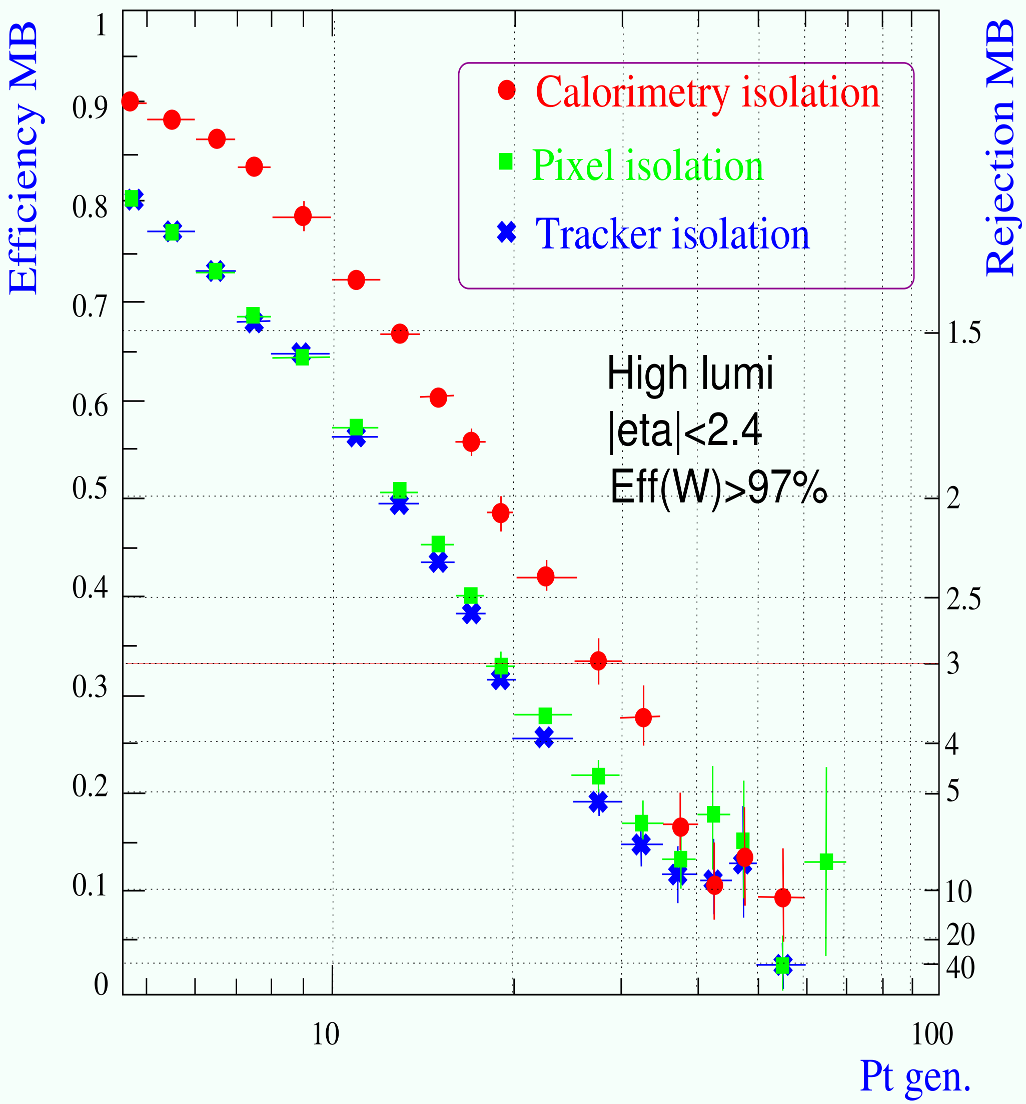
p_T

Muon Isolation (1)

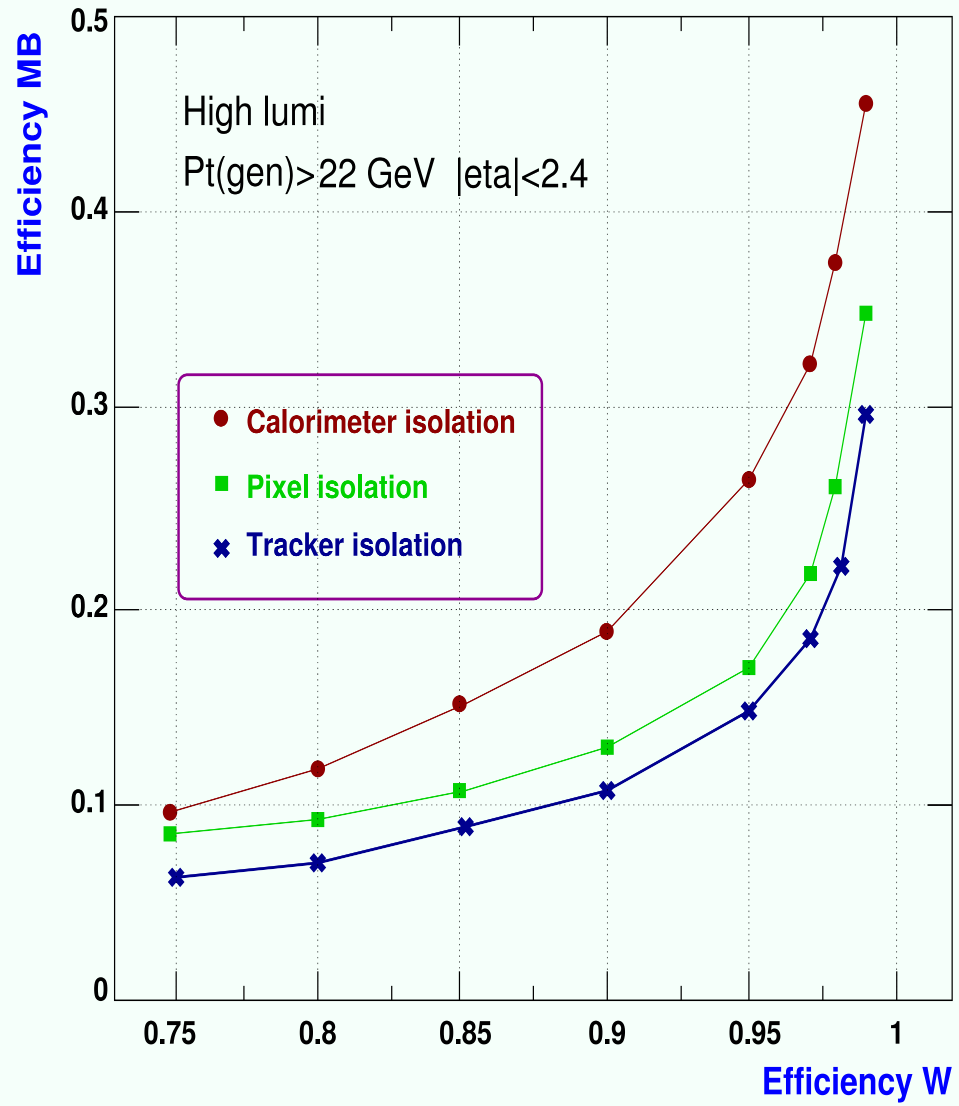
- Based on $\sum E_t$ or $\sum p_t$ in cones around reconstructed muons,
  - Cones sizes and thresholds are optimized to get maximum rejection for minimum bias events above trigger p_t threshold for a fixed efficiency on reference signal ($W \to \mu\nu$)
  - Flat $\epsilon(\eta)$ by construction,
- Calorimeter isolation, @ L2
  - $\sum E_t$ from ECAL & HCAL towers: sensitive to PileUp,
- Pixel isolation, @ L2.5
  - $\sum p_t$ from $3-$hit tracks in the pixel detector,
  - Need 3 layers, no with pixel staging, problem if pixel inefficiencies,
  - Take tracks from the same vertex as μ, reduce PU ,
- Tracker isolation, @ L3
  - $\sum p_t$ from tracker tracks, regional reconstruction around muon,

Muon Isolation (2)

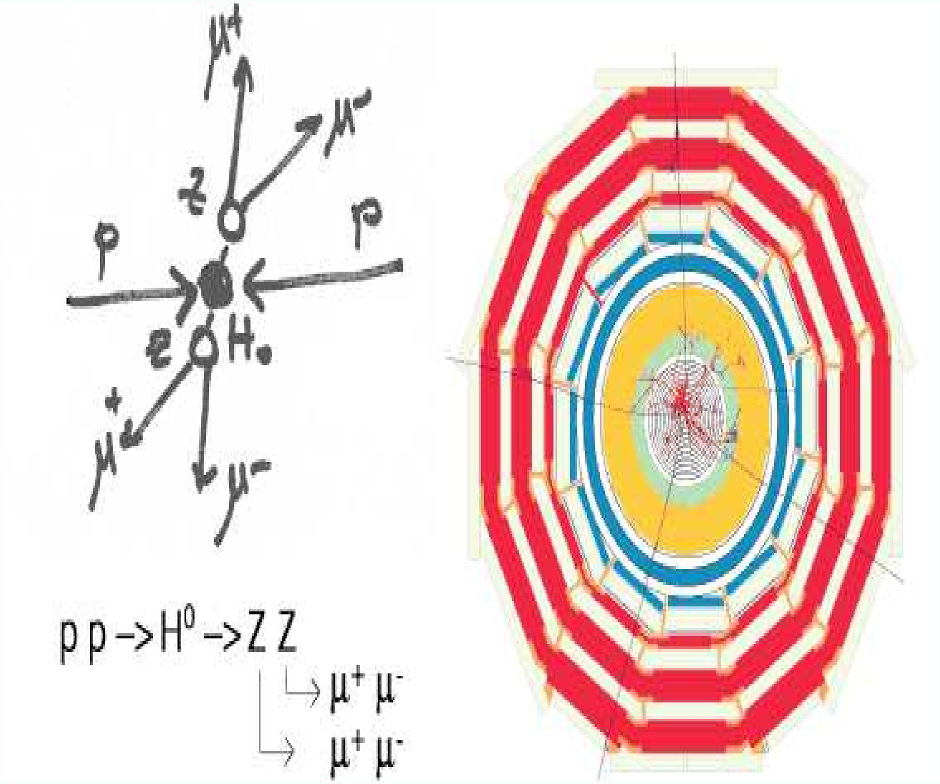
ϵ_{MB} vs p_t^{gen} for $\epsilon_W \geq 97\%$



ϵ_{MB} vs ϵ_W

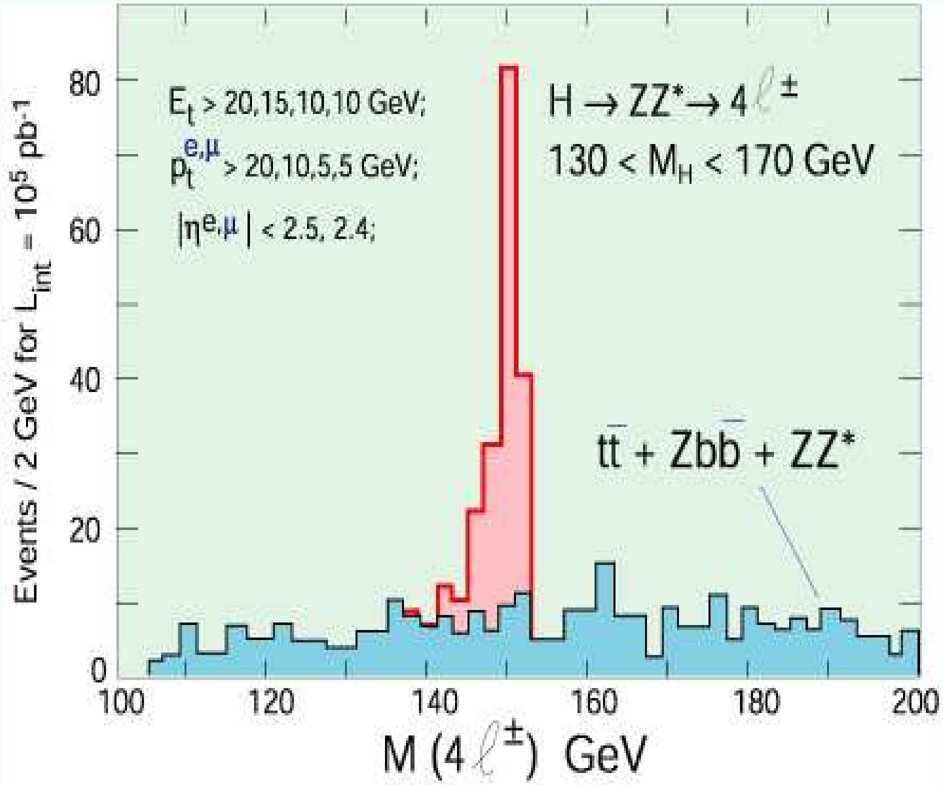


Physics Performance



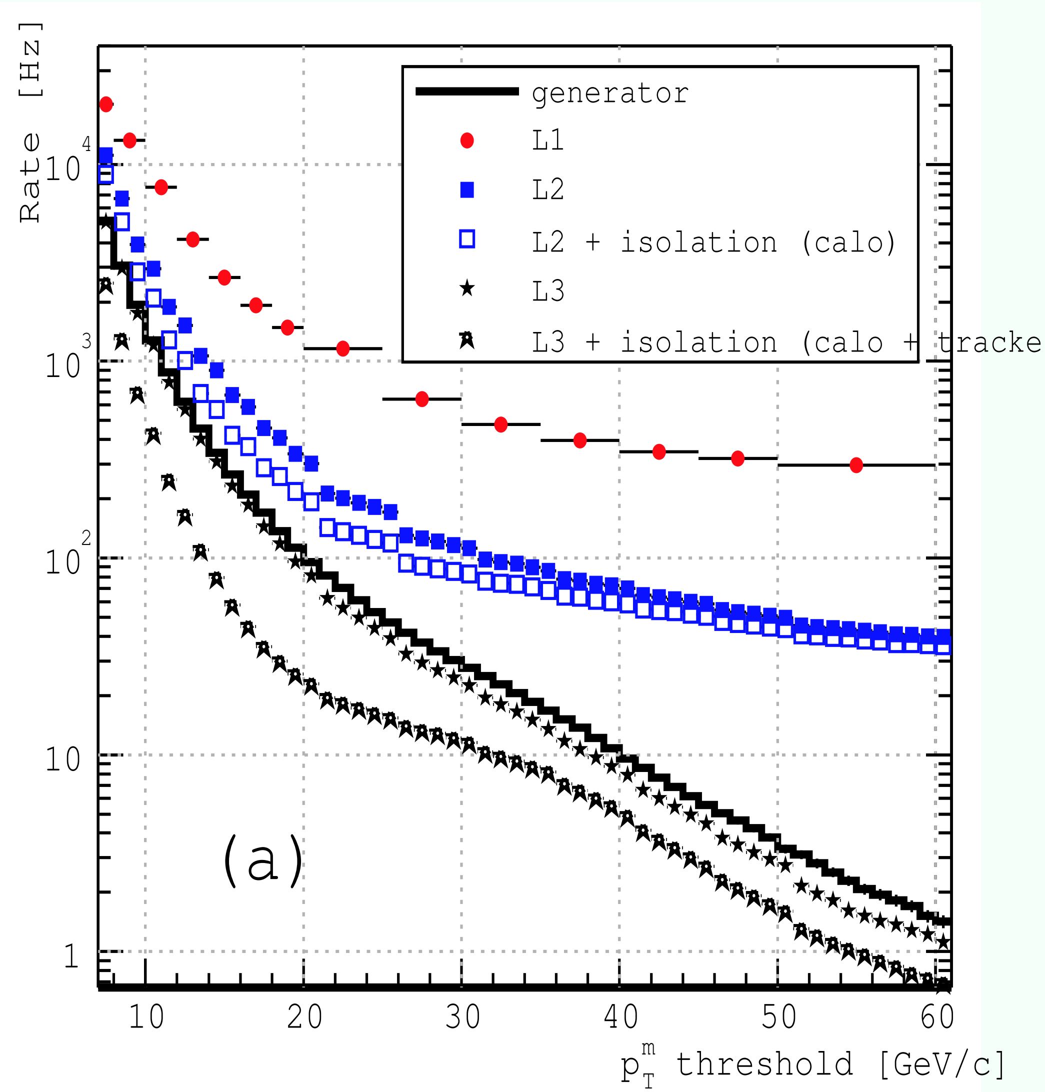
From here...

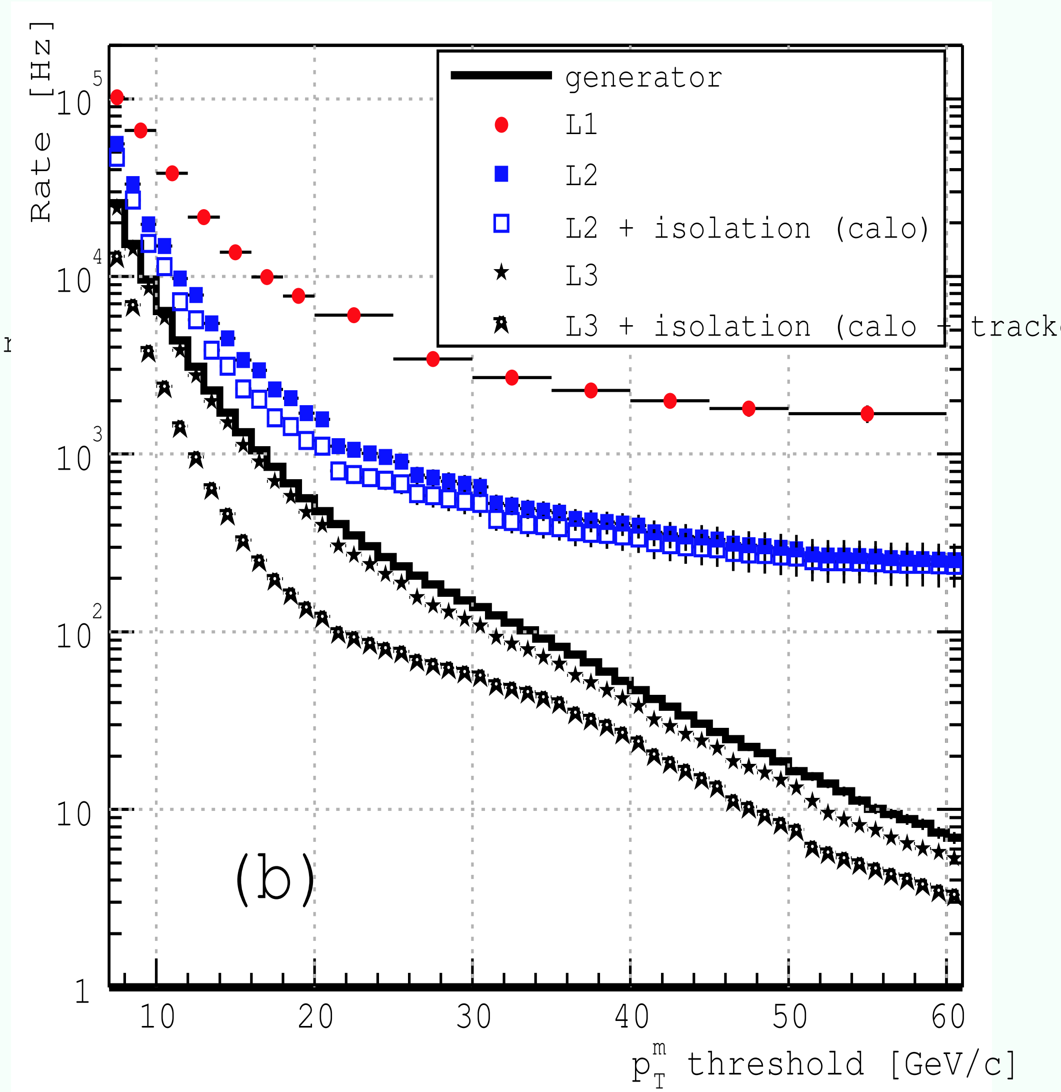
to here!



Physics Performance (1)

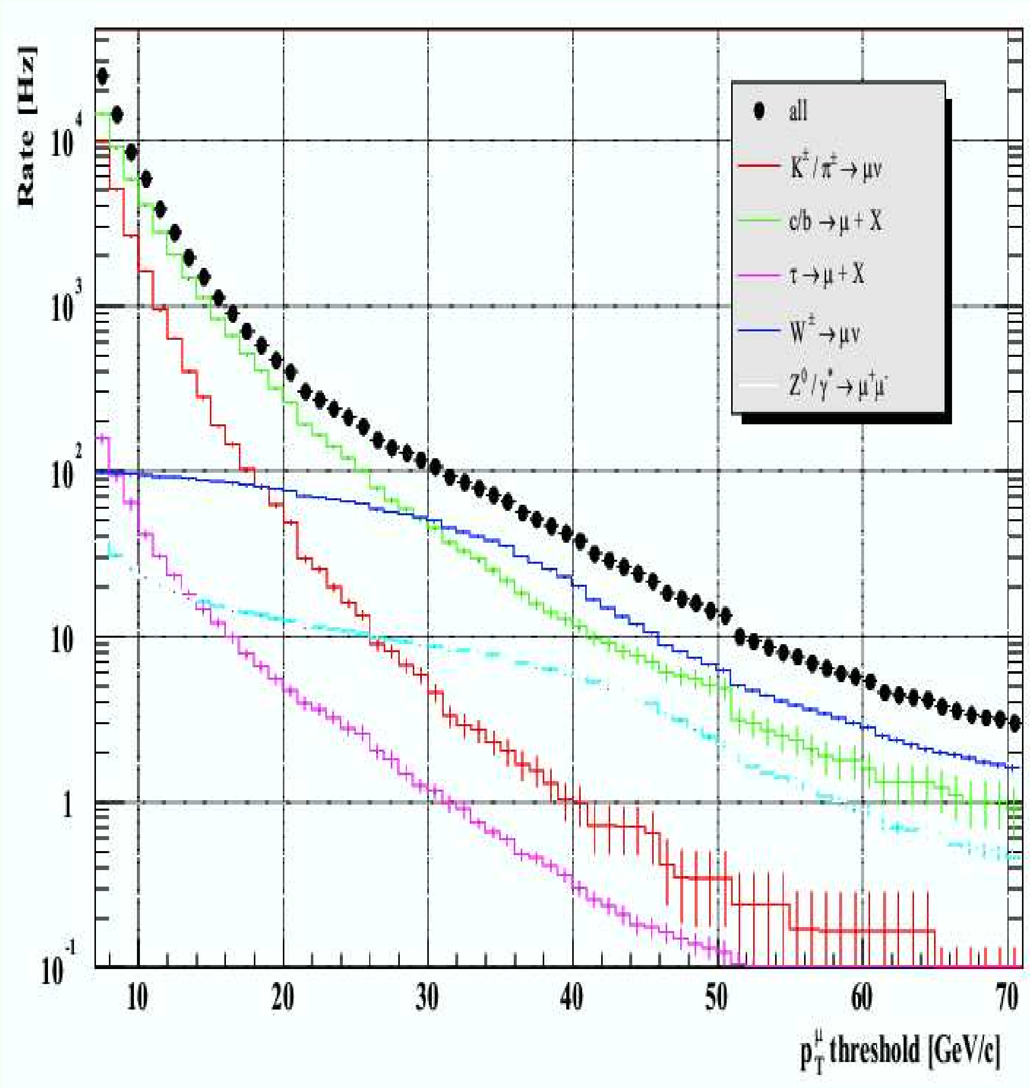
Single muon rate Low (a) and High (b) lumi:

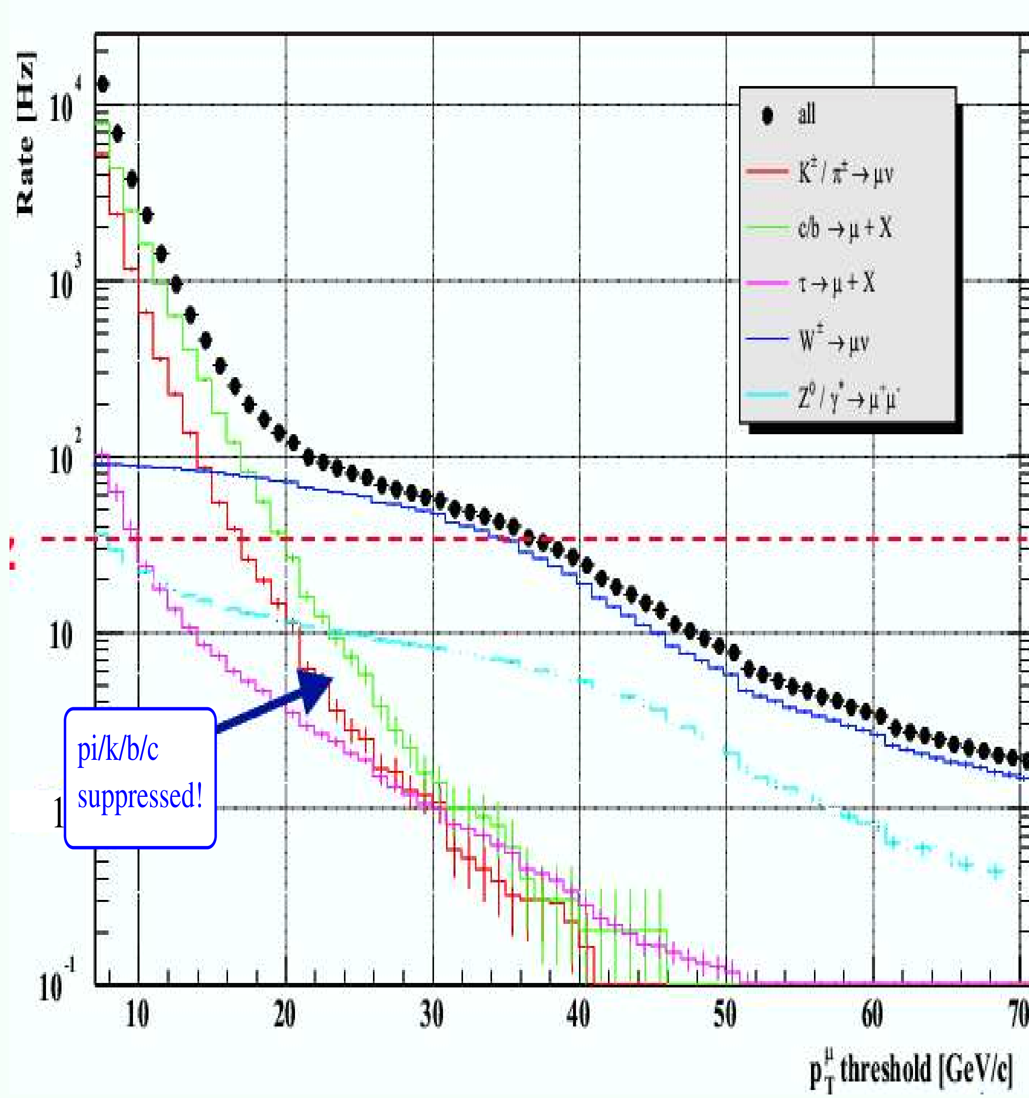




Physics Performance (2)

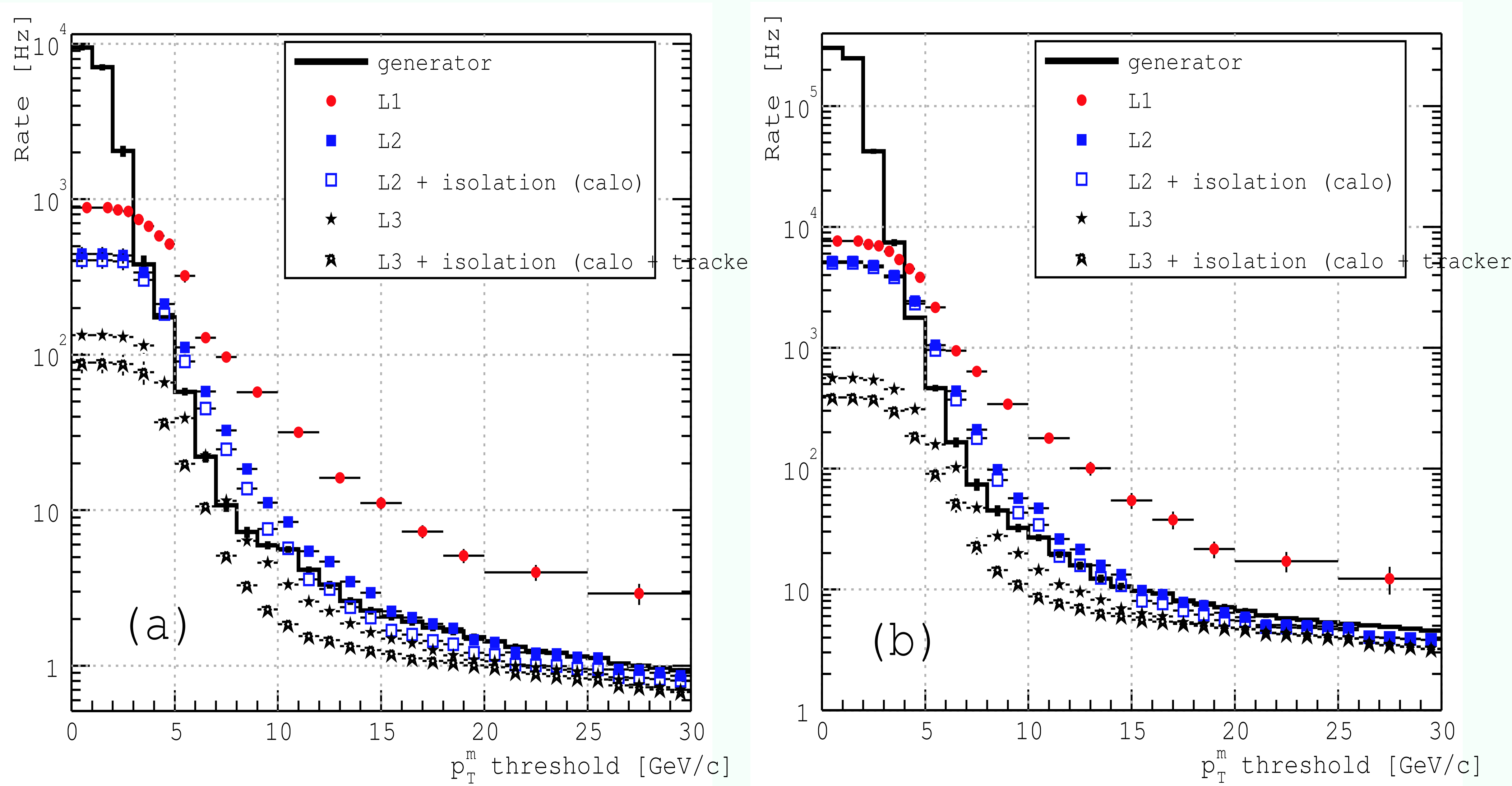
Contribution to single μ rate High Lumi before and after isolation:





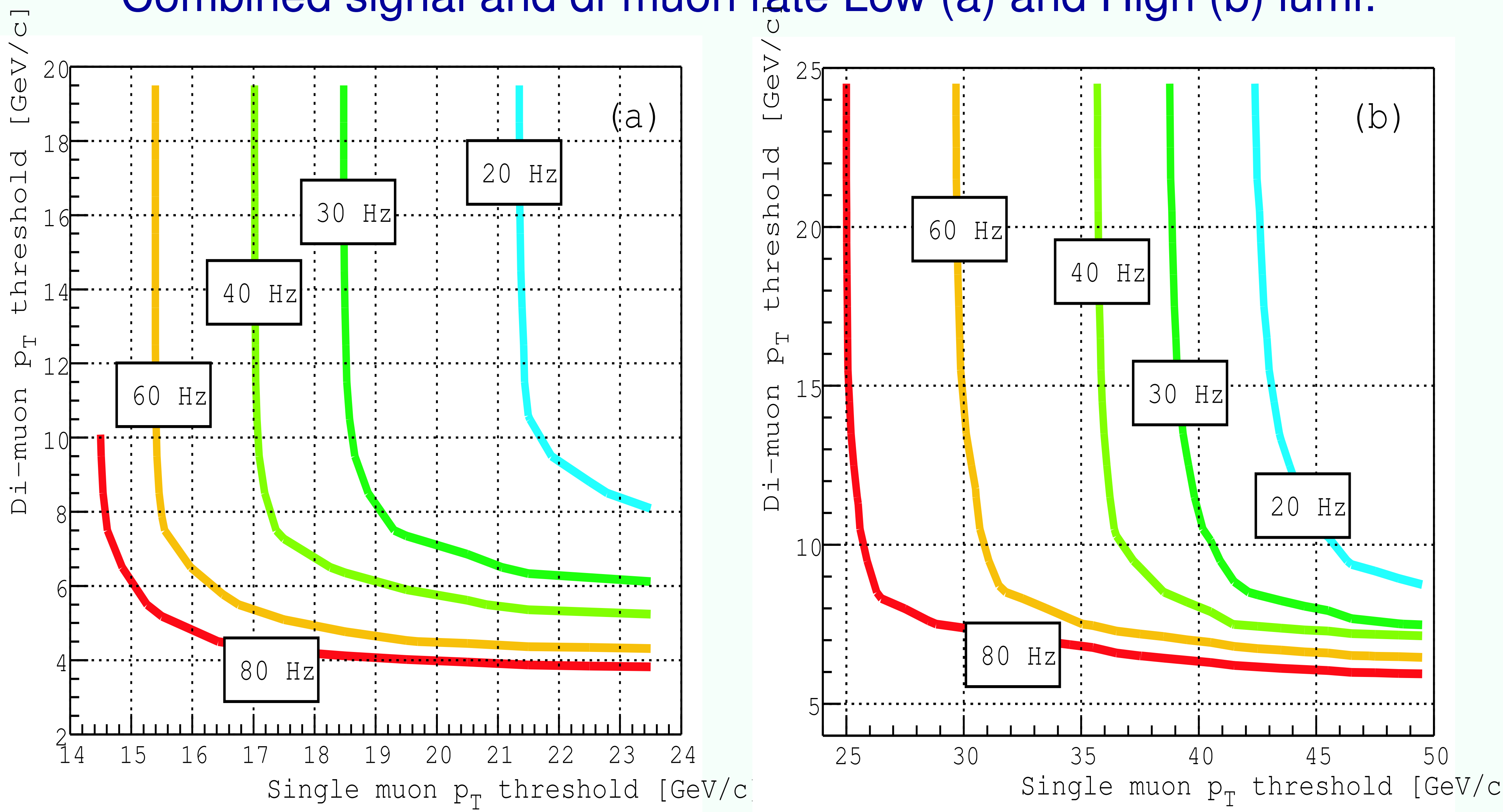
Physics Performance (3)

Di-muon rate (symmetric p_T thr.) Low (a) and High (b) lumi:



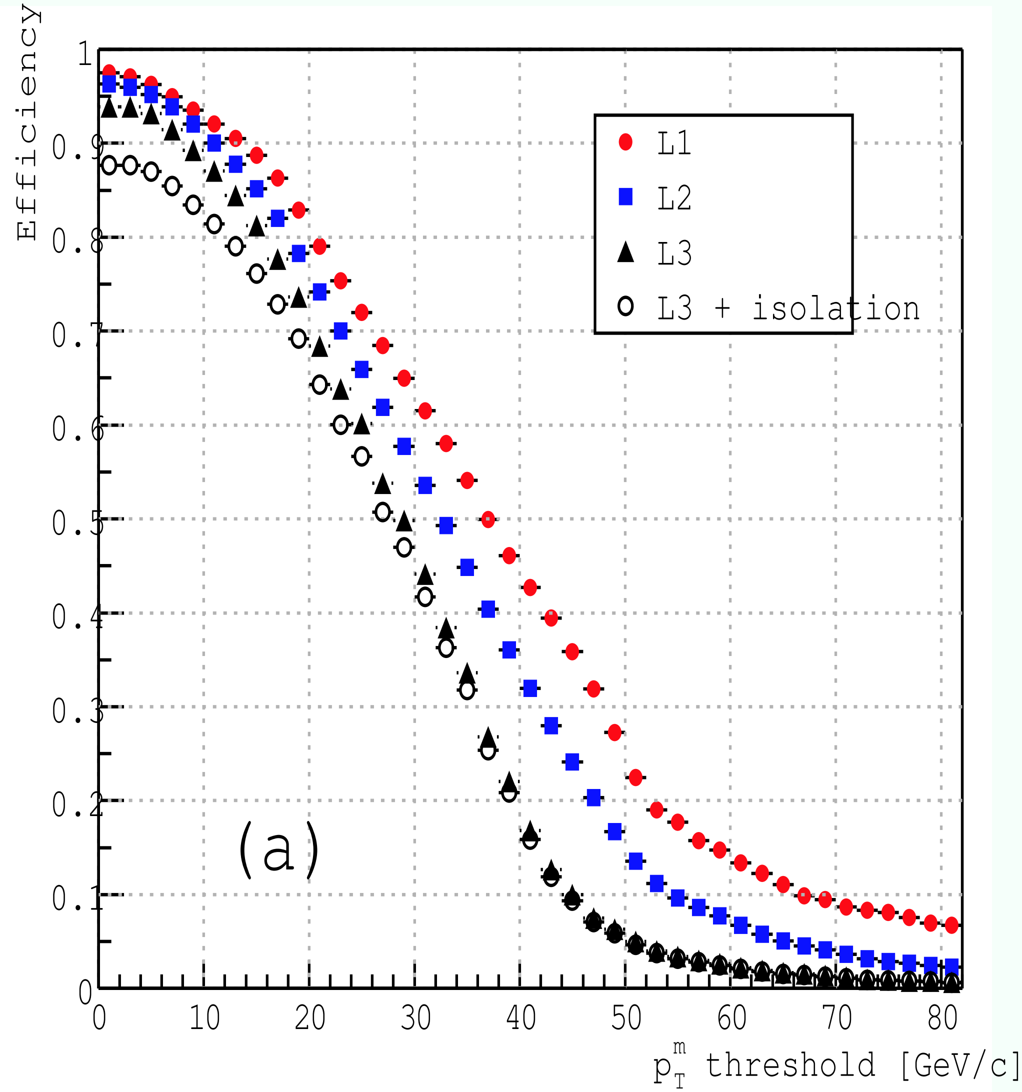
Physics Performance (4)

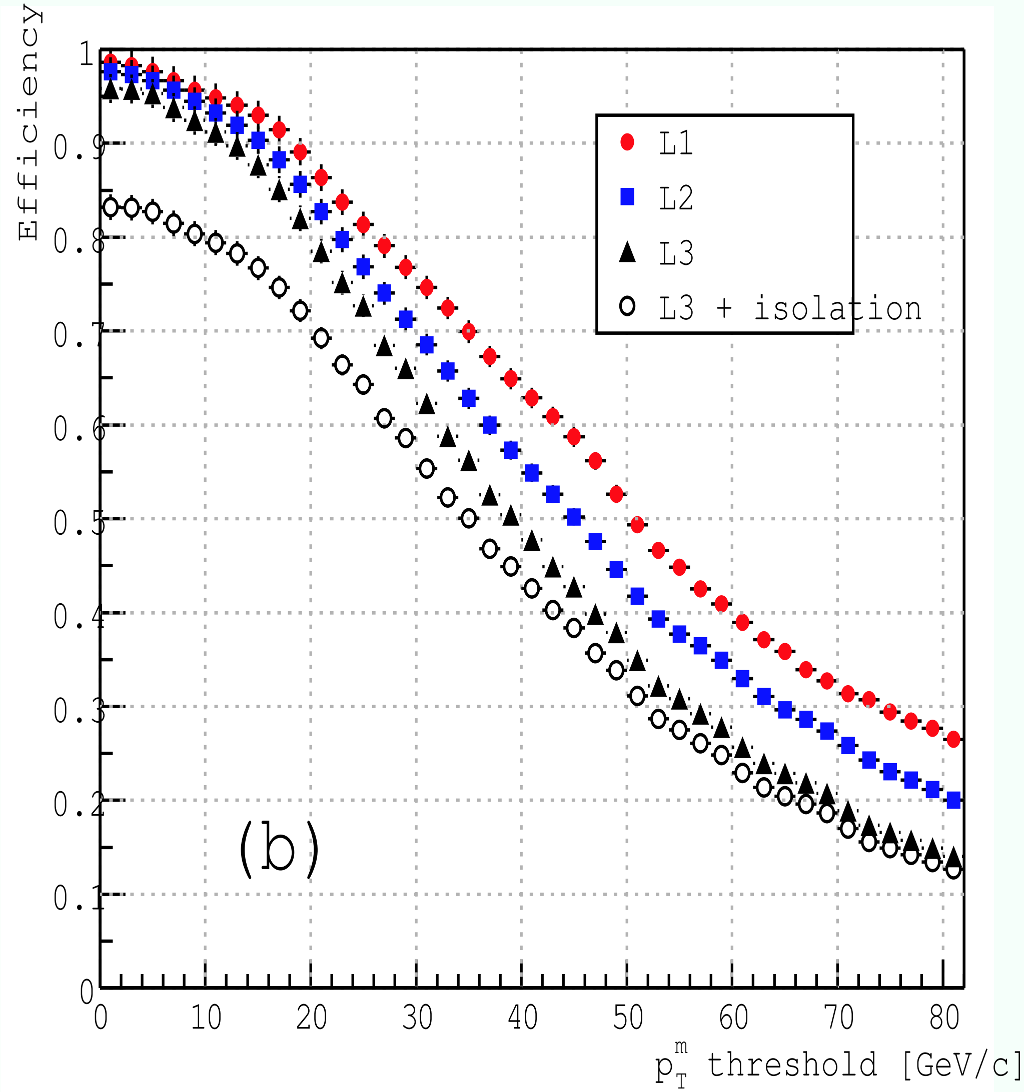
Combined signal and di-muon rate Low (a) and High (b) lumi:



Physics Performance (5)

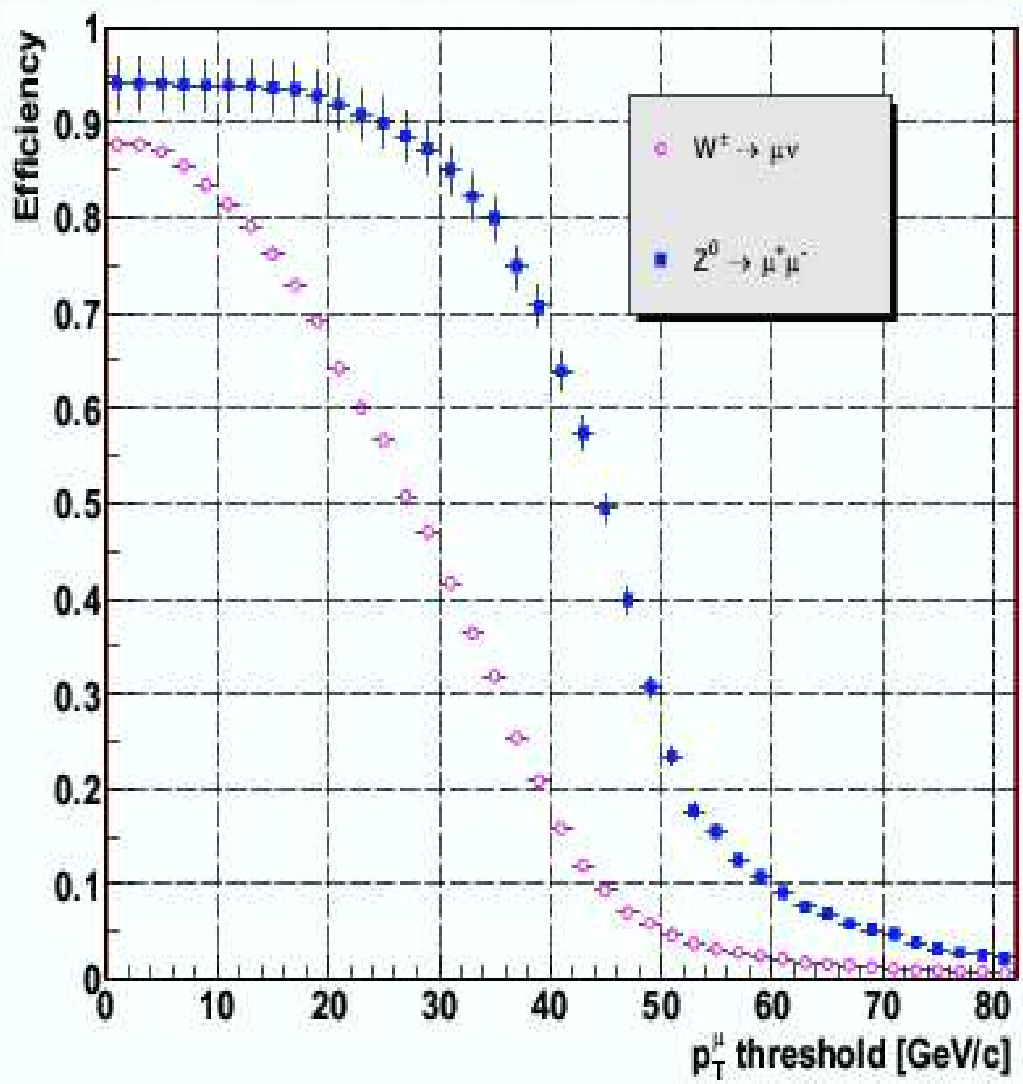
Efficiency for $W \to \mu\nu$ and $t\bar{t} \to \mu + X$:

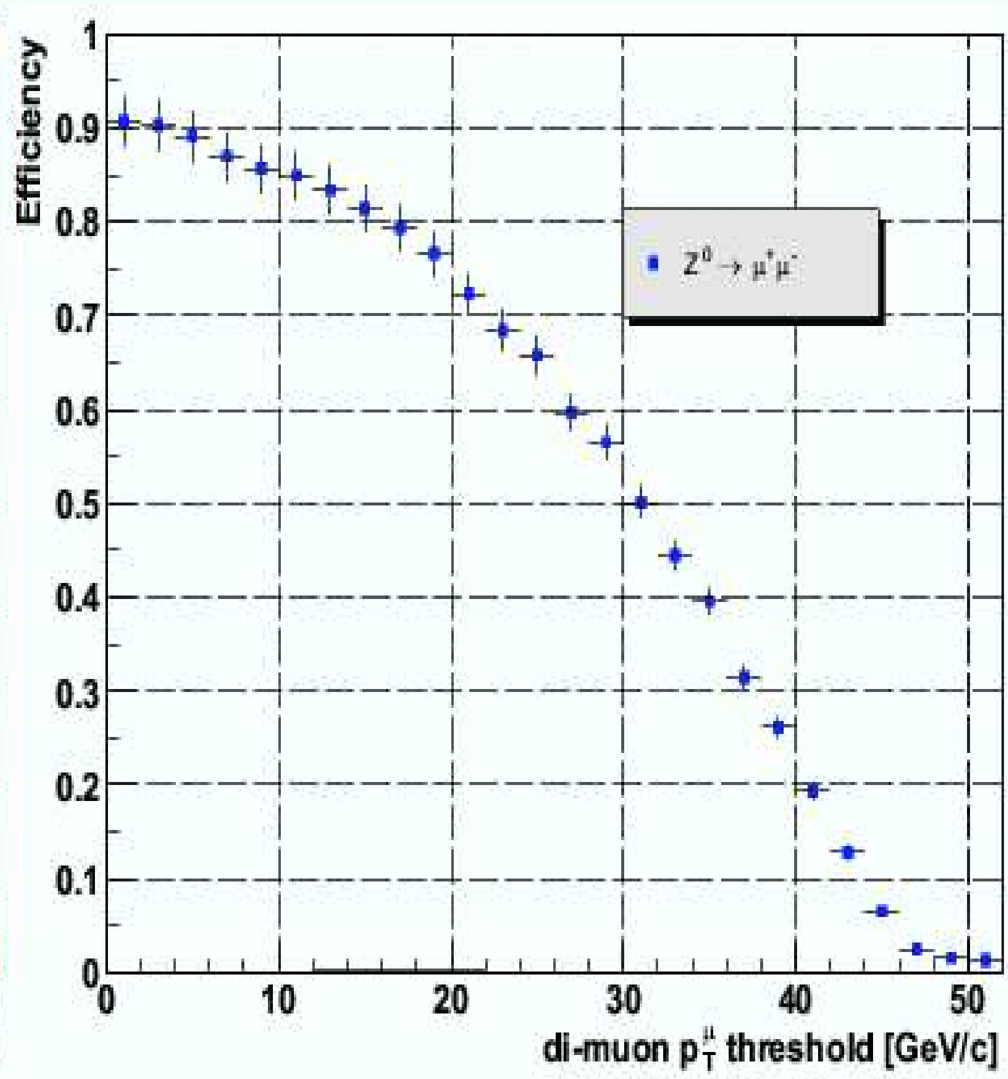




Physics Performance (6)

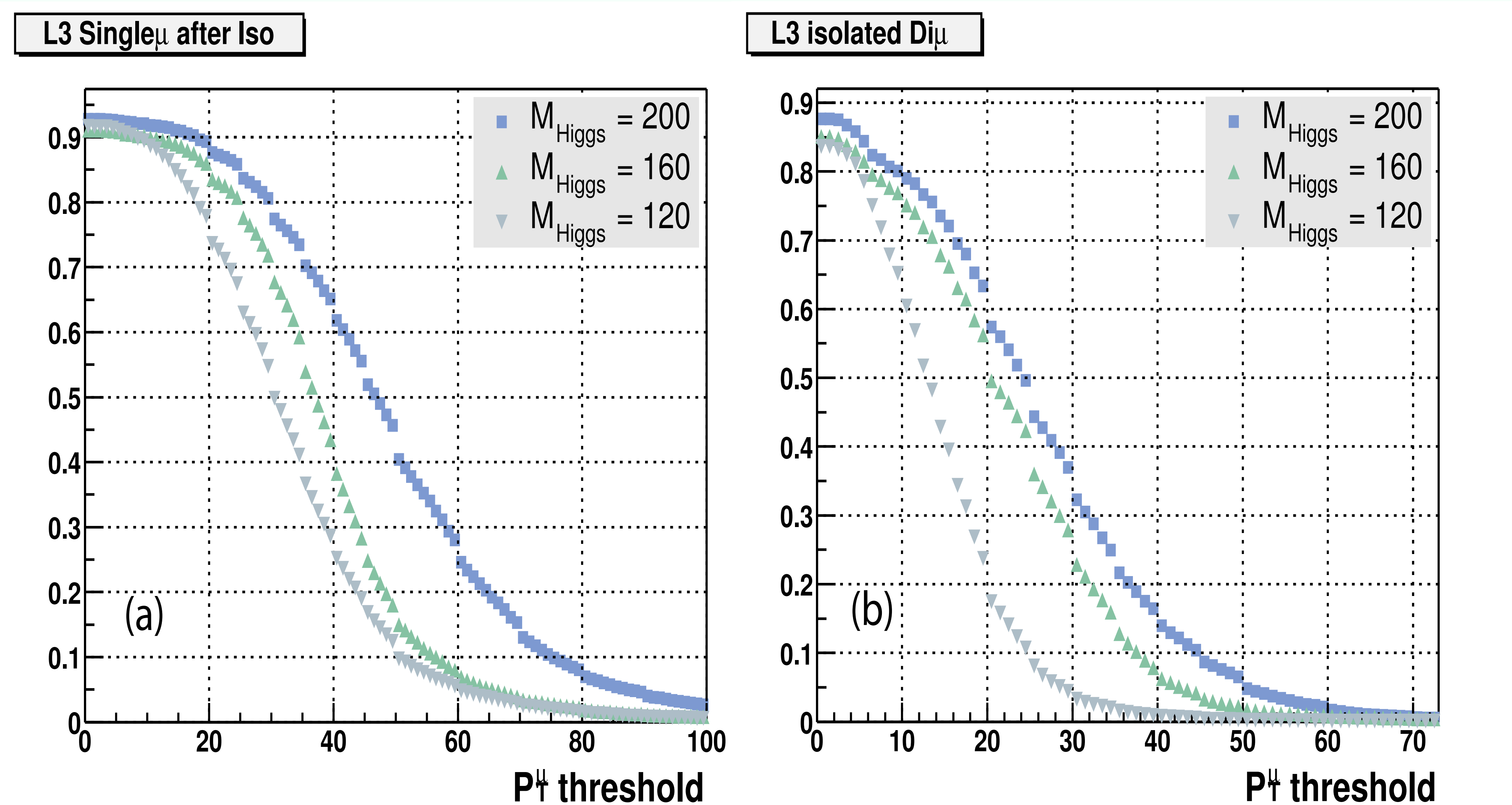
Efficiency for $W \to \mu\nu$ and $Z \to \mu\mu$:





Physics Performance (7)

Efficiency for $H^0 \to WW \to 2\mu 2\nu$ vs single and di-μ thr.:



Possible Working Point at Low and High Lumi

Lumi	1 μ thr. L1-HLT GeV	di μ thr. L1-HLT GeV	total rate ($\pi K/bc\tau/W/Z$) Hz (~frac)
LL	14-19	3-7	29 ($3.4/8.7/14.5/2.4$)
HL	20-31	5-10	55 ($0.8/2/42/7.6$)

- Different threshold for L1 and HLT, room for more exclusive HLT selection at lower threshold (correlation, topological trigger, $m_{\mu\mu}$ selection, ...),
- b physics contents is relevant at low lumi, and can be enhanced with dedicated trigger below HLT threshold,
- e.g. $B_s \to J/\psi\phi$: trigger at L1 di-μ + regional tracker reco + J/ψ mass reconstruction ($\delta m \sim 55\ MeV$, $\sim 30\ MeV$ with full reco) can give $\epsilon \sim 5\%$ for signal $\rightarrow \sim 10^5$ ev/yr $(20\ fb^{-1})$
- total rate is dominated (especially at High Lumi) by W, to lower the threshold must reject part of these events, without losing efficiency,

Signal Efficiency at Nominal Threshold

Signal	ϵ_{LL}	ϵ_{HL}
$W \to \mu\nu$	69%	42%
$Z \to \mu\mu$	92%	86%
$t\bar{t} \to \mu + X$	72%	58%
$H_{120} \to WW \to 2\mu 2\nu$	87%	64%
$H_{160} \to WW \to 2\mu 2\nu$	92%	77%
$H_{150} \to ZZ^* \to 4\mu$	98%	97%
$H_{200} \to ZZ \to 4\mu$	99%	99%

- $W, Z, t\bar{t}$ efficiency relative events with at least one muon in $|\eta| < 2.1$,
- Higgs efficiency relative to events with $n_\mu \geq 1$ within $|\eta| < 2.1$, and all within $|\eta| < 2.4$.

Summary

- CMS muon system has been designed with high redundancy for selection and reconstruction,
- High Level Trigger reconstruction already developed, will be very close to the offline reco,
- Fully exploit muon and tracker detectors to give excellent performance in term of resolution and efficiency,
- Still room for further optimization and development,
- Physics performance very promising,

(eagerly) Waiting for first $p - p$ collision!!

Backup Slide

Muon Alignment Issue

- ⋆ Rate of μ usable for alignment ($p_t > 50$ GeV from L1 trigger): $0.2 \div 1\ Hz$ μ/sector
- ⋆ With perfect knowledge of $B-$field, ~ 4 days even at Low luminosity to reach ~ 200 μm precision,
- ⋆ But with $\Delta B/B \sim 0.1\%$ need several months,
- ⋆ to achieve ~ 100 μm precision (i.e. better than chamber resolution) years!!
- ⋆ must have external alignment for ~ 100 μm precision
- ⋆ web of laser and optical link to align muon detectors also with inner tracker will be present in CMS
- ⋆ in the endcaps might use halo muons, need special trigger

Muon Reconstruction Timing

algorithm	mean CPU time Low Lumi total	(ms/event) $p_t > 10\ GeV$ excluding GEANE	mean CPU time High Lumi total	(ms/event) $p_t > 18\ GeV$ excluding GEANE
L2	640	100	580	100
Calo iso	100	25	90	40
L3	420	200	590	420
Pixel iso	65	65	320	320
Tk iso	190	190	370	370
Total	710	125	660	150

- Average CPU time (on INTEL PIII 1 GHz) for 1 event passing previous selection,
- expect a factor $2 \times 2 \times 2$ from Moore's law in 2007,
- most of time spent in propagation in iron with GEANE,
- work in progress to replace it with a fully customizable and optimized propagator, expected major improvement.