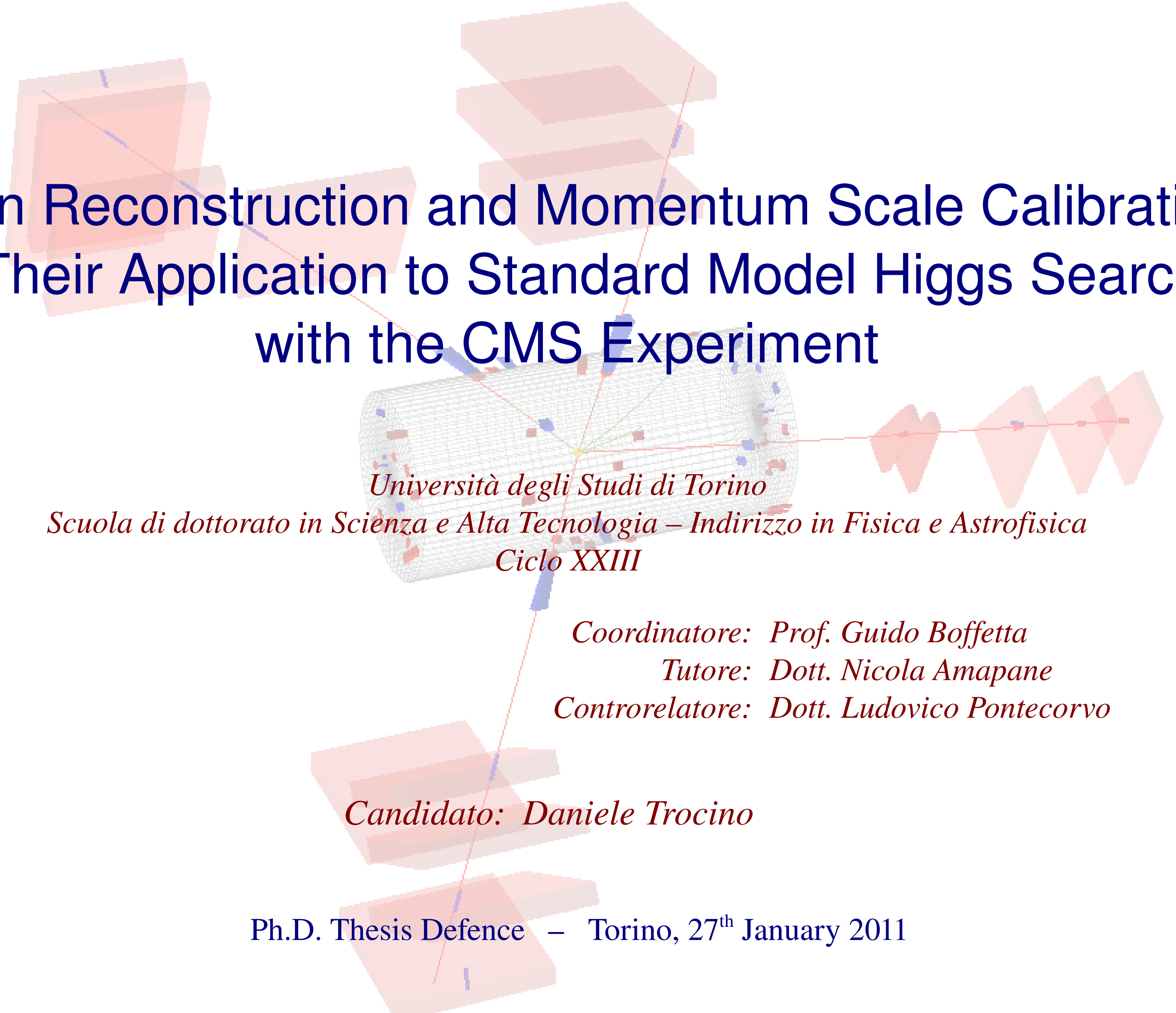


Muon Reconstruction and Momentum Scale Calibration and Their Application to Standard Model Higgs Searches with the CMS Experiment

Università degli Studi di Torino
Scuola di dottorato in Scienza e Alta Tecnologia – Indirizzo in Fisica e Astrofisica
Ciclo XXIII

Coordinatore: Prof. Guido Boffetta
Tutore: Dott. Nicola Amapane
Controrelatore: Dott. Ludovico Pontecorvo

Candidato: Daniele Trocino

Ph.D. Thesis Defence – Torino, 27th January 2011

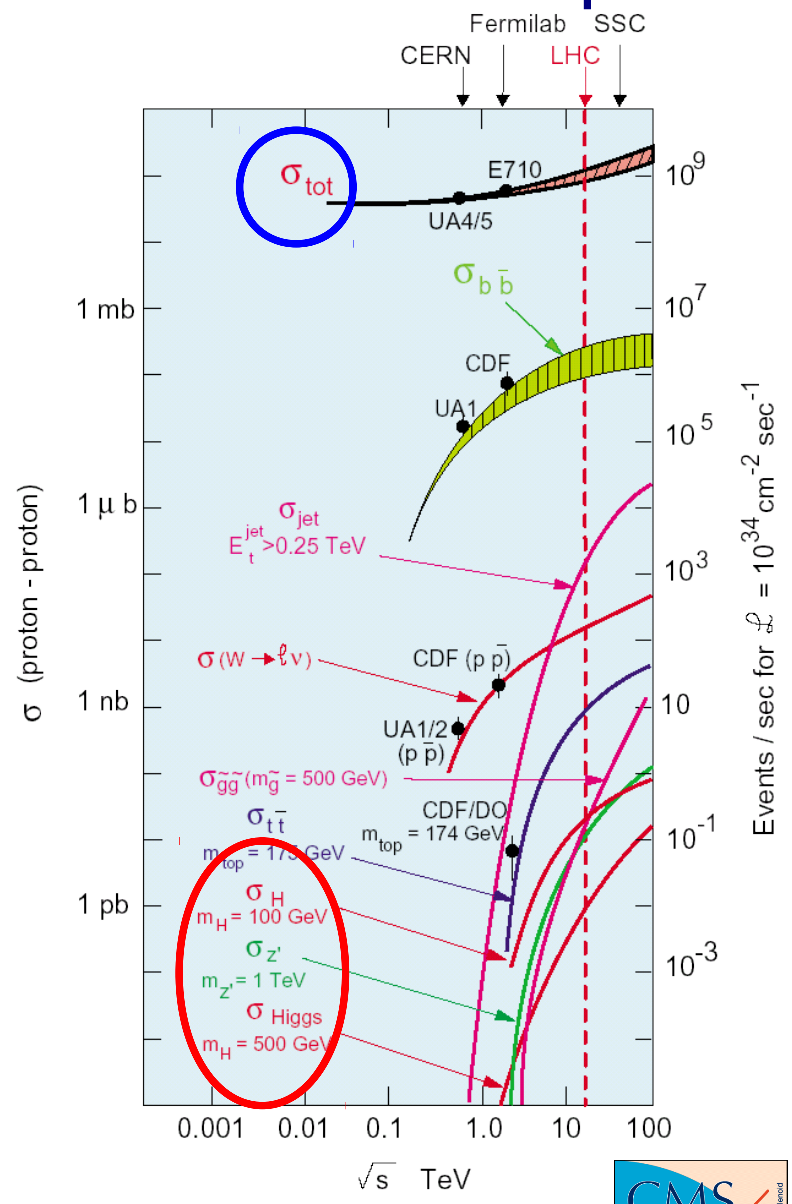
Prelude

- The LHC will give a final answer to the question about the existence of the Higgs boson
  - all the allowed mass range is accessible

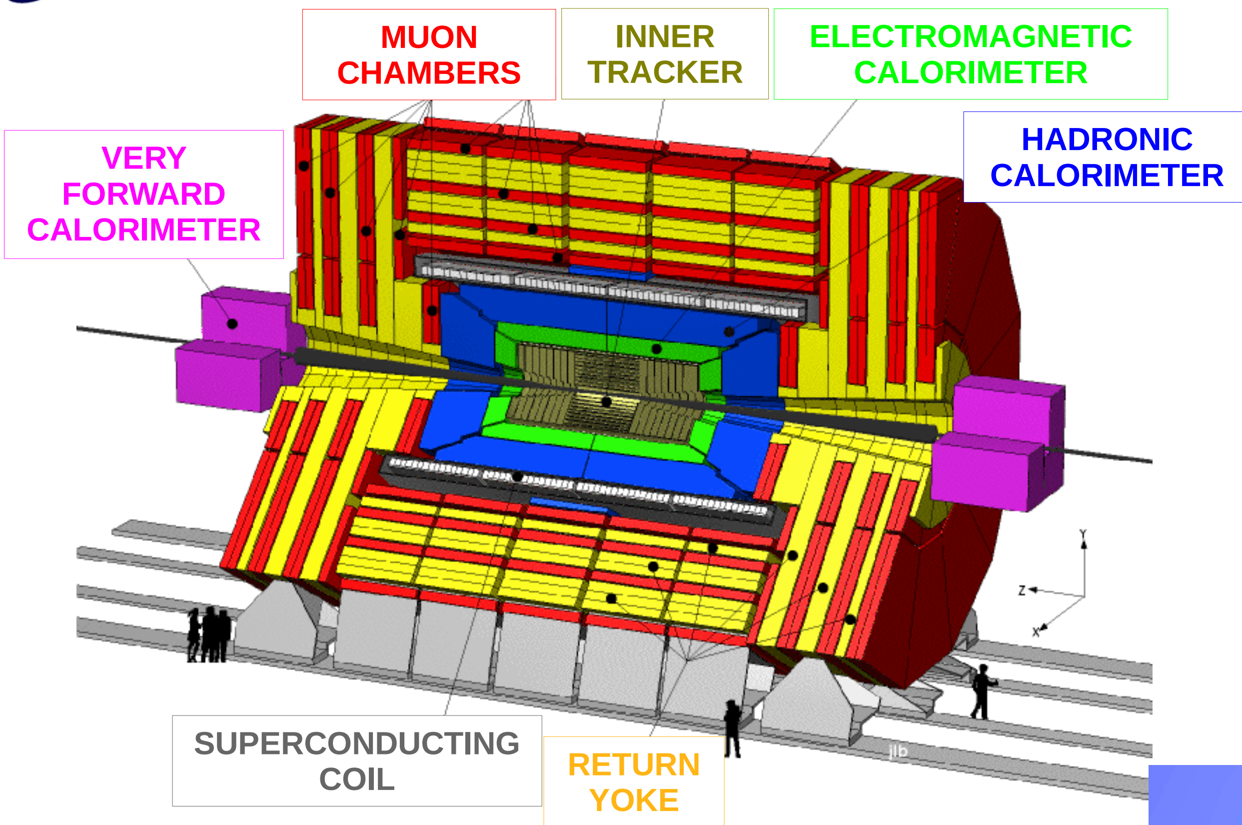
    $114\ \mathrm{GeV}/c^2 < m_H < O(1\ \mathrm{TeV}/c^2)$
  - either confirm or rule out its existence
- A “needle in a haystack”
  - Total inelastic cross section

    $\sigma_{tot} \sim 100$ mb
  - Higgs production cross section

    $\sigma_H \sim 1\text{-}100$ pb (depending on mass, $\sqrt{s}$)
- Need for a clear signature
  - high trigger efficiency
  - strong background rejection



The Compact Muon Solenoid

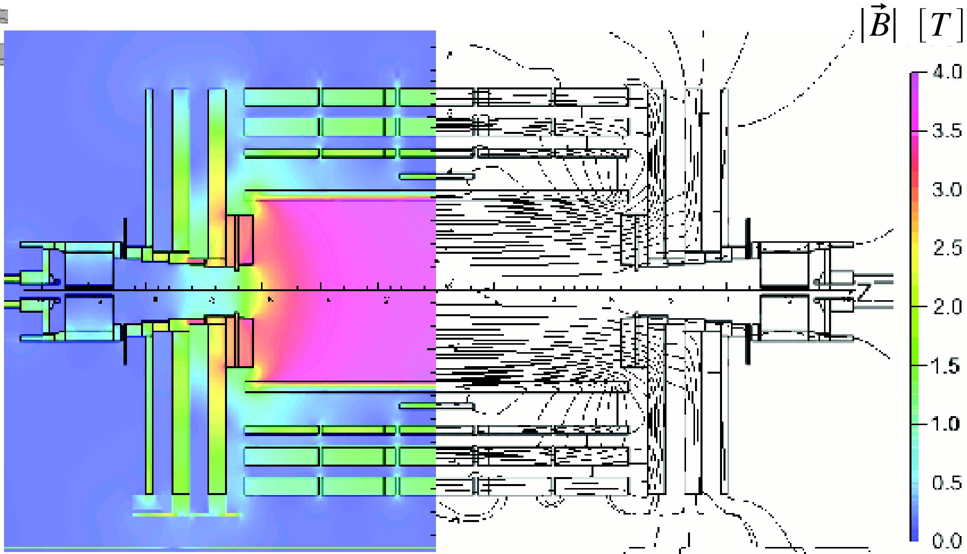


Inside the Solenoid

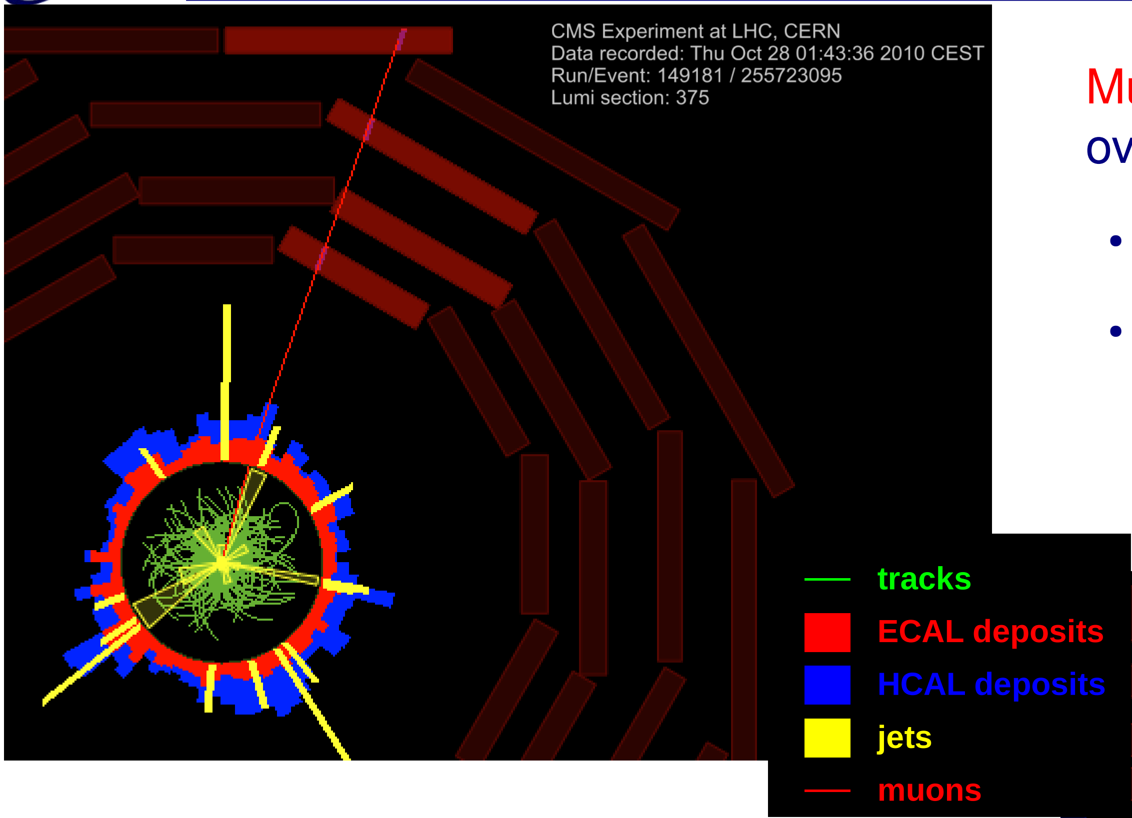
- 3.8 T magnetic field
- longitudinal, ~homogeneous
- tracker, ECAL, HCAL

Outside the Solenoid

- ~1.8 T return field, mostly in the Iron Yoke
- muon spectrometer



Why Muons?

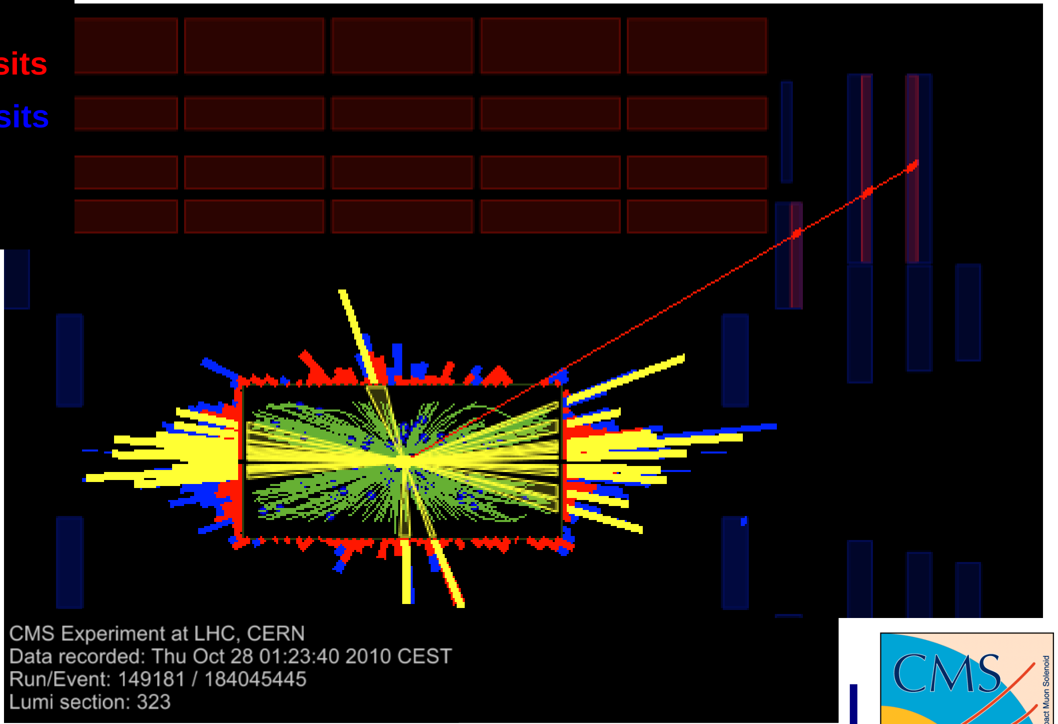


Muons provide the cleanest signal over the hadronic background

- little interaction with detector material
- the only charged particles that reach the outermost subdetectors

"Golden channel" for the Higgs boson discovery at the LHC

$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$



But, Before...

$H \rightarrow ZZ^{(*)} \rightarrow 4\mu$

But, Before...

Muon Reconstruction

$H \to ZZ^{(*)} \to 4\mu$

But, Before...

Muon Reconstruction

Muon Momentum Calibration

$H \to ZZ^{(*)} \to 4\mu$

Outline

Muon Reconstruction

- Algorithms
- Local, Stand-Alone, Global Reconstruction
- Developments in Stand-Alone
- Performance with 2010 CMS Data

Muon Momentum Calibration

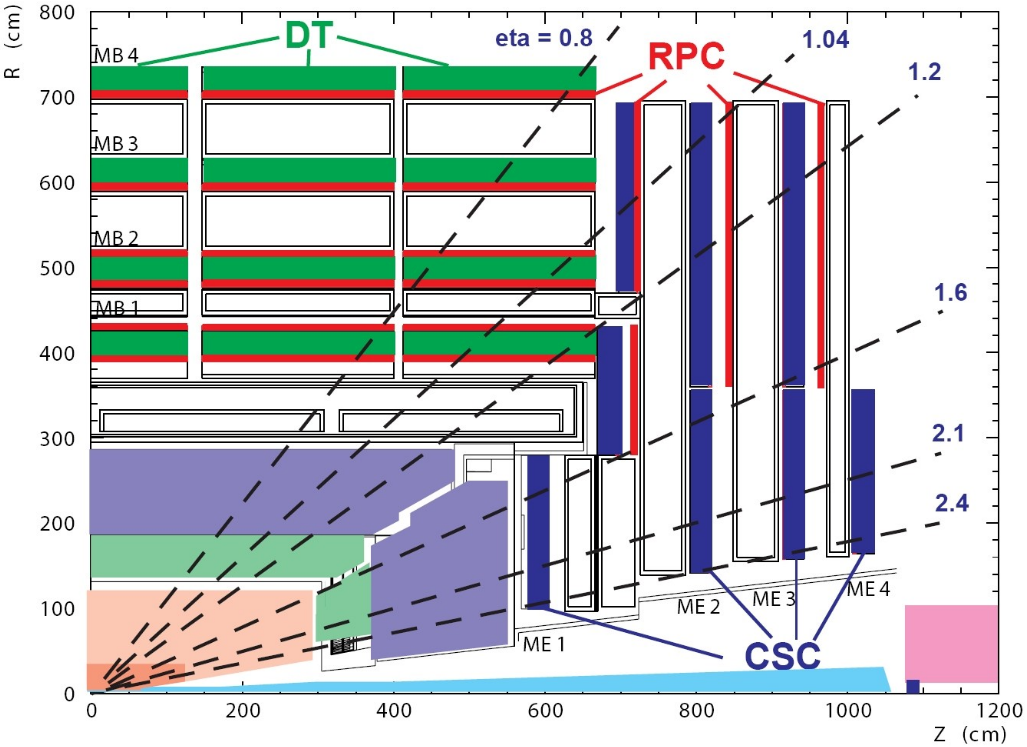
- The `MuScleFit` Algorithm
- Low Momentum Muons: J/ψ
- Medium/High Momentum Muons: Z

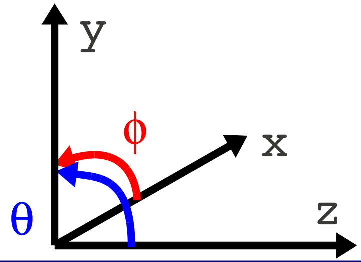
$H \to ZZ^{(*)} \to 4\mu$

- Signal and Backgrounds
- Selection
- Results on Simulation at 1 fb^{-1}
- Results on 2010 CMS Data

Muon Reconstruction

Detectors for Muon Reconstruction





$$\eta = -\ln\tan\frac{\theta}{2}$$

Detectors for Muon Reconstruction

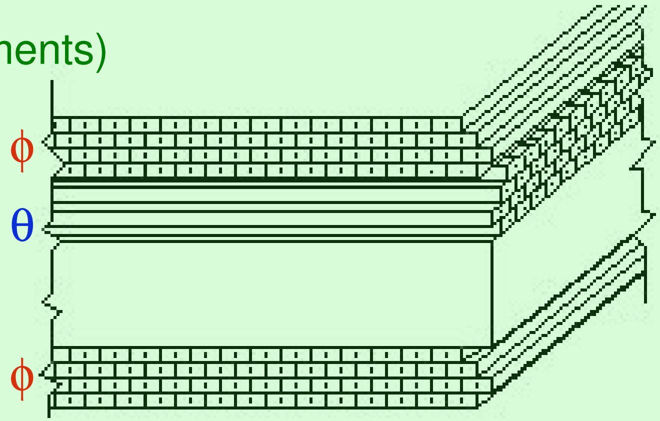
250 Drift Tube Chambers (DT)

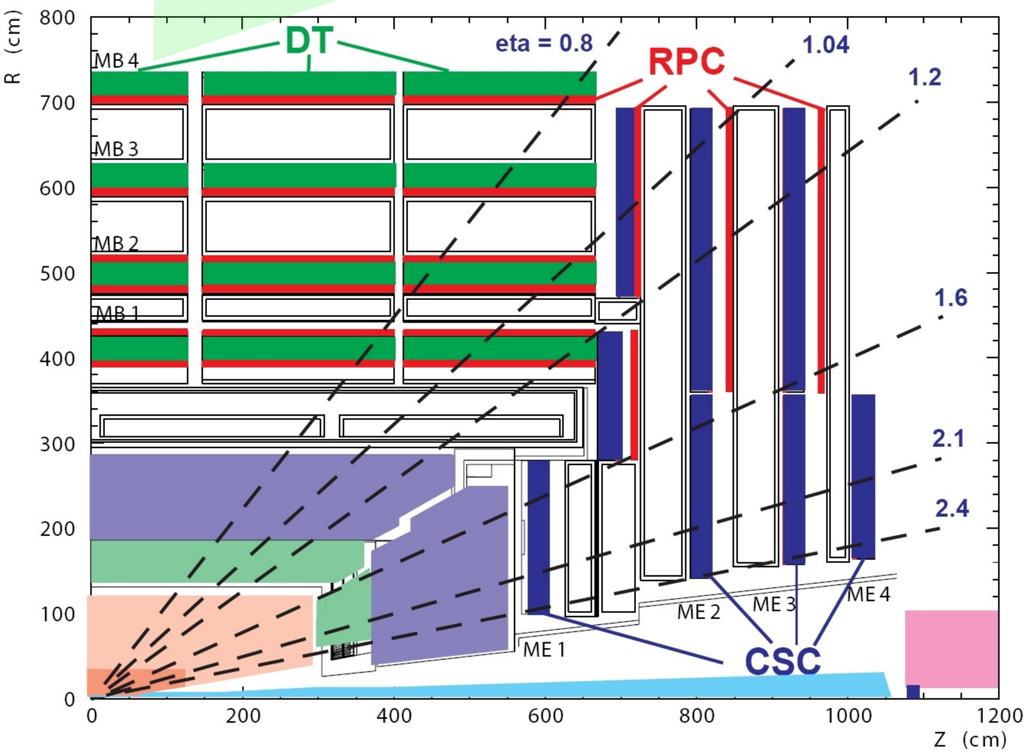
(1D hits, 3D segments)

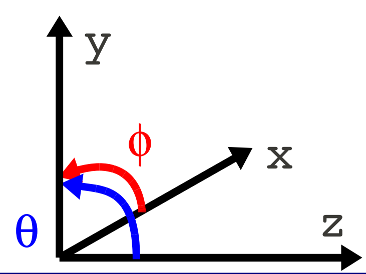
- 4 stations

Spatial resolution
(segments)

~70 µm (in ϕ)







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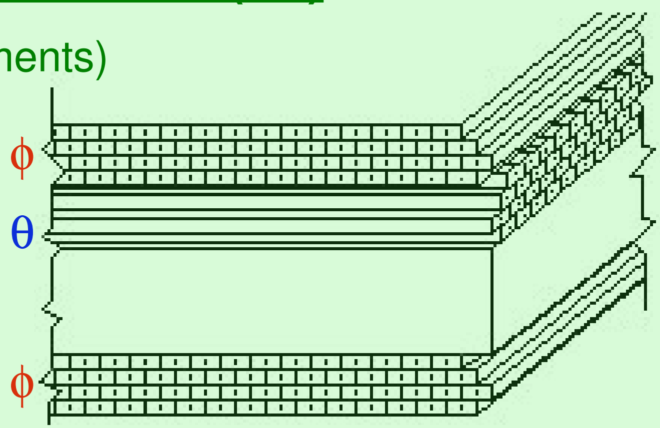
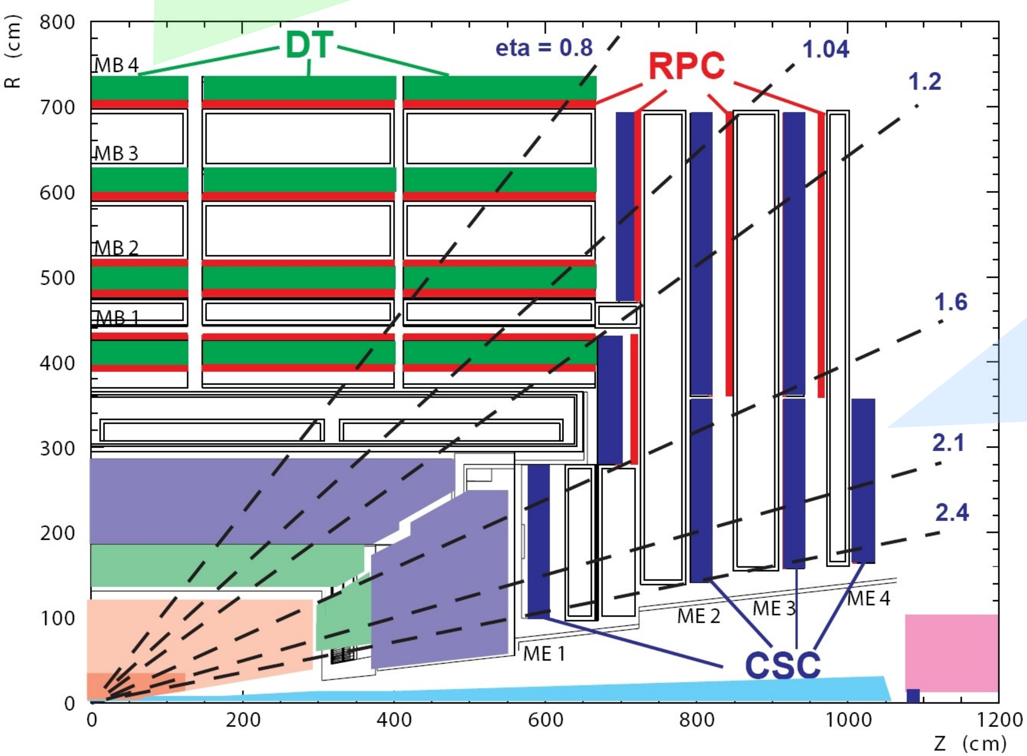




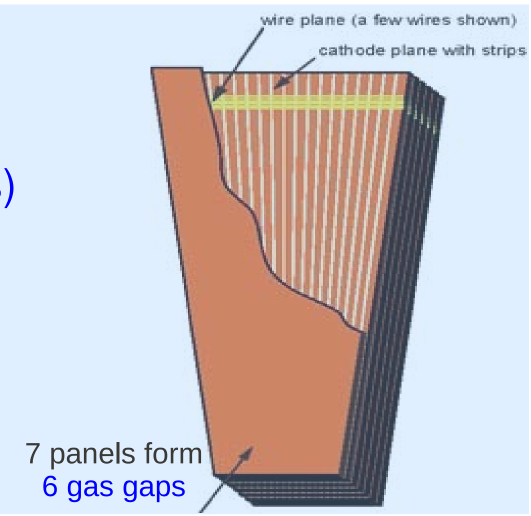
540 Cathode Strip Chambers (CSC)

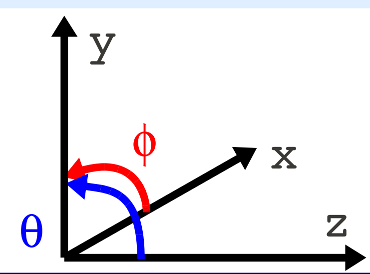
(2D hits, 3D segments)

- 4 stations

Spatial resolution
(segments)

50-250 µm





$$\eta = -\ln \tan \frac{\theta}{2}$$

Detectors for Muon Reconstruction

250 Drift Tube Chambers (DT)

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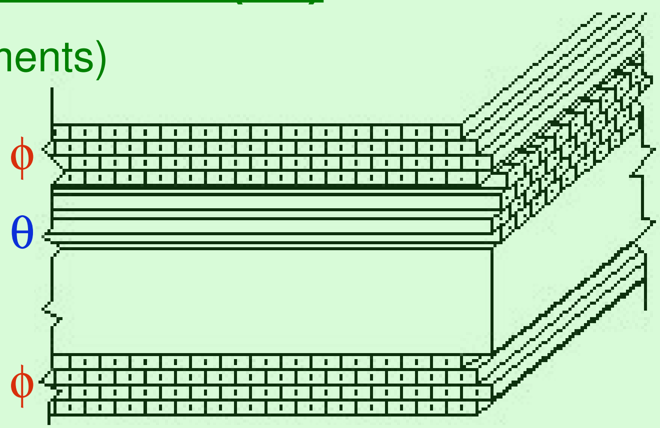
Spatial resolution
(segments)

~70 µm (in ϕ)



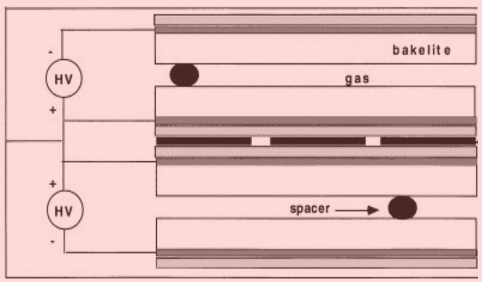
Resistive Plate Chambers (RPC)

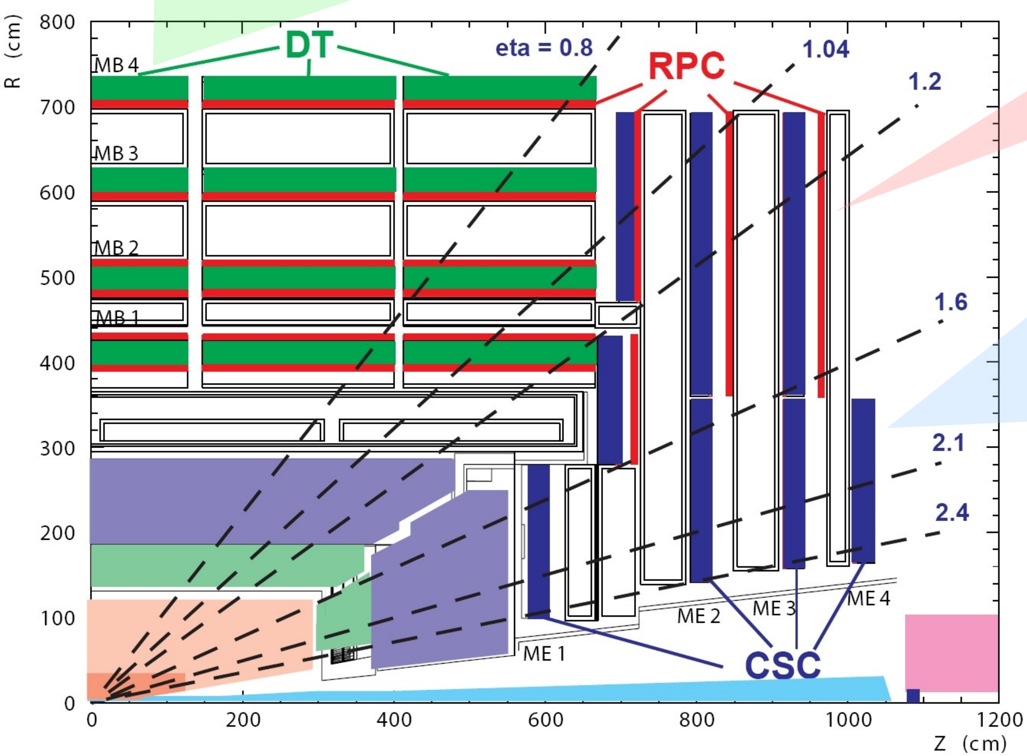
(1D hits, fast response < 10 ns)

- 6 stations (barr.)
- 3 stations (endc.)

Spatial resolution

~1 cm (only ϕ)





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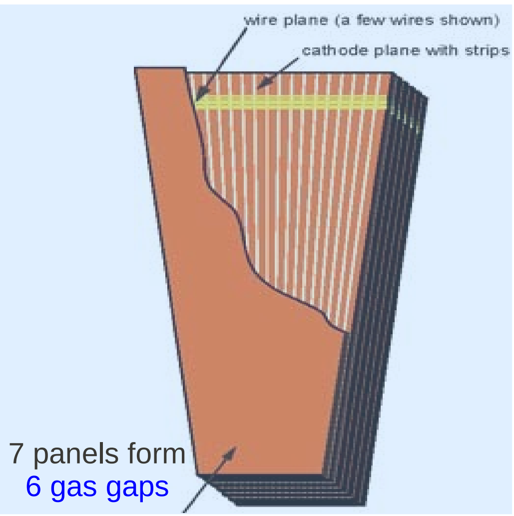
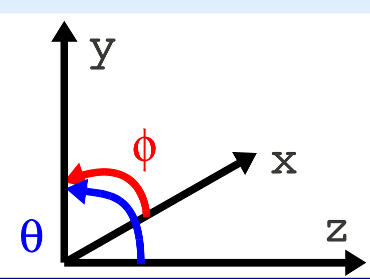


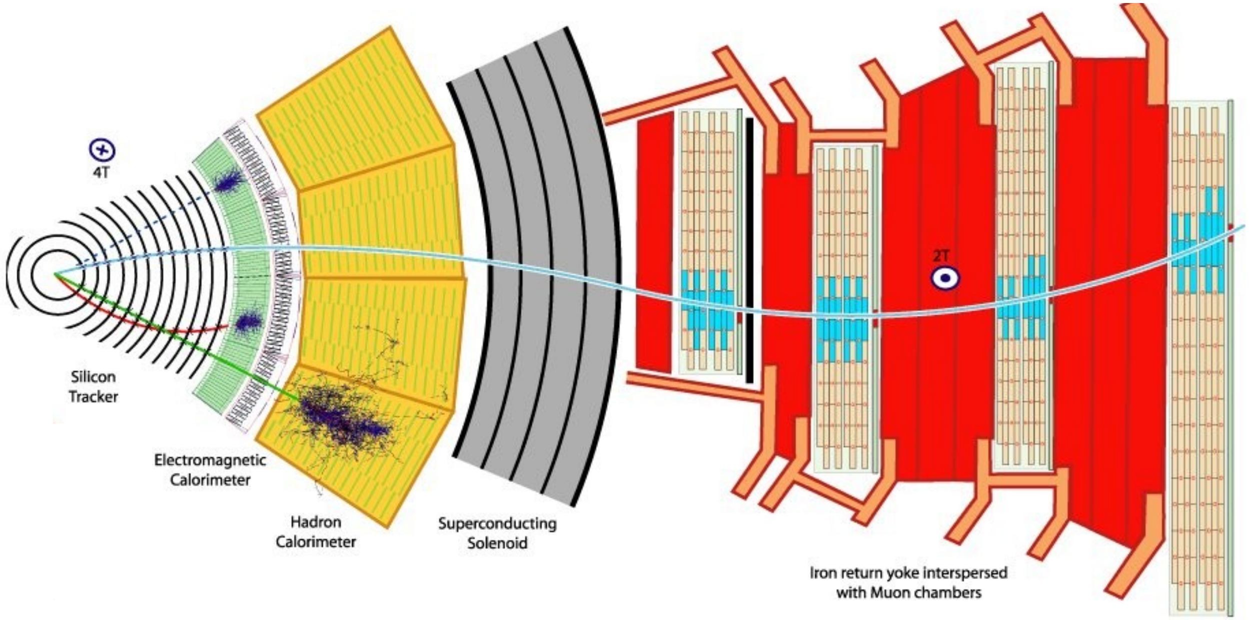


$$\eta = -\ln \tan \frac{\theta}{2}$$

Reconstruction of Muon Tracks

Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → Global Reconstruction

Kalman filter (Forward + Backward)



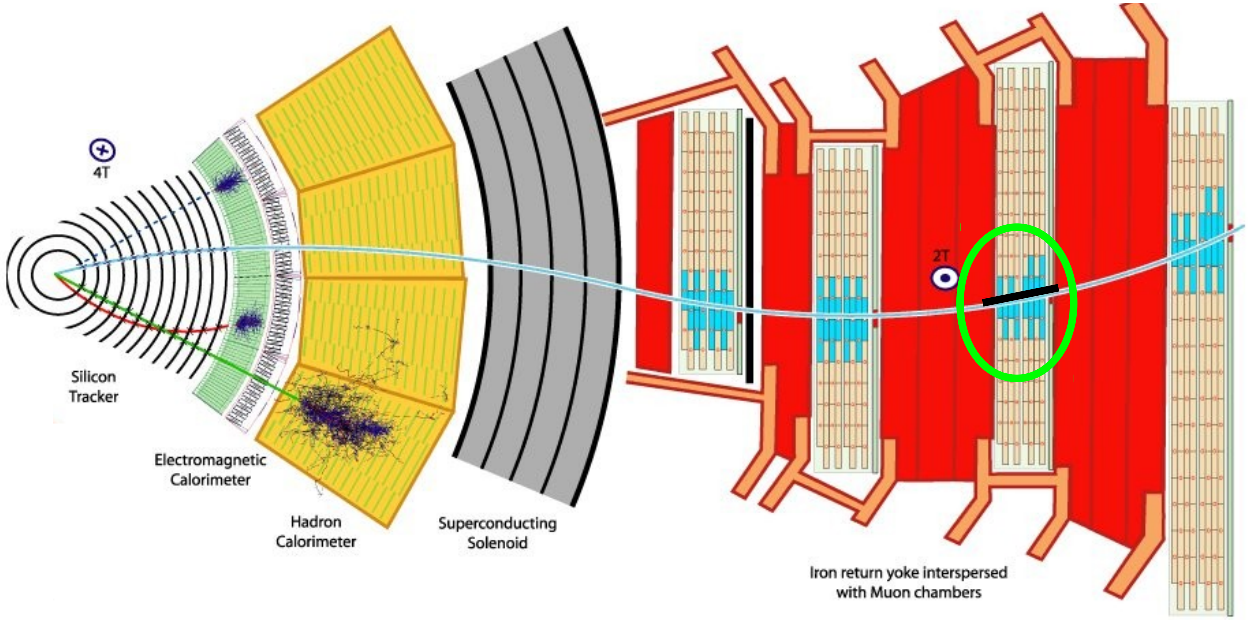
Reconstruction of Muon Tracks

Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → Global Reconstruction

Kalman filter

1. Local Reconstruction

Reconstruction of **hits and track segments** inside a **chamber**



Reconstruction of Muon Tracks

Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → Global Reconstruction

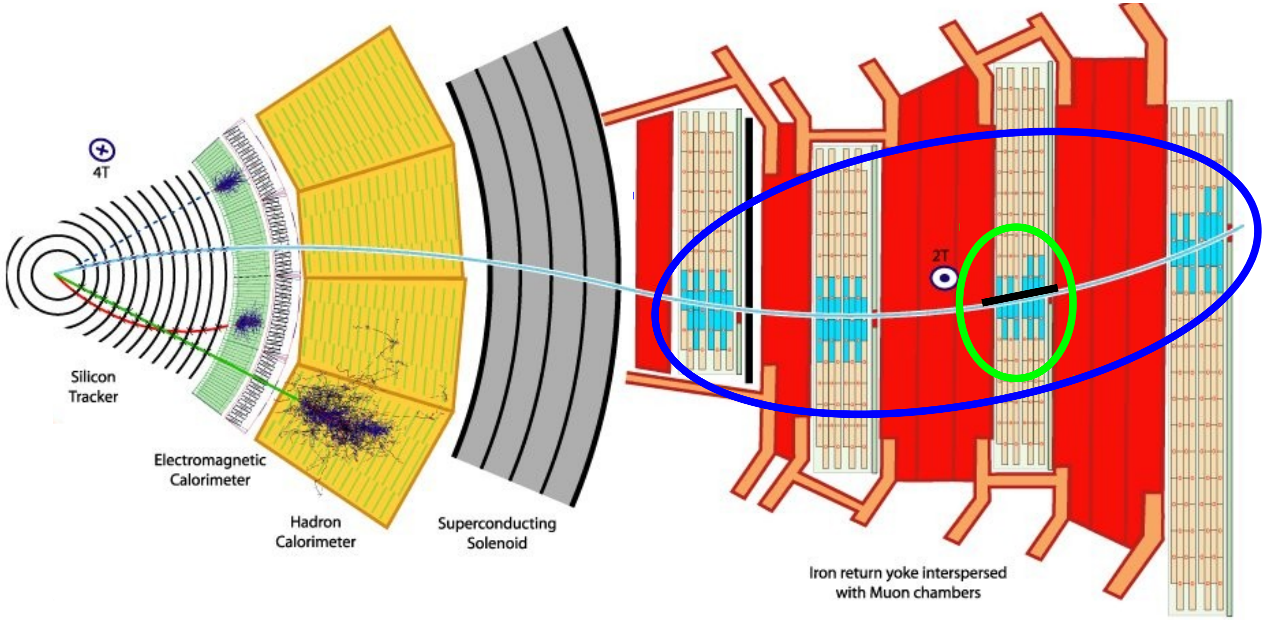
Kalman filter (Forward + Backward)

1. Local Reconstruction

Reconstruction of **hits** and **track segments** inside a **chamber**

2. Stand-alone Reconstruction (Level-2)

Reconstruction of the **track** inside the **muon system**



Reconstruction of Muon Tracks

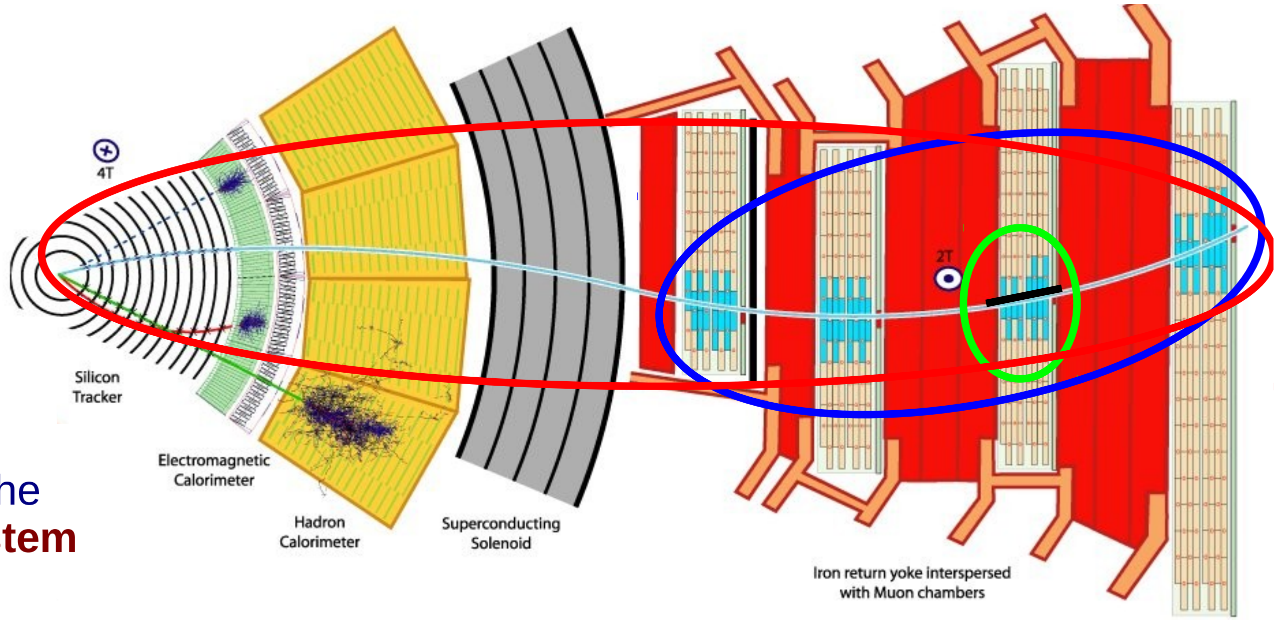
Local Reconstruction → Initial State (seed) → Forward (inside-out) → Backward (outside-in) → Ghost suppression → Beam spot constraint → **Global Reconstruction**

Kalman filter

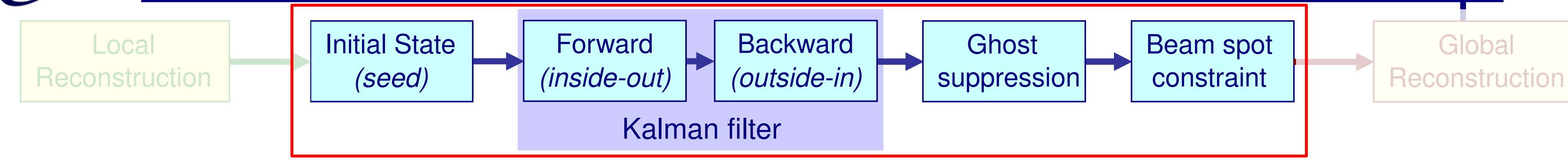
1. Local Reconstruction
Reconstruction of **hits** and **track segments** inside a **chamber**

2. Stand-alone Reconstruction (Level-2)
Reconstruction of the **track** inside the **muon system**

3. Global Reconstruction (Level-3)
Reconstruction of the **track** combining the information from **tracker** and **muon system**



Reconstruction of Muon Tracks



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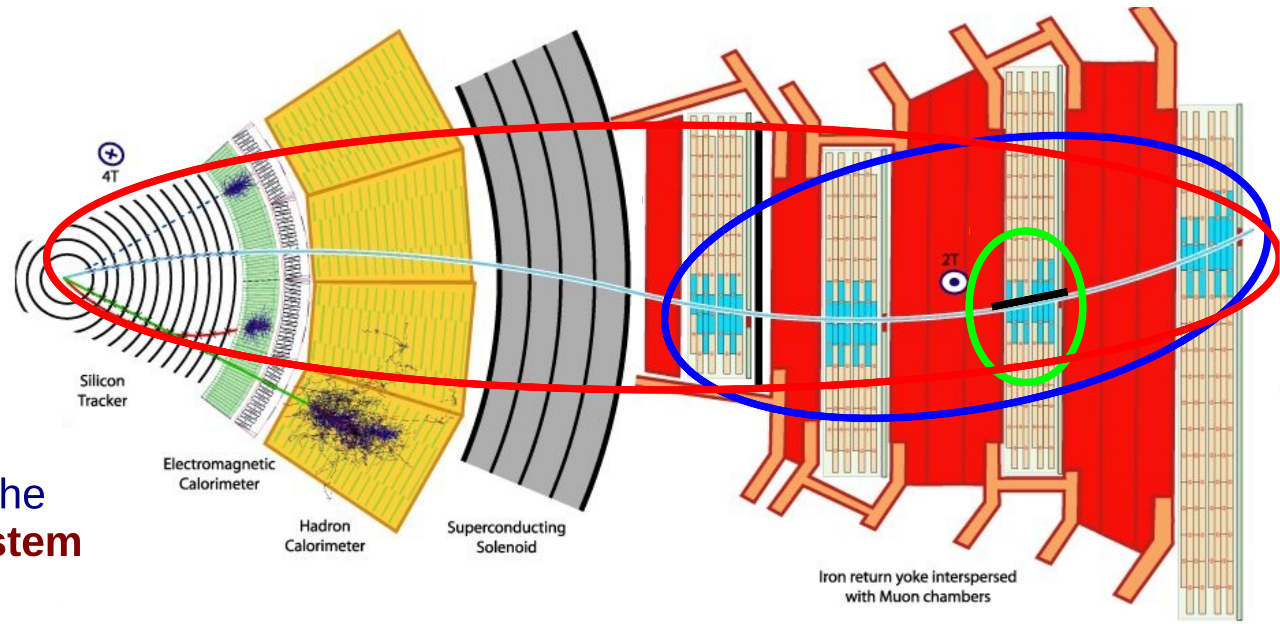


- I worked in particular on the development of stand-alone muon reconstruction

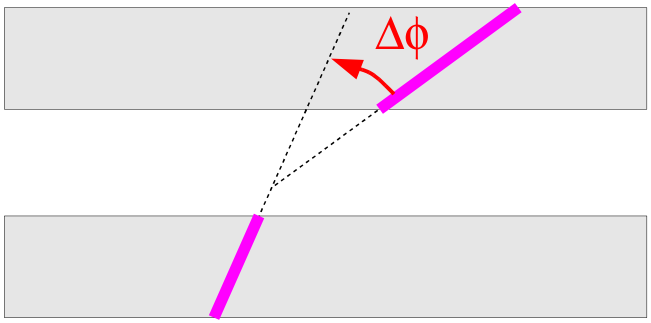
  ➔ *responsible in CMS since 2010*

- The following description will be focused on it

Stand-Alone Reconstruction
Seed

Local Reconstruction → **Initial State *(seed)*** → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → Global Reconstruction

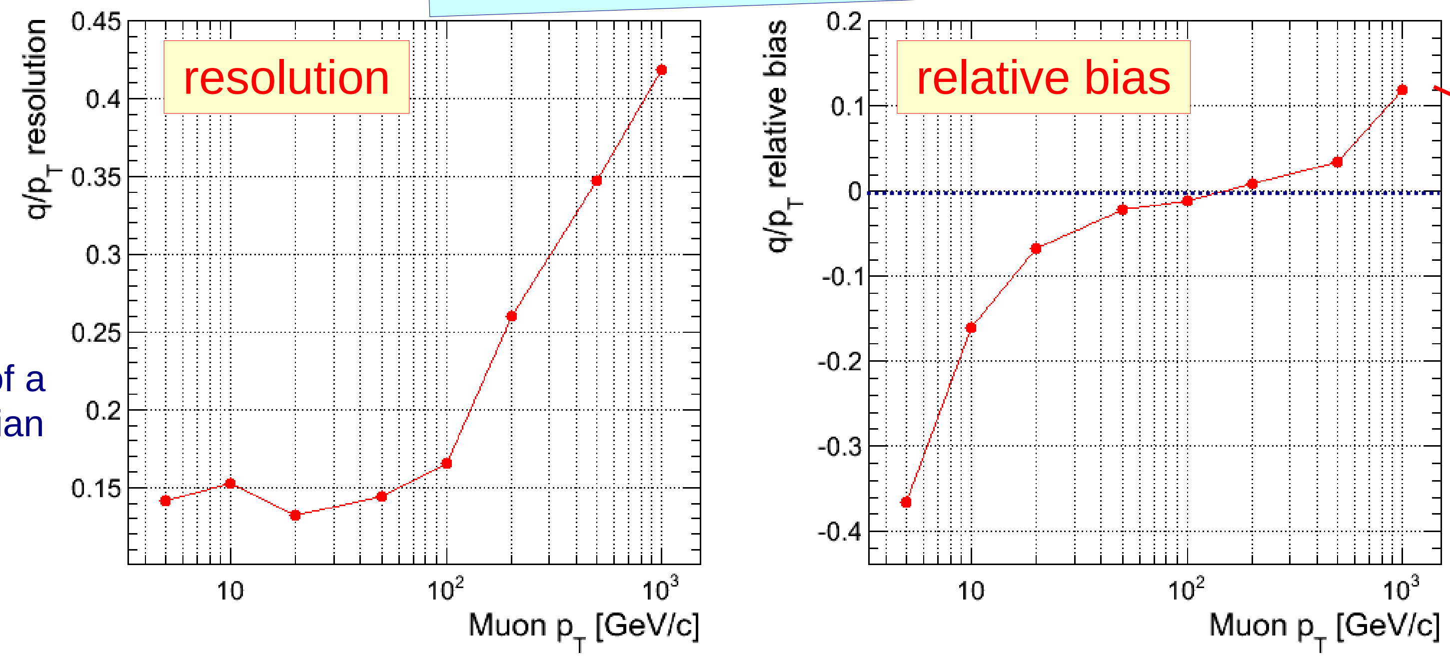
Kalman filter



Built using one or more track segments in DT and CSC

p_T parametrized as a function of ϕ slope of segments: $p_T = A - B/\Delta\phi$

Simulated muons with design geometry



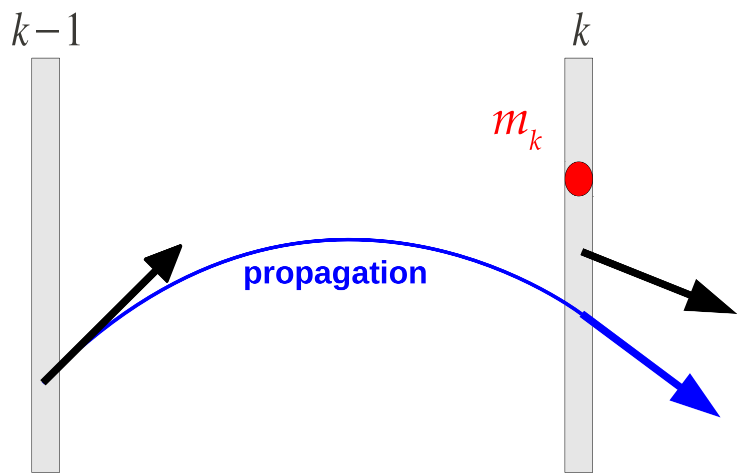
σ of the core of a double Gaussian

mean of the core of a double Gaussian

Stand-Alone Reconstruction
Kalman Filter

Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → Global Reconstruction

Kalman filter



Iterative method:

- starts from the intial seed state
- the seed state is propagated to the next layer
- on this layer, the *most compatible* measurement is found (on a χ^2 basis) and used to update the track parameters
- starting from the new state, the procedure is repeated on each reachable layer

Forward filter

- starts from the seed state
- removes *biases* from the seed

Backward filter

- starts from the last state of the Forward filter (outermost)
- less affected by seed biases

Stand-Alone Reconstruction
Ghost Suppression and Beam Spot Constraint

Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → Global Reconstruction

Kalman filter

- The ghost suppression or *cleaning* removes possible duplicates of the same track (coming from multiple seeds for the same muon)

➔ *if two tracks share any hit, only the higher-quality track is kept, based on number of hits, χ^2/d.o.f. and p_T*

- The track is extrapolated to the *point of closest approach* to the *beam line*

  The *beam spot* is constrained to be a point of the track, to improve the p_T resolution (up to 40%)

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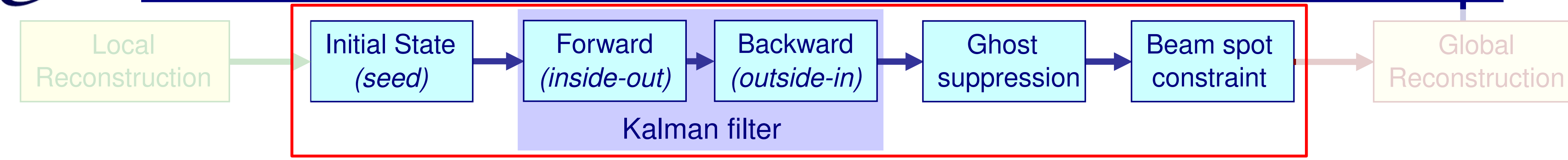
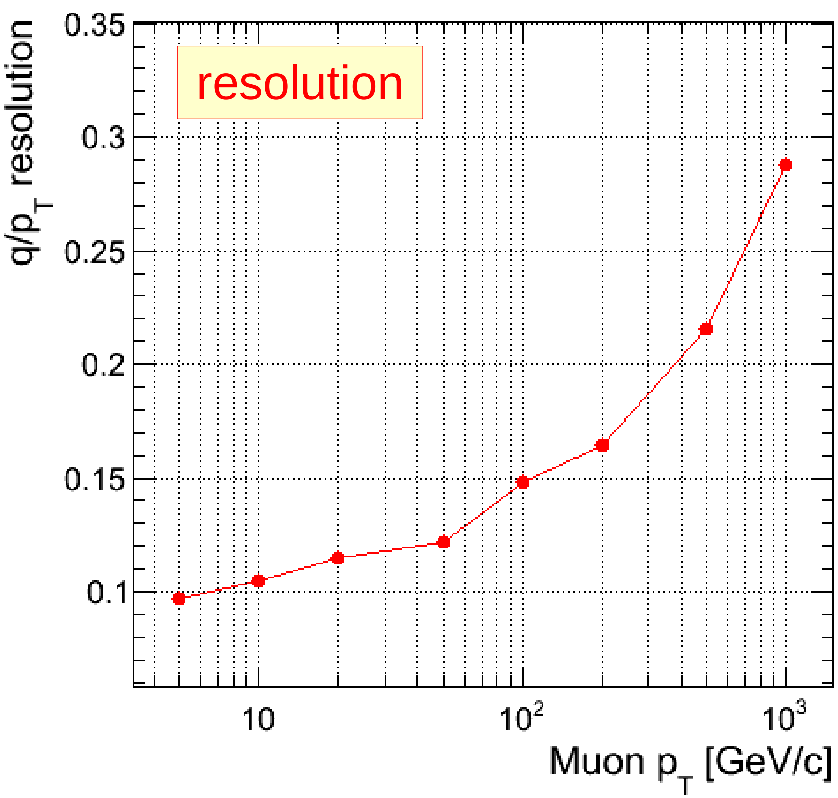
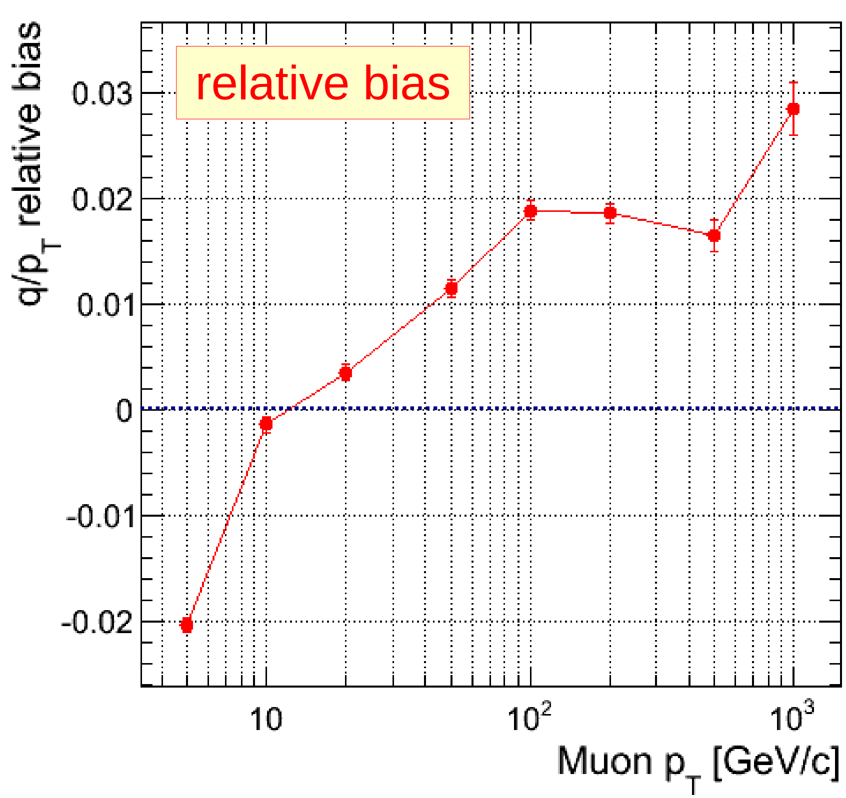
Stand-Alone Reconstruction

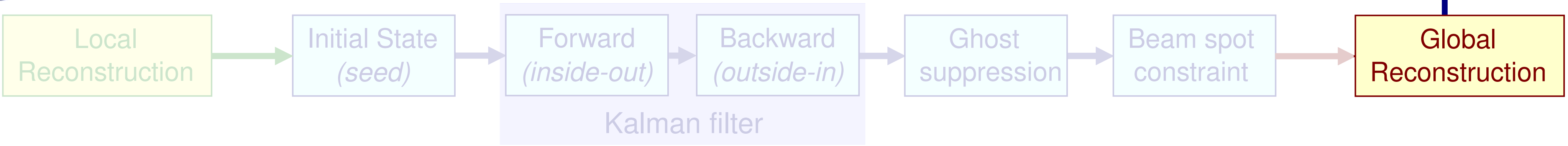


Simulated muons with design geometry





Global Reconstruction



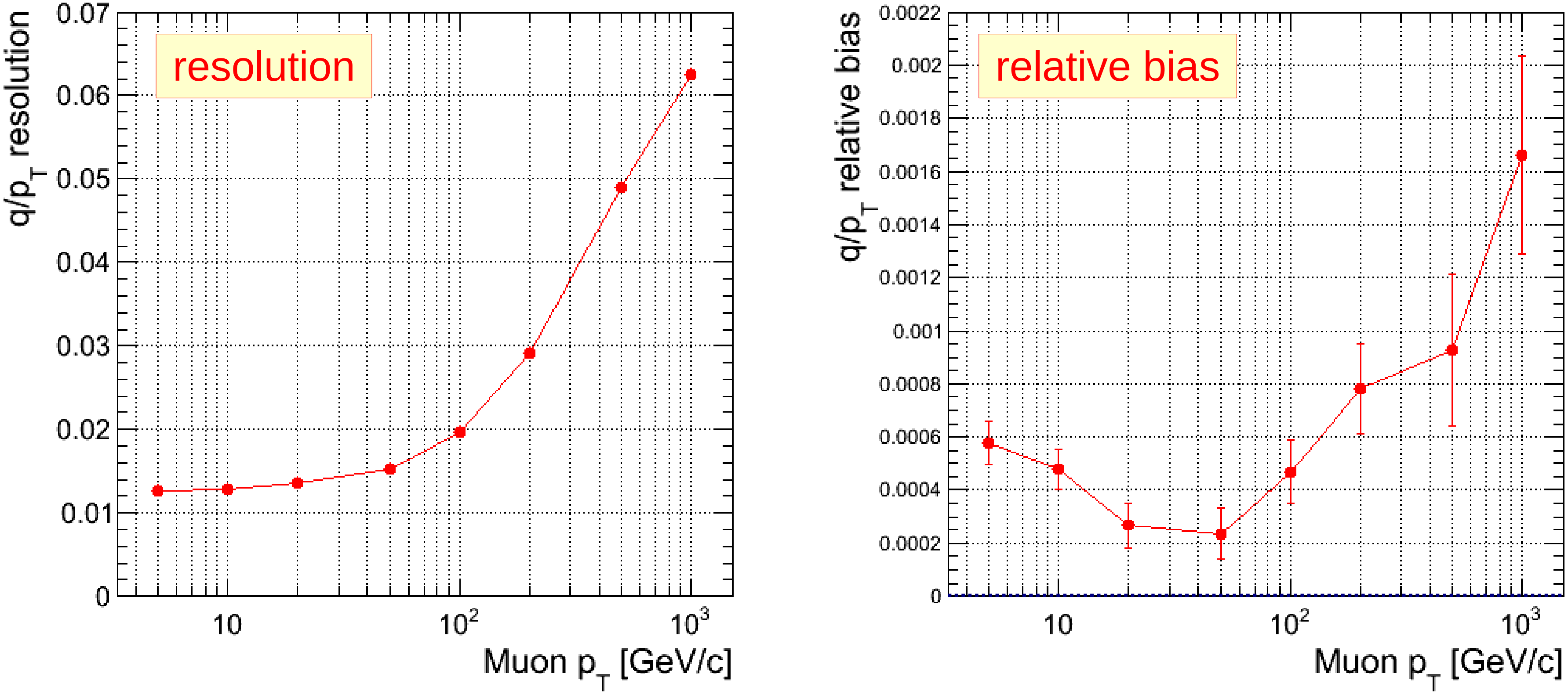
- The stand-alone track defines a *region of interest* (ROI) in the tracker
- compatible tracker tracks are chosen in the ROI
- for each compatible track, the stand-alone–tracker track pair is refitted, using the whole set of hits (tracker + muon)
- ghost suppression is applied

Global Reconstruction

Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → **Global Reconstruction**

Kalman filter

Simulated muons with design geometry



Development of Stand-Alone Reconstruction

I have taken care of the stand-alone reconstruction software and coordinated the works for its development (I was appointed as *responsible* in 2010)

- *monitoring of reconstruction performance*
  - in data and simulation
- *maintenance and update of the software, following new specific requirements*
  - in particular, driven by the data taking
- *dedicated studies for the improvement of the algorithms, e.g.*
  - optimisation of track fitting and pattern recognition
  - optimisation of criteria for ghost suppression, both in *off-line* and *on-line* (trigger) reconstruction

One Example...

In the Kalman filter, the selection of measurements for the fit is crucial to balance between *track quality* and *reconstruction efficiency*

- I introduced new criteria for the *selection of hits* and *rejection of outliers*
  ➔ improve the measurement resolution *without* losing efficiency!

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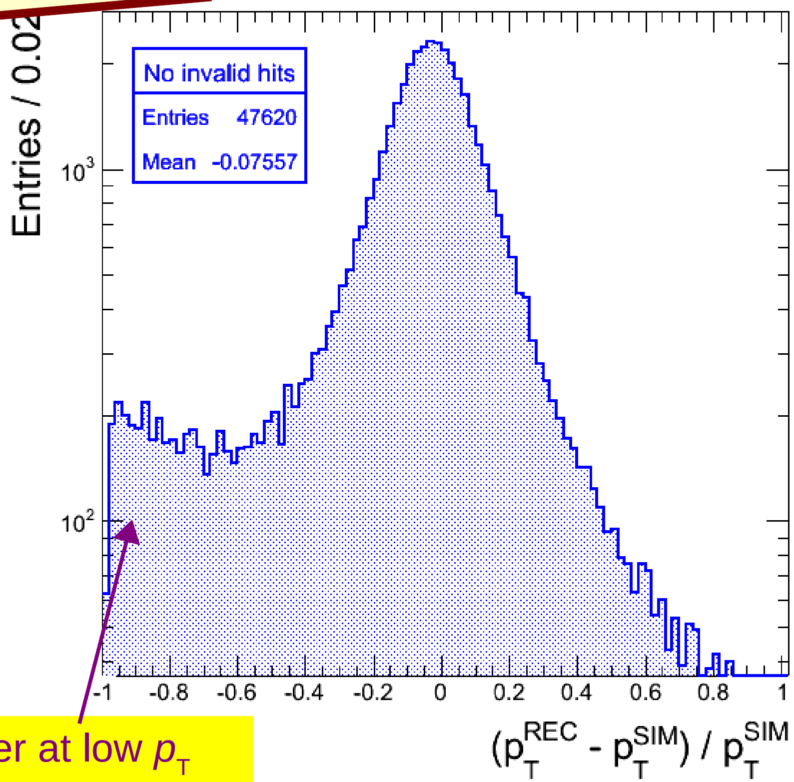
Stand-alone muons
$p_T^{REC} / p_T^{SIM} - 1$

Simulated muons with p_T = 100 GeV/c



Shoulder at low p_T
(bremsstrahlung, δ-rays)

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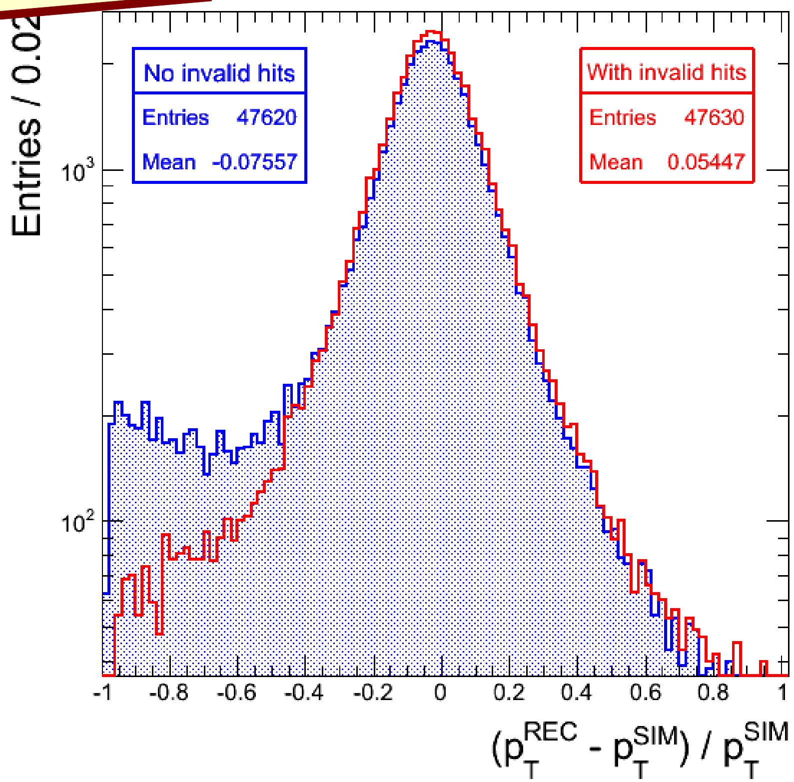

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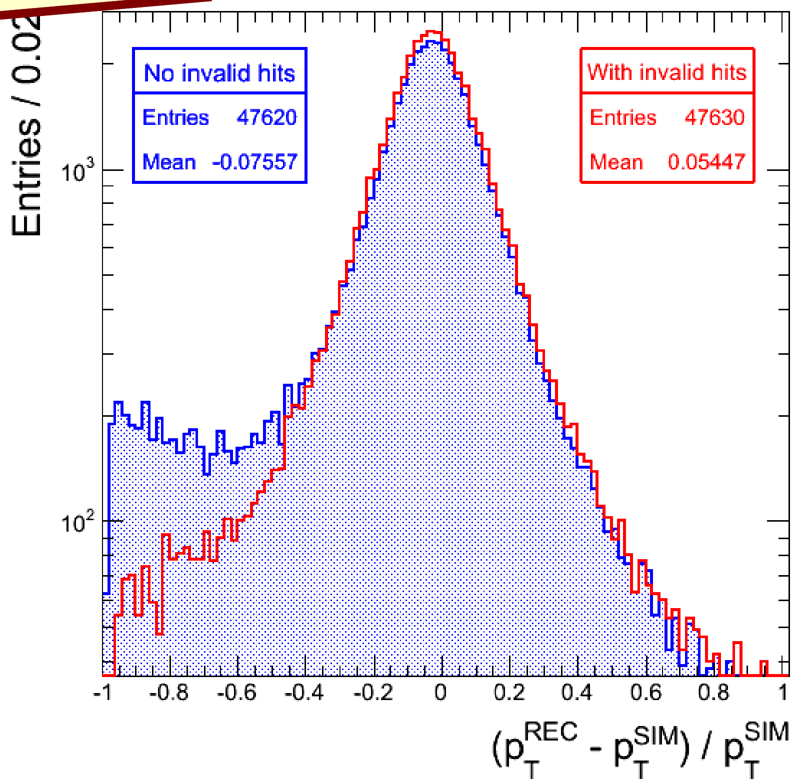
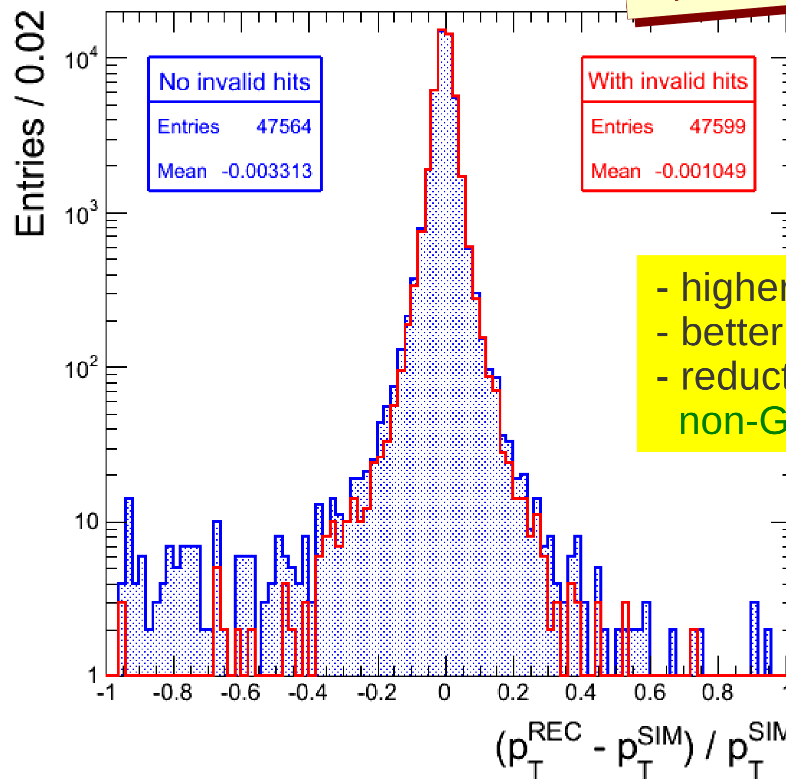


Global muons
$p_T^{REC} / p_T^{SIM} - 1$



- higher efficiency
- better resolution
- reduction of non-Gaussian tails

Performance of Muon Reconstruction with 2010 CMS Data

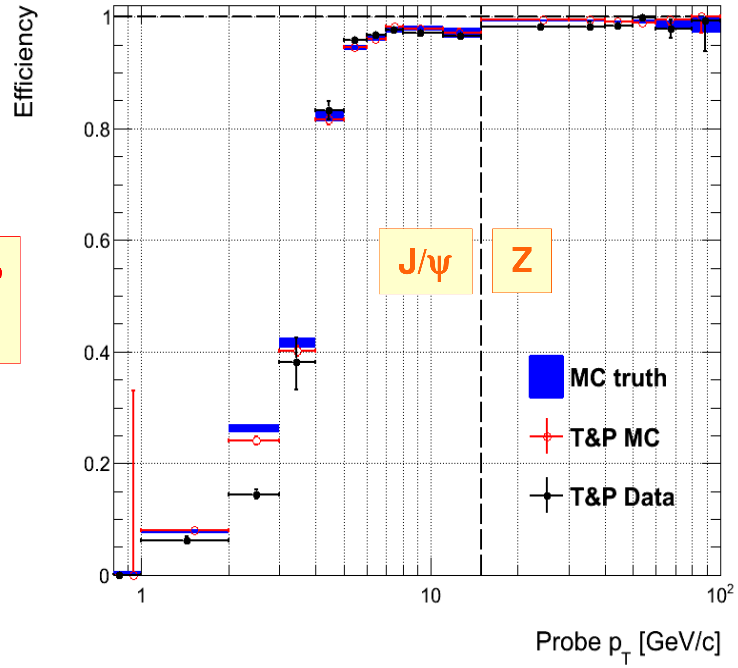
- I used samples of 2010 CMS data to test the performance of muon reconstruction
- To compare data and simulations, muons were selected with the same criteria and quality requirements
- Efficiency was determined with the *tag-and-probe* technique, using di-muons from
  - Z boson candidates
  - J/ψ meson candidates (for low momentum: $p_T < 15$ GeV/c)
- Track properties are tested on muons from $Z \to \mu^+\mu^-$ candidate samples
- Resolutions of stand-alone tracks are estimated w.r.t. tracker tracks

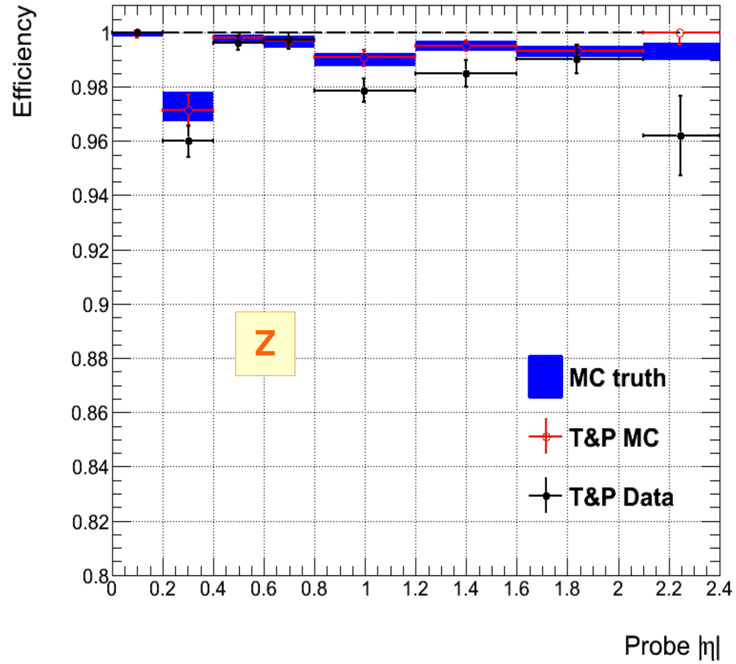
$$\begin{cases} q/p_T \text{ resolution} = \dfrac{(q/p_T)_{STA} - (q/p_T)_{TRK}}{(q/p_T)_{TRK}} \\ \eta \text{ resolution} = \eta_{STA} - \eta_{TRK} \\ \phi \text{ resolution} = \phi_{STA} - \phi_{TRK} \end{cases}$$

Resolution of tracker tracks is about *one order of magnitude* better than that of stand-alone tracks

Muon Reconstruction in 2010 CMS Data Efficiency

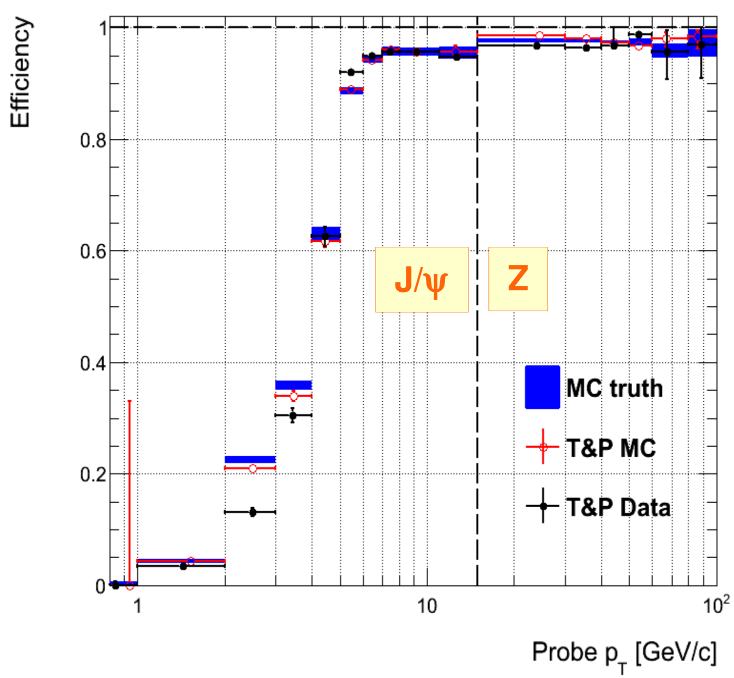
Stand-alone muons

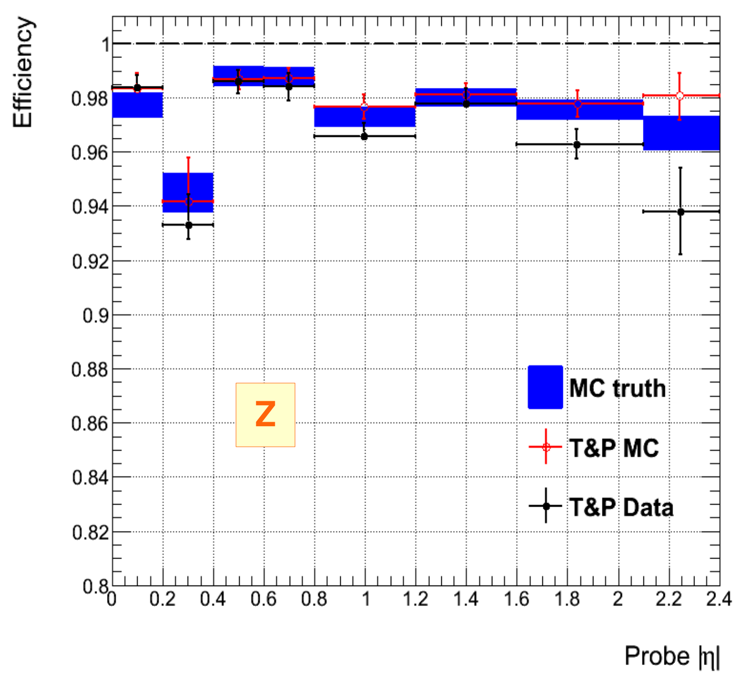




Global muons

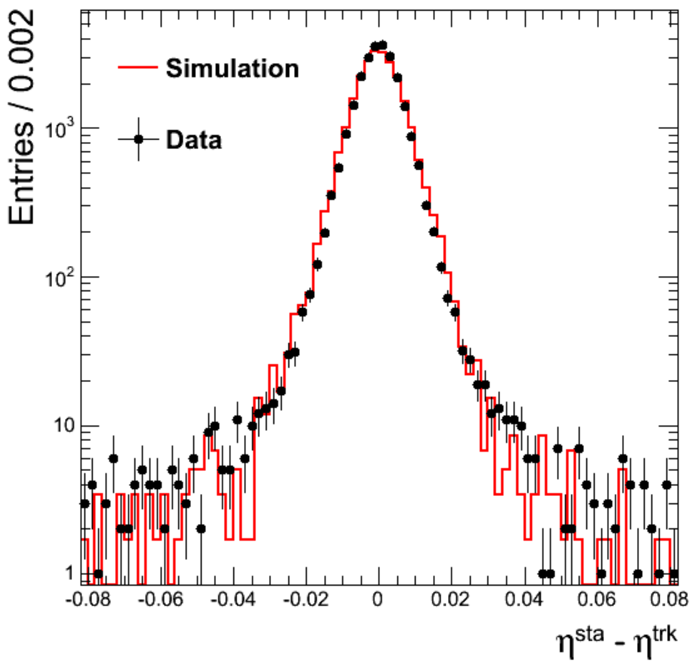
including some quality cuts



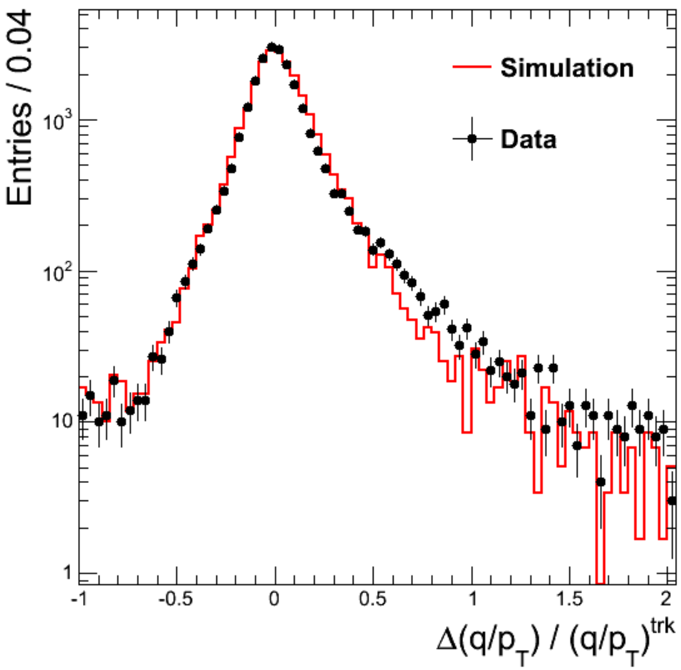


Muon Reconstruction in 2010 CMS Data
Resolutions of Stand-Alone Tracks

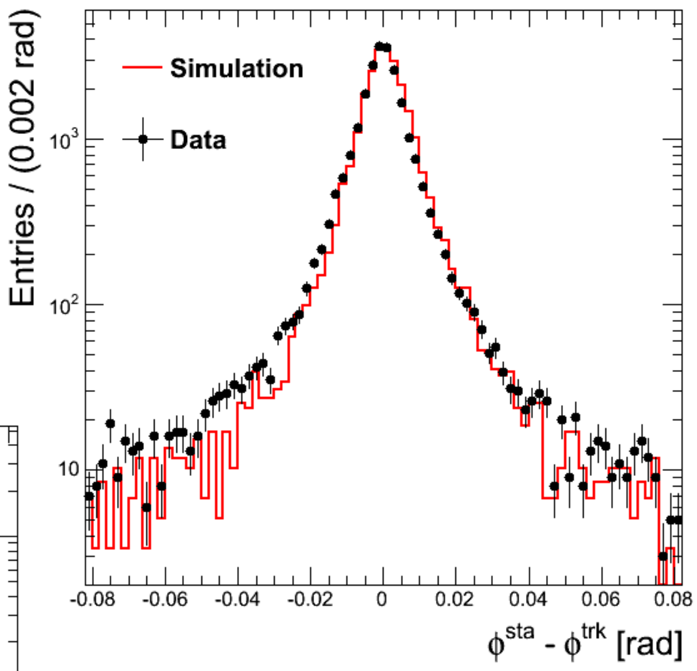
η resolution



q/p_T resolution



ϕ resolution

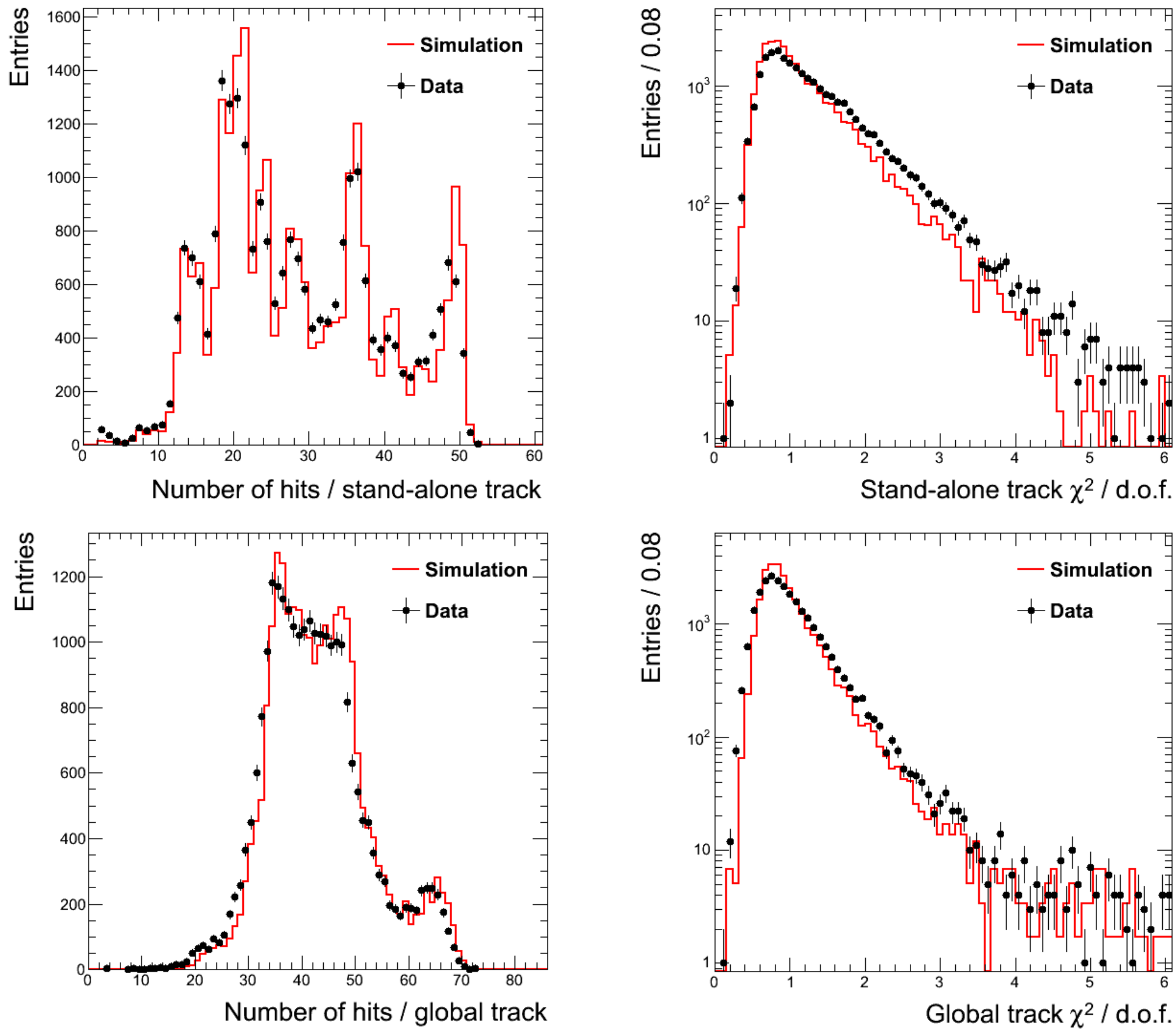


Muon Reconstruction in 2010 CMS Data

Number of Hits χ^2

Stand-alone muons

Global muons



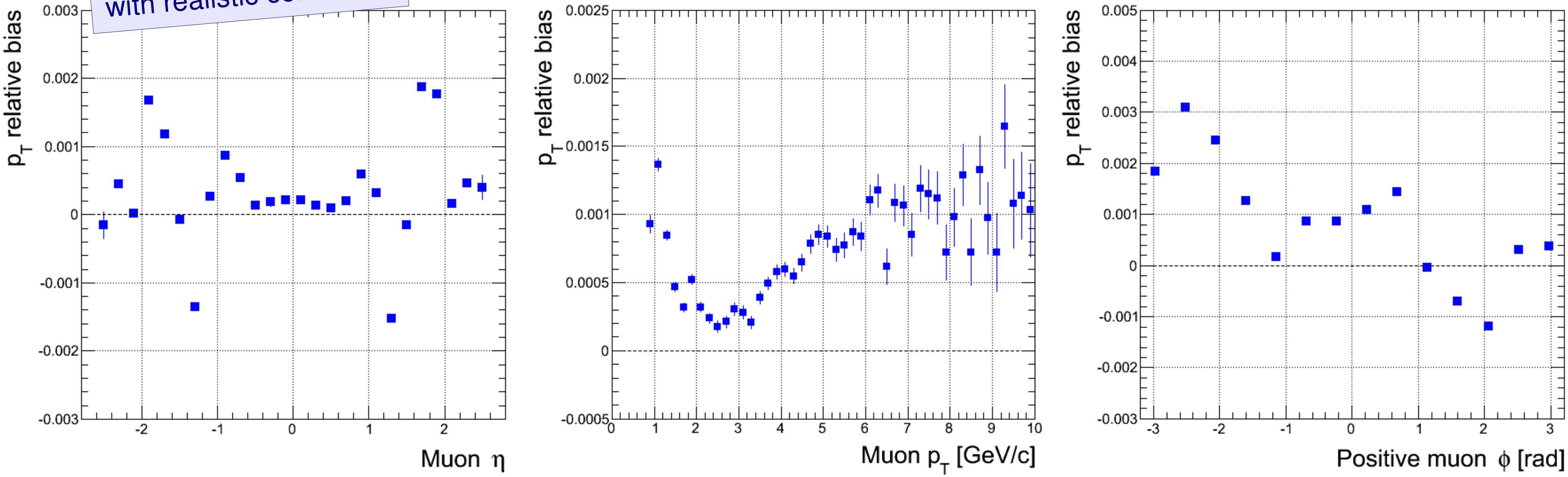
Muon Momentum Scale and Resolution Studies

Muon Momentum Scale

- After the reconstruction, the measurement of muon momentum can be affected by *biases*, coming from several sources: reconstruction algorithm, limited knowledge of the detector (material budget, alignment), magnetic field

muons from simulated $J/\psi \rightarrow \mu\mu$ with realistic conditions

p_T relative bias = mean of the distribution $\dfrac{p_T^{REC} - p_T^{SIM}}{p_T^{SIM}}$ → fit with a Gaussian

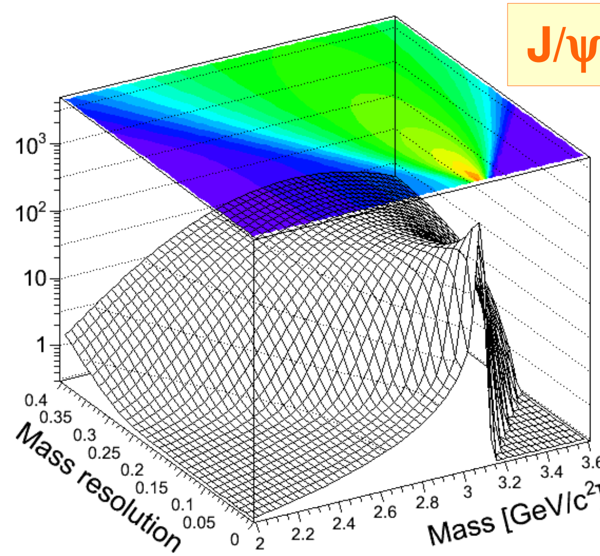


➔ Need to correct these biases and measure the momentum resolution

The MuScleFit Algorithm

MuScleFit: algorithm for muon momentum scale calibration, using muons from well known resonances (J/ψ, ϒ, Z) and a multivariate likelihood

→ corrects the momentum of muons, in order to "force" the mass of the resonance to its expected value



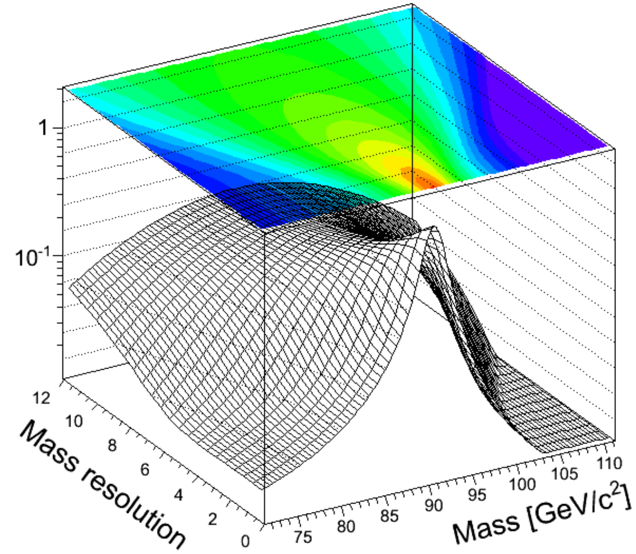
- For a given resonance, construct a model for mass profile:

$$P(m,\sigma) = \int L(m';\, M_{0,}\Gamma) \times Gauss(m-m';\, \mu=0, \sigma)\, dm'$$

- find *ansatz function* for scale and resolution:

$$p_T^{corr} = f(x_i,\, a_j) \cdot p_T\;, \qquad \sigma(x_i) = g_i(x_k,\, b_j) \cdot p_T$$

where $x_i = p_T,\ \mathrm{cotg}\theta,\ \phi$ and a_j, b_j are free parameters



- from data, compute likelihood:

$$-\ln L = -\sum_{events} \ln P(m(x_i^{(1)},\, x_j^{(2)}),\, \sigma(x_i^{(1)},\, x_j^{(2)}))$$

- minimizing $-\ln L$, one obtains scale correction f and resolution functions g_i

My work in the MuScleFit group

- Find suitable ansatz functions for scale correction and resolution in data, using muons from different resonances (J/ψ, Z) – i.e. different p_T scales

  ➔ find dependencies of scale and resolution on *muon kinematics*

  ➔ find the best fit strategy

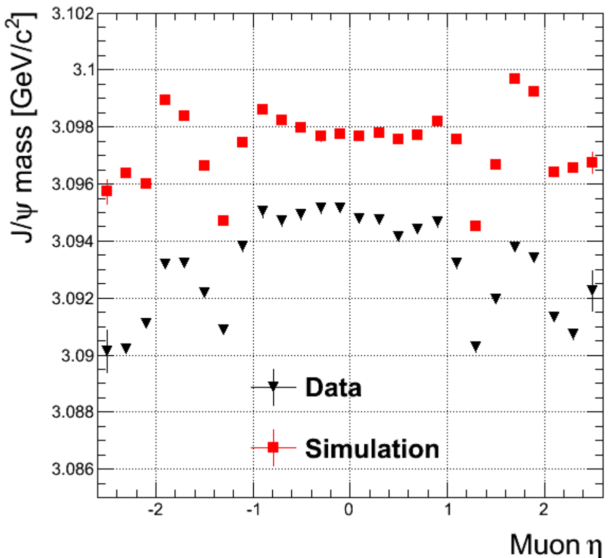
- Provide analysis groups (e.g. J/ψ, ϒ) with
  - momentum scale corrections
  - systematics from momentum scale and resolution

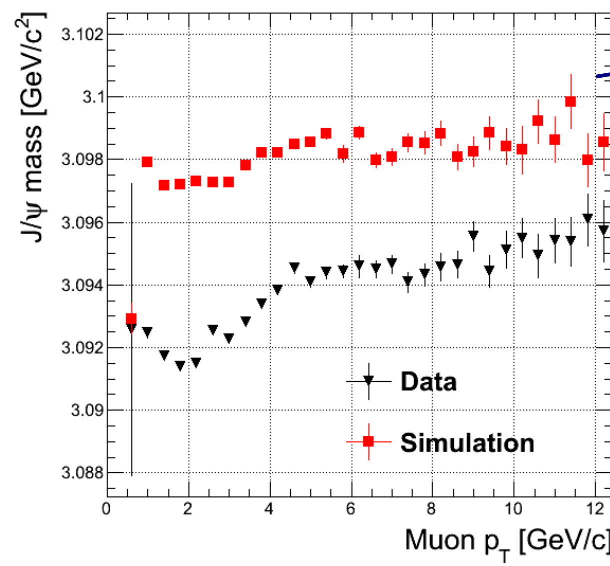
- Evaluate resolution and bias of different muon reconstruction algortihms (tracker, global, stand-alone) and compare to MC expectations

Momentum Calibration Using J/ψ

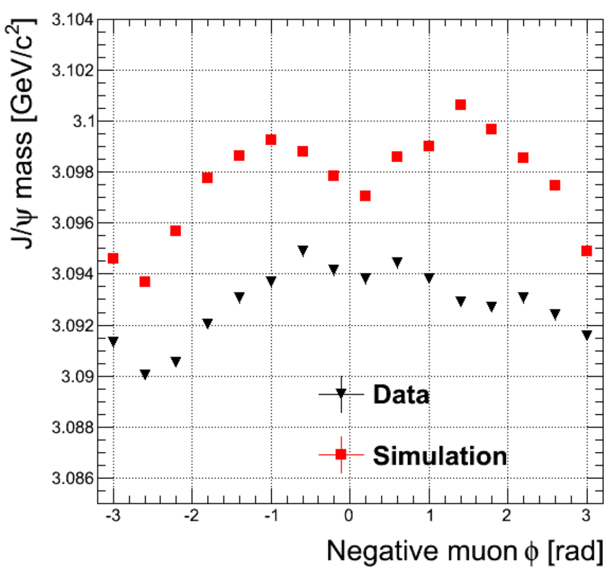
- ■ Simulated $J/\psi \to \mu\mu$ sample with realistic alignment conditions (~ 13 pb^{-1})
- ▼ $J/\psi \to \mu\mu$ candidates from 2010 CMS data (~ 19 pb^{-1})

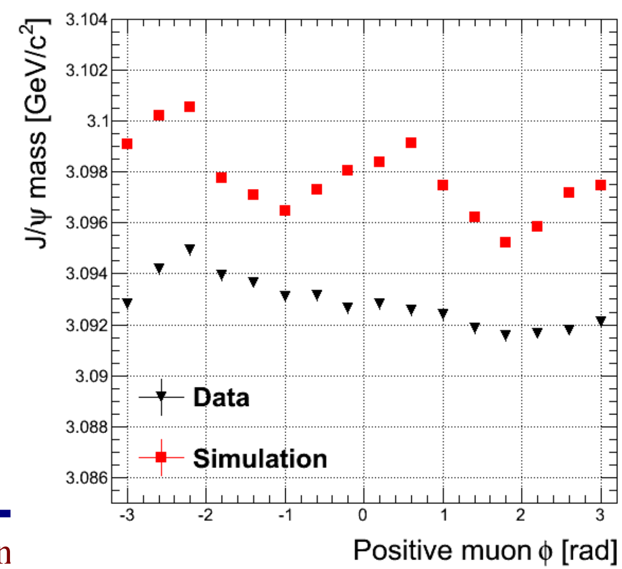
J/ψ mass





mean of Crystal-Ball fits to mass distributions in each bin

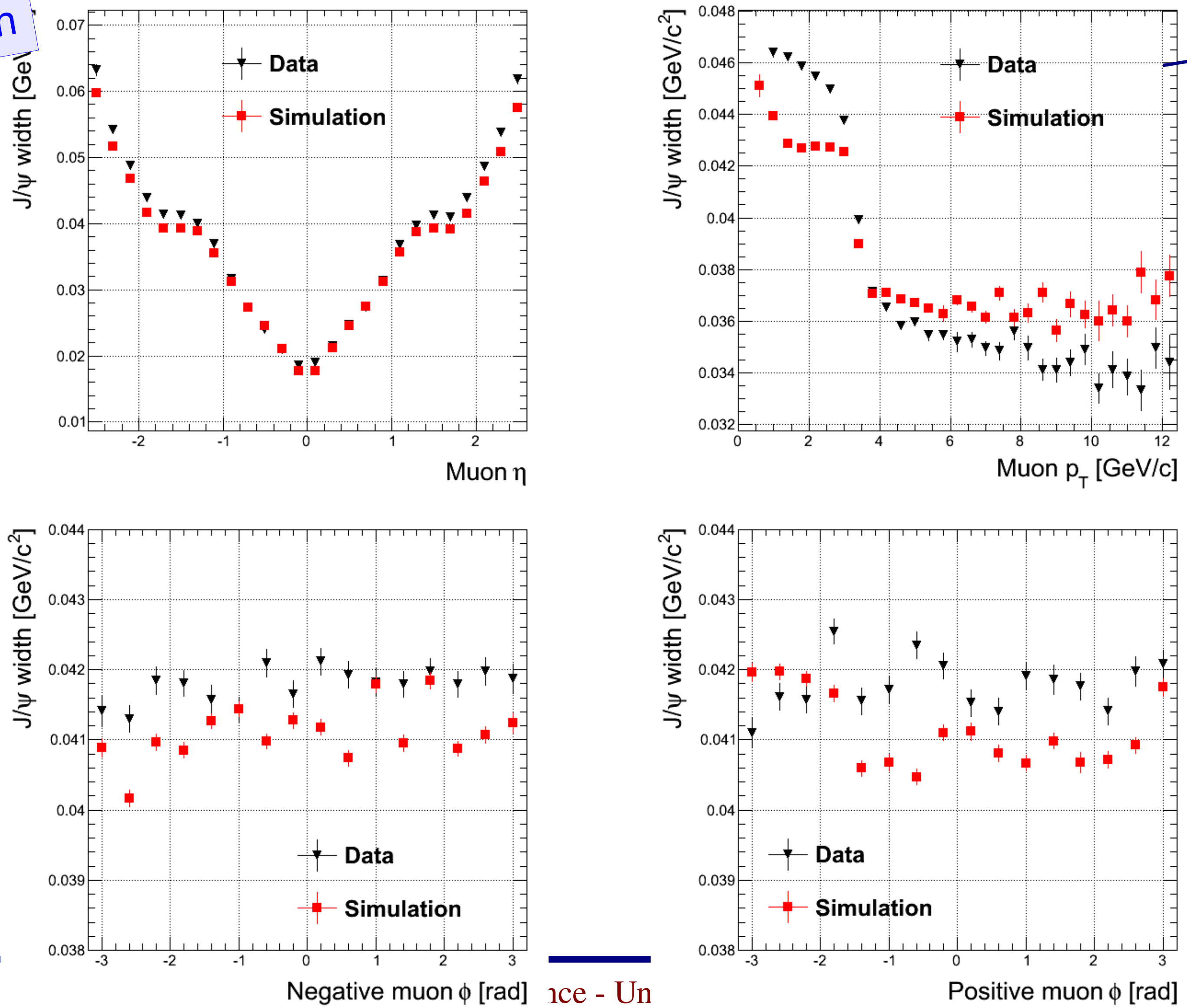




Momentum Calibration Using J/ψ

- ■ Simulated J/ψ → μμ sample with realistic alignment conditions (~ 13 pb^{-1})
- ▼ J/ψ → μμ candidates from 2010 CMS data (~ 19 pb^{-1})

Mass resolution



σ of Crystal-Ball fits to mass distributions in each bin

J/ψ: Calibration Strategy

- The following ansatz functions are chosen, based on the main features observed in simulation and in data

- *Resolution*

$$\frac{\sigma(p_T)}{p_T} = \begin{cases} f(p_\mathrm{T}) + a_3 + a_4\,\eta^2 & \text{for } |\eta| \le a_0 \\ (|\eta| - a_0)\,(y_2 - y_1)/(a_1 - a_0) + y_1 & \text{for } a_0 < |\eta| \le a_1 \\ f(p_\mathrm{T}) + a_5 + a_6\,(|\eta| - a_7)^2 & \text{for } a_1 < |\eta| \le a_2 \\ f(p_\mathrm{T}) + a_8 + a_9\,(|\eta| - a_{10})^2 & \text{for } |\eta| > a_2 \end{cases}$$

→ *3 parabolas in η*

with $f(p_\mathrm{T}) = a_{11}\,p_\mathrm{T}$ → *linear in p_T*

- *Scale correction*

$$p_\mathrm{T}^{corr} = p_\mathrm{T} \cdot (\,1 + A + B\,f(|\eta|) + C_{q,h}\,|\phi|\,\sin(2\phi + D_{q,h})\,)$$

$q = +, -$ (charge)

$h = up, down$ ($\phi > 0$, $\phi < 0$)

with $f(|\eta|)$ tabulated from the actual *mass vs. |η|* distribution (by-point function)

- *Exponential background*

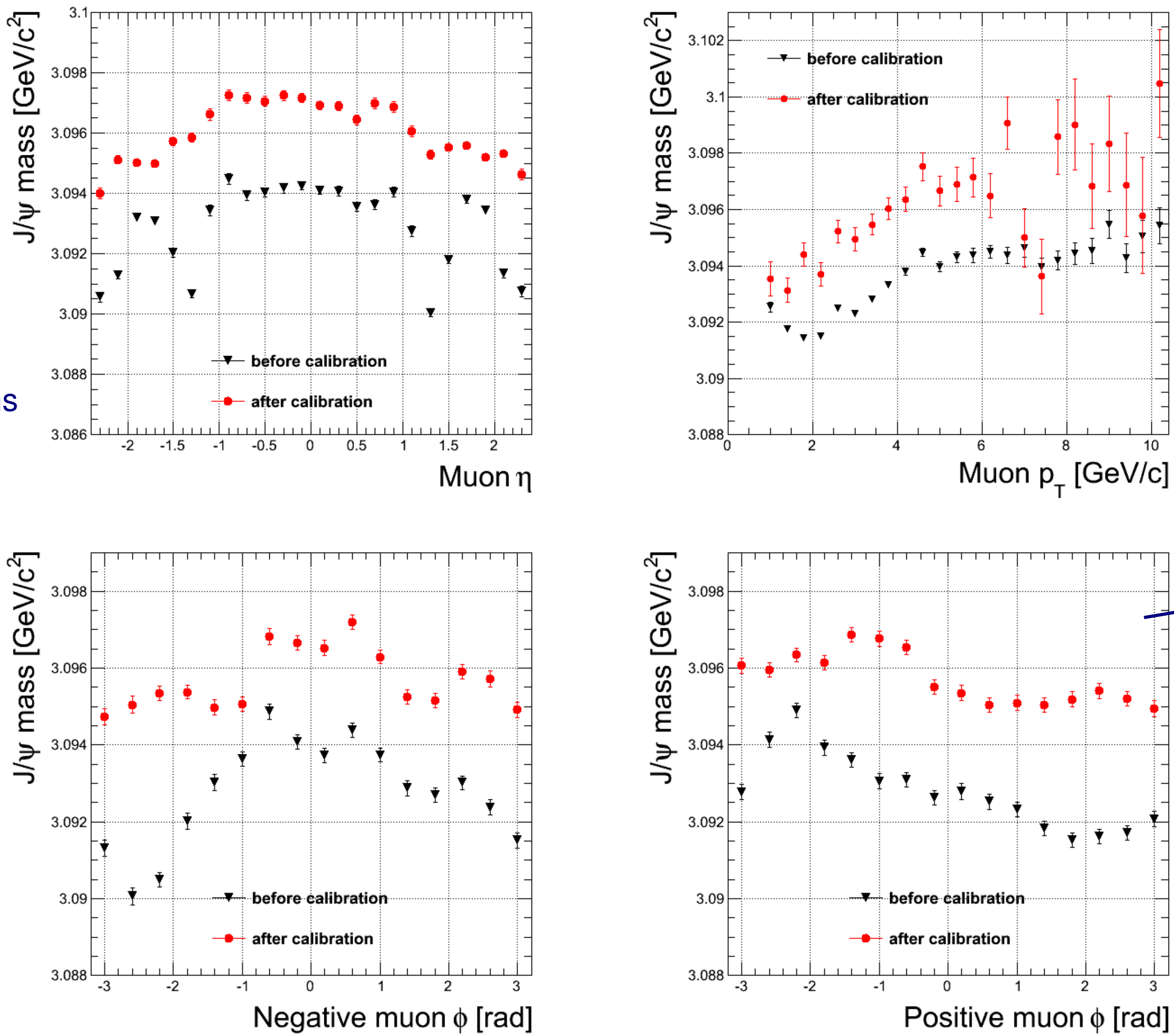
→ different in $(\,\eta(\mu^+), \eta(\mu^-)\,)$ bins

J/ψ: Mass After Correction

J/ψ mass

▼ Before corrections

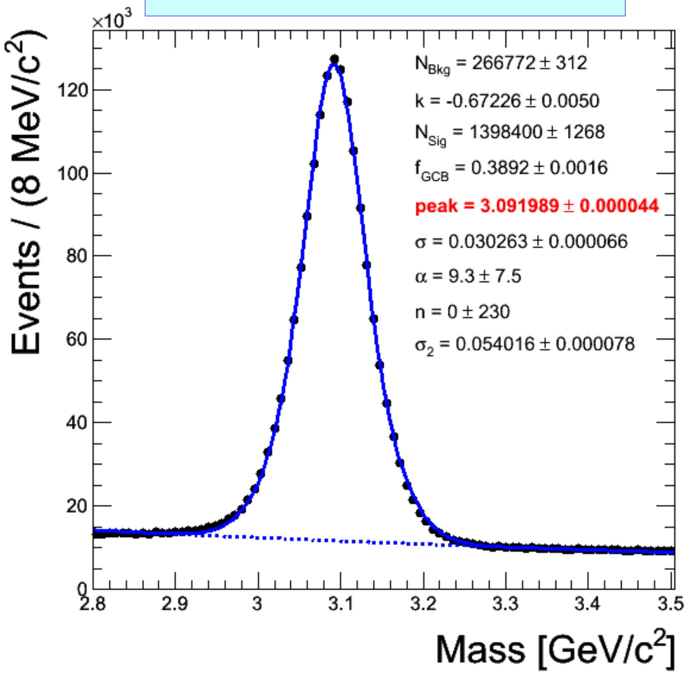
■ After corrections



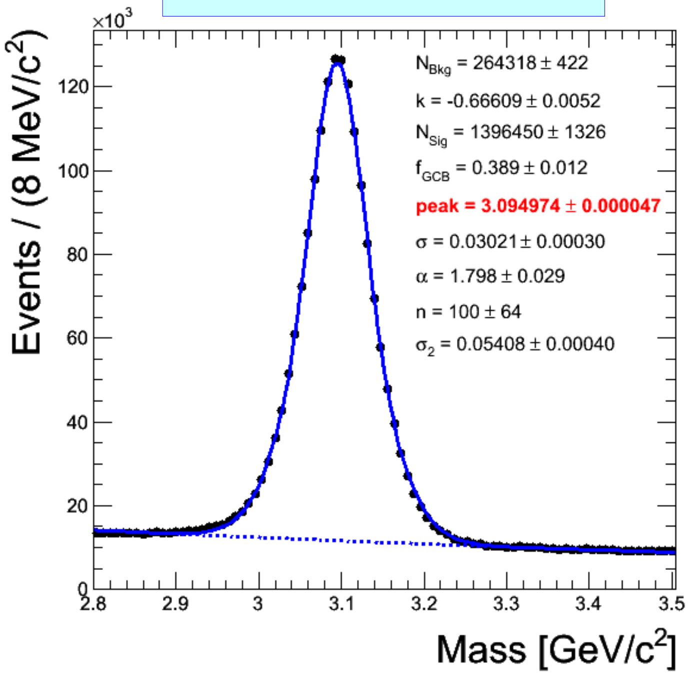
mean of Crystal-Ball fits to mass distributions in each bin

J/ψ: Line-Shape After Correction

Before the correction



After the correction



fit with Crystal-Ball + Gaussian, exponential background

Peak value

(3091.989 ± 0.044) MeV/c²

(3094.974 ± 0.047) MeV/c²

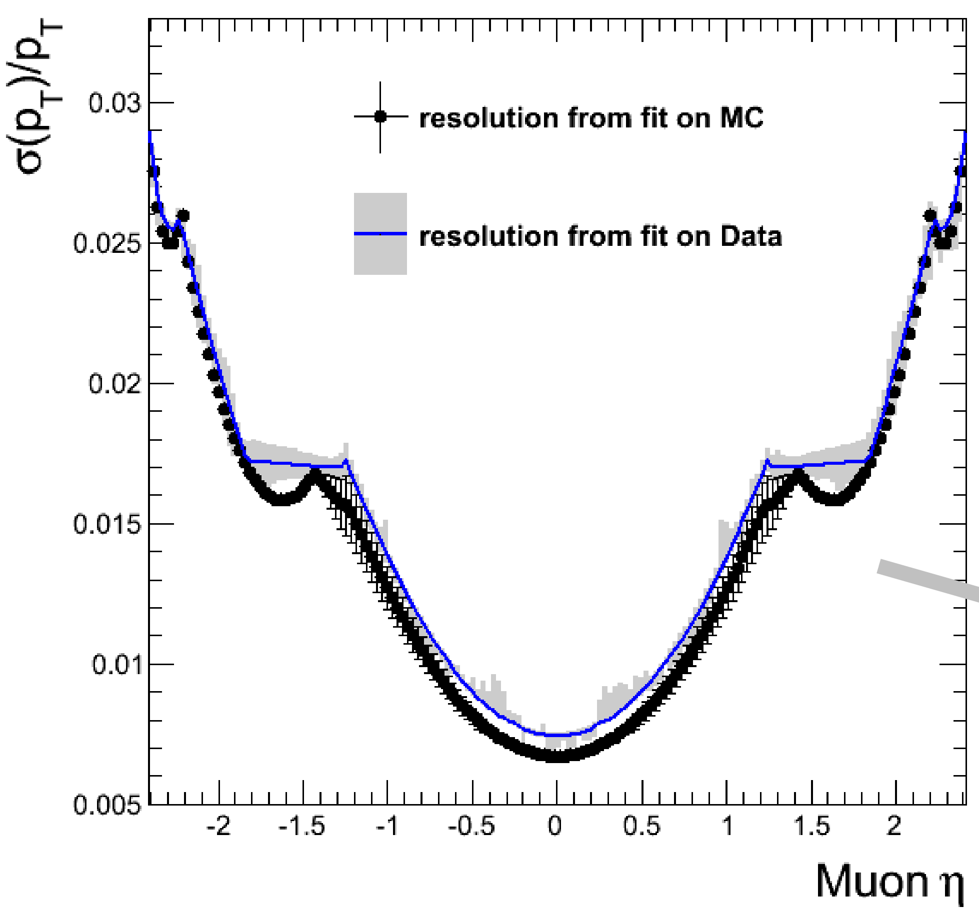
+3 MeV/c² shift

compatible with PDG J/ψ mass: (3096.916 ± 0.011) MeV/c²

~ 2 MeV/c² shift is expected (due to the function used for the fit)

J/ψ: p_T Resolution

Resolution function after the fit



Parametrisation:

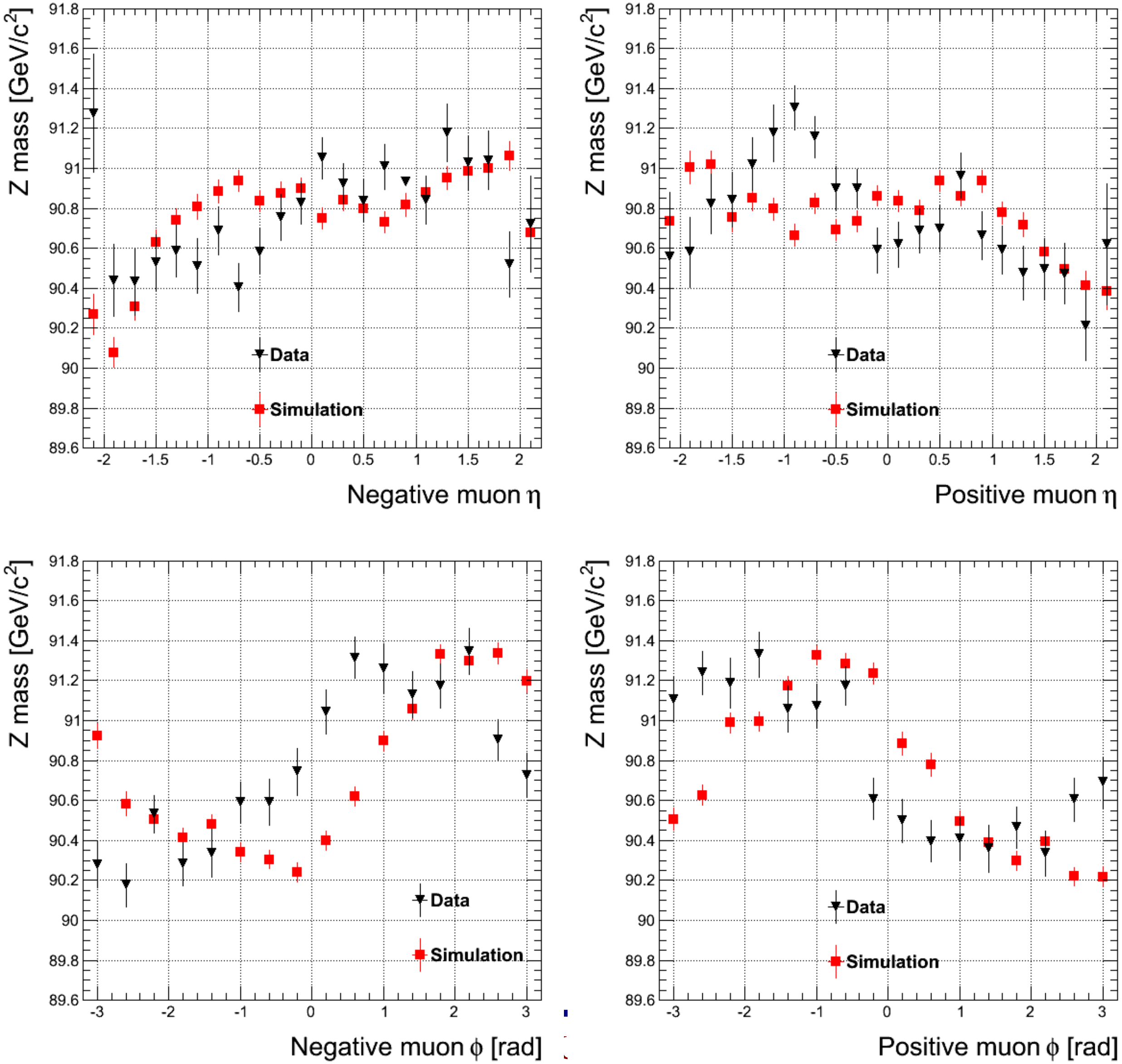
$$\frac{\sigma(p_T)}{p_T} = \begin{cases} f(p_T) + a_3 + a_4\,\eta^2 & \text{for } \; |\eta| \leq a_0 \\ (|\eta| - a_0)\,(y_2 - y_1)/(a_1 - a_0) + y_1 & \text{for } \; a_0 < |\eta| \leq a_1 \\ f(p_T) + a_5 + a_6\,(|\eta| - a_7)^2 & \text{for } \; a_1 < |\eta| \leq a_2 \\ f(p_T) + a_8 + a_9\,(|\eta| - a_{10})^2 & \text{for } \; |\eta| > a_2 \end{cases}$$

The gray band accounts for statistical and systematic uncertainties

Momentum Calibration Using Z

- Simulated $Z \rightarrow \mu\mu$ sample with realistic alignment conditions ($O(100\ pb^{-1})$)
- ▼ $Z \rightarrow \mu\mu$ candidates from 2010 CMS data (~ 30 pb^{-1})

Z mass



→ mean of Voigtian fits to mass distributions in each bin

Z: Calibration Strategy

Ansatz functions:

- *Resolution*

$$\frac{\sigma(p_T)}{p_T} = \begin{cases} f(p_\mathrm{T}) + a_2\,\eta^2 & \text{for } |\eta| \le a_0 \\ f(p_\mathrm{T}) + a_3\,(|\eta| - a_4)^2 & \text{for } \eta < -a_0 \\ f(p_\mathrm{T}) + a_5\,(|\eta| - a_6)^2 & \text{for } \eta > a_0 \end{cases}$$

→ *central parabola*

→ *parabolas at high $|\eta|$ (different for $\eta < 0$ and $\eta > 0$)*

with $f(p_\mathrm{T}) = a_1 + 1.8 \cdot 10^{-4}\, p_\mathrm{T}$ → *fitted on simulation*

- *Scale correction*

$$p_\mathrm{T}^{corr} = b_0 + b_1\,p_\mathrm{T} + q\,b_2\,\eta + q\,b_3\,\sin(\phi + b_4)$$

→ q = charge

- *Exponential background*

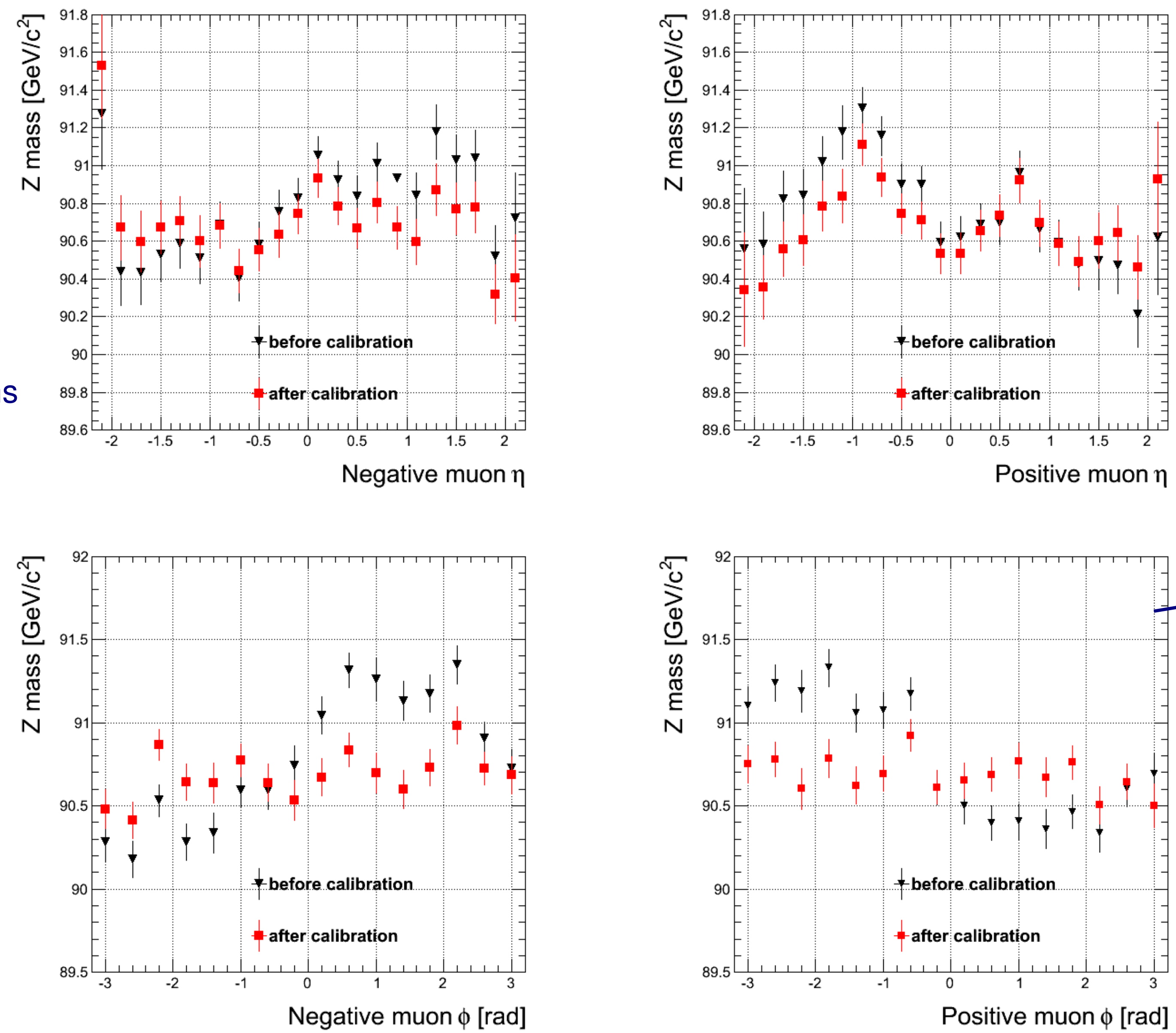
  → the background level is very low,
  a single exponential function is used

Z: Mass After Correction

Z mass

▼ Before corrections

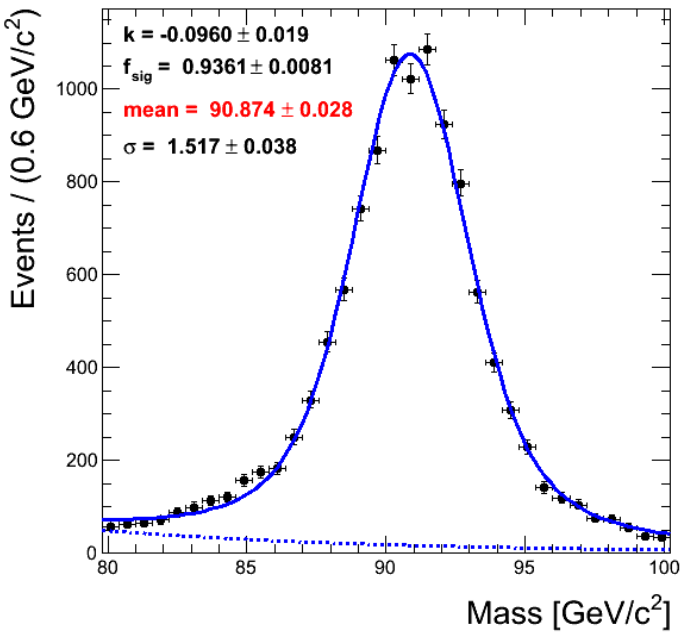
■ After corrections



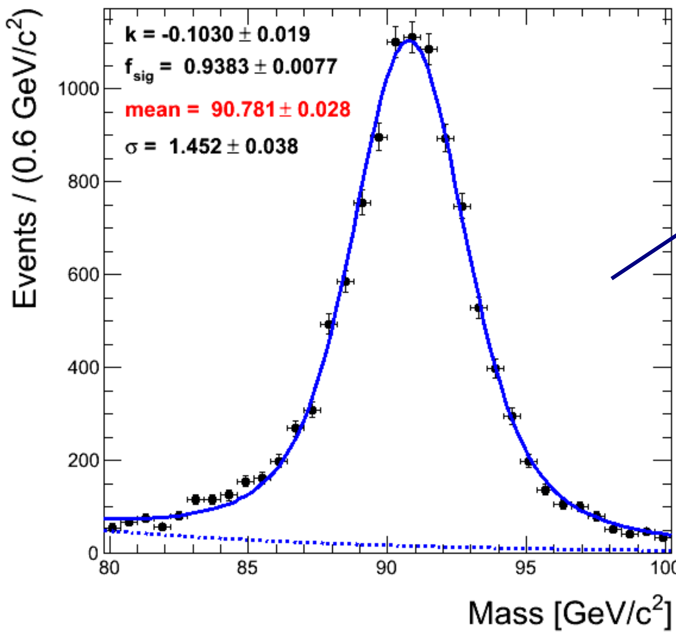
mean of Voigtian fits to mass distributions in each bin

Z: Line-Shape After Correction

Before the correction



After the correction



fit with a Voigtian profile, exponential background

Mean of the fit

(90.874 ± 0.028) GeV/c² → (90.781 ± 0.028) GeV/c²

–0.1 GeV/c² shift

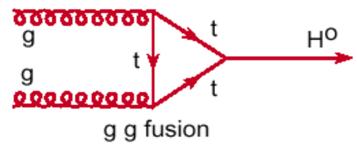
→ peak of Z resonance expected at the LHC: ~ 90.7 GeV/c², due to PDFs and FSR

σ = 1.52 → 1.45 GeV/c² → ~ 4.6 % improvement in resolution from momentum correction

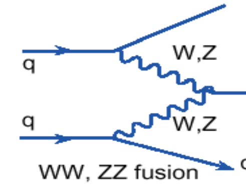
Standard Model Higgs Boson Searches in the 4 Muons Channel

Higgs Boson Search at LHC

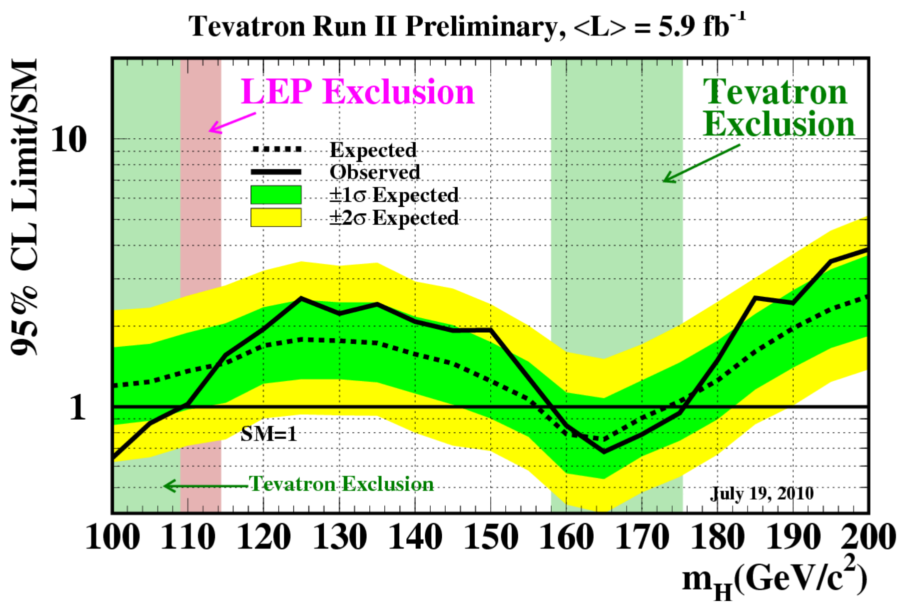
gluon-gluon fusion:
main production channel

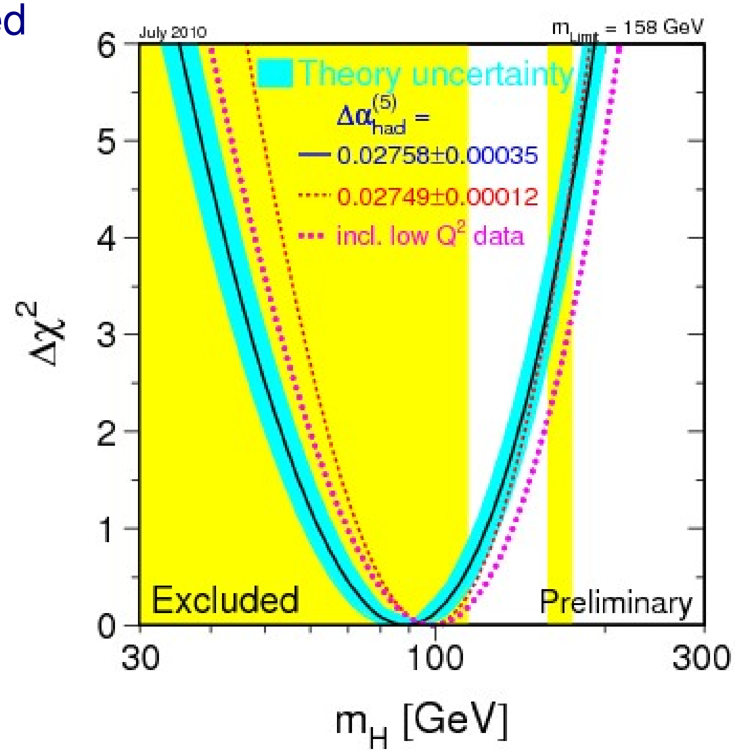


vector boson fusion:
important at high mass



The Higgs mass (m_H) is a free parameter of the SM, but it's related to known parameters through *virtual corrections* (~ log m_H)





Experimental constraints

95% C.L.

m_H > 114.4 GeV/c² (*LEP exclusion*)

m_H ≠ 158-175 GeV/c² (*Tevatron exclusion*)

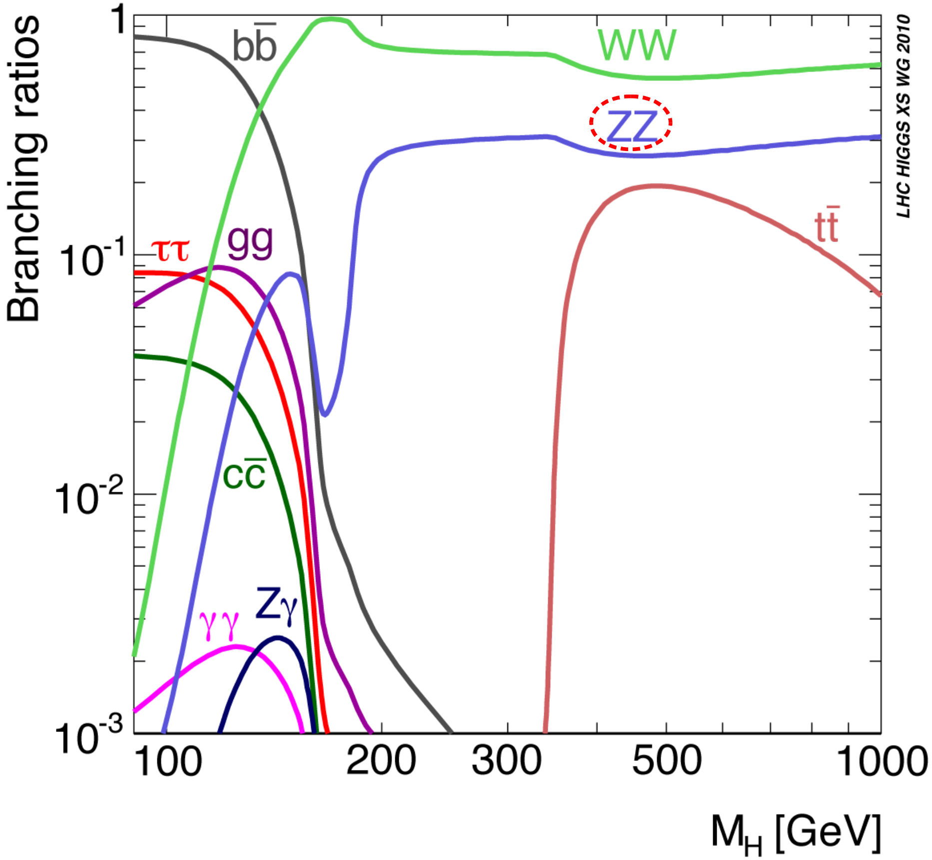
m_H < 158 GeV/c² (*global EW fit*)

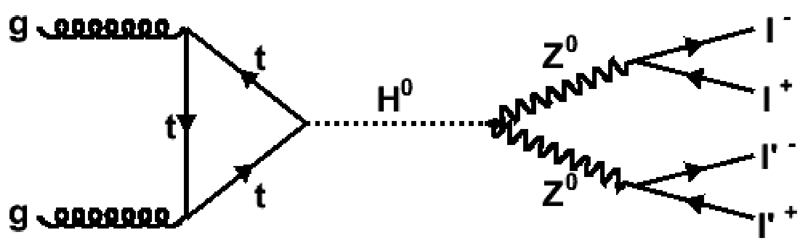
Theoretical constraints

$m_H \lesssim$ 1 TeV/c²

The "Golden Channel"

Higgs decay branching ratios





For high Higgs masses ($m_H > 2 \cdot m_Z$):

- $H \to W^+W^-$ main decay channel
- $H \to ZZ$ has $BR(H \to WW) \approx 3 \times BR(H \to ZZ)$

But Z can decay in *2 charged leptons*

- clean signature over the hadronic background
- good resolution on Higgs mass

So: **$H \to ZZ \to 4\ell$** **(ℓ = e, μ)**

is the *"golden channel"*
for a Higgs discovery at the LHC

$$\sigma_{NNLO} \times BR(H \to ZZ \to 4\ell) = 1 - 16 \text{ fb}$$

(here $\ell = e, \mu, \tau$)

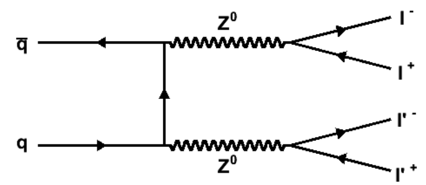
signature: 4 leptons in the final state with

- high p_T
- isolated (not inside a *jet* of hadrons)
- prompt (emerging from the *primary vertex*)

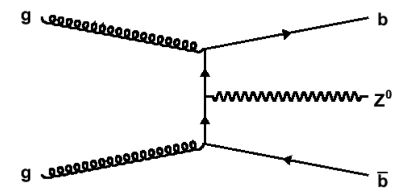
Main Backgrounds

$\ell = e, \mu, \tau$

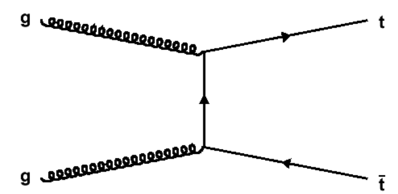
- *Irreducible* *(same final state as the signal)*
  - $ZZ^{(*)} \rightarrow 4\ell$ $\sigma_{NLO} \times BR = 4.80$ pb



- *Reducible* *(2 leptons from jets)*
  - $Zb\bar{b} \rightarrow 4\ell + X$ $\sigma_{NLO} \times BR = 2.93$ pb



  - $t\bar{t} \rightarrow 4\ell + X$ $\sigma_{NLO} \times BR = 16.71$ pb

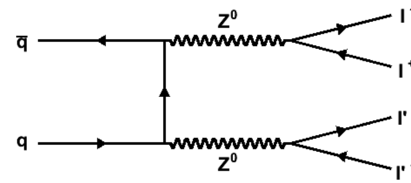


- *Other backgrounds:* *n*-jets (QCD), W + *n*-jet, Z + *n*-jet

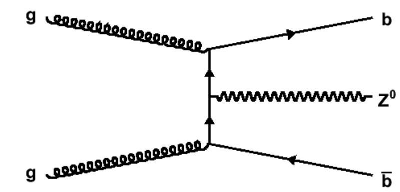
Main Backgrounds

$\ell = e, \mu, \tau$

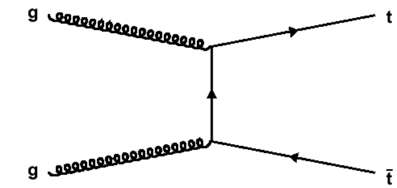
- *Irreducible* (*same final state as the signal*)
  - $ZZ^{(*)} \rightarrow 4\ell$ $\sigma_{NLO} \times BR$ = 4.80 pb



- *Reducible* (*2 leptons from jets*)
  - $Zb\bar{b} \rightarrow 4\ell + X$ $\sigma_{NLO} \times BR$ = 2.93 pb



  - $t\bar{t} \rightarrow 4\ell + X$ $\sigma_{NLO} \times BR$ = 16.71 pb



- *Other backgrounds:* *n*-jets (QCD), W + *n*-jet, Z + *n*-jet

> - In the following, a prospective analysis for the 4μ final state is presented, for a centre-of-mass energy of 7 TeV and integrated luminosity of 1 fb^{-1}
> - Two parallel analyses, for the $4e$ and $2\mu 2e$ final states, are performed using the same strategy
> - Combined results of the three channels are shown in the conclusion

Preliminary Selections

1. Trigger

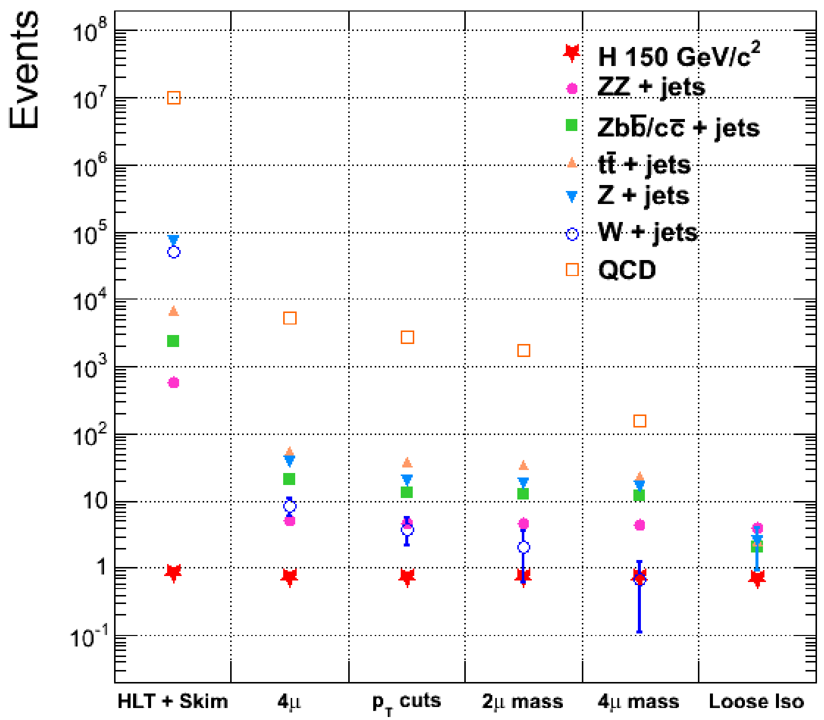
   single and double muon triggers (no isolation)

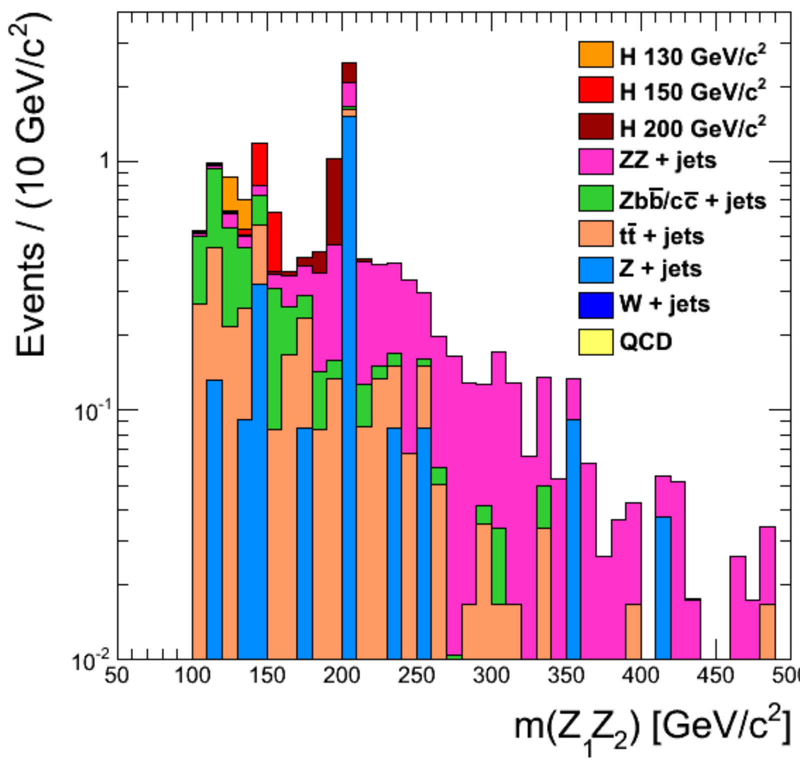
2. Skimming

   – suppress QCD, W+jets, Z+jets events
   – based on p_T cuts

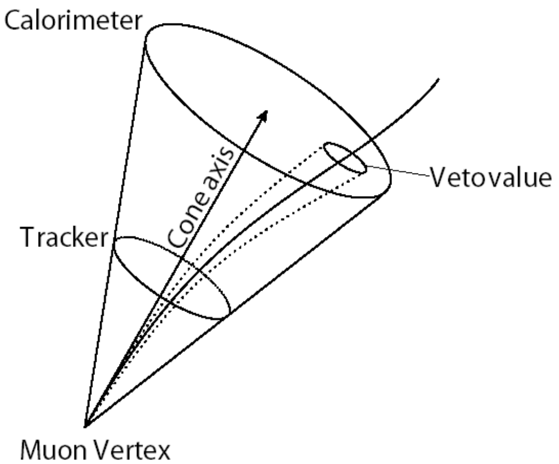
3. Preselection

   – reduce fake muons and lower QCD
   – require 2 $\mu^+\mu^-$ pairs with cuts on 2-muon and 4-muon invariant mass





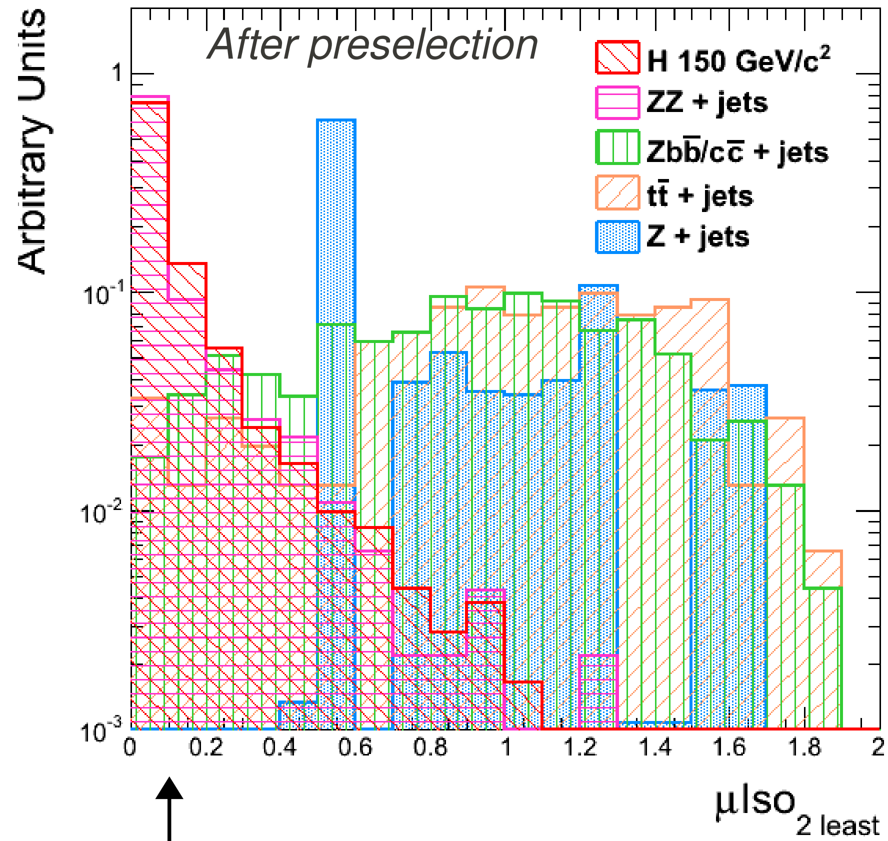
Selection: Isolation

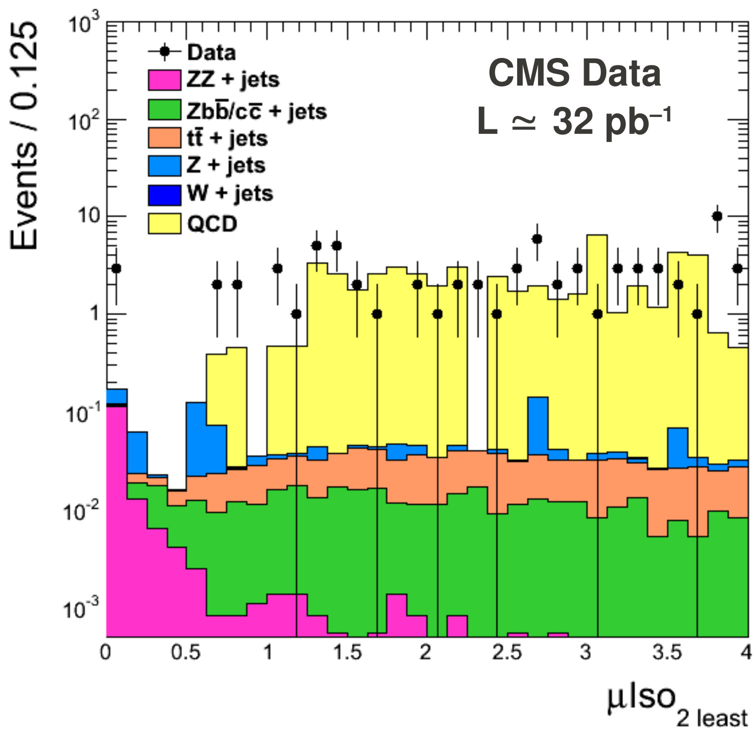


Isolation variable

momentum / energy
of tracks inside a cone
around the muon

Normalised area





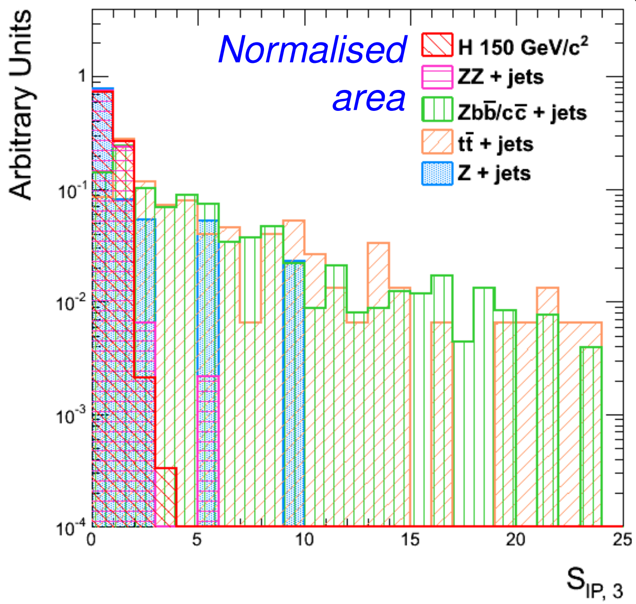
Selection applied on variable
$\mu Iso_{2\ least}$ = sum of the isolation
of the 2 least isolated muons

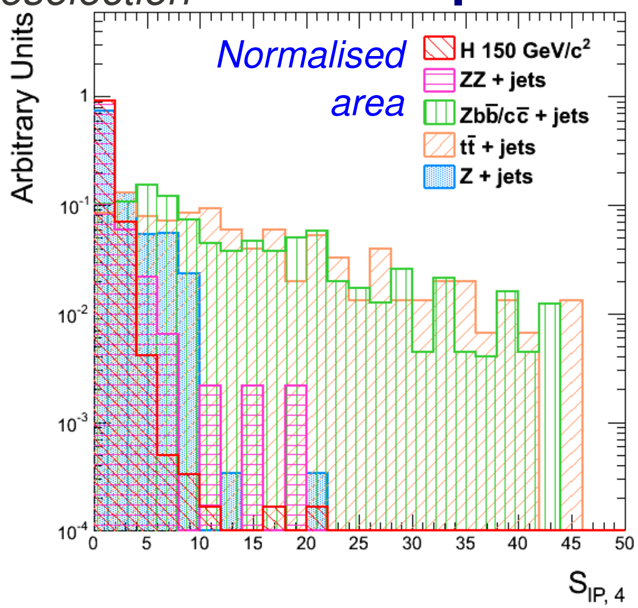
Selection: Impact Parameter

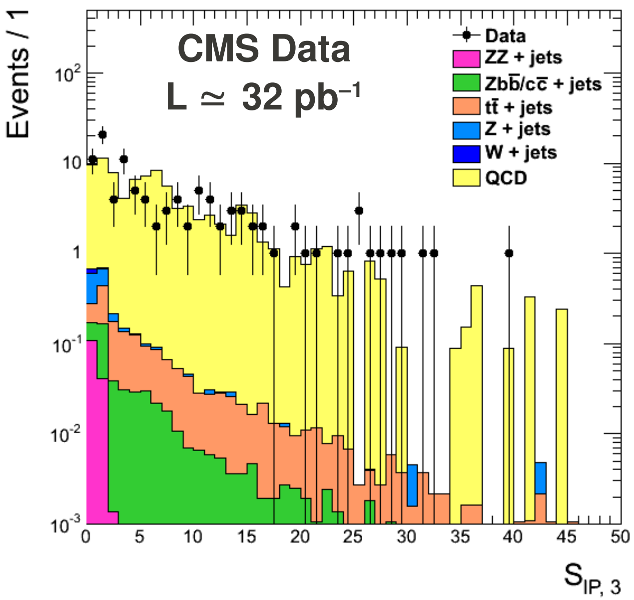
<u>*Impact parameter significance*:</u>

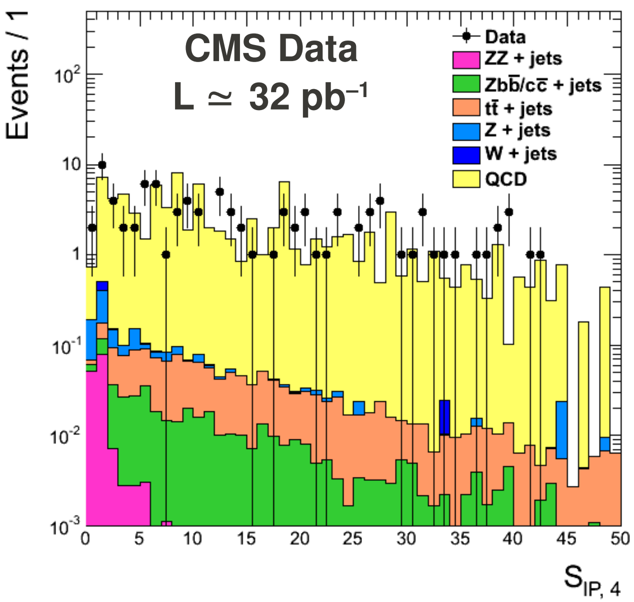
$$S_{IP} = \frac{IP^{3D}}{\sigma_{IP^{3D}}}$$

After preselection









Cuts applied to the 2 highest S_{IP} muons

(muons from *b*-jets have higher S_{IP})

Selection: Isolation vs. p_T

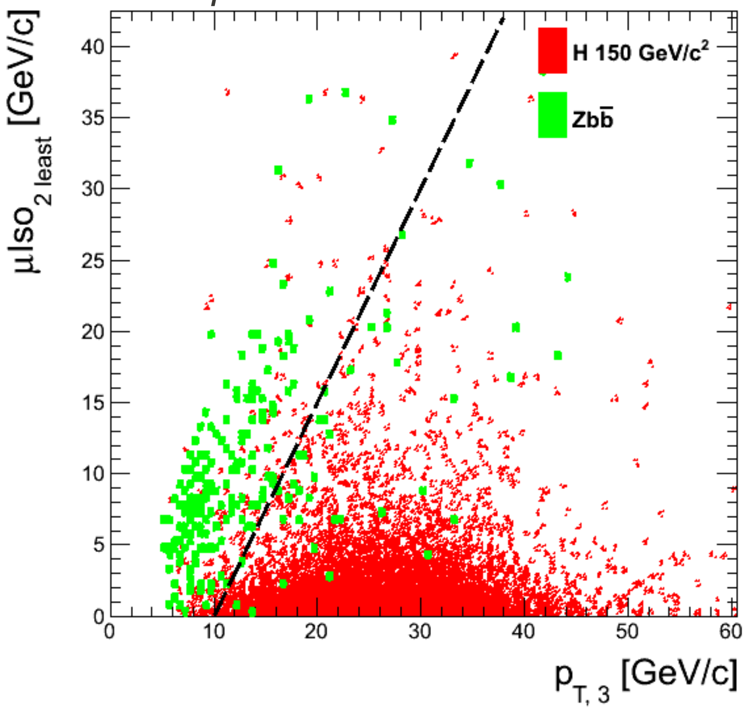
- A p_T-dependent isolation cut proves more effective on *Zbb* background

The *bidimensional* distributions
isolation variable vs p_T of muons
show a very strong rejection power

The 3rd and 4th muon, sorted by decreasing p_T

- are inside *b*-jets
- have a softer p_T spectrum

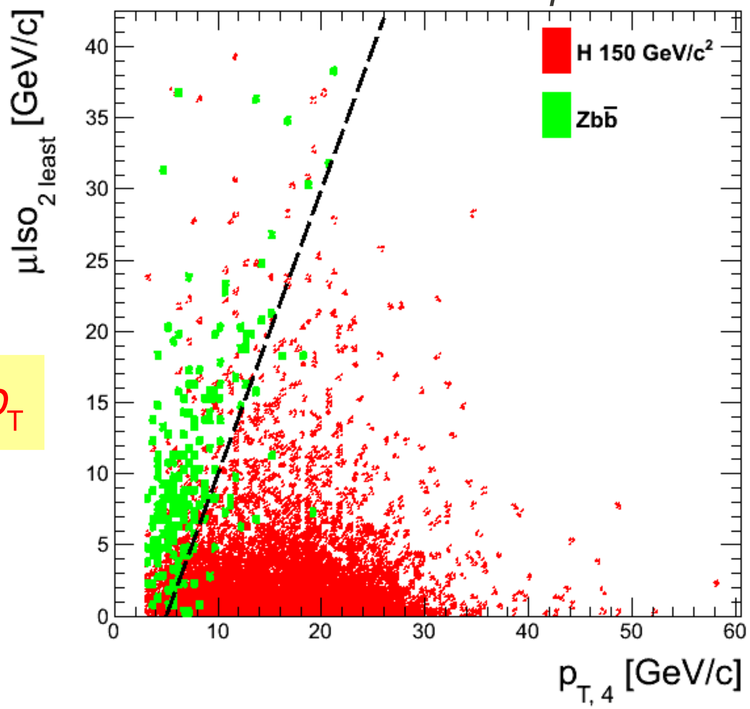
After preselection



Cut:

$$\mu Iso_{2\,least} = A - B\, p_T$$

After preselection



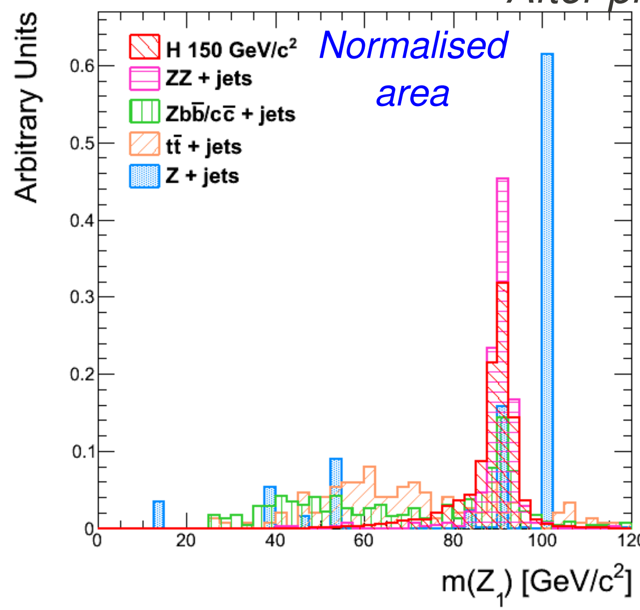
Selection: Dimuon Invariant Mass

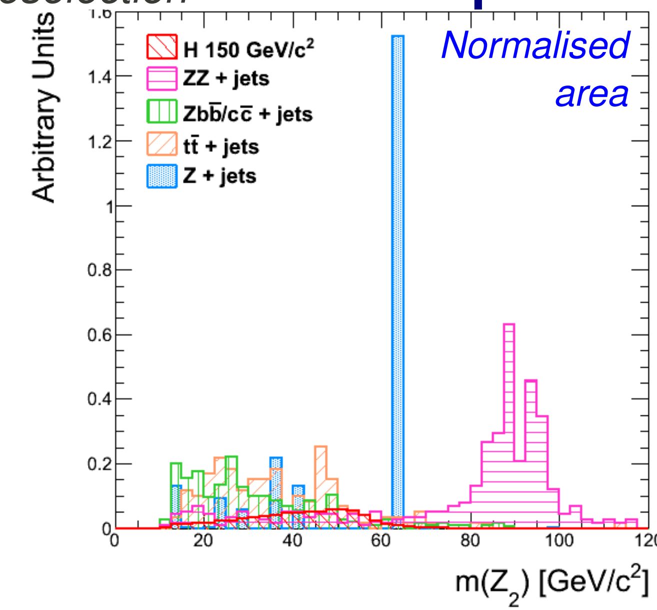
Definition of Z:

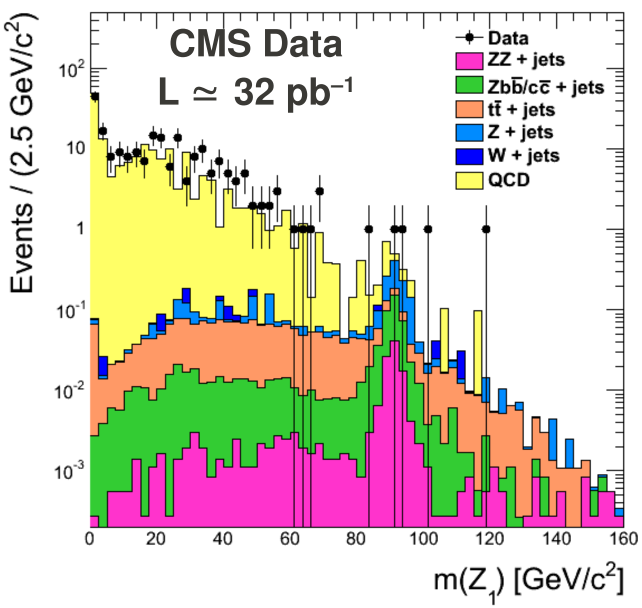
Z_1: the muon pair *closest* to the nominal *Z mass*

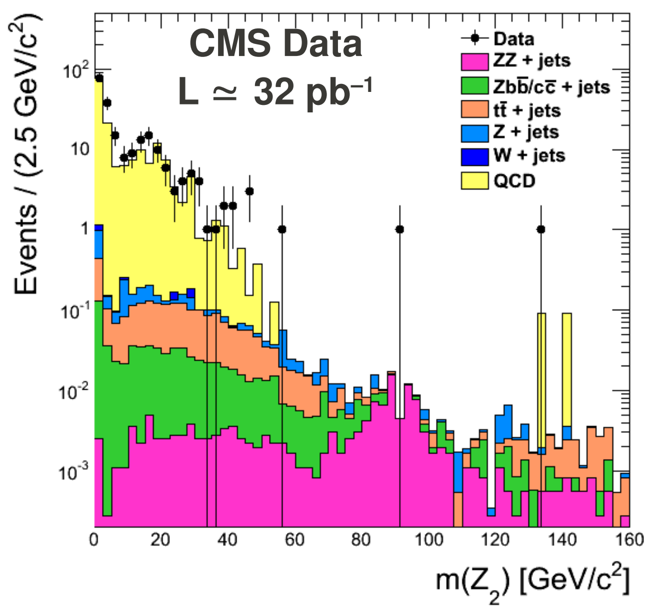
Z_2: the 2 remaining muons with the *highest* p_T

After preselection

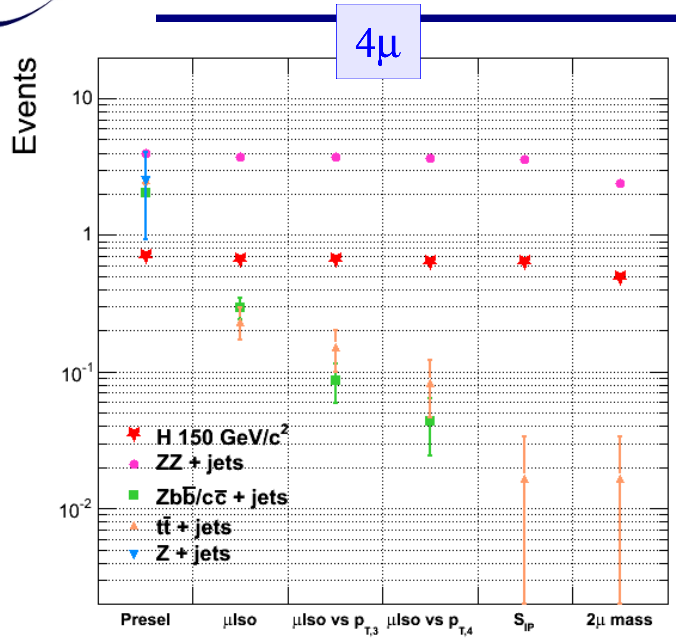


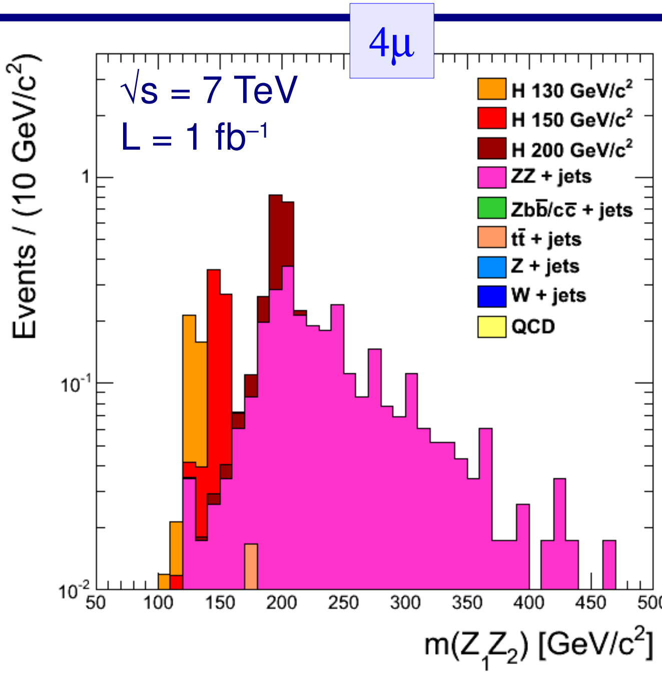






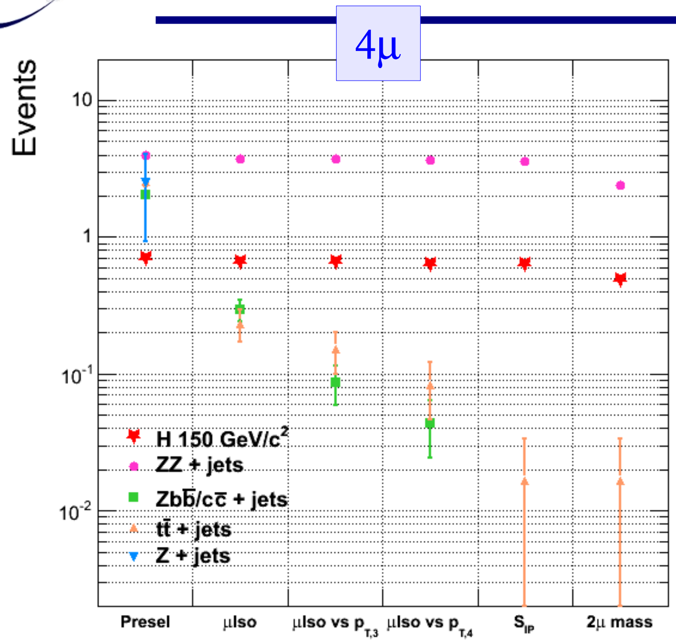
Results

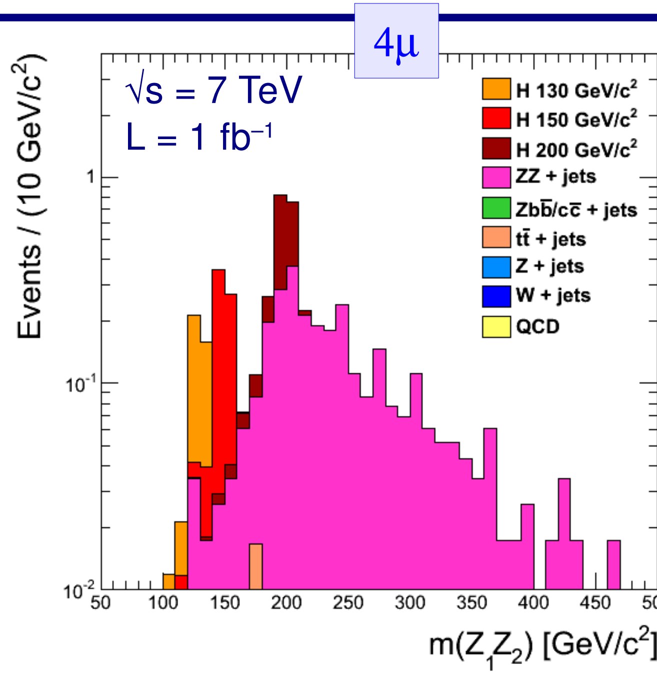




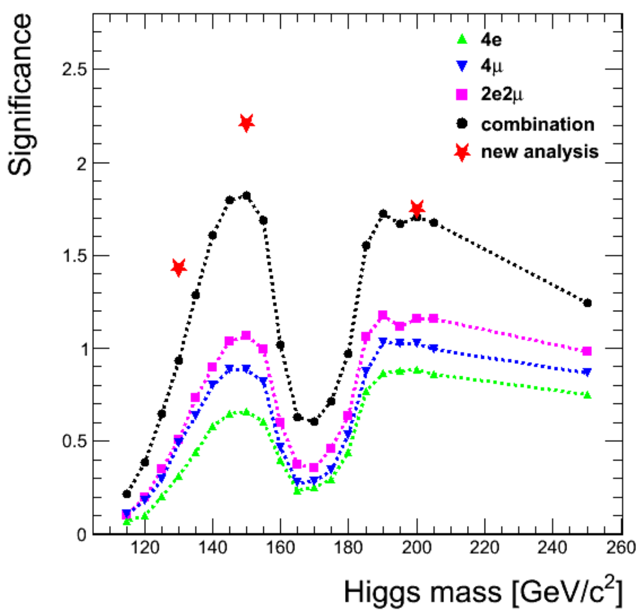
A narrow peak emerges over the continuum of the remainging ZZ background

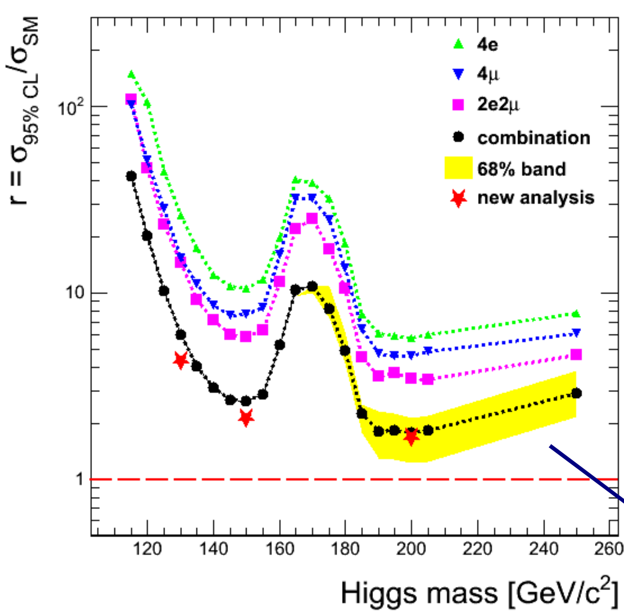
Results





A narrow peak emerges over the continuum of the remainging ZZ background





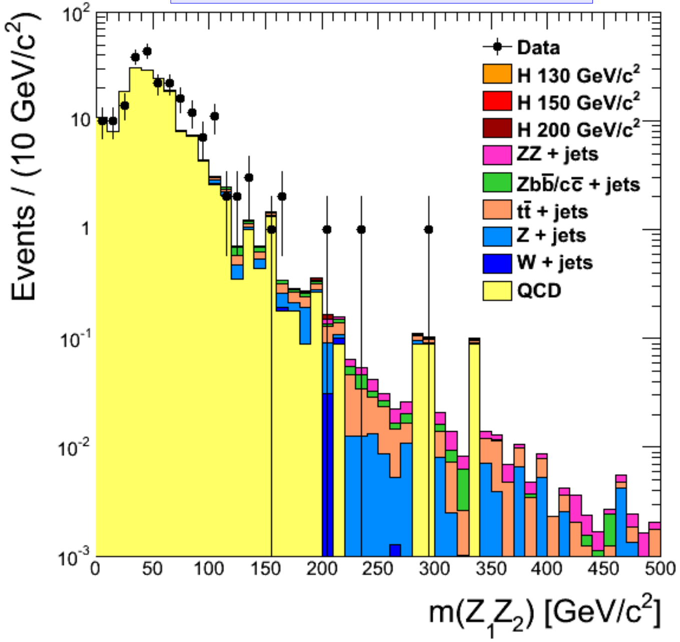
At 7 TeV with 1 fb⁻¹, neither discovery nor exclusion are possible, for all the mass range

Lines: extrapolations of a similar analysis at √s = 10 TeV

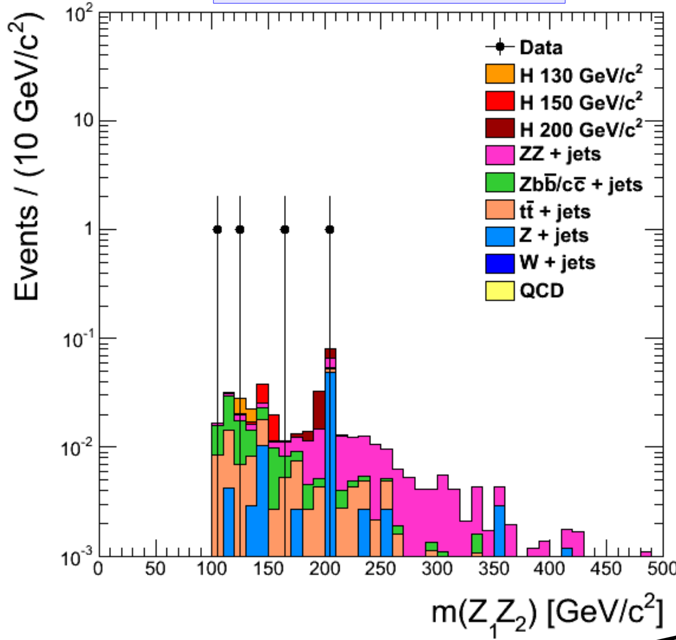
Stars: results of this analysis

Results on Data (32 pb^{-1})

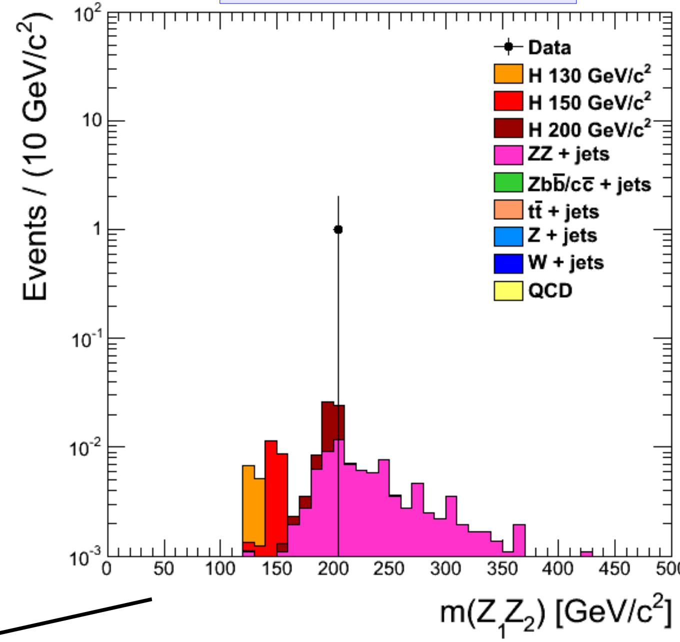
After HLT + skimming



After preselection



After full selection



4μ inv. mass [GeV/c²]	2μ inv. mass [GeV/c²]	Muon p_T [GeV/c]
201.7	92.12	19.56
201.7	92.12	25.88
201.7	92.23	48.14
201.7	92.23	43.44

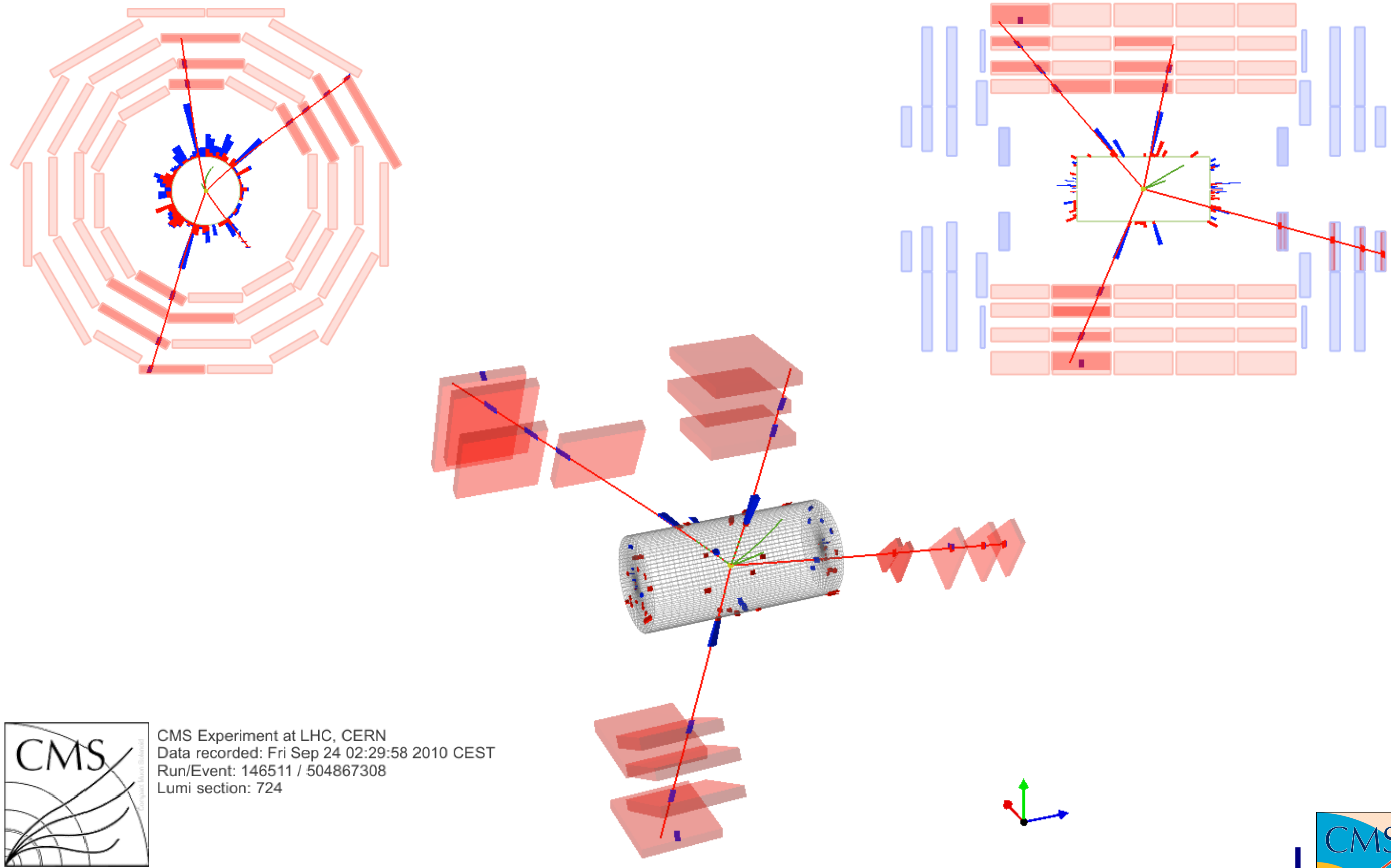
all isolated, with S_{IP} ~ 0

At $\sqrt{s}$ = 7 TeV, L = 32 pb^{-1}:

Prob (1 evt ZZ → 4μ) = 0.08

Prob (1 evt ZZ → 4ℓ) = 0.23

4μ Golden Event



Conclusions

- *Muon Reconstruction*
  - Reconstruction algorithms
  - Stand-alone reconstruction and its improvements
  - Test of muon reconstruction performance on 2010 LHC data and comparison with simulations
- *Muon Momentum Scale Calibration*
  - Algorithm developed for momentum calibration
  - Application of the algorithm to J/ψ and Z samples from 2010 CMS data
  - Scale corrections and resolution measurements in different p_T ranges
- *Higgs Boson Searches in the Four Muons Channel*
  - Development of a prospective analysis for a low luminosity scenario
  - Expected results on simulations at 7 TeV energy and 1 fb^{-1} luminosity
  - Application of this analysis to 2010 CMS data and first results

Thanks for the attention!

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Acknowledgements

Acknowledgements

So many people have contributed to the accomplishment of this thesis that it is almost impossible to mention all of them.

First, I would like to thank the CMS Torino group: Amedeo, Nadia, Silvia, Vincenzo and all the others. Special thanks to Prof. Alessandra Romero, for her wise advice and support.

All my gratitude goes to my advisor, Nicola, for his constant presence, his invaluable suggestions and the exceptional care he put in revising this thesis.

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I will never find enough words to thank Chiara, for the physics she has taught me, but mostly for the support and friendship she has always shown me.

There are a number of people to whom I am indebted for their help and the important contribution to my work: Slava, Martijn, Marco D., Sara, Nicola D., Yves, Giovanni, Zoltan, Gianluca, and many more – I apologise to all those I forgot. Special thanks go to Dott. Ludovico Pontecorvo, for the careful and enthusiastic revision of this thesis, and to Dott. Alessandro Ballestrero, for his useful suggestions.

A thought to all friends that have made my life at CERN so pleasant: Grazia, Bruno, Alessia, Nhan, Alessandro, Alberto and Matteo, just to mention a few. But first of all, the crew of "*Casa Torino*": Cristina, Roberto, Giorgia, Marco and Susy. In particular, I am grateful to Cri, with whom I have shared work and worries.

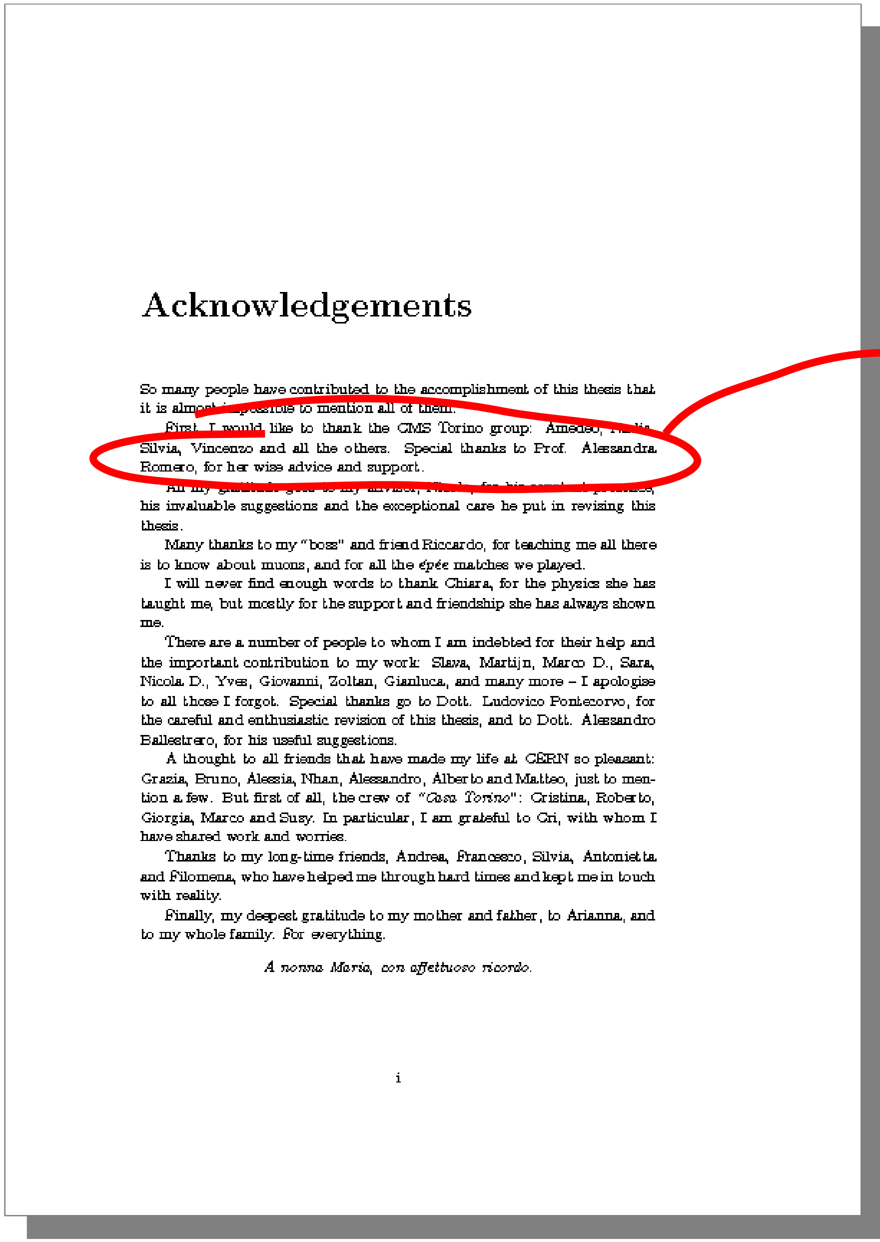
Thanks to my long-time friends, Andrea, Francesco, Silvia, Antonietta and Filomena, who have helped me through hard times and kept me in touch with reality.

Finally, my deepest gratitude to my mother and father, to Arianna, and to my whole family. For everything.

A nonna Maria, con affettuoso ricordo.

i

Acknowledgements



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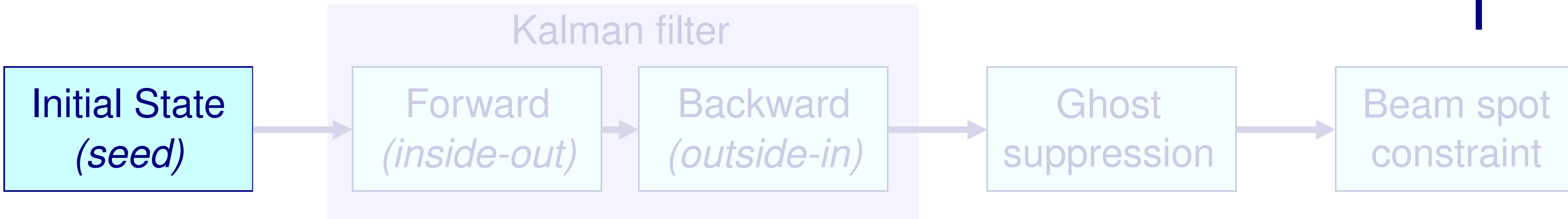
i

Especially

CMS Torino

Backup slides

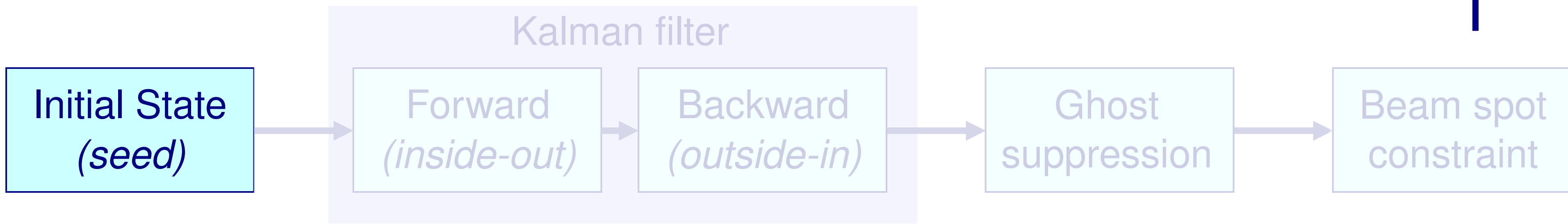
Stand-Alone Reconstruction seed



It is estimated in different ways in the the *off-line* and *on-line* (trigger) reconstruction:

- *on-line*: input from Level 1 trigger
- *off-line*: built from one or more track segments
  p_T parametrized as a function of ϕ slope (or $\Delta\phi$ slope) of segments: $\boldsymbol{p_T = A - B/\Delta\phi}$

Stand-Alone Reconstruction seed



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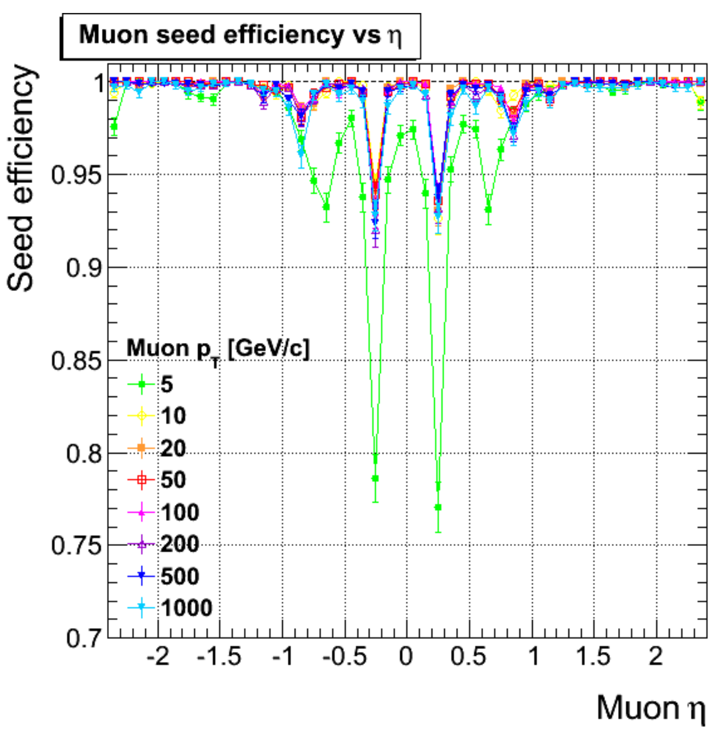
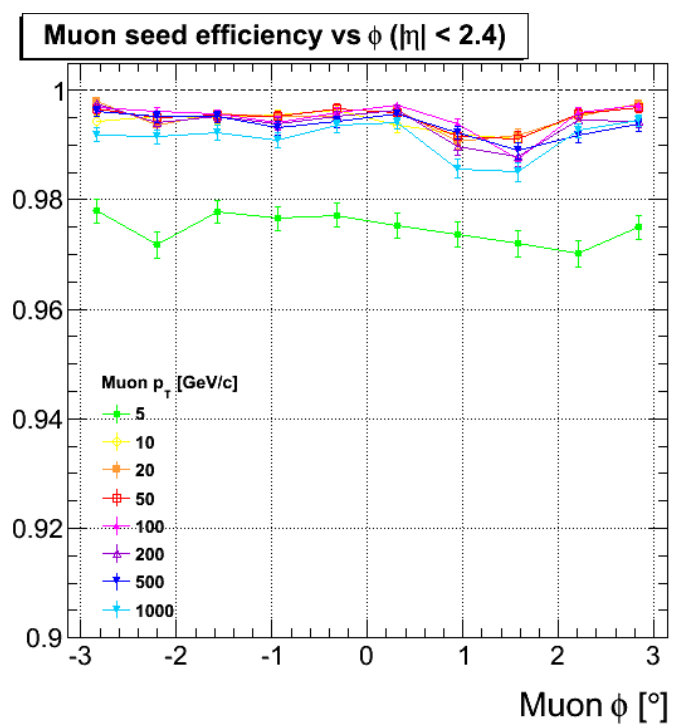
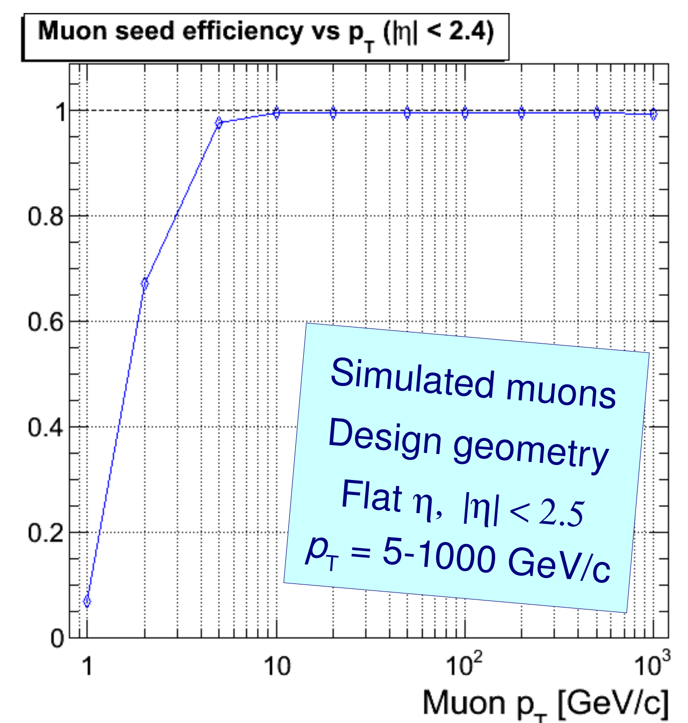
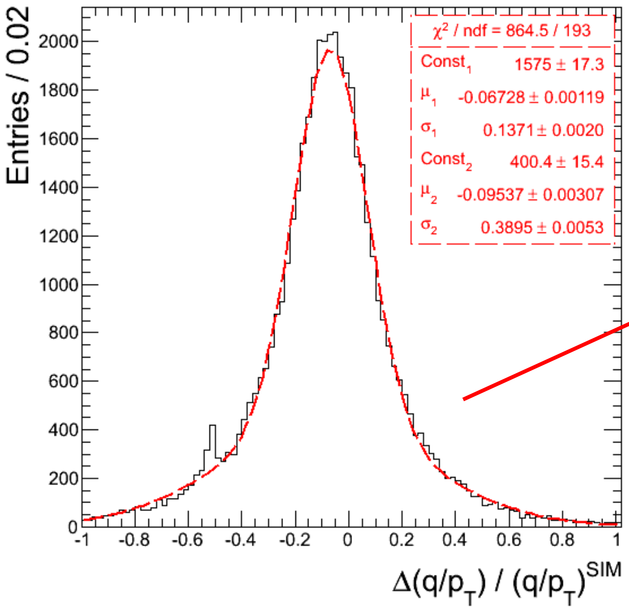






Stand-Alone Reconstruction seed



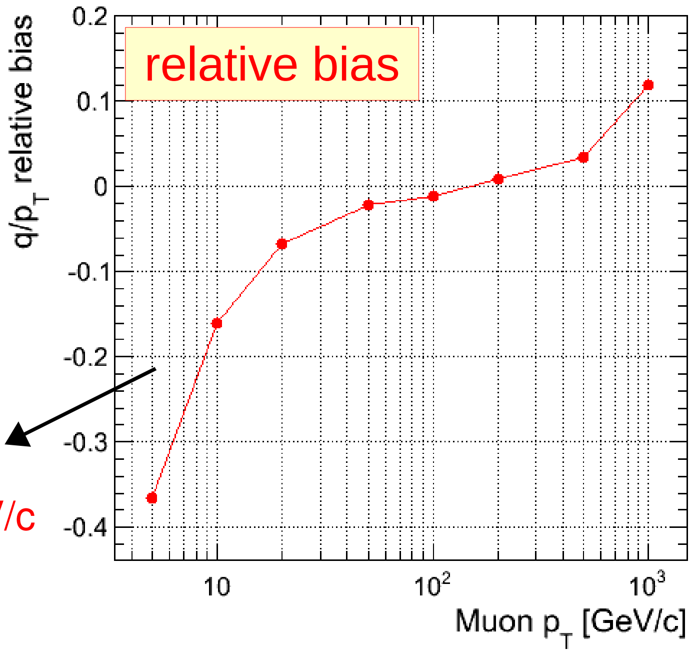
$$\frac{(q/p_{\mathrm{T}})_{\mathrm{MEAS}} - (q/p_{\mathrm{T}})_{\mathrm{SIM}}}{(q/p_{\mathrm{T}})_{\mathrm{SIM}}}$$

Fit with a double Gaussian

- the narrow Gaussian for the core of the distribution
- the large Gaussian accounts for tails (mult. scattering)

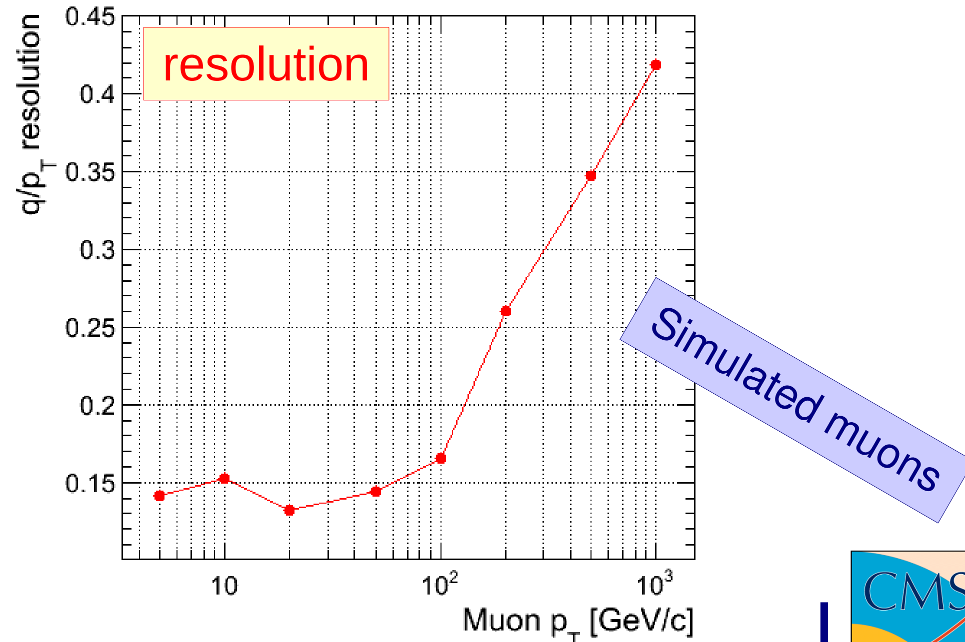
From the core distribution

- mean: q/p_{T} relative bias
- σ: q/p_{T} resolution

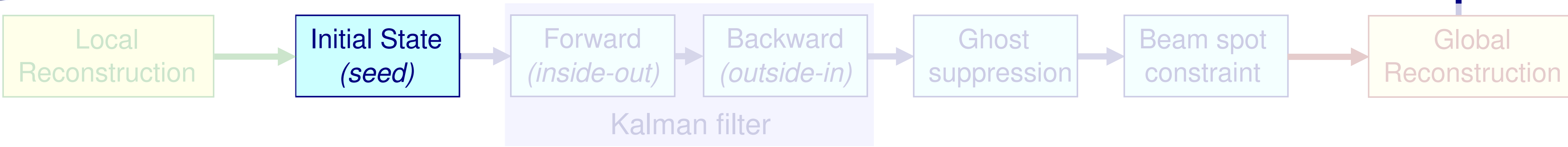


up to ~ 40% at low p_{T}

~10% at 1 TeV/c

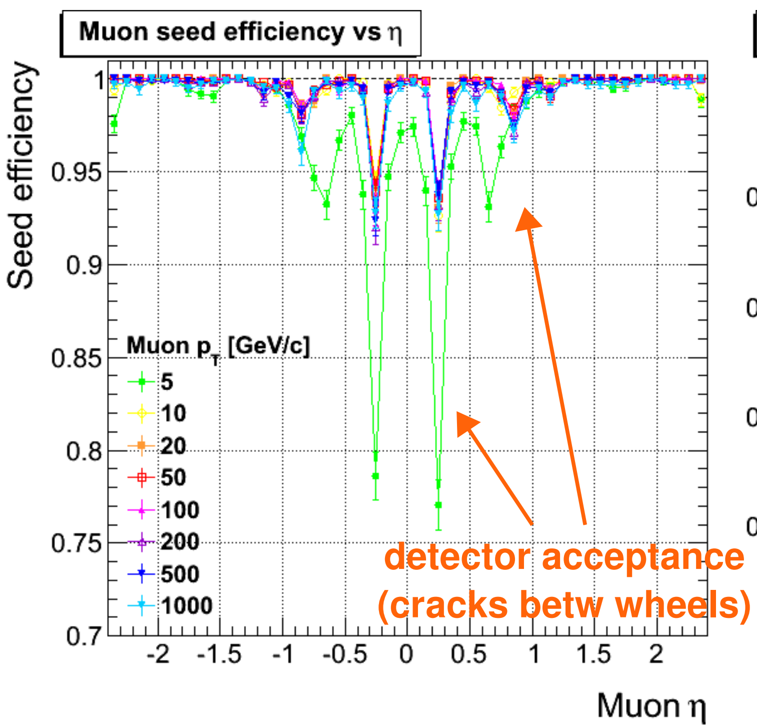


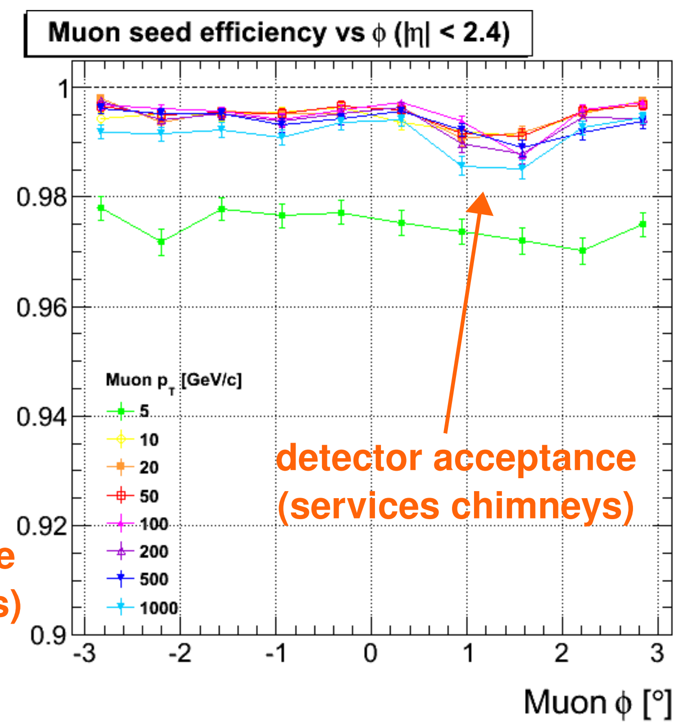
Stand-Alone Reconstruction seed

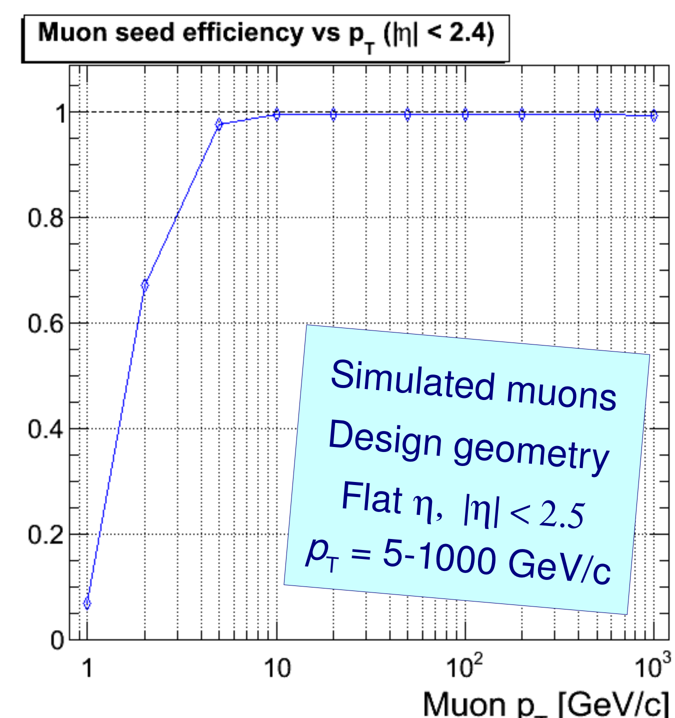


Built using one or more track segments in DT and CSC

p_T parametrized as a function of ϕ slope of segments: $p_T = A - B/\Delta\phi$







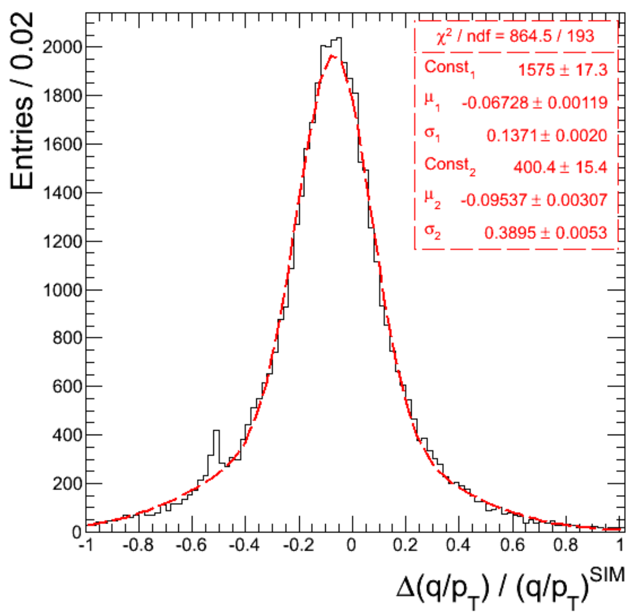
Stand-Alone Reconstruction seed

Local Reconstruction → **Initial State *(seed)*** → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → Global Reconstruction

Kalman filter

q/p_T resolution: $$\frac{(q/p_T)_{MEAS} - (q/p_T)_{SIM}}{(q/p_T)_{SIM}}$$

Fit with a double Gaussian
- the narrow Gaussian for the core of the distribution
- the large Gaussian accounts for tails (mult. scattering)



From the core distribution

- σ → q/p_T resolution
- mean → q/p_T relative bias

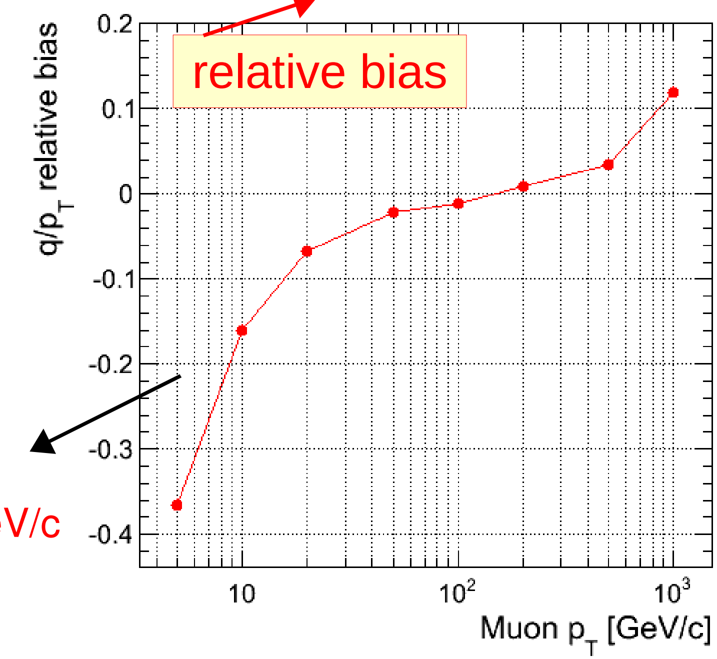
Stand-Alone Reconstruction seed

Local Reconstruction → **Initial State *(seed)*** → Forward *(inside-out)* → Backward *(outside-in)* [Kalman filter] → Ghost suppression → Beam spot constraint → Global Reconstruction

q/p_T resolution: $$\frac{(q/p_T)_{MEAS} - (q/p_T)_{SIM}}{(q/p_T)_{SIM}}$$

Fit with a double Gaussian
- the narrow Gaussian for the core of the distribution
- the large Gaussian accounts for tails (mult. scattering)

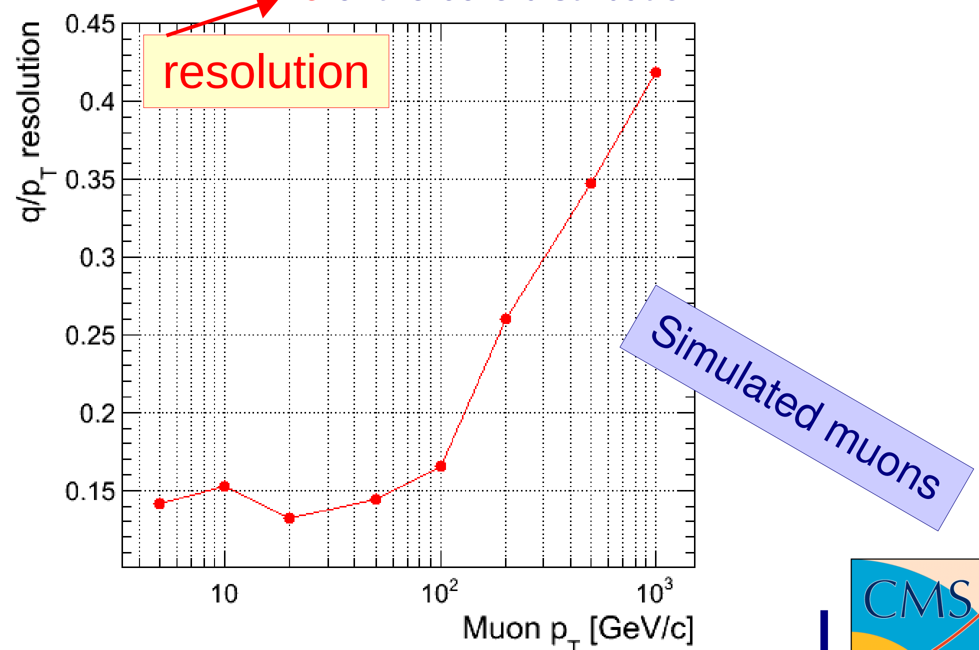
mean of the core distribution



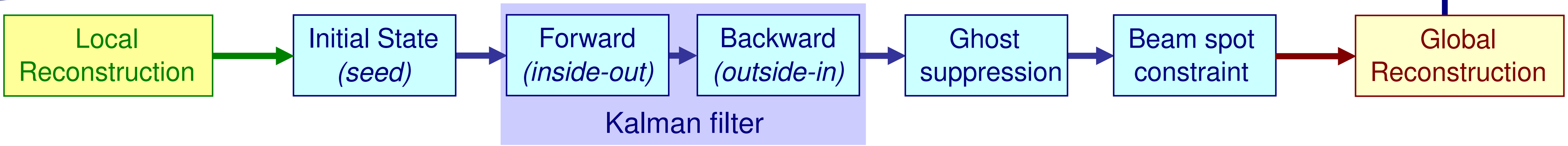
up to ~ 40% at low p_T

~10% at 1 TeV/c

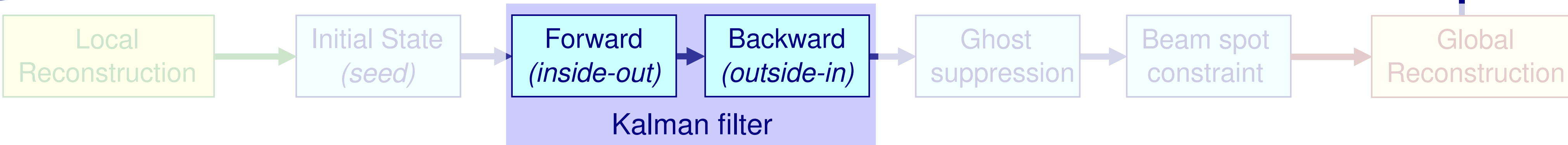
σ of the core distribution

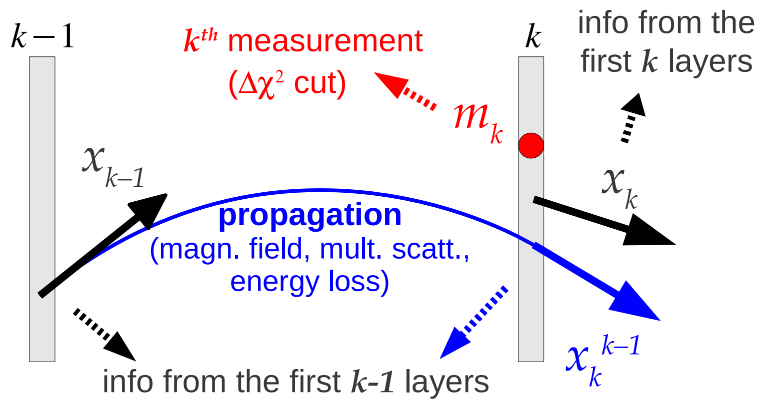


Stand-Alone Reconstruction



Stand-Alone Reconstruction
Kalman filter





Iterative method:

- starts from the intial seed state
- the seed state is propagated to the next layer
- on this layer, the *most compatible* measurement is found (on a χ^2 basis) and used to update the track parameters
- starting from the new state, the procedure is repeated on each reachable layer

Forward filter

- starts from the seed state
- segments in DT and CSC, and individual points in RPC are fitted
- removes possible *biases* from the seed

Backward filter

- starts from the last state of the Forward filter (outermost)
- individual points in DT, CSC and RPC are fitted
- not affected by possible seed biases

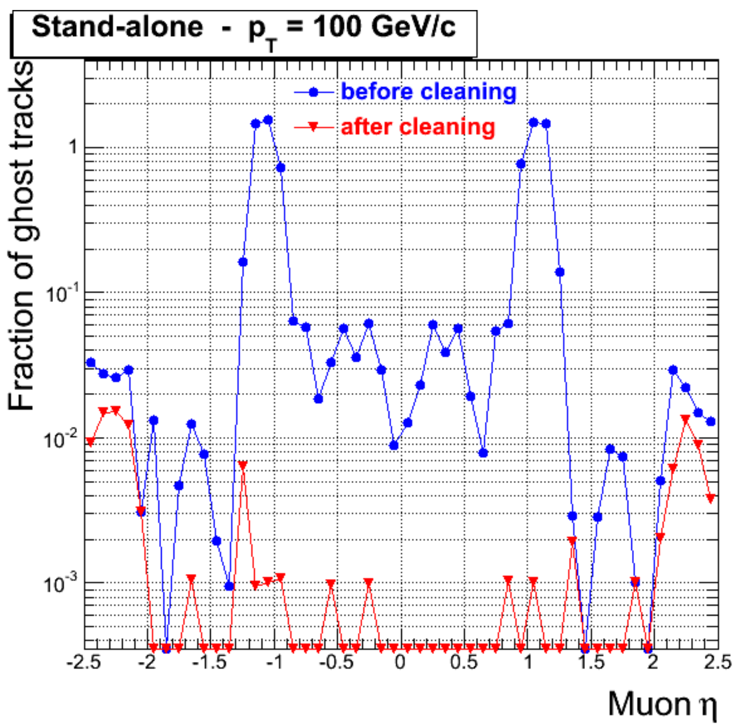
Stand-Alone Reconstruction
Ghost Suppression

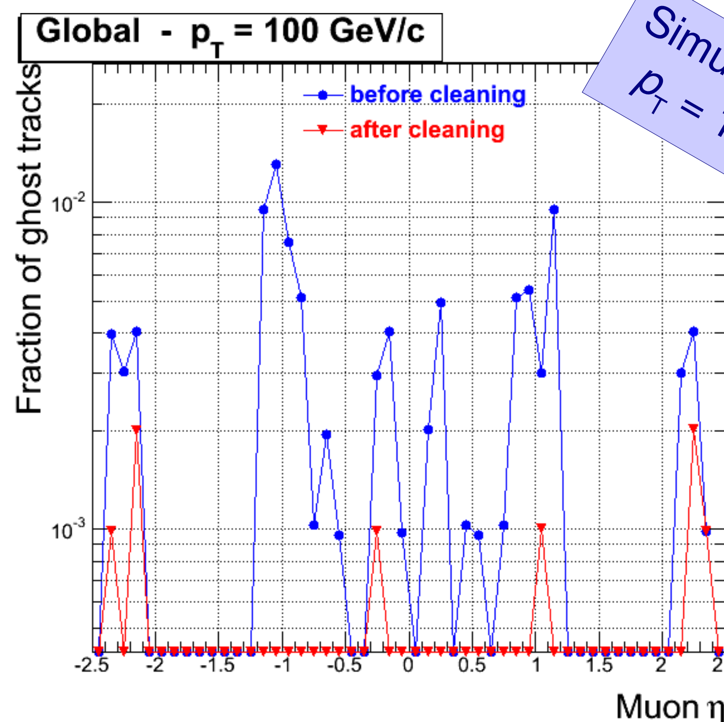
Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → **Ghost suppression** → Beam spot constraint → Global Reconstruction

Kalman filter

The ghost suppression or *cleaning* removes possible duplicates of the same track (coming from multiple seeds for the same miuon)

➔ *if two tracks share any hit, only the highest-quality track is kept, based on number of hits, χ^2/d.o.f. and p_T*

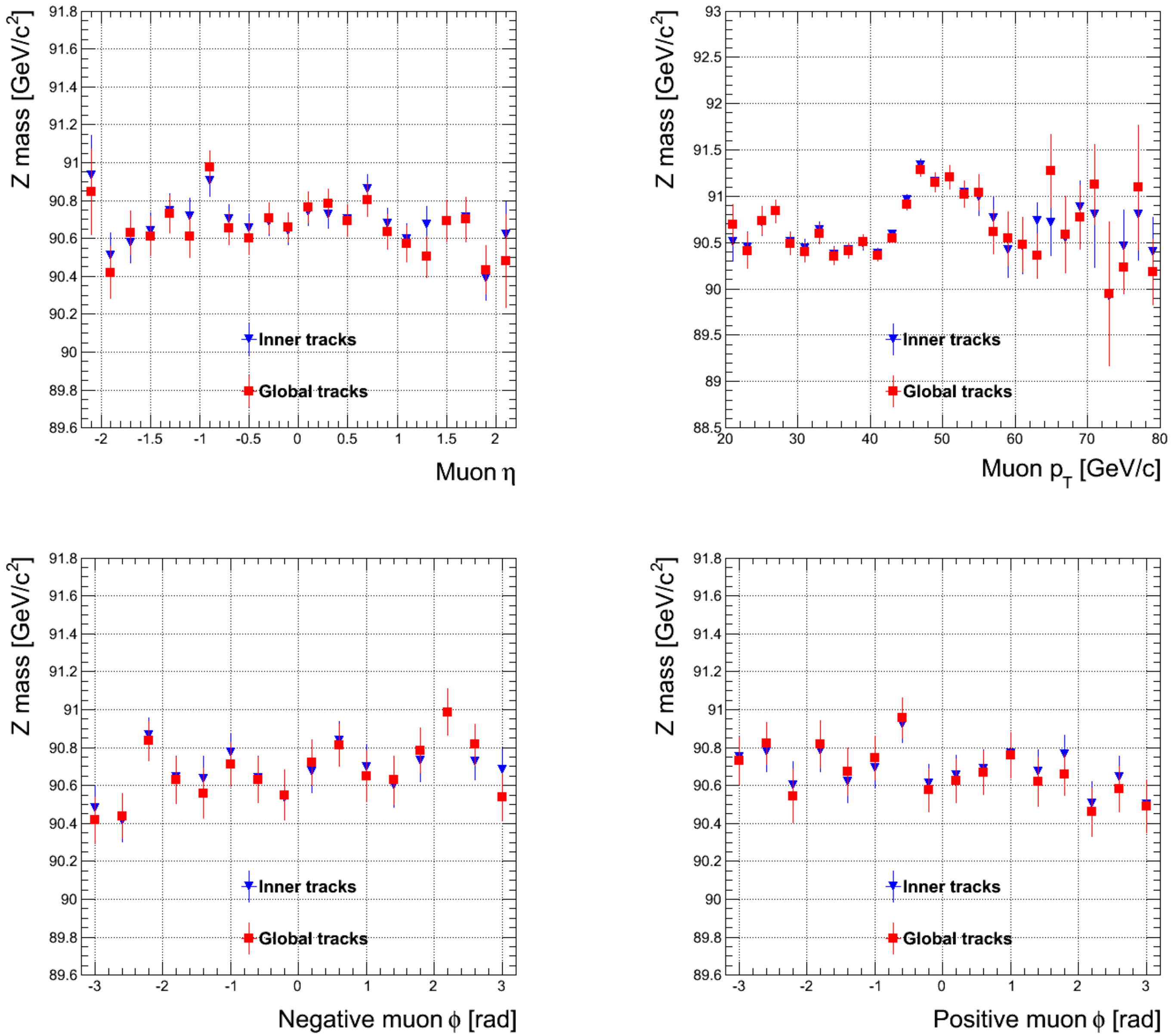




Simulated muons
p_T = 100 GeV/c

Z: Comparison Tracker-Global (I)

Z mass

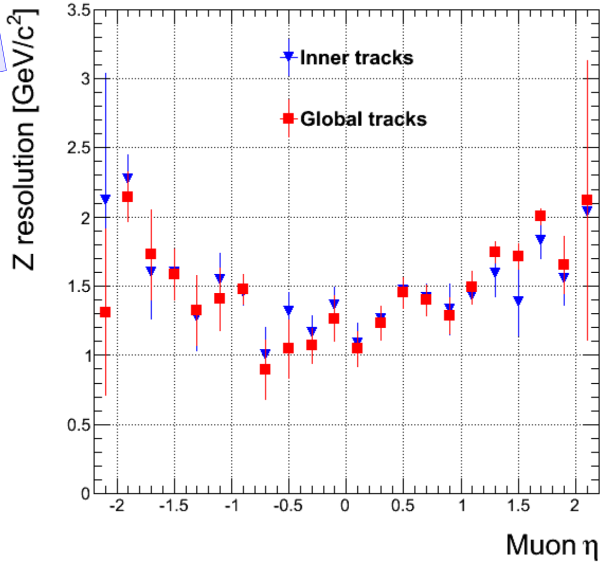


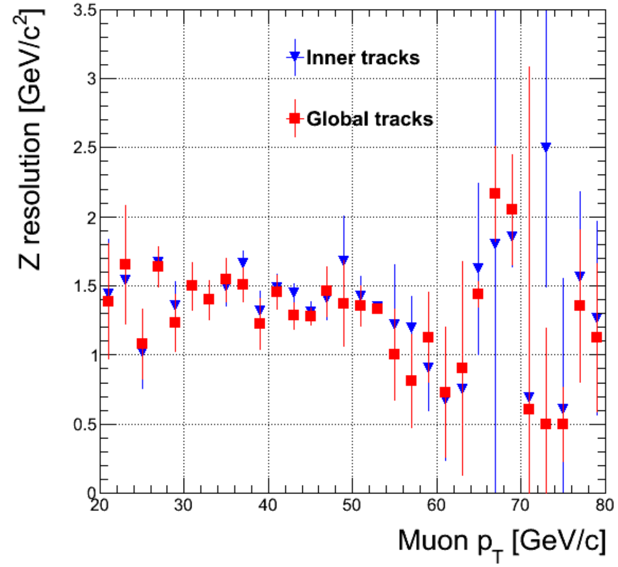
▼ Inner tracks

■ Global tracks

Z: Comparison Tracker-Global (II)

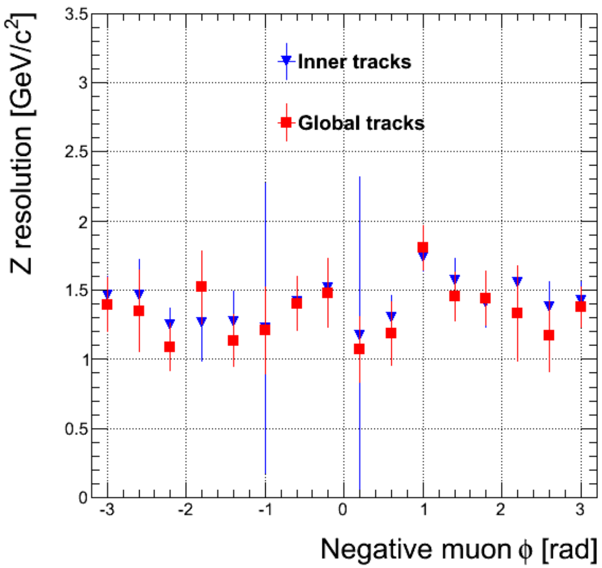
Mass resolution

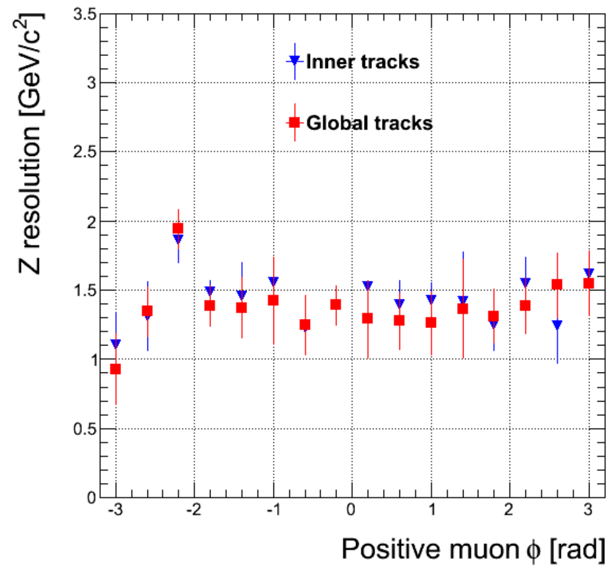




Inner tracks

Global tracks





Reconstruction of Muon Tracks

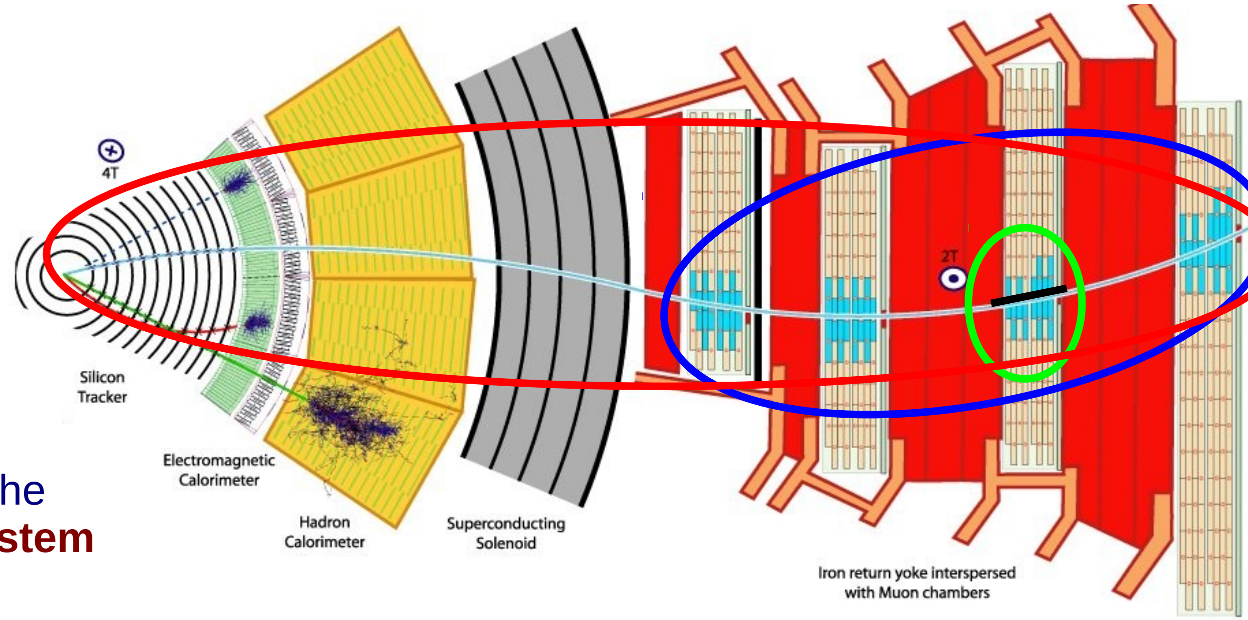
Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → Global Reconstruction

(Forward and Backward: Kalman filter)

1. Local Reconstruction
Reconstruction of **hits** and **track segments** inside a **chamber**

2. Stand-alone Reconstruction (L2)
Reconstruction of the **track** inside the **Muon System**

3. Global Reconstruction (L3)
Reconstruction of the **track** combining the information from **Tracker** and **Muon System**

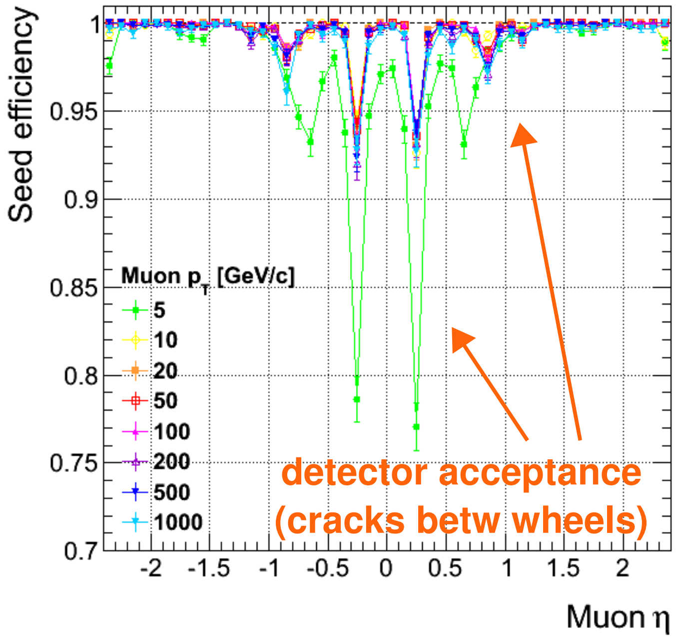


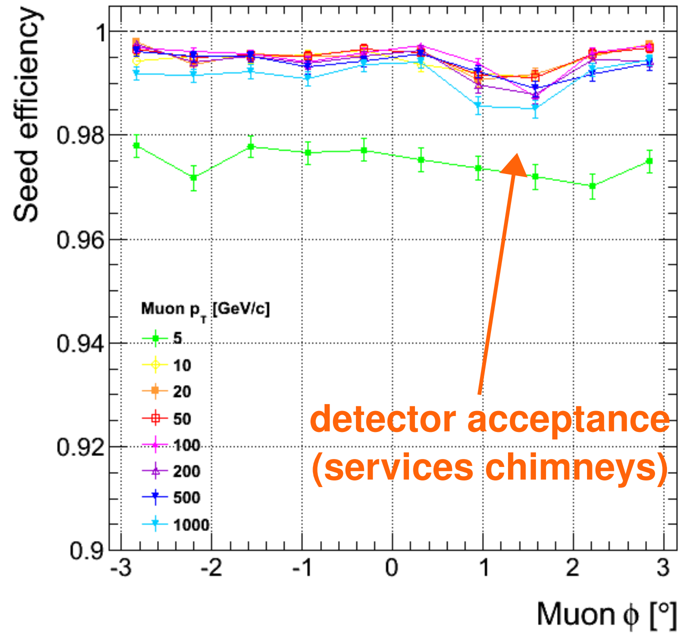
The track is built from position (direction) measurements with an iterative method called Kaman filter, which provides

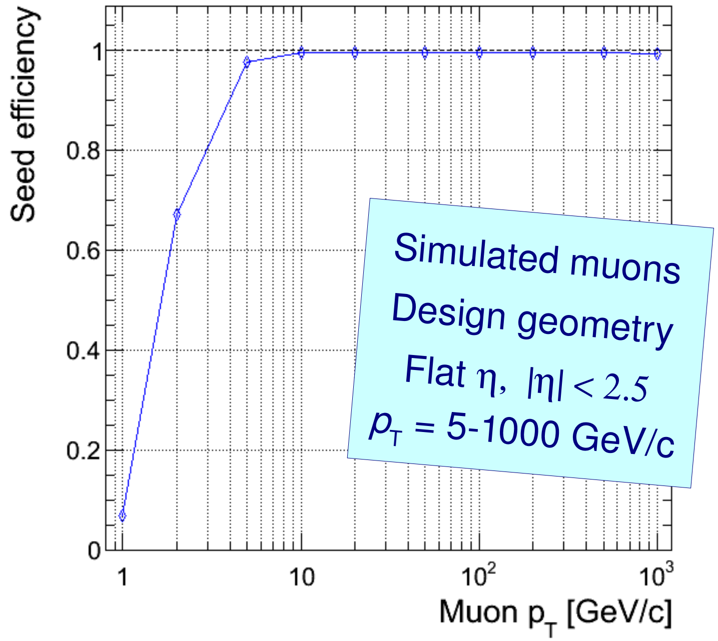
- *pattern recognition* → *collection of hits*
- *best estimation of track parameters* → *minimum* χ^2
- *fast reconstruction* → *well-suited also for HLT*

Stand-Alone Seed Performance

efficiencies



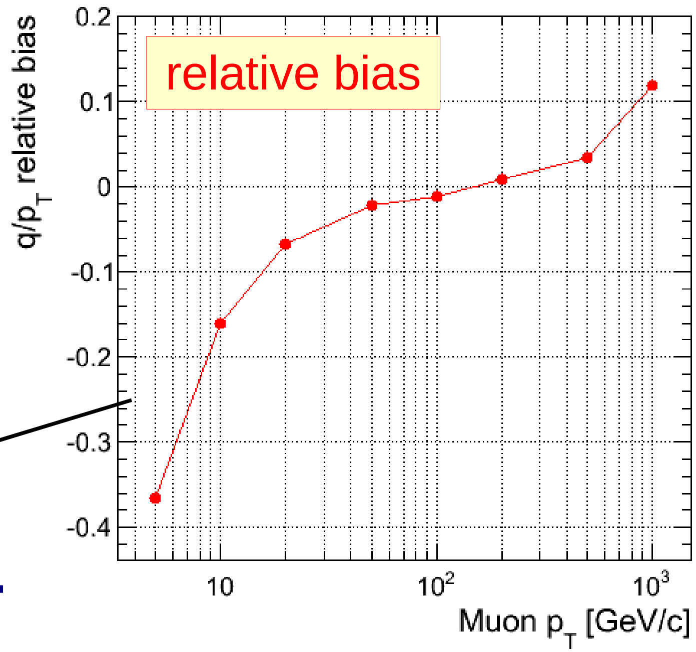


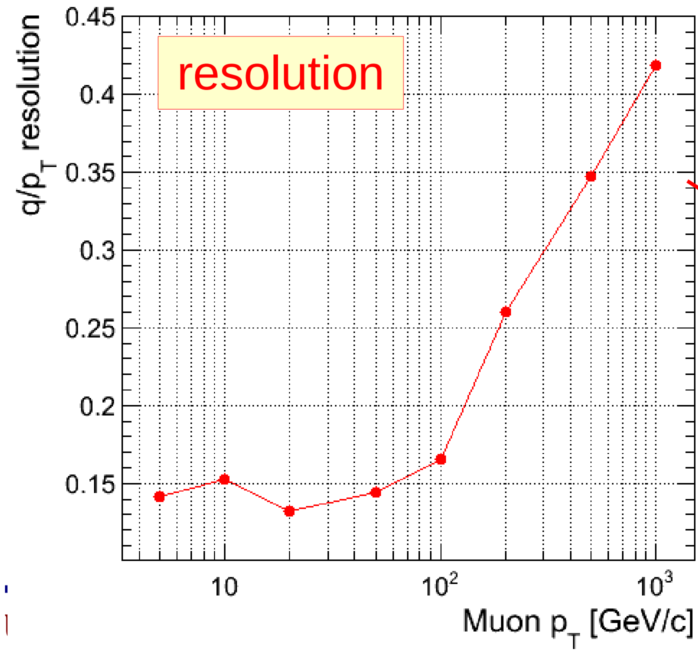


mean of the core distribution of a double Gaussian

up to ~ 40% at low p_T

~10% at 1 TeV/c



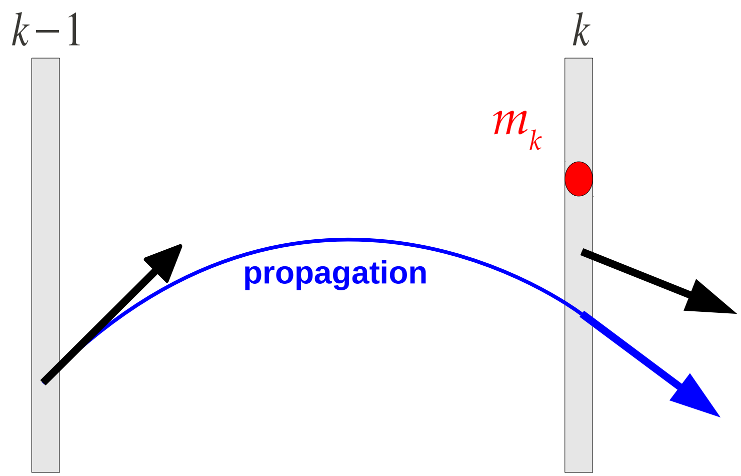


σ of the core distribution of a double Gaussian

Stand-Alone Reconstruction
Kalman Filter

Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → Beam spot constraint → Global Reconstruction

Kalman filter



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Ghost Suppression

Local Reconstruction → Initial State (seed) → Forward (inside-out) → Backward (outside-in) → **Ghost suppression** → Beam spot constraint → Global Reconstruction

Kalman filter

The ghost suppression or *cleaning* removes possible duplicates of the same track (coming from multiple seeds for the same miuon)

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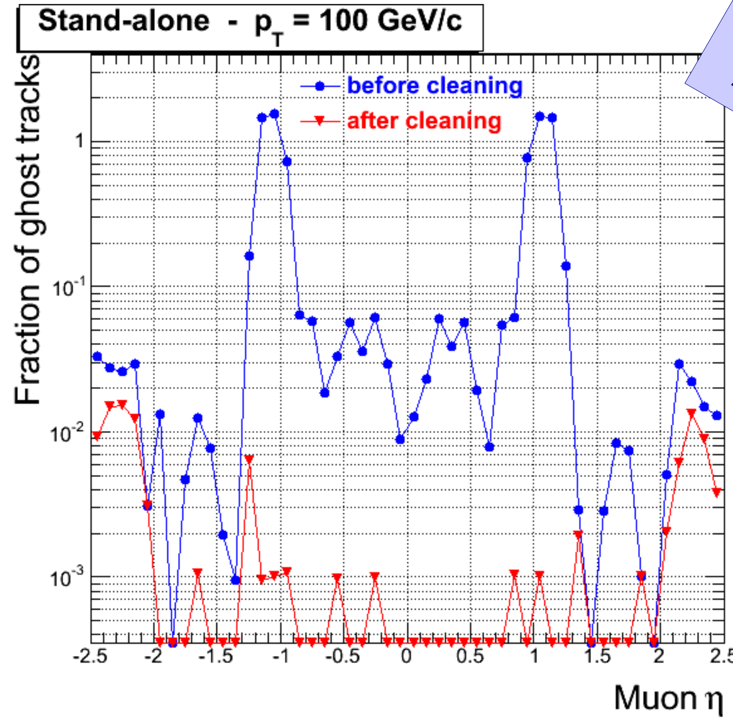


Simulated muons
p_T = 100 GeV/c

Stand-Alone Reconstruction
Beam Spot Constraint

Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* → Ghost suppression → **Beam spot constraint** → Global Reconstruction

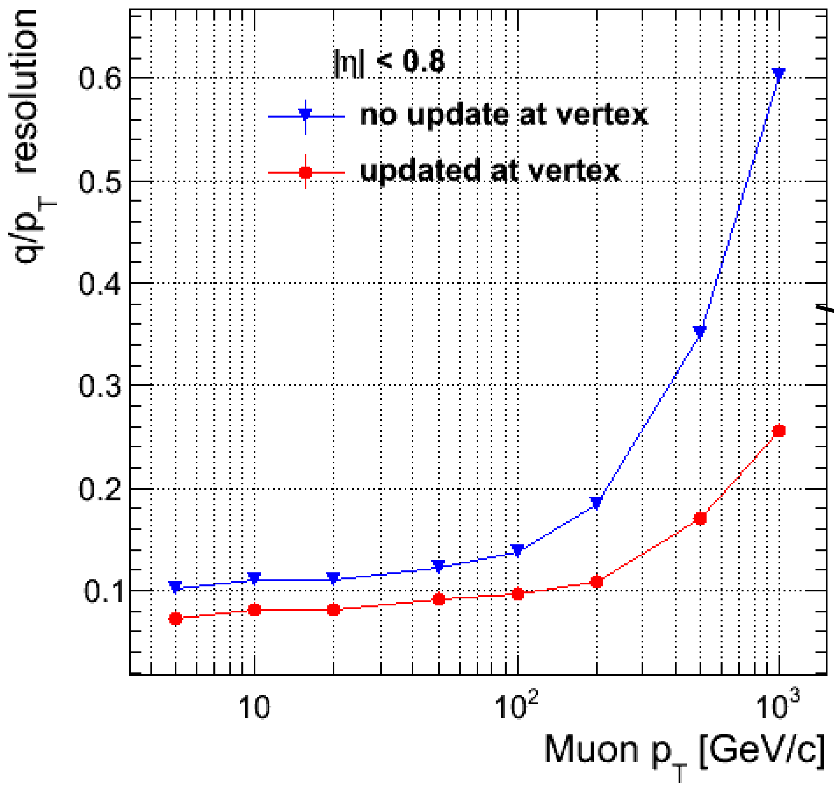
Kalman filter

The track is extrapolated to the *point of closest approach* to the *beam line*

The *beam spot* is constrained to be a point of the track, to improve the p_T resolution

σ of the core of a double Gaussian fit to the distribution

$$\frac{(q/p_T)_{REC} - (q/p_T)_{SIM}}{(q/p_T)_{SIM}}$$



Simulated muons

some % improvement at low pT

up to 30-40% at 1 TeV/c

Stand-Alone Reconstruction
Ghost Suppression and Beam Spot Constraint

Local Reconstruction → Initial State *(seed)* → Forward *(inside-out)* → Backward *(outside-in)* [Kalman filter] → **Ghost suppression** → Beam spot constraint → Global Reconstruction

- The ghost suppression or *cleaning* removes possible duplicates of the same track (coming from multiple seeds for the same muon)

➔ *if two tracks share any hit, only the higher-quality track is kept, based on number of hits, χ^2/d.o.f. and p_T*

- The track is extrapolated to the *point of closest approach* to the *beam line*

The *beam spot* is constrained to be a point of the track, to improve the p_T resolution

some % improvement at low p_T

up to 30-40% at 1 TeV/c

Stand-Alone Reconstruction
Ghost Suppression and Beam Spot Constraint

Local Reconstruction → Initial State (*seed*) → Forward (*inside-out*) → Backward (*outside-in*) → Ghost suppression → **Beam spot constraint** → Global Reconstruction

Kalman filter

- The ghost suppression or *cleaning* removes possible duplicates of the same track (coming from multiple seeds for the same muon)

  ➔ *if two tracks share any hit, only the higher-quality track is kept, based on number of hits, χ^2/d.o.f. and p_T*

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some % improvement at low p_T

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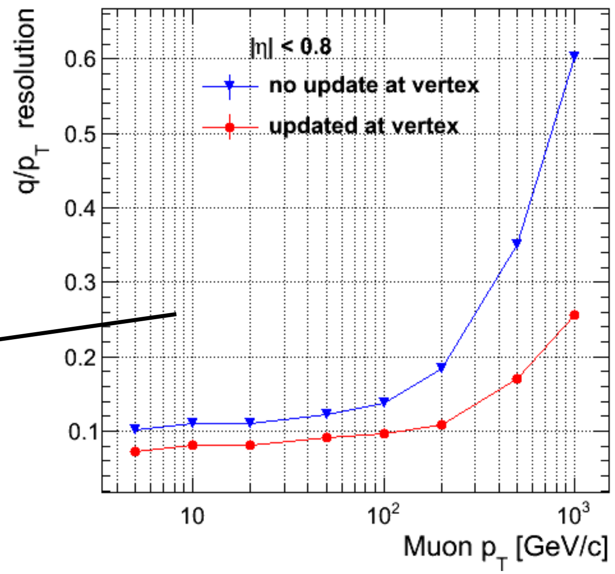


Development of Stand-Alone Reconstruction

- Development and maintenance of the reconstruction software in the muon spectrometer (*stand-alone reconstruction*)
  - development and optimisation of algorithms for *pattern recognition* and *track fitting*
  - improvement of criteria for *ghost track suppression*
  - specialisation for *on-line reconstruction* (HLT)
- Monitoring of reconstruction performance on data and simulation (*stand-alone* and *global* reconstruction)
- Drift Tube chambers
  - DT calibration (responsibility of the CMS Torino group)
  - Since Dec. '09, *contact person* for the operation of the DT FEDs (part of the read-out electronics, designed and produced in Torino)

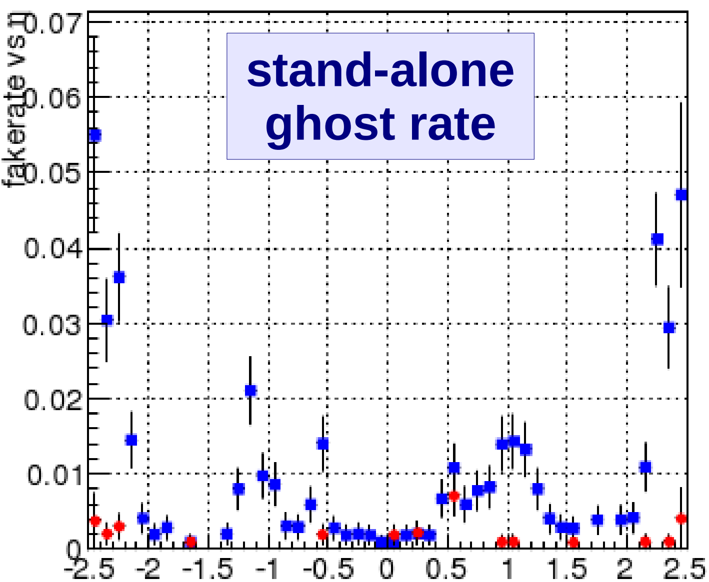
Some Examples (II)

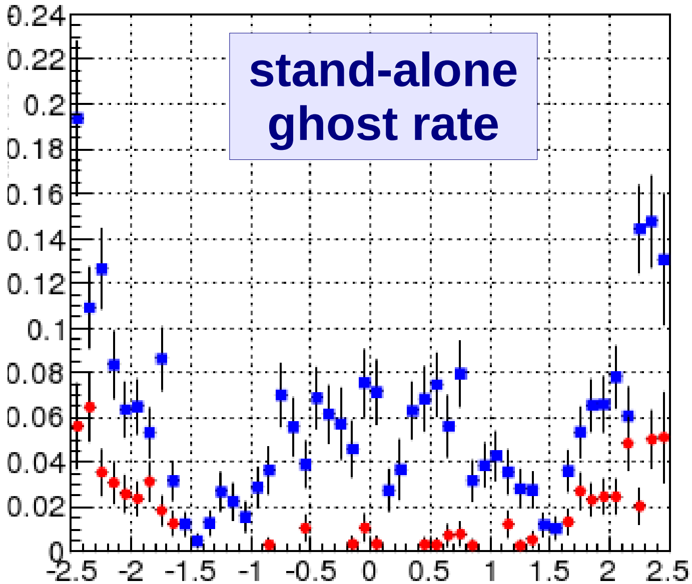
- Ghost suppression stategy and criteria improved,
  in particular to cope with the new features of fitting algorithms

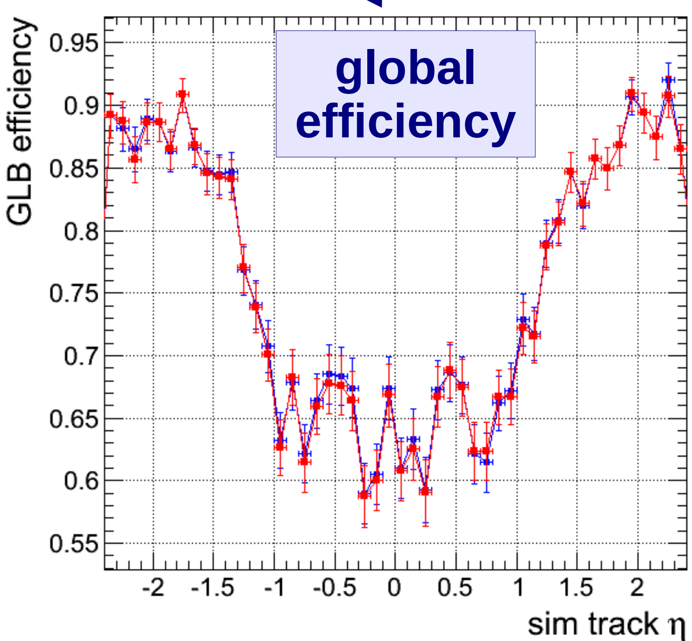
➔ ghost rate decreases, without affecting stand-alone and global efficiencies

MC – single-μ - p_T = 10 GeV/c

MC – J/ψ → μμ







– default ghost suppression
– new cleaning criteria

Some Examples (II)

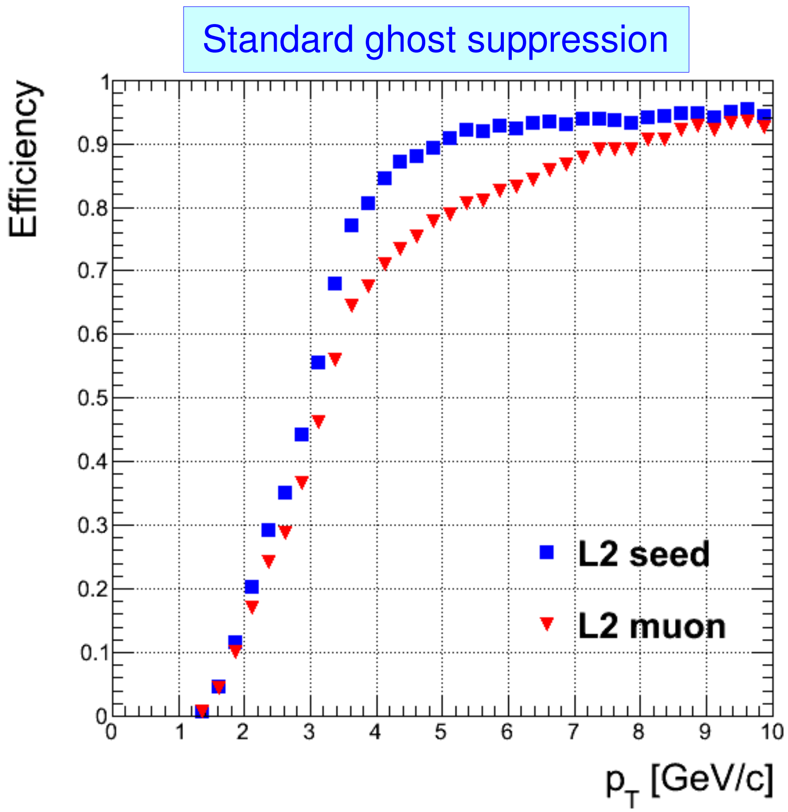
In the *trigger* reconstruction, the initial state (seed) comes from the *Level-1* trigger electronics

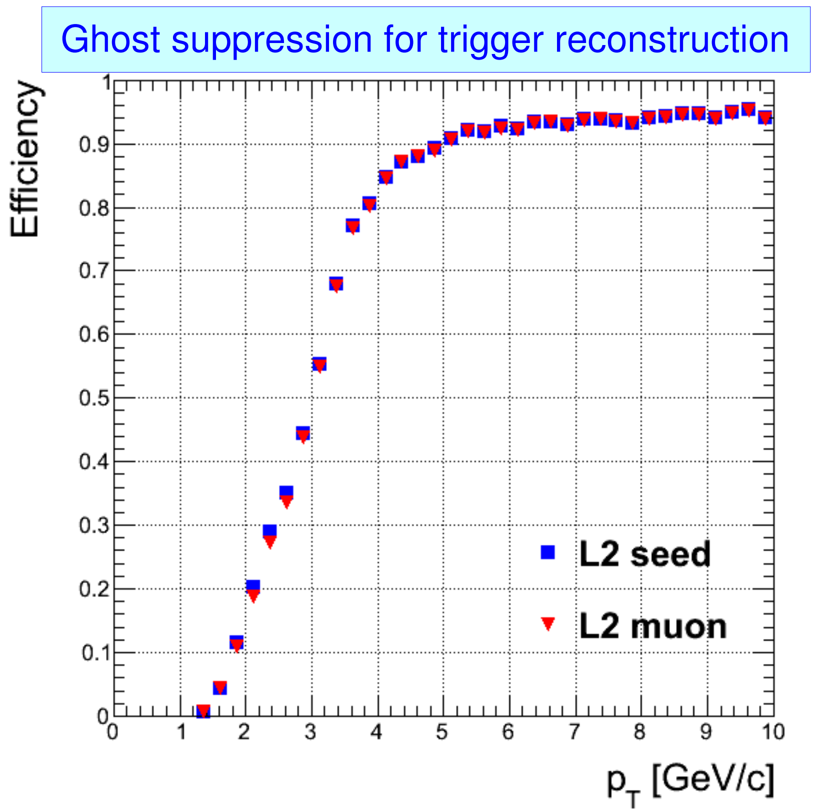
The same muon can produce multiple Level-1's → multiple seeds → *ghost tracks*

Ghost suppression is crucial:

- reject ghosts
- do not affect the efficiency

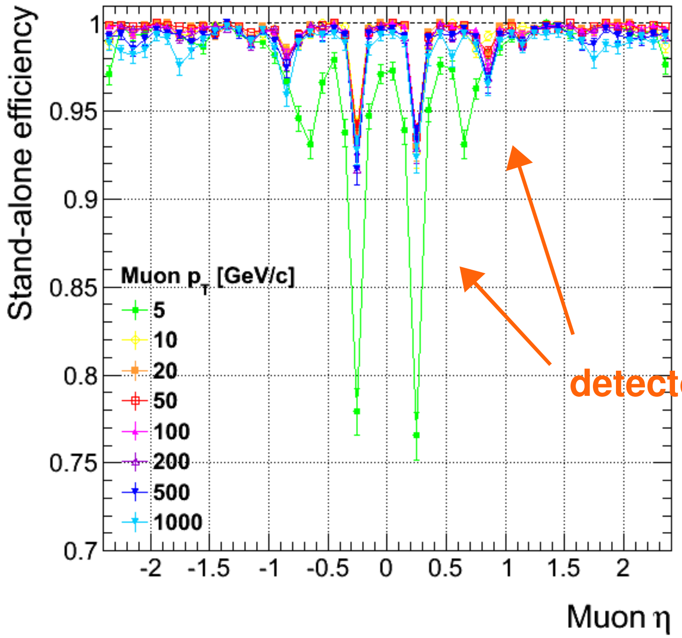
⇨ *ghost suppression specialised for on-line reconstruction*



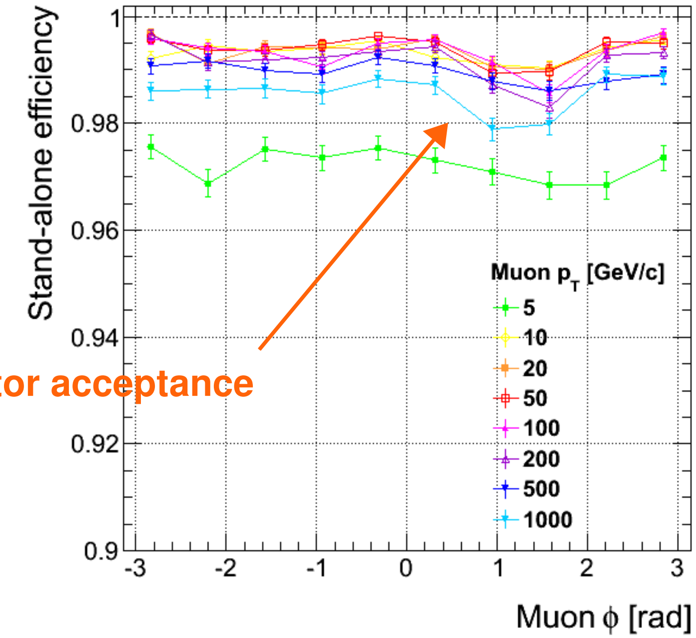


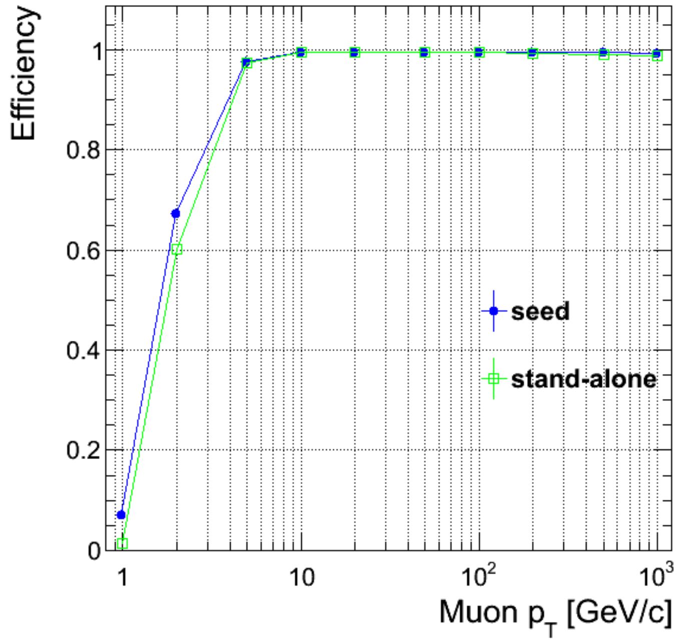
Performance of Reconstruction in Simulations
Stand-Alone Muons

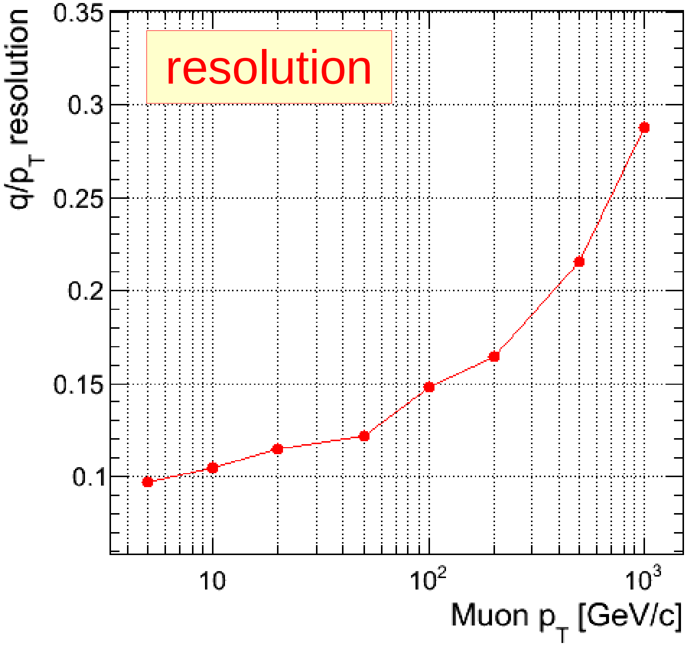
efficiencies

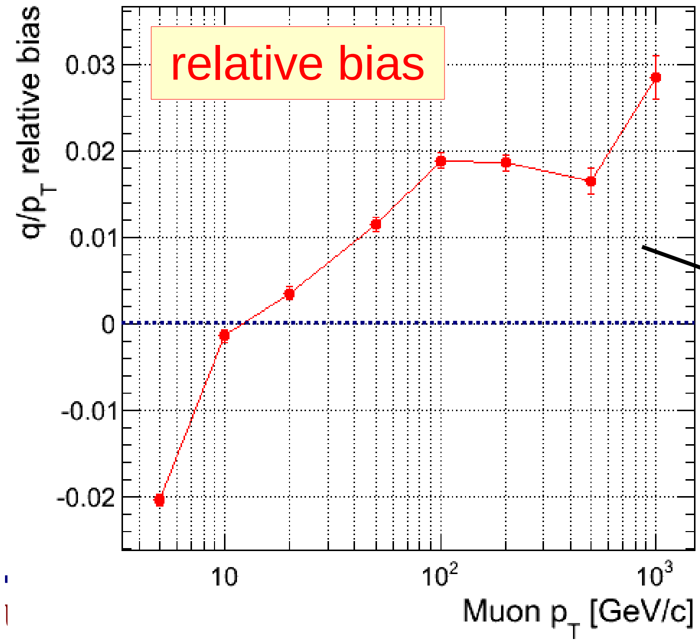


detector acceptance





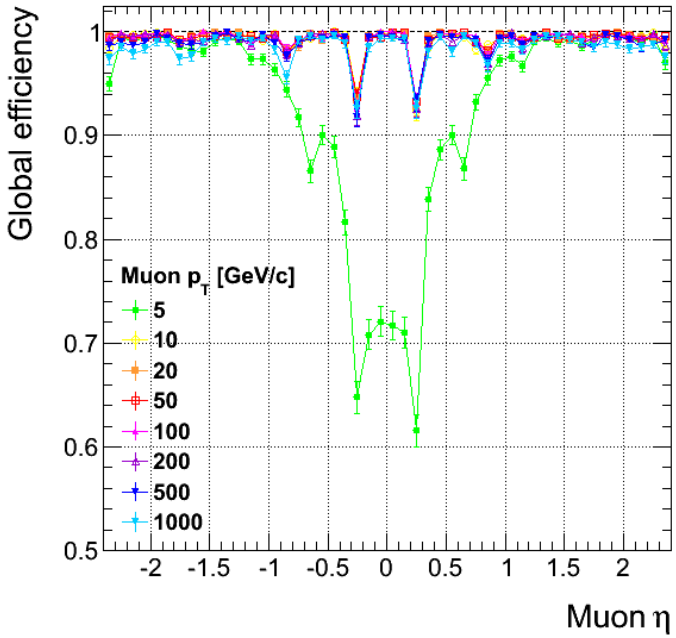


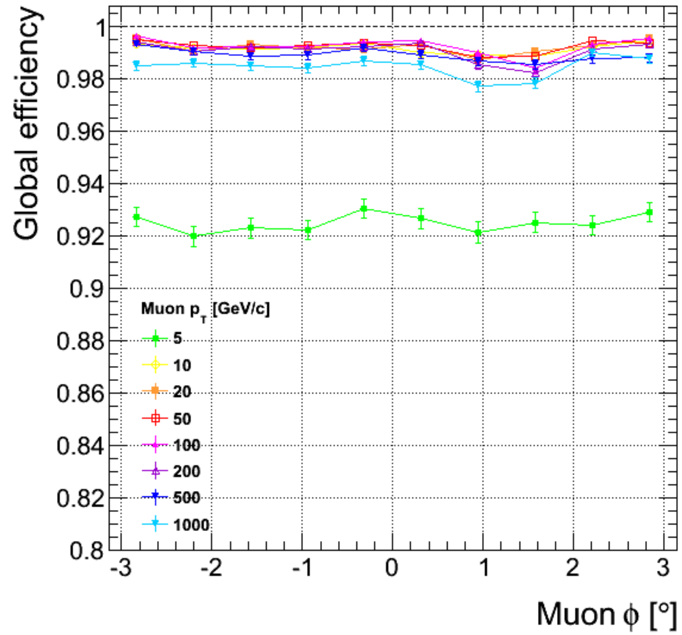


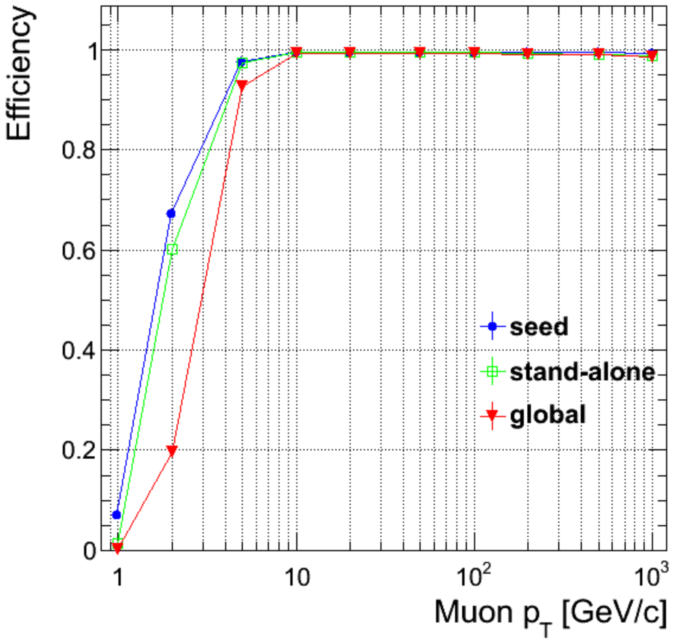
bias up to ~ 2-3%

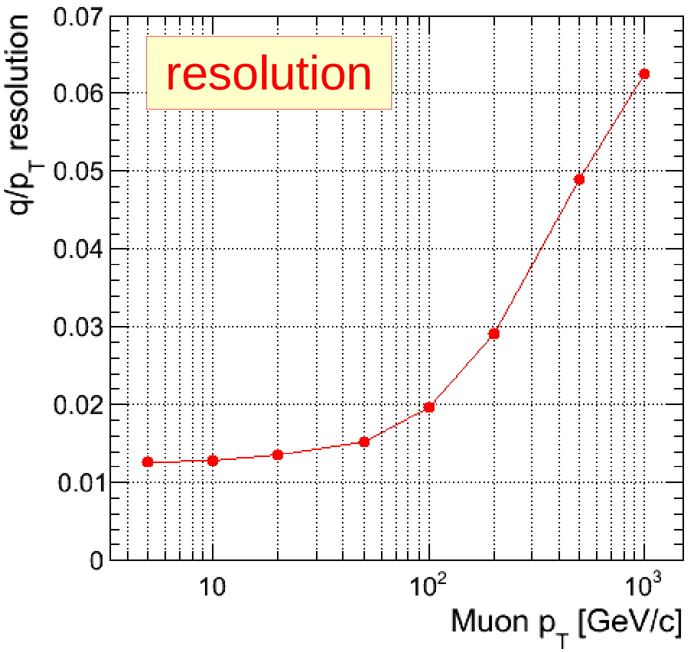
Performance of Reconstruction in Simulations Global Muons

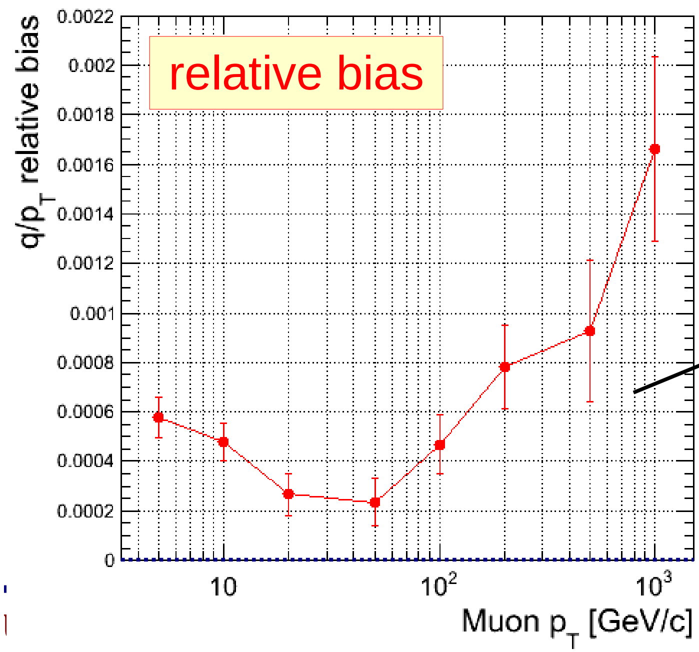
efficiencies







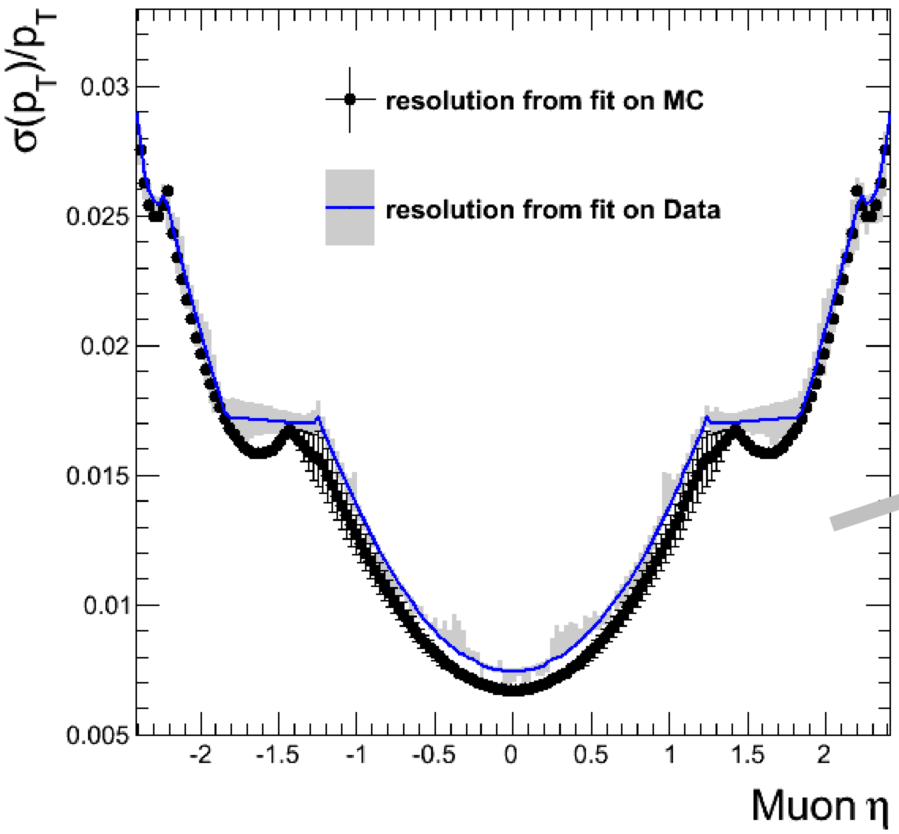




< 0.1% up to 500 GeV/c

J/ψ: p_T Resolution

Resolution function after the fit



$$\frac{\sigma(p_T)}{p_T} = \begin{cases} f(p_T) + a_3 + a_4\,\eta^2 & \text{for } |\eta| \le a_0 \\ (|\eta| - a_0)\,(y_2 - y_1)/(a_1 - a_0) + y_1 & \text{for } a_0 < |\eta| \le a_1 \\ f(p_T) + a_5 + a_6\,(|\eta| - a_7)^2 & \text{for } a_1 < |\eta| \le a_2 \\ f(p_T) + a_8 + a_9\,(|\eta| - a_{10})^2 & \text{for } |\eta| > a_2 \end{cases}$$

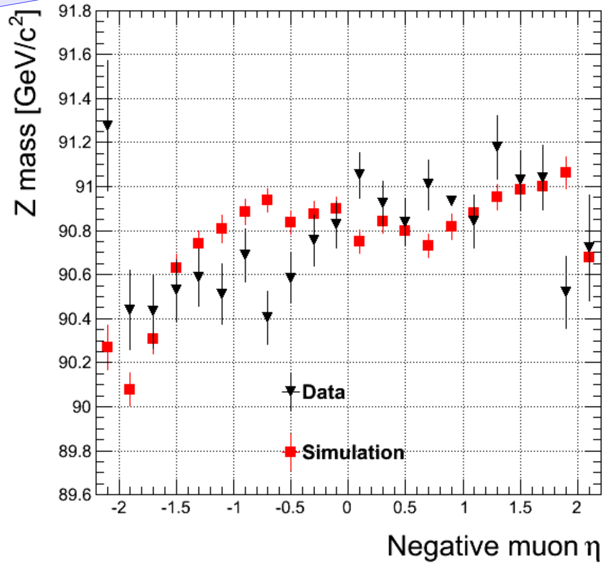
The gray band accounts for statistical and systematic uncertainties

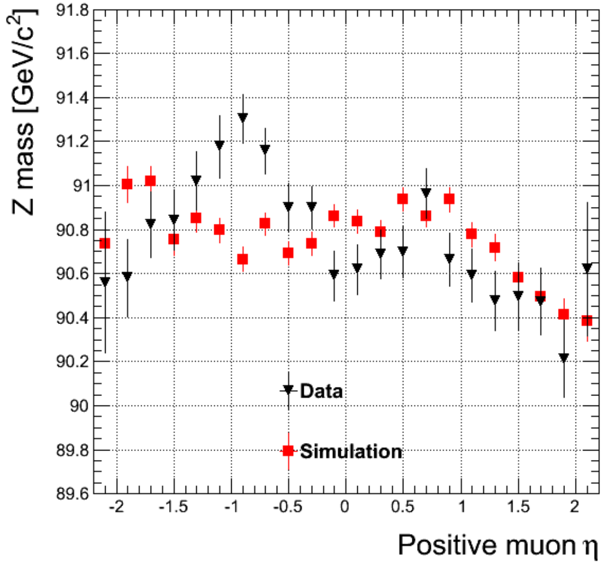
Systematic error is estimated as the difference between the resolution function fit on MC and the MC truth

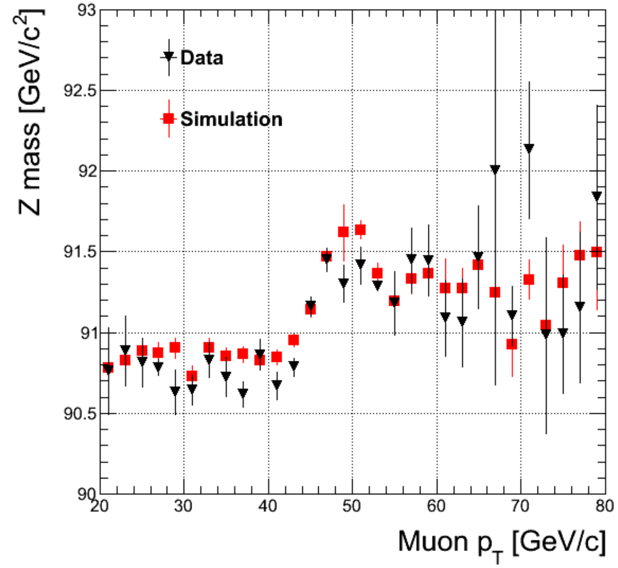
Momentum Calibration Using Z

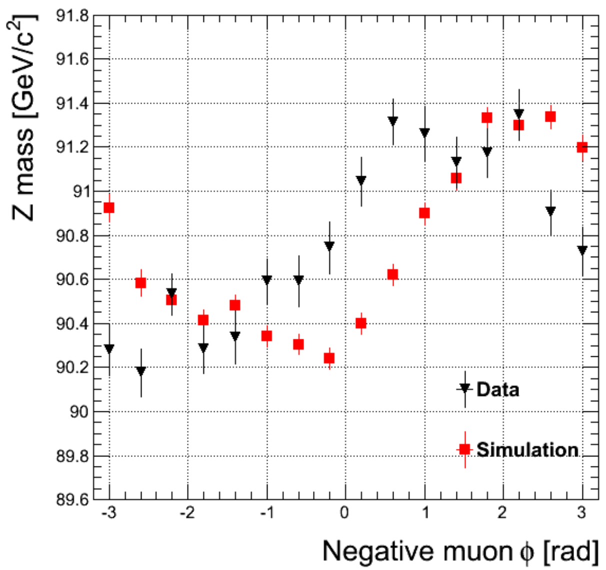
- ■ Simulated $Z \rightarrow \mu\mu$ sample with realistic alignment conditions (O(100 pb^{-1}))
- ▼ $Z \rightarrow \mu\mu$ candidates from 2010 CMS data (~ 30 pb^{-1})

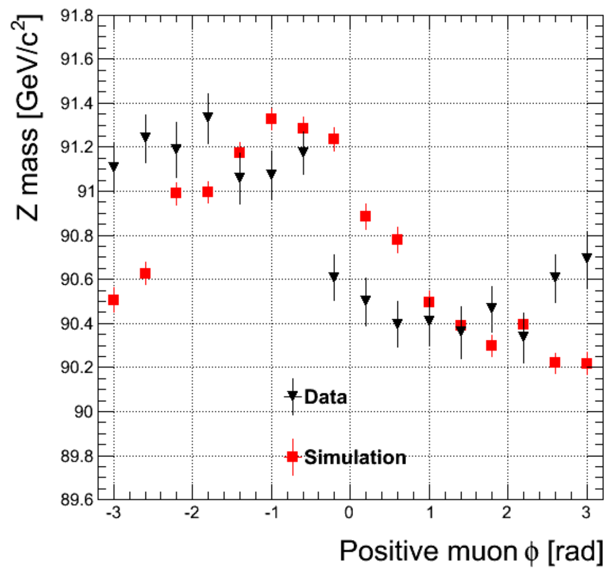
Z mass









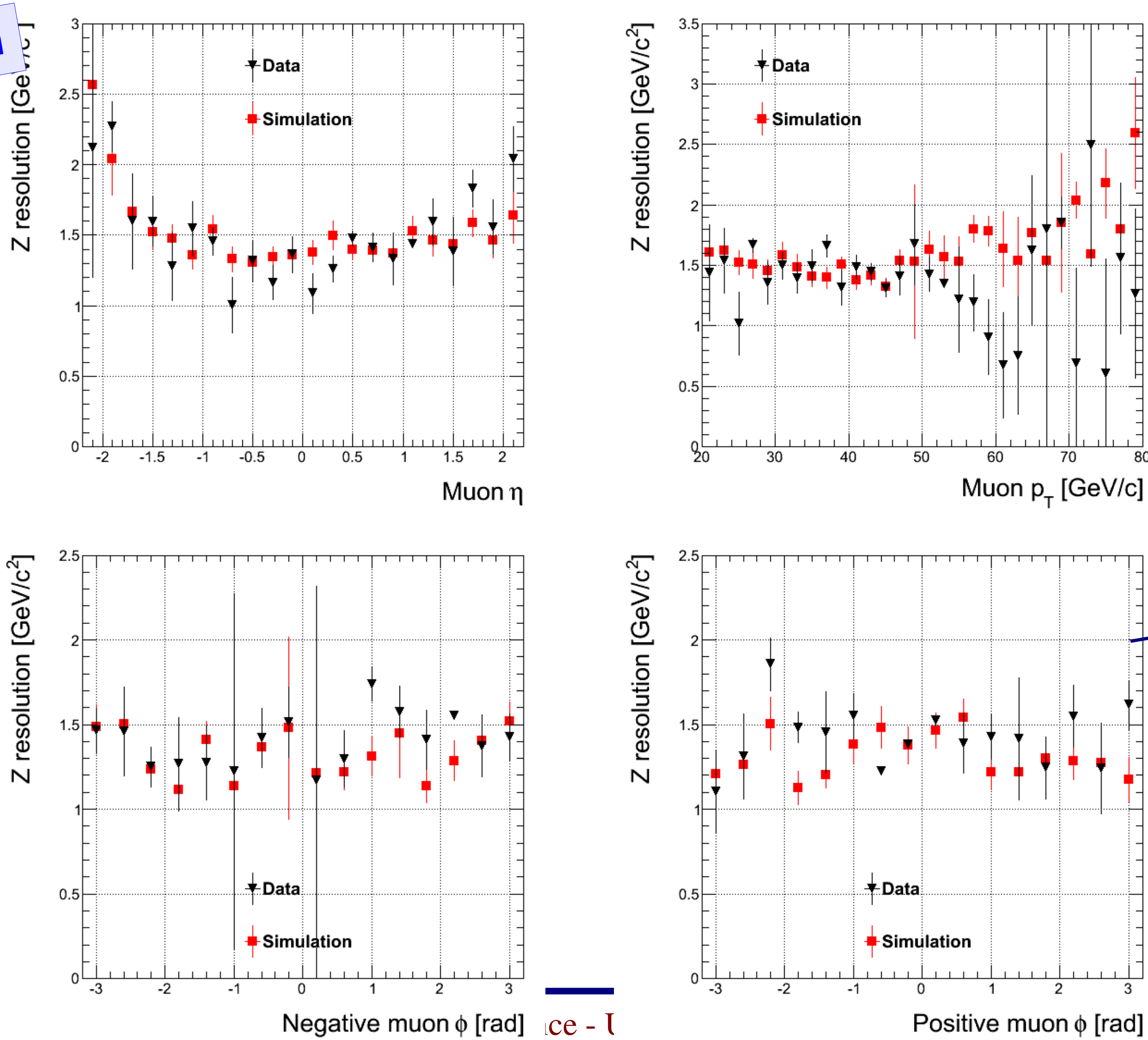


→ mean of Voigtian fits to mass distributions in each bin

Momentum Calibration Using Z

- ■ Simulated $Z \to \mu\mu$ sample with realistic alignment conditions ($\mathcal{O}$(100 pb^{-1}))
- ▼ $Z \to \mu\mu$ candidates from 2010 CMS data (~ 30 pb^{-1})

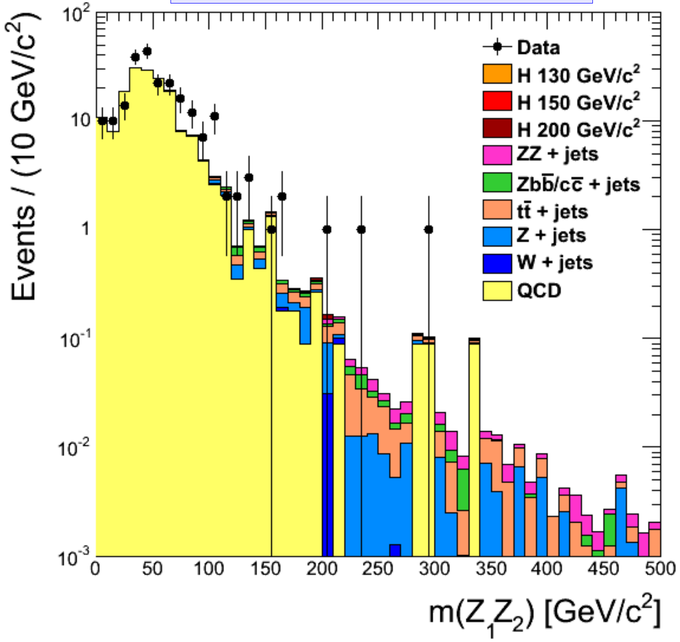
Mass resolution



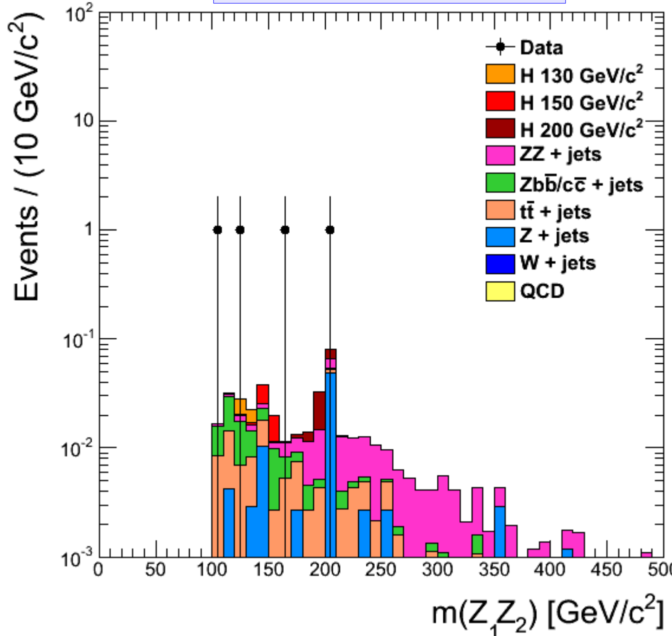
Gaussian σ of Voigtian fits to mass distributions in each bin

Results on Data (32 pb^{-1})

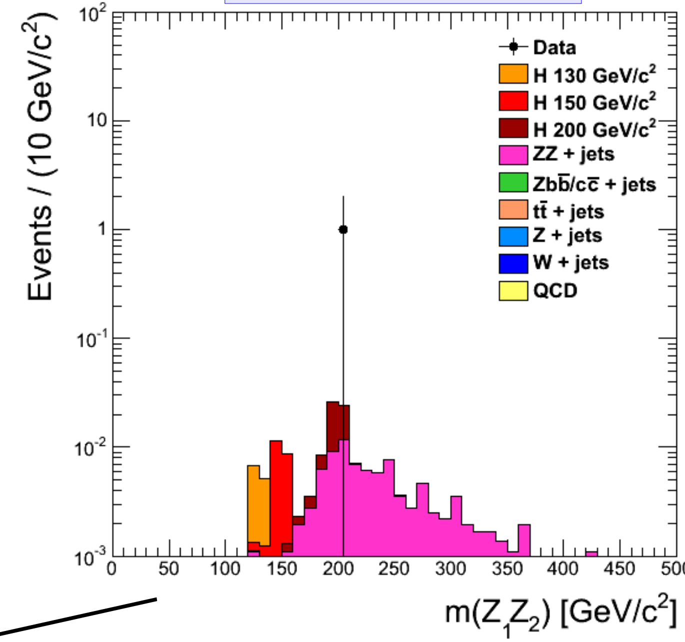
After HLT + skimming



After preselection



After full selection



4μ inv. mass [GeV/c²]	2μ inv. mass [GeV/c²]	Muon p_T [GeV/c]
201.7	92.12	19.56
		25.88
	92.23	48.14
		43.44

all isolated, with S_{IP} ~ 0

At $\sqrt{s}$ = 7 TeV, L = 32 pb^{-1}:

Prob (1 evt ZZ → 4μ) = 0.08

Prob (1 evt ZZ → 4ℓ) = 0.23

Prob (1 evt H → 4μ) = 0.032

Prob (1 evt H → 4ℓ) = 0.099