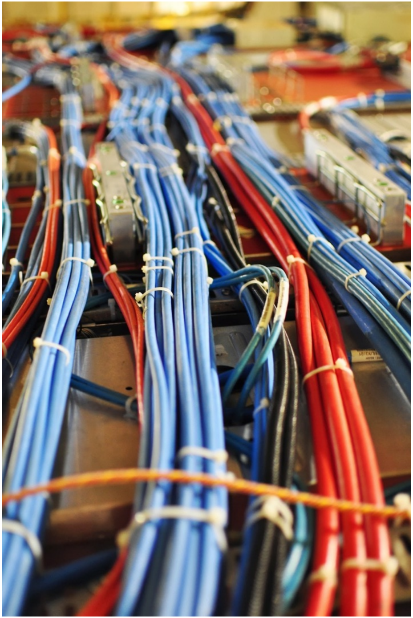
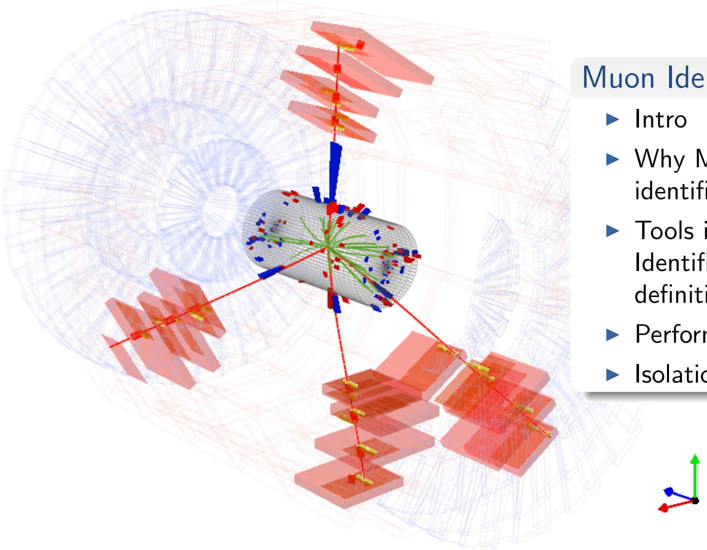


4. Muons in data analysis

Piet Verwilligen

INFN Sezione di Bari

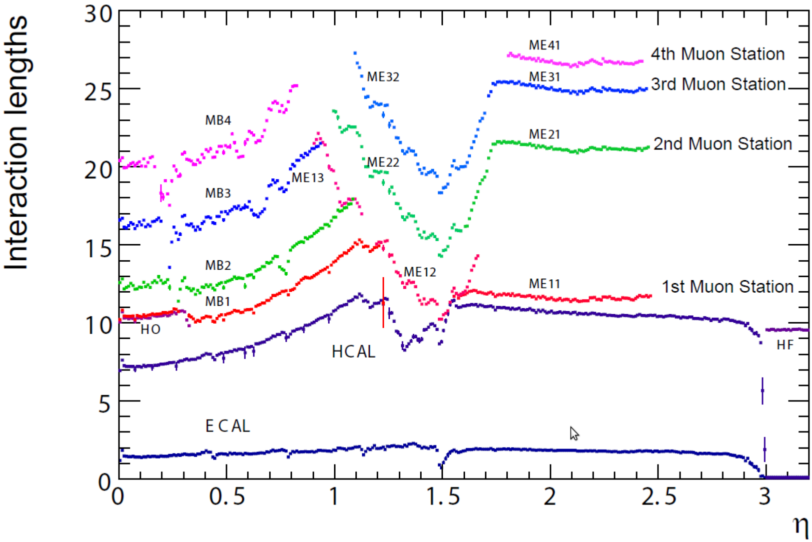
Capita Selecta in HEP
Vrije Universiteit Brussel
April 9-10, 2014



Muon Identification

- Intro
- Why Muon identification?
- Tools in hand & Identification definitions
- Performance
- Isolation

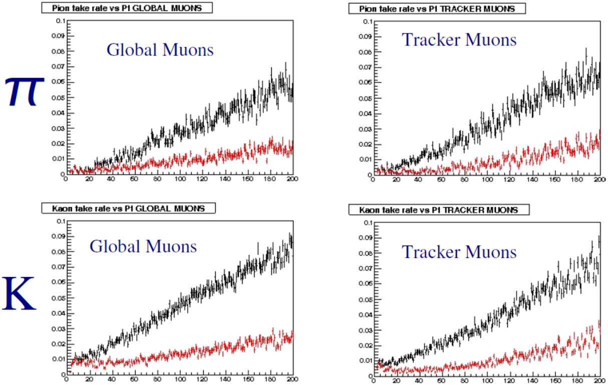
Why Muon identification?



Riccardo Bellan — https://indico.cern.ch/event/210563/

Why Muon identification?

- Out-of-the-box Global and Tracker Muon pion/kaon fake rates



Black: total contribution

Red: decays in flight
(existence of Sim-level muon)

As a function of pT (GeV)

Global Muons at 100 GeV/c

- Pion Fake rate: 3% (total) 1% (decay)
- Kaon Fake rate: 5% (total) 1% (decay)

Tracker Muons at 100 GeV/c

- Pion Fake rate: 3% (total) 0.75% (decay)
- Kaon Fake rate: 3% (total) 0.75% (decay)

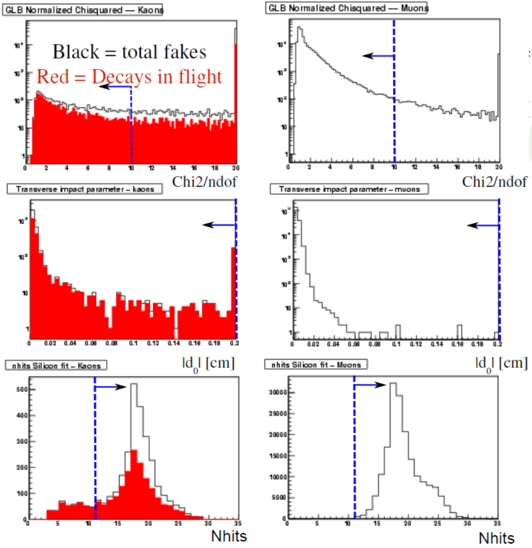
Riccardo Bellan — https://indico.cern.ch/event/210563/

Tools available for identification

Handles for Global Muon ID fake rejection

- Inner track information:
  - hits in pixel tracker
  - hits in strip tracker
  - quality of the track fit (χ^2/ndof)
  - kink in track?
  - impact parameters
- Calorimeter based information:
  - energy deposition in ECAL and HCAL (compatible with MIP?)
- Muon system information:
  - hits and segments in muon system
  - penetration depth in muon system
  - Stand-Alone muon quality
- Global Fit information: fit quality (χ^2/ndof)

Why Muon identification?



Riccardo Bellan — https://indico.cern.ch/event/210563/

Kaons vs Muons

- **Quality of Global Muon fit ::** $\chi^2/\text{ndof} < 10$

  ... but long tails ...

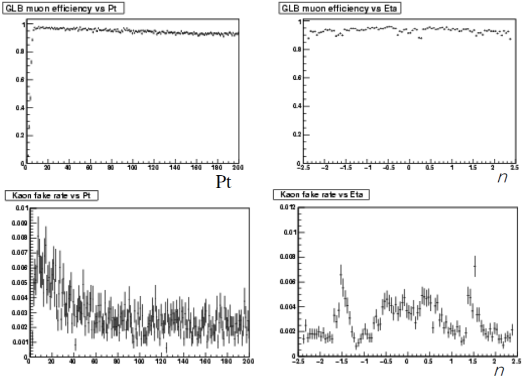
- **Inner track ::** $d_{xy} < 0.2\,\text{cm}$

  ... room for optimization

- **Inner track ::** $n_{\text{hits}} > 11$

  ... could be made as function of η

Why Muon identification?



Riccardo Bellan — https://indico.cern.ch/event/210563/

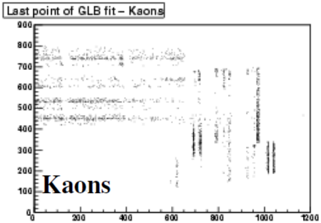
- **Cuts used:**
- Global Muon fit: $\chi^2/\text{ndof} < 10$
- Inner track :: $d_{xy} < 0.2\,\text{cm}$
- Inner track :: $n_{\text{hits}} > 11$

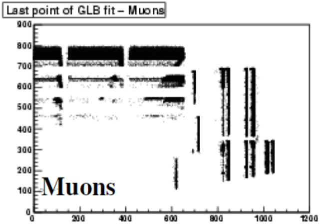
- **Results:**
- Muon ID efficiency high
- Kaon Fake Rate reduced with factor 10

  0.3% vs 3% (before) at 100 GeV/c

Why Muon identification?

- Reduce fakes from punch-through further by removing muons whose global fit ends in the first station of the muon detector
  - if (abs(z) < 660 && r > 400 && r < 480) keepMuon = false;
  - If (abs(z) > 600 && abs(z) < 650 && r < 300) keepMuon = false;
  - If (abs(z) > 680 && abs(z) < 730 && r < 480) keepMuon = false;





- Rejecting these muons results in a ~20% reduction in fake rate at very little cost in efficiency
- Notice many global fits for real muons end in the first layer of the endcap muon system. This problem is fixed in CMSSW 2_2_X

Muon Identification :: 4 definitions

Soft Muon ID :: [muons from b-decays]

- **Tracker Muon Arbitrated** (TMA)
- **TMOneStationTight:** Tracker track matched with at least one muon segment in both X and Y coordinates ($< 3\sigma$)
- number of strip tracker hits > 5
- number of pixel tracker hits > 1
- χ^2/ndof of inner track Fit < 1.8
- inner track transverse impact parameter $d_{xy} < 3$ cm
- inner track longitudinal impact parameter $|d_z| < 30$ cm

High Pt Muon ID :: [high p_T muons]

- p_T and inner track defined by TuneP
- Tight ID without PF ID & χ^2/ndof < 10
- $\Delta p_T / p_T < 0.3$

Tight Muon ID :: [muons from W,Z]

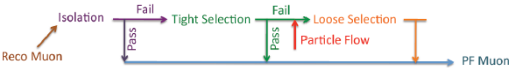
- muon reconstructed as **Global Muon**
- muon identified as **Particle Flow Muon**
- χ^2/ndof of Global Muon Fit < 10
- at least 1 muon chamber hit included in the Global Fit
- muon segments in at least 2 stations
- inner track transverse impact parameter $d_{xy} < 0.2$ cm
- inner track longitudinal impact parameter $|d_z| < 0.5$ cm
- number of pixel tracker hits > 0
- number of strip tracker hits > 5

Loose Muon ID :: [multiple muons]

- **PF Muon**
- TMA OR Global Muon

Particle Flow Muon Identification

- The starting point for PF muon selection is “standard” global and tracker muons.
  - In this respect, it is similar to many other selections, e.g., those adopted by the EWK and top PAGs (but there are plans to include standalone muons as well).
- The main novelty is the two-step selection applied to non-isolated muon candidates:



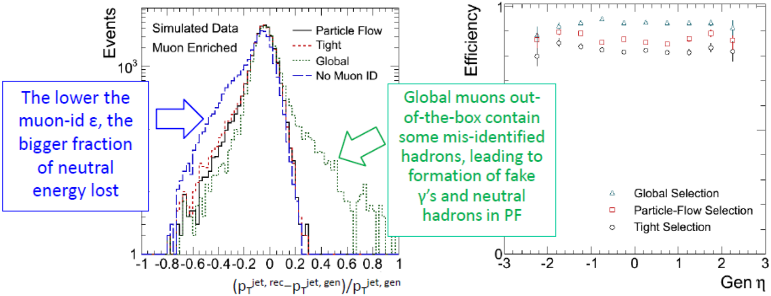
  - If the muon is reconstructed as global and isolated (scalar sum of p_T and E_T in a cone of $\Delta R < 0.3$ smaller than $0.1 \cdot p_T^{\mu}$), no extra cuts are applied.
  - If it is not, it has two chances to be selected:
    - Before PF algorithm is run, if it passes the tight selection.
    - After PF algorithm is run, if its *p* is not compatible with the *E* assigned by the PF algorithm, and if it passes the loose selection.

Therefore, the PF muon selection is designed to improve identification of non-isolated muons in jets, which in turn improves jet and MET resolution.

Slava Valuev — https://indico.cern.ch/event/110072/

Particle Flow Muon Identification

PF jet resolution and muon identification efficiency for Global, "Tight" (VBTF-like) and PF muons in μ-enriched QCD MC events, for events with muons with $p_T^{rec} > 50$ GeV:



For muons in jets, PF muons have a higher efficiency than VBTF-like muons at a similar fake rate (the latter needs to be confirmed on data).

Particle Flow Muon Identification

What is a PF Muon

Basic Idea: provide Muon ID including recovery of muons in jet-like environment to improve jet and met resolution

PF Muon ID proceed in two steps:

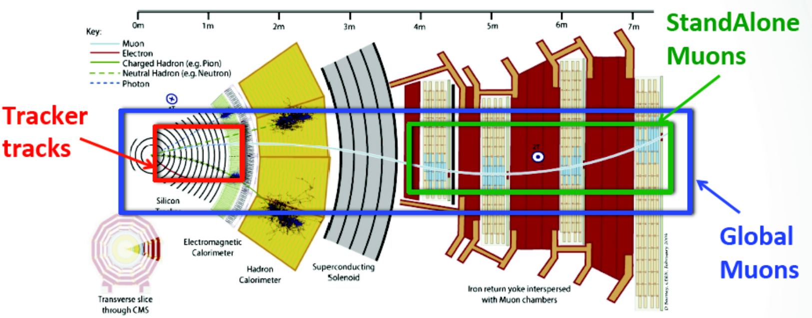
Without use of PF Information, accept any of:

- **GlobalMuon with detBased CombRelIso<0.1**
- **GlobalMuon with Tight Selection**
  [similar to the Tight Muon Selection
  includes also Global Muons without Tracker Muon but with good Stand Alone Muon]
- **TrackerMuon with Tight Selection**
  [using TM2DCompatibilityTight Selector (+other criteria)]

Accept either of the following, only if a muon is associated in PF to a charged hadron candidate with small energy deposit in calorimeters

- **GlobalMuon with Loose Selection**
  [includes also Global Muons without Tracker Muon but with good Stand Alone Muon]
- **TrackerMuon with Loose Selection**
  [using TMLastStationAngTight selector (+other criteria)]

Muon Identification :: Overview



- **Loose muons:** Particle identified as a muon by the **Particle-Flow** event reconstruction. Combine **information from all the CMS subdetectors** (including calorimeters) to reconstruct individual particles per event. Used tracker and muon system hits.
- **Soft muon:** a **tracker track matched** to at least **one CSC or DT** stub, to collect muons down to lower p_T values in the endcaps (e.g. for J/Ψ)
- **Tight muon:** a good quality track from **a combined fit** of the hits in the tracker and muon system, requiring signal in at least **two muon stations** to improve purity (global muon). Used e.g. for W, Z analyses

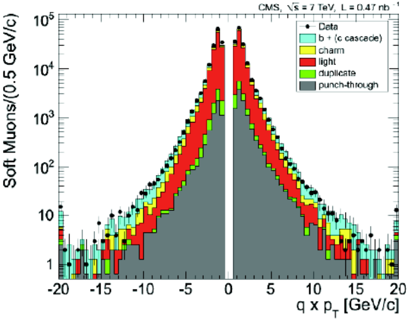
Muon Identification :: Kinematics

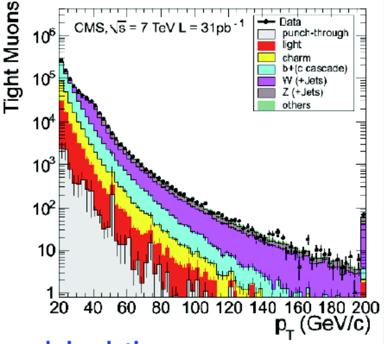
- **Soft muons**
  - Minimum bias trigger

→ 79% Muons from Light hadrons (**decay in flight of π and K**)

- **Tight muons**
  - Single Mu trigger ($p_T > 15$ GeV)

→ 65% Muons from Heavy flavour (**b-hadron**, **c-hadron**, τ)





Good agreement data and simulation

Muon Identification :: Kinematics :: Soft Muon

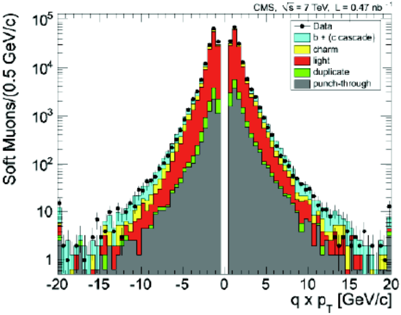
- **Data:** Collected with Minimum Bias trigger with at least 1 vertex
- **Simulation:** Minimum Bias separated according to their origin

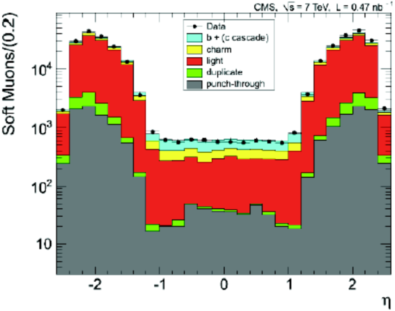
→ **13%** Muons from Heavy flavour (b-hadron, b → c decays, τ)

→ **5%** Hadron punch – through

→ **79%** Muons from Light flavour (decay in flight of π and K)

→ **3%** Duplicates





Muon Identification :: Kinematics :: Tight Muon

- **Data:** Collected with single muon trigger ($p_T > 15$ GeV)
- **Simulation:**

→ **21%** Prompt Muon from W
→ **0.1%** Top

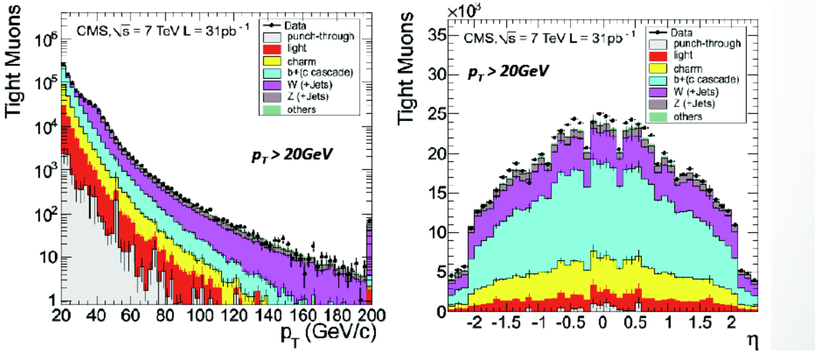
→ **65%** Muons from Heavy flavour
(b-hadron, b → c decays, τ)

→ **8%** Muons from Light flavour
(decay in flight of π and K)

→ **4.7%** Prompt Muon from Z
→ **0.7%** Quarkonia

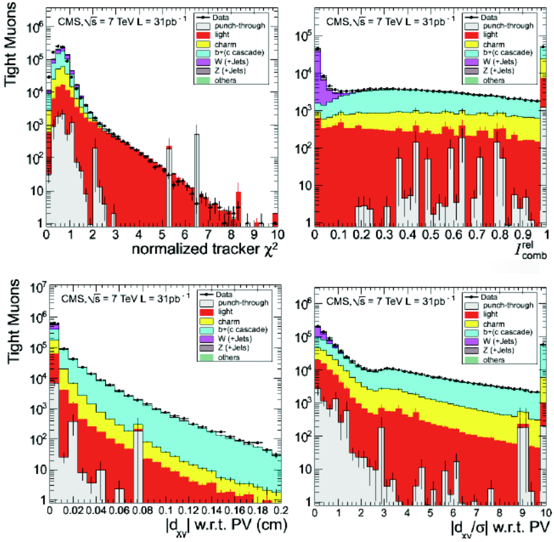
→ **<1%** Hadron punch - through

→ **<0.00%** Duplicates



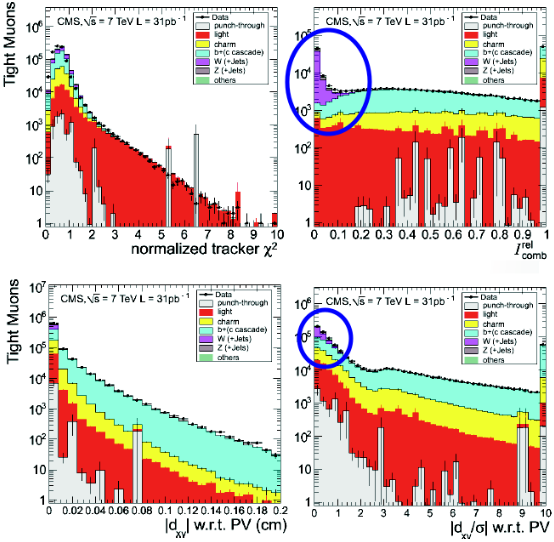
Muon Identification :: Kinematics :: Tight Muon

- Tight muons $p_T > 20$ GeV
- Single Mu trigger
- Good discriminant to select prompt μ against other sources



Muon Identification :: Kinematics :: Tight Muon

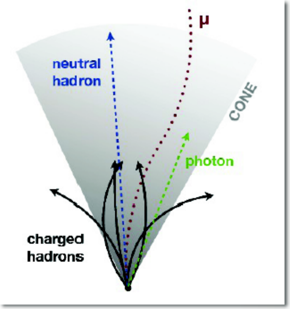
- Tight muons $p_T > 20$ GeV
- Single Mu trigger
- Good discriminant to select prompt μ against other sources



Muon Isolation :: Intro

- **Muon isolation is an important tool used in physics analyses**
  - Powerful to discriminate against QCD (muons in jets)
- **Default CMS isolation based on particle flow:**
  Sum of all particle candidates in a cone $(\Delta\phi^2 + \Delta\eta^2)^{1/2} < 0.4$:

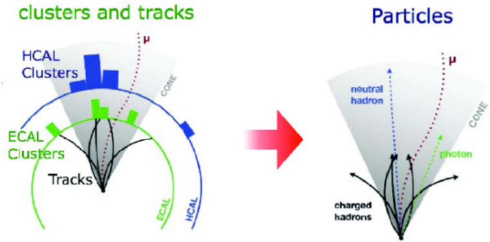
  (Σ charged hadrons + Σ neutral hadrons + Σ photons) / p_T^{μ}



- **Pile-up (PU) effect** is manifested by appearance of multiple Primary Vertices in an event:
  - leads to isolation inefficiency as the probability of "random" energy deposits from other interactions to occur around the muon of interest
- **Reduce PU effect:**
  - Charged hadrons are constrained to the primary interaction vertex (PV)
  - Neutral components are corrected using known relation between energy from neutral hadrons and charge hadrons from non primary vertexes

Particle Flow Muon Identification

Particle-based alternative to the traditional detector-based isolation:

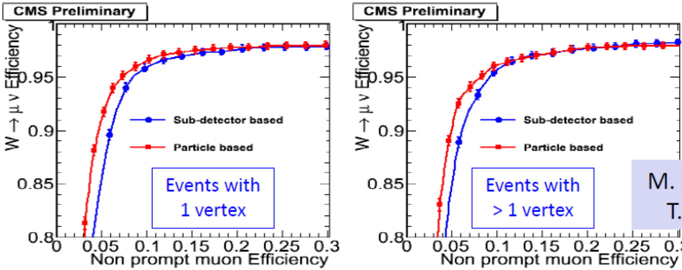


- Instead of using $\Sigma(p_T^{tracks} + E_T^{ECAL} + E_T^{HCAL})$, relies upon $\Sigma(p_T^{charged} + E_T^{\gamma} + E_T^{neutral})$
- Avoids double-counting of energy deposited in the calorimeters by charged tracks.

Slava Valuev — https://indico.cern.ch/event/110072/

Particle Flow Muon Identification

- Signal-enriched ($W \rightarrow \mu\nu$) sample: M_T("Tight" muons with $p_T > 15$ GeV; MET) > 60 GeV. MC-predicted purity is 97%.
- Background-enriched (QCD) sample: $\Delta\phi$("Tight" muons with $p_T > 15$ GeV; MET) < 1.5 rad.
- In PF-based isolation, charged hadrons are required to originate from the primary vertex.
- Efficiency vs background rejection for relative combined isolation. Optimal cone sizes used ($\Delta R < 0.3$ for detector-based and < 0.4 for PF-based). Efficiencies are corrected for background contamination.



M. Bachtis, T.J. Kim

PU-corrections :: Effective Area correction

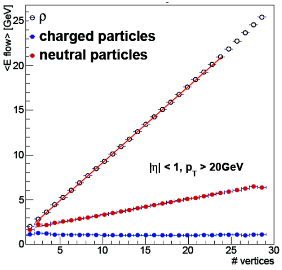
Effective Area correction

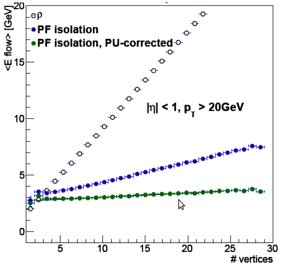
$$\text{PFRelIso} = \frac{\sum_{\text{no PU}}^{\text{ch had}} p_T + \sum^{\text{neutr had}} E_T + \sum^{\gamma} E_T}{p_T^{\text{lepton}}}$$

- Estimate mean PU contribution in isolation cone of the lepton:
- Calculate FASTJET energy density for each jet: ρ
- Median of ρ for each event is chosen
- Effective area A_{eff} is ratio of slopes ρ/uncorrected iso

$$\sum_{corr}^{\text{neutr had}+\gamma} E_T = \max\left(\sum_{\text{uncorr}}^{\text{neutr had}+\gamma} E_T - \rho \cdot A_{\text{eff}}, 0 \right)$$

- cumbersome computations
- A_{eff} calculated for different η intervals
- A_{eff} not determined event-by-event, but averaged over data taking period



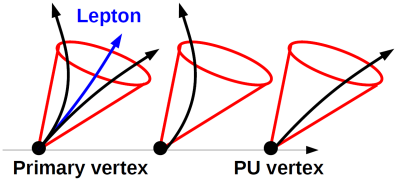


PU-corrections :: $\Delta\beta$ correction

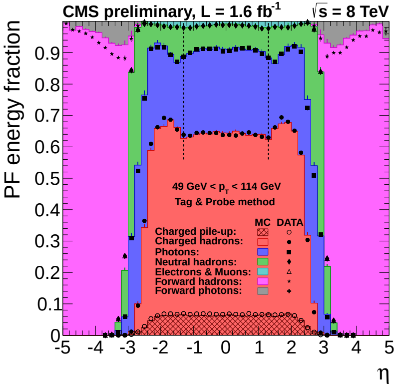
Charged particles can be identified to originate from a PU vertex, but this cannot be done for γ and neutral hadrons

$\Delta\beta$ correction

- Estimate: $\sum_{\text{PU}}^{\text{neutr had}} E_{\text{T}} + \sum_{\text{PU}}^{\gamma} E_{\text{T}}$
- Open same cone in PU-vertex and collect charged energy from PU: $\sum_{\text{PU}}^{\text{ch had}}$



- Neutral energy $\approx$ half of charged energy
- This estimate is $\Delta\beta \approx \frac{1}{2} \sum_{\text{PU}}^{\text{ch had}} p_{\text{T}}$



$$\text{PFRelIso} = \frac{\sum_{\text{no PU}}^{\text{ch had}} p_{\text{T}} + \max\left(\sum^{\text{neutr had}} E_{\text{T}} + \sum^{\gamma} E_{\text{T}} - \Delta\beta, 0\right)}{p_{\text{T}}^{\text{lepton}}}$$

PU-corrections :: the future

In the upcoming LHC runs, **identifying pileup** will become one of the biggest challenges

CMS currently has some handles on pileup and jets

Charged Hadron Subtraction - removing particle flow constituents which are identified to not be from the primary vertex

Downfall: removes only charged particles, what about the neutrals? makes a hard cut on imperfect vertexing information

Pileup Jet ID - uses shape variables and tracking information, identifies low pT jets that originate from clustered energy due to several PU vertices

Downfall: does not address pileup in real jets

Area subtraction - subtracts a median energy density proportional to jet area

Downfall: currently does not correct for jet mass/shapes, "average" corrections wash out jet resolutions/local features

PU-corrections :: the future

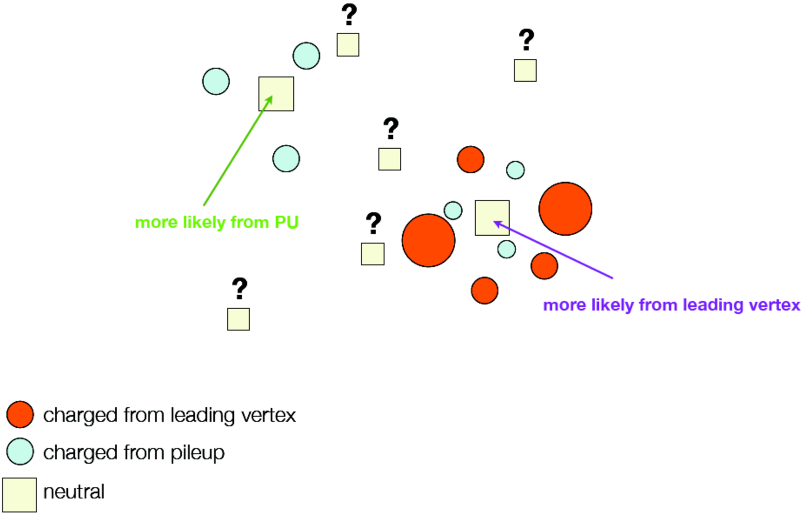
Can we use the **full event information** to get a ***per particle* probability** of the likelihood a particle is from pileup or not?

A few helpful new ideas from the theory community:

- **Jet cleansing**: uses the fraction of tracks from the leading vertex (LV) and pileup vertices (PU) in a subjet to modify the subjet pT
  - **idea**: use charged particle information to tell you something about the neutrals
- **Jets without jets**: looks at an event at particle level ***without clustering*** and computes event quantities by weighting each particle
  - **idea**: per particle weights to compute jet and event quantities, can **combine weights with experimental info** (e.g. vertex χ^2 and timing information)

Nahn Viet Tran & Phillip Coleman Harris — work in progress

PU-corrections :: the future



Nahn Viet Tran & Phillip Coleman Harris — work in progress

Cosmic Ray Muon Rejection

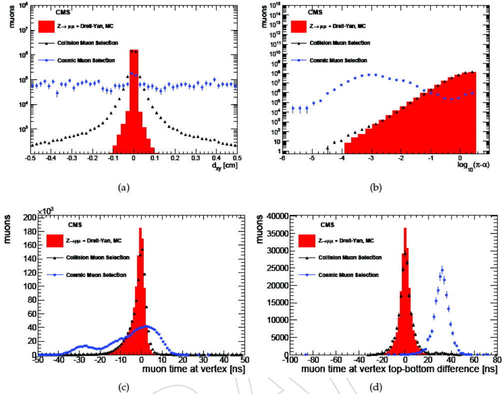


Figure 25: Distributions of variables used for identification of cosmic-ray muons, shown for collision and cosmic-ray muon data samples described in the text, and for Z+Drell–Yan MC samples: (a) muon transverse impact parameter with respect to the nominal beam-spot position; (b) $\log_{10}(\pi - \alpha)$ (see text); (c) muon timing; (d) timing difference between upper and lower muon legs.

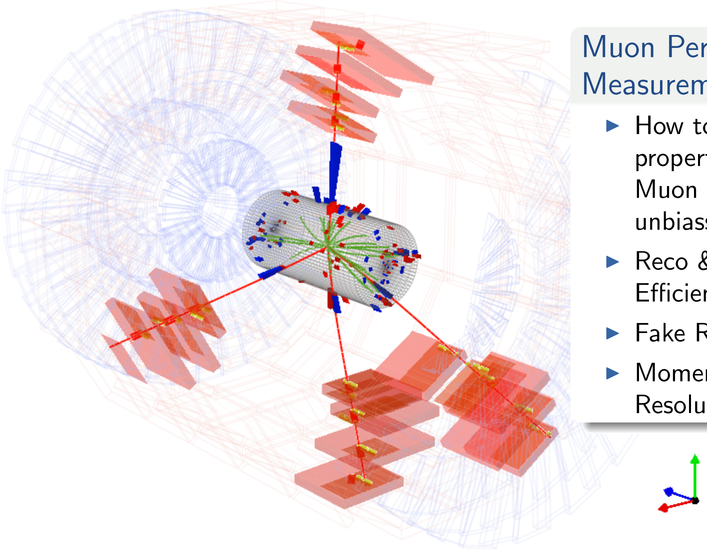
Cosmic Muons

- generally not passing through the vertex region
- hence not reconstructed
- generally not in synch with LHC collisions
- $\angle$(2 legs) $\alpha \approx \pi$

Variables

- Impact parameter
- $\log_{10}(\pi - \alpha)$
- muon time at vtx
- Δt muon legs

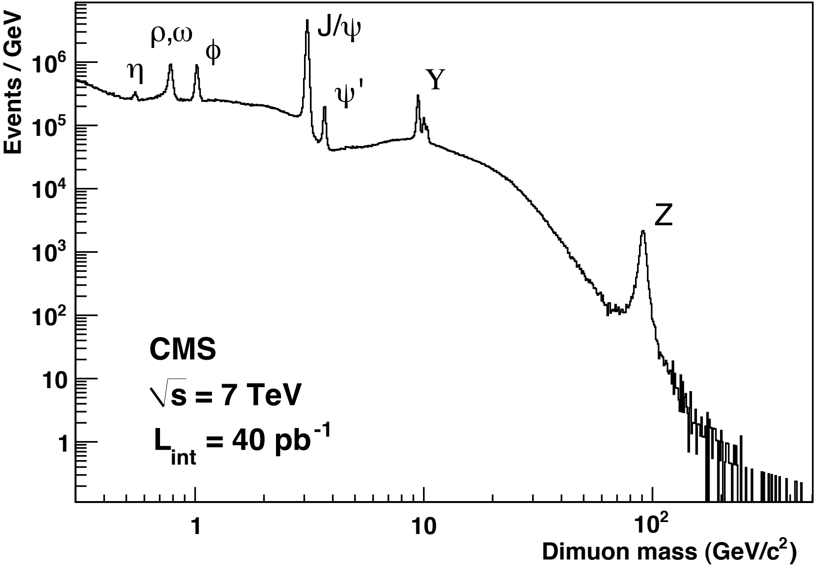
Cosmic muons pointing to the vertex can be identified by searching for a tracker track back-to-back with the Reco muon: $(\alpha - \pi) \ll 1$
Remaining contribution of in-time Cosmic muons could be estimated from out-of-time cosmics



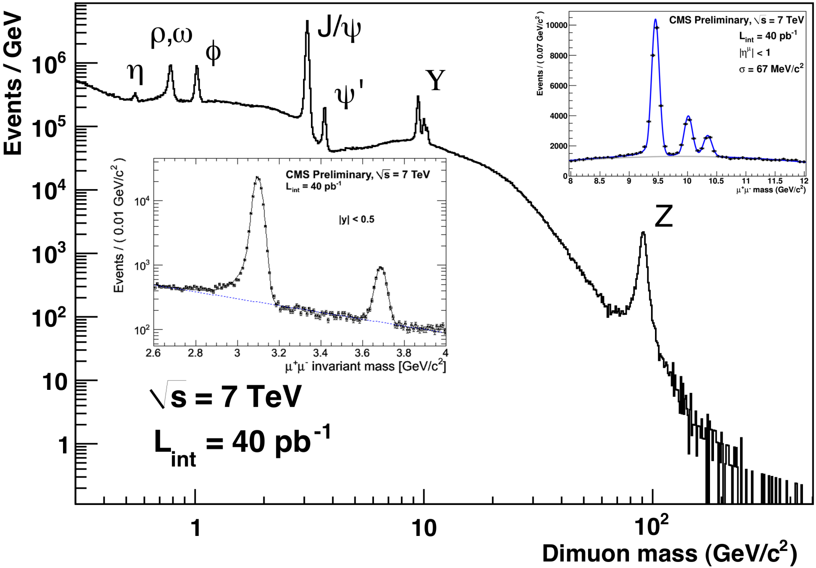
Muon Performance Measurements

- How to measure properties of the Muon object in an unbiassed way?
- Reco & Selection Efficiency
- Fake Rates
- Momentum Scale and Resolution

Resonances used as a source of pure muons

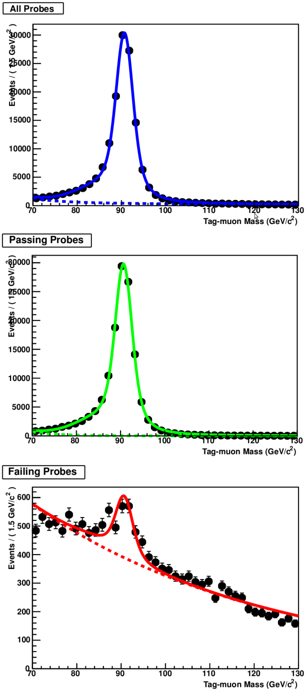


Resonances used as a source of pure muons



Measuring Muon Efficiencies

- Resonances reconstructed as **pairs** with:
  - a tightly identified leg: **tag**-muon
  - a loosely identified leg: **probe**-muon
- Tightly identified **tag** and the constraints on **tag-and-probe pair** ensure origin of the probe to be a **real muon**
- **Efficiency** to pass certain selection criteria is measured on **probe**-muons:
  - pass critera $\Rightarrow$ **passing probes**
  - fail criteria $\Rightarrow$ **failing probes**
- Same (signal + background) lineshape is fit separately to passing and failing probes
- **Efficiency** is calculated as the **ratio of the signal yields** in above fits
- Efficiency is **relative** to the loose probe-identification:
  - $\varepsilon(X) = \varepsilon(X|\text{Tracking})$
- Procedure is repeated in bins of probe-variables (p_T, η, n_vtx, ...)



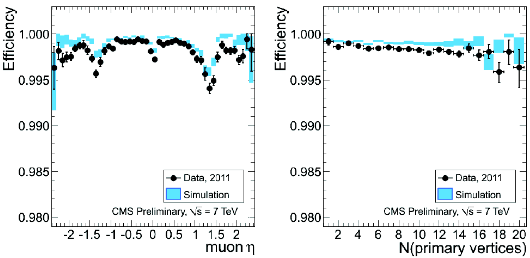
Tracking Efficiency

Efficiency factorization for Muons

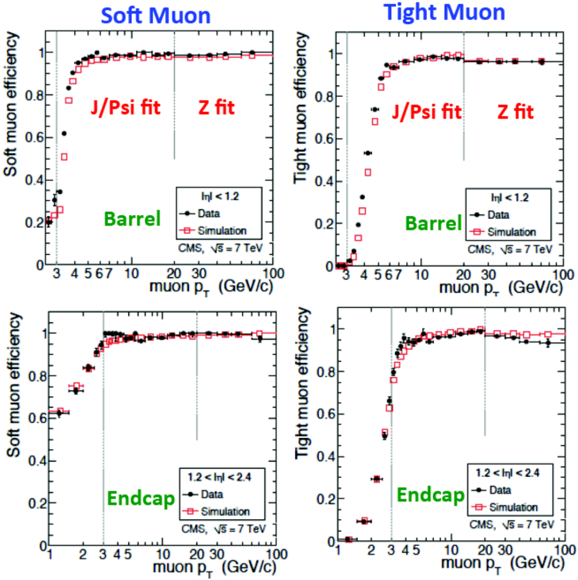
$$\varepsilon = \varepsilon(\text{Tracking}) \cdot \varepsilon(\text{RECO+ID}|\text{Tracking}) \cdot \varepsilon(\text{ISO}|\text{RECO+ID}) \cdot \varepsilon(\text{TRIG}|\text{ISO})$$

- How well can the tracker reconstruct tracks?
- Use Tag & Probe technique to estimate how often an inner track of a muon is **not** reconstructed
- Tag :: Tight Muon
- Probe :: Stand-Alone Muon
- Check whether an inner track is associated to the Stand-Alone Muon (Probe)
- Fortunately very high Tracking efficiency

Tracking Efficiency (2011)



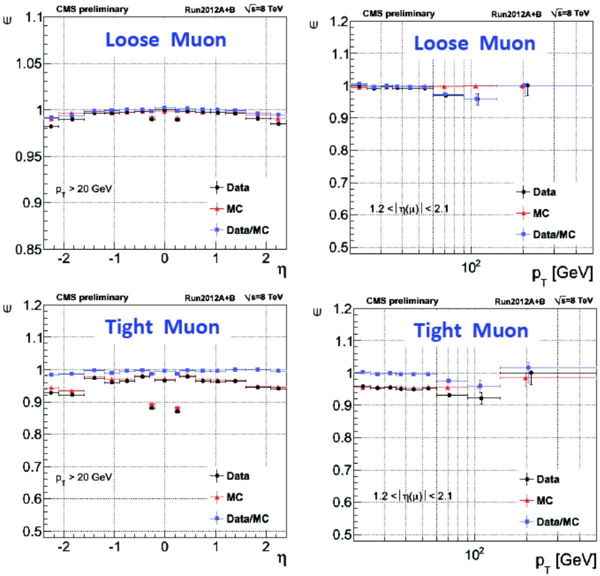
Muon ID Efficiency :: 7 TeV



Data at 7 TeV

- Muon identification reach > 95% in the plateau region
- Agreement data/MC at the level of few % for p_T > 5 GeV

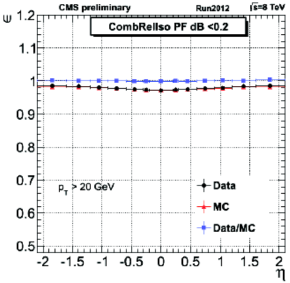
Muon ID Efficiency :: 8 TeV

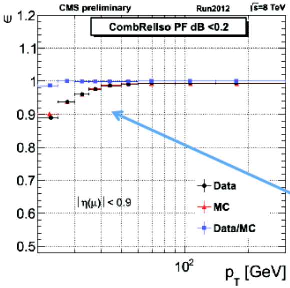


From Z mass resonance

- Muon identification reach > 95% in the plateau region
- Agreement data/MC at the level of 1-2%

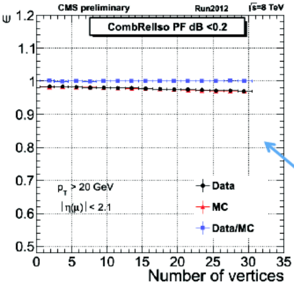
Muon ISO Efficiency





From Z mass resonance

Relatived isolation lower dependence with pT



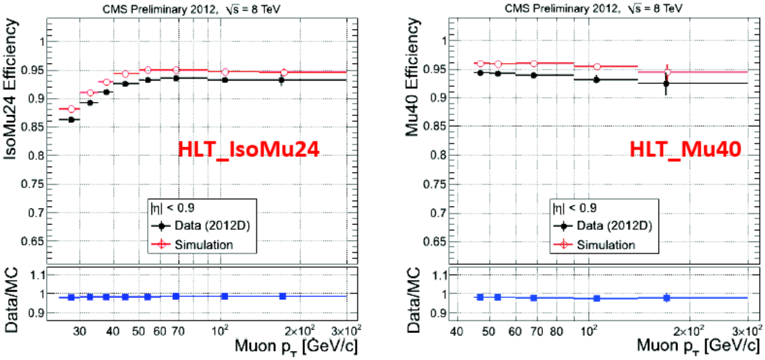
- Muon isolation reach > 95% in the plateau region
- Agreement data/MC at the level of 1-2%
- **After neutral components are corrected using the charged hadrons from non-primary vertices inside the isolation cone, almost independent of PU**

Muon TRG Efficiency

- Trigger efficiencies can be absolute (probes: tracker tracks) or relative (to an offline selection, probes: tight or soft muons)

From Z mas resonance

Efficiencies relative to tight muons

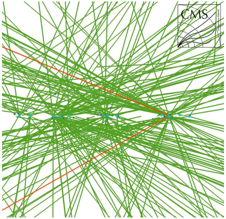


- **Differences are corrected with proper scale factors from data/MC ratios**

Double Muon Trigger :: Problem

2011

- A Double Muon Trigger selects two muons independently
- MUO-10-04 studies show uncorrelated *Leg* efficiencies for $dR > 0.5$ (on J/Ψ)



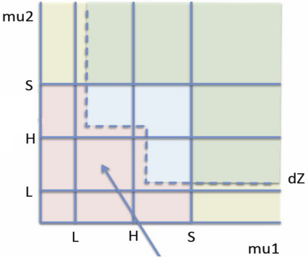
2012

- Double Muon Trigger contaminated by two muons coming from different PV (increasing with PU)
- Trigger Rate reduction obtained by requiring the *z*-coordinate of the Point of Closest Approach (PCA) of the two Muons: $dz < 0.2\,\text{cm}$
- Rate Red. of 40% at a price of $\sim 1 - 3\%$ Eff. loss

dZ filter applied to **HLT_Mu17_Mu8** and **HLT_Mu17_TkMu8**

- **Suboptimal** dZ filter due to suboptimal (muon) tracking in HLT, causing worse tails in dz resolution and thus a lower efficiency of the dz filter (∼ 10% for HLT_Mu17_Mu8, ∼ 5% for HLT_Mu17_TkMu8)
- runs 190456 - 199608 :: dZ filter suboptimal, then fixed during 2012C and good for runs 199698 – 208357 → overall Scale Factor provided

Double Muon Trigger :: Method



- L = Double Mu: lower th
- H = Double Mu: higher th
- S = Single Mu

Component Method

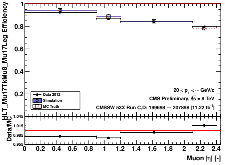
- Efficiency of (H_L OR S):

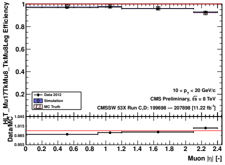
$$\begin{aligned} \varepsilon(H\_L||S) &= s_1 + s_2 - s_1 s_2 && [Y+G] \\ &+z_{12}(h_1 l_2 + l_1 h_2 - h_1 h_2) && [B+G] \\ &-z_{12}(s_1 l_2 + l_1 s_2 - s_1 s_2) && [G] \end{aligned}$$

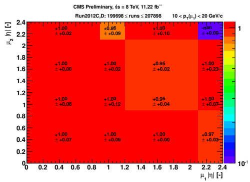
- **Efficiency of (H_L):**

$$\varepsilon(H\_L) = z_{12}(h_1 l_2 + l_1 h_2 - h_1 h_2) \quad [B+G]$$

Muon Leg Efficiencies (best Z mass) dZ Filter Efficiency





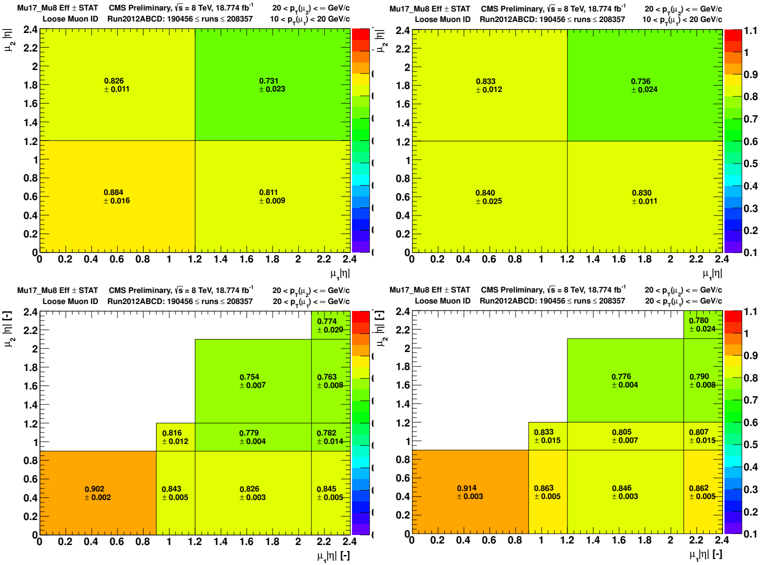


Run2012ABCD :: Mu17Mu8 Eff :: [DATA][Loose ID][±STAT]

$\Delta R < 0.1$ $\Delta R < 0.3$

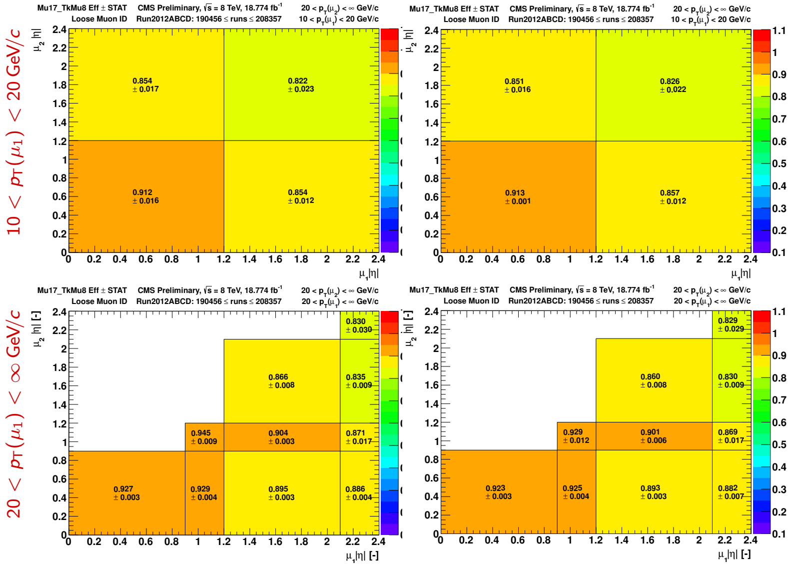
$10 < p_T(\mu_1) < 20$ GeV/c

$20 < p_T(\mu_1) < \infty$ GeV/c



Run2012ABCD :: Mu17TkMu8 Eff :: [DATA][Loose ID][±STAT]

$\Delta R < 0.1$ $\Delta R < 0.3$

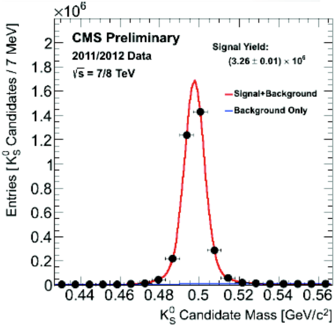


Fake Rate Measurement

- Fraction of events in which **hadron tracks are identified as soft/loose/tight muon** is computed using pure samples of charged hadrons (K, π, p) from resonances, as ϕ , Λ, K_s, B^+, reconstructed from their decay tracks.

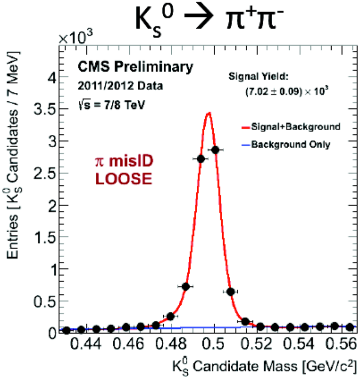
- **Measure the probability that a hadron track is identified as muons:**
  - for protons, this is the punch-through probability
  - for π/K, this is the sum of decay in flight and punch-through probabilities

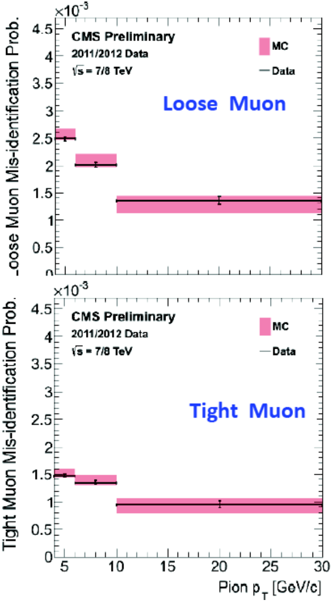
- **Important proper background subtraction**



Pion misidentification from $K_s^0 \to \pi^+\pi^-$ selection

pT > 4GeV, K transverse flight length **Lxy<4cm** (decay within the beam pipe)

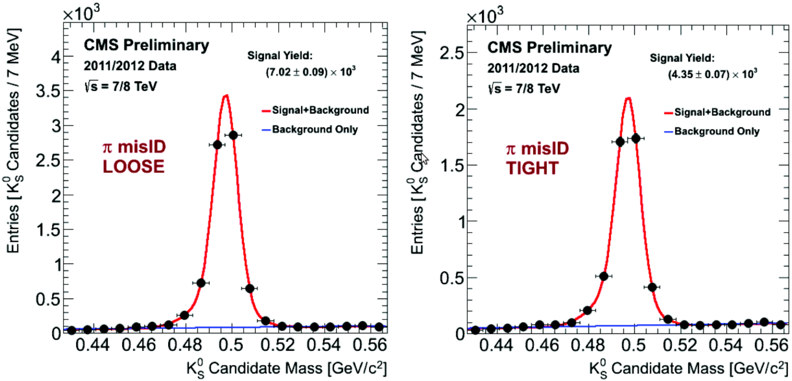




π mis ID (loose μ): **2.16±0.03 x 10⁻³**
π mis ID (tight μ): **1.34±0.02 x 10⁻³**

Pion misidentification from $K_s^0 \to \pi^+\pi^-$ selection

Pion p_T > 4 GeV

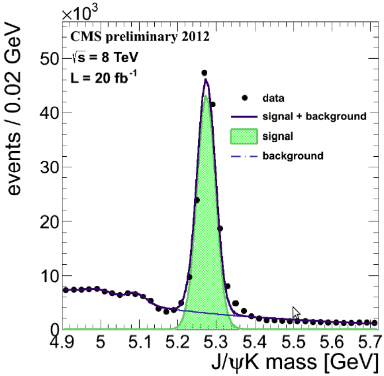


π misID (Loose μ) : $2.16 \pm 0.03 \times 10^{-3}$

π misID (Tight μ) : $1.34 \pm 0.02 \times 10^{-3}$

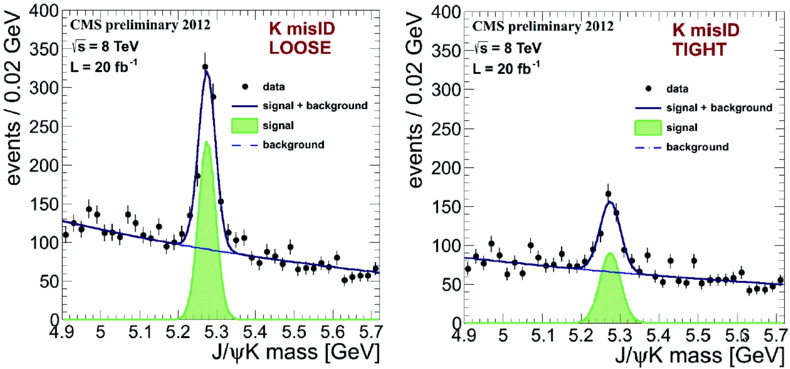
$B \to J/\Psi K$ selection

- Datasets from a Double Muon Trigger selecting displaced J/ψ -> μ+μ−
- Clean selection of the B->J/ψK decay channel
- Muon pair from the J/ψ decay matched to the trigger objects firing the event to remove any residual bias from the trigger.
- K track $p_T > 4$ GeV
- Signal fit with a Gaussian, background with an exponential plus two Gaussians for the structures on the low mass sideband



Kaon misidentification from $B \to J/\Psi K$ selection

Kaon p_T > 4 GeV



K misID (Loose μ) : 0.51 ± 0.05 %

K misID (Tight μ) : 0.22 ± 0.02 %

Muon Momentum Scale

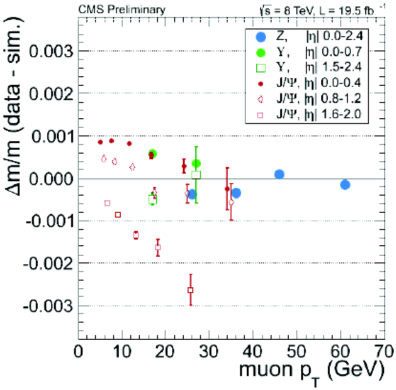
- At medium pT two different approaches:
  - **MuScleFit** (Muon momentum Scale Calibration Fit): absolute measurement of momentum scale and resolution by using a reference model of the generated Z lineshape convoluted with a gaussian function.
  - MuscleFit correcting the azimuthal modulation of the average momentum scale, mainly related to residual imperfections of TRK alignment (particularly visible in promt reco at 8 TeV)
  - **Rochester** method (arXiv:1208.3710):
    - 1) uses the mean $1/P_T$ for muons from Z decays to determine the momentum scale corrections in bins of charge, η and φ.
    - 2) the corrections are tuned by using the average invariant mass Mz from Z events in the same bins of charge η and φ.
- Both approaches gives almost equivalent results

Muon Momentum Scale

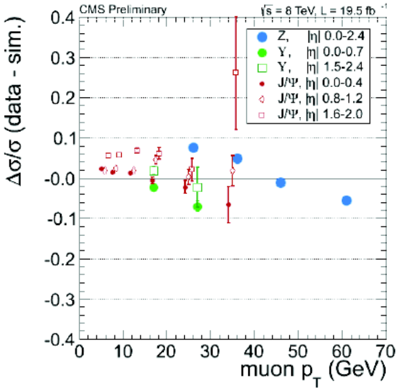
- Relative difference between data and simulation extracted from J/Ψ, Υ and Z decays after momentum corrections
  - On momentum scale < 0.2 %
  - On momentum resolution < 10%

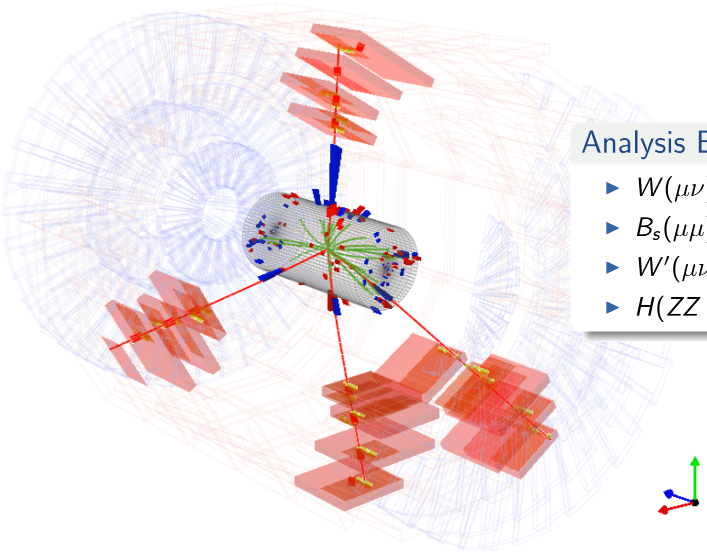
Data at 8 TeV

Data-MC Scale



Data-MC resolution

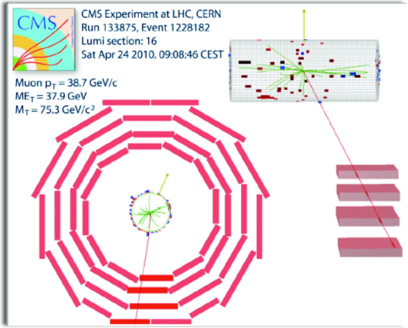


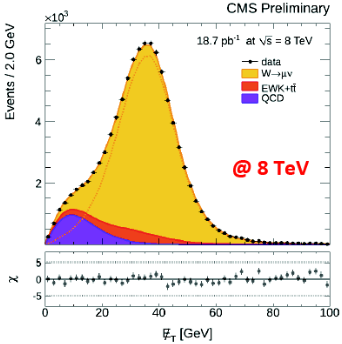


Analysis Examples

- $W(\mu\nu)$ & $Z(\mu\mu)$
- $B_s(\mu\mu)$
- $W'(\mu\nu)$ & $Z'(\mu\mu)$
- $H(ZZ \rightarrow 4\mu)$

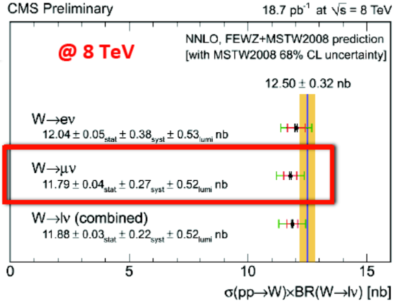
W→ μ ν



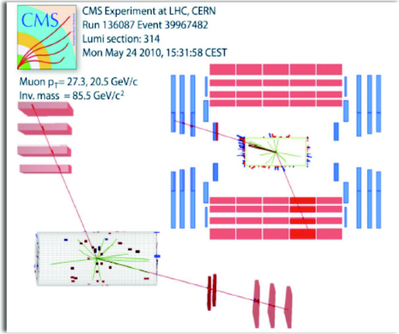


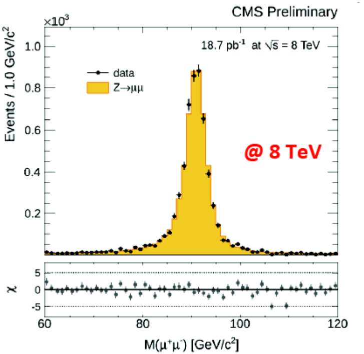
CMS-PAS-SMP-12-011

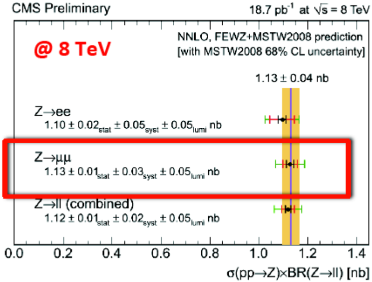
- **Single Mu15 trigger, Tight Muon ID, PFIsolation/pT < 0.12**
- Comparable experimental and theory uncertainty: 2-3% systematic and 4.4% luminosity



Z→ μ μ







CMS-PAS-SMP-12-011

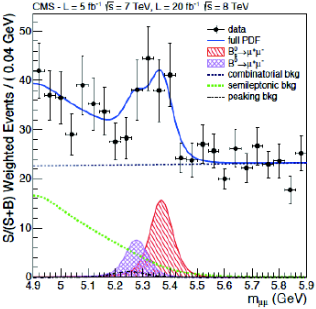
- **Single Mu15 trigger, Tight Muon ID, PFIsolation/pT < 0.12**
- Comparable experimental and theory uncertainty: 2-3% systematic and 4.4% luminosity

$B_s(\mu\mu)$ results

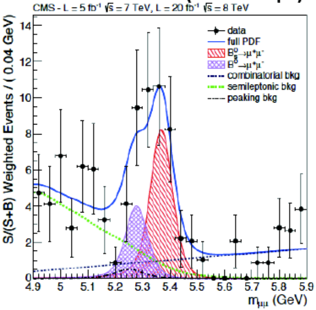
Phys.Rev.Lett.111 (2013) 101804

- **Low pT special muon ID selection using MVA technique:**
  - Takes into account more variables to lower muon fake rates, specially from kaons.
- **Double muon triggers (low pT) with a Bs mass window requirement**

Cat. BDT: 4.3 σ (4.8 σ exp.)



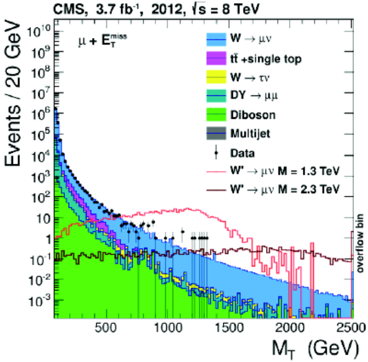
1D BDT: 4.8 σ (4.7 σ exp.)



Searches with high p_T muons

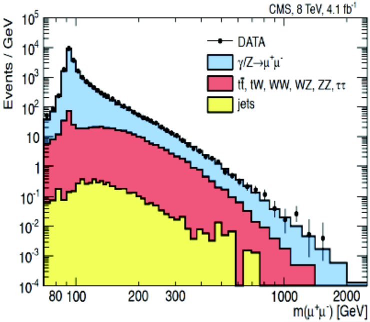
- Special re-fit algorithms for high-p_T muon reconstruction and momentum assignment:
  - Take into account electromagnetic showering in the iron yoke that can alter muon trajectory
- Single muon HLT_Mu40 trigger

W-prime→μν @ 8 TeV



Phys.Rev.D 87, 072005 (2013) 072005

Narrow resonances to 2μ @ 8 TeV



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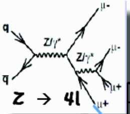
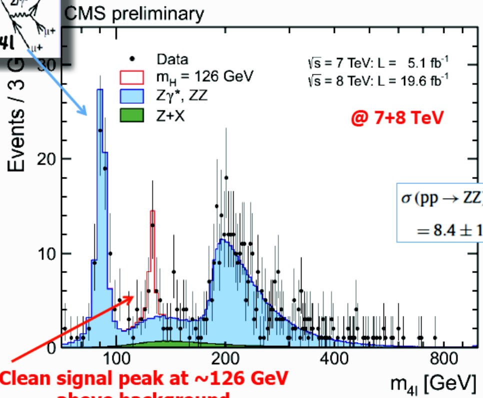
H→ ZZ →4 leptons

CMS-PAS-HIG-13-002

- **Single muon and double muon triggers, Loose Muon ID (Particle Flow)**
- 4-lepton reconstructed mass in full mass range for the sum of the 4e, 4μ, and 2e2μ channels





Clean signal peak at ~126 GeV above background

Very good control of the ZZ background

$$\sigma(pp \to ZZ) = 8.4 \pm 1.0(\text{stat.}) \pm 0.7(\text{syst.}) \pm 0.4(\text{lum.})\ \text{pb.}$$

(Th. NLO 7.7 ± 0.4 pb)

$H(ZZ \to 4\ell)$ :: Event Selection

leptons

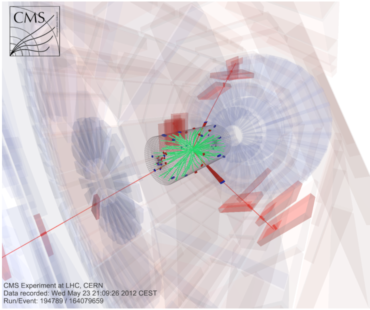
- $p_T(\mu) > 5\,\text{GeV}/c$, $\eta^{\mu} < 2.4$
  $p_T(e) > 7\,\text{GeV}/c$, $\eta^{e} < 2.5$
- $|\frac{\sigma_{IP}}{IP}| < 4.0$ $\qquad I^{PF}_{rel} < 0.4$

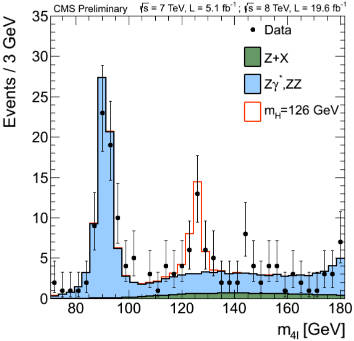
signal

- Narrow resonance
  $\mathcal{O}(2 - 4\,\text{GeV}/c^2)$

background

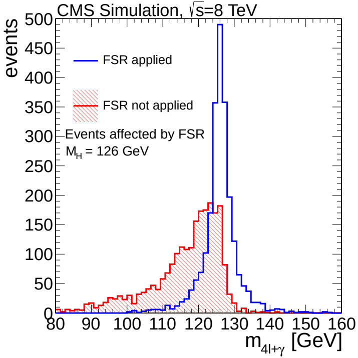
- $Z + X$ (reducible)
  - $Z + \text{jets}$
  - $Z + bb$
  - estimated from data
- ZZ (ireducible)
  - estimated from MC

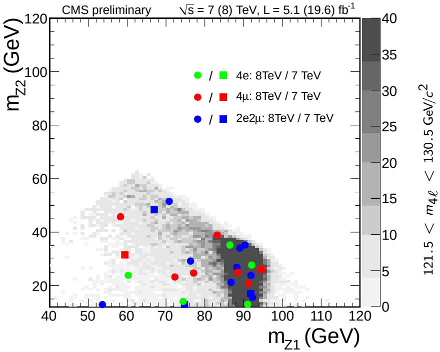




At the time of Discovery

$H(ZZ \to 4\ell)$ :: Building 4ℓ candidates





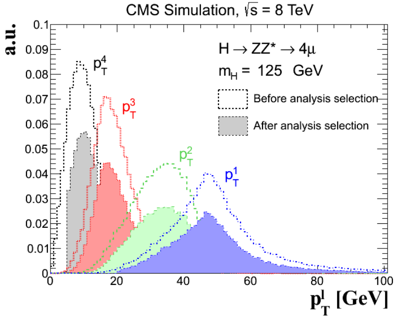
- Z candidates formed from $\ell^+\ell^-$ pair of same flavour
- FSR recovery: $|m_{\ell\ell\gamma} - m_Z| < |m_{\ell\ell} - m_Z|$
- $\exists \ell_a$ with $p_T(\ell_a) > 20$ GeV/c
- $\exists \ell_b$ with $p_T(\ell_b) > 10$ GeV/c

- $40 < m_{Z_1} < 120$ GeV/c^2
- Z_1 closest to PDG mass Z

- $12 < m_{Z_2} < 120$ GeV/c^2
- Z_2 with highest p_T

$$m_{4\ell} > 100 \text{ GeV}/c^2 \;\&\; \forall \ell : m_{2\ell} > 4 \text{ GeV}/c^2$$

$H(ZZ \to 4\ell)$ :: Lepton Selection

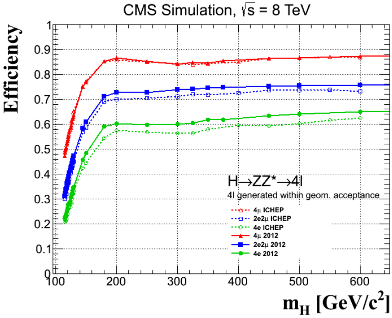


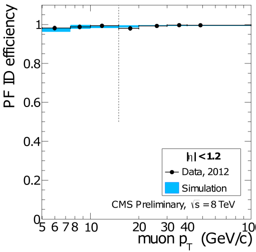
one on-shell $Z \Rightarrow$ hard ℓ
one off-shell $Z \Rightarrow$ soft ℓ:

- 50% below 10 GeV/c

this is a big **Challenge**

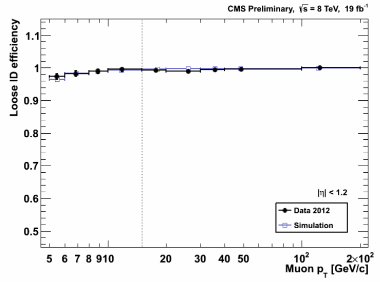
- background rate
- selection efficiency

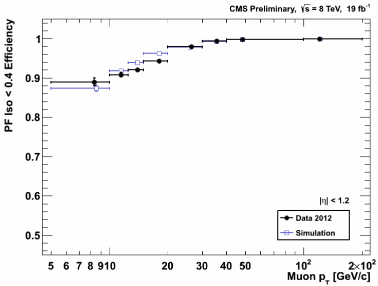


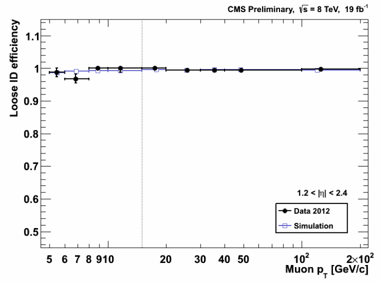


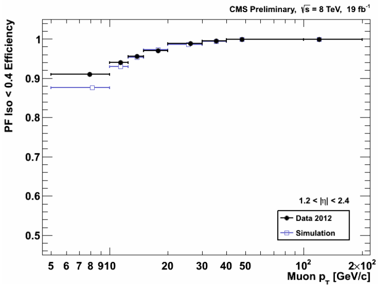
My Work!

$H(ZZ \to 4\ell)$ :: Loose Muon ID & ISO Efficiency

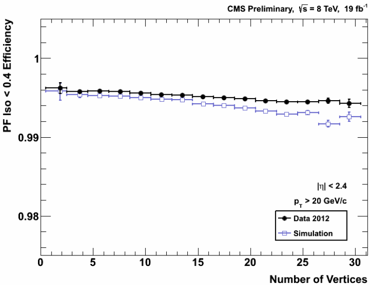


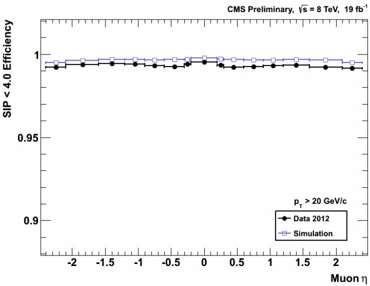






$H(ZZ \to 4\ell)$ :: ISO & SIP



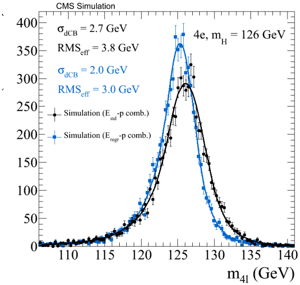


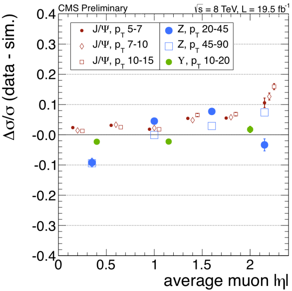
- Loose Muon ID has high and uniform efficiency
- PF-Isolation at low p_T is challenging
- PU-corrections to PF-Isolation give flat curve
- Significance of Impact parameter:

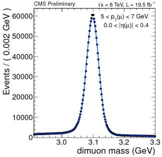
$$\text{SIP} = \frac{\text{IP}}{\sigma_{\text{IP}}}$$

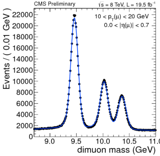
- uniform behaviour (while tracker resolution is worse in endcap)
- SIP used to discover sudden pixel misalignment in 2012 data

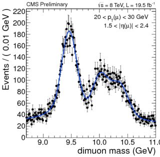
$H(ZZ \to 4\ell)$ :: Lepton Resolution and Scale

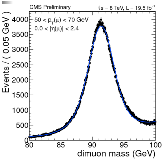






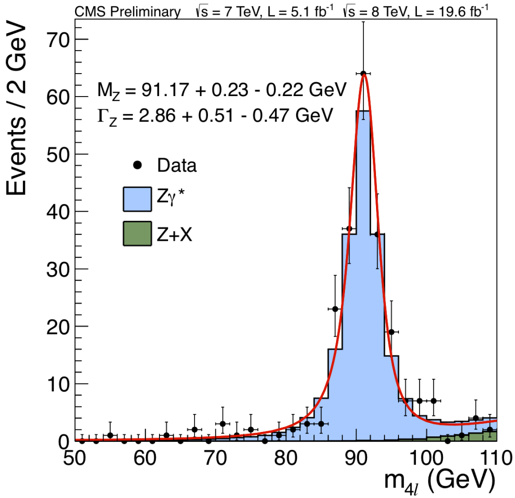


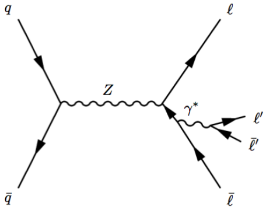




- e :: Momentum Regression in ECAL
  - BDT trained on DY MC leads to 10% improvement
- e :: Momentum Scale: using Z, $J/\Psi \to ee$
- μ :: Resolution & Scale: improved by correction of Tracker Misalignment ($\langle 1/p_T \rangle$)
- μ :: Validation on J/Ψ, Y and Z decays

$H(ZZ \to 4\ell)$ :: Precise Measurement of $Z \to 4\ell$

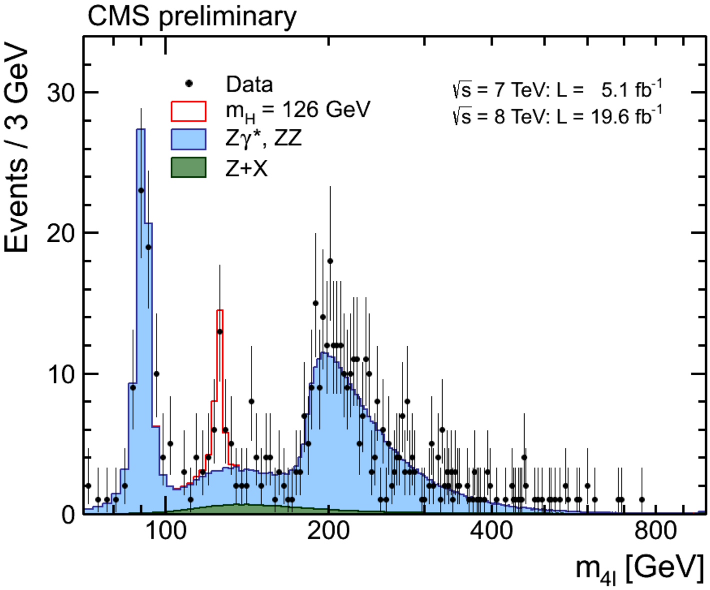




- First observation at CMS
- JHEP 12 (2012) 034
- Same Fit procedure as for $m_{4\ell}$
- Good Data/MC agreement on width

- $M_Z = 91.1876 \pm 0.0021\,\mathrm{GeV}/c^2$
- $\Gamma_Z = 2.4952 \pm 0.0023\,\mathrm{GeV}/c^2$ [PDG]

$m_{4\ell}$ distribution

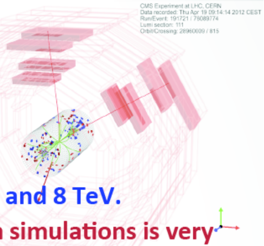


Slow Animation

Fast Animation

Animation!

Summary



- The CMS muon reconstruction and trigger has been studied on pp collisions at 7 TeV and 8 TeV.
- The agreement with the expectations from simulations is very good, both in the overall picture and in the individual performance measurements: efficiencies, resolutions, ...
- Identification efficiencies higher than 95% for selected pT thresholds
- Mis–identification probabilities from hadrons:
  - Order of per mille per K, π, p
- Momentum scale bias consistent with zero
- Relative resolution in the range of 1 to 2% (barrel) and 6% (endcap)for muons below 100 GeV
- Very good performance on muons with the CMS detector:
  - *Allows incredible physics results with muons!*

Sources

- Riccardo Bellan — Muon intro at Quarkonia Workshop — https://indico.cern.ch/event/60388/
- Slava Valuev — Muon Object in Particle Flow — https://indico.cern.ch/event/110072/
- Cristina Botta — Muon Object developments — https://indico.cern.ch/event/185274/
- CMS-MUO-10-004 — Performance of CMS muon reconstruction in pp collision events at $\sqrt{7}$ TeV — http://cds.cern.ch/record/1456510
- CMS-Note-2008-097 — Muon Reconstruction in CMS
- CMS-Note-2008-098 — Muon Identification in CMS
- Alicia Calderon — 14th ICATPP Conference Como 2013 — http://cds.cern.ch/record/1609525