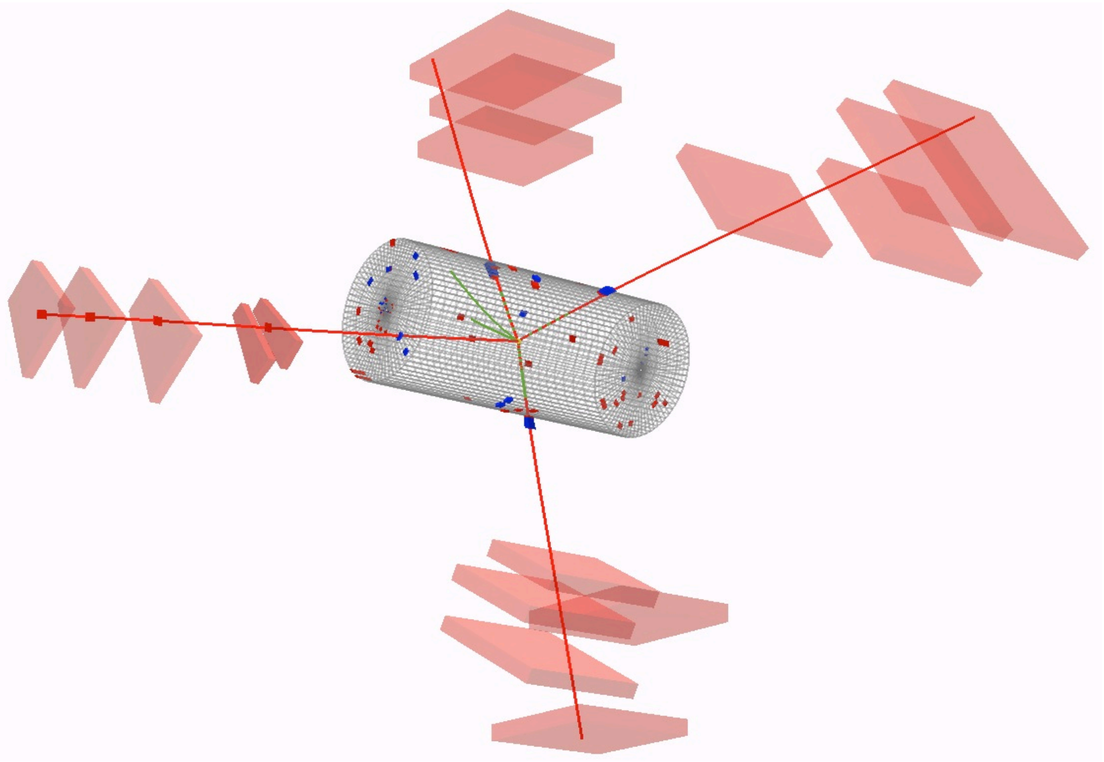
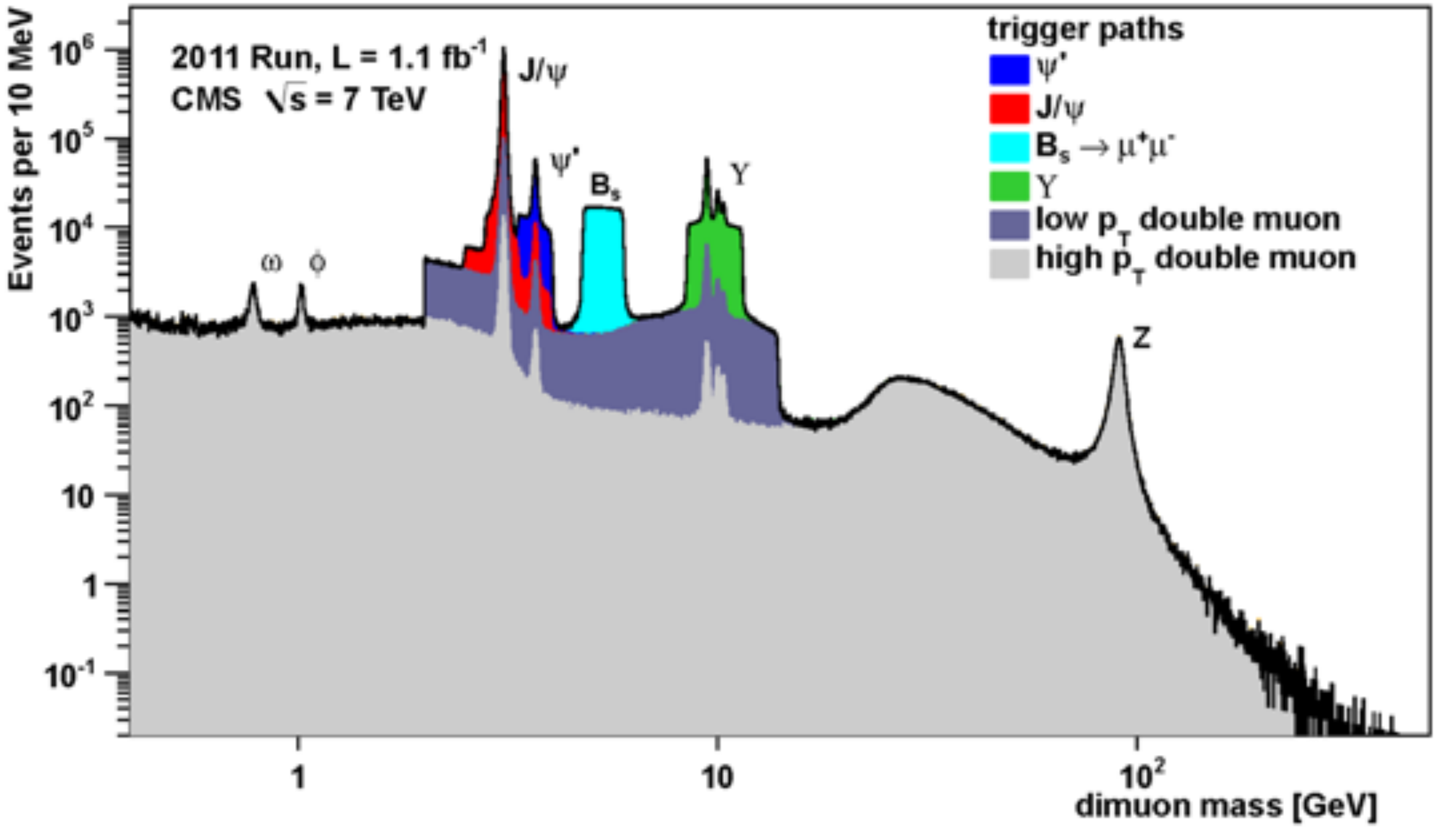
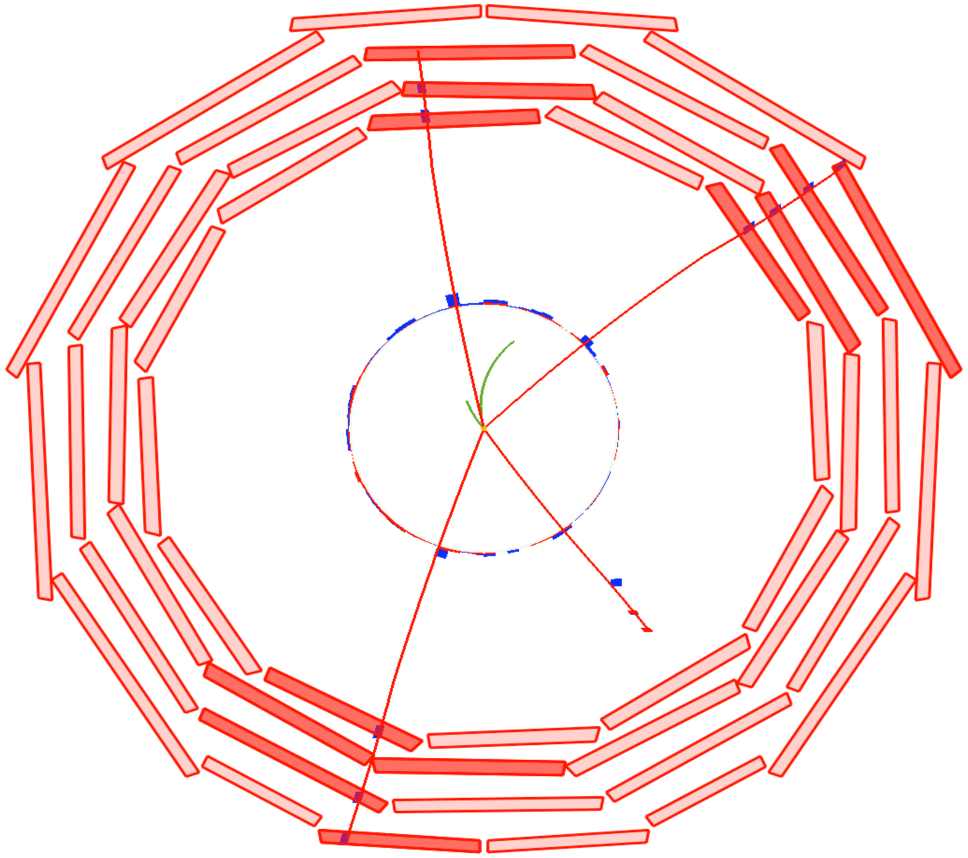




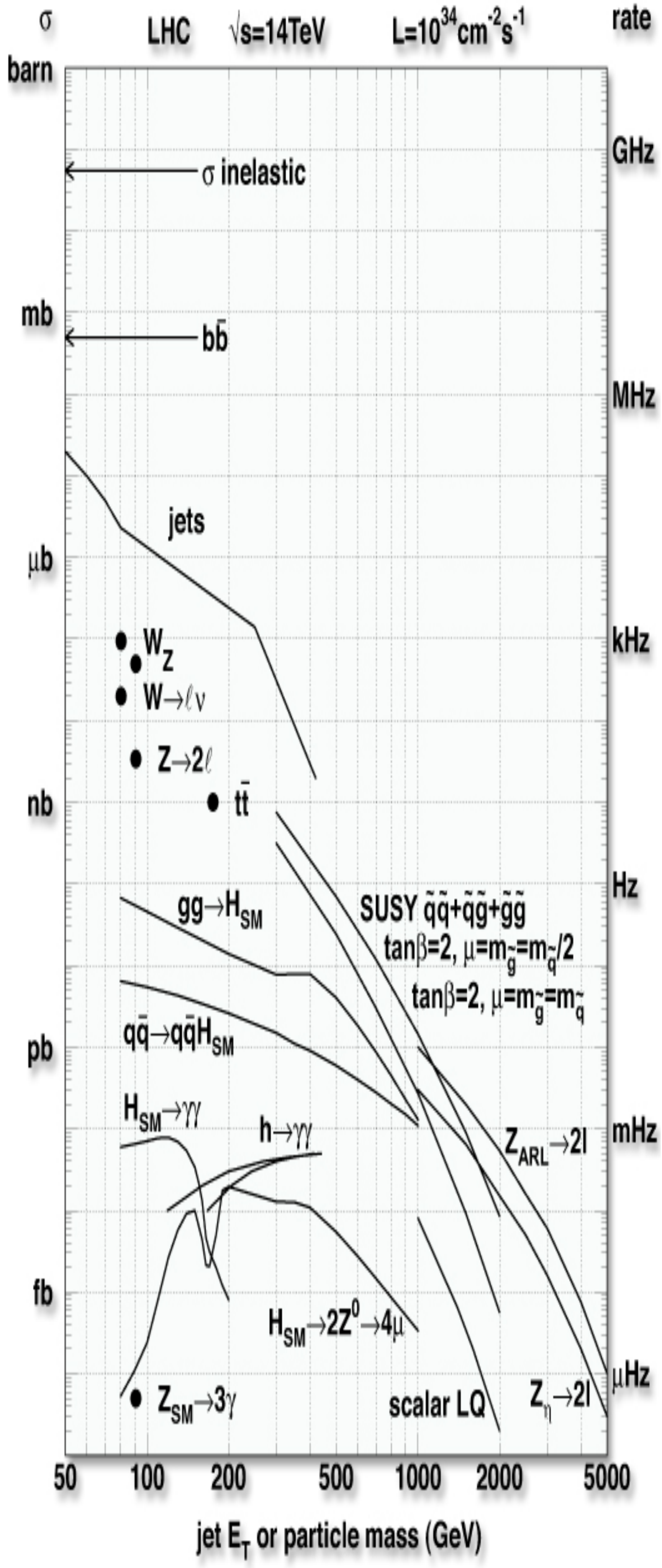


Muon identification in CMS and selected muon based analyses

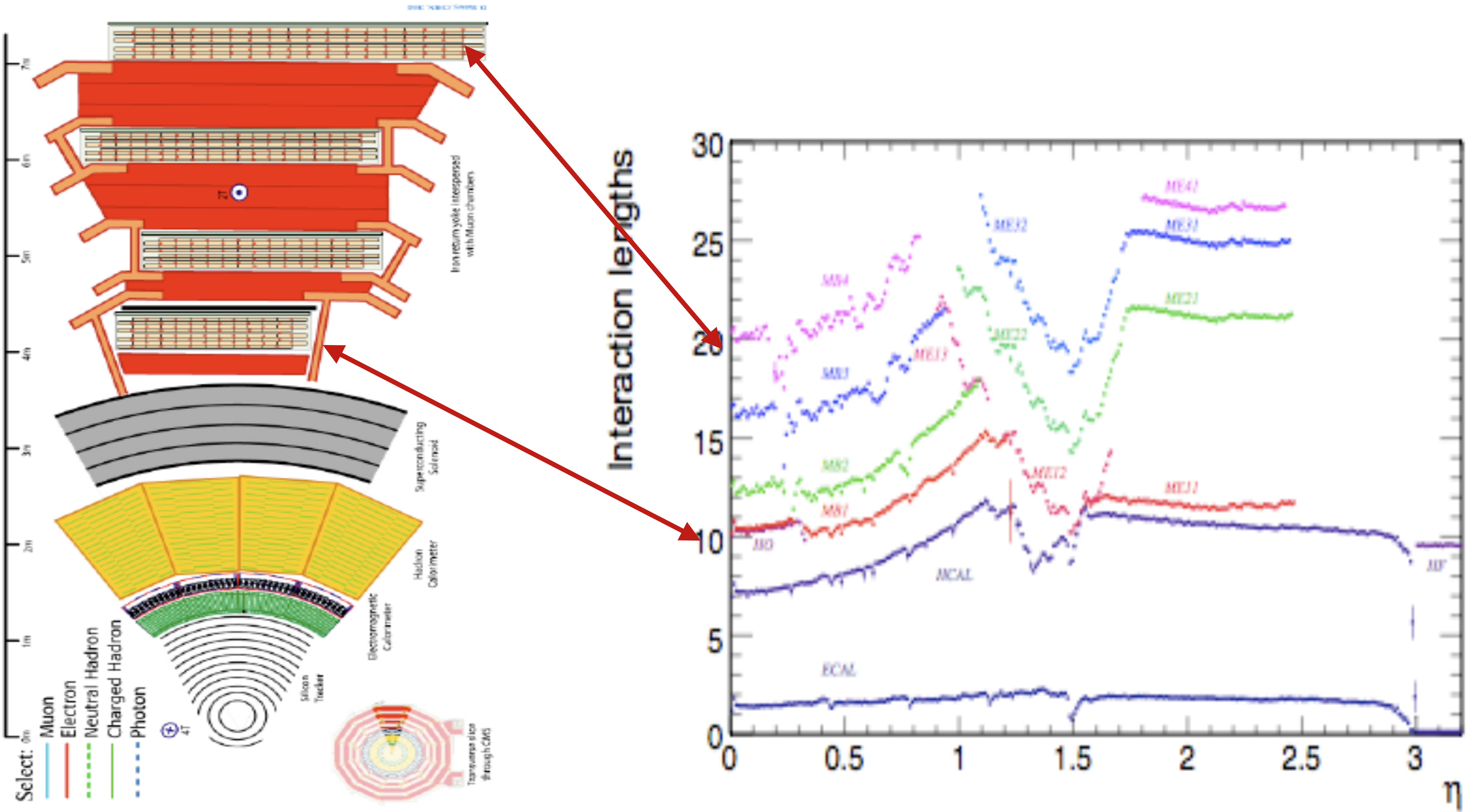
ICTP-NCP School on LHC Physics

Tuesday 18 October 2014

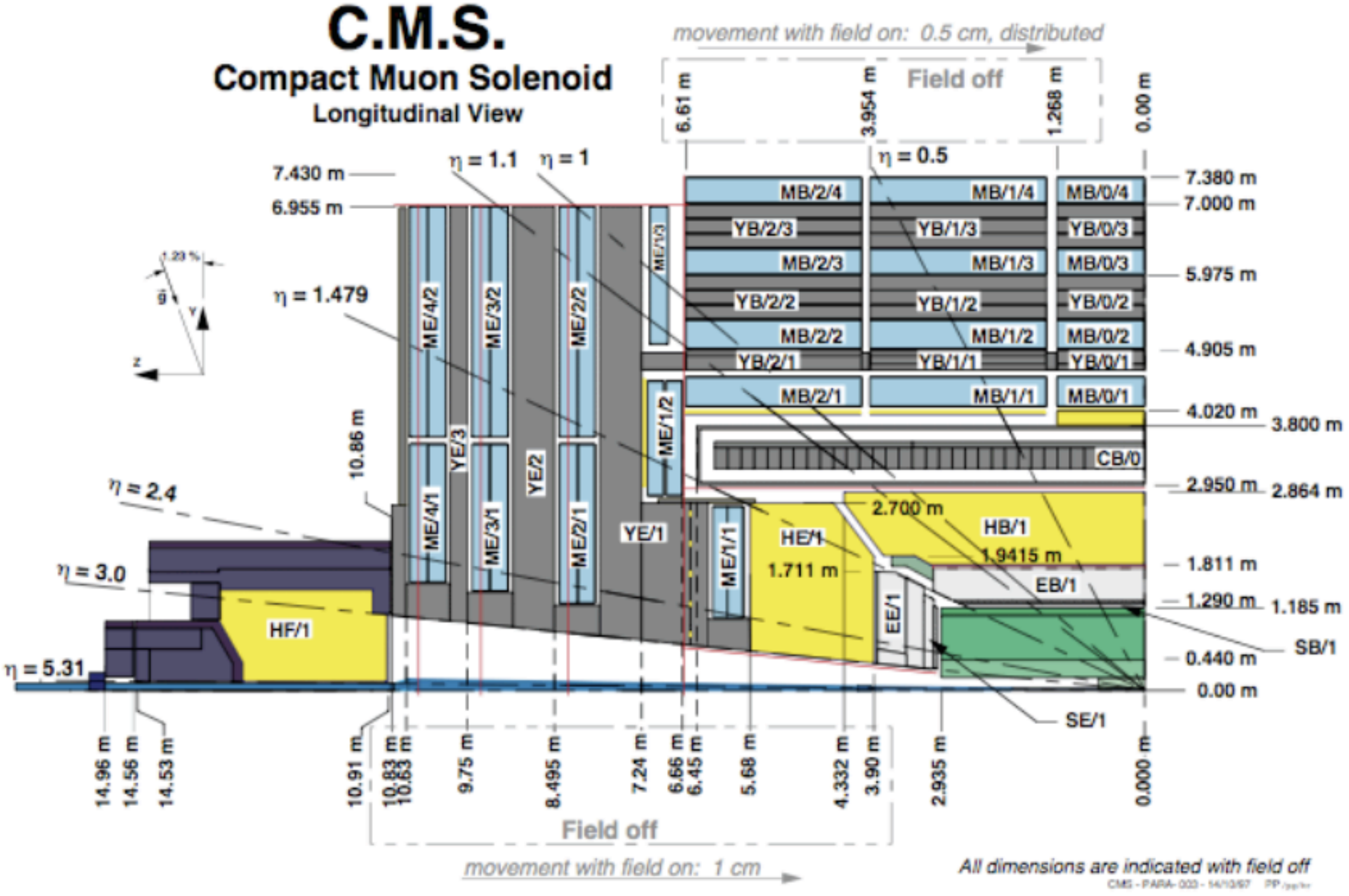
gigi.rolandi@cern.ch



At LHC, EWK and new phenomena have cross sections much smaller than production of jets. Reconstructing and identifying a muon (or electron) in the event is a key element in separating these rare phenomena from the overwhelming QCD background

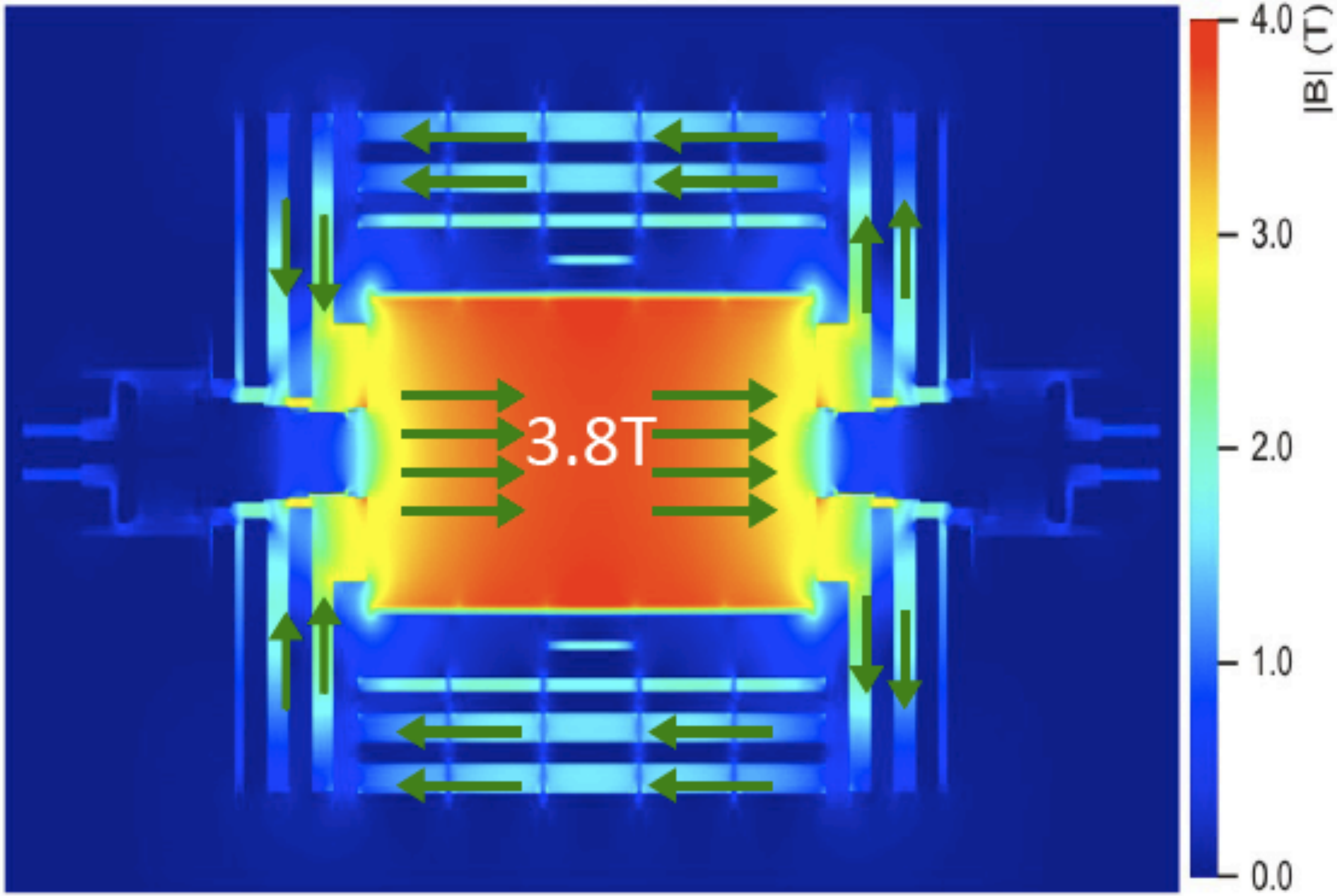


There are at least 10 interaction lengths before the first muon chamber and some 20 interaction lengths before the last muon chambers. The hadrons produced in the pp interaction are absorbed before the muon system.



Drift tubes in the barrel region and Cathode strip chambers in the endcaps provide “Tracks Stubs” (a vector in space) . This information is supplemented by Resistive Plate Chambers that provide precise time information and coarse position measurement.

CMS MAGNETIC FIELD



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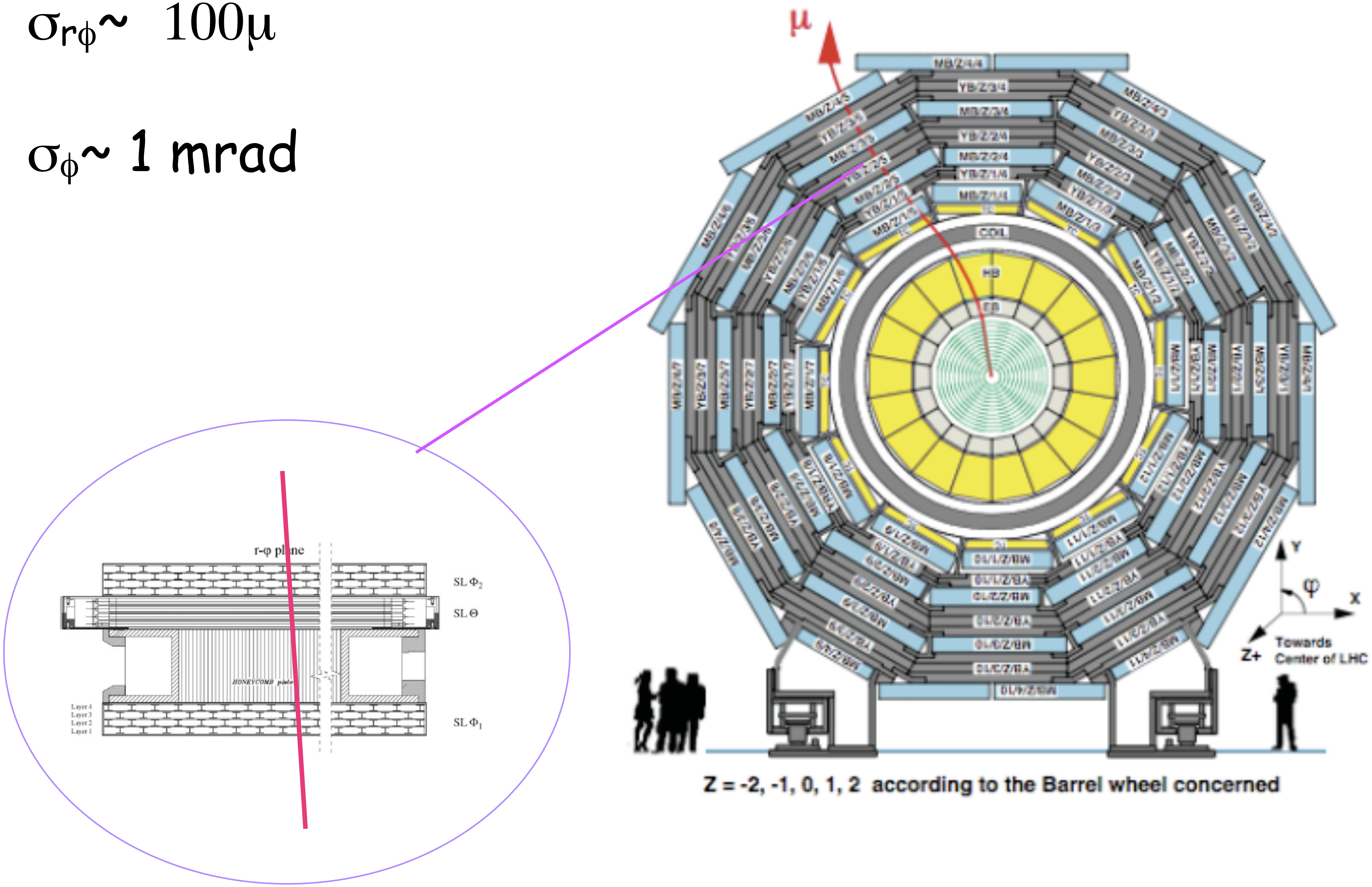
$\sigma_{r\phi} \sim 100\mu$

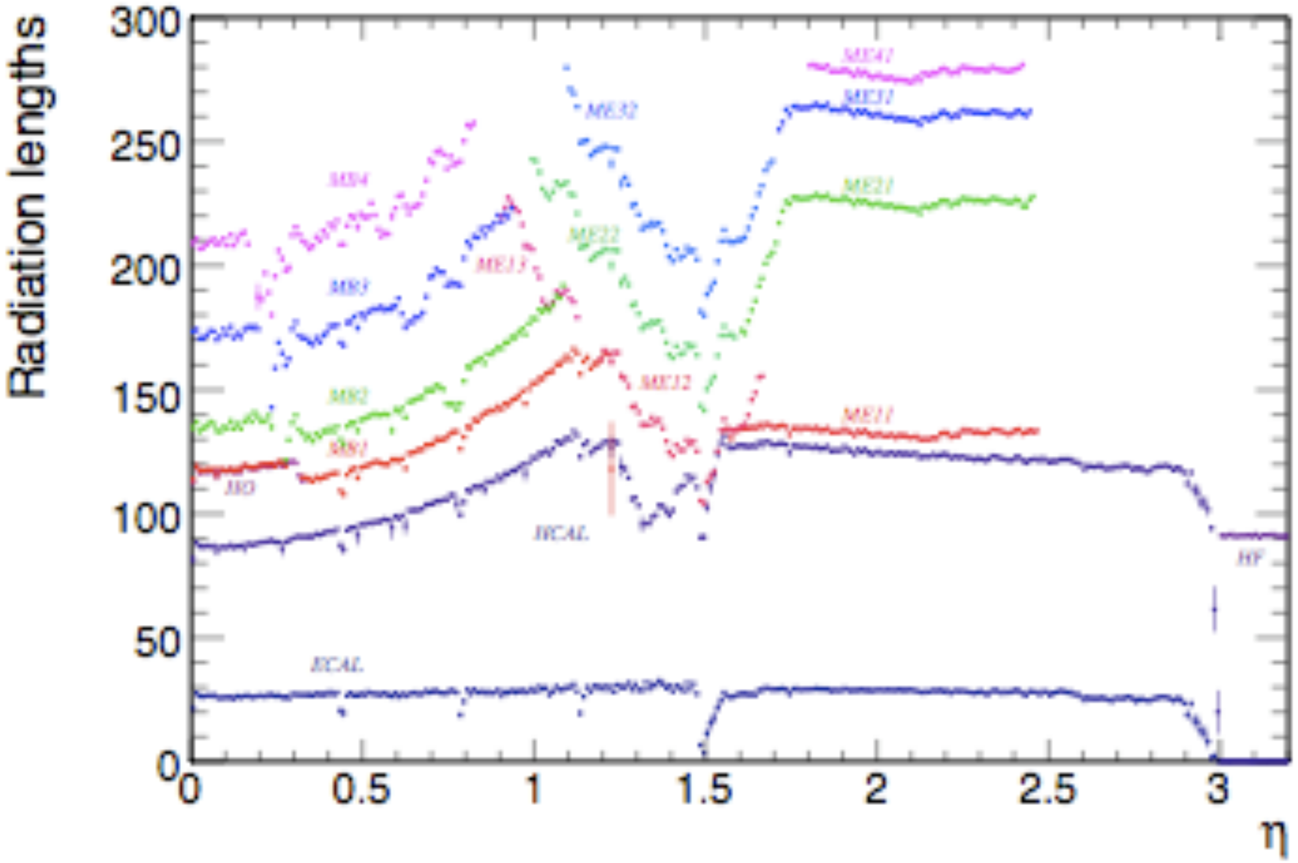
$\sigma_{\phi} \sim 1$ mrad



Z = -2, -1, 0, 1, 2 according to the Barrel wheel concerned

gigi.rolandi@cern.ch

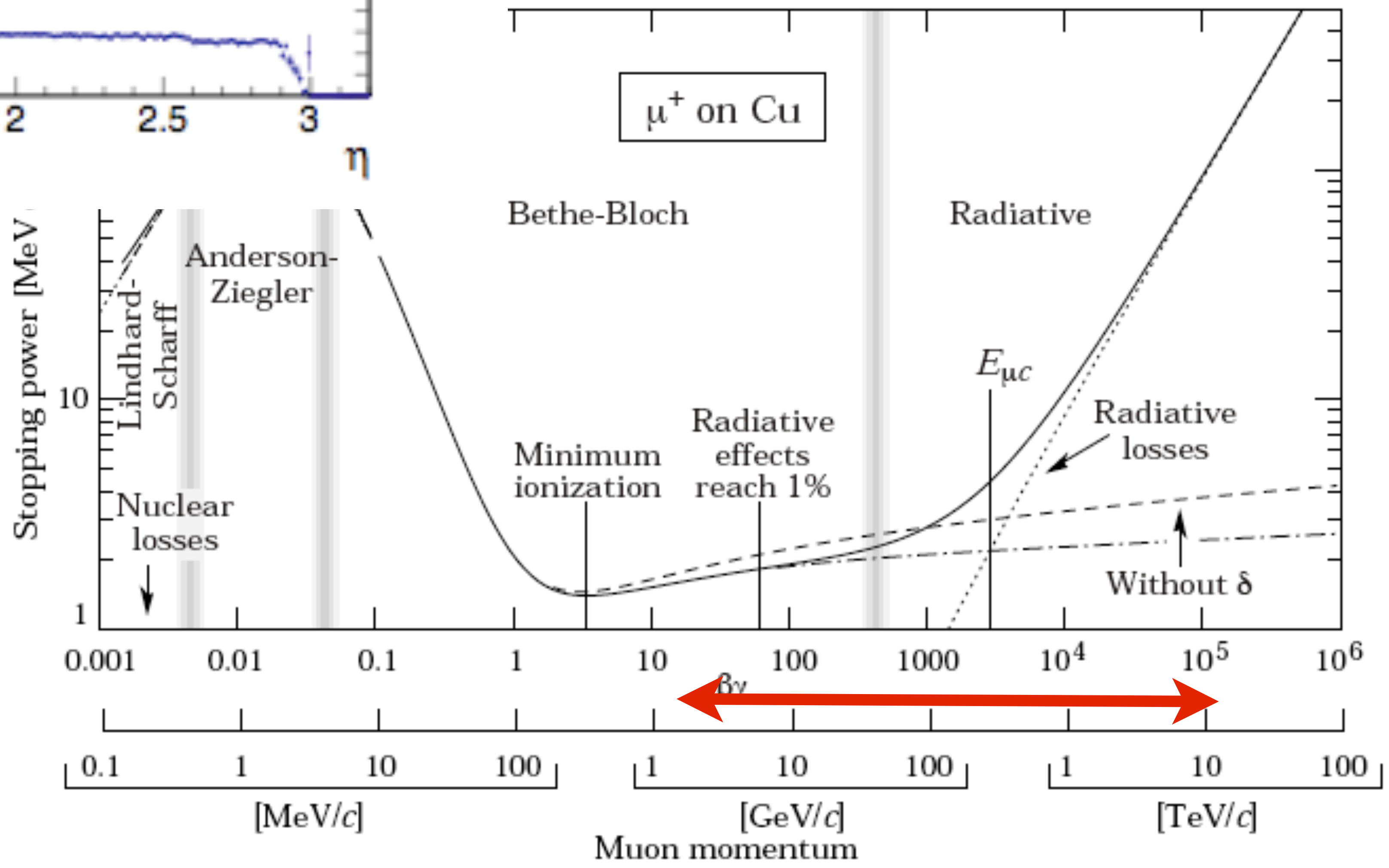
Propagation of a muon through CMS



Material effect are important muons loose about 3 GeV when traversing the material between the tracker and the first muon chamber

100 * 15 (g cm^{-2}) * 2 (MeV g^{-1} cm^{2}) ~ 3 GeV

Multiple scattering dominates the resolution for low momentum muons: a 150 GeV muons has a multiple scattering angle of 1 mrad after 120 Radiation lengths

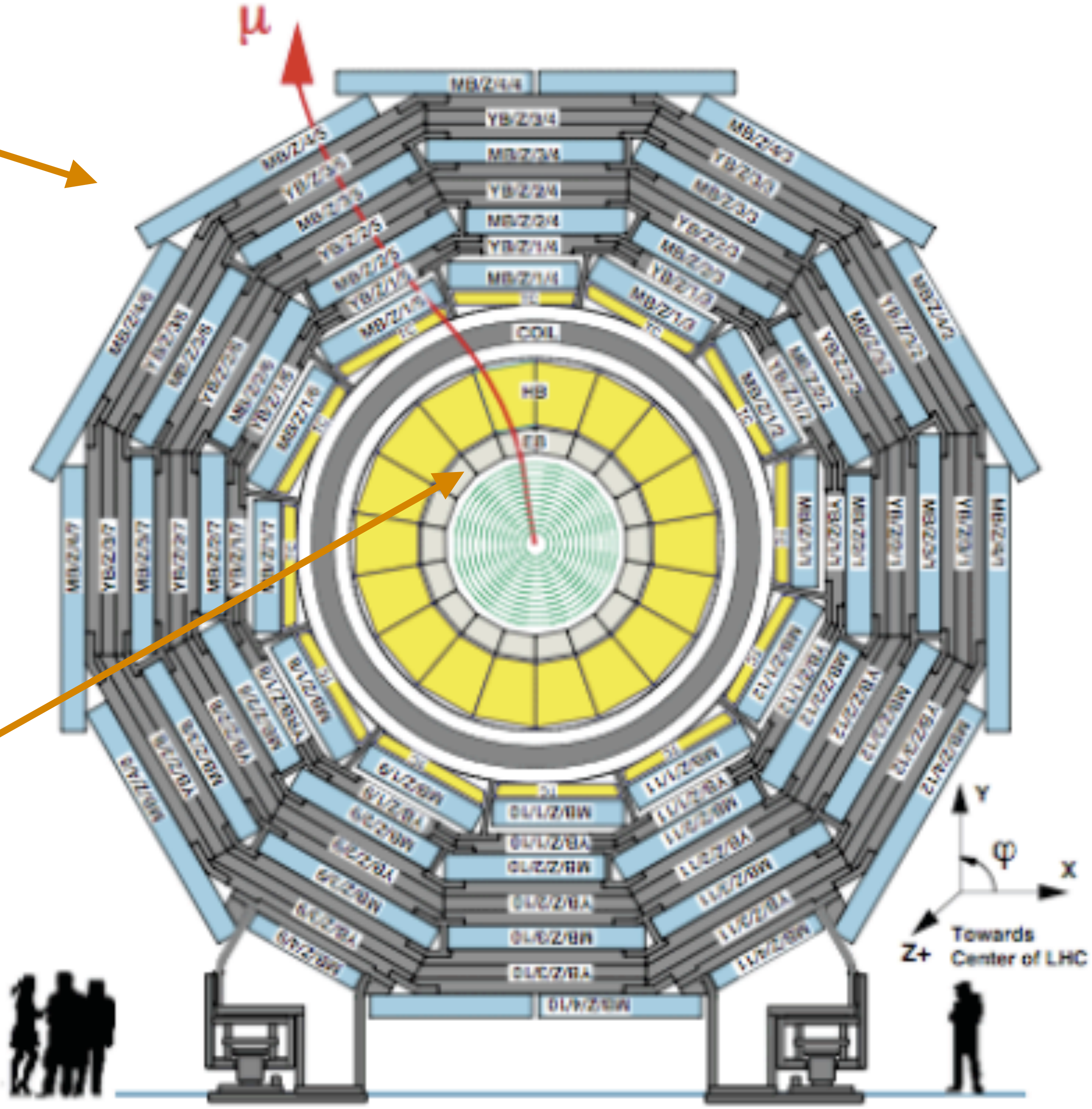


Stand alone muon : muon chambers + beam spot constraint, limited by multiple scattering up to very large momenta

Beam constraint is very important

12 Tm vs 2 Tm

Tracker Track: ~ no material effect but small lever arm and only 4 Tm bending.



Z = -2, -1, 0, 1, 2 according to the Barrel wheel concerned

gigi.rolandi@cern.ch

Muon Tracks

- OUTSIDE IN APPROACH
  - Build a track on the muon system
  - Match it with a track built independently on the tracker
    - In very few cases (<1%) there is no match
- Inside out approach
  - Take a tracker track and extrapolate it to the muon system searching for hits
  - Useful for low momentum muons that stop inside the muon spectrometer
- MOST MUONS ARE FOUND BY BOTH METHODS

gigi.rolandi@cern.ch

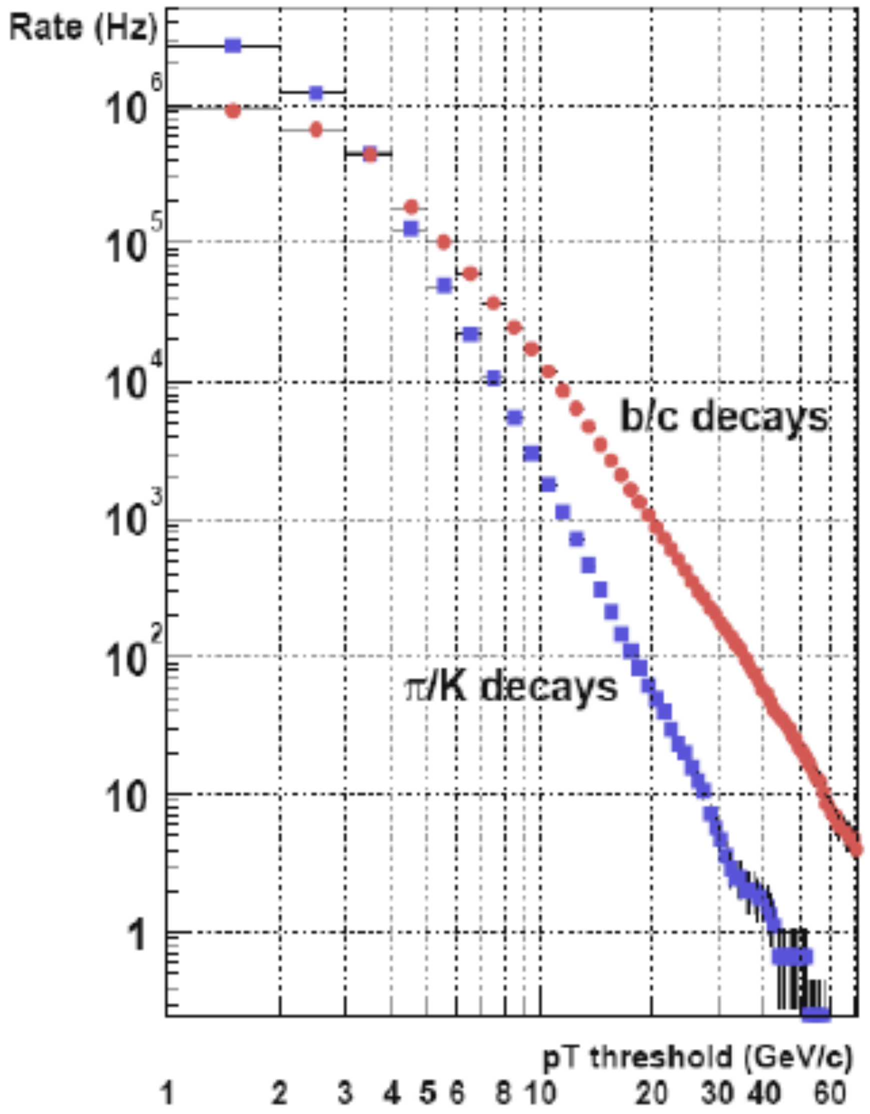
Muons in CMS

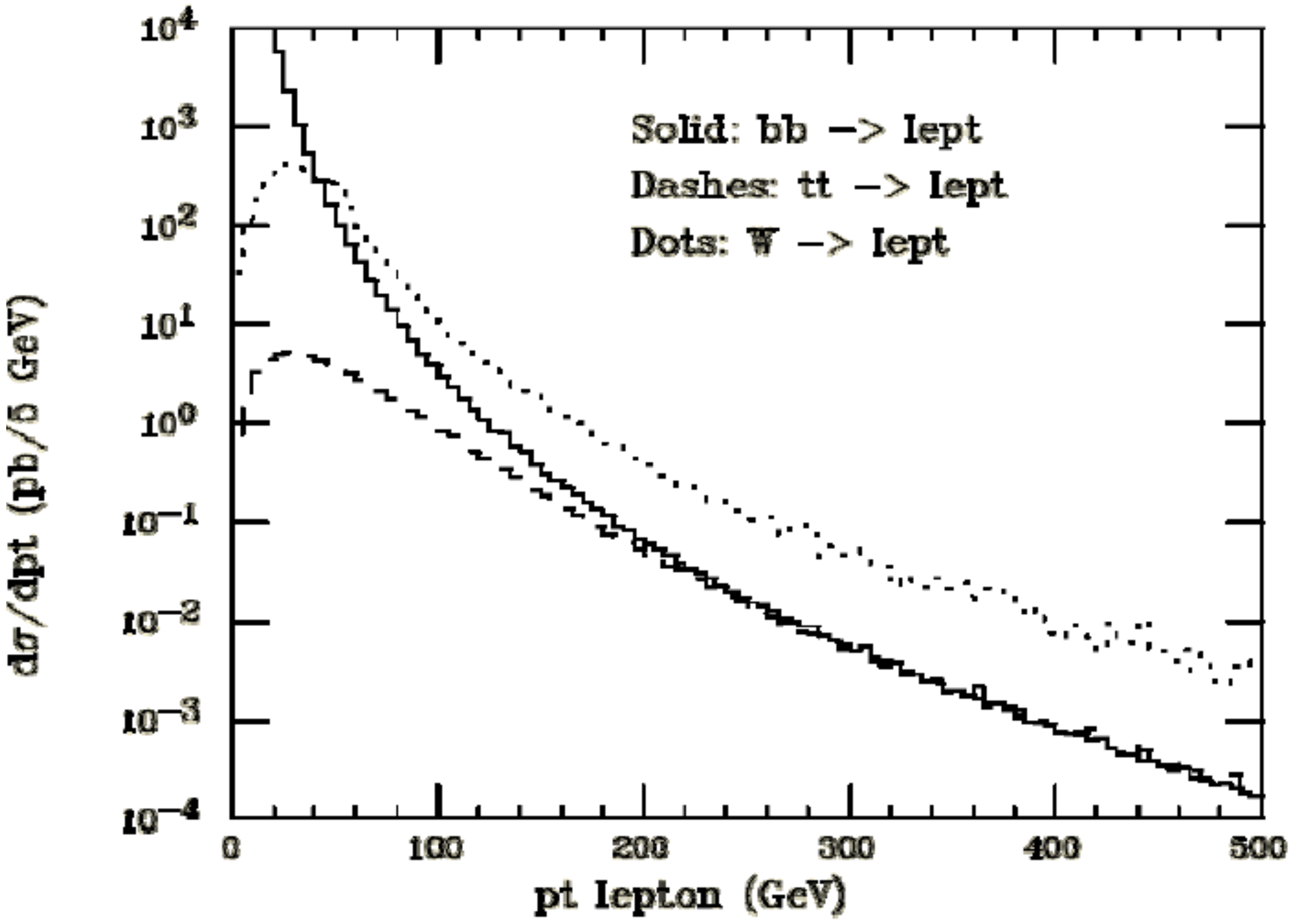
- Muons are not color charged under the QCD SU(3) interaction, and can be produced only through electroweak processes, including also electroweak-mediated decays of hadrons.

- The relevant sources of muons at LHC are:
  - in-flight decay of light hadrons produce through strong interaction (π, K)
  - semi-leptonic decays of hadrons with heavy quarks (bottom, charm) produced through strong interactions
  - prompt production through electroweak gauge bosons (W, Z/γ^*), or similar processes with tau leptons followed by $\tau \rightarrow \mu \nu \bar{\nu}$ decays
  - chain decays of top quarks ($t \rightarrow Wb \rightarrow \mu \bar{\nu} b$)
  - ....

gigi.rolandi@cern.ch

RATES @ L = 10^{34} cm^{-2} s^{-1}

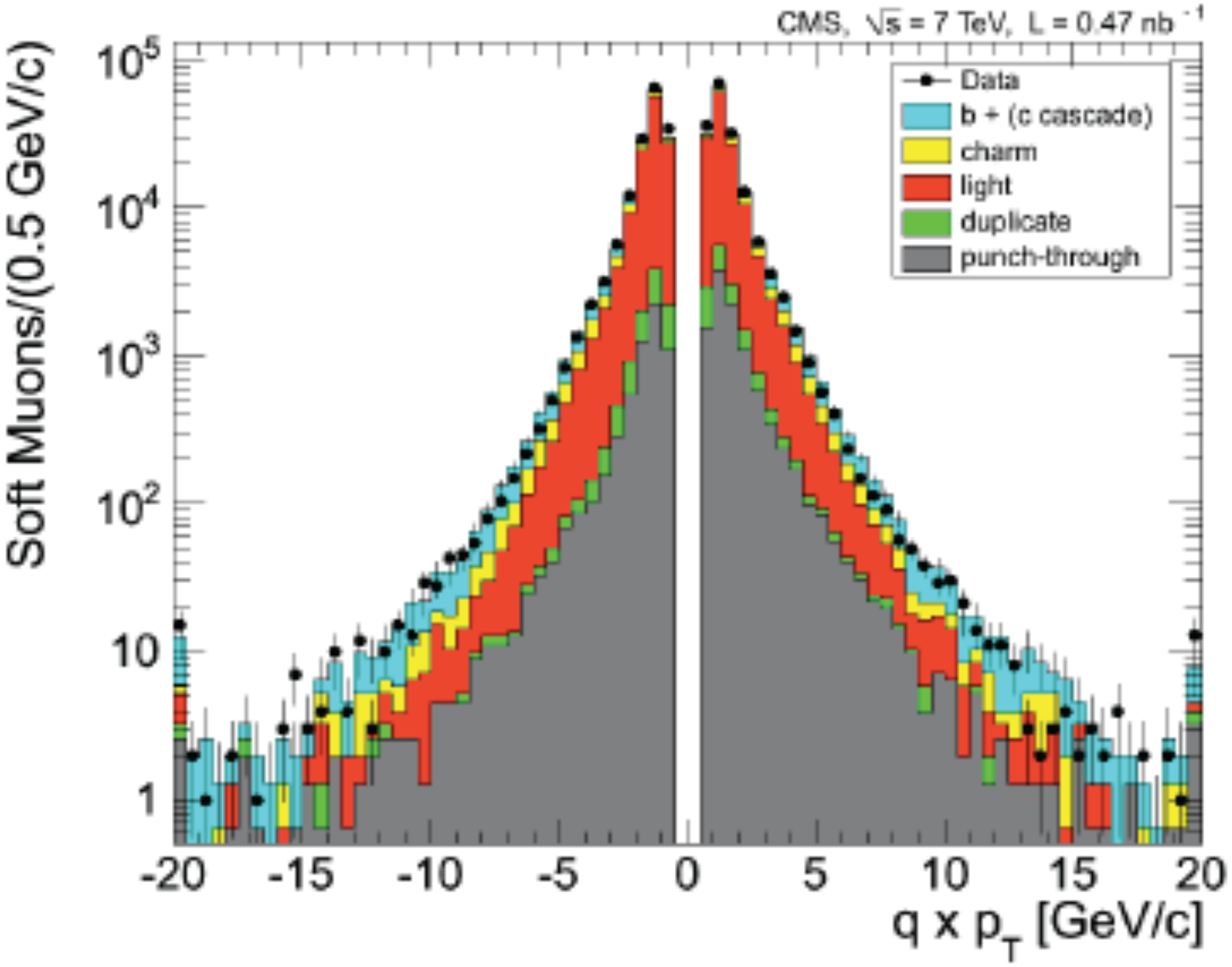




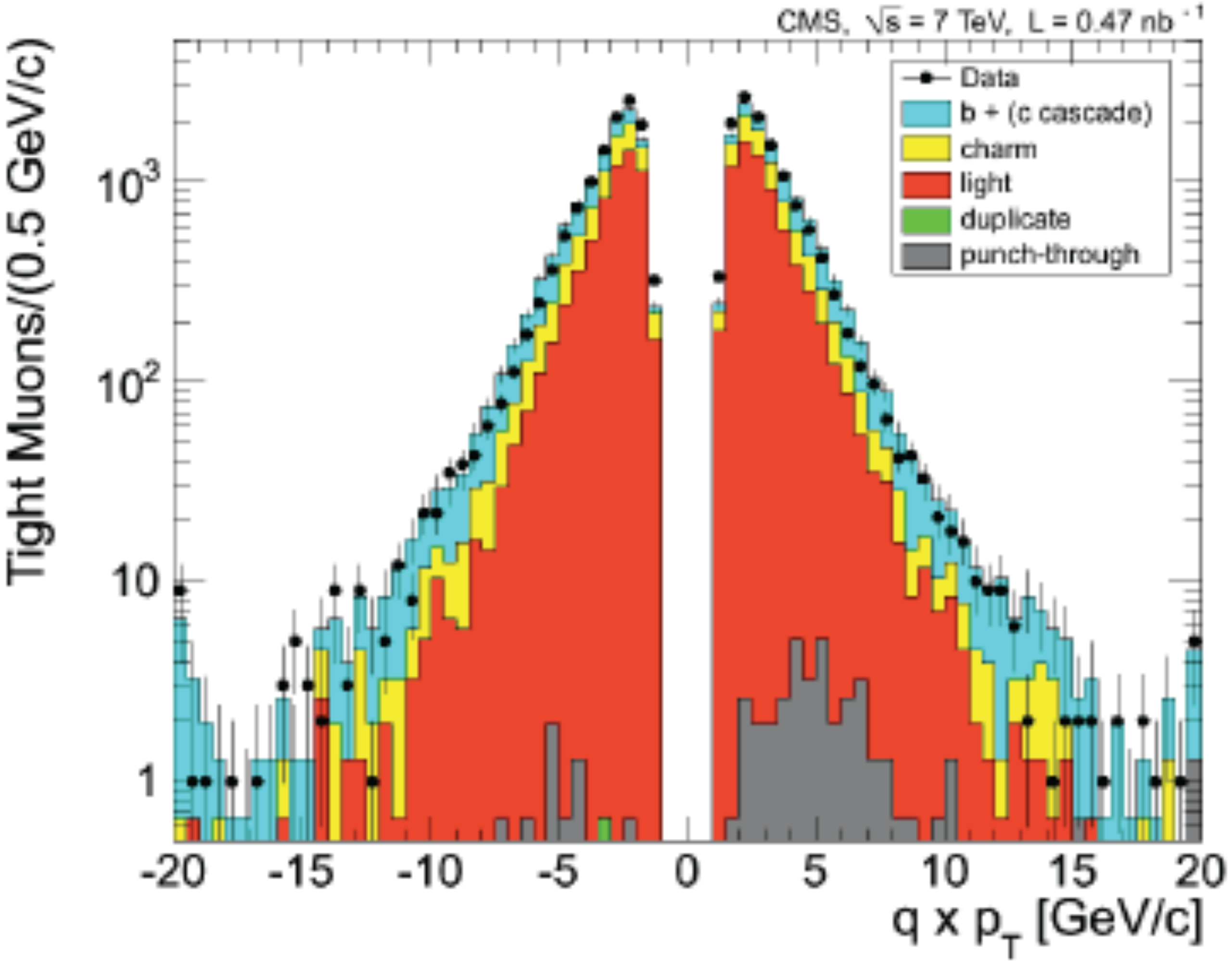
At 50 GeV ~ 10 Hz from b and 10 Hz from W

gigi.rolandi@cern.ch

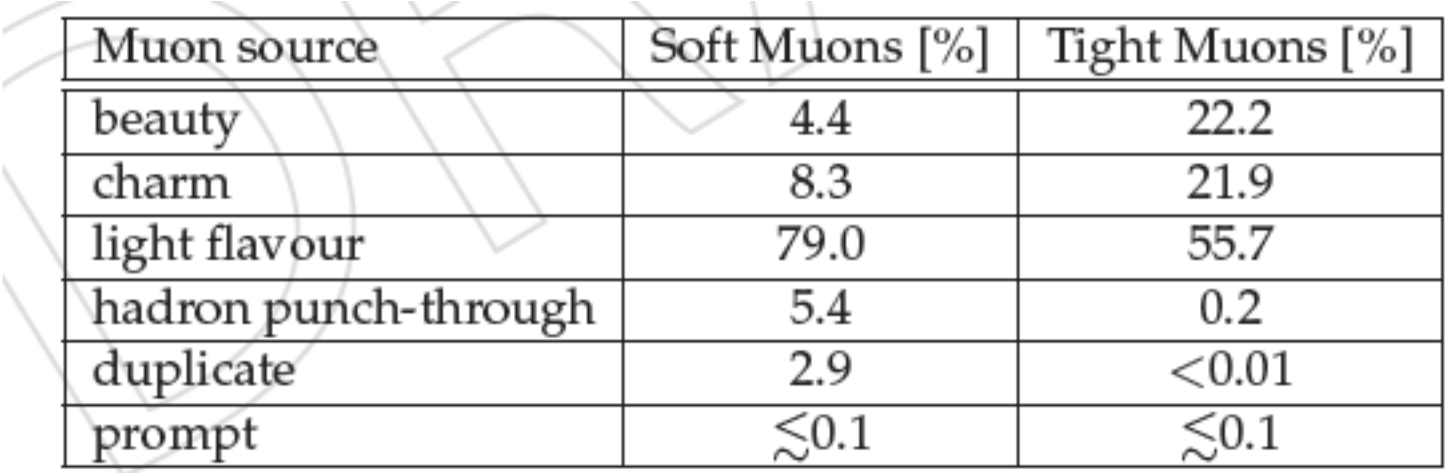
0-bias trigger data



Soft Muon = inside-out with some quality requirement



Tight Muon = outside-in with some quality requirement

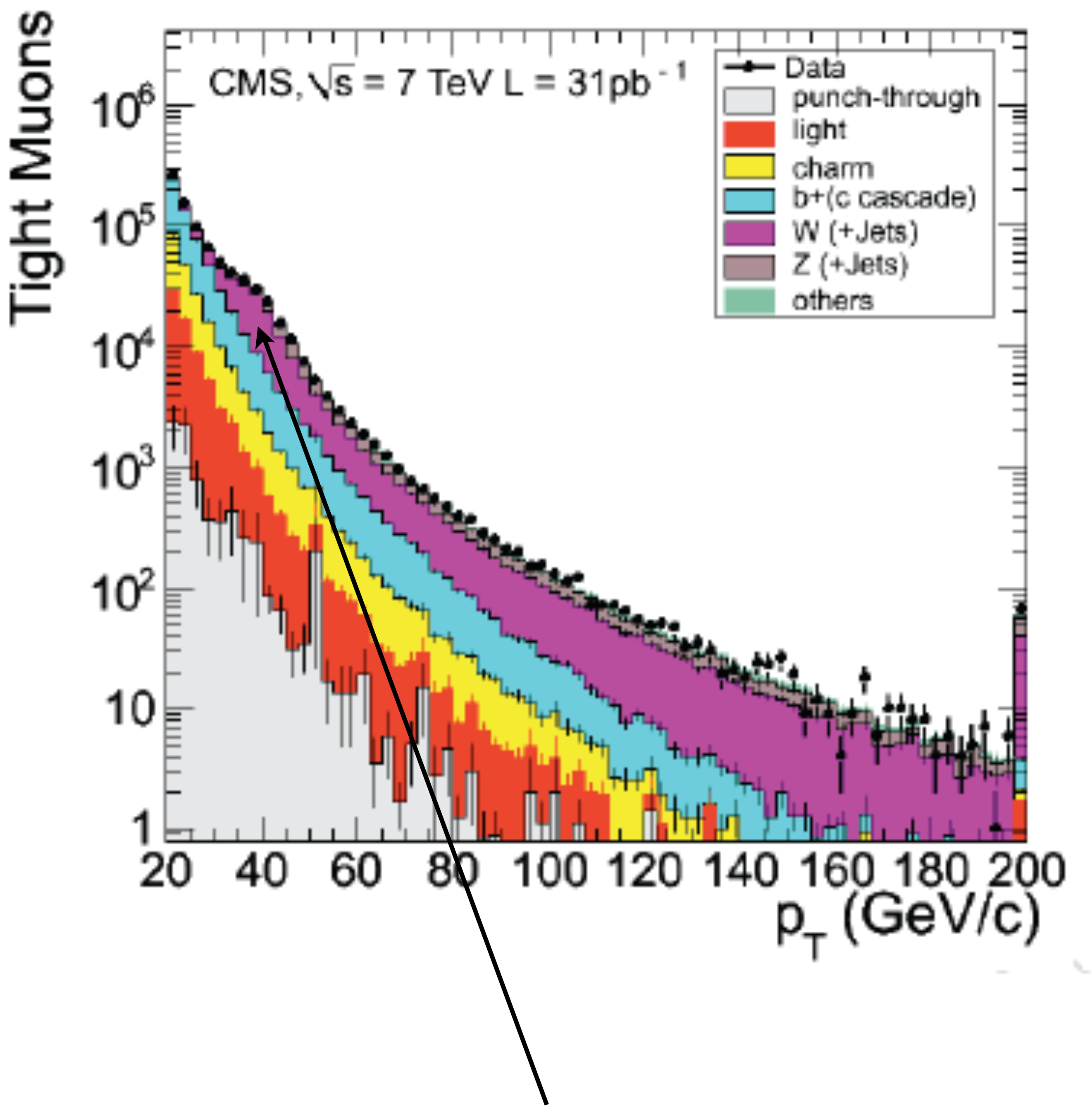


Muon source	Soft Muons [%]	Tight Muons [%]
beauty	4.4	22.2
charm	8.3	21.9
light flavour	79.0	55.7
hadron punch-through	5.4	0.2
duplicate	2.9	<0.01
prompt	$\lesssim$0.1	$\lesssim$0.1

0-Bias sample is dominated by light hadrons decays

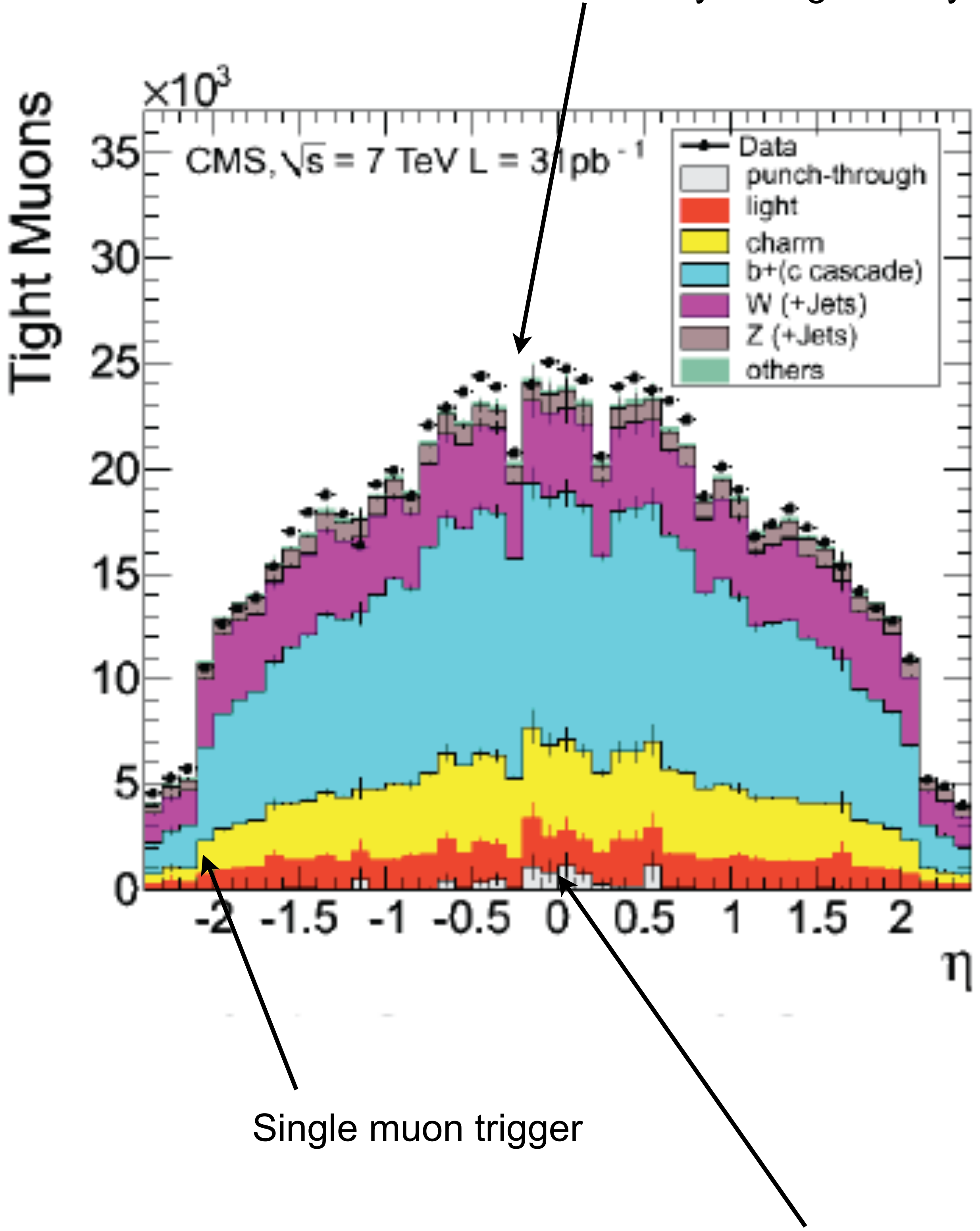
gigi.rolandi@cern.ch

Muon trigger data



W/Z Jacobian peak

Inefficiencies due to muon system geometry



Single muon trigger

Punch through ~ 0.1%

gigi.rolandi@cern.ch

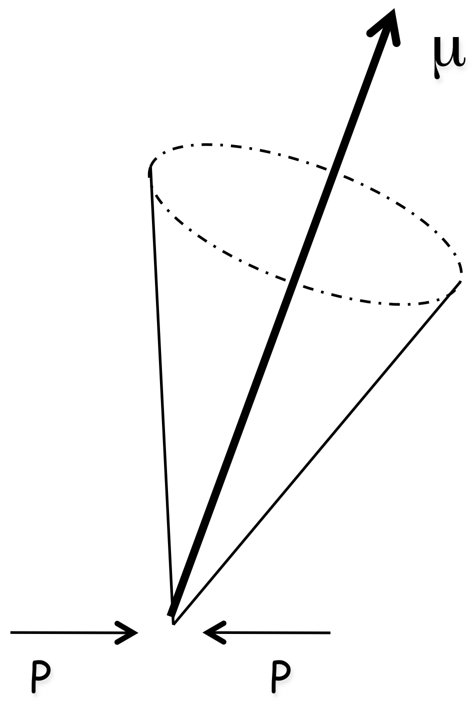
Separation of muon sources

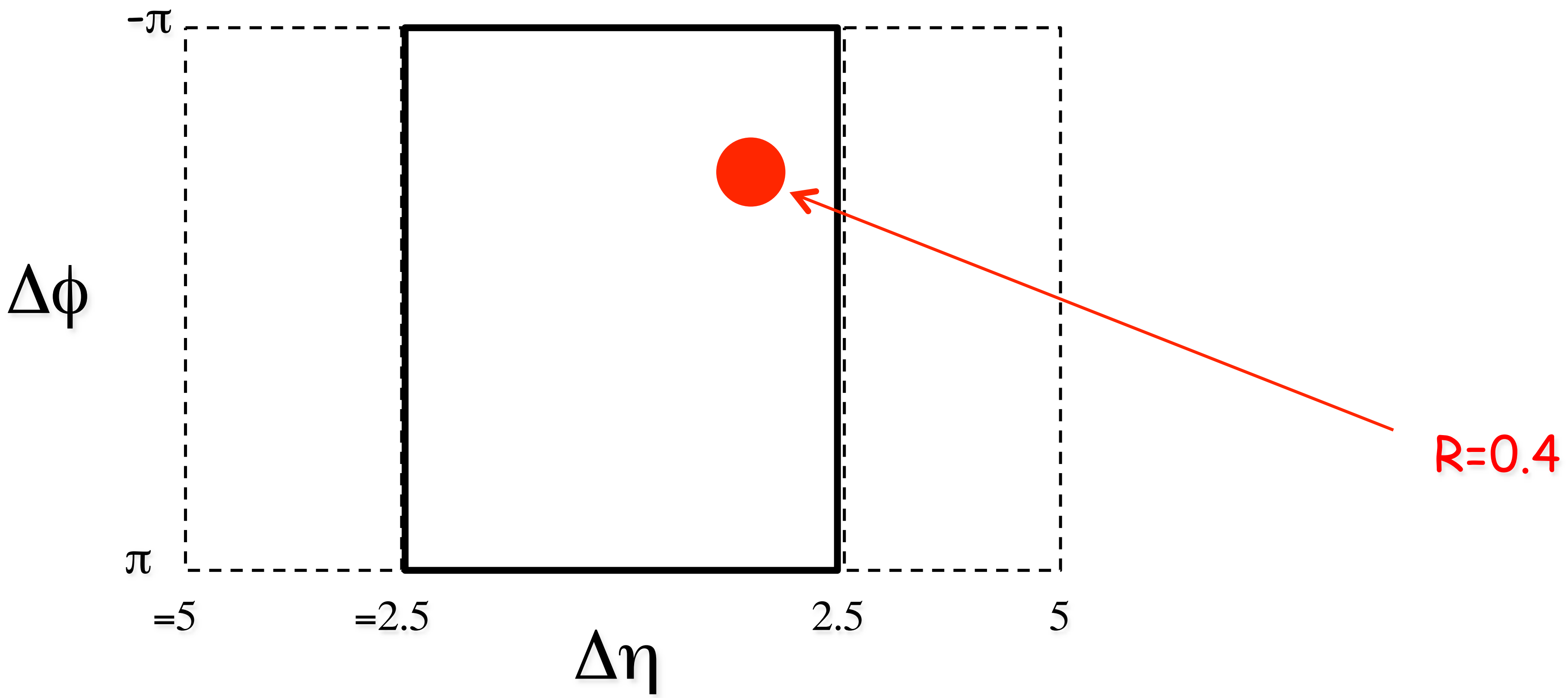
- Muons from light hadrons
  - Their decay point is uniformly distributed and the track may have a kink (more for kaons than for pions)
    - Track chi^2
- Muons from hadrons
  - they do not come from the primary vertex
    - Impact parameter
- Muons from hadrons
  - They come in jets and muons from hadron decays are often accompanied by other tracks
    - Isolation

gigi.rolandi@cern.ch

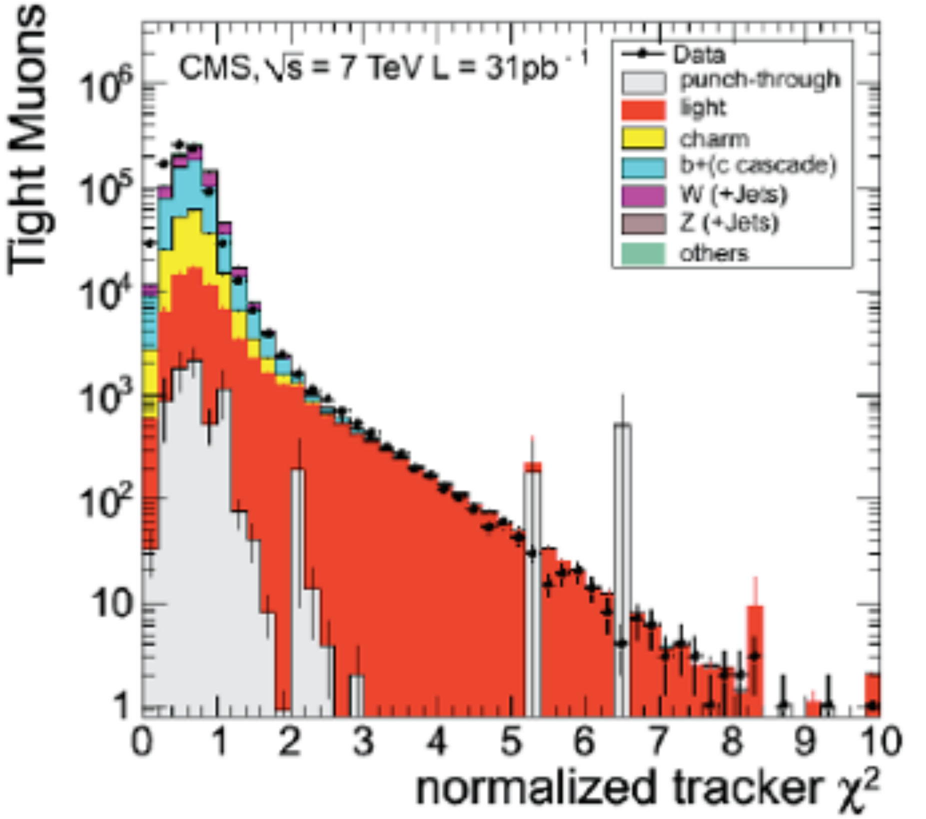
Muons from heavy and light flavors decays are often inside a jet of particles from quark fragmentation or hadron decay . This is not the case for V decays, that decay directly to muons.

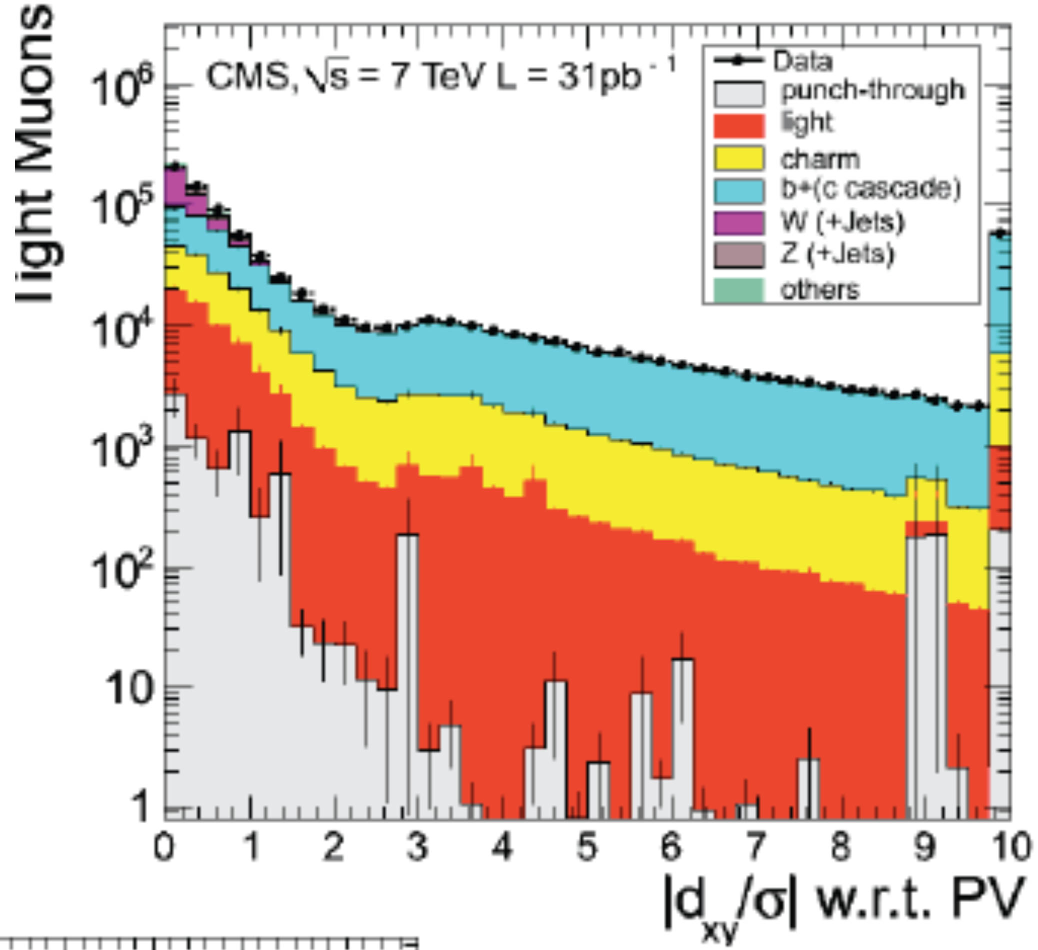
A good discriminating variable is the energy contained in a cone of angle $R=\sqrt{(\Delta\varphi^2+\Delta\eta^2)}$ centered around the muon.

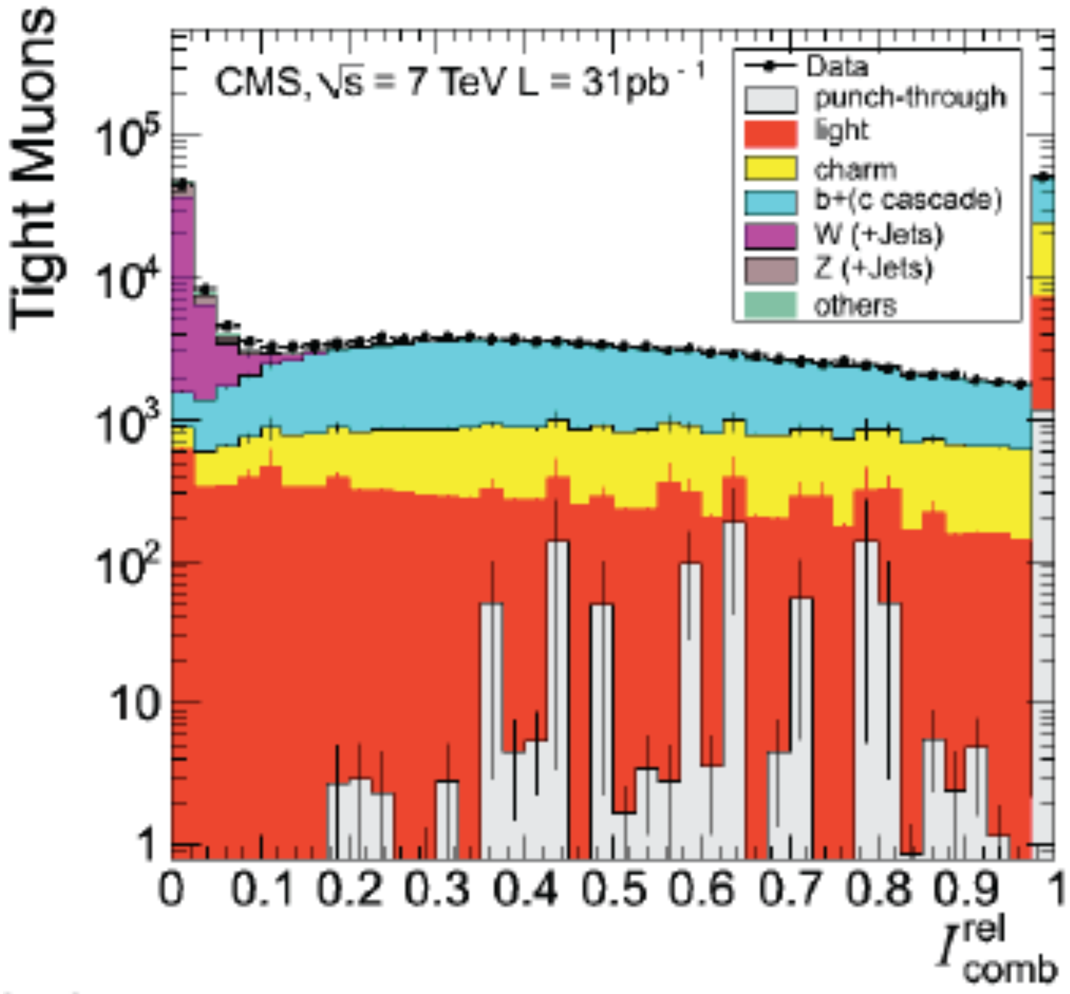




gigi.rolandi@cern.ch







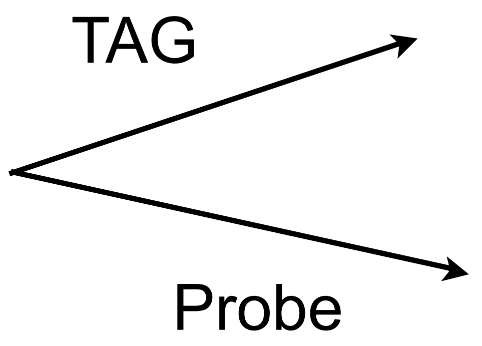
gigi.rolandi@cern.ch

Measurement of efficiency via T&P

- How well do we identify a muon ?
  - Efficiency = Probability of a muon to be identified as such
- Can be computed with MonteCarlo but this is affected by the systematic errors of the simulation
- Can be computed exploiting the shape of a resonance , this is called Tag and Probe method

gigi.rolandi@cern.ch

Consider a resonance decaying into two muons

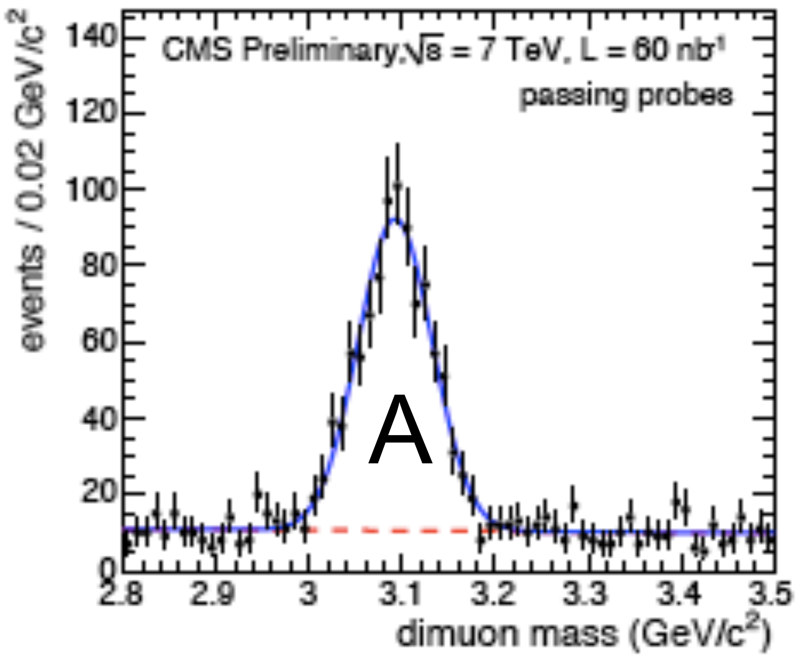


TAG

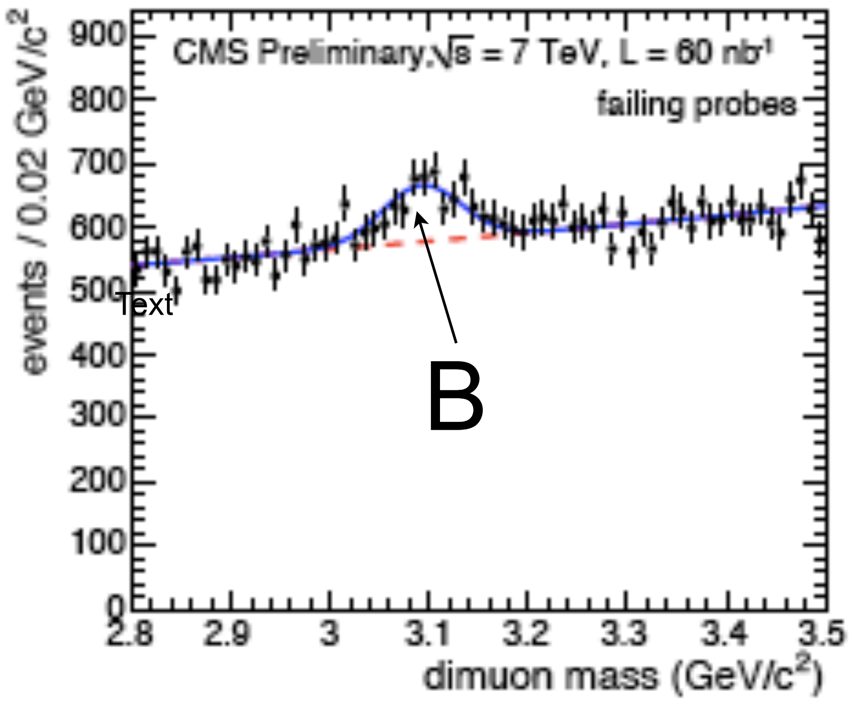
Probe

Make invariant mass of a well identified muon (TAG) with

a) All tracks identified as muon



b) All tracks NOT identified as muons

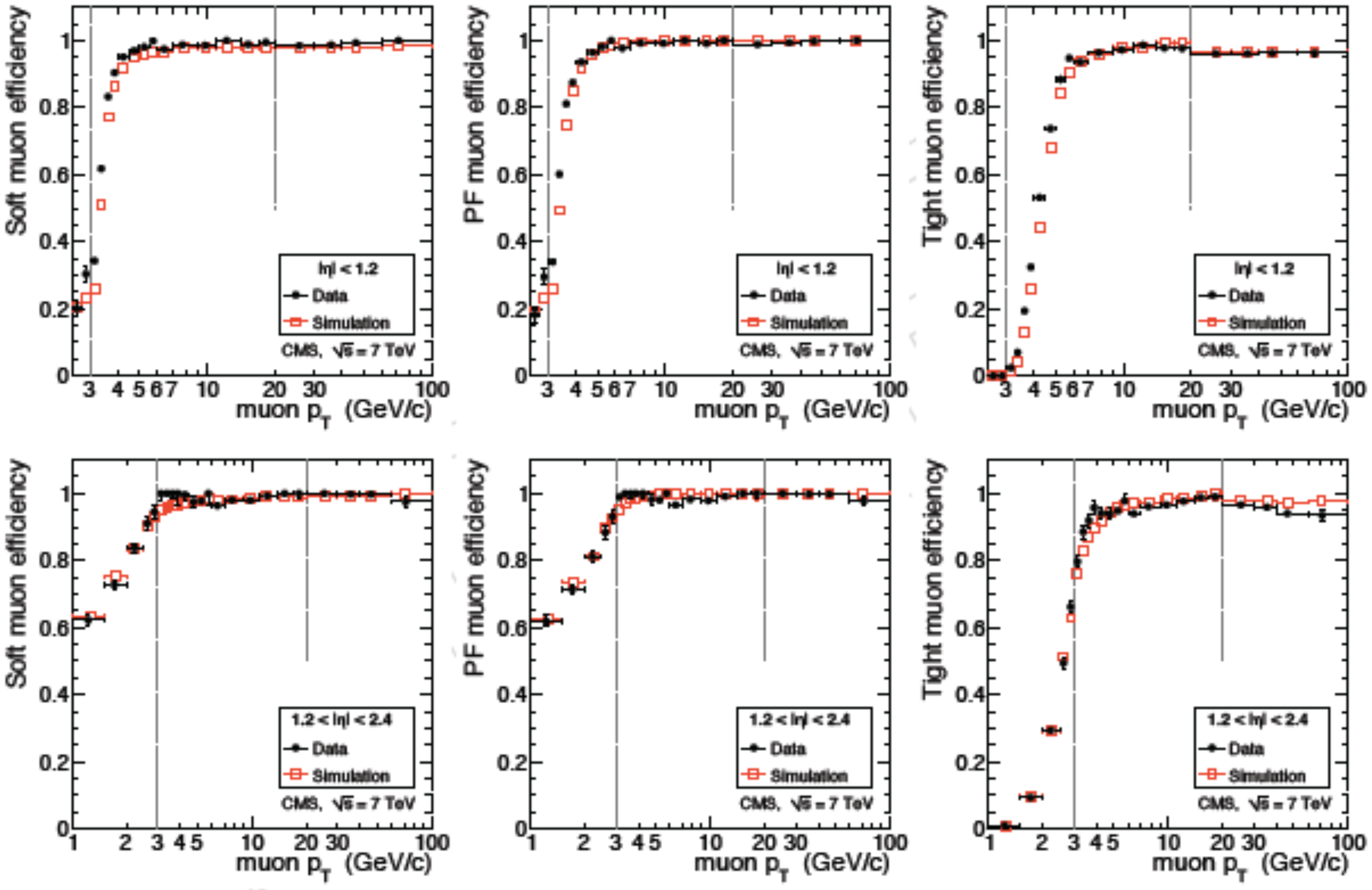


Measure the AREAS (A, B) under the two peaks

Efficiency = A/(A+B)

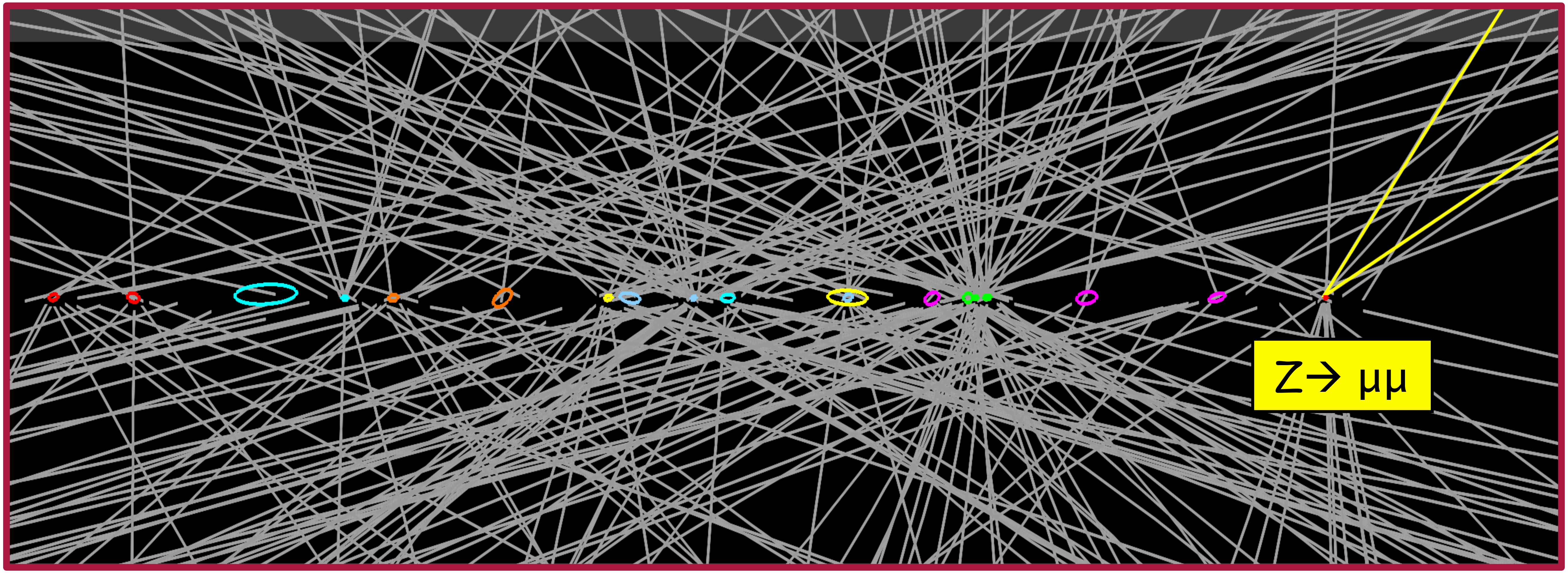
gigi.rolandi@cern.ch

Muon Identification Efficiencies



gigi.rolandi@cern.ch

Isolation and pileup



In presence of multiple interaction the efficiency of the isolation is reduced , since particles produced in the pileup vertices may enter randomly in the isolation cone.

gigi.rolandi@cern.ch

Isolation and pileup

- tracker relative isolation $((\sum pT(TRK))/pT) < 0.1$ (cone $\Delta R=0.3$)

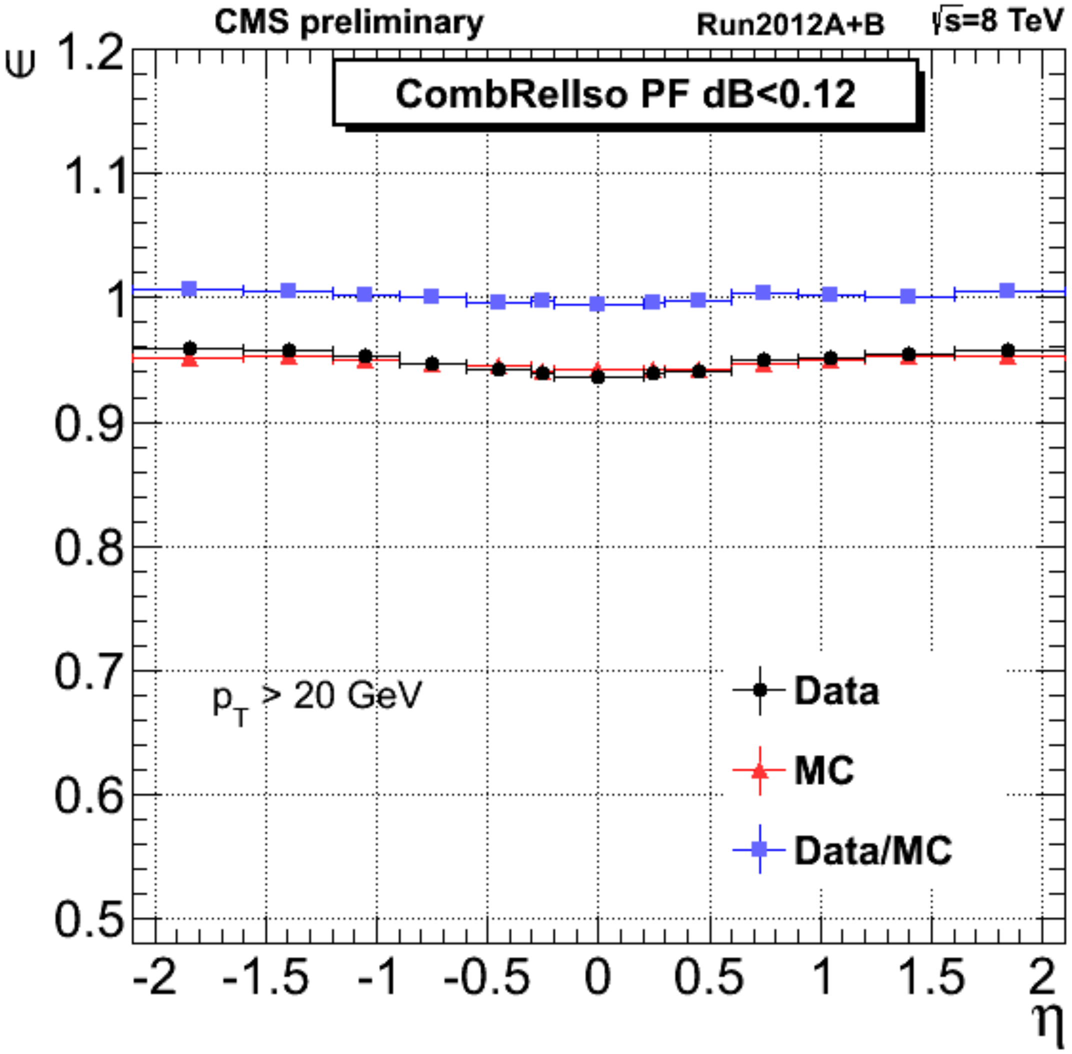
  Uses only charged particles from the primary vertex

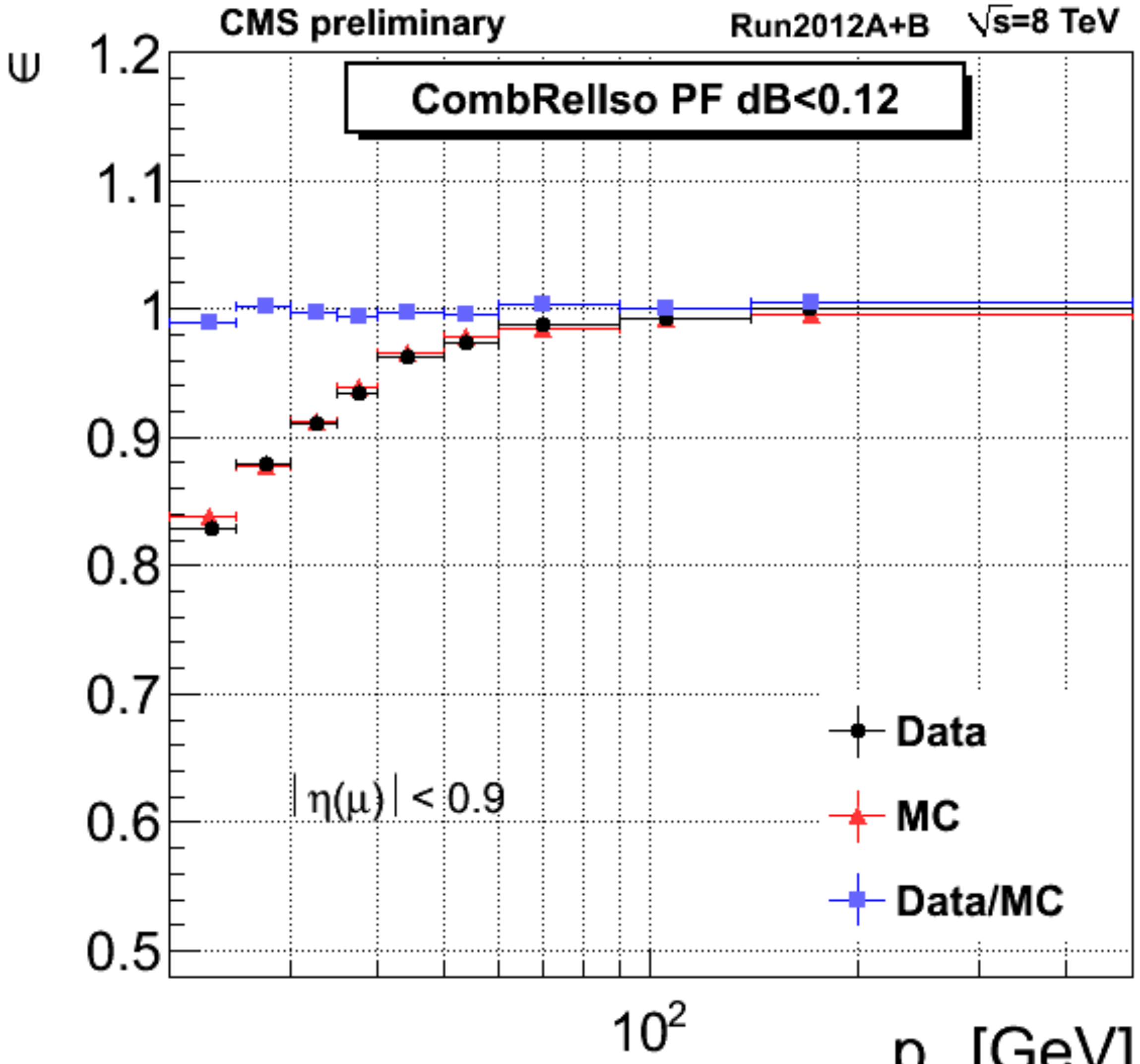
- combined relative PF isolation $(\sum ET(\text{chHad from PV}) + \sum ET(\text{neutHad}) + \sum ET(\text{photons}))/pT < 0.12$ with dBeta correction for pile up (cone $\Delta R = 0.4$).

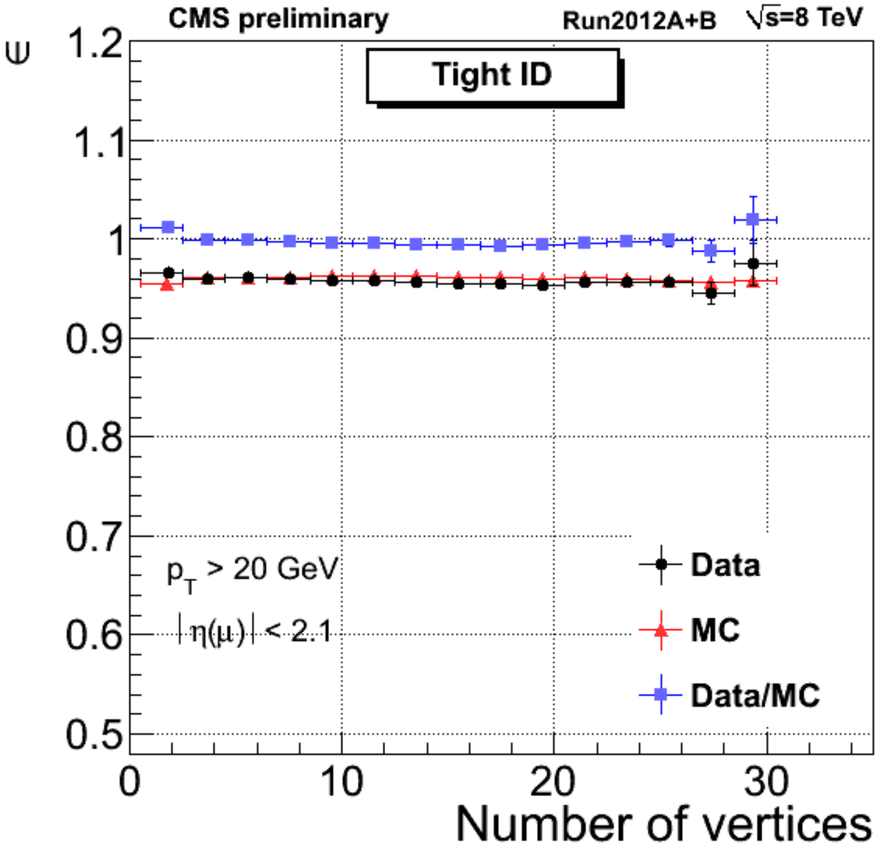
- dBeta: Correction to the neutral component of the combined isolation, taking into account the charged particles in the cone of interest but with particles not originating from the primary vertex, and the average of neutral to charged particles as measured in jets

Uses charged particles from the pileup vertices to compute the amount of energy to subtract inside the cone

gigi.rolandi@cern.ch

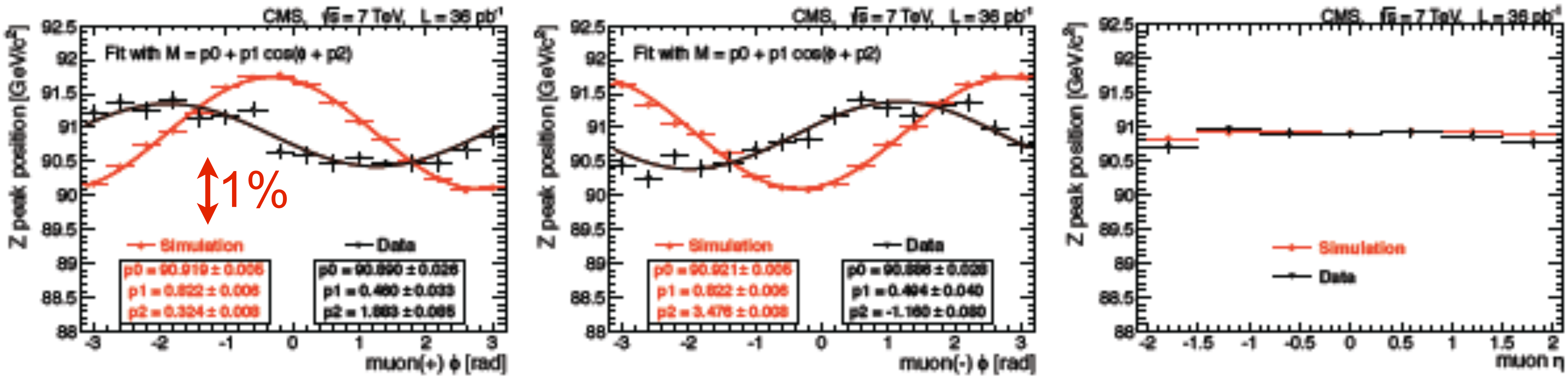

CMS preliminary
Run2012A+B
√s=8 TeV
CombRelIso PF dB<0.12
ψ
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
p_T > 20 GeV
Data
MC
Data/MC
-2
-1.5
-1
-0.5
0
0.5
1
1.5
2
η


CMS preliminary
Run2012A+B
√s=8 TeV
CombRelIso PF dB<0.12
ψ
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
|η(μ)| < 0.9
Data
MC
Data/MC
10^2
p_T [GeV]

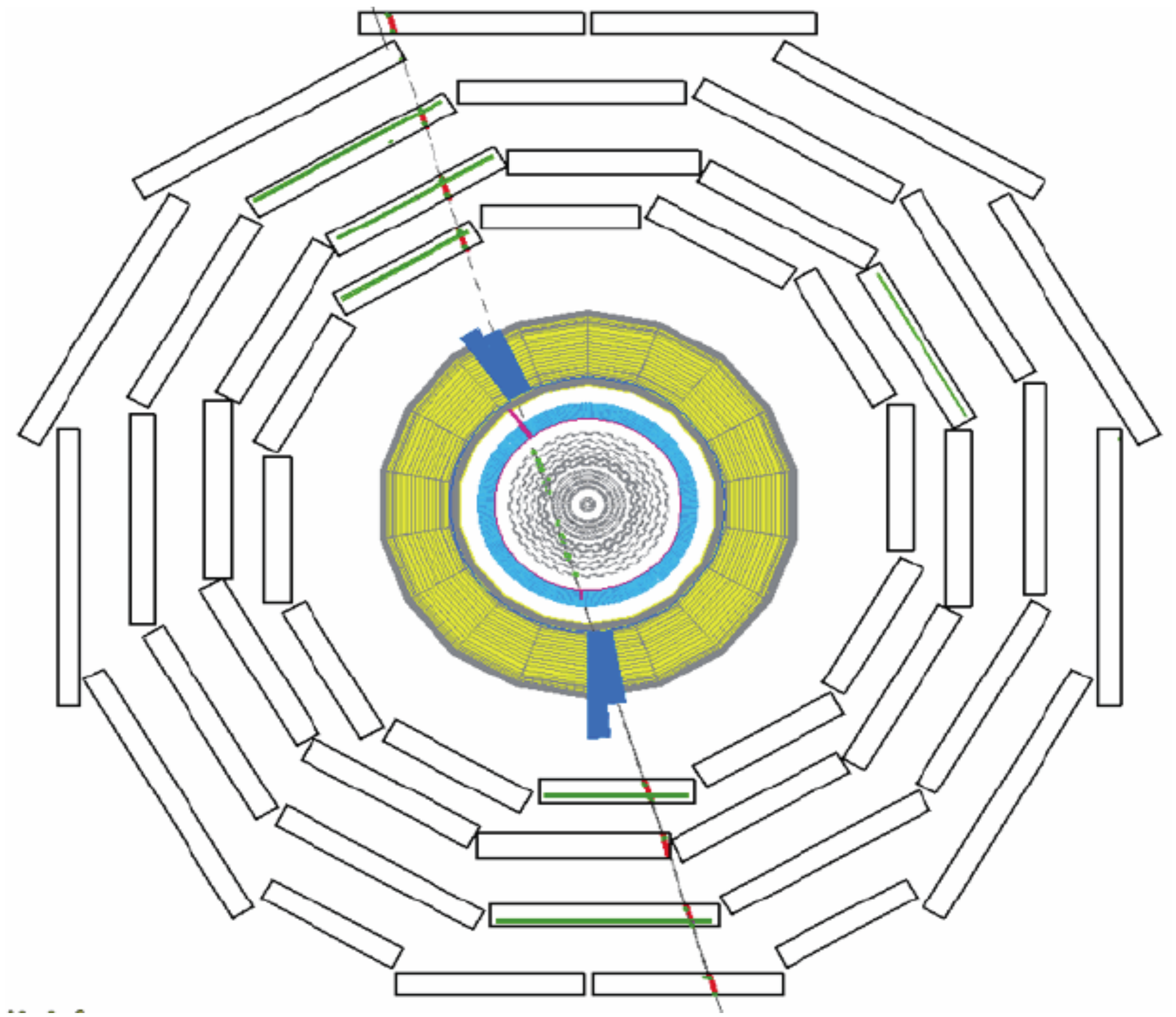

CMS preliminary
Run2012A+B
√s=8 TeV
Tight ID
ψ
1.2
1.1
1
0.9
0.8
0.7
0.6
0.5
p_T > 20 GeV
|η(μ)| < 2.1
Data
MC
Data/MC
0
10
20
30
Number of vertices

Muon Momentum Scale

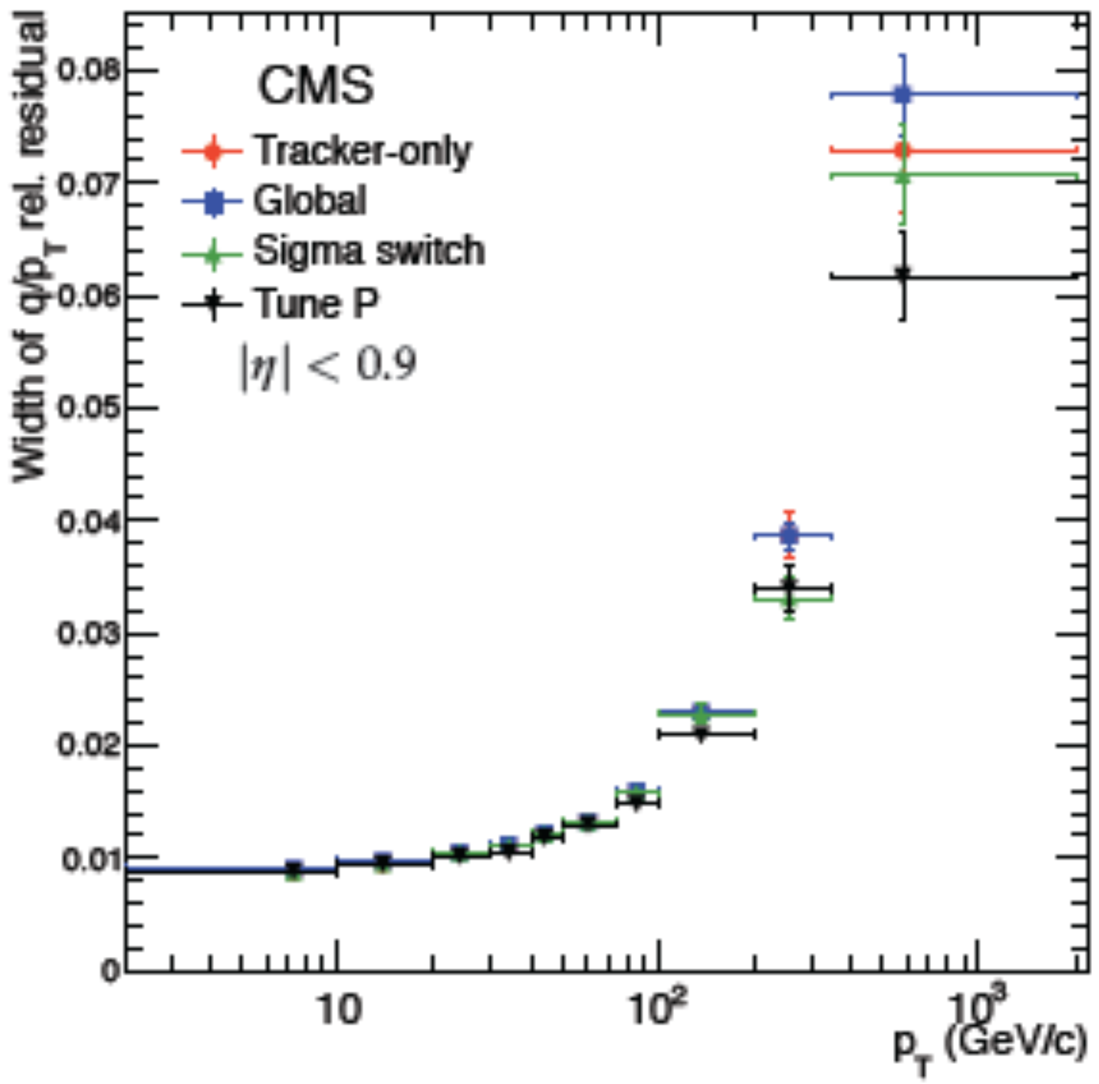
- The precision on the muon momentum depends on how well the tracker is aligned
  - Distortions in the alignment can produce bias
- This can be tested reconstructing the mass of the Z boson



Use cosmic rays to measure high energy muons

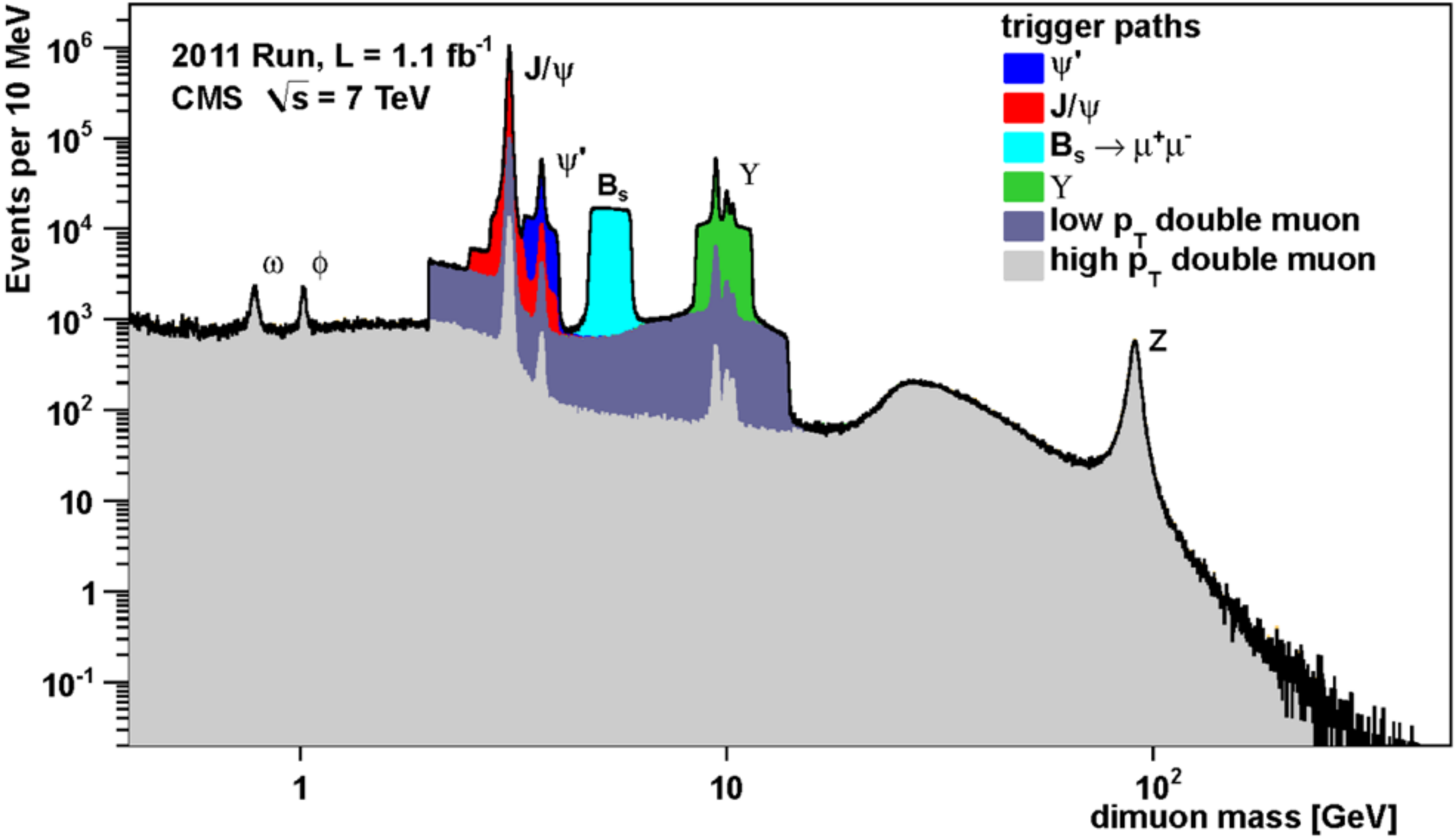


$$R(q/p_T) = \frac{(q/p_T)^{\text{upper}} - (q/p_T)^{\text{lower}}}{\sqrt{2}(q/p_T)^{\text{lower}}}$$



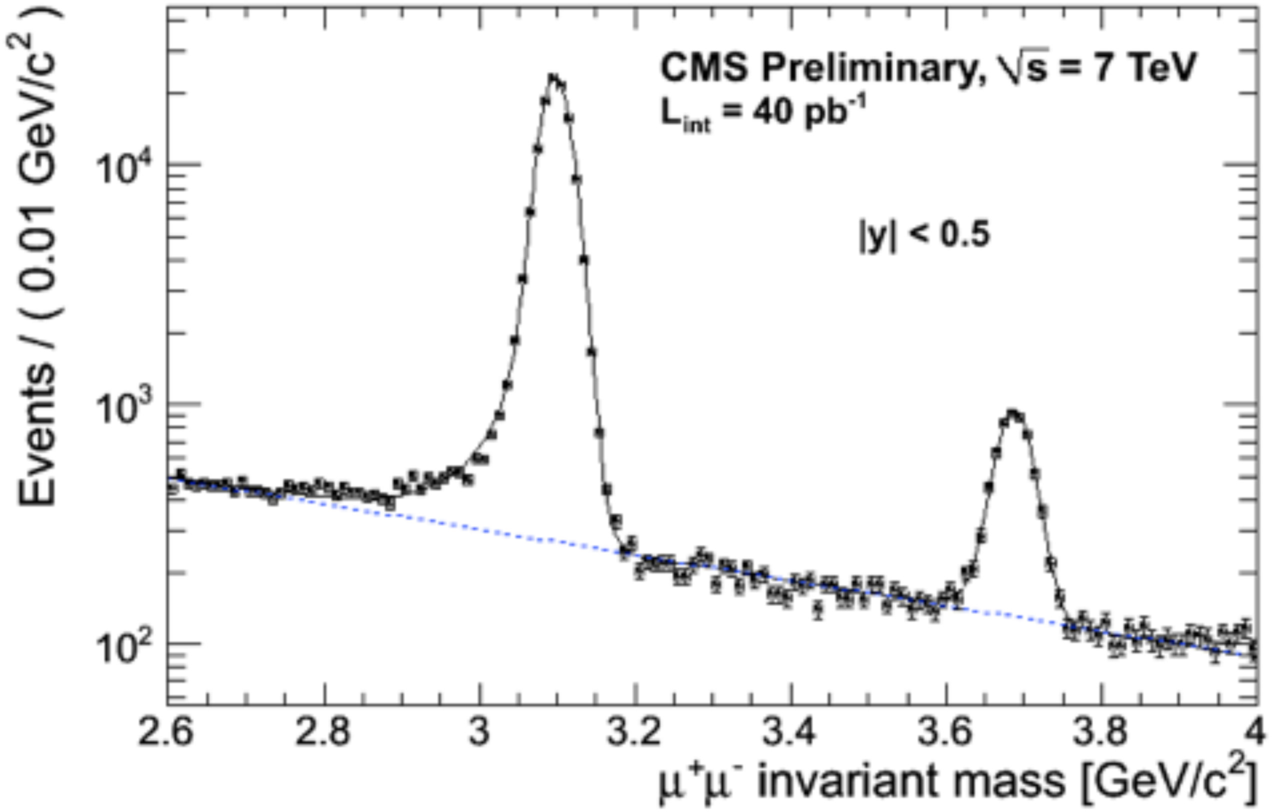
Resolutions, gaussian width of the R(q/P) distribution

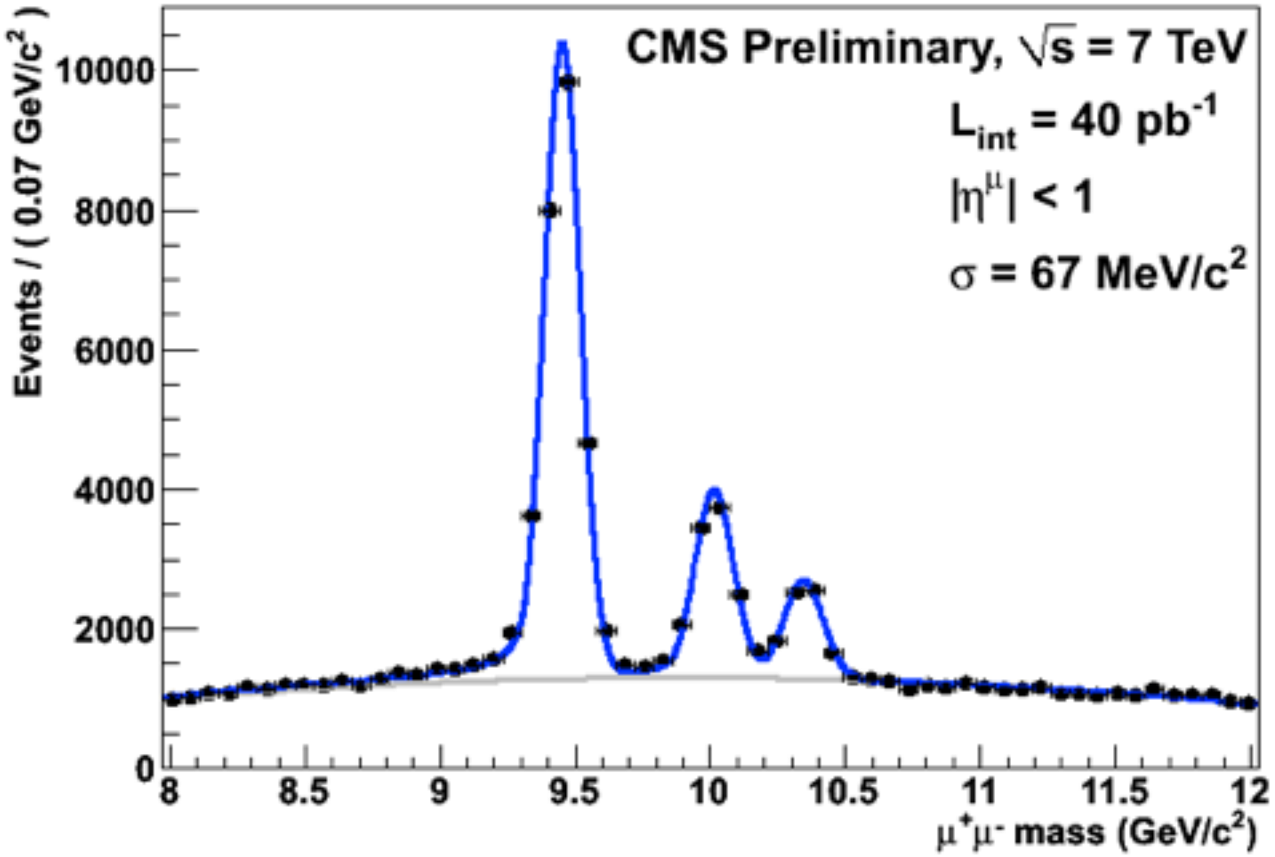
Di-Muon Trigger



gigi.rolandi@cern.ch

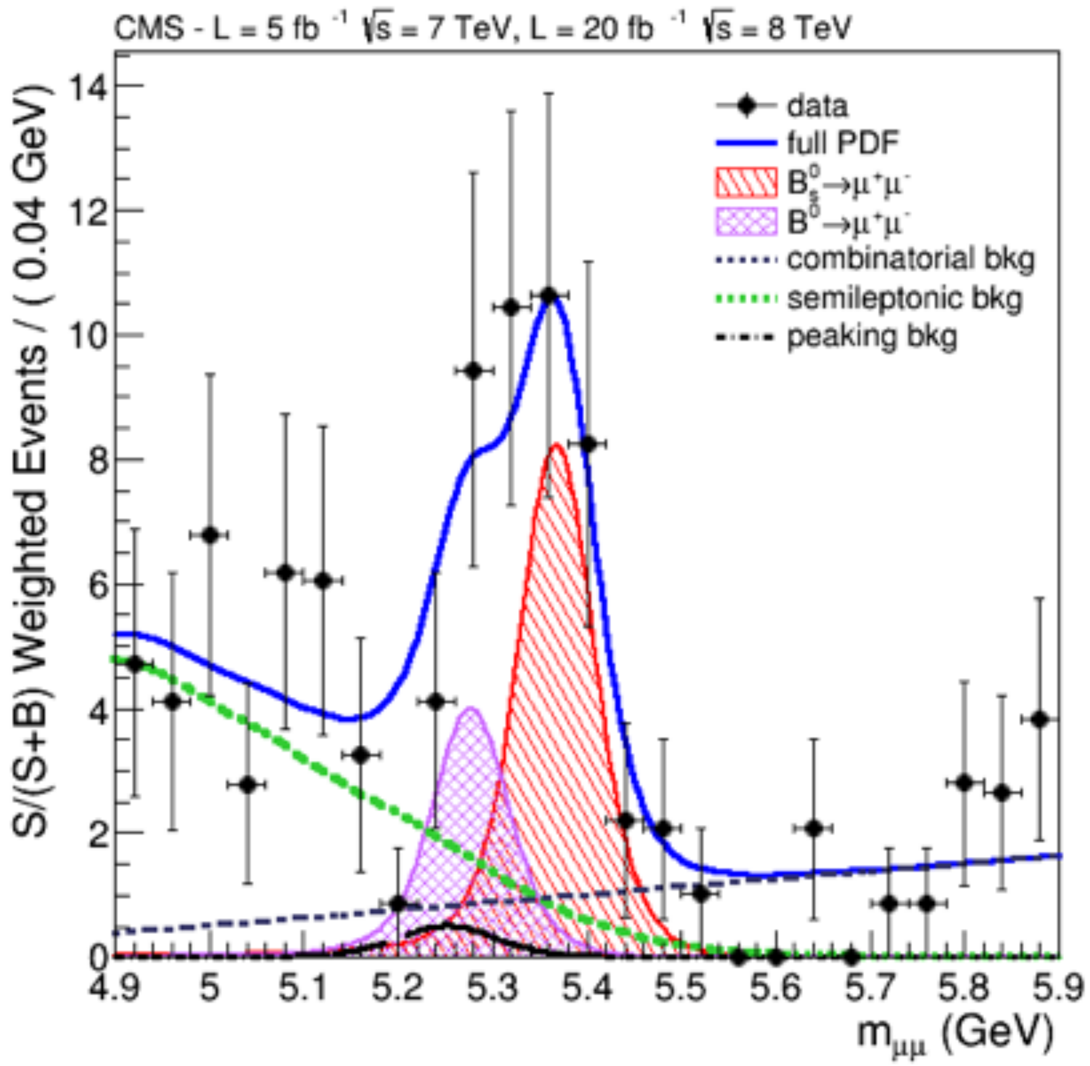
Di-Muon Trigger

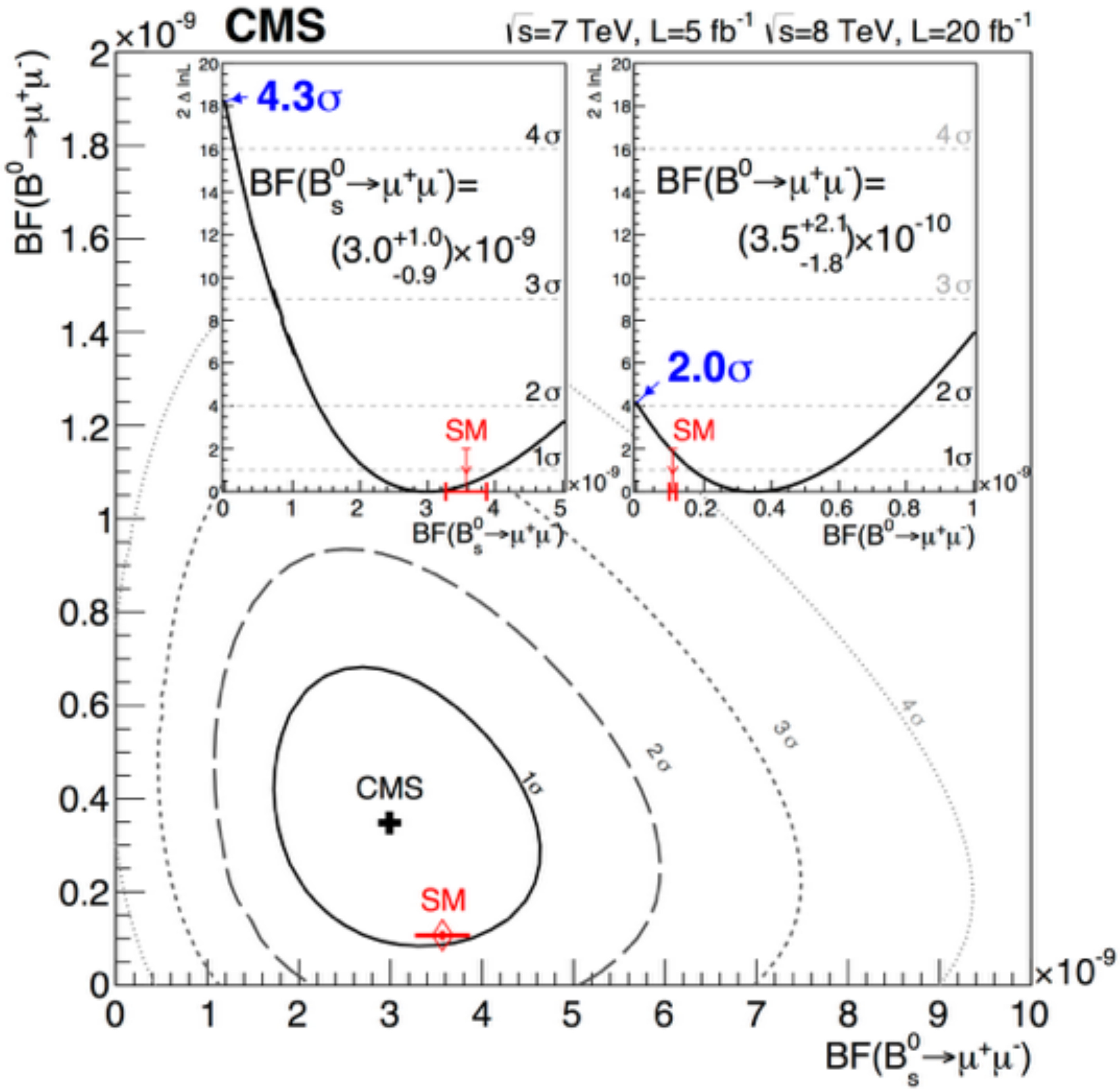




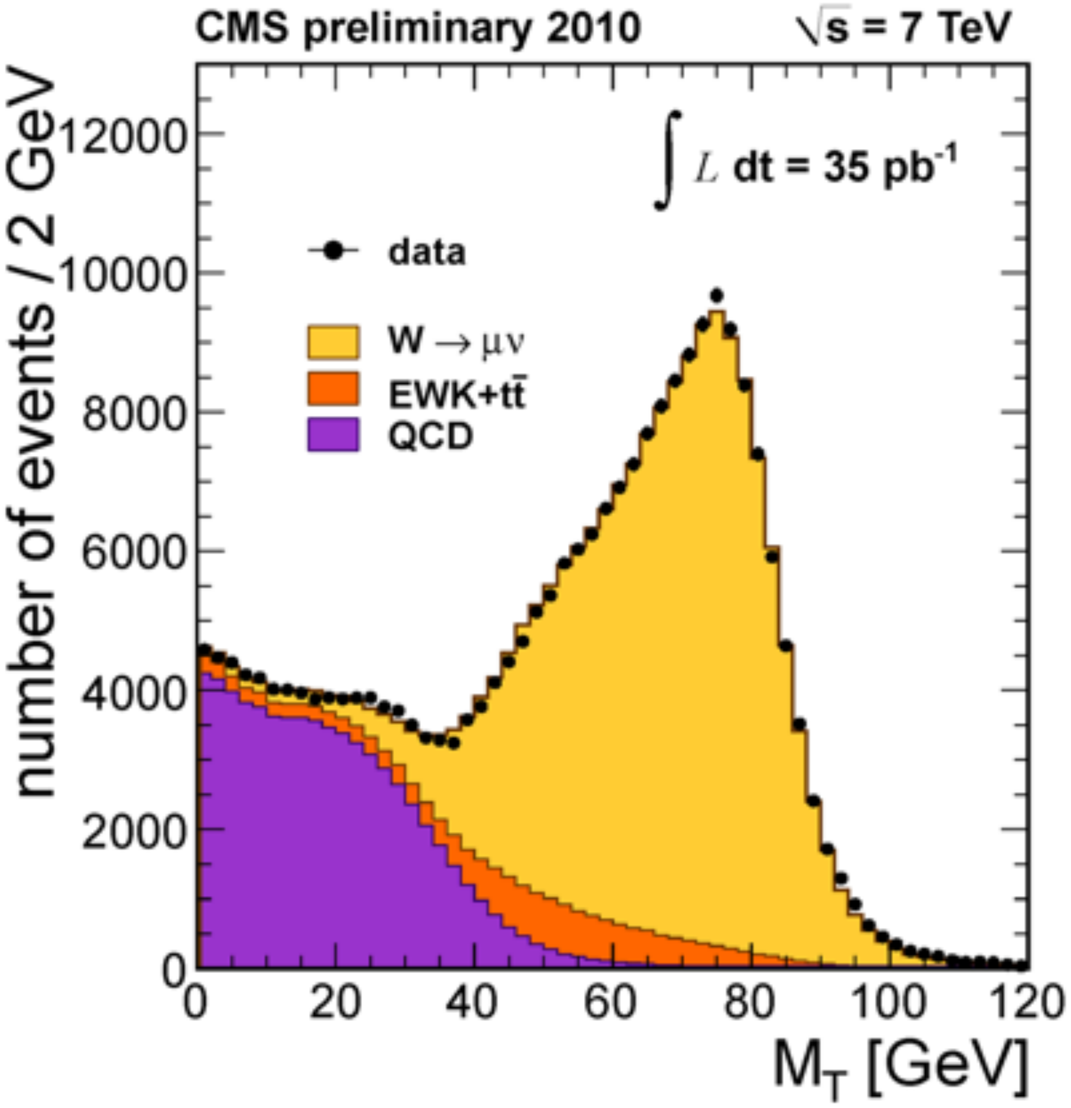
gigi.rolandi@cern.ch

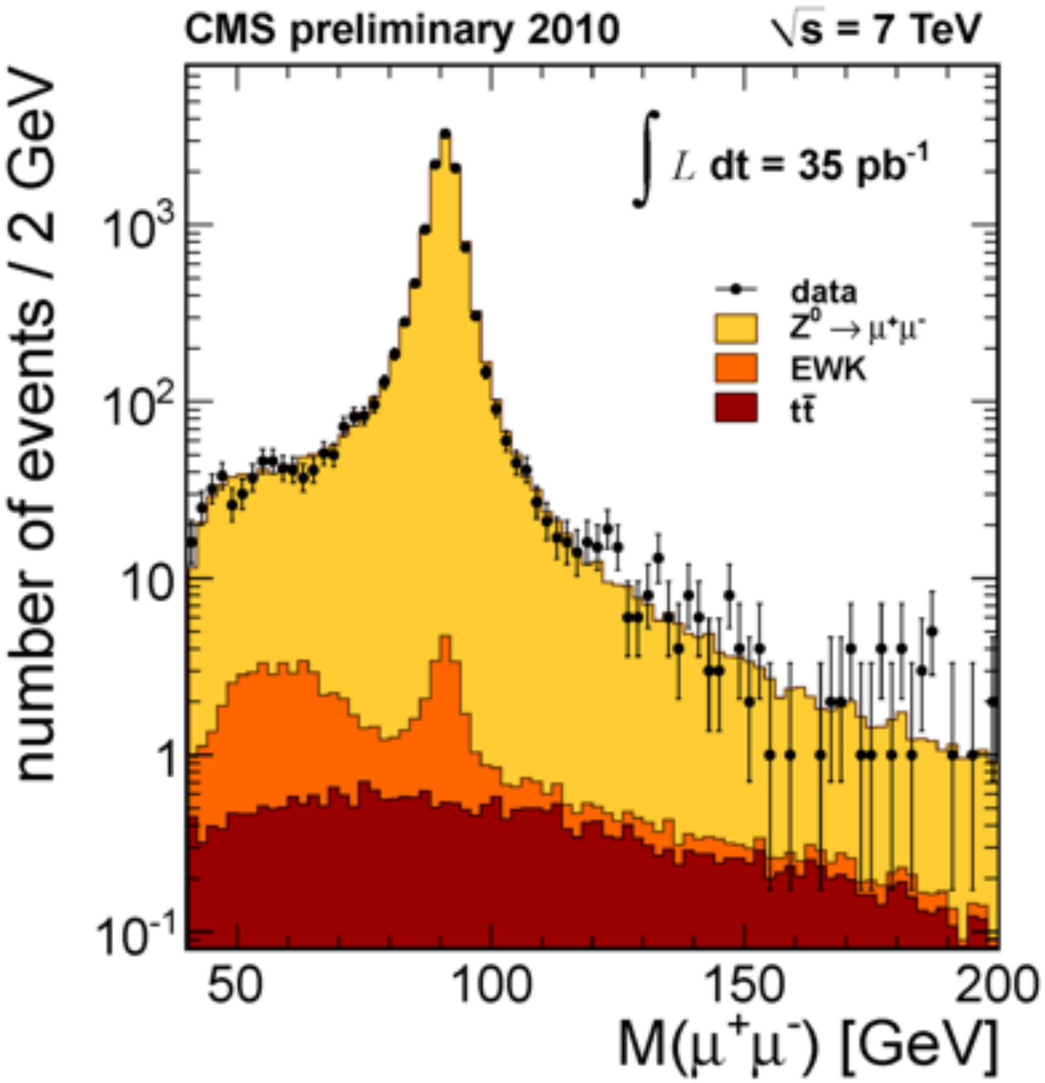
Bs/Bd —> μμ


CMS - L = 5 fb^{-1} √s = 7 TeV, L = 20 fb^{-1} √s = 8 TeV
S/(S+B) Weighted Events / (0.04 GeV)
data
full PDF
$B_s^0 \to \mu^+\mu^-$
$B^0 \to \mu^+\mu^-$
combinatorial bkg
semileptonic bkg
peaking bkg
0
2
4
6
8
10
12
14
4.9
5
5.1
5.2
5.3
5.4
5.5
5.6
5.7
5.8
5.9
$m_{\mu\mu}$ (GeV)

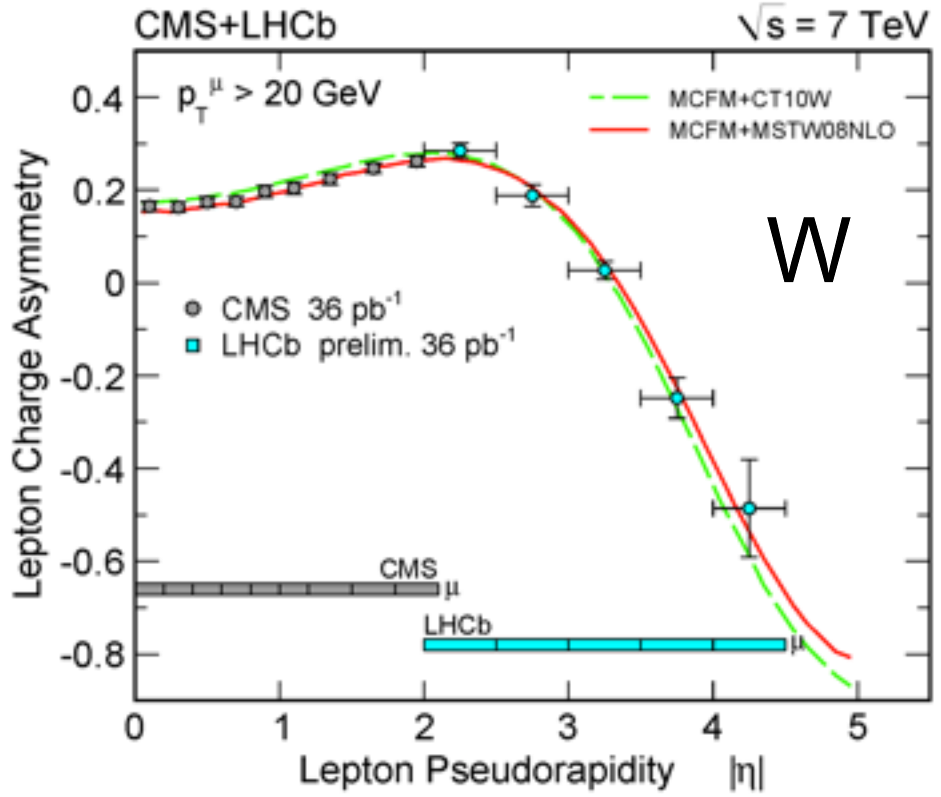

CMS
√s=7 TeV, L=5 fb^{-1} √s=8 TeV, L=20 fb^{-1}
$\times 10^{-9}$
$BF(B^0 \to \mu^+\mu^-)$
$BF(B_s^0 \to \mu^+\mu^-)$
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
2
0
1
2
3
4
5
6
7
8
9
10
$\times 10^{-9}$
CMS
SM
1σ
2σ
3σ
4σ
2 Δ lnL
4.3σ
$BF(B_s^0 \to \mu^+\mu^-) = (3.0^{+1.0}_{-0.9}) \times 10^{-9}$
4σ
3σ
2σ
1σ
SM
$BF(B_s^0 \to \mu^+\mu^-)$
$\times 10^{-9}$
2.0σ
$BF(B^0 \to \mu^+\mu^-) = (3.5^{+2.1}_{-1.8}) \times 10^{-10}$
SM
$BF(B^0 \to \mu^+\mu^-)$
$\times 10^{-9}$

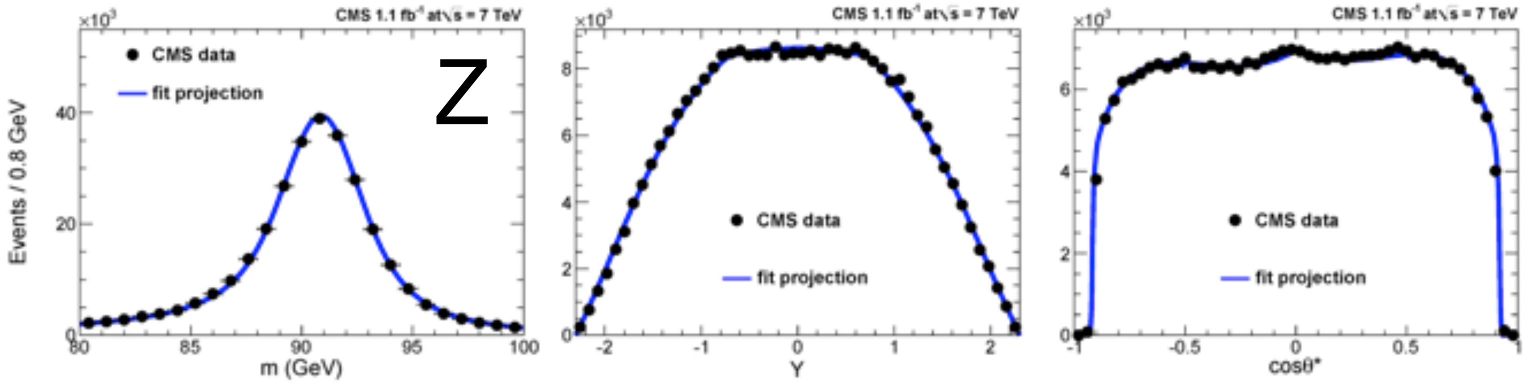
Single Muon Trigger



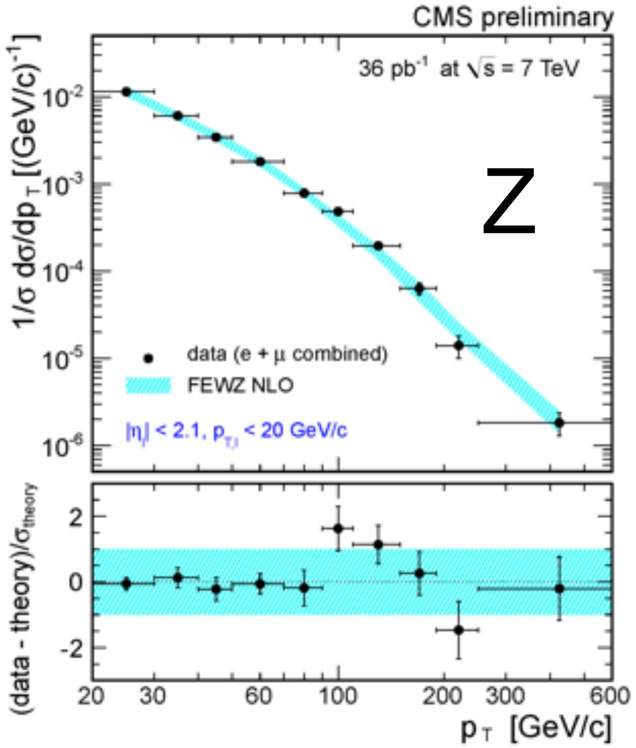


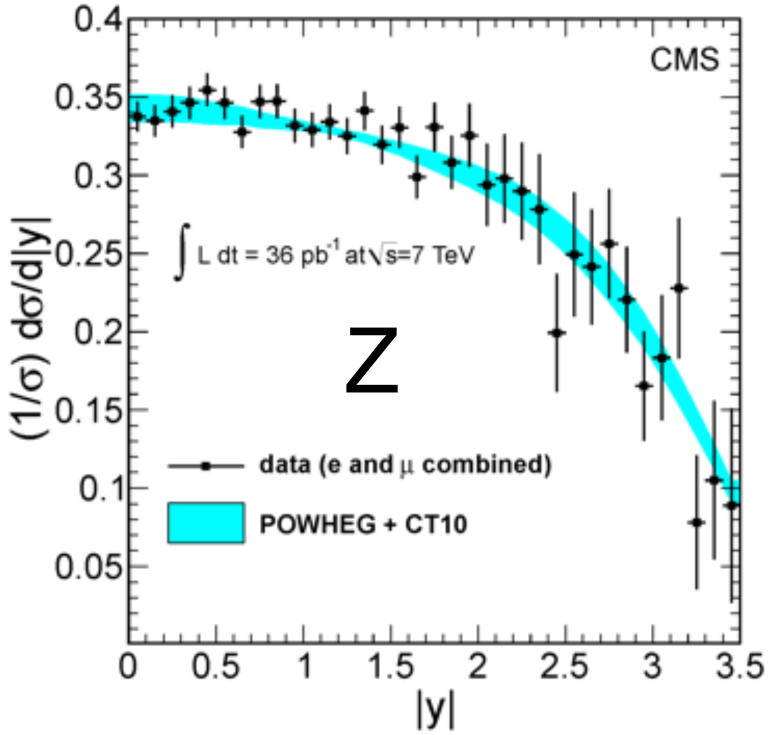
Electroweak

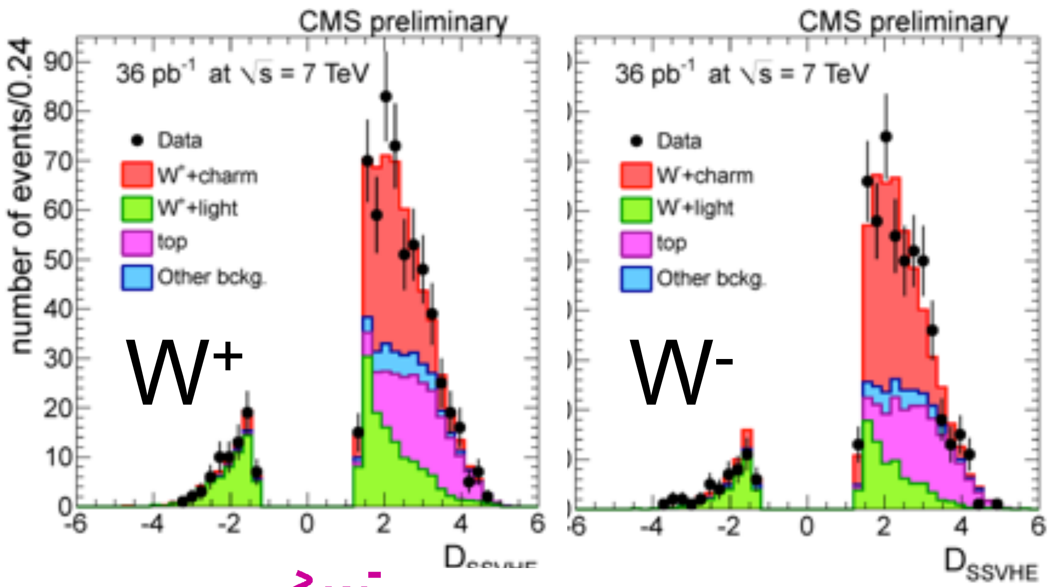


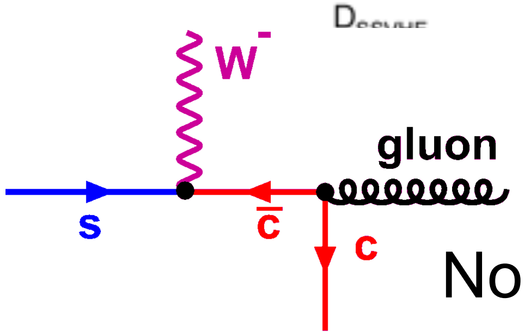


sin2(θ$_{eff}$) = 0.2287 +/- 0.0020 (stat.) +/- 0.0025 (syst.)

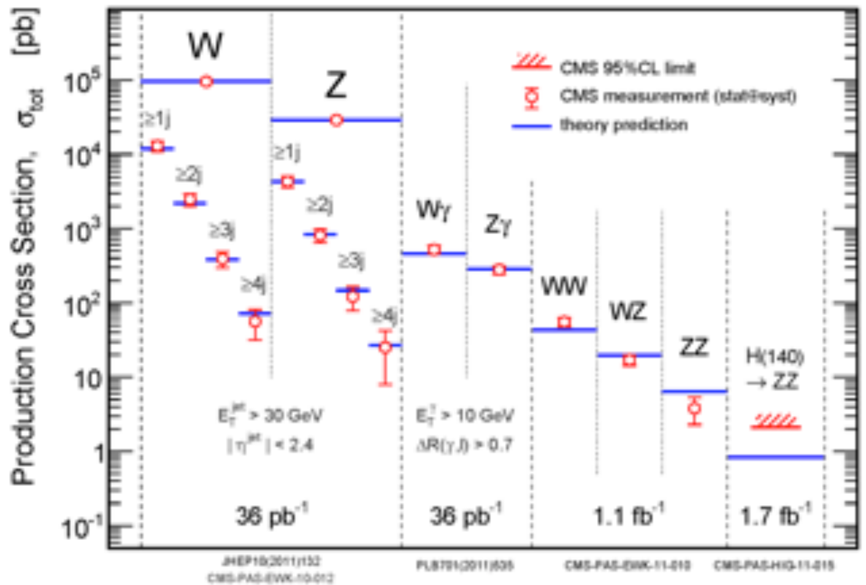








No asymmetry



Francois Englert

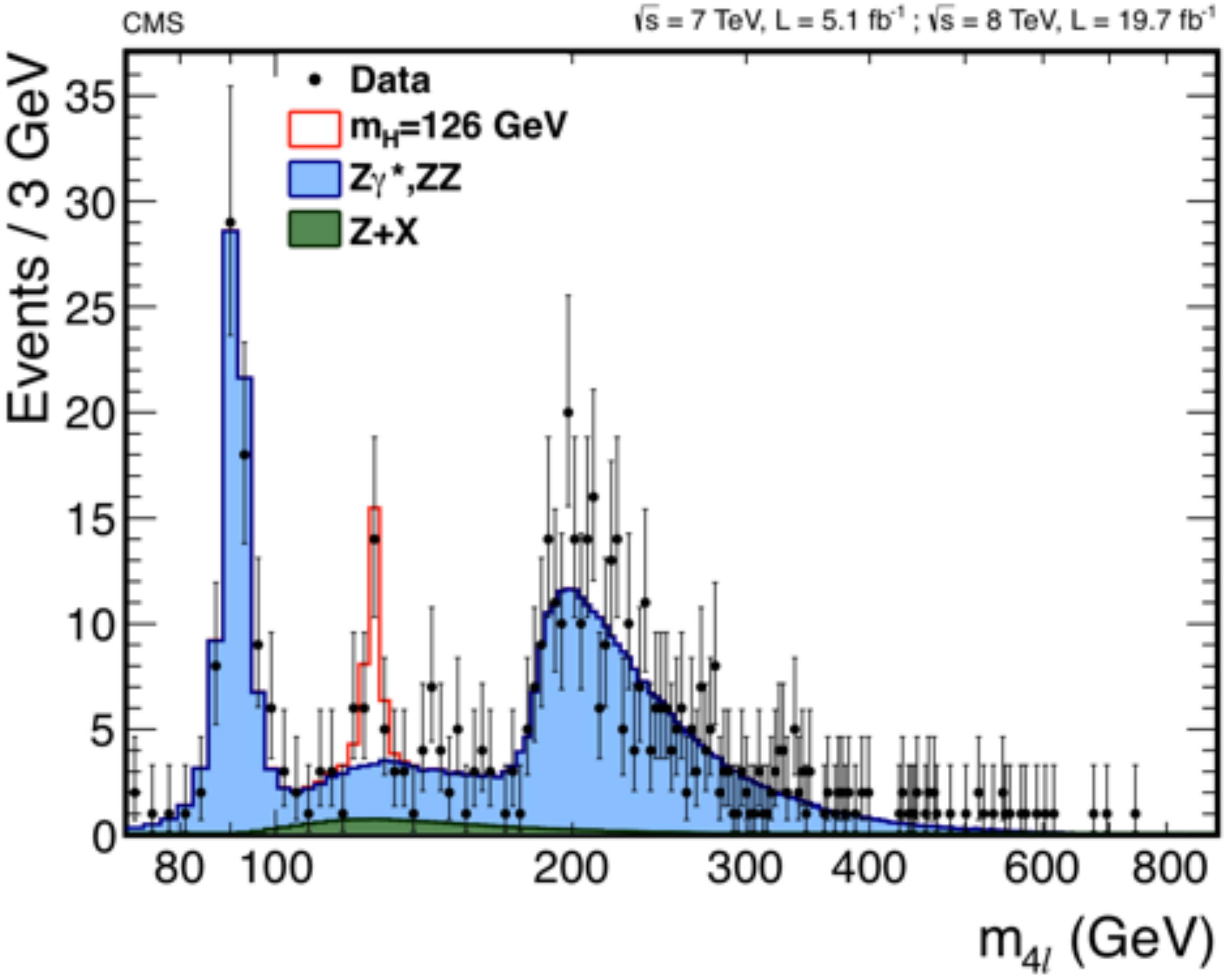
Peter Higgs

Robert Brout

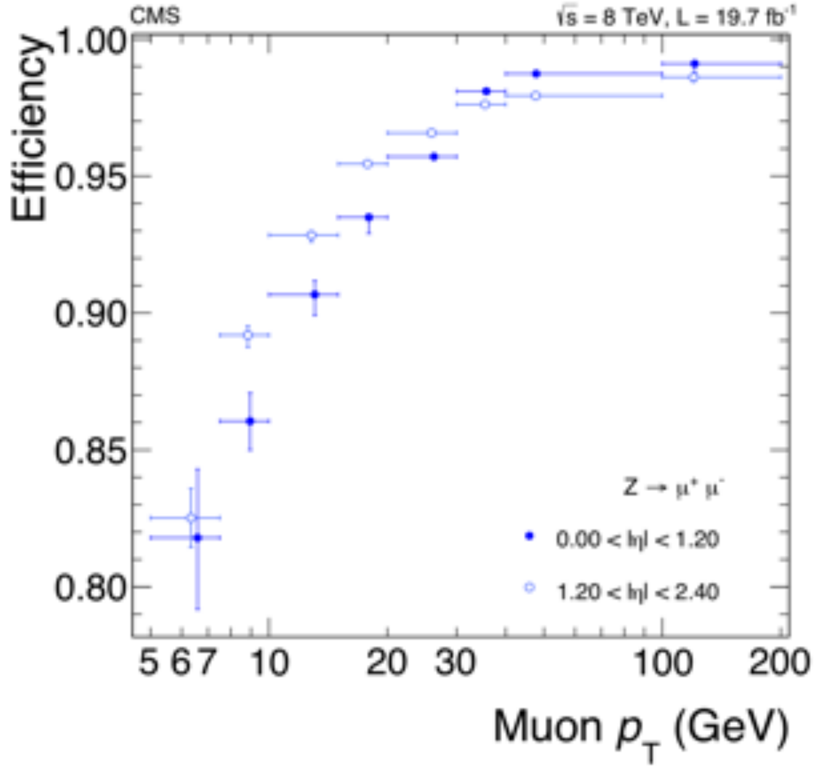
Muons and Higgs Observation:

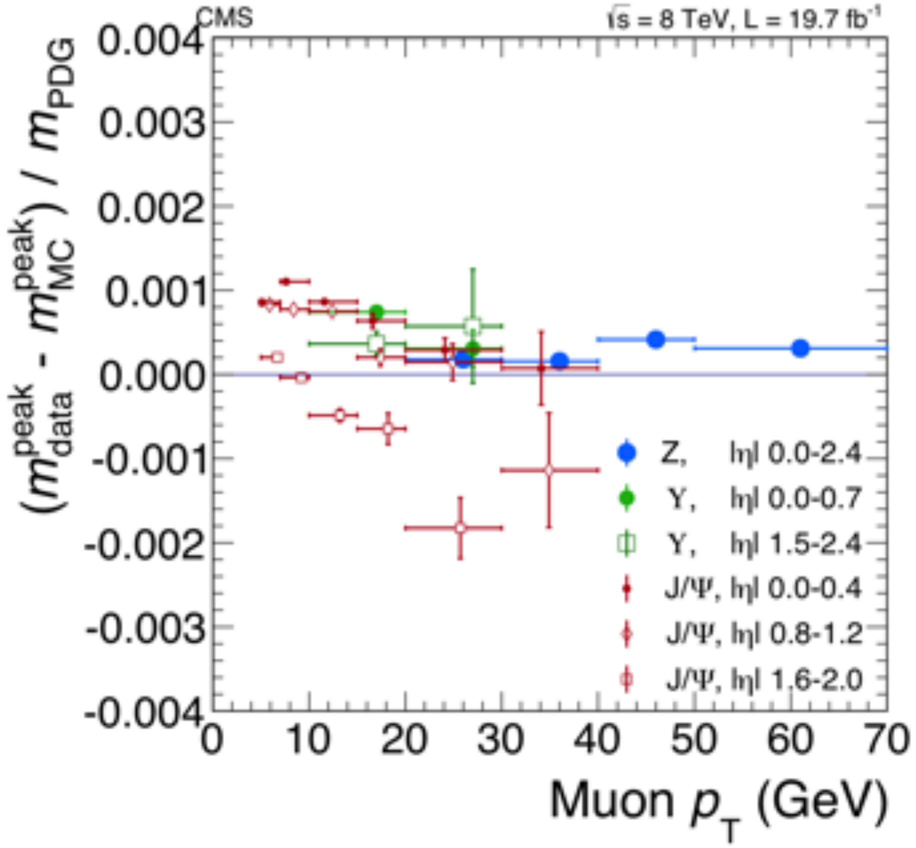
- H--> 4 leptons   Largest sensitivity with muons
- H-->tau tau $\mu\,\tau_h$ most sensitive channel
- H—>WW e μ most sensitive channel

H--> 4 leptons   Largest sensitivity with muons



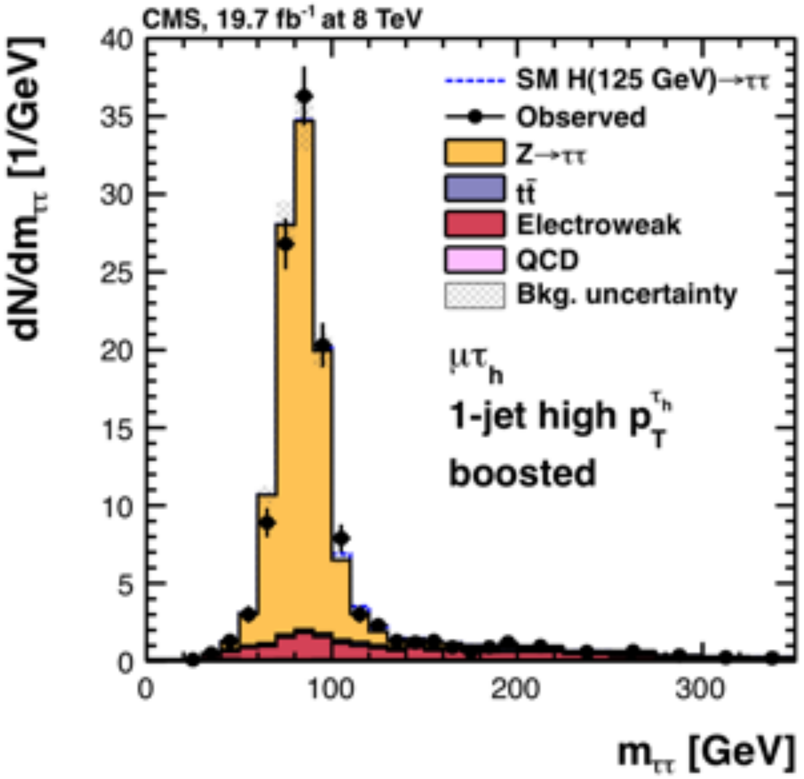
Channel	4e	2e2μ	4μ	4l
ZZ background	1.1 ± 0.1	3.2 ± 0.2	2.5 ± 0.2	6.8 ± 0.3
Z + X background	0.8 ± 0.2	1.3 ± 0.3	0.4 ± 0.2	2.6 ± 0.4
All backgrounds	1.9 ± 0.2	4.6 ± 0.4	2.9 ± 0.2	9.4 ± 0.5
m_H = 125 GeV	3.0 ± 0.4	7.9 ± 1.0	6.4 ± 0.7	17.3 ± 1.3
m_H = 126 GeV	3.4 ± 0.5	9.0 ± 1.1	7.2 ± 0.8	19.6 ± 1.5
Observed	4	13	8	25

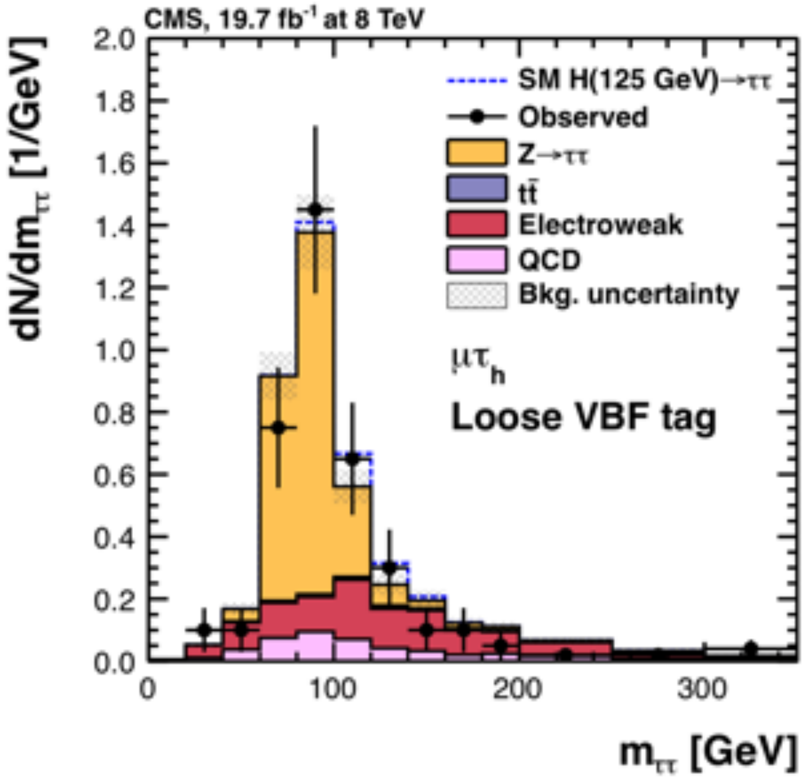


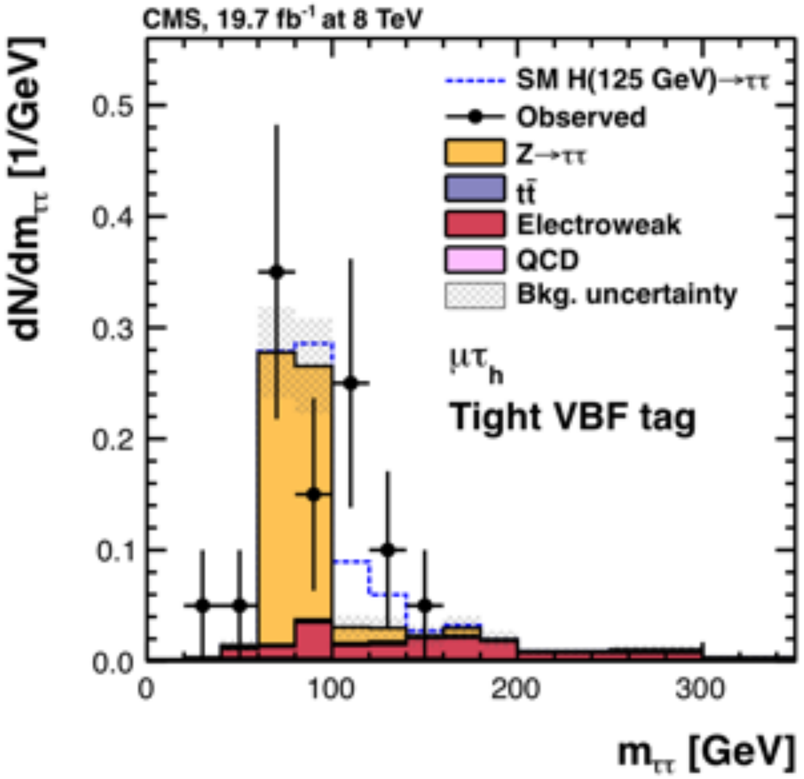


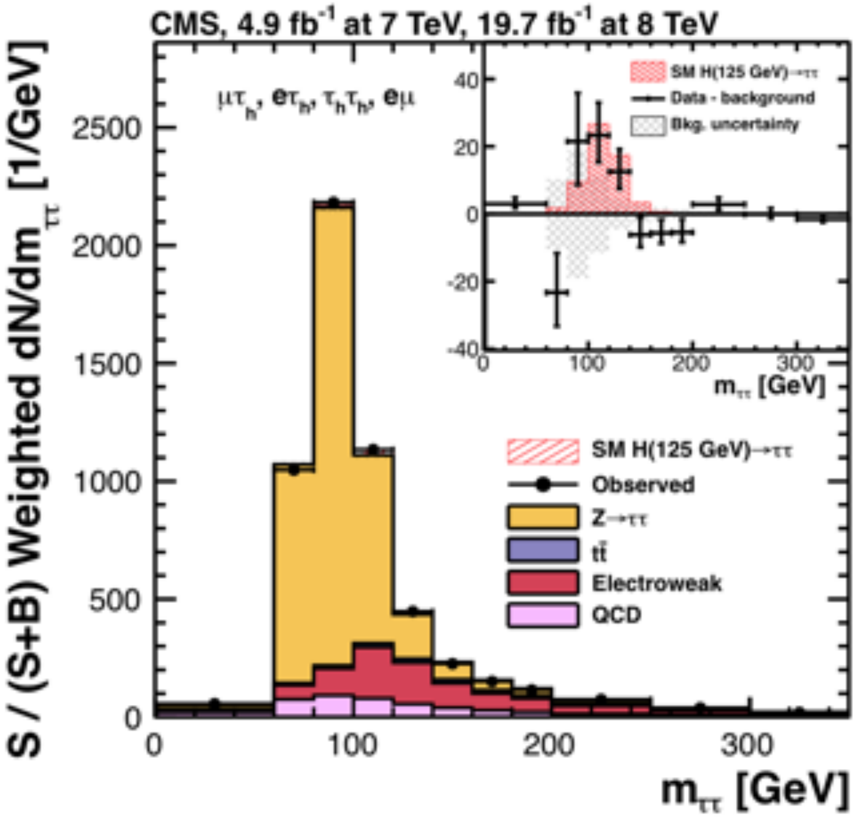
m_h=125.6 ± 0.4 (stat) ± 0.2 (syst)

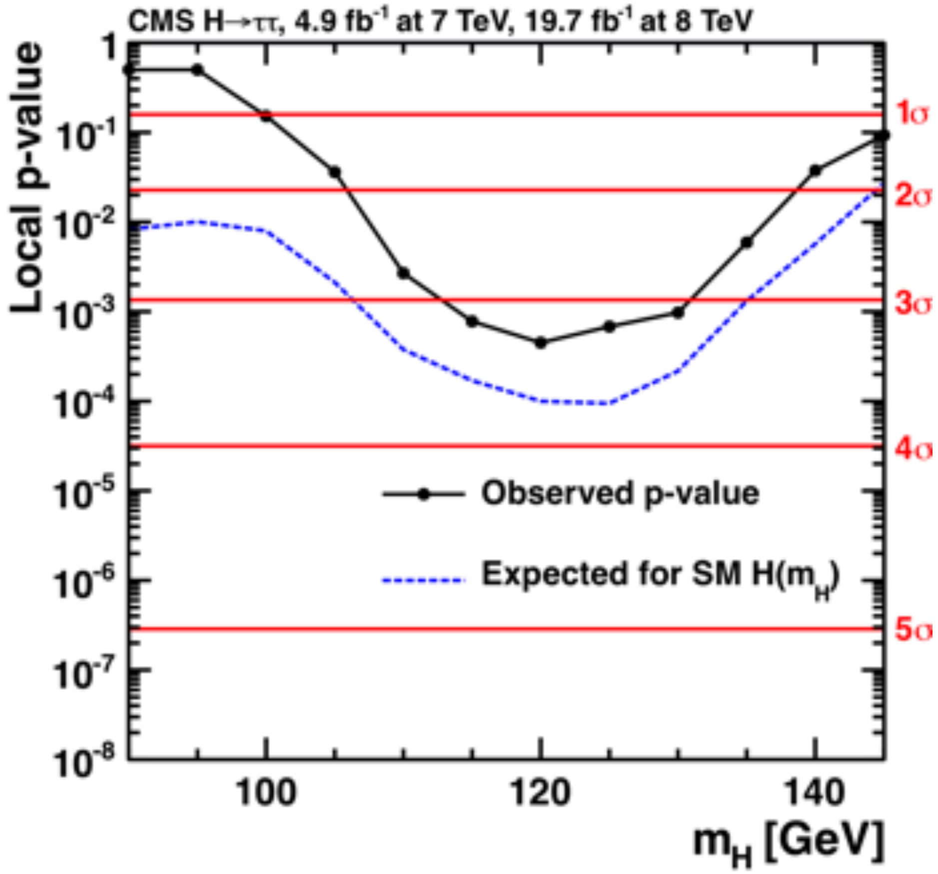
•H-->tau tau $\mu\,\tau_h$ most sensitive channel





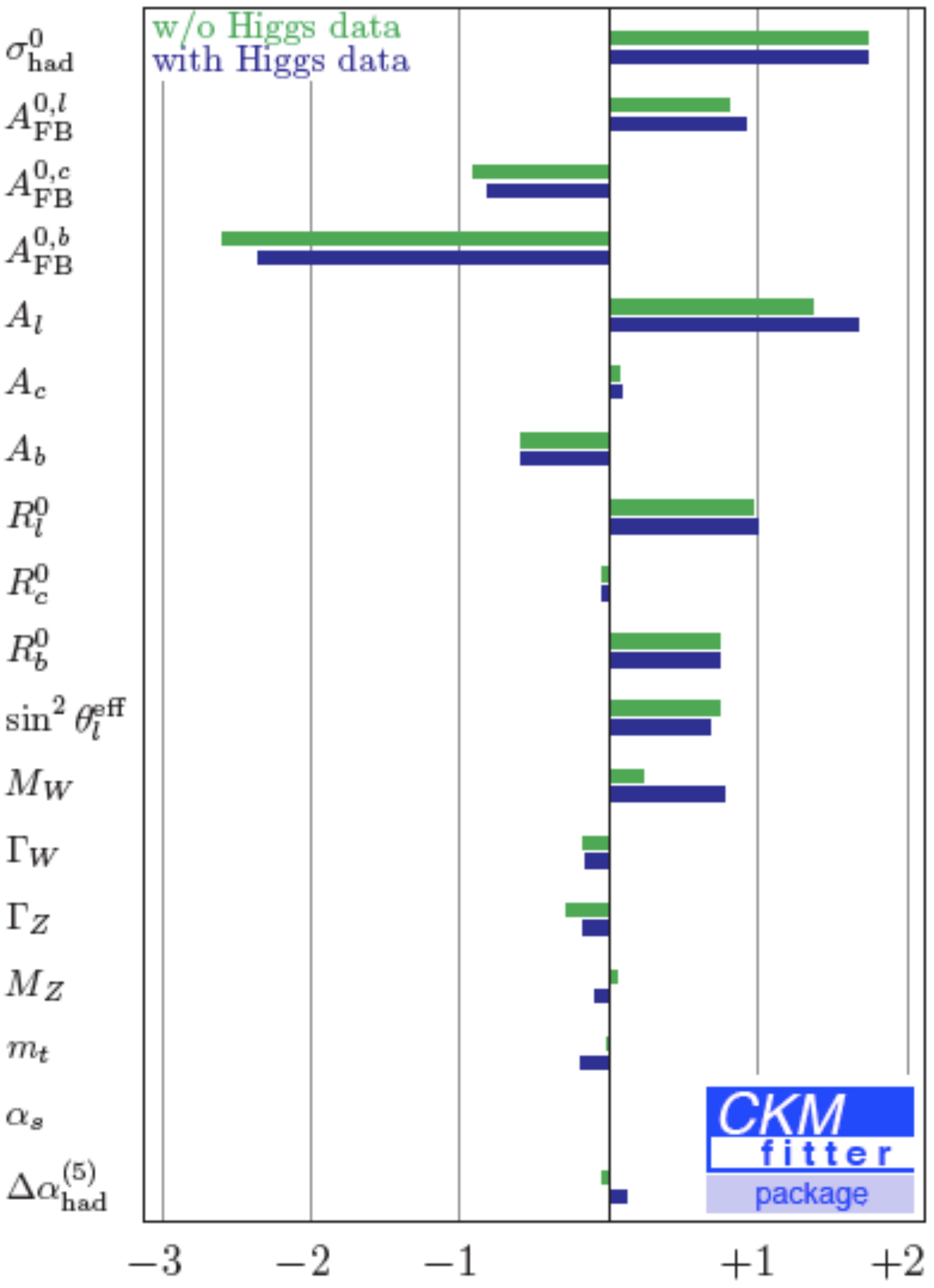






M_H and Precision EWK data

http://arxiv.org/pdf/1407.3792v1



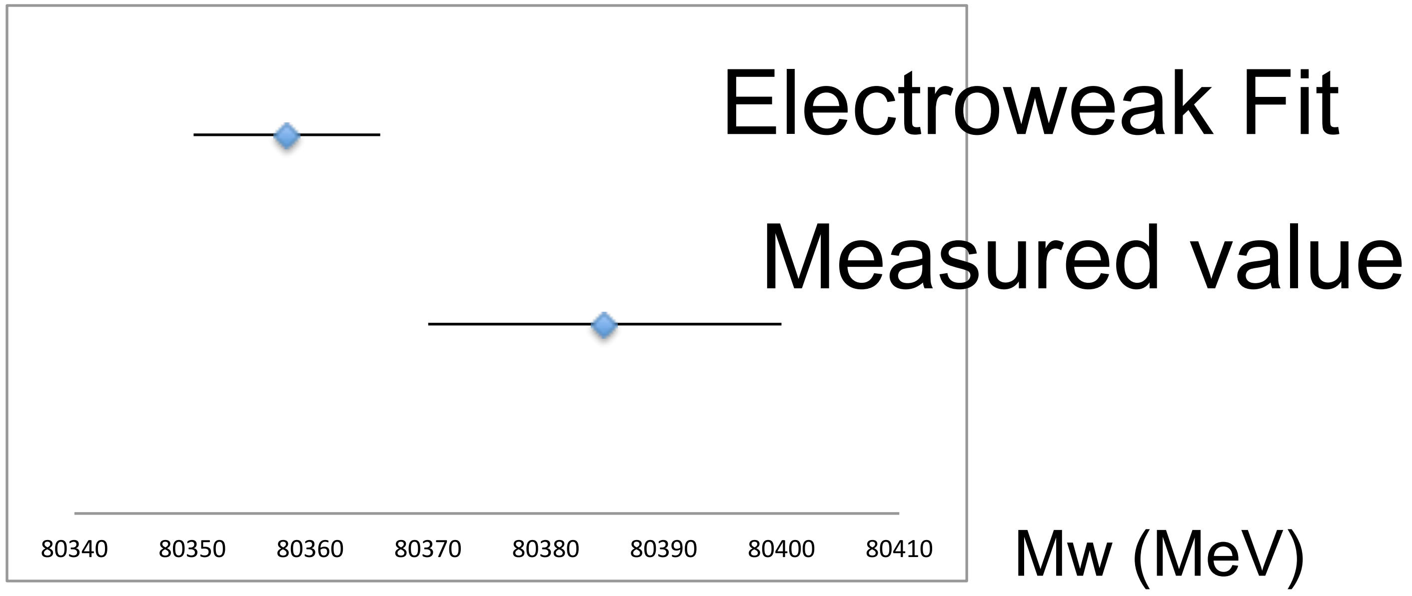
adding m_H=125 ± 2 GeV to the EWK fit:

- gives χ^2 / Ndf = 17.95 / 14, Prob = 20.9%

- was before: 16.85 / 13, Prob = 20.6%

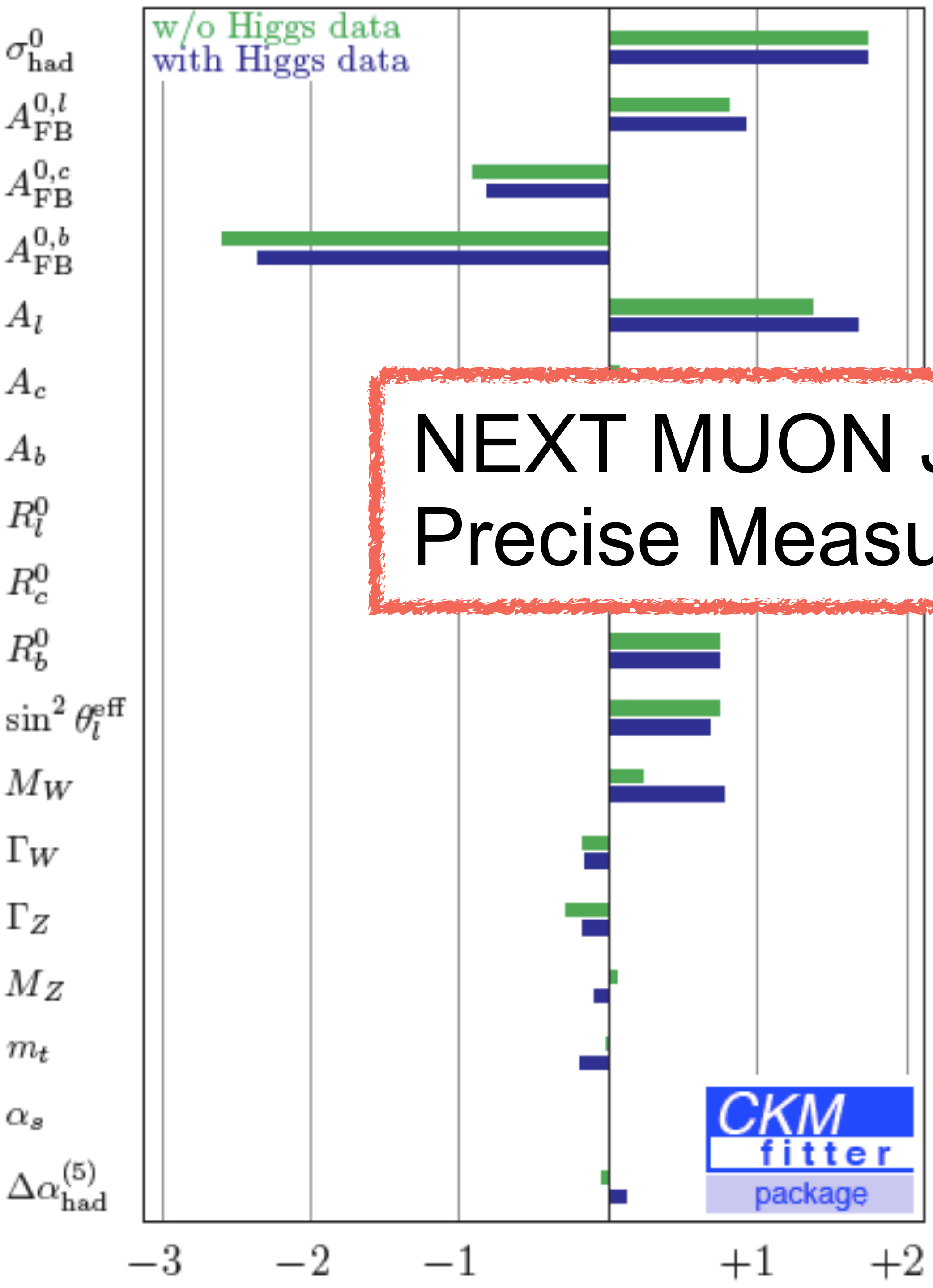
(M. Grunewald)

Improved Mw prediction in the EW Fit



M_H and Precision EWK data

http://arxiv.org/pdf/1407.3792v1



adding m_H=125 ± 2 GeV to the EWK fit:

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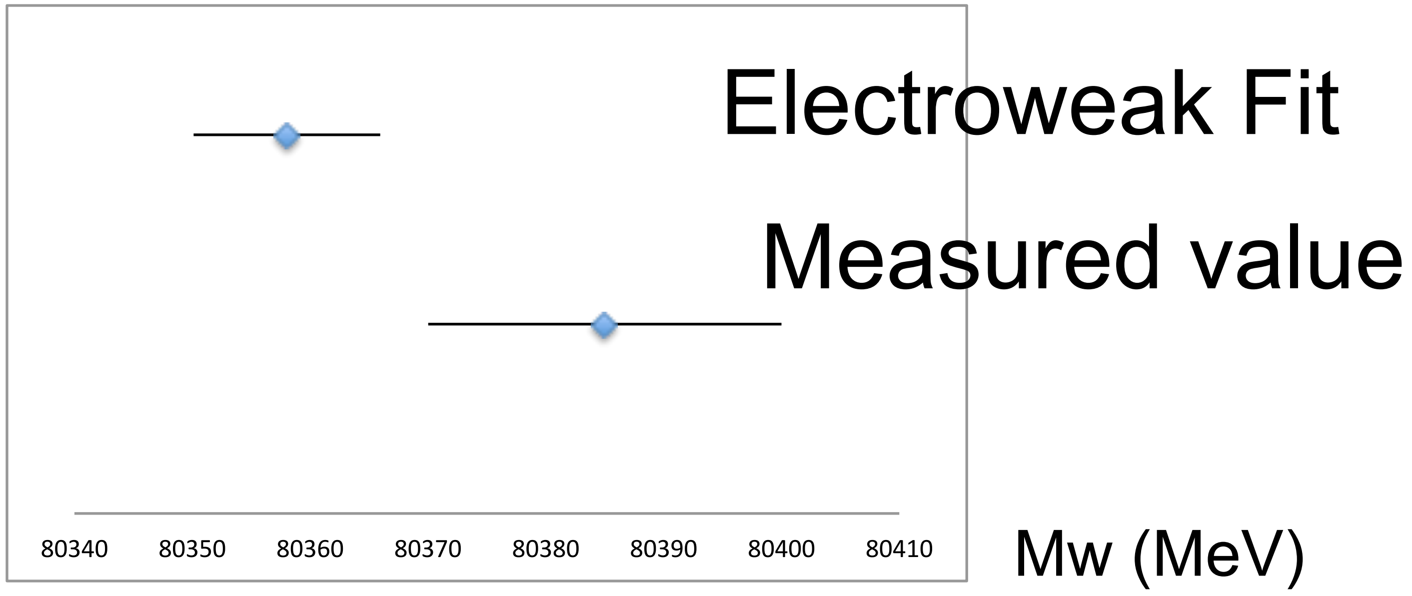
- was before: 16.85 / 13, Prob = 20.6%

(M. Grunewald)

NEXT MUON JOB in CMS
Precise Measurement of the W mass ?

Improved Mw prediction
in the EW Fit



gigi.rolandi@cern.ch