Searching for exotic neutrinos at LHCb

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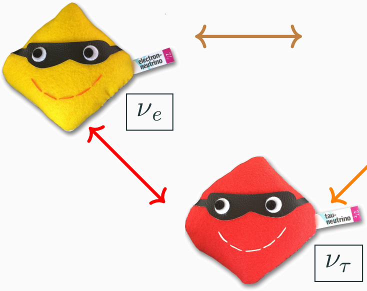
b-physics group
Nikhef

Introduction

Neutrinos portrait



- Before 1998 : assumed to be massless and left-handed.
- In 1998 : neutrino oscillation evidence $\Rightarrow$ neutrinos are massive.

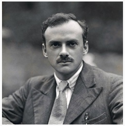
Neutrino mixing matrix

$$\text{Flavour states} \longrightarrow \begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \overbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}}^{\text{Mixing matrix}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \longleftarrow \text{Mass states}$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

- Mixing between different neutrino flavour can be described by the PMNS matrix
- In the Standard Model neutrinos are massless and left-handed
- Massive neutrinos ⇒ adjust the Standard Model accordingly, but how ?

Dirac VS Majorana



Paul Dirac

- Particle $\neq$ anti-particle :

$$\psi \neq \psi^C$$

- No lepton number violation.

Ettore Majorana

- Particle = anti-particle :

$$\psi = \psi^C$$

- $\Delta L = 2 \Rightarrow$ lepton number violation.

Neutrinos and existential crisis

ν_μ $\bar{\nu}_\mu$

Dirac **VS** **Majorana**

Neutrino mass and seesaw type I mechanism

$$-L_{mass} = \begin{bmatrix} \bar{N}_1 & \bar{N}_2 \end{bmatrix} \begin{bmatrix} m_L & m_D \\ m_D & m_R \end{bmatrix} \begin{bmatrix} N_1 \\ N_2 \end{bmatrix}$$

where N_1, N_2 are general neutrino states.

Neutrino mass and seesaw type I mechanism

$$-L_{mass} = \begin{bmatrix} \bar{N}_1 & \bar{N}_2 \end{bmatrix} \begin{bmatrix} \cancelto{0}{m_L} & m_D \\ m_D & m_R \end{bmatrix} \begin{bmatrix} N_1 \\ N_2 \end{bmatrix}$$

Neutrino mass and seesaw type I mechanism

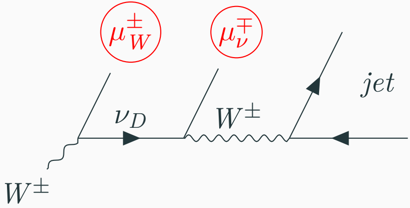
$$-L_{mass} = \begin{bmatrix} \nu_L & N_R \end{bmatrix} \begin{bmatrix} -m_D^2/m_R & 0 \\ 0 & m_R \end{bmatrix} \begin{bmatrix} \nu_L \\ N_R \end{bmatrix}$$

where ν_L is a light neutrino, N_R is a heavy neutrino.

Neutrino mass and seesaw type I mechanism

$$-L_{mass} = \begin{bmatrix} \nu_L & N_R \end{bmatrix} \begin{bmatrix} -m_D^2/m_R & 0 \\ 0 & m_R \end{bmatrix} \begin{bmatrix} \nu_L \\ N_R \end{bmatrix}$$

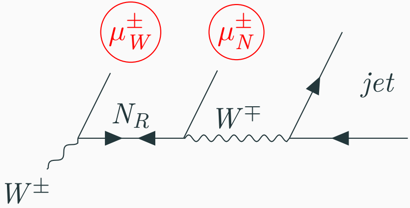
Difference between Majorana and Dirac signal



Opposite charge μ

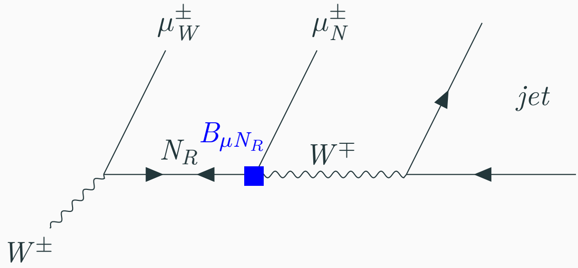
Dirac

Same charge μ



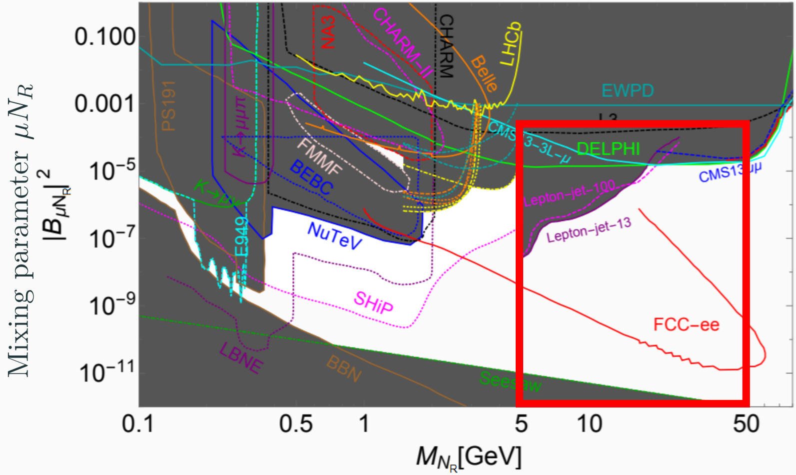
Majorana

Parameter of interest



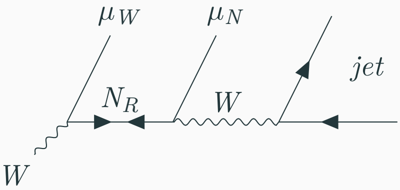
Majorana

Current state of mixing parameter and our phase space



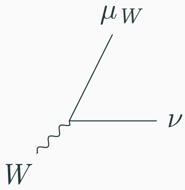
Grey area is excluded. [1805.00070]

A strategy to measure mixing parameter



Signal channel

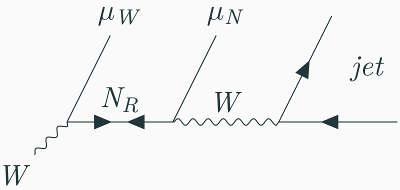
$$= \varepsilon_{sig}\mathcal{L}\sigma_W BR(W \to \mu\nu)$$
$$BR\big(N_R \to \mu jet\big)|B_{\mu N_R}|^2$$



Normalization channel

$$= \varepsilon_{nor}\mathcal{L}\sigma_W BR(W \to \mu\nu)$$

A strategy to measure mixing parameter



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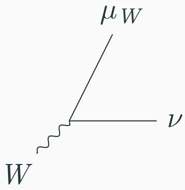
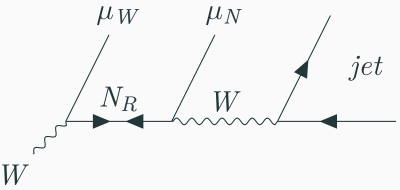


Normalization channel

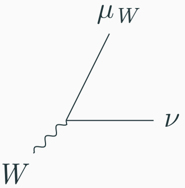
$$= \varepsilon_{nor}\mathcal{L}\sigma_W BR(W \to \mu\nu)$$

$$BR\big(N_R \to \mu jet\big)|B_{\mu N_R}|^2 = \frac{N_{sig}\varepsilon_{nor}}{N_{nor}\varepsilon_{sig}}$$

Majorana signal and backgrounds



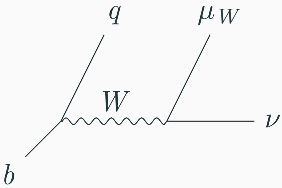
$W \to \mu\mu q q'$



Electroweak

$W \to \mu\nu$

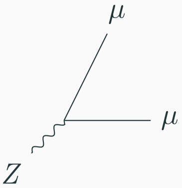
$W \to \tau\nu$



Semileptonic

$b \to q\mu\nu$

$c \to q\mu\nu$

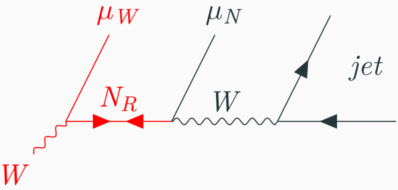


Electroweak

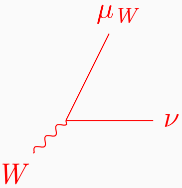
$Z \to \mu\mu$

$Z \to \tau\tau$

Majorana signal and backgrounds

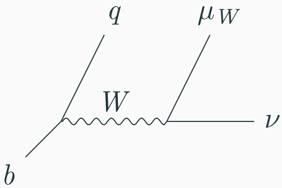


$W \to \mu\mu q q'$



$W \to \mu\nu$

$W \to \tau\nu$



$b \to q\mu\nu$

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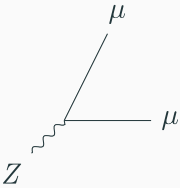
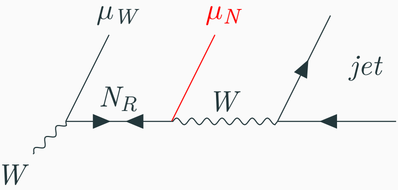


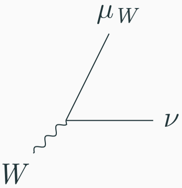
$Z \to \mu\mu$

$Z \to \tau\tau$

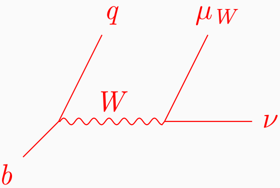
Majorana signal and backgrounds



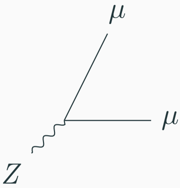
$$W \to \mu\mu qq'$$



$$W \to \mu\nu$$
$$W \to \tau\nu$$



$$b \to q\mu\nu$$
$$c \to q\mu\nu$$



$$Z \to \mu\mu$$
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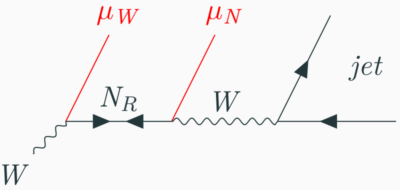
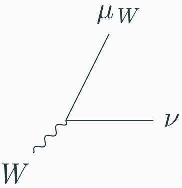
Majorana signal and backgrounds

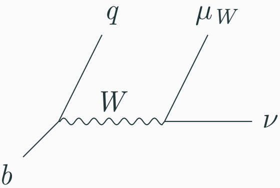


$W \to \mu\mu qq'$



$W \to \mu\nu$

$W \to \tau\nu$



$b \to q\mu\nu$

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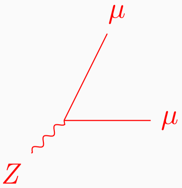
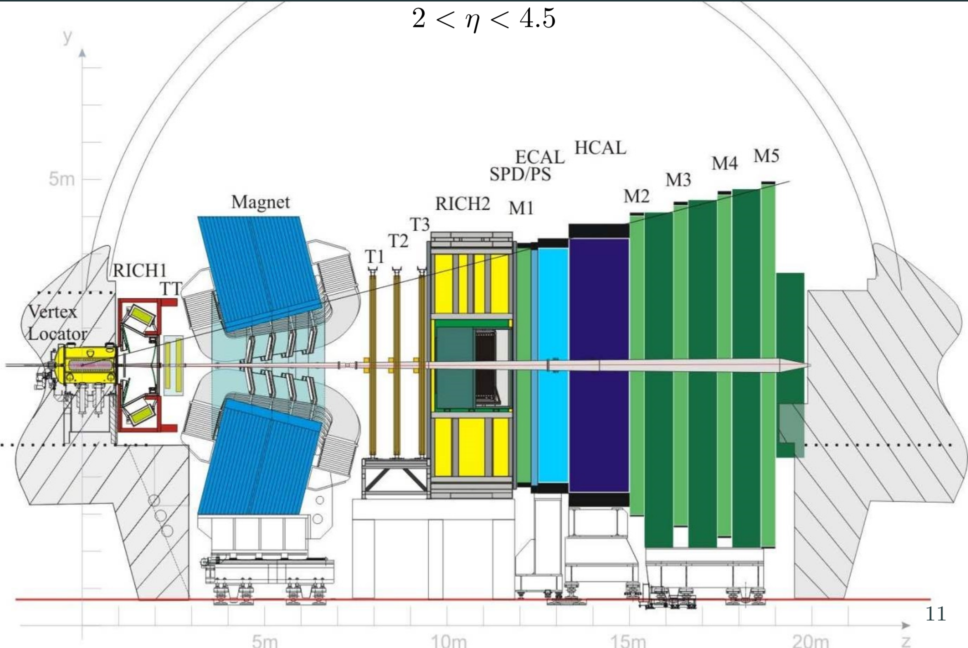


$Z \to \mu\mu$

$Z \to \tau\tau$

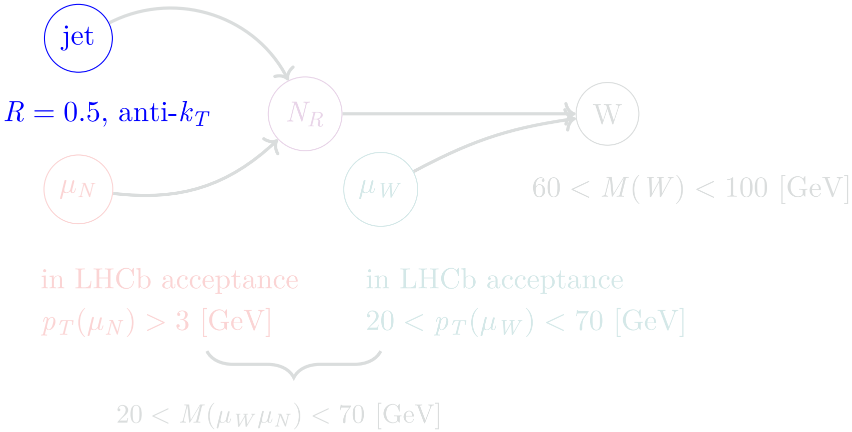
LHCb detector : an extremely quick overview

$$2 < \eta < 4.5$$



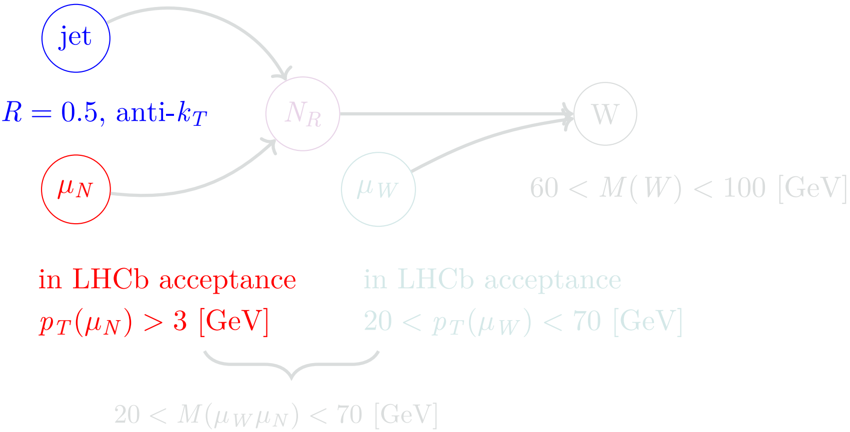
Reconstruction and Selection

Reconstruction & preselection

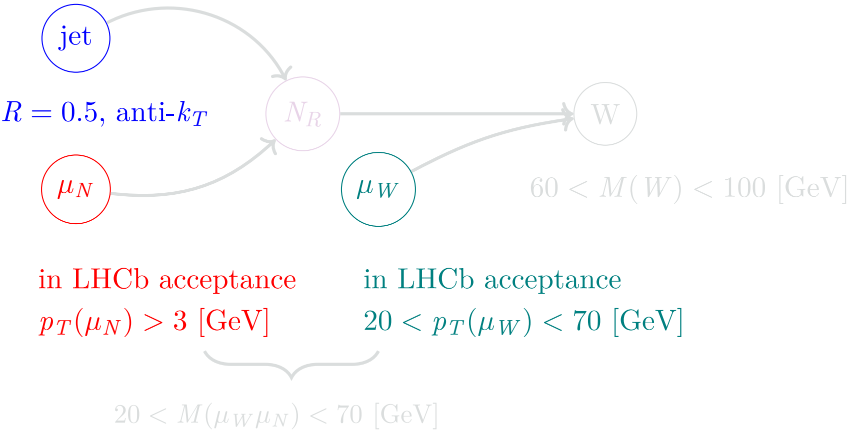


* $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

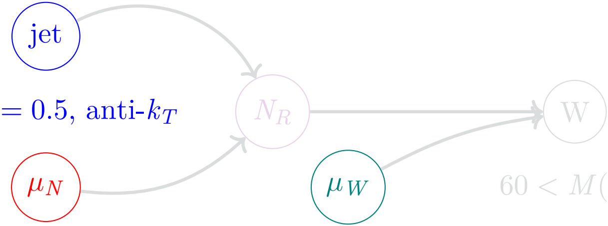
Reconstruction & preselection



Reconstruction & preselection



Reconstruction & preselection



$R = 0.5$, anti-k_T

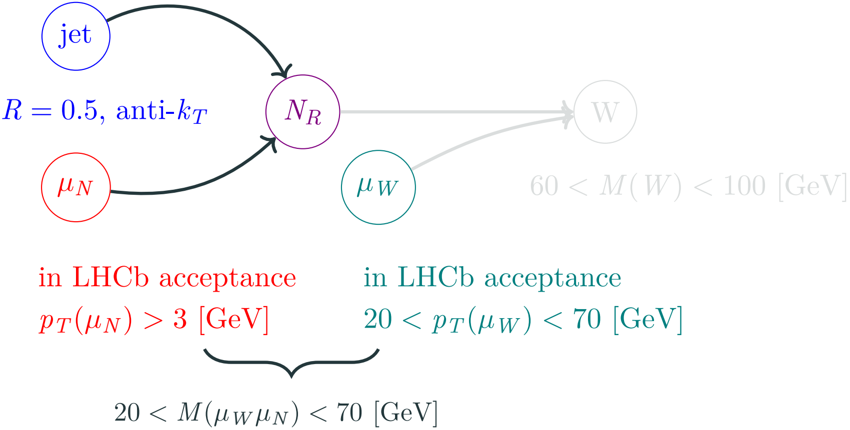
$60 < M(W) < 100$ [GeV]

in LHCb acceptance
$p_T(\mu_N) > 3$ [GeV]

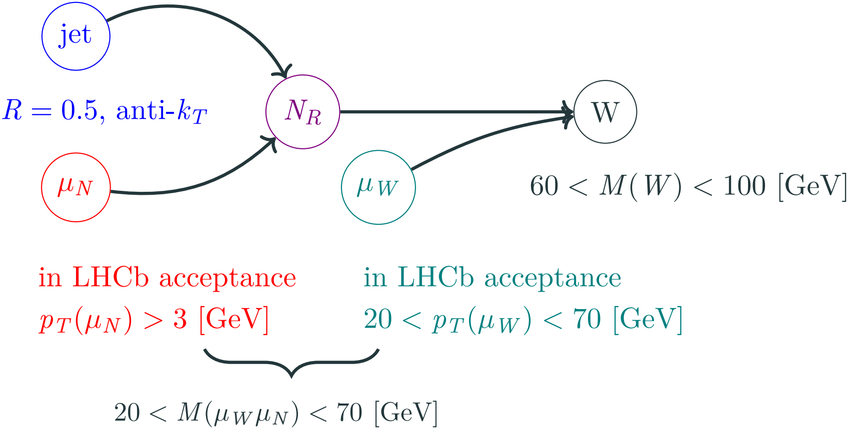
in LHCb acceptance
$20 < p_T(\mu_W) < 70$ [GeV]

$20 < M(\mu_W \mu_N) < 70$ [GeV]

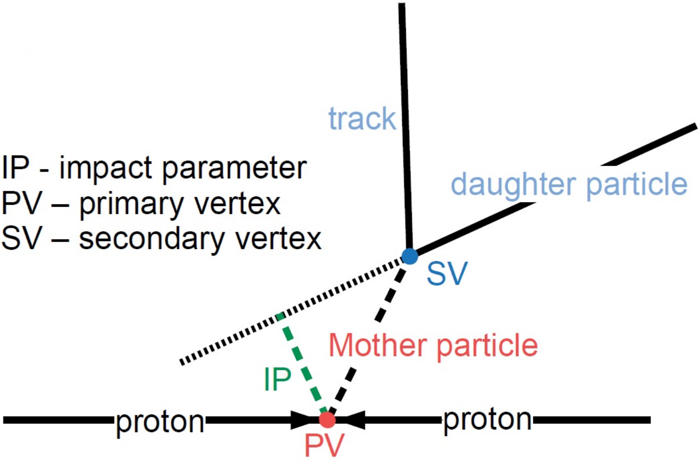
Reconstruction & preselection



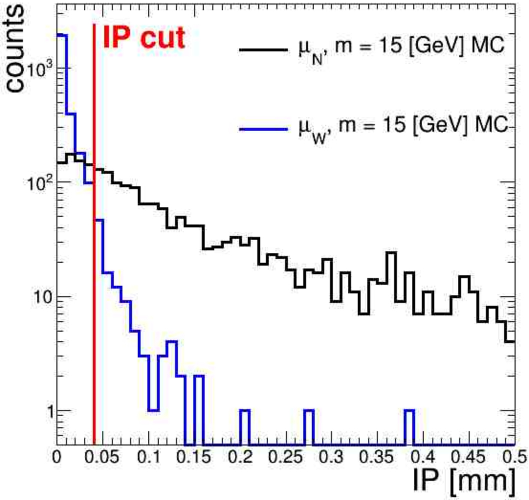
Reconstruction & preselection



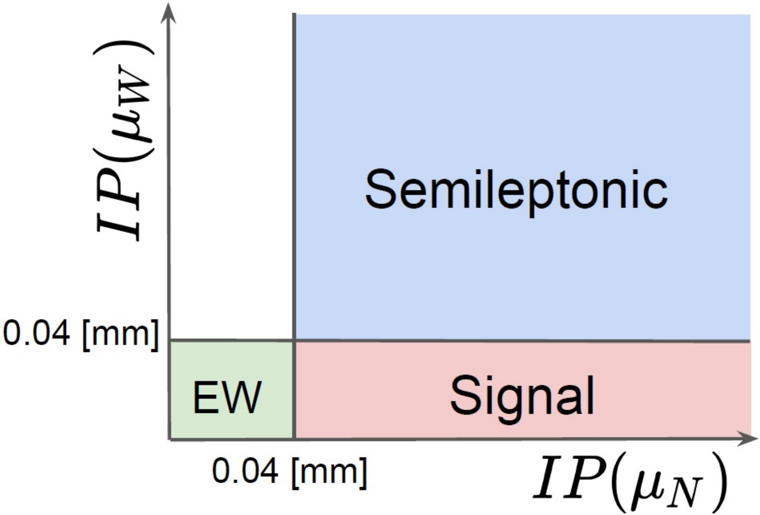
Impact parameter cut



Impact parameter cut : signal selection



Impact parameter cut : control regions

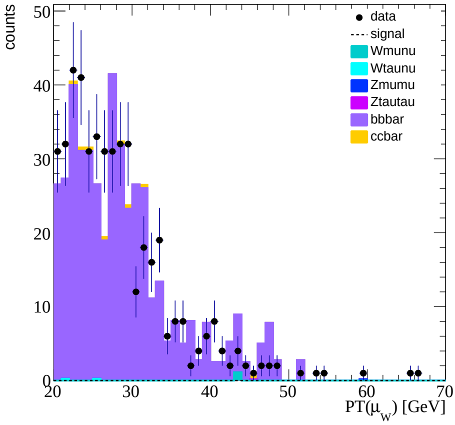


A boost with Boosted decision tree classifiers

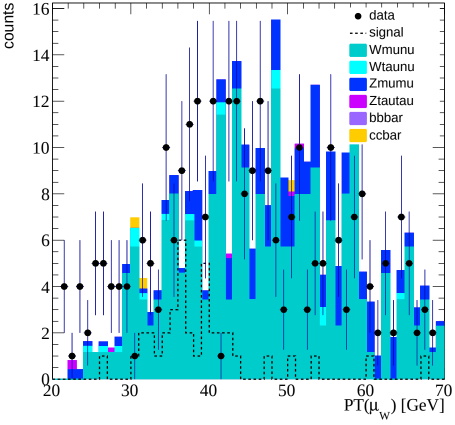
μ_W classifier	identification hypothesis for μ_W	like/not-like μ_W ✓/×
μ_N classifier	identification hypothesis for μ_N	like/not-like μ_N ✓/×
global classifier	explore kinematics of event	signal/background

	signal	Semileptonic	EW
μ_W classifier	✓	×	✓
μ_N classifier	✓	×	×
global classifier	signal	background	background

Understanding backgrounds : PT(μ_W)



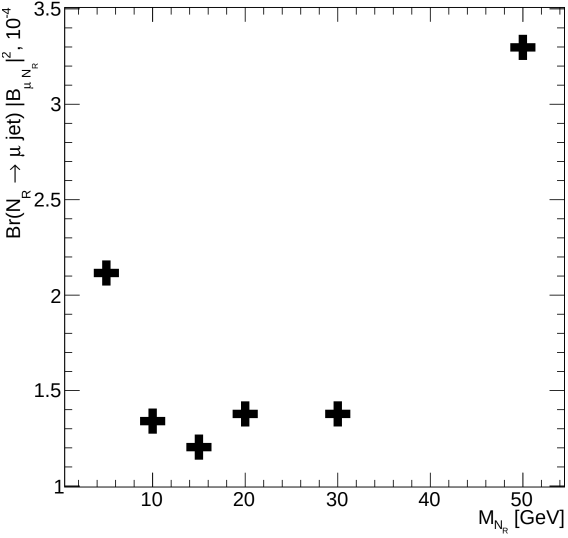
Semileptonic region



EW region

Expected limit

Results



Expected limit as a function of a heavy neutrino mass

Conclusion and outlook

Conclusions & outlook

1. Expected limit has arrived : 10^{-4}
2. Space for improvements for this analysis
3. How competitive are we ?

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Conclusions & outlook

1. Expected limit has arrived : 10^{-4}
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Conclusions & outlook

Thank you for attention !

Backup

Full preselection : muons

μ_N candidates
isMuon
$2< \eta < 4.5$
$p_T(\mu_N)$ >3 GeV
$\frac{\|(q/p)\|}{\sigma(q/p)} > 10$
μ_W candidates
isMuon, $p_T > 20$ GeV
$2< \eta < 4.5$
$20 < p_T(\mu_W) < 70$ GeV
$(E_{ECAL} + E_{HCAL})/p < 4\%$
$P(\chi^2) > 0.01$
NumTThits > 0
$\frac{\|(q/p)\|}{\sigma(q/p)} > 10$
$20< M(\mu_W \mu_N)$ <70 GeV

Table 1 – Candidate preselection.

Full preselection : jet, N_R, W

jet candidates
R = 0.5 p_T >10 GeV 1 track p_T >1.2 GeV, all tracking stations fraction of charged particles > 10% maximum p_T of a track > 1.2 GeV
N candidates
$M(N) < 80$ GeV $p_T(N) > 10$ GeV
W candidates
$60 < M(W) < 100$ GeV

Table 2 – Candidate preselection.

$W \to \mu\nu$ selection

$W \to \mu\nu$
μ_W is applied
$IP(\mu_W) < 0.04$
μ_W-like

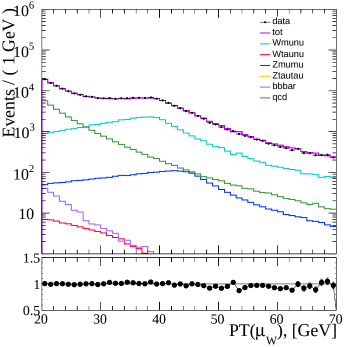
Stripping

stripping line	description
Stripping21	$p_T > 20$ GeV, isMuon
trigger line	**description**
L0MuonDecision	nSPDhits< 600, $p_T >$1.5 GeV.
Hlt1SingleMuonHighPTDecision	L0Muon, $p_T >$4.8 GeV, $p > 8$ GeV, $\chi^2/ndf < 4$
Hlt2SingleMuonHighPTDecision	$p_T > 10$ GeV.

Table 3 – Stripping and trigger lines cuts.

Normalization channel fit yield

1. Normalization channel yields are taken from a fit of p_T spectra with MC shapes.
2. Fits are performed in bins of η : 8 bins in total.



W^- p_T spectrum
$(2.0 < \eta < 2.25)$

Total efficiency

	total
Signal 5 [GeV]	$0.10 \pm 0.01 \pm 0.01$ %
Signal 10 [GeV]	$0.15 \pm 0.01 \pm 0.02$ %
Signal 15 [GeV]	$0.17 \pm 0.01 \pm 0.02$ %
Signal 20 [GeV]	$0.15 \pm 0.01 \pm 0.02$ %
Signal 30 [GeV]	$0.15 \pm 0.01 \pm 0.02$ %
Signal 50 [GeV]	$0.06 \pm 0.01 \pm 0.01$ %
Normalization	$8.80 \pm 0.89 \pm 0.26$ %

Full list of systematics

Correction	Signal 15 [GeV]	$W \rightarrow \mu\nu$
global event cut	0.80 %	-
total muon	0.92 %	0.48 %
`Wmu_uBoost`	0.20%	0.20%
`Nmu_uBoost`	0.73%	-
momentum calibration	-	2.65 %
jet energy scale*	8.64 %	-
jet energy resolution*	1.83 %	-
jet energy identification**	1.70 %	-
total	9.16%	3.19 %

*taken from prompt analysis

**taken from [LHCB-PAPER-2016-011]

anti-k_T algorithm*

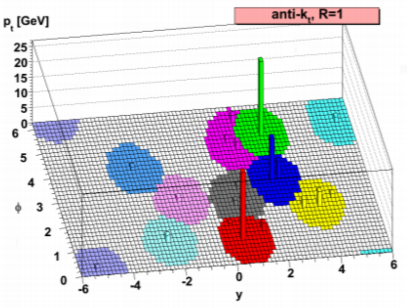
- Cone-shaped jet
- Collinear safe : collinear split safe
- Infrared (soft radiation) safe

$$d_{ij} = min(k_{Ti}^{-2}, k_{Tj}^{-2})\frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{Ti}^{-2}$$

$$d_{ij} < d_{iB} \Rightarrow i + j = i$$

$$d_{ij} > d_{iB} \Rightarrow i = jet$$



anti-k_T jets

d_{ij} - distance betw. i- and j-particle

d_{iB} - distance betw. i- particle and the beam

k_T - transverse momentum

R- jet radius

$$\Delta_{ij} = (\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2$$

*[0802.1189]

Multivariate analysis : Boosted Decision Tree

Three `uBoost` classifiers :

classifier	purpose	input
`Wmu_uBoost`	μ_W identification	isolation, PID, E/P
`Nmu_uBoost`	μ_N identification	isolation, PID, E/P, p_T
`global_uBoost`	signal/background	kinematics

*`uBoost` = uniform boosted decision tree ;
has a uniform signal efficiency as a function of a heavy neutrino mass.

Multivariate analysis : Boosted Decision Tree

Input parameters		
μ_W uBDT	μ_N uBDT	global uBDT
muon isolation	muon isolation	cos between muons
muon PID	muon PID	jet cone R
muon E/P	muon E/P	p_T(jet)
	muon p_T	missing p_T
		M($\mu_1\mu_2$)
		M(W)

Table 4 – BDT input variables

For more on the BDT training consult Elena's Dall'Occo thesis.

BDT Efficiency

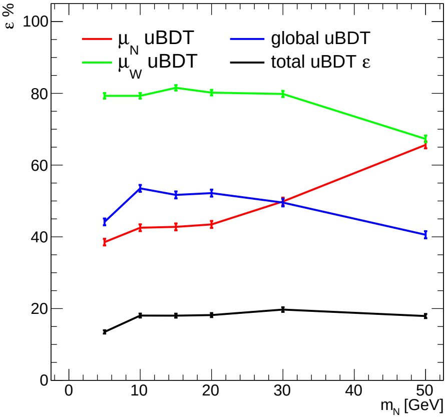


Figure 2 – BDT signal efficiency with respect to signal mass, MC.

Corrections data vs Monte Carlo

Never trust your Monte Carlo!

Muon correction* : $c_{muon} = c_{rec} \cdot c_{ID} \cdot c_{trigger}$

Total correction $\longrightarrow$ $c_{tot} = c_{muon} \cdot c_{GEC} \cdot c_{BDT}$ $\longleftarrow$ `uBoost` correction

$c_{BDT} = c_{\texttt{Nmu}} \cdot c_{\texttt{Wmu}}$

Global event cut correction

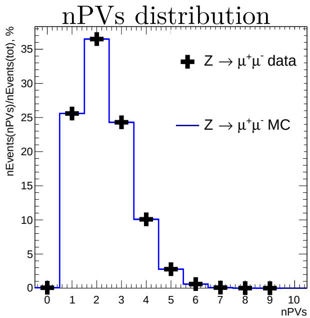
*taken from [LHCb-INT-2014-030]

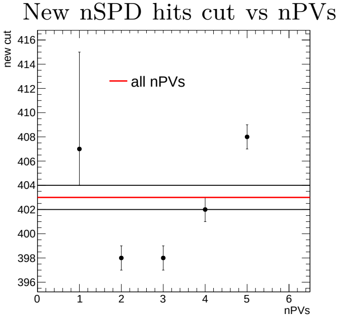
GEC correction

- Number of SPD hits trigger cut efficiency in $Z \to \mu^+\mu^-$ data.
- New number of SPD hits cut N with same efficiency in $Z \to \mu^+\mu^-$ Monte Carlo.
- $c_{GEC} = \frac{\varepsilon(nSPDhits<N)}{\varepsilon(nSPDhits<600)}$

*nPVs = number of primary vertices

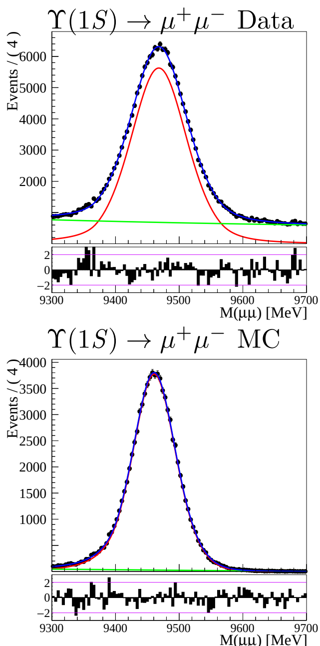
*nSPD hits = number of SPD hits





uBoost correction

- $c = \frac{\varepsilon(data)}{\varepsilon(MC)}$
- `Wmu_uBoost` correction - use cut and count on $Z \to \mu^+\mu^-$
- `Nmu_uBoost` correction - combine $Z \to \mu^+\mu^-$ and $\Upsilon(1S) \to \mu^+\mu^-$

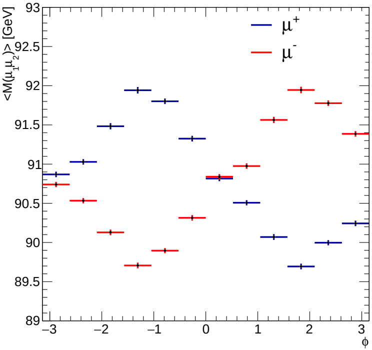


Ipatia function

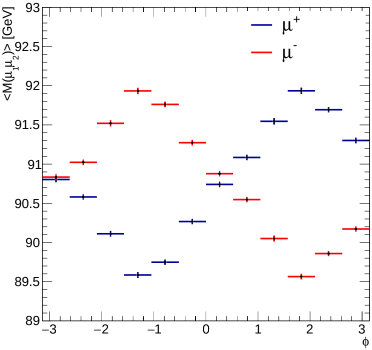
- two-tailed Crystal-Ball function with a hyperbolic core function
- fits a mass spectrum with unknown/different per-event mass uncertainties

$$I2 = N \begin{cases} G(m,\mu,\sigma,\lambda,\zeta,\beta) & -\alpha_1 < \frac{m-\mu}{\sigma} < \alpha_2 \\ \frac{G(m,\mu,\sigma,\lambda,\zeta,\beta)}{\left(1-m/(n_1 \cdot \frac{G(m-\alpha_1\sigma,\mu,\sigma,\lambda,\zeta,\beta)}{G'(m-\alpha_1\sigma,\mu,\sigma,\lambda,\zeta,\beta)}-\alpha_1\sigma)\right)^{n_1}} & \frac{m-\mu}{\sigma} \le -\alpha_1 \\ \frac{G(m,\mu,\sigma,\lambda,\zeta,\beta)}{\left(1-m/(n_2 \cdot \frac{G(m-\alpha_2\sigma,\mu,\sigma,\lambda,\zeta,\beta)}{G'(m-\alpha_2\sigma,\mu,\sigma,\lambda,\zeta,\beta)}-\alpha_2\sigma)\right)^{n_2}} & \frac{m-\mu}{\sigma} \ge \alpha_2 \end{cases}$$

$I2$ - Ipatia function ; G - generalized hyperbolic function ;
N - normalization ; α_1 and n_1 - left-side tail parameters ;
α_2 and n_2 - right-side tail parameters



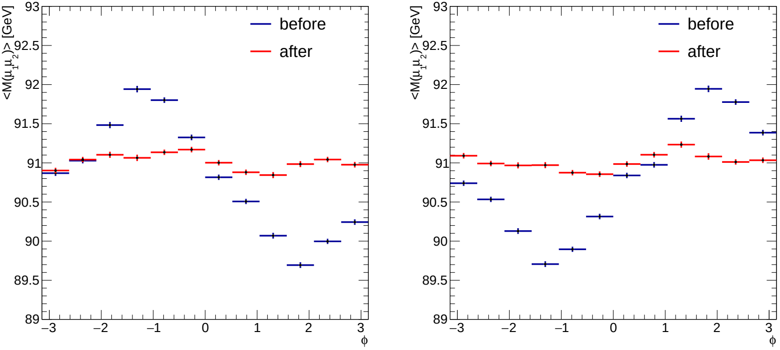
(a) Magnet Up



(b) Magnet Down

Figure 3 – Mean dimuon mass from $Z \to \mu^+\mu^-$ as a function of muons ϕ.

Momentum calibration : after



(a) μ^+ **(b)** μ^-

Figure 4 – Mean dimuon mass from $Z \to \mu^+\mu^-$ as a function of muons ϕ before and after calibration, MU.