ETH zürich

CMS

Search for long-lived heavy neutral leptons in the decays of B mesons at CMS

Anne-Mazarine Lyon(*),

On behalf of the CMS Collaboration

(*) *ETH Zürich*

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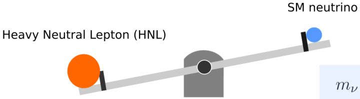
Context

- Heavy neutral leptons (HNLs) predicted in the Type I seesaw mechanism

$$\mathcal{L}_{\text{mass}} = -\frac{1}{2}\begin{pmatrix}\bar{\nu}_L & \bar{\nu}_R^c\end{pmatrix}\begin{pmatrix}0 & m_D \\ m_D & M\end{pmatrix}\begin{pmatrix}\nu_L^c \\ \nu_R\end{pmatrix} + \text{h.c}$$

$m_D \ll M$



$m_\nu = \frac{m_D^2}{M}$

$\nu \approx (\nu_L + \nu_L^c)$

$m_{\text{HNL}} = M$

$\text{HNL} \approx (\nu_{\text{R}} + \nu_{\text{R}}^{\text{c}})$

Context

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- Heavy neutral leptons (HNLs) predicted in the Type I seesaw mechanism

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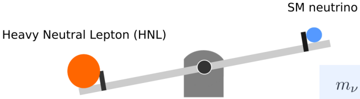


$m_{\text{HNL}} = M$

$\text{HNL} \approx (\nu_{\text{R}} + \nu_{\text{R}}^c)$

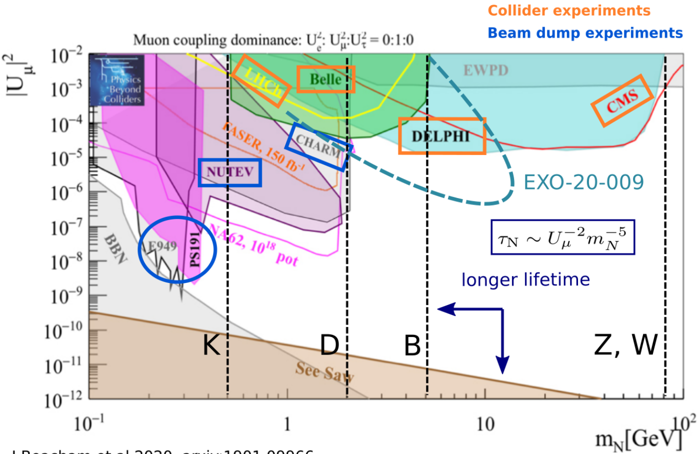
$m_\nu = \frac{m_D^2}{M}$

$\nu \approx (\nu_L + \nu_L^c)$

- Phenomenology based on Bondarenko et al. (2018) (arXiv:1805.08567)
  - HNLs are not degenerate in mass $\Rightarrow$ they do not oscillate between themselves
  - HNLs interact through the mixing with SM neutrinos

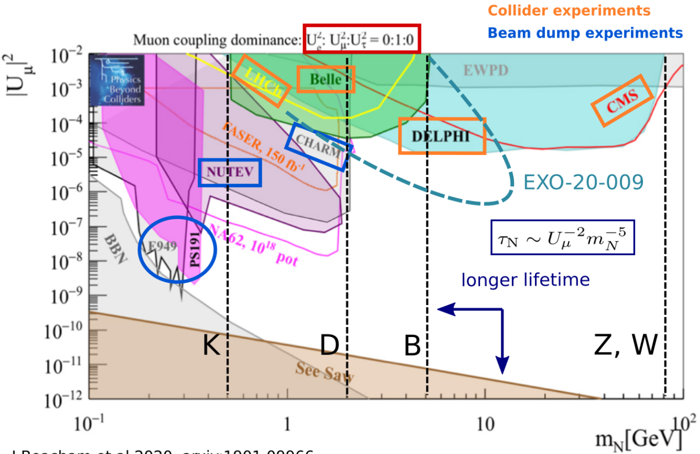
  - Four model parameters: m_{N}, $V_{e\text{N}}$, $V_{\mu\text{N}}$, $V_{\tau\text{N}}$
  - Lifetime $\tau_{\text{N}} \sim m_{\text{N}}^{-5}|V_{\text{N}}|^{-2}$; $\quad |V_{\text{N}}|^2 = |V_{e\text{N}}|^2 + |V_{\mu\text{N}}|^2 + |V_{\tau\text{N}}|^2$

Experimental landscape



J Beacham et al 2020, arxiv:1901.09966

Experimental landscape



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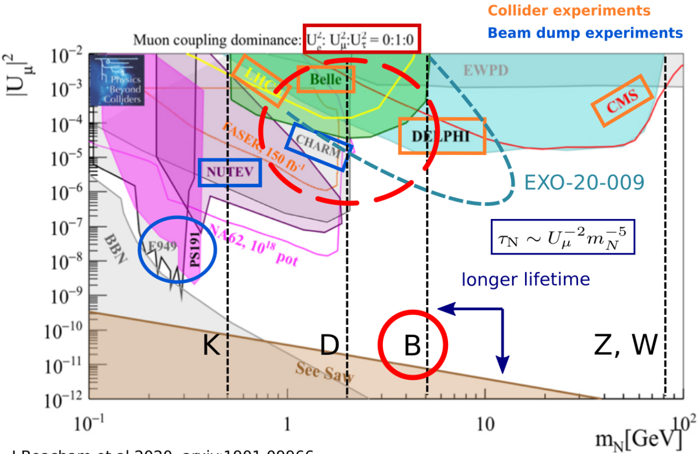

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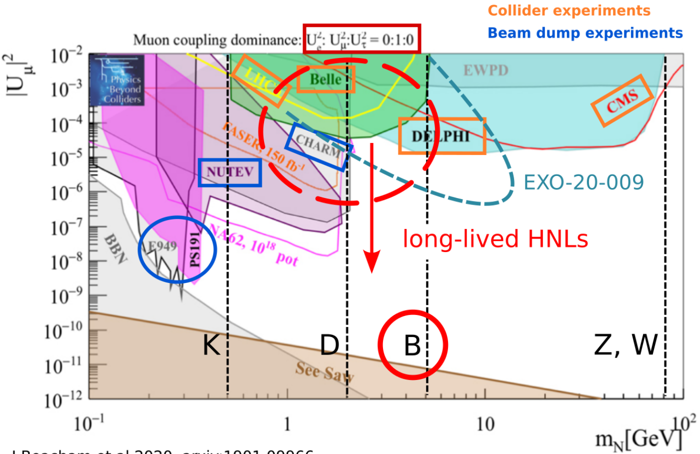
- Search for long-lived HNLs in leptonic and semileptonic decays of B mesons
  - Abundant source of SM neutrinos
  - Daughters of B meson less boosted than those of W ⇒ better acceptance

Experimental landscape



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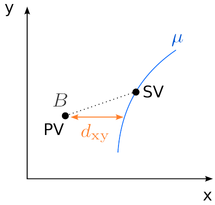
B-parking data set

- More information in Andre's talk and Kiley's talk
- Large data set of $b\bar{b}$ pairs (arXiv:2403.16134)
  - Data collected in 2018
  - $\mathcal{O}(10^{10})$ $b\bar{b}$ events
  - Total luminosity of 41.6 fb^{-1}
- Set of triggers designed to capture the signatures of a B meson decay
  - Single muon trigger
  - Low transverse momentum (p_T) requirement (from 7 GeV on)
  - Large transverse impact parameter significance



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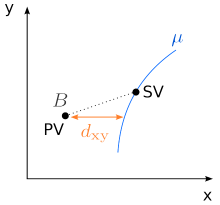
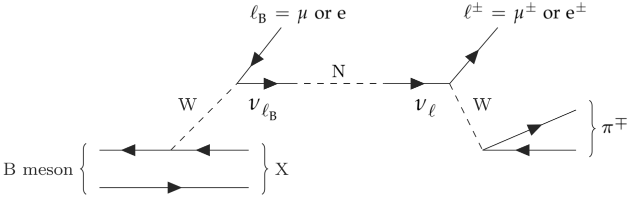


⇒ **Unprecedented possibility to study B decays at CMS**

Process



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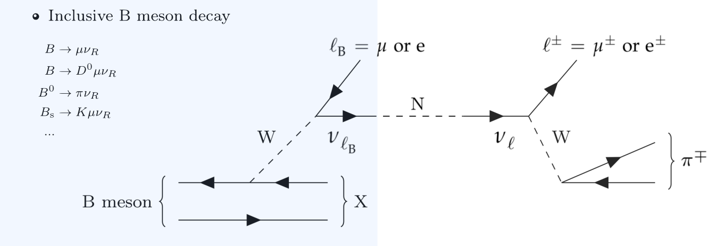
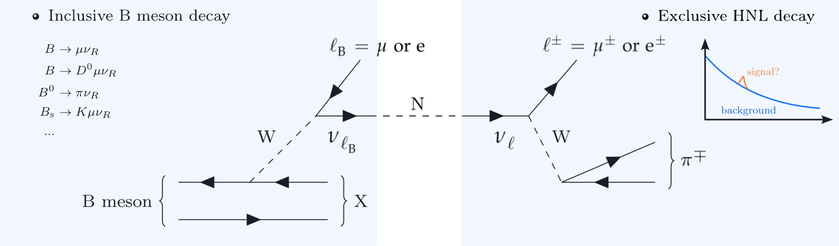


- Inclusive leptonic and semileptonic decays of $B^\pm$, B^0, B_s, and B_c mesons

Process



- Inclusive leptonic and semileptonic decays of $B^\pm$, B^0, B_s, and B_c mesons
- Perform a **bump hunt** in the $\ell\pi$ invariant mass spectrum
    - Masses probed in the range $1 < m_N < 3$ GeV with unprecedented resolution

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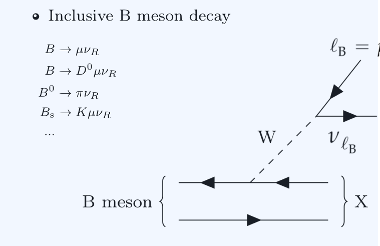

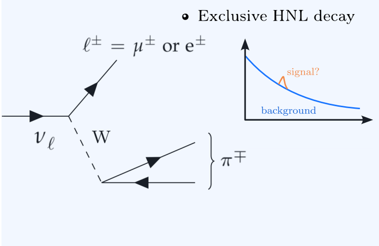

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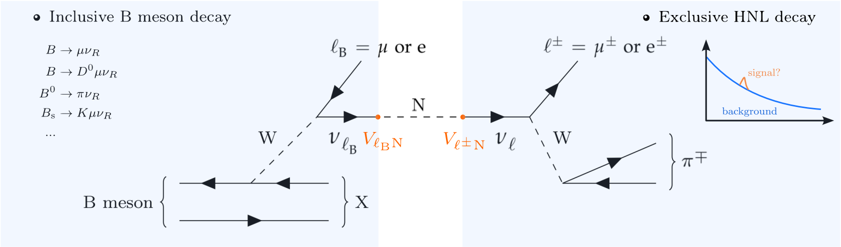
- At least one lepton is a μ that fires a B-parking trigger line
  - $B \to \mu_B NX$, $N \to \mu^\pm\pi^\mp \Rightarrow$ dimuon channel
  - $B \to \mu_B NX$, $N \to e^\pm\pi^\mp$ } mixed-flavour channel
  - $B \to e_B NX$, $N \to \mu^\pm\pi^\mp$

Process



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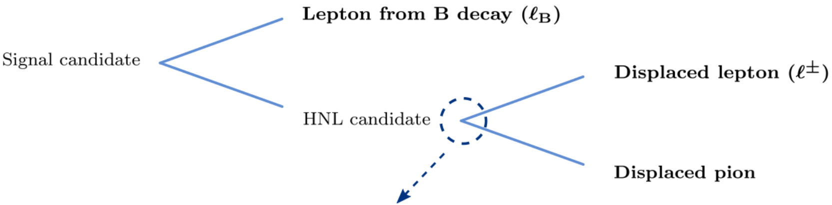
- Interpret the results against **mixed-flavour** mixing scenarios

Strategy

Reconstruction → Categorisation → Signal selection → Background → Signal extraction →

1. Reconstruct the signal candidates



- Displaced pion and lepton fitted to a common vertex using a *kinematic vertex fitter*

- HNLs constrained to decay within the tracker volume ($L_{xy} < 1$ m)
- The efficiency of the signal candidate reconstruction reaches a few percent for transverse displacement $L_{xy} > 50$ cm

Strategy

Reconstruction → Categorisation → Signal selection → Background → Signal extraction

2. Categorise the events to enhance sensitivity on different signal hypotheses

Quantity	Label	Definition
$L_{xy}/\sigma_{L_{xy}}$	low $L_{xy}/\sigma_{L_{xy}}$	$L_{xy}/\sigma_{L_{xy}} < 50$
	medium $L_{xy}/\sigma_{L_{xy}}$	$50 < L_{xy}/\sigma_{L_{xy}} < 150$
	high $L_{xy}/\sigma_{L_{xy}}$	$L_{xy}/\sigma_{L_{xy}} > 150$
Relative lepton sign	OS	ℓ_B charge $\neq \ell$ charge
	SS	ℓ_B charge $= \ell$ charge
$\ell_B\ell^\pm\pi^\mp$ mass	low $\ell_B\ell^\pm\pi^\mp$ mass	$\ell_B\ell^\pm\pi^\mp$ mass < 5.7 GeV
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Flavour channel	dimuon	$\ell_B\ell = \mu\mu$
	mixed-flavour	$\ell_B\ell = (\mu e, e\mu)$

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- Emphasizes signals with different lifetime hypotheses
- Discriminate between Majorana and Dirac scenarios

Strategy

Reconstruction → Categorisation → Signal selection → Background → Signal extraction →

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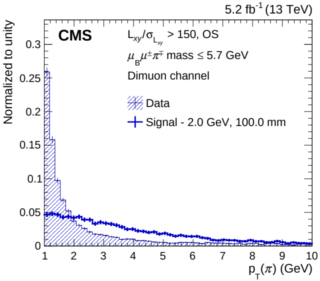
- Emphasizes signals with different lifetime hypotheses
- Discriminate between Majorana and Dirac scenarios
- Emphasizes signals originating from different B meson species

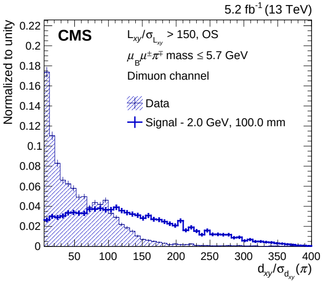
Strategy

Reconstruction → Categorisation → **Signal selection** → Background → Signal extraction

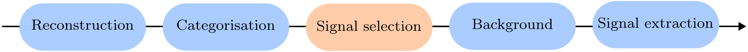
3. Reject the background while preserving the large variety of signal signatures

- The different signal hypotheses ($m_{\rm N}$, $c\tau_{\rm N}$) can give rise to significantly different signatures
- A multivariate-based selection algorithm is designed such that an optimal signal to background discrimination is achieved for the various signal hypotheses
- It takes as input highly discriminating kinematic and topological variables



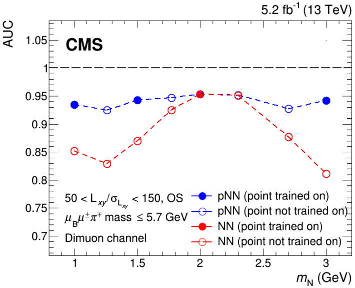


Strategy



3. Reject the background while preserving the large variety of signal signatures

- Selection algorithm based on parametric Neural Networks (pNNs) (arXiv:1601.07913)
  - NNs with extra discrete parameter that is concatenated to the features
  - Allows a single training for different signal hypotheses
  - Maintains good performance for the intermediate signal points
- Separate pNN trainings in the different analysis categories
- Events are selected if pNN score > 0.99



Strategy

Reconstruction → Categorisation → Signal selection → **Background** → Signal extraction

4. Model the background

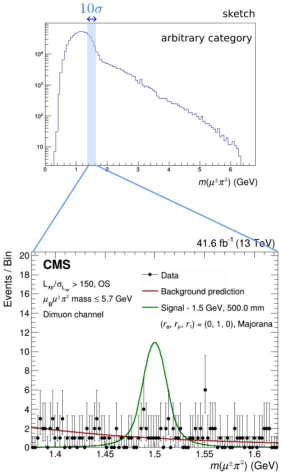
- Background primarily arises from
  - B cascade decays
  - Combinatorial processes
- Parametric fit to the data
- Use the discrete profiling method (arXiv:1408.6865)
  - Consider set of functions that provide a good description of the background
  - Treat the choice of the function as a discrete nuisance parameter (profiled)

Strategy

Reconstruction → Categorisation → Signal selection → Background → Signal extraction →

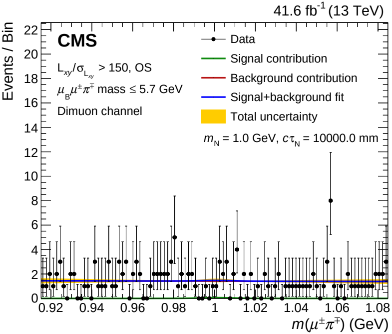
5. Extract the signal

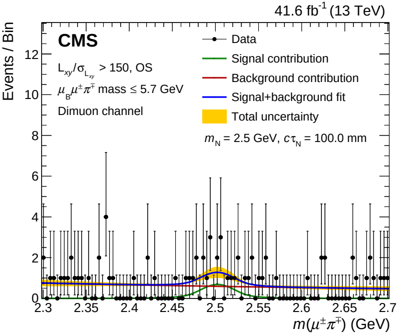
- Extract signal for ~ 60 mass hypotheses in $1 < m_{\mathrm{N}} < 3$ GeV in step of 2σ
- When probing an HNL of mass M, extract signal in a mass window of size $\pm 10\sigma$ centred at M
- Select events using pNN evaluated at mass M
- Model the background from the mass sidebands
- Extract signal with simultaneous maximum likelihood fits to $m(\ell^{\pm}\pi^{\mp})$ in each event category



Results

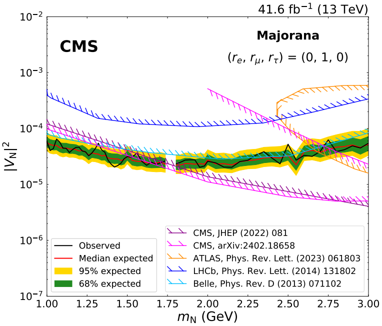
- No significant excess from the predicted background is observed in any of the $\ell^{\pm}\pi^{\mp}$ invariant mass distributions

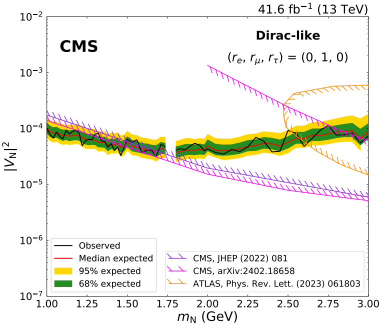




Interpretation

1. Upper exclusion limits at 95% CL on $|V_N|^2$ are presented for the muon-exclusive mixing scenario, and for both the Majorana and Dirac hypotheses



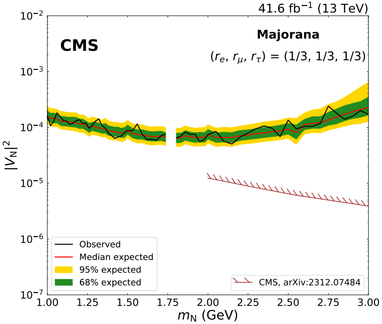


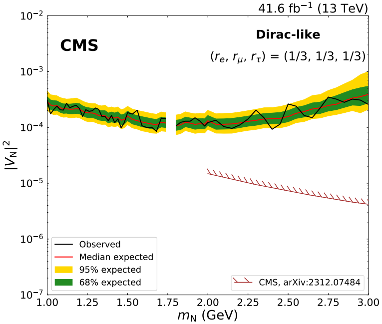
- Most stringent limits obtained in the mass range $1 < m_N < 1.7$ GeV at a collider experiment to date

Interpretation

2. Additionally, limits on $|V_\mathrm{N}|^2$ are derived for mixed-flavour mixing scenario

- Mixing scenarios specified by the ratios $(r_\mathrm{e},\, r_\mu,\, r_\tau)$ defined as $r_\ell \equiv |V_{\ell\mathrm{N}}|^2/|V_\mathrm{N}|^2$, $\ell = (\mathrm{e},\, \mu,\, \tau)$
- Three mixed-flavour scenarios are constrained (arXiv:2207.02742)
  - $(r_\mathrm{e},\, r_\mu,\, r_\tau) = (0,\, 1/2,\, 1/2)$
  - $(r_\mathrm{e},\, r_\mu,\, r_\tau) = (1/2,\, 1/2,\, 0)$
  - $(r_\mathrm{e},\, r_\mu,\, r_\tau) = (1/3,\, 1/3,\, 1/3)$



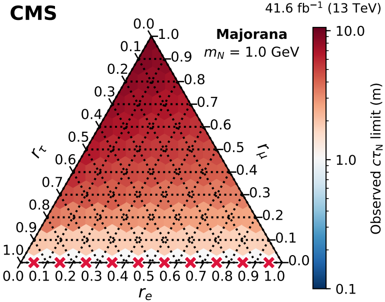


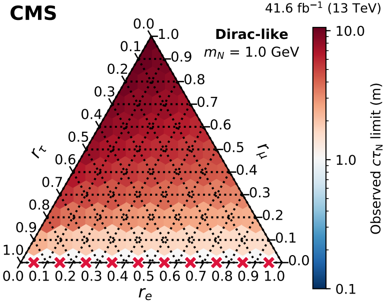
- First limits presented for these scenarios for $1 < m_\mathrm{N} < 2$ GeV

Interpretation

3. Finally, lower exclusion limits on $c\tau_{\mathrm{N}}$ are presented for 66 different mixing scenarios for $m_{\mathrm{N}} = 1$, 1.5, and 2 GeV.

- The condition $r_{\mathrm{e}} + r_{\mu} + r_{\tau} = 1$ allows the values to be shown in the form of ternary plots





- First time that this type of constraints is presented for $m_{\mathrm{N}} = 1$ and 2 GeV

Summary

- A search for long-lived heavy neutral leptons has been performed at CMS in the decays of B mesons
- Possible thanks to the collection of the B-parking data set, containing $\mathcal{O}(10^{10})$ $\mathrm{b\bar{b}}$ events
- Signal masses in the range $1 < m_\mathrm{N} < 3$ GeV were probed with unprecedented resolution
- No significant excess over the background prediction was observed
- Exclusion limits on $|V_\mathrm{N}|^2$ and $c\tau_\mathrm{N}$ were derived for various mixing scenarios and for both the Majorana and Dirac hypothesis
  - Most stringent limits to date at a collider experiment for masses $1 < m_\mathrm{N} < 1.7$ GeV
  - First limits for the mixed-flavour mixing scenarios for masses $1 < m_\mathrm{N} < 2$ GeV
- The results have been published two days ago in JHEP (10.1007/JHEP06(2024)183, arXiv:2403.04584)

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Thank you!

Backup

Backup

- List of systematic uncertainties

Source	Value (%)
Signal shape	15
$\sigma^{\mathrm{eff}}_{\mathrm{B}^{\pm}}$	15
f_{c}	24
Signal selection	5–20
Limited simulated signal sample size	<15
Matching	5
Tracking efficiency	5
Trigger scale factors	5
Muon identification scale factors	1
Electron identification scale factors	3
Total	<42