CLFV $\tau \to 3\mu$ decays: LHC experiments

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CLFV tau workshop
23 July 2020

Introduction

- Searching for CLFV $\tau \to 3\mu$ decays is feasible at hadron colliders
  - Huge number of τ produced at the LHC
  - $\tau \to 3\mu$ has a clean signature (as opposed to 3e, μμe, μγ)
  - LHC experiments have good capability of muon detection and vertex reconstruction
- World best limit: Belle ~ 2.1×10^{-8} @ 90% CL [*] Phys.Lett.B 687 (2010) 139

Process	number of τ leptons (L=100 fb^{-1})
$pp \to c\,\bar{c} + ...$	
$D \to \tau\nu$	1.2×10^{13} (95% D_s, 5% $D^{\pm}$)
$pp \to b\,\bar{b} + ...$	
$B \to \tau\nu + ...$	4.5×10^{12} (44% $B^{\pm}$, 45% B^0, 11% B_s^0, 0% $B_c^{\pm}$)
$B \to D(\tau\nu) + ...$	1.9×10^{12} (98% D_s, 2% $D^{\pm}$)
$pp \to W + ... \to \tau\nu + ...$	2.0×10^9
$pp \to Z + ... \to \tau\tau + ...$	$3.8 \times 10^8 (60 < m(\tau\tau) < 120\ GeV)$

Sources of τ

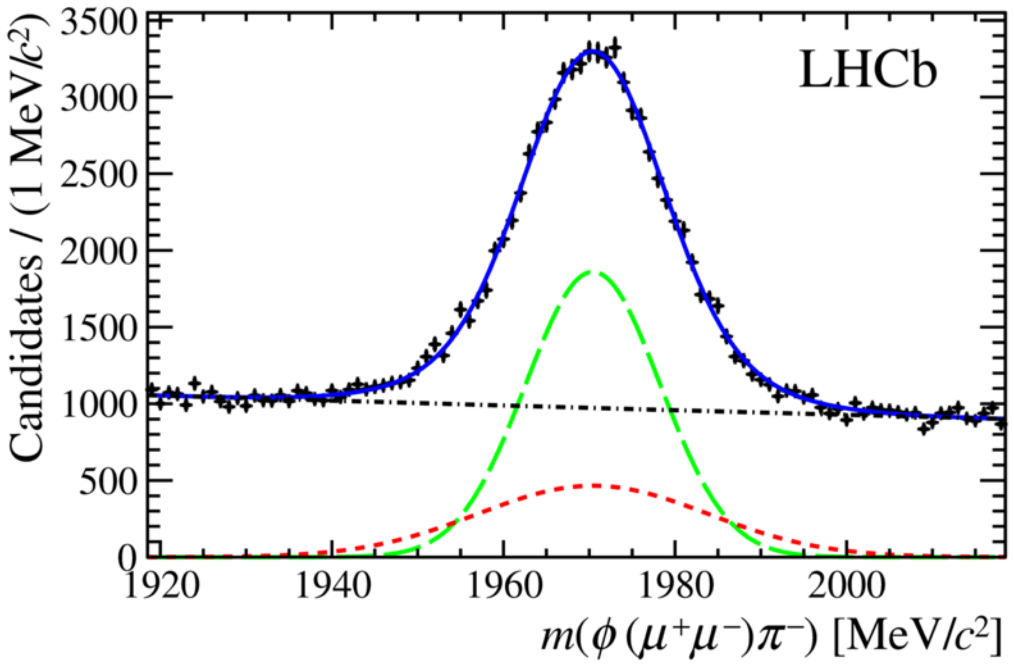
- Heavy Flavor (HF) semi-leptonic decay: large cross section; low p_T, high pseudorapidity (η); high background
- W decay: relatively small cross section; high p_T; low background

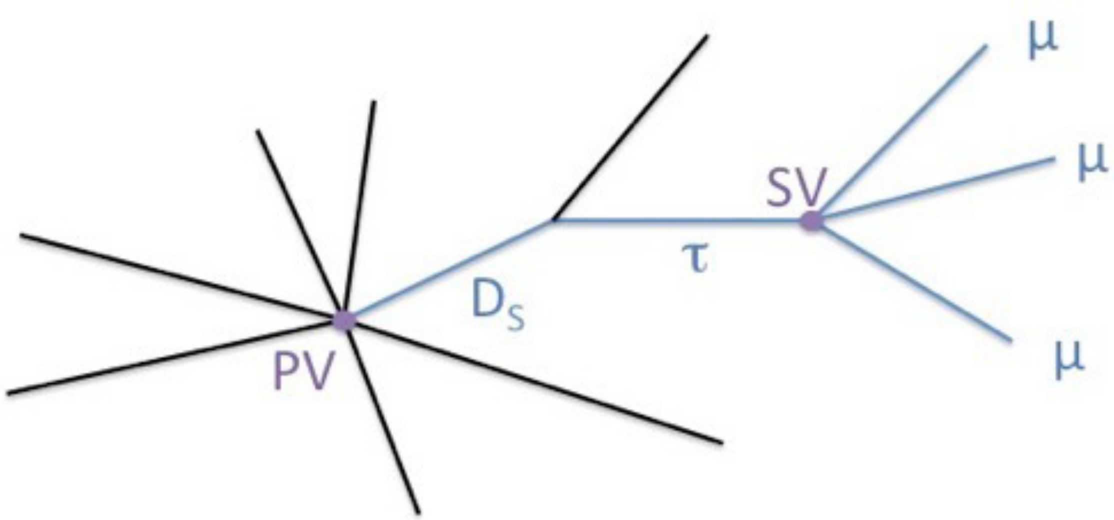
[*] 90% CL limits are quoted throughout this talk

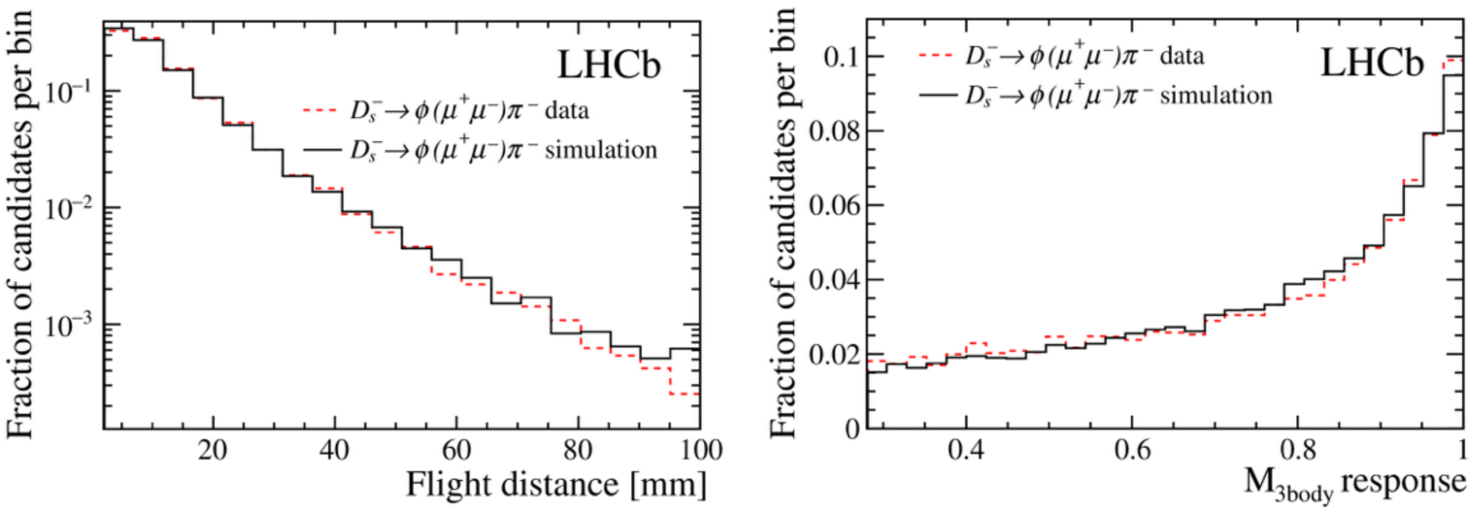
1409.8548
JHEP 02 (2015) 121

HF channel - LHCb

- Run 1: 1 fb^{-1} @ 7 TeV + 2 fb^{-1} @ 8 TeV
- Select 3 muons sharing a common displaced vertex
- Normalisation channel: $D_s \to \phi\pi \to (2\mu)\pi$
- Mass resolution ~ 10 MeV
- Train 2 multivariate classifiers (background from MC)
  - M(3body): event topology (vertex, pointing-angle, etc)
  - M(PID): muon identification







HF channel - LHCb

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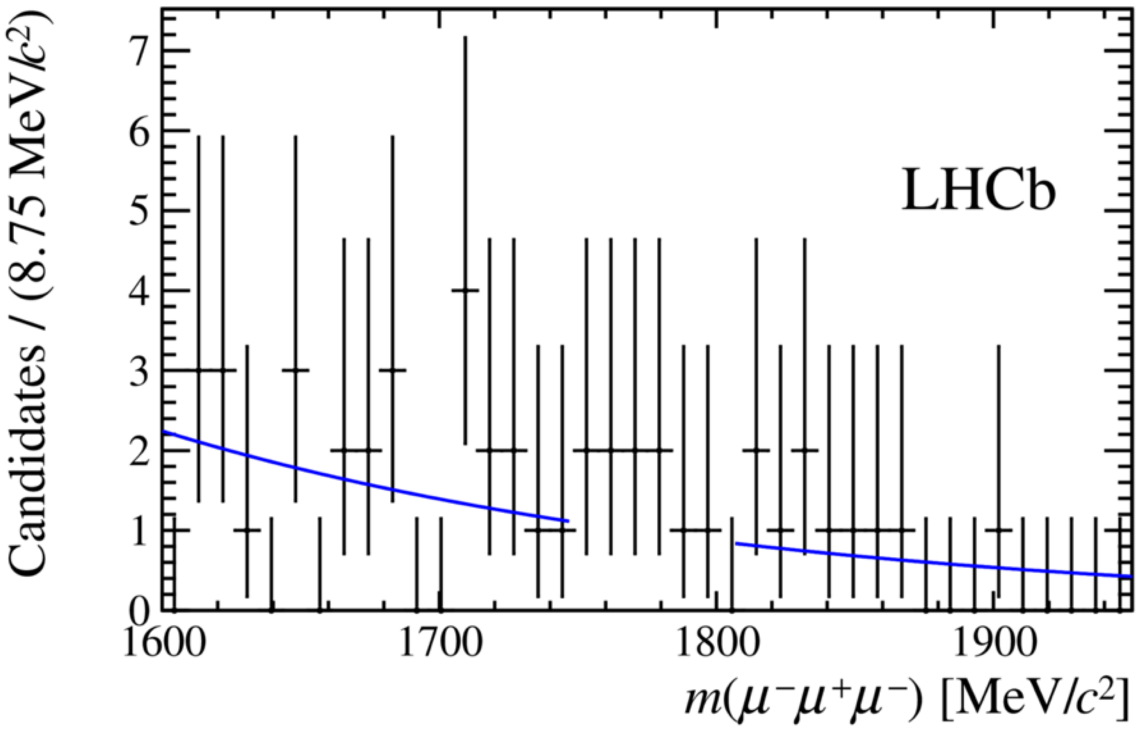
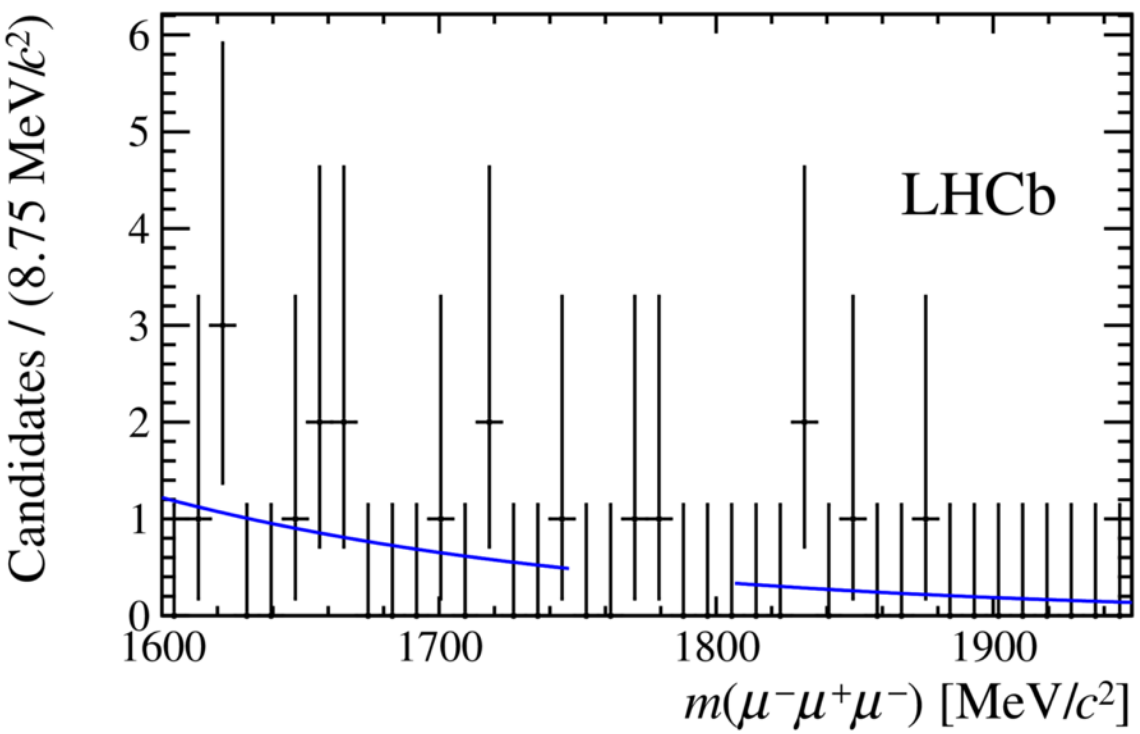
- 65 event categories (30 @ 7TeV + 35 @ 8TeV) based on M(3body) and M(PID) outputs
    - Events with very low M(3body) or M(PID) outputs already excluded
- Fit m(3μ) spectra, excluding signal region, to estimate background
- Total event yields (in ±2 times mass resolution window) in 35 categories of 8 TeV
    - ~30 signal (assuming $B(\tau \to 3\mu) = 10^{-7}$)
    - ~300 data events
- Upper limit on $B(\tau \to 3\mu)$: 4.6×10^{-8} (expected: 5.0×10^{-8})

One of the best categories in 7 TeV data



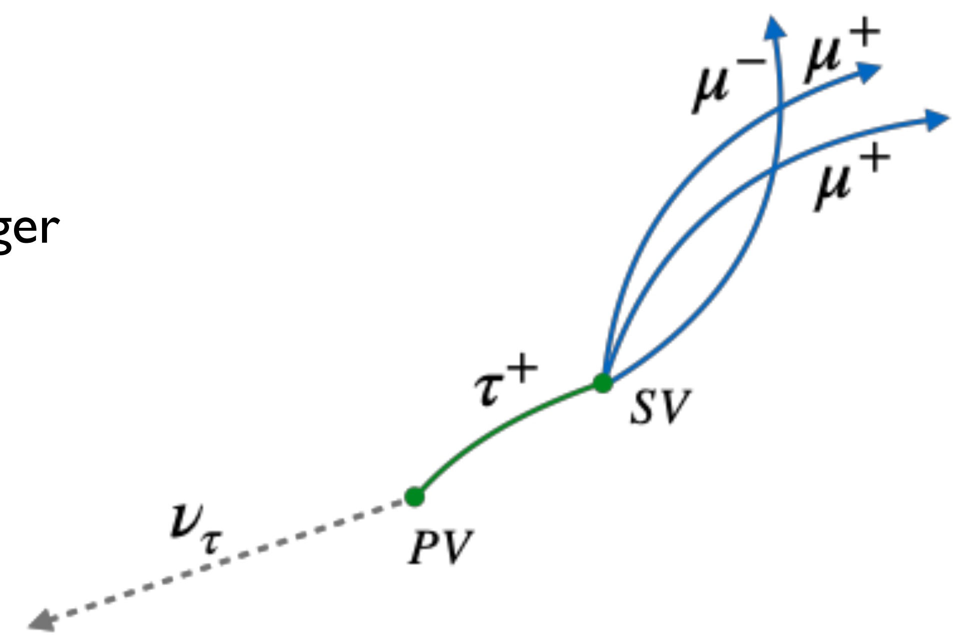
One of the best categories in 8 TeV data

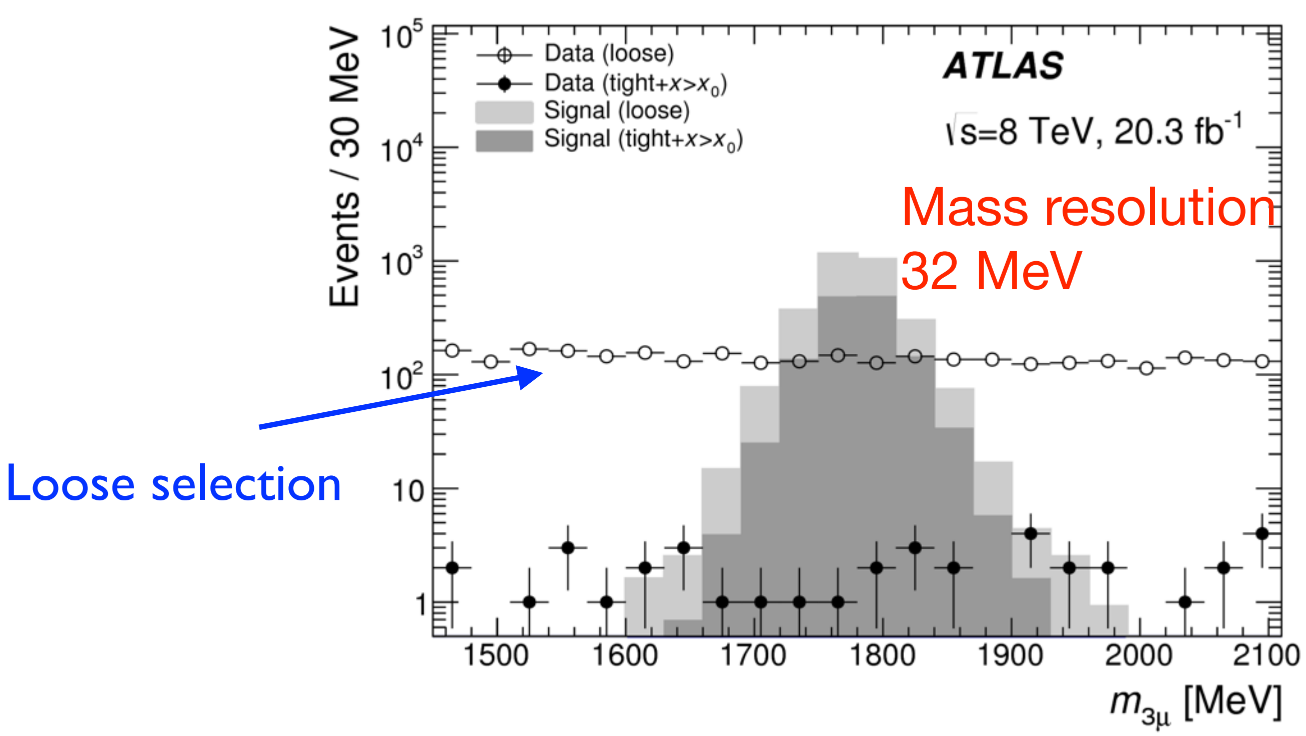


W channel - ATLAS

1601.03567
Eur. Phys. J. C (2016) 76:232

- Run I data: 8 TeV; L = 20 fb^{-1}
  - Number of $W \to \tau$ produced is 2.4 x 10^8
- Six different multi-muon triggers, and one dimuon + MET trigger
- Event selection:
  - Three "high-quality" muons
  - Loose selection (vertex and kinematics) to obtain a data sideband sample to train BDT (about 4000 events)





Signal characteristics:

- $p_T(3\mu)$ ~ 20-50 GeV
- Common vertex, displaced wrt the primary vertex
- Boosted topology (muon dR ~ 0.07)
- Missing transverse momentum opposite to 3μ
- Transverse mass of the system consistent with m(W)
- Little hadronic activity

W channel - ATLAS

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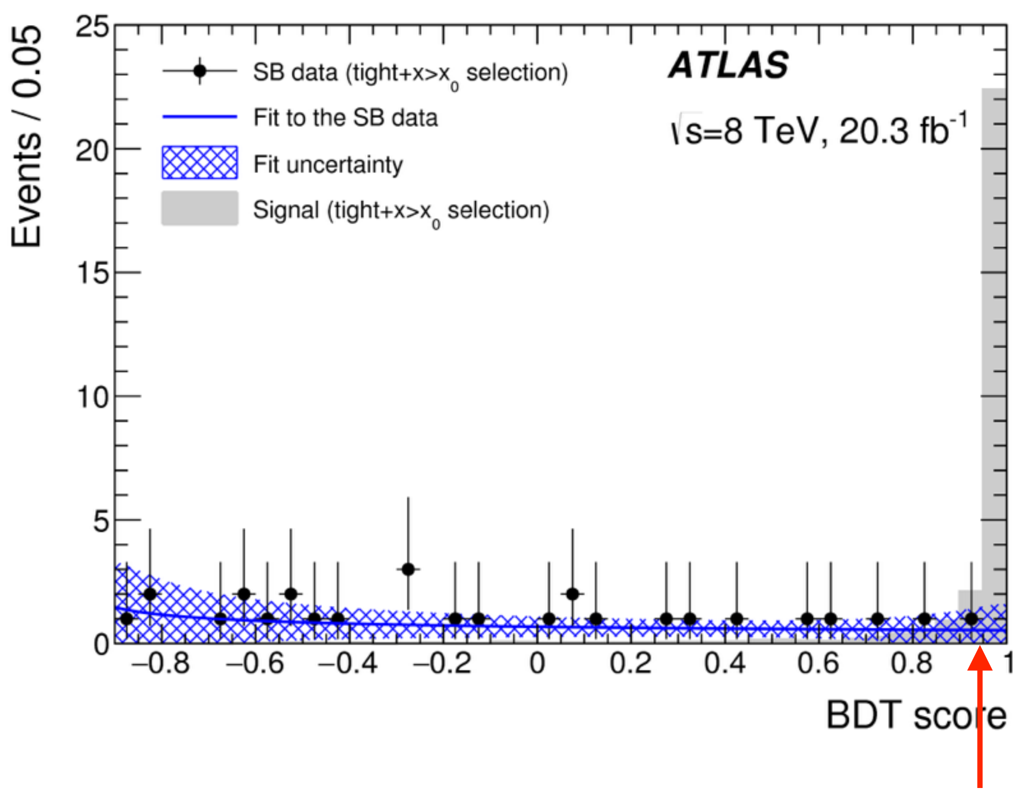
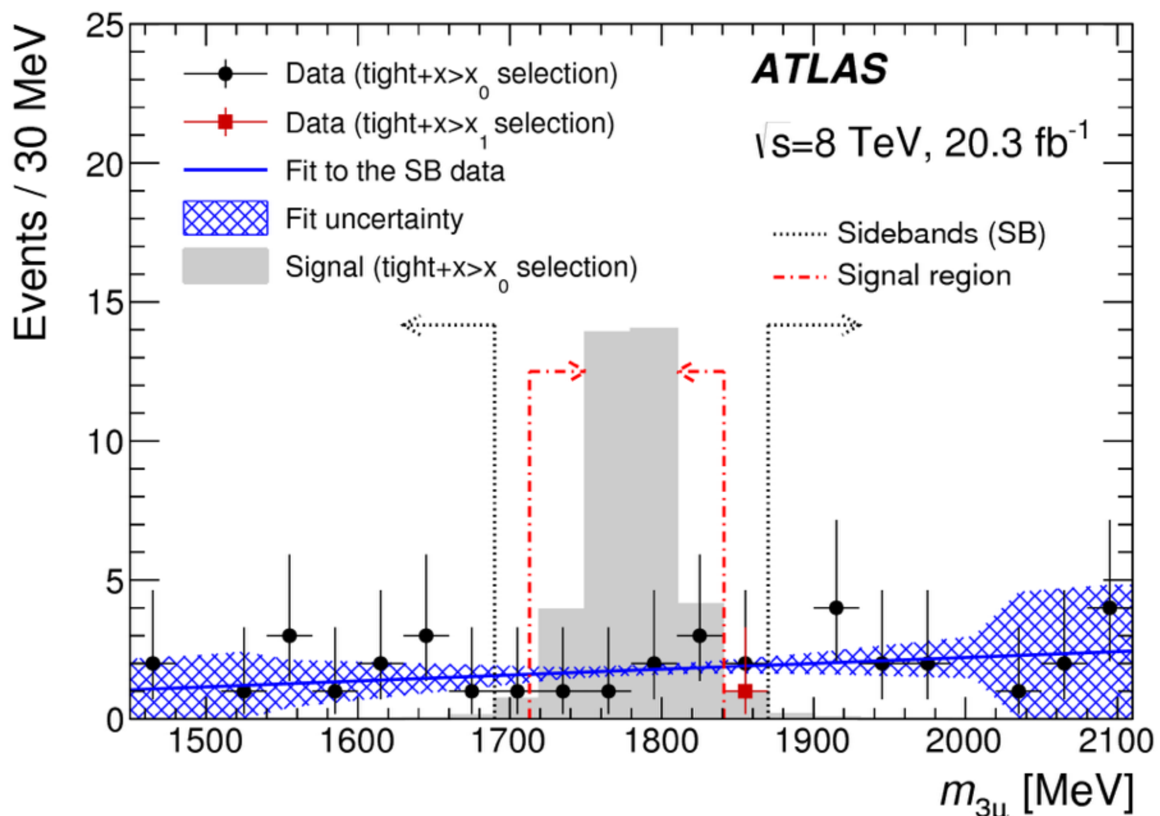
- Signal region after final selections (including BDT cut)
  - Total signal acceptance x efficiency = 2.3%
  - Background estimation: 0.19
  - Observed: 0
- Upper limit on B($\tau \to 3\mu$): 3.8 x 10^{-7} (expected: 3.9 x 10^{-7})



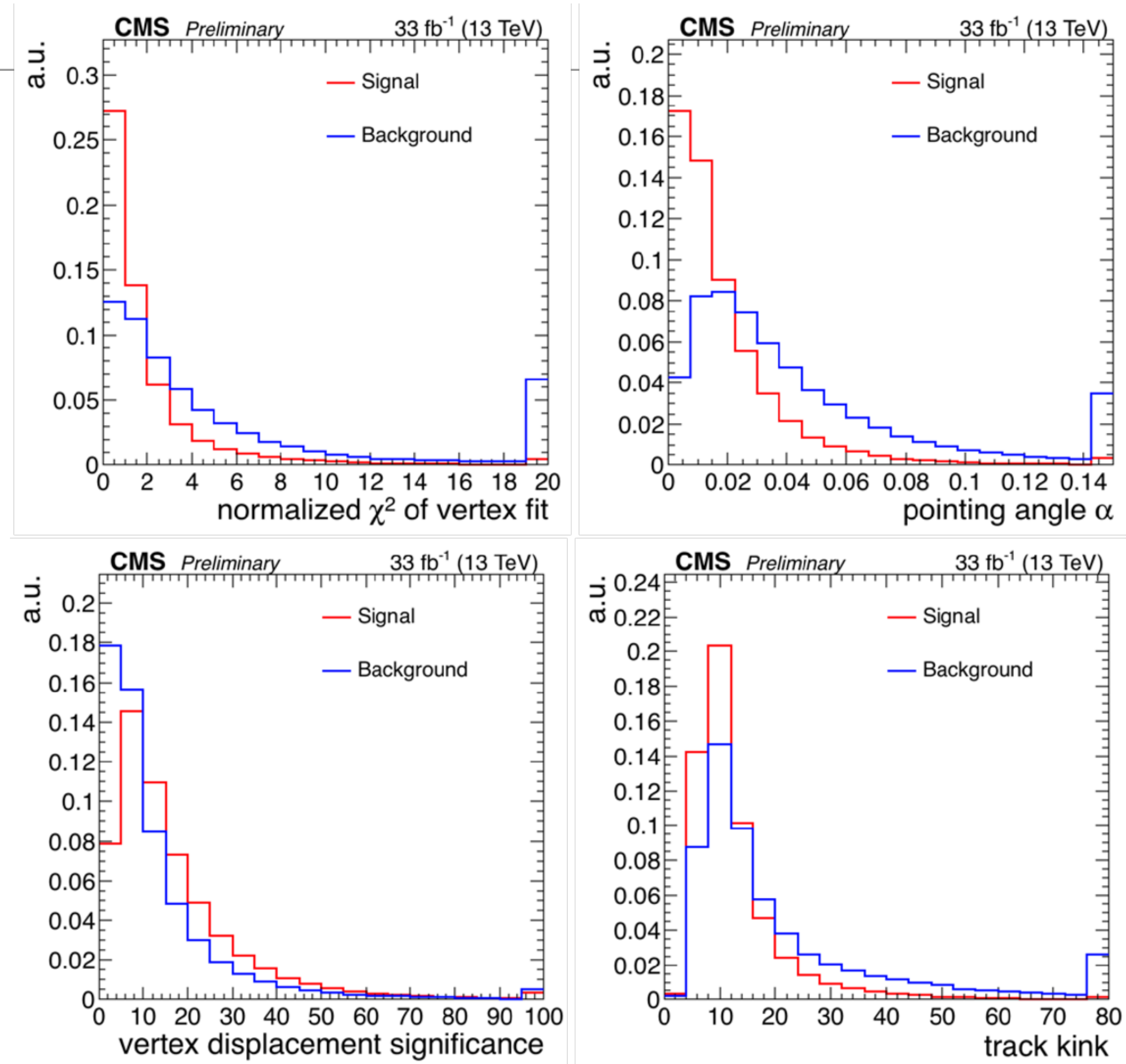


Final BDT cut at 0.933

2007.05658

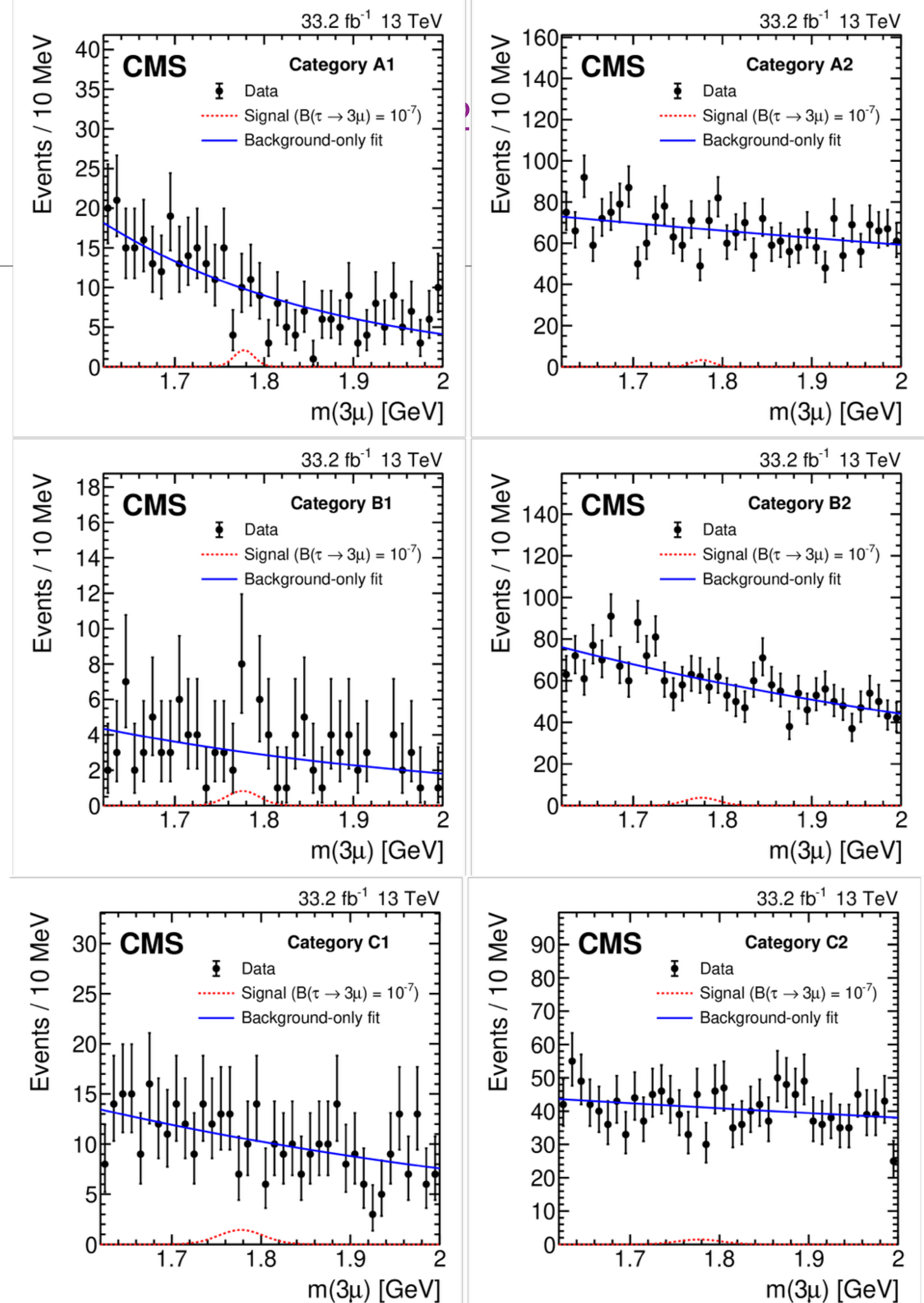
HF channel - CMS

- 2016 data: 13 TeV; L = 33 fb^{-1}
- Trigger: 2 muons of p_T > 3 GeV, plus another track, sharing a displaced vertex
    - So it collects $\tau\to3\mu$ signal and at the same time $D_s\to\phi\pi\to(2\mu)\pi$ events, which are used to validate and correct signal MC
- Select 3μ candidates
- Train BDT to separate signal (MC) from background (data sidebands)
    - The most discriminating ones being vertex chi2, pointing-angle, vertex displacement, etc



HF channel - CMS

- Overall signal acceptance x efficiency ~ 10^{-4}
- Six event categories in total
  - 3 categories based on mass resolution (12 MeV, 19 MeV and 25 MeV respectively, dictated by inner tracker detector)
  - 2 sub-category based on BDT scores
- Simultaneous fit of m(3μ) of 6 categories
- Events yields in the 3 higher BDT score categories
  - 20 signal (assuming $B(\tau\rightarrow 3\mu)= 10^{-7}$)
  - ~200 data events
- The observed (expected) upper limit on $Br(\tau\rightarrow 3\mu)$ is 9.2×10^{-8} (10.0×10^{-8})



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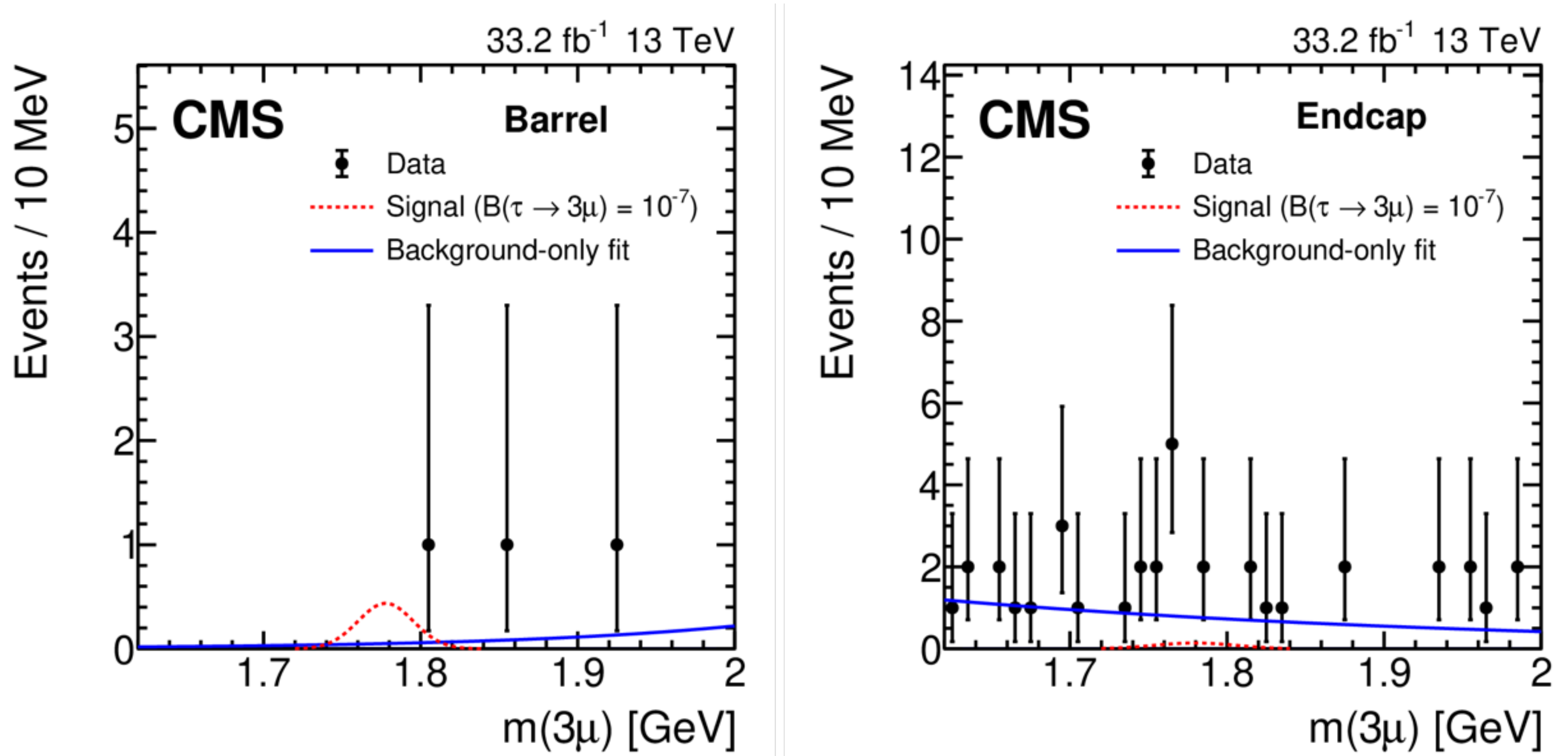
W channel and combination - CMS

2016 data: 13 TeV; L = 33 fb-1

- Use the same trigger as the HF channel (2 muons of p_T > 3 GeV, plus another track, sharing a displaced vertex)
- The most powerful variables to reject background are the typical W→l+nu observables - p_T, transverse mass, isolation
  - The same is true in the ATLAS analysis



W channel

- Observed (expected) upper limit on Br(τ→3μ) is 20 x 10^{-8} (13 x 10^{-8})

CMS HF and W channel combination:

- Observed (expected) upper limit on Br(τ→3μ) is 8.0 x 10^{-8} (6.9 x 10^{-8})

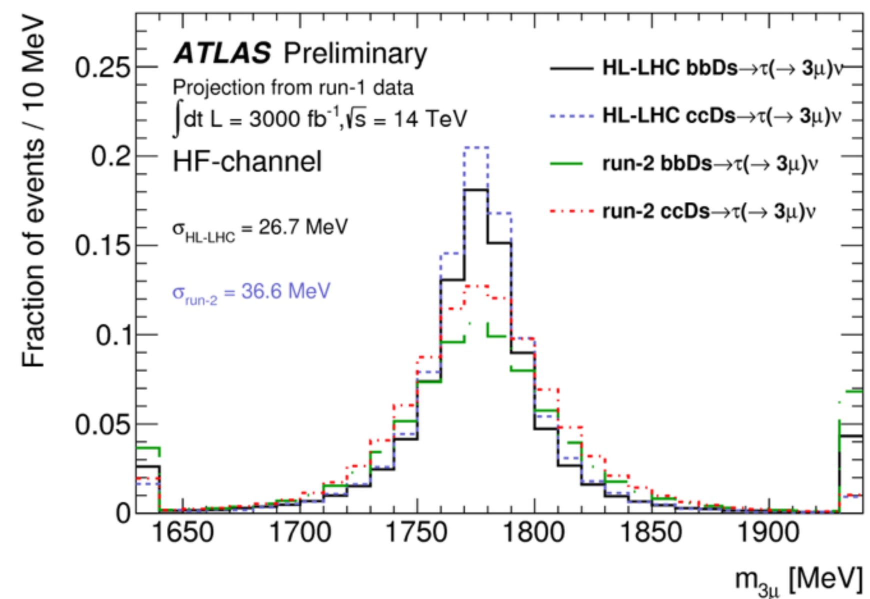
Sidenotes

- HF channel
  - LHCb has much larger acceptance, compared to CMS, as D and B mesons are boosted; also better mass resolution
  - S/B ~ 0.05-0.15 (assuming $B(\tau \to 3\mu) = 10^{-7}$), with LHCb slightly better
  - LHCb paper mentions "3 real muon" irreducible background, $D_s \to \eta(\mu\mu\gamma)\mu\nu$, being important
- W channel
  - The CMS analysis uses a dedicated low threshold trigger (which is believed to be the plan for ATLAS future analysis on this channel), but the gain by doing so is not big
  - S/B ~ 3 for both CMS and ATLAS analyses (assuming $B(\tau \to 3\mu) = 10^{-7}$)
  - Almost zero background - the search sensitivity grows faster than sqrt(N)
- S/B ratio is more than a factor 20 worse in HF channel than in W channel

ATL-PHYS-PUB-2018-032

HL-LHC projection - ATLAS

- 3000 fb^{-1} at 14TeV
- Both W channel and HF channel projections are based on W channel published result ("datacard" level projection)
- Assuming no deterioration due to high pile-up
- W channel:
    - Intermediate scenario: lower trigger thresholc
    - Improved scenario: upgraded inner tracker detector
- HF channel
    - Acceptance and efficiency based on MC
    - Background estimation: High/Medium/Low background levels are taken as a factor of 10/3/1 as that in W channel analysis



25% better mass resolution after inner tracker upgrade

W channel

Scenario	$\mathcal{A} \times \epsilon$ [%]	$N_{\mathrm{bkg}}^{\mathrm{exp}}$	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
Run 1 result	2.31	0.19	276
Non-improved	2.31	50.71	13.52
Intermediate	5.01	50.71	6.23
Improved	5.01	40.06	5.36

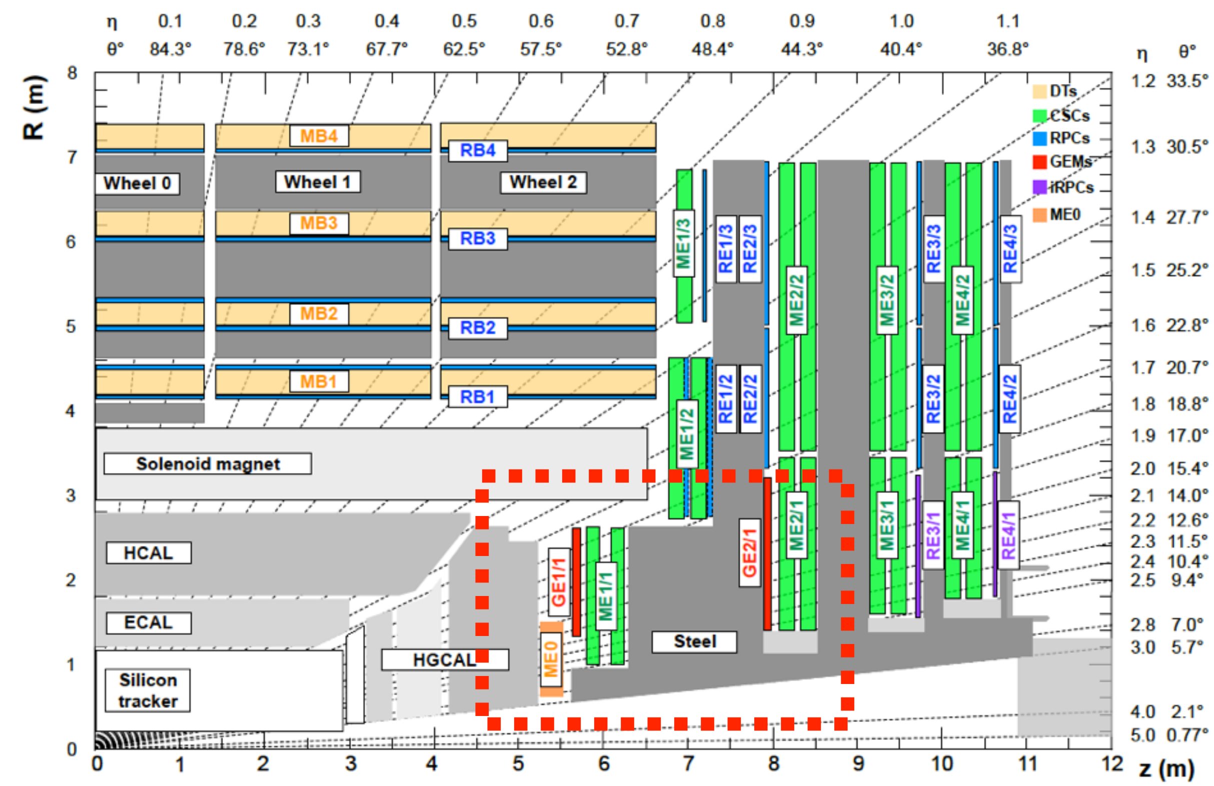
HF channel

Scenario	$\mathcal{A} \times \epsilon$ [%]	$N_{\mathrm{bkg}}^{\mathrm{exp}}$	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
High background	0.88	507.05	6.40
Medium background	0.88	152.12	2.31
Low background	0.88	50.71	1.03

CMS Muon Phase-2 Upgrade TDR
CERN-LHCC-2017-012

HL-LHC projection - CMS

- 3000 fb^{-1} at 14TeV
- HF channel only (6 x 10^{14} tau)
- Based on full simulation of signal and QCD background
  - 200 pile-up, upgraded detector
- CMS detector upgrade most relevant for $\tau \rightarrow 3\mu$ search
  - Enhanced forward muon system
  - Track-trigger capability for tracks with p_T > 2 GeV
  - Higher trigger bandwidth (100 kHz → 750 kHz)

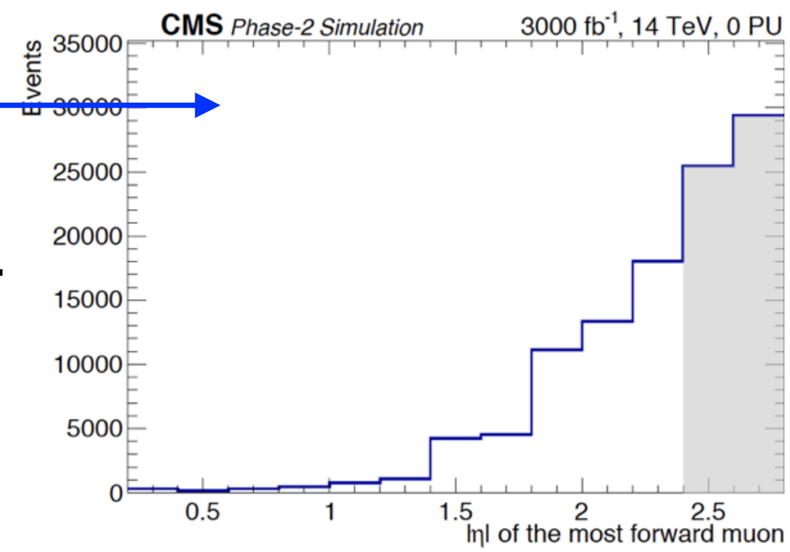


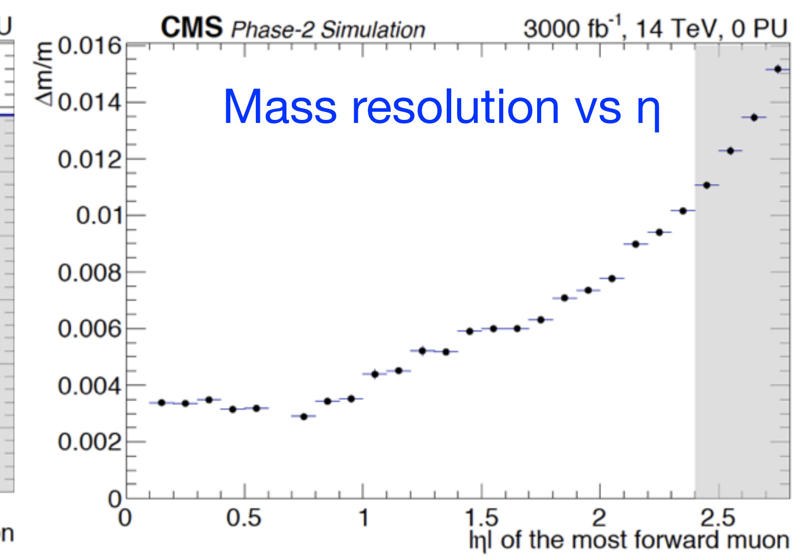
Adding new GEM detectors
- more layers
- extended pseudorapidity (η) coverage

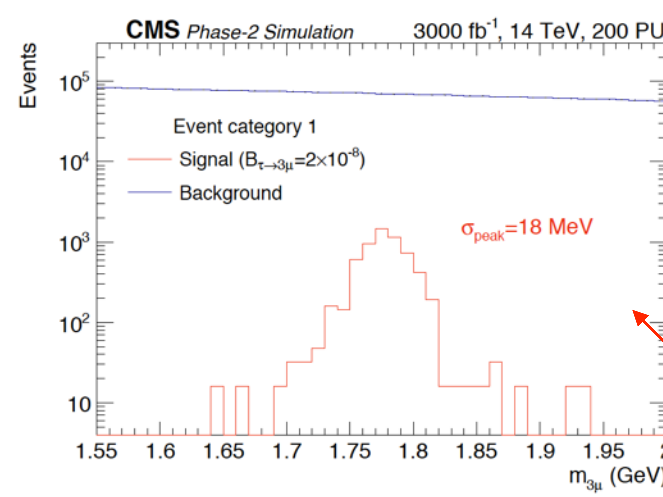
CMS Muon Phase-2 Upgrade TDR
CERN-LHCC-2017-012

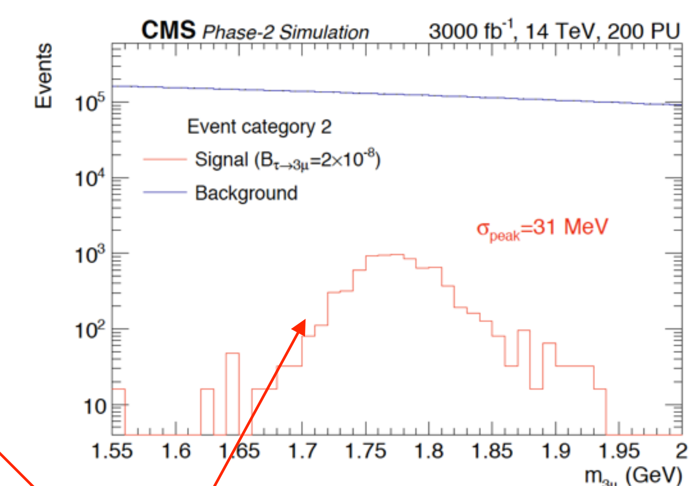
HL-LHC projection - CMS

- A factor of 2 gain due to η-coverage extension from 2.4 to 2.8
- The gained events have a worse tri-muon mass resolution (dictated by inner tracker)
- High pile-up has a visible effect on signal selection efficiency, but not dramatic
- Multivariate likelihood is built, using mostly event topology variables









	Category 1	Category 2
Number of background events	2.4×10^6	2.6×10^6
Number of signal events	4 580	3 640
Trimuon mass resolution	18 MeV	31 MeV
$B(\tau \to 3\mu)$ limit per event category	4.3×10^{-9}	7.0×10^{-9}
$B(\tau \to 3\mu)$ 90%C.L. limit	3.7×10^{-9}	
$B(\tau \to 3\mu)$ for 3σ-evidence	6.7×10^{-9}	
$B(\tau \to 3\mu)$ for 5σ-observation	1.1×10^{-8}	

Two event categories based on whether muons in η [2.4, 2.8] are used

"Category 2" has worse mass resolution, while the S/B ratio is not much worse

Summary

- Both D, B meson decays and W decays have been exploited for the $\tau \to 3\mu$ search, by LHCb, ALTAS and CMS

	Published result	Channel	Dataset	HL-LHC projection
LHCb	4.6×10^{-8}	HF	3 fb^{-1} 7or 8 TeV	
ATLAS	38×10^{-8}	W	20 fb^{-1} 8 TeV	a few 10^{-9}
CMS	8.0×10^{-8}	W+HF	33 fb^{-1} 13 TeV	a few 10^{-9}

- HL-LHC is a prolific source of tau-leptons (6×10^{14})
- LHC experiment analyses are not limited by the number of taus, but rather by how well to separate signal and background
- Belle-II projection for 50 ab^{-1} $B(\tau \to 3\mu) < 4 \times 10^{-10}$ [PoSFPCP2015 (2015) 049]
    - Breakthrough in analysis techniques is required for LHC experiments in order to compete

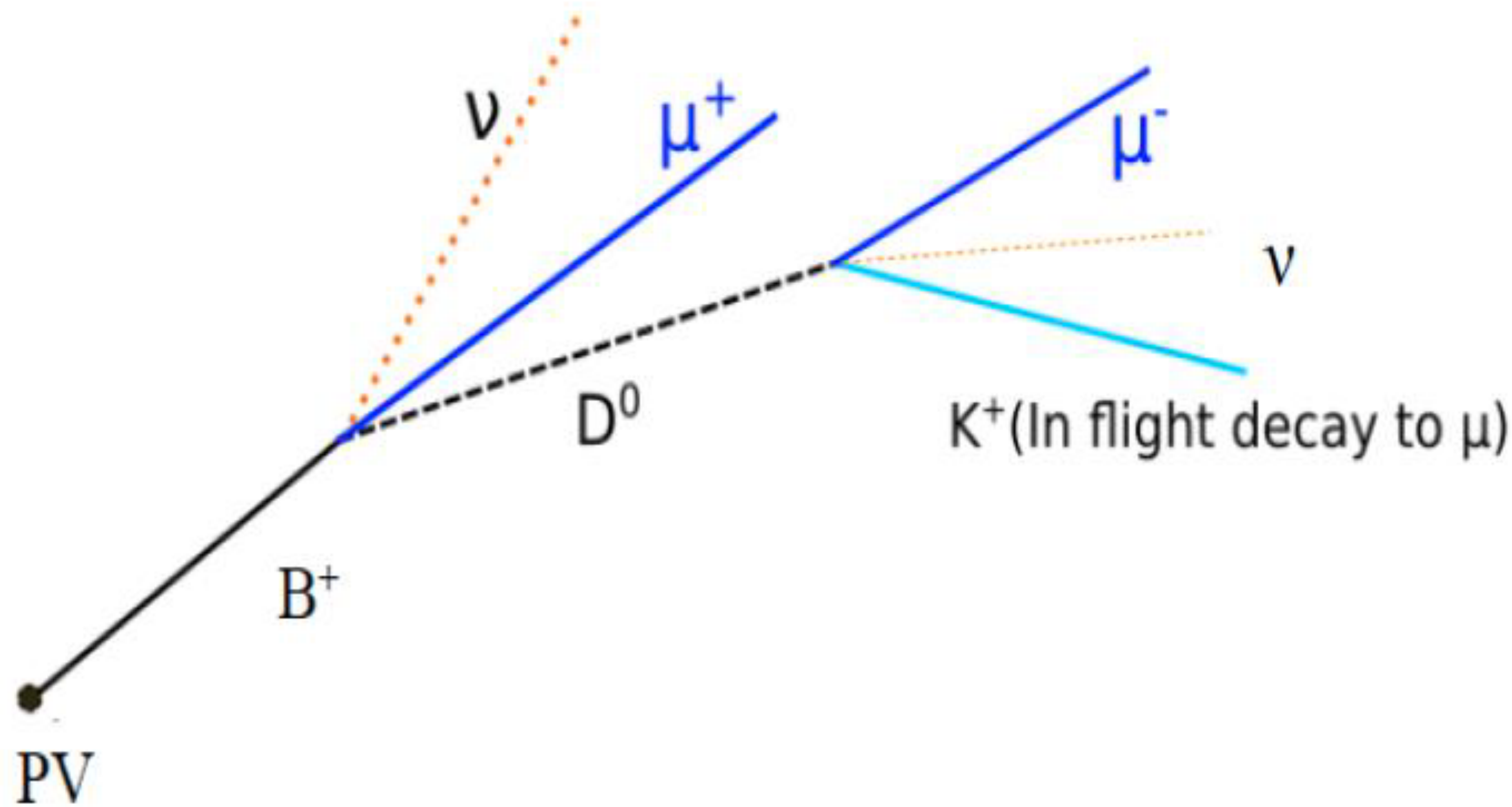
BACK-UP

LHCb trigger

The trigger [13] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which applies a full event reconstruction. Candidate events are first required to pass the hardware trigger, which selects muons with a transverse momentum $p_{\mathrm{T}} > 1.48\,\mathrm{GeV}/c$ in the 7 TeV data or $p_{\mathrm{T}} > 1.76\,\mathrm{GeV}/c$ in the 8 TeV data. In the software trigger, at least one of the final-state particles is required to have both $p_{\mathrm{T}} > 0.8\,\mathrm{GeV}/c$ and IP $> 100\,\mu\mathrm{m}$ with respect to all of the primary pp interaction vertices (PVs) in the event. Finally, the tracks of two or more of the final-state particles are required to form a vertex that is significantly displaced from the PVs.

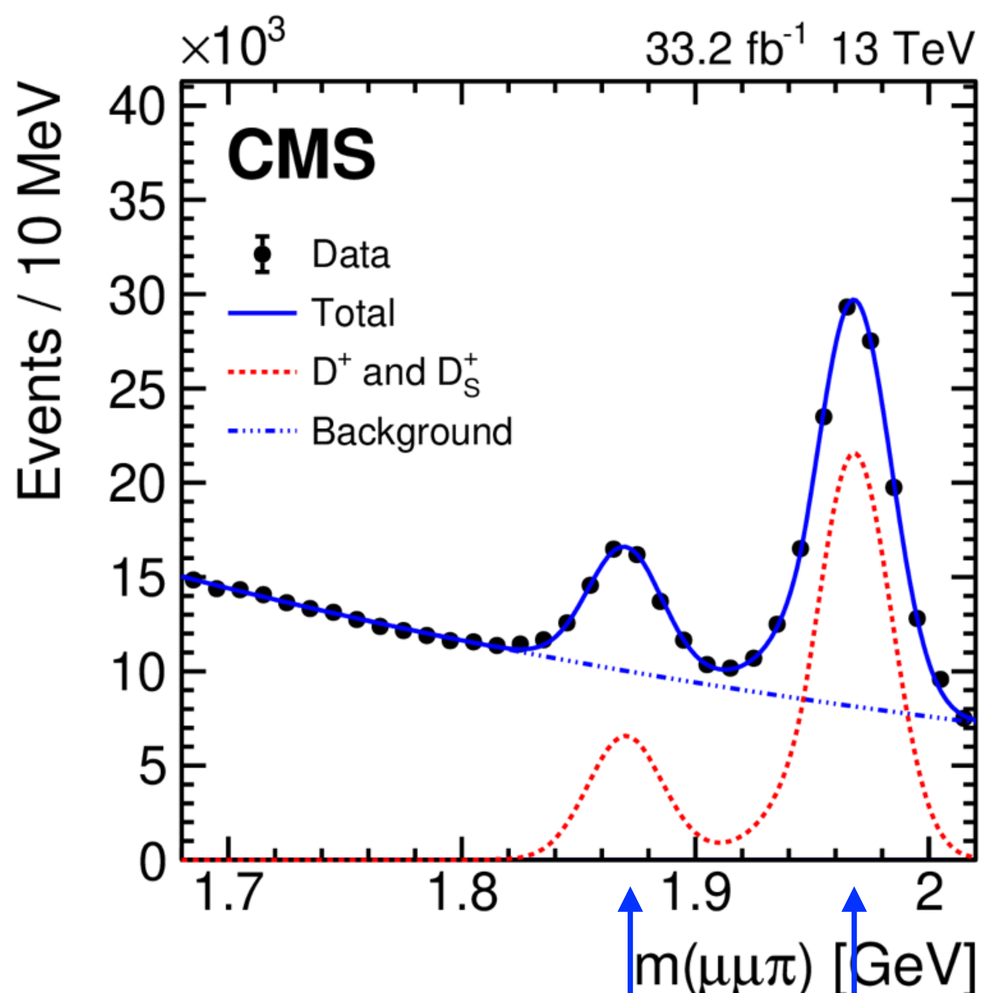
ATLAS trigger

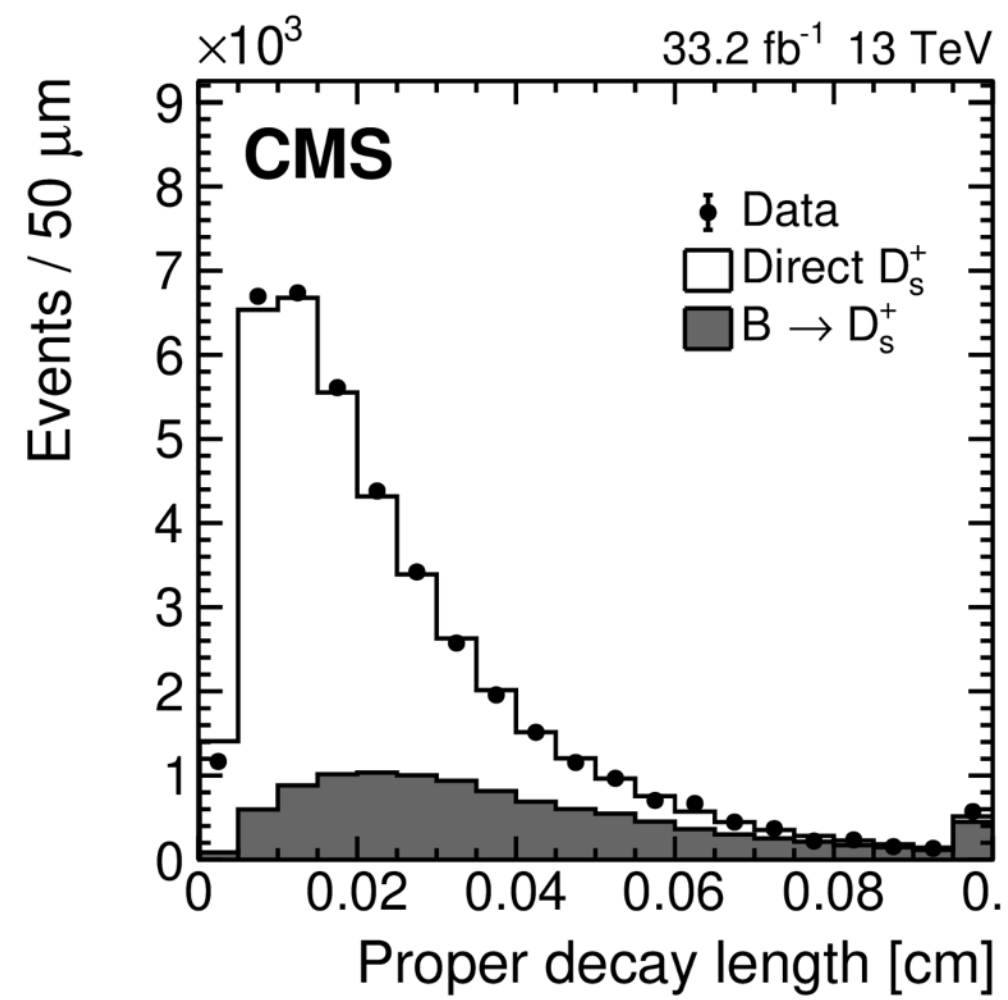
To maximise the signal acceptance times efficiency, events are required to pass at least one of seven triggers. These are six multi-muon triggers and one dimuon plus $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger. The software-based trigger thresholds used for the muons range from 4 to 18 GeV in transverse momentum while the $E_{\mathrm{T}}^{\mathrm{miss}}$ threshold is 30 GeV. The trigger efficiency for simulated signal events within the muon-trigger acceptance (three generator-level muons with $p_{\mathrm{T}} > 2.5$ GeV and $|\eta| < 2.4$) is $\sim 31\%$ for the combination of all triggers used in the analysis. To evaluate the trigger performance in the region where the muons have a small


ν
μ+
μ-
ν
D0
K+(In flight decay to μ)
B+
PV

The control channel Ds→ϕπ→(2μ)π

The Ds rate is measured using the control channel





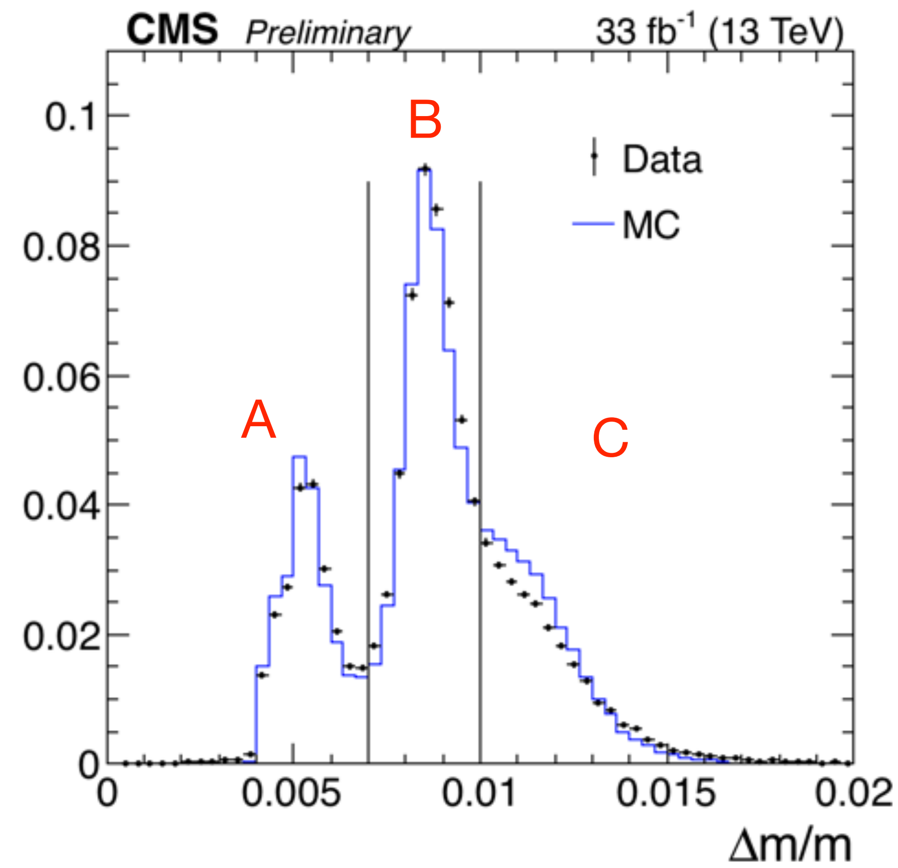
D±→ϕ(2μ)π

Ds→ϕ(2μ)π

Ds→ϕπ channel was also used to

- Valid B/D fractions predicted by PYTHIA
- Compare mass scale and resolution in data/MC
- Some BDT analysis validation

Event categorisation based on mass resolution



The three parts strongly correlated with Inner Tracker barrel, overlap and endcap regions

Signal shapes fit using Crystal Ball +Gaussian