Search for CLFV decays $\tau \rightarrow 3\mu$ with ATLAS and CMS Detectors

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Preamble

There are no fundamental symmetries explicitly forbidding CLFV processes

- In fact, in SM CLFV decays are possible via neutrino oscillations, e.g. $B(\tau \rightarrow 3\mu) \sim O(10^{-14})$
- In BSM, such decays can be "naturally" enhanced, e.g. $B(\tau \rightarrow 3\mu)$ can be as large as $O(10^{-8})$

Theoretical considerations in favor of $\tau \rightarrow 3\mu$:

- Tau lepton's large mass means large phase space for decays
- couplings for new physics may be enhanced for heavy particles

Experimental considerations in favor of $\tau \rightarrow 3\mu$:

- there-muon signature is the cleanest at LHC (as opposed to $3e$, $\mu\mu e$, $\mu\gamma$, etc.)

Recent experimental limits (90% CL):

Belle:	2.1×10^{-8} (expected $\sim 2.3 \times 10^{-8}$)	*Phys. Lett. B687 (2010) 139*
BaBar:	3.3×10^{-8} (expected 4.0×10^{-8})	*Phys. Rev. D81 (2010) 111101*
LHCb (Run 1):	4.6×10^{-8} (expected 5.6×10^{-8})	*JHEP 02 (2015) 121*
ATLAS (Run 1, 8 TeV):	3.8×10^{-7} (expected 3.9×10^{-7})	*Eur. Phys. J. C76 (2016) 5, 232*
CMS (Run 2, 2016 dataset):	coming soon	

Presented in this talk:

- **ATLAS Run 1 analysis** *Eur. Phys. J. C76 (2016) 5, 232*
- **CMS Projections for HL-LHC** *Phase 2 Muon Upgrade TDR, CMS-TDR-016 (2017)*

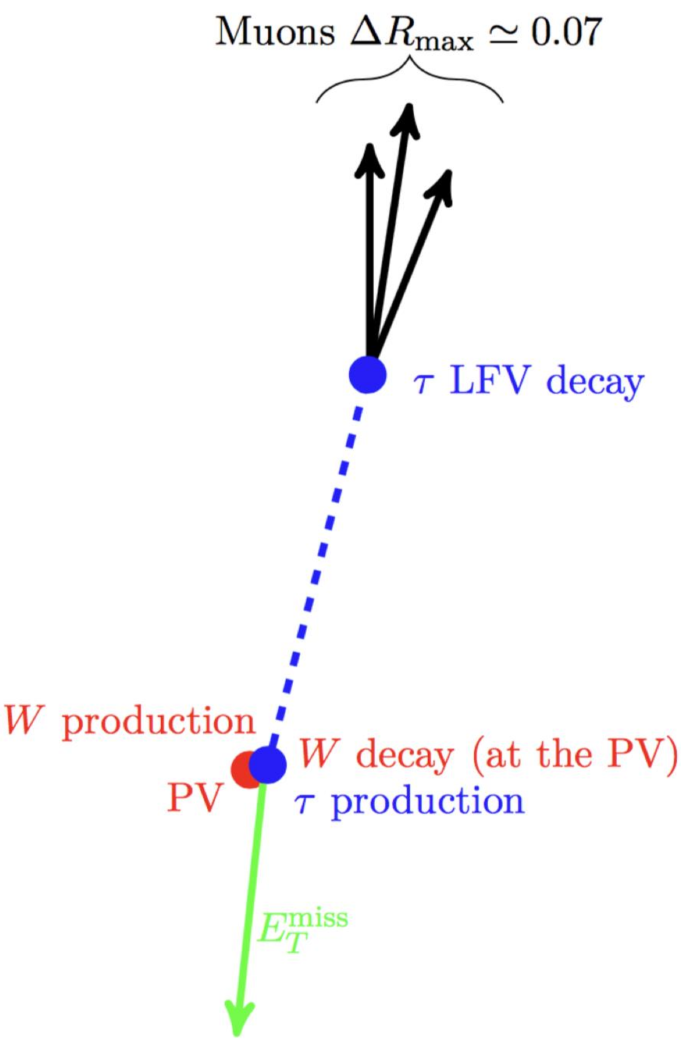
Tau production at HL-LHC (3000 fb^{-1})

	Process	# of taus	Comment
PYTHIA	pp → cc, D→$\tau\nu$	3.6×10^{14}	95% D_s, 5% $D^{\pm}$
	pp → bb, B→τ+…	1.4×10^{14}	44% $B^{\pm}$, 45% B^0, 11% B_s
	B→D($\tau\nu$)+…	0.6×10^{14}	98% D_s, 2% $D^{\pm}$
NNLO	pp → W → $\tau\nu$	6.0×10^{10}	
	pp → Z→ $\tau\tau$	1.2×10^{10}	60 < $m_{\tau\tau}$ < 120 GeV

LHC is a prolific source of tau leptons: ~ 6×10^{14} at HL-LHC (3000 fb^{-1})

- **Hadronic taus:** lots, but challenging (soft, forward, poor S/B)
- **W/Z taus:** ~10^4 fewer, but relatively easier

ATLAS: search using W-decay taus



Run 1, 8 TeV dataset:

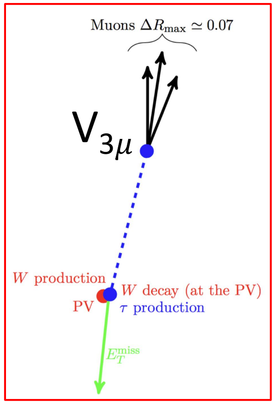
- $L = 20.3\ fb^{-1}$
- Expected number of $W \rightarrow \tau\nu$ events: $\mathbf{2.4\times10^8}$

Main signal characteristics exploited:

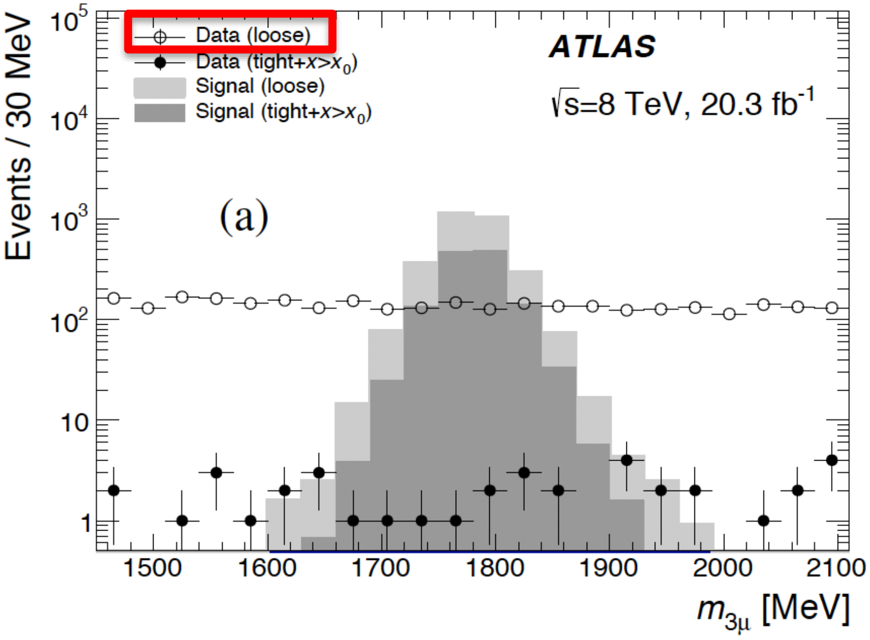
- **Three muons:**
  - Q = $\pm$1
  - $p_T(3\mu)$~20-50 GeV
  - common vertex, displaced wrt PV
  - boosted topology (muons close together)
  - trimuon system is isolated
  - trimuon invariant mass peaks at m_τ – the final observable
- **Missing transverse momentum**
  - 20-50 GeV
  - opposite to $p_T(3\mu)$
- **Transverse mass of $p_T(3\mu)$ and MET**
  - Consistent with m_W
- **Little hadronic activity in an event**

Event selection (1)

Trigger:
- Five different multi-muon triggers
- One dimuon trigger + MET
- Trigger efficiency in fiducial acceptance is **~30%**
  (*fiducial signal acceptance: $p_T > 2.5$ GeV, $|\eta| < 2.4$*)



Reconstruction and event selection:
- three high-quality muons, Q=1
- $m_{3\mu} < 2.5$ GeV
- common vertex $V_{3\mu}$
- **Loose** trimuon event selection cuts on:
  - $V_{3\mu}$ – PV displacement significance
  - impact parameter formed by $p_T(3\mu)$ vector
  - $p_T(3\mu)$
  - Isolation
  - MET
  - m_T



Total signal efficiency: **6.6%**

BDT-training sideband [750; 1450] and [2110; 2500]: **4672 events**

Event selection (2)

After the final selection, the signal sideband (SB) is expected to have too few or even no events

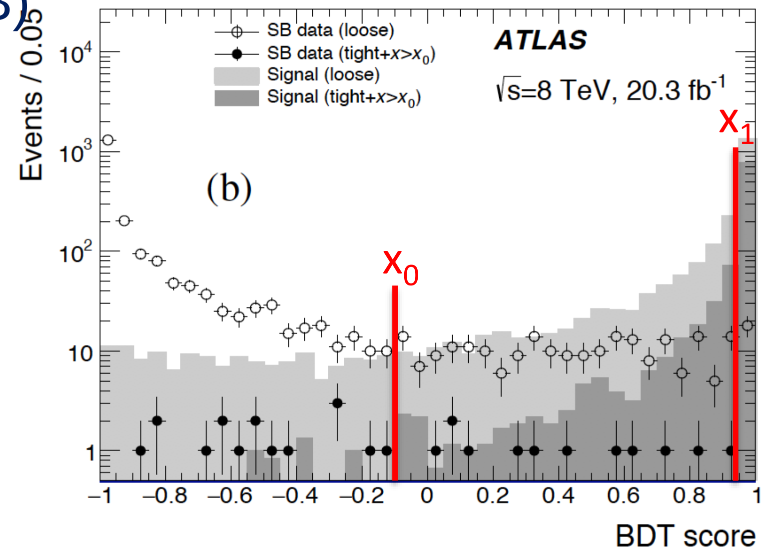
The following analysis strategy is employed

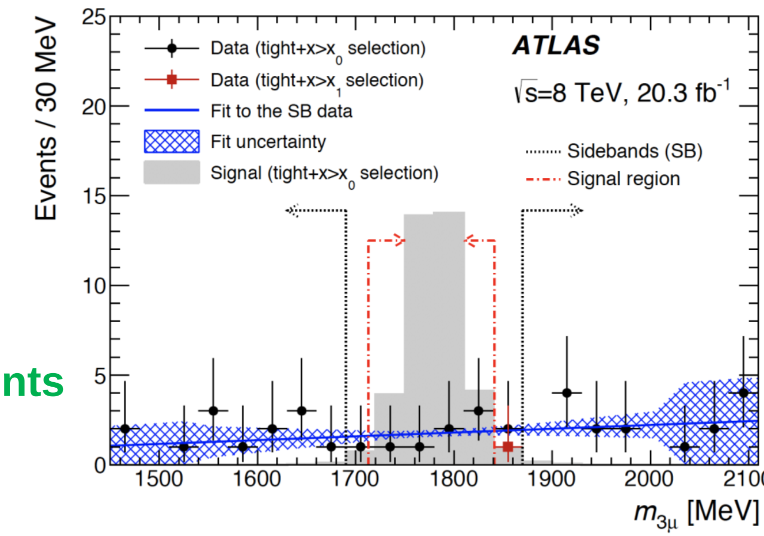
- Train BDT using:
  - **signal MC**
  - **data from BDT-training sideband**
- Apply BDT **cut $x > x_0$**
- Apply **tight event selection**
  - Use the signal sidebands to predict background in signal region **B_{SR}(tight, $x > x_0$)**
  - Use the BDT distribution to compute a reduction factor ***f*** for going from $x > x_0$ to $x > x_1$
- Apply BDT **cut $x > x_1$**

- **Predicted background in the signal region SR**

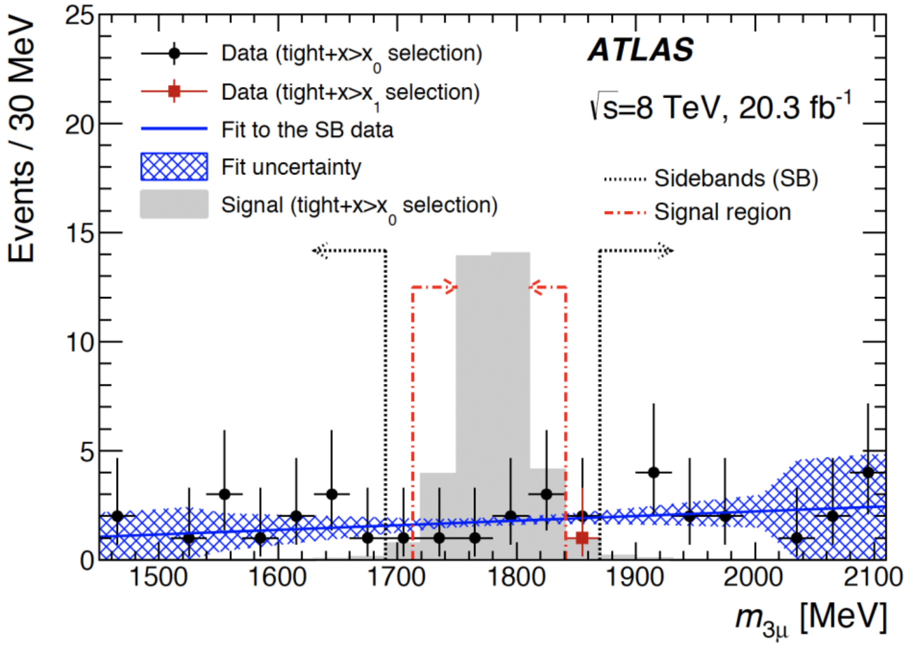
  B_{SR}(tight, $x > x_1$) = B_{SR}(tight, $x > x_0$) × *f* = 0.19 events

- **Overall signal selection efficiency: 2.3%**





Results



Expected $W \to \tau\nu$ events: 2.4×10^{8}

Signal region:

- Signal A x eff = **0.023**
- Background (how?) = **0.19 events**
- Observed: **0 events**

Exclusion limits on B at 90% CL

- Expected: **3.9×10^{-7}**
- Observed: **3.8×10^{-7}**

Side note: for B = 2×10^{-8}, S/B ~ 1:2

My naïve extrapolation toward HL-LHC

If I <u>naively</u> assume (all faults are mine!)

- no deterioration due to high PU
- no improvements in the detector
- no changes in the analysis
- no systematic uncertainties whatsoever
- background event rate scales from 8 TeV to 14 TeV in sync with the W rate

Number of $\boldsymbol{W \to \tau\nu}$ events:

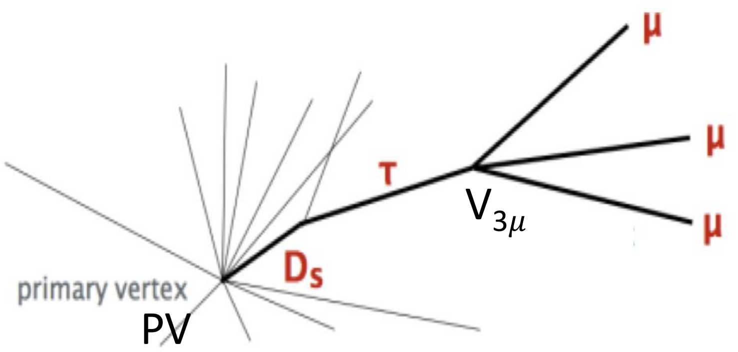
$$\sigma_{14\mathrm{TeV}}(\boldsymbol{W}) \times \boldsymbol{B}(\boldsymbol{W} \to \boldsymbol{\tau\nu}) \times L = (2 \times 10^{8}\, fb) \times 0.11 \times (3000\, fb^{-1}) = \mathbf{6 \times 101^{0}}$$

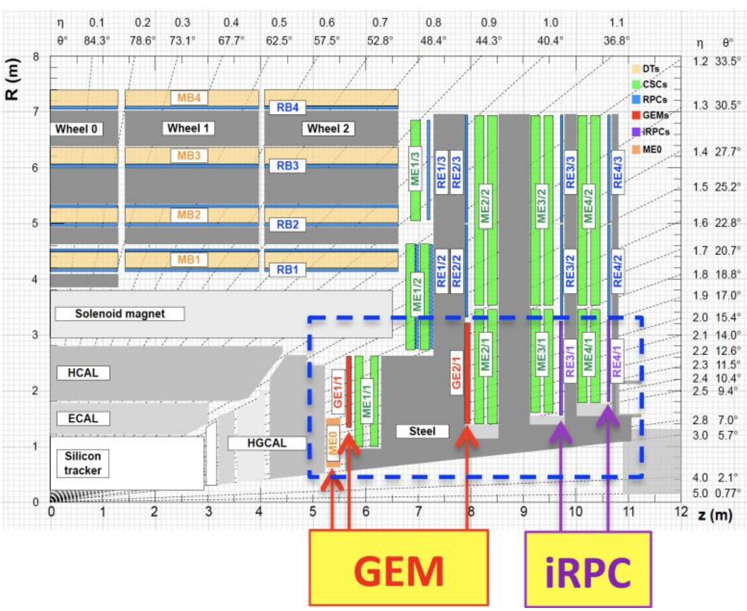
Signal A x eff = **0.023** (no changes)

Background in signal region: $(6 \times 10^{10} / 2.4 \times 10^{8}) \times 0.19$ ~ **50 events**

Such naïve extrapolation gives expected limit 9×10^{-9} at 90% CL

CMS: Search projection using hadronic taus





HL-LHC:

- 14 TeV
- PU = 200 (L ~ 7.5x10^{34} $cm^{-2}s^{-1}$)
- L_{int} = 3000 fb^{-1}
- Expected number of hadronic taus: **5.6×10^{14}**

  (72% of which originate from $D_s \to \tau\nu$)

CMS Upgrades most relevant for this analysis:

- Enhanced forward muon system:
  - improved momentum measurement at L1 Trigger
  - extended eta-coverage from 2.4 to 2.8
- Track-trigger capabilities for tracks with p_T>2 GeV
- Higher trigger bandwidth (100 kHz → 750 kHz)

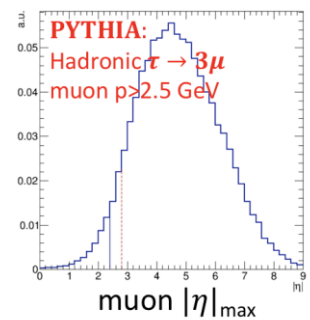
Main signal trimuon characteristics exploited:

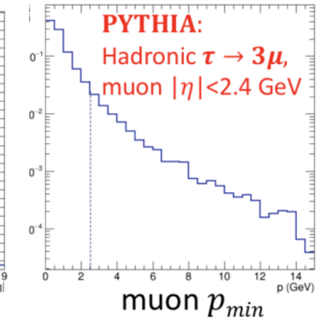
- Q=1
- common vertex, $V_{3\mu}$
- V – PV displacement
- collinearity of p(3μ) and PV-$V_{3\mu}$ vectors
- trimuon invariant mass peaks at m_τ – the final observable

Event Selection (1)

Basic signal acceptance ($|\eta| < 2.8$, p > 2.5 GeV): **2.6%**

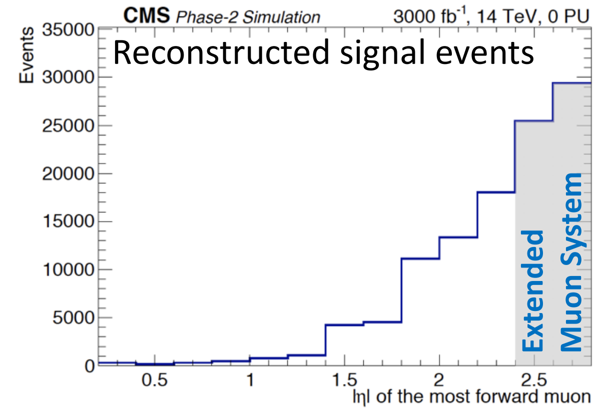
factor of two gain due to extension of muon η-acceptance from 2.4 to 2.8





Muon reconstruction:

- Tracker-muons: Tracker track + at least one matching segment in Muon System
- Signal efficiency in acceptance is about **30%**
- the gained events due to the Muon System extension have a **worse trimuon mass resolution**

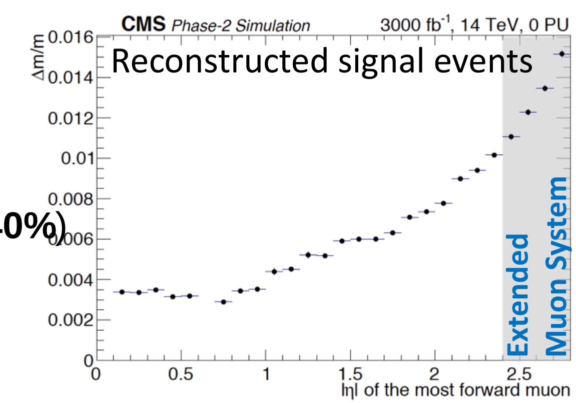


Two event categories are introduced:

- **Category 1:** events reconstructed using the present muon chambers
- **Category 2:** events with at least one ME0-only muon

Trigger:

- **Category 1:**
  - At least two tracker-muons (p_T > 2 GeV, $\delta p_T/p_T \sim$ 2–3%)
  - One station-1 **ME0-CSC** segment (**$\delta p_T/p_T \sim$ 20%**)
  - Trimuon mass < 3 GeV
  - Efficiency wrt reconstructed/selected trimuon events: **~80%**
- **Category 2:**
  - At least one tracker-muon
  - Two station-1 segments, allowing for **ME0-only** segments (**$\delta p_T/p_T \sim$ 40%**)
  - Trimuon mass < 3 GeV
  - Trigger efficiency for reconstructed/selected trimuon events: **~50%**



Event selection (2)

Loose cuts on variables to mitigate pile-up background

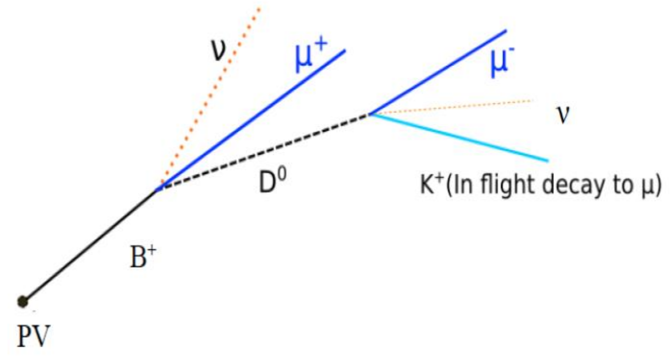
- Q = $\pm$1
- minimum trimuon vertex χ^2
- minimum transverse displacement of the trimuon vertex
- maximum ΔR distance between the three muons

This basic event selection

- has signal efficiency **~30%** for events with all three muons reconstructed
- and practically eliminates pile-up background

Remaining background is mostly due to B production with

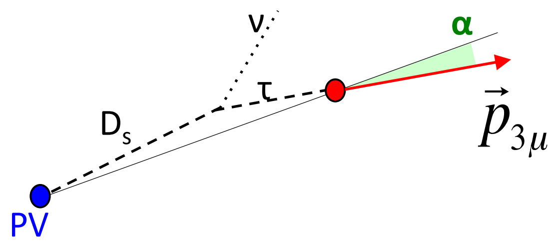
- two muons from B cascade decays
- and one “fake” muon from π/K-decays in flight accidental “alignment” of a track in the Tracker stub found in a muon chamber



Event Selection (3)

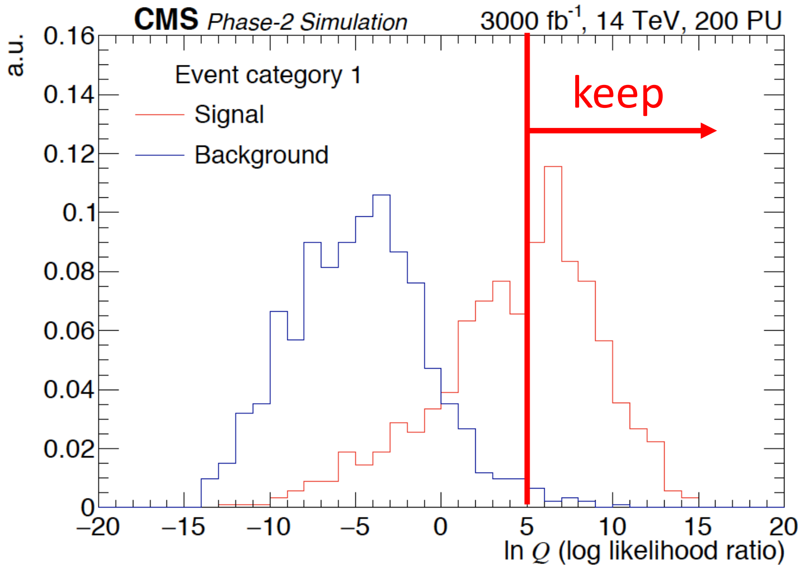
Observables used to build the final S/B log-likelihood ratio, lnQ, where $Q = \prod \frac{pdf_s(x_i)}{pdf_b(x_i)}$

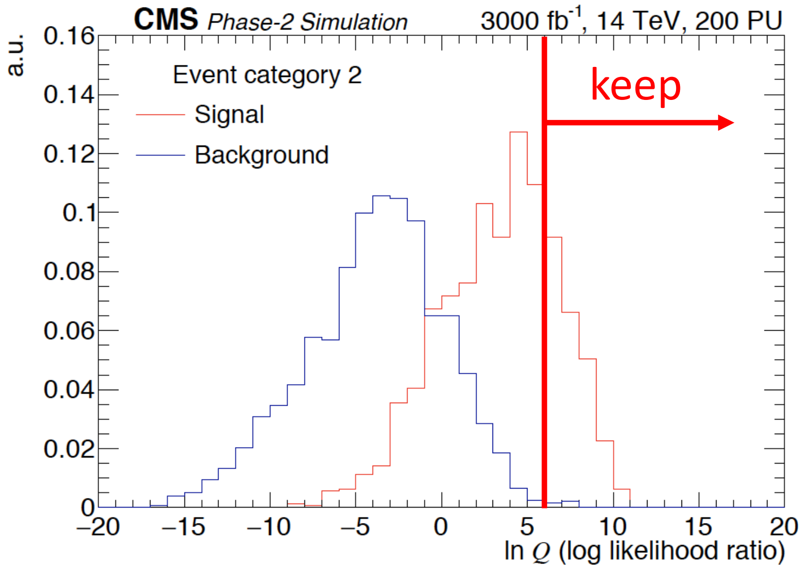
- trimuon vertex χ^2
- transverse displacement of the trimuon vertex
- decay collinearity angle α
- minimum ΔR distance between between dimuon pairs
- highest and lowest muon momentum
- number of b-jets in the event
- …



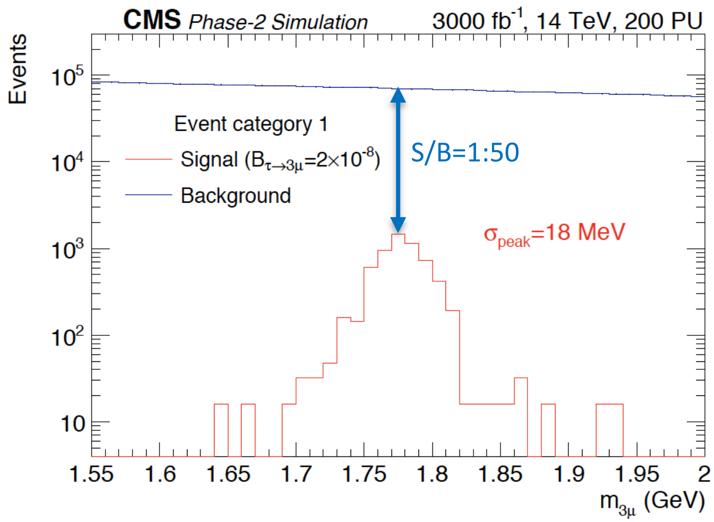
A cut on lnQ is then imposed

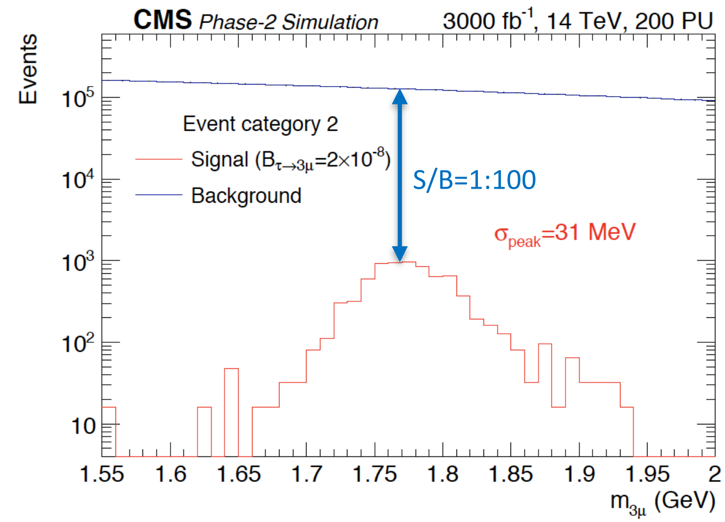
The final overall signal efficiency ~0.06%





Final mass distributions and sensitivity





	Category 1	Category 2
Number of background events	2.4×10^6	2.6×10^6
Number of signal events (B = 2×10^{-8})	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}	

Conclusions

The present best limit on τ→3μ decays: **B(τ→3μ) < 2.1×10^{-8} at 90% CL**

Belle-II projection for 50 ab^{-1} [PoS FPCP2015 (2015) 049]: 4×10^{-10} at 90% CL

HL-LHC is a prolific source of tau leptons: $\boldsymbol{\sigma(pp \rightarrow \tau + X) \sim 2 \times 1011}$ **fb**

– Both **hadronic** and **electroweak** ($\sigma\sim2\times10^7$ fb) taus can be exploited for the τ→3μ search; each branch is being explored by both ATLAS and CMS

– **HL-LHC Projections (limit at 90% CL) <u>based on the three public results available so far</u>:**

	Luminosity	Tau source	Source of projection	Limit
ATLAS	3000 fb^{-1}	W→$\tau\nu$	**My naïve extrapolation** from the Run 1 (8 TeV, 20.3 fb^{-1}) results (slide 8)	9×10^{-9}
CMS	3000 fb^{-1}	Hadronic	**Simulated analysis** for the Upgraded CMS at HL-LHC	4×10^{-9}
LHCb	300 fb^{-1}	Hadronic	**My naïve $1/\sqrt{N}$ extrapolation** from the Run 1 (8 TeV, 3 fb^{-1}) results	6×10^{-9}

– LHC analyses are not limited by the number of taus, but rather by how well one can separate signal from large background – **plenty of opportunities for further optimization.** The actual results will be for sure better than the presented simplified/naïve projections (*e.g., compare the earlier projections and the actual results for ttH, H→bb, VBF H→invisible*)