Potential of $\tau \rightarrow 3\mu$ search in CMS experiment in HL-LHC phase

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Knocking at the Heaven's door

- After several years of LHC operation, data still do not indicate presence of *New Physics* beyond Standard Model (SM).

- On the contrary, experimental results match well with SM predictions for TeV energy scale physics accessible till now ➔ remarkable success of SM!

- However SM does not have a flavour theory based on any symmetry consideration.

- Flavour is conserved at the tree level by all neutral current interactions mediated by the neutral gauge bosons Z and γ, but is violated by charged current weak interactions mediated by $W^{\pm}$.

- Flavor and/or CP violating processes are a traditional window for new physics and the studies are complementary to new particle searches in collider physics.

- Of course, flavour changing neutral current (FCNC) in quark sector is explained in terms of GIM mechanism and CKM matrix.

Flavour violation in leptonic sector

- In charged leptonic sector no FCNC has been observed till now.

- In studying muon decays, it was noted that $\mu \rightarrow e\,\gamma$ and $\mu \rightarrow 3e$ do not occur even though they are allowed by all known conservation laws.
  → explained by introducing 2 new quantum numbers, L_e and L_μ (the electron and muon lepton numbers) which are conserved in all interactions.

- When τ was discovered, the same pattern is repeated: the decays $\tau \rightarrow \mu(e)\,\gamma$ or $\tau \rightarrow 3\mu$ (e) do not occur ➔ hence 3rd lepton number L_τ introduced.

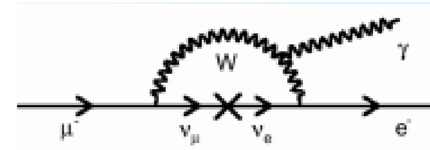
- The observation of neutrino oscillations indicates that the conservation of L_e, L_μ and L_τ are not exact ➔essentially, violation of neutral lepton flavour no.
  ➔ first indication of beyond SM physics. PhysRevLett.81 (1998) 1562

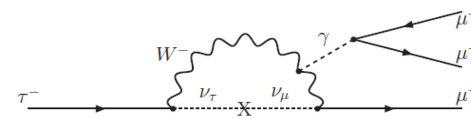
- ν-oscillations arise due to neutrino masses and mixings ➔ any ν-mass model will predict non-zero values for charged lepton flavour violating (LFV) decays.

- Charged LVF can actually occur in several modes: leptonic decays, radiative decays, semi-leptonic decays, and conversion.

Charged lepton flavour violation

- If ν-masses arise through the same mechanism as charged lepton masses do in SM, then charged LFV rates are very small:
  Br.($\mu \rightarrow e\,\gamma$) ~ 10^{-54} , Br.($\tau \rightarrow \mu\,\gamma$) ~ 10^{-40}
  while due to additional diagrams Br.($\tau \rightarrow 3\mu$) = 10^{-14}





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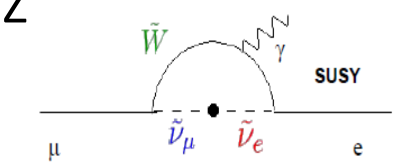
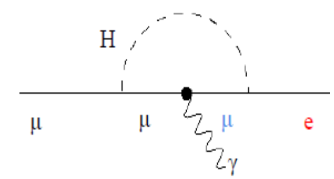
- Several BSM scenarios potentially increase this rate: RPV SUSY, Z` Lepto-quarks, Higgs, extra-dimension, GUT, Majorana-ν, ...



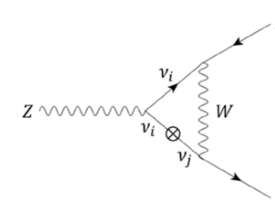
- Charged lepton flavour violation can also occur in decays of Higgs and Z.

- In pre-LHC era study of LFV via virtual Higgs constrained Br.(H→ μ τ), which still holds.



- Searches have been performed in CMS with LHC Run1, Run2 data in direct decays of Z → e μ, H → μ τ, and heavy ν, etc.

  PAS-EXO-13-005., PAS-HIG-16-005, CMS-PAS-HIG-17-001, EXO-16-045



Br.($Z \rightarrow e\mu$) < 7.3×10^{-7}, Br.($H \rightarrow e\mu$) < 0.035%, Br.($H \rightarrow e\tau$) < 0.61%, Br.($H \rightarrow \mu\tau$) < 0.25%

95% CL upper limits

Rekindled interest in LFV

- ***Talk of the town***: recently various anomalies in semi-leptonic decays of B-meson have been observed wrt predictions of SM:
  a) R_D , R_{D*} by Babar, Belle and LHCb experiments
  b) R_K , R_{K*} by LHCb

PRD 88 072012 (2013)
PRD 92 072014 (2015)
PRL 115, 11803 (2015)

- If these anomalies are indications of NP then it is expected that the corresponding particles couple preferentially to 2nd and 3rd generation fermions.

- **Discovery of charged LFV will provide smoking gun signal for new physics** and also provide vital clues in constructing ν-mass models. eg. Seesaw mechanism of different types or Left-Right symmetric models, ….

- Currently best experimental limit (by Belle collaboration) at 90% CL
  $Br.(\tau \rightarrow 3\mu) < 2.1 * 10^{-8}$

PLB 687(2010) 139

- **At LHC, $\tau \rightarrow 3\mu$ process has the cleanest signature ➔ being searched extensively.**

- On-going CMS analysis with Run2 data (√s=13 TeV, L=20/fb) using $W \rightarrow \tau\nu$ decays.

Search for $\tau \rightarrow 3\mu$ in CMS at HL-LHC

- Large integrated luminosity is needed for discovery of $\tau \rightarrow 3\mu$ at LHC.
  $\rightarrow$ possible with only high luminosity LHC operation (~10^{15} τ s will be produced)
  ➔ CMS experiment has the potential to search for the process with proposed Phase2 upgraded detector. **CMS TDR-17-003**

- CMS Phase2 study utilize the main source τ in LHC: $D_s \rightarrow \tau\, \nu_\tau$ decays (Br = 0.055) in minimum bias events.
  Better reconstruction software will actually improve the anticipated sensitivity.

meson	quark composition	mass (GeV)	relative tau yield
D_s	$c\bar{s}$	1.97	72%
D^+	$c\bar{d}$	1.87	3%
B^+	$\bar{b}u$	5.28	11%
B^0	$\bar{b}d$	5.28	11%
B_s	$\bar{b}s$	5.37	3%
W		80.4	10^{-4}
Z		91.2	2×10^{-5}

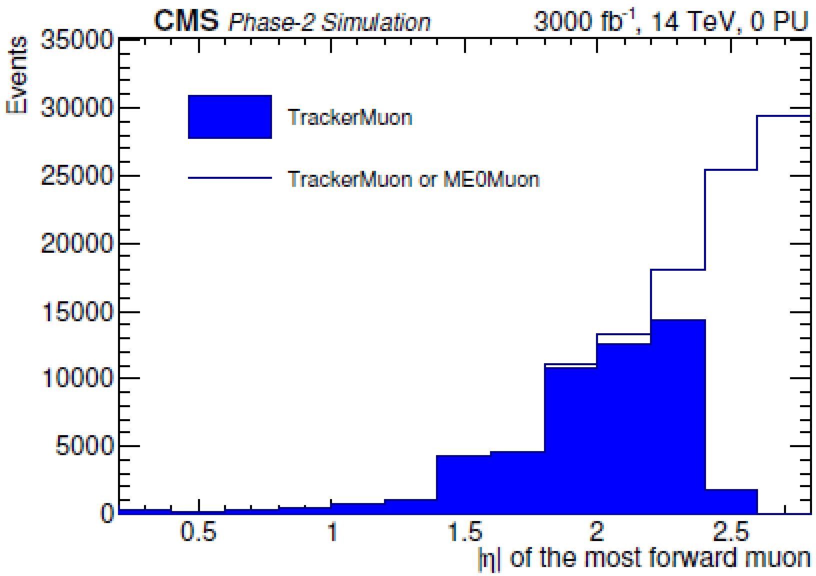
Pythia event generator used for simulation study:
- Total min. bias $\sigma = 4.8 * 10^8$ pb
- Ds filter efficiency ~ 3%
- 2μ filter eff. ~ 20%

- Problem: Signal is very low p_T muons, highly boosted in forward region !
  $\rightarrow$only ~ 1.3% of the events have all 3 muons with $p_T > 2.5$ GeV

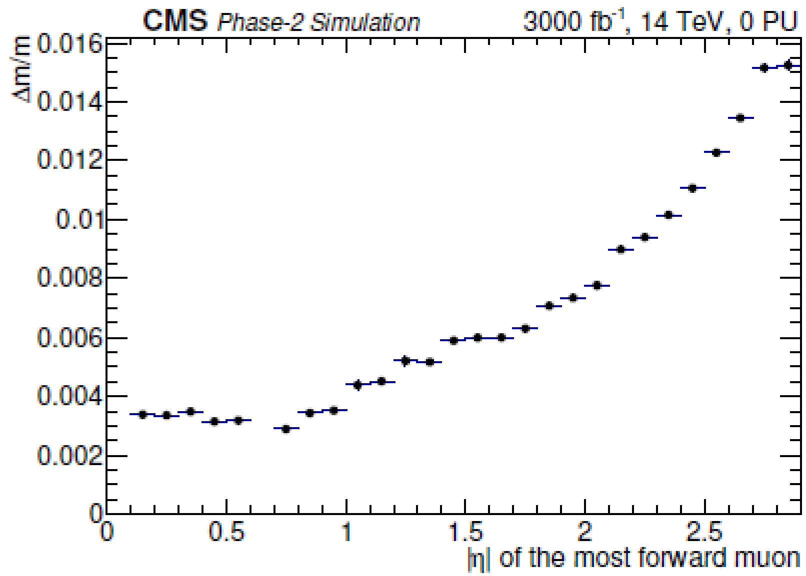
- Require very good low energy muon identification and measurement at high $|\eta|$.

Kinematics of signal muons

Psuedo-rapidity of most forward μ at generator level



Average trimuon invariant mass resolution as a fn. of psuedo-rapidity of most forward μ



Event characteristics:

- very low p_T muons
- no missing energy in τ decay
- 3 muons with invariant mass $m_{3\mu} \sim m_\tau$
- Displaced vertex

Searches with τ from W, Z decays have large acceptance for high p_T muons in central part of the detectors;
Trigger is also not an issue.
But relatively less statistics for signal

➔ NO striking experimental signature to discriminate against background

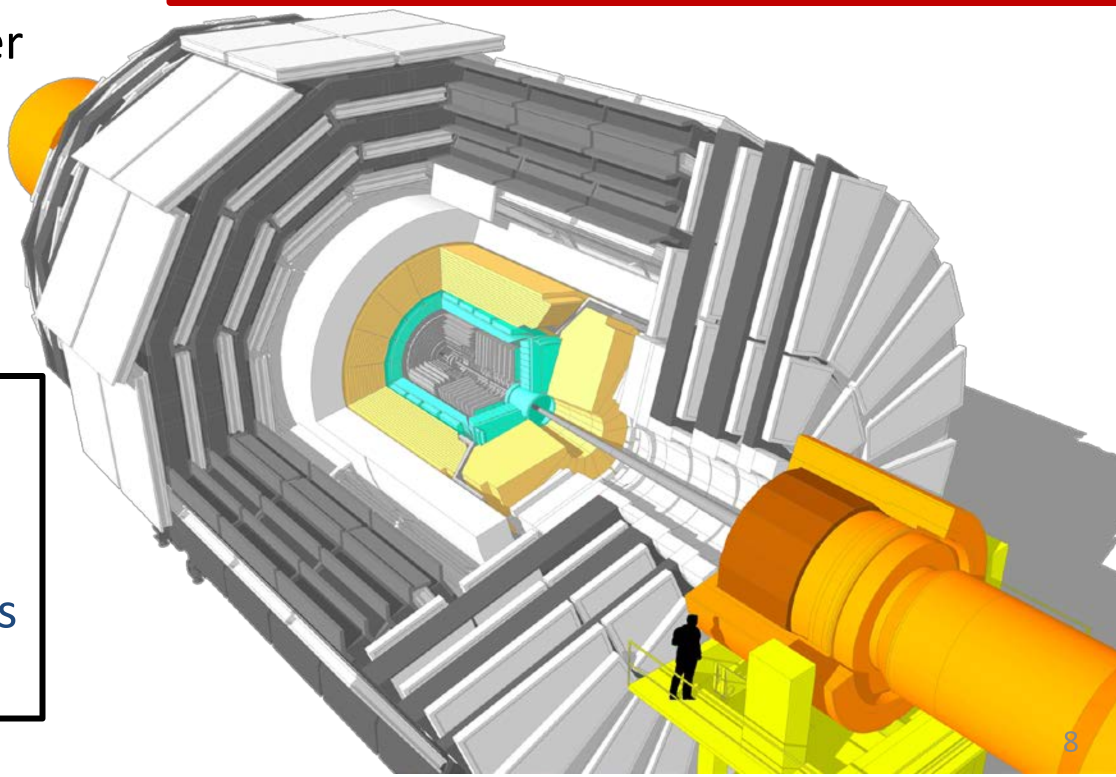
Planned upgrades of CMS for HL-LHC phase

- New Tracker with extended coverage to $\eta \simeq 3.8$
- New Endcap Calorimeters
- Barrel EM calorimeter + HCAL
- **Muon system extended**
- Timing detector
- Trigger/HLT/DAQ with enhanced capabilities :
  → Track information in Trigger
  →Trigger latency 12.5 µs

Muon system

- New electronics
- better coverage for $1.5 < |\eta| < 2.4$
- Muon tagging $2.4 < |\eta| < 2.82$

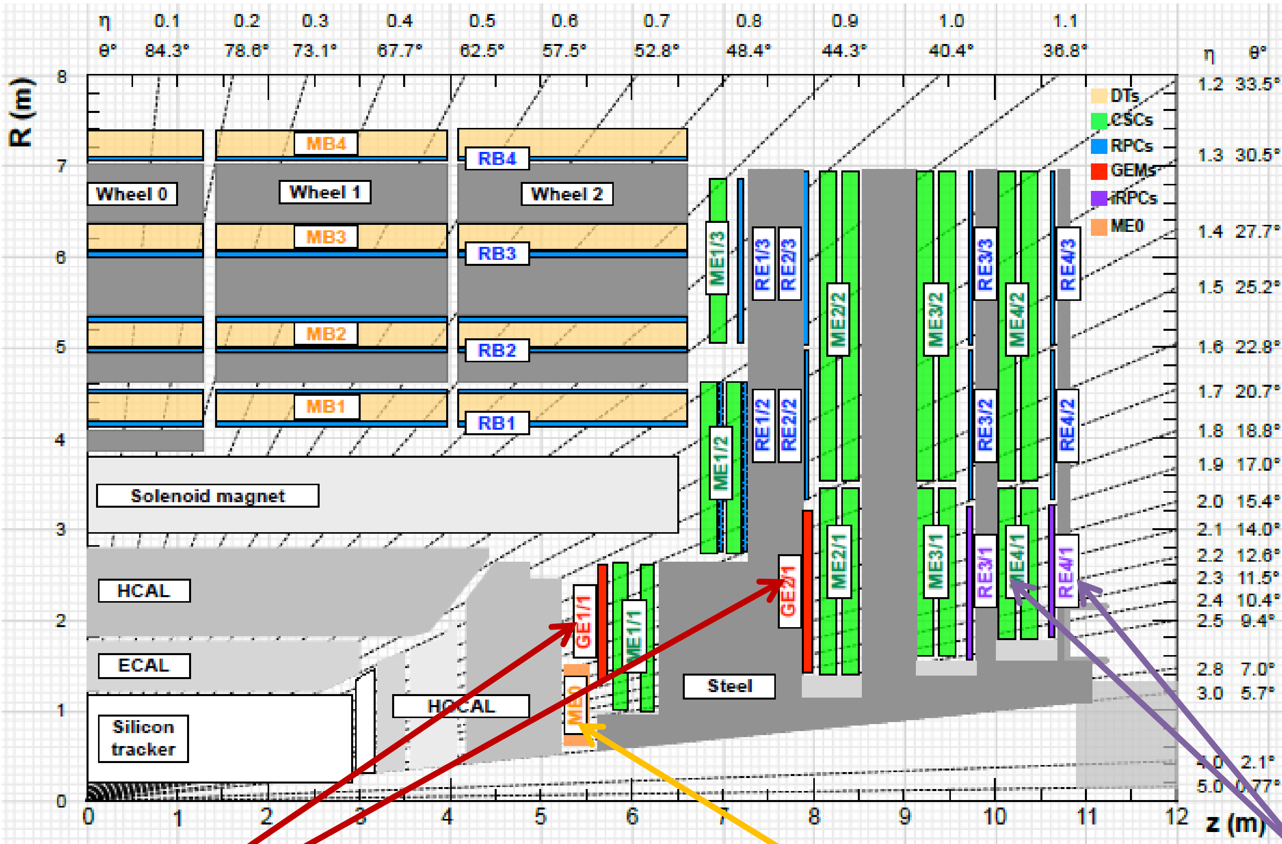
→ **fiducial acceptance increases for processes with multi-lepton final state , eg., $\tau \rightarrow 3\mu$ by X 2**



Main issues in forward region:
- higher background
- weaker magnetic field : field lines are parallel to tracks

→ moderate p_T resolution

Extension of muon system



Additional detectors in forward region increase redundancy and reduces ambiguity in track reconstruction.

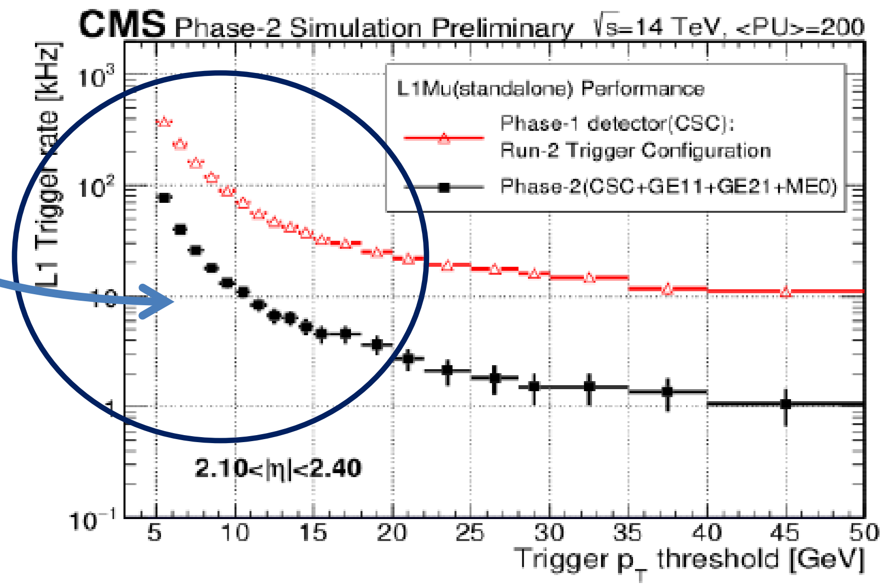
Improved RPC (iRPC) to complete the coverage of endcap in forward region up to |η|< 2.4.
→ reconstruction within one muon station due to GEM-CSC tandem.

3 layers of GEM detectors to enhance sensitivity of forward region : 1.6<|η|<2.4

6 layers of GEM detectors for trigger in very forward region <|η|<2.8

Triggering with forward muons

Reduction in trigger rate in upgraded detector



- **Low p_T threshold for level1 trigger, suitable for this search, is affordable**
- 2 categories with efficiencies: 80% & 50%
  - a) one GEM-CSC segment in the first muon endcap station ($\delta p_T / p_T < 20\%$) + 2 tracker muons ($\delta p_T / p_T < 3\%$)
  - b) One tracker muon + 2 segments in first muon endcap station, including ME0 $|\eta| = 2.4 - 2.8$ ($\delta p_T / p_T \sim 40\%$)

- Also demand invariant mass $m_{3\mu} < 3$ GeV

Analysis

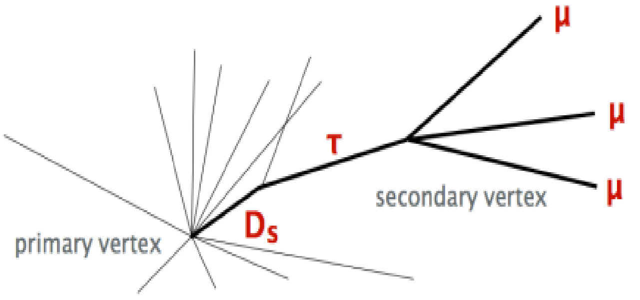
- Signal: $D_s \rightarrow \tau + X$ (same approach as LHCb , for the time being)

- Background:

90% is due to B meson events: $B \rightarrow \mu\nu$ D +X , followed by $D \rightarrow \mu\nu$ + X', additional μ either from π/K decay in flight or accidental alignment of charged hadron track with first muon station.

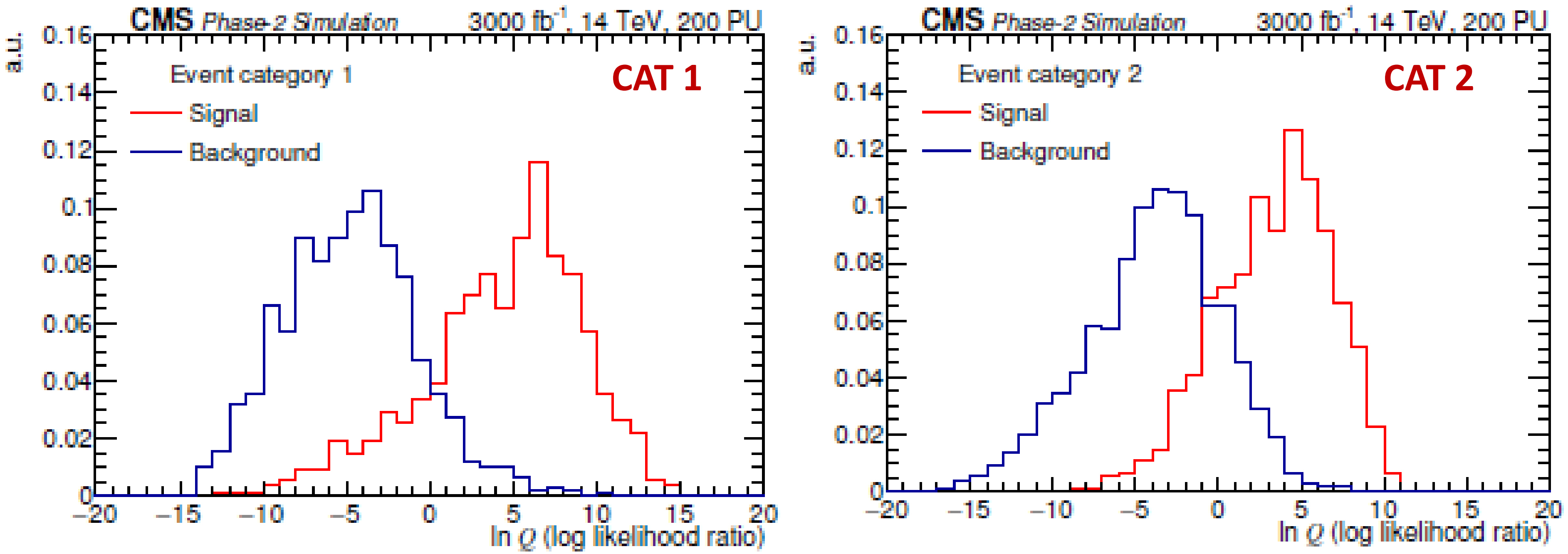
- Strategy: Discriminant (Q) constructed as a product of ratios of 1-d signal & background probability density functions for multiple variables, eg.,

➢ χ^2/dof of tri-muon vertex
➢ Transverse displacement of of trimuon vertex wrt primary interaction vertex
➢ Minimum ΔR distance among three pairs of muons in the event candidate.
➢ Angle between τ (trimuon) direction and the line connecting the primary interaction vertex and the trimuon vertex.
➢ Highest and lowest momenta among 3μ
➢ Number of b-jets, etc. …



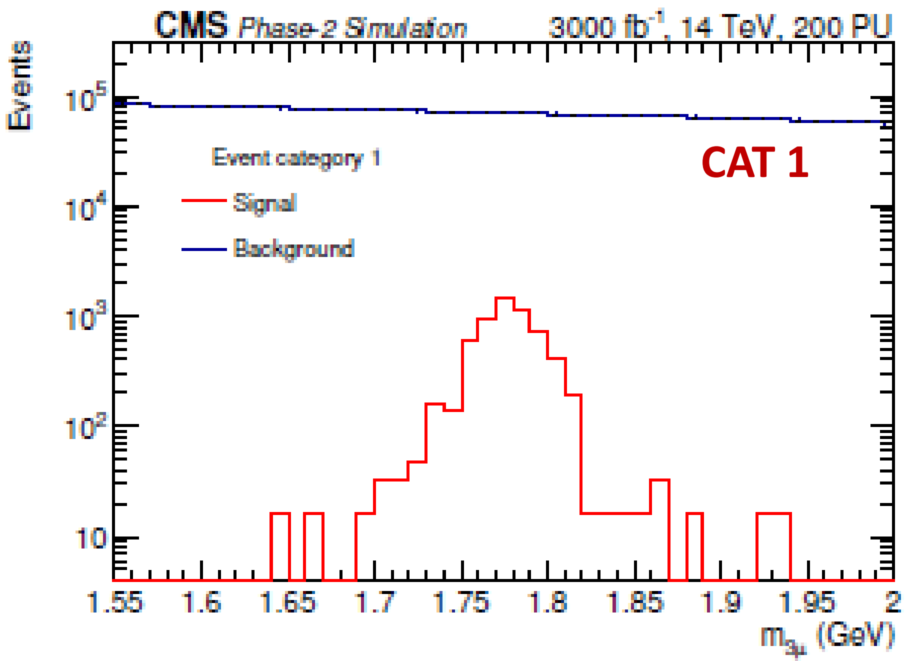
→ Correlations among variables ignored

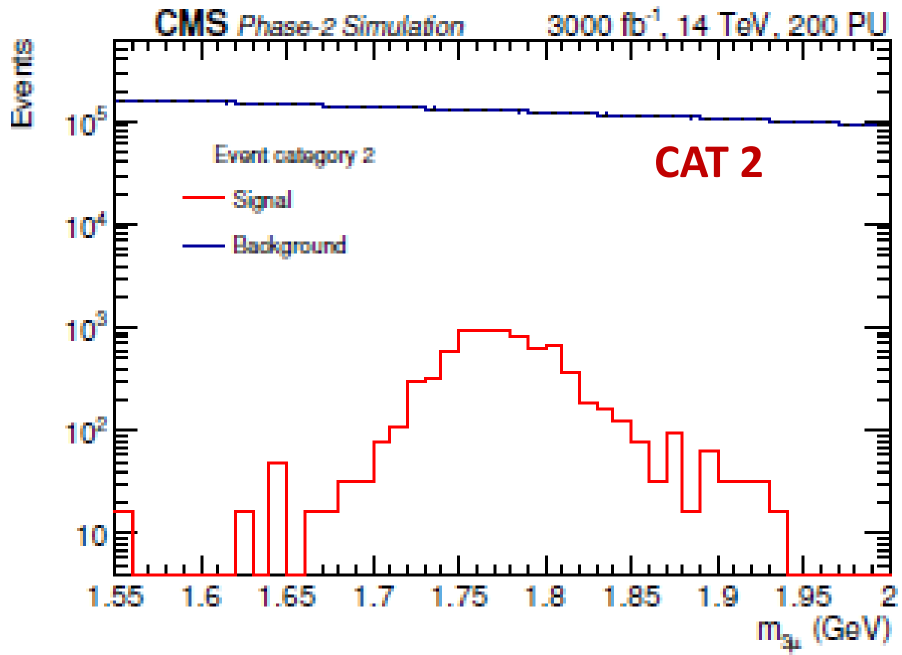
Distribution of discriminator Q



- Select events with ln Q > 6 (5) for category 1(2).
- Efficiency in each category : 30%

Invariant mass distribution





- No tail in peak distribution: muons being picked up correctly
- Continuum background estimated from side bands
- Fit signal peak to determine # of signal event or upper limit on Ns
- Systematic uncertainty of bkg. Shape does not affect signal Br.

- Normalize final event yield from data to determine branching ratio by estimating $D_s \rightarrow \phi\pi \rightarrow \mu\mu\pi$ from data
- Production of D mesons estimated with 10% systematic uncertainty.

Expected event yield

- Assume for signal Br.($\tau \rightarrow 3\mu$) = $2*10^{-8}$
- Consider invariant mass region 1.55< (3μ) <2.00 GeV
- Integrated luminosity = 3000/fb

	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}	

Conclusion

- For high luminosity LHC operation CMS experiment plans to search extensively for $\tau \rightarrow 3\ \mu$ process.

- Phase2 upgrade plan of CMS detector includes extension of the coverage of the muon system to higher $|\eta|$ region beyond 2.4 which is very relevant for the search.

➔ highly detrimental for searches like $\tau \rightarrow 3\ \mu$

➔ due to effective increase in gain via luminosity

- **Encouraging results obtained already with preliminary studies.**

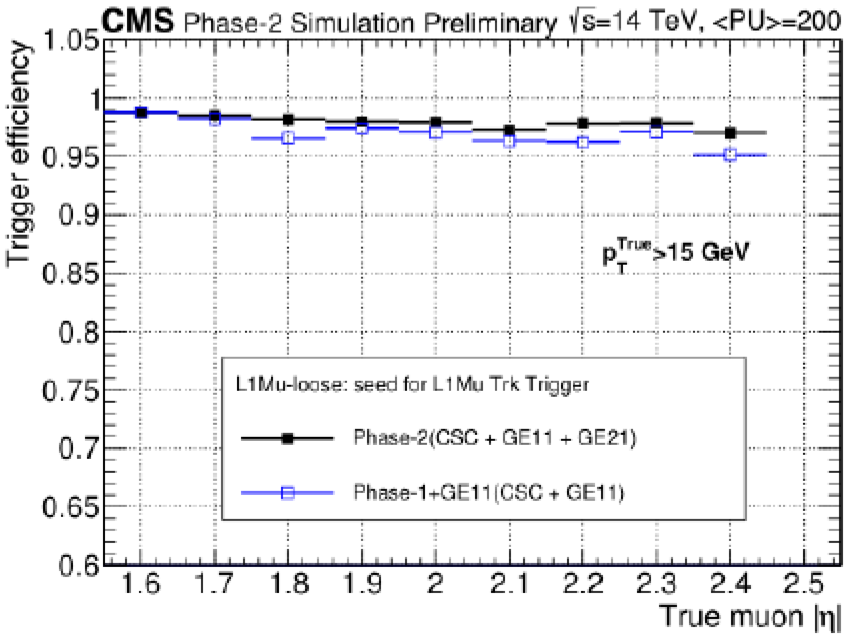
  Expected result with L = 3000/fb at 14 TeV ,
- exclusion limit at 90% CL: Br.($\tau \rightarrow 3\ \mu$) = $3.7*10^{-8}$
- 5σ observation sensitivity for Br.($\tau \rightarrow 3\ \mu$) up to = $1.1*10^{-8}$

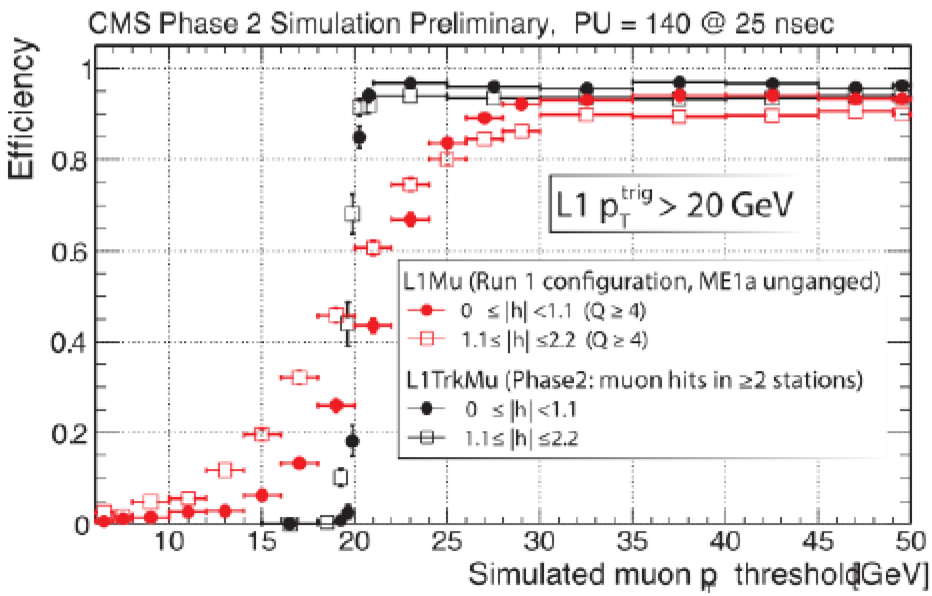
- **Projections will further improve with development of forward muon reconstruction software in near future.**

Stay tuned!

backup

Improvement in momentum resolution





High efficiency over full trigger coverage

Combination with track trigger → improvemnet in momentum resoution

Low pile up at 14 TeV

Extension of muon accetance
Muon id till |h|> 2.8
Improvement in pT resolution ad reduction in rate due to GE1/1