Search for the $\tau \to 3\mu$ decay at the CMS experiment at LHC

WIN2019
The 27th International Workshop on Weak Interactions and Neutrinos
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Rosamaria Venditti
On behalf of the CMS Collaboration

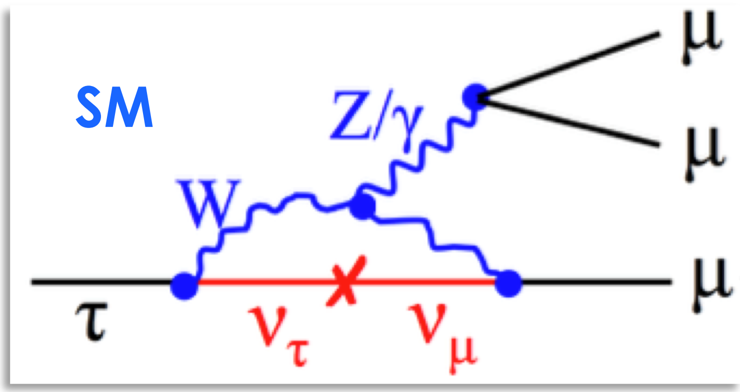
Motivations

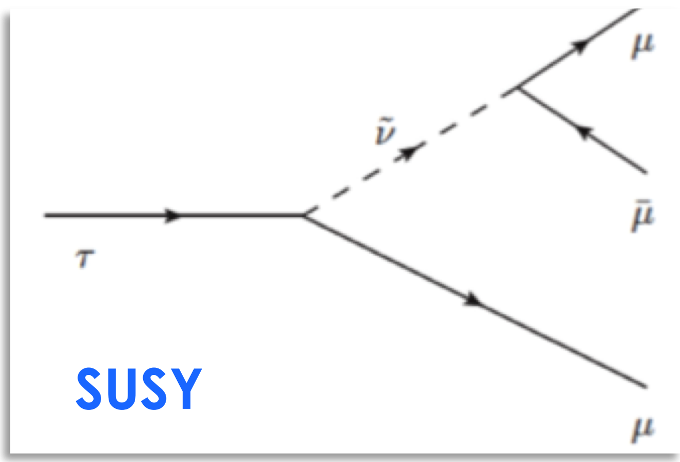
Why LFV

- The lepton flavor conservation is not protected by any particular symmetry in Nature.
- Charged Lepton flavor violation (LFV) is allowed in the Standard Model including the neutrino oscillation, with extremely small BR
  - E.g. $B(\tau \to 3\mu) \sim O(10^{-14})$
- Some extensions of the SM (SUSY, 2HDM) allow for LFV decays with sizeable branching fractions $\sim \mathcal{O}(10^{-8})$ that can be probed with the present day esperiments

Why $\tau \to 3\mu$

- 3-μ decay has very clean final state topology
- BR enahnced in some BSM models
- *$\tau \to 3\mu$ observation is a powerful tool to probe the NP*





State of the art

@ e-e+ colliders

BaBar: $B(\tau \rightarrow 3\mu) < 3.3 \times 10^{-8}$ at 90% CL

Belle: $B(\tau \rightarrow 3\mu) < 2.1 \times 10^{-8}$ at 90% CL

→ Best limit!!

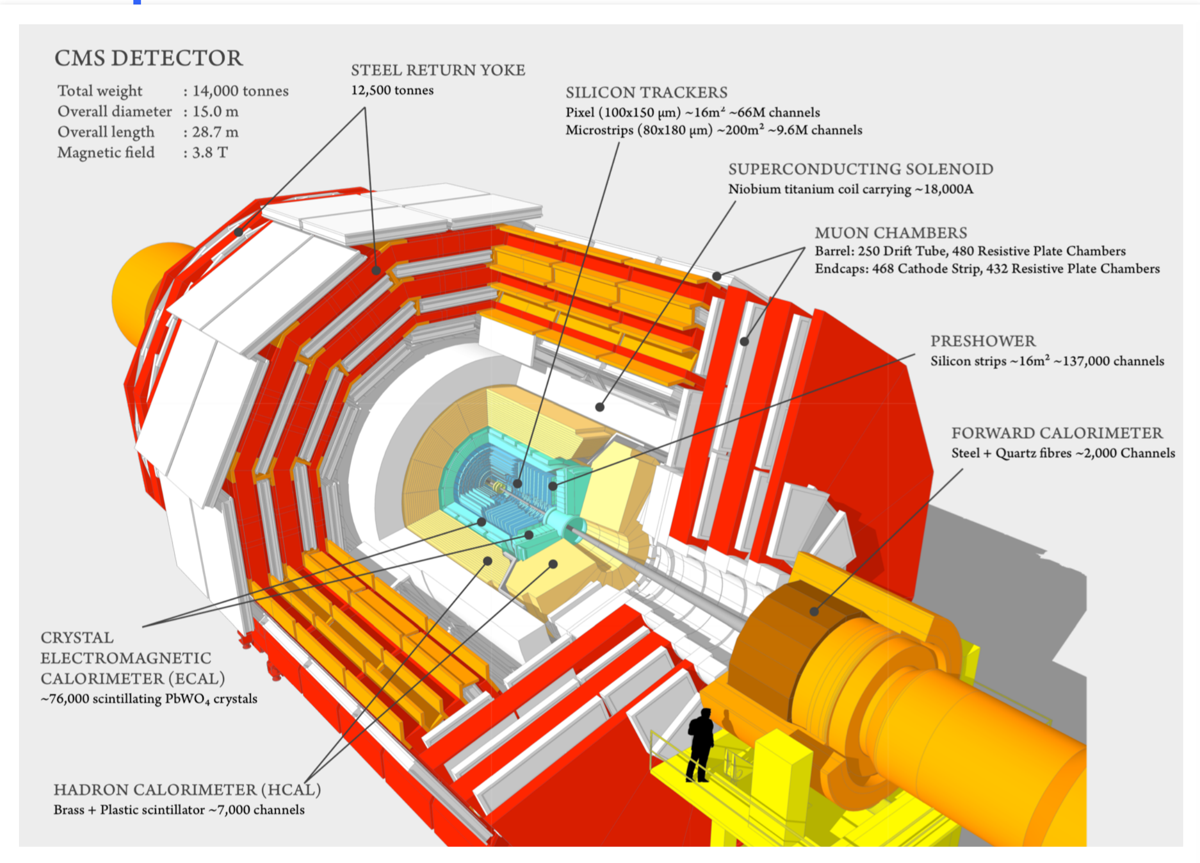
→ update expected from Belle-II

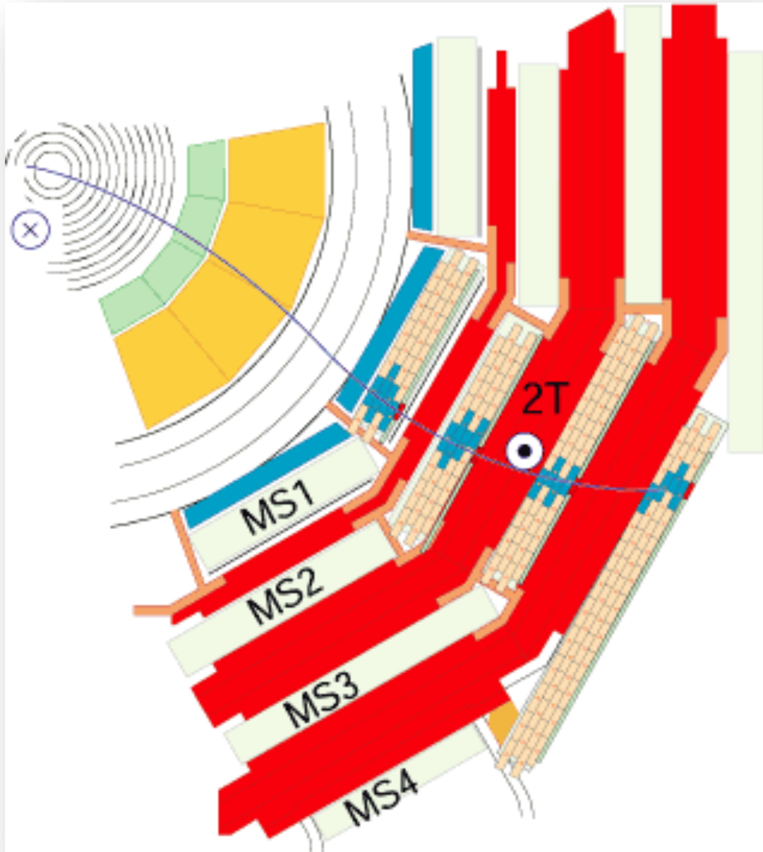
- LHC is a τ *factory!* Proton-proton collisions are a prolific source of τ-leptons
  - the expected inclusive production cross section at LHC is about 2×10^{11} fb

State of the art (@ LHC)

- LHCb : $BR(\tau \longrightarrow 3\mu) < 4.6 \times 10^{-8}$ at 90% CL [https://doi.org/ 10.1007/JHEP02(2015)121]
- ATLAS : $BR(\tau \longrightarrow 3\mu) < 3.8 \times 10^{-7}$ at 90% CL [arXiv:1601.03567]
- **CMS: First public results this year → Topic of this talk** **CMS BPH-17-004**

The Compact **Muon** Solenoid Experiment at LHC





- Event reconstruction based on **the particle-flow**
- Exploits information from all the CMS subdetectors
- Identify and reconstruct individual particle candidates in the event

- The Muon reconstruction combines information from the tracker and the muon system
- **Detector Acceptance set by :**
  - **Instrumented area→abs(η)<2.4**
  - **Muon Reco → p>2.5 GeV**

$\tau \to 3\mu$ searches at CMS in 2016 data

- **2016 Data analyzed (pp @ 13 TeV)**
  - integrated luminosity of 33 fb^{-1}

Process	Number of τ leptons (33 fb^{-1})
$pp \to c\,\bar{c} + \ldots$	
$D \to \tau\nu$	4.0×10^{12} (95% D_s, 5% $D^{\pm}$)
$pp \to b\bar{b} + \ldots$	
$B \to \tau\nu + \ldots$	1.5×10^{12} (44% $B^{\pm}$, 45% B^0, 11% B_s^0, 0% $B_c^{\pm}$)
$B \to D(\tau\nu) + \ldots$	6.3×10^{11} (98% D_s, 2% $D^{\pm}$)

- **Two channels:**
  - Heavy Flavour (**HF**) ($D \longrightarrow \tau\nu$, $B \longrightarrow \tau\nu\ldots$, $B \longrightarrow D(\tau\nu)\ldots$)
  - **W** boson production ($W \longrightarrow \tau\nu$)

- **HF channel:** $\mathcal{O}(10^{12})$ produced τ leptons
  - $\sim \mathbf{10^4}$ $\boldsymbol{\tau \longrightarrow 3\mu}$ *events* (assuming upper limit by Belle)
  - $\sim \mathbf{10^2}$ $\boldsymbol{\tau \longrightarrow 3\mu}$ *events* in the CMS detector acceptance
  - Challenging →low transverse muon momenta
  - Analysis freezed and Approved

- **W channel:** $\mathcal{O}(10^9)$ produced τ leptons
  - $\sim\mathbf{10}$ $\boldsymbol{\tau \longrightarrow 3\mu}$ *events* (assuming upper limit by Belle exp.)
  - Clean final state High-pT muons and large missing energy
  - Analysis in the final step of the review

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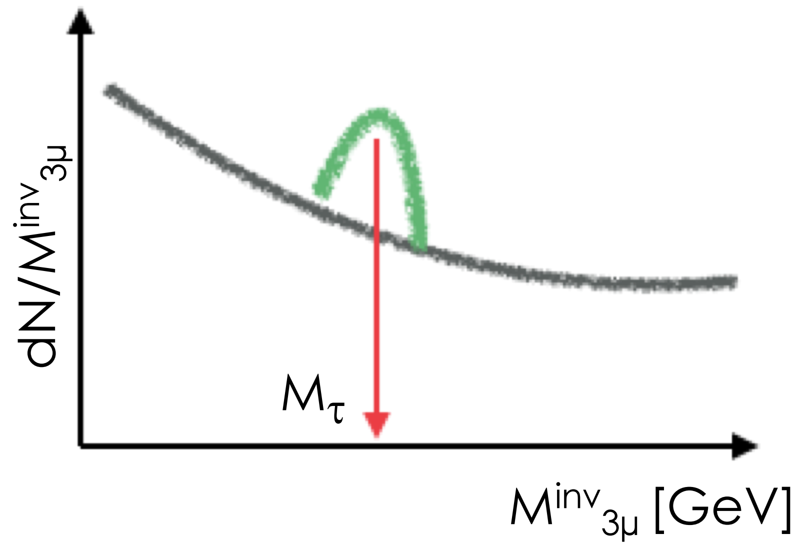
$\tau \rightarrow 3\mu$ Search Strategy (HF)

- Search for a bump at nominal τ mass peak in the invariant mass distribution of the 3μ-system
  - We expect a smoothly distributed background.
- The production rate of D and B mesons is obtained from data by measuring the event rate coming from $D_s \rightarrow \Phi\pi \rightarrow \mu\mu\pi$ decays.



- MVA discriminator for signal/background rejection
- Event categorization to improve the search sensitivity. Events are binned in
  - 3μ-system mass resolution
  - MVA discriminator
- The $\tau \rightarrow 3\mu$ signal is extracted by a simultaneous maximum likelihood fit of the thus-formed six unbinned mass distributions.

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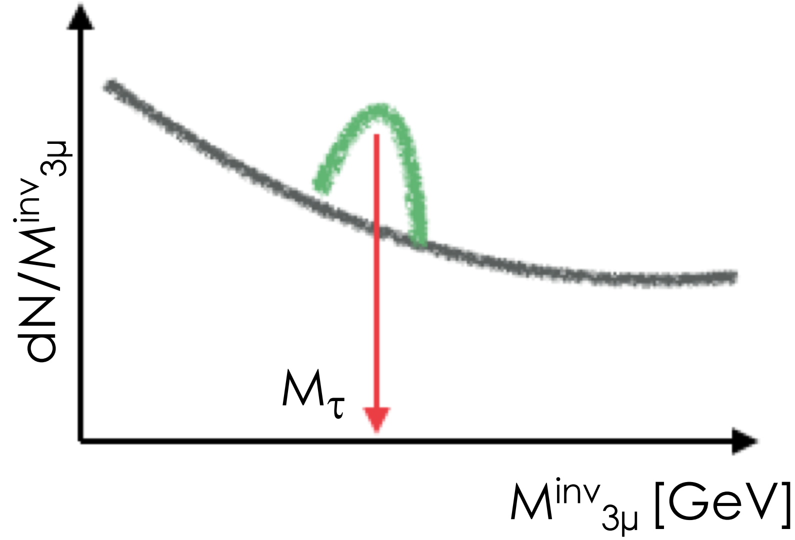

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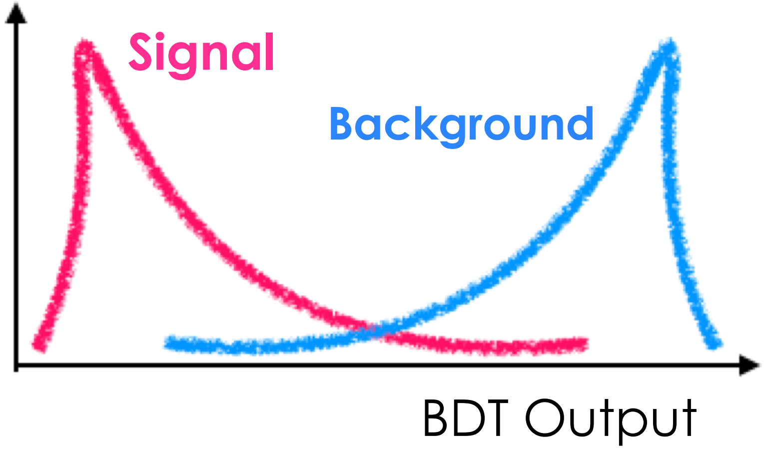
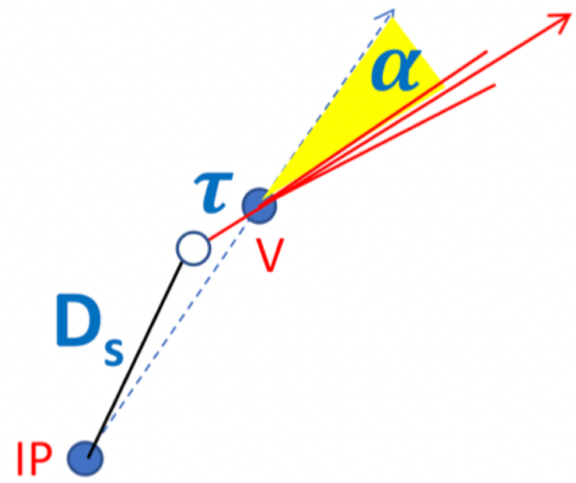


HF Channel: Event selections

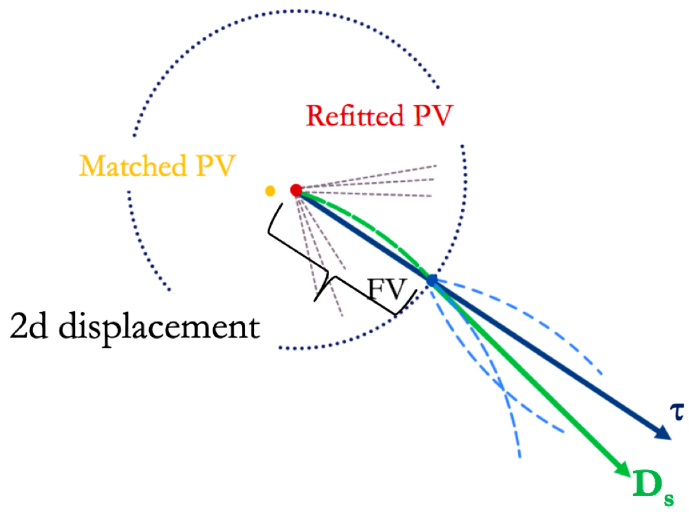
Online Selections

- **L1: 3 muons or 2 muons with kin requirement**
- **Dedicated High Level Trigger**
  - two collimated muon tracks with common vertex and $p_T > 3$ GeV
  - one track compatible with the 2μ vertex and $p_T > 1.2$ GeV
  - invariant mass (2μ+trk) in the range 1.60-2.02 GeV
  - vertex(2μ+trk) displaced from beam-spot by >2 sigma



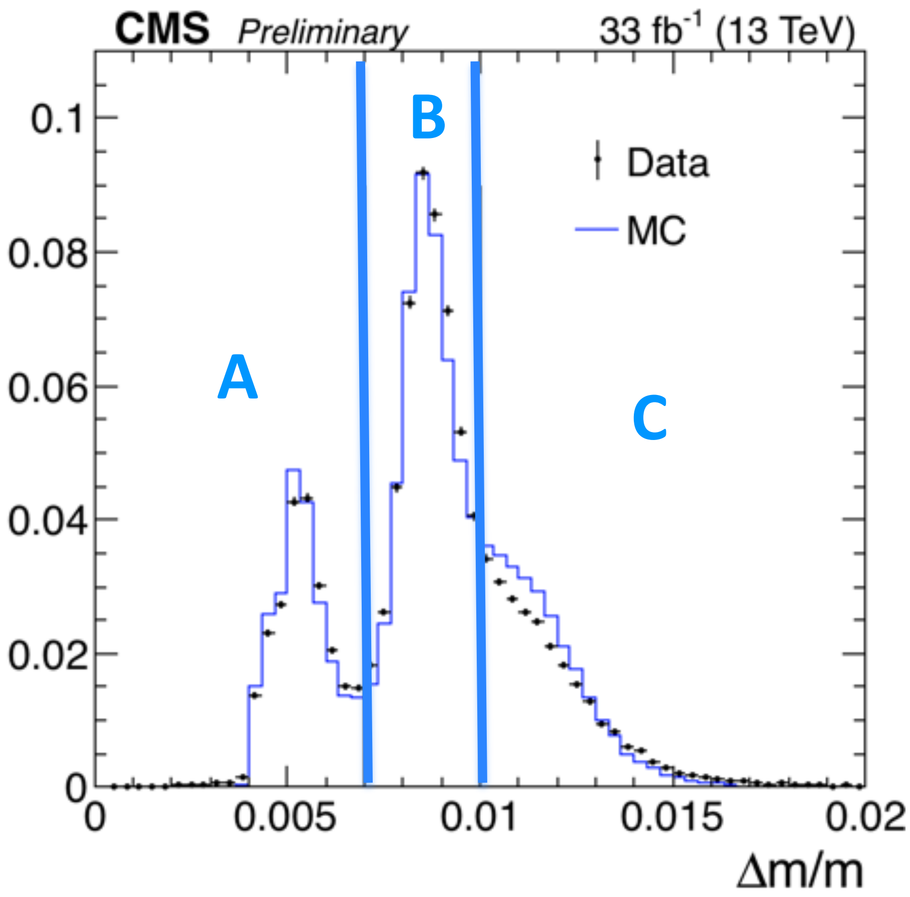
Offline Selections

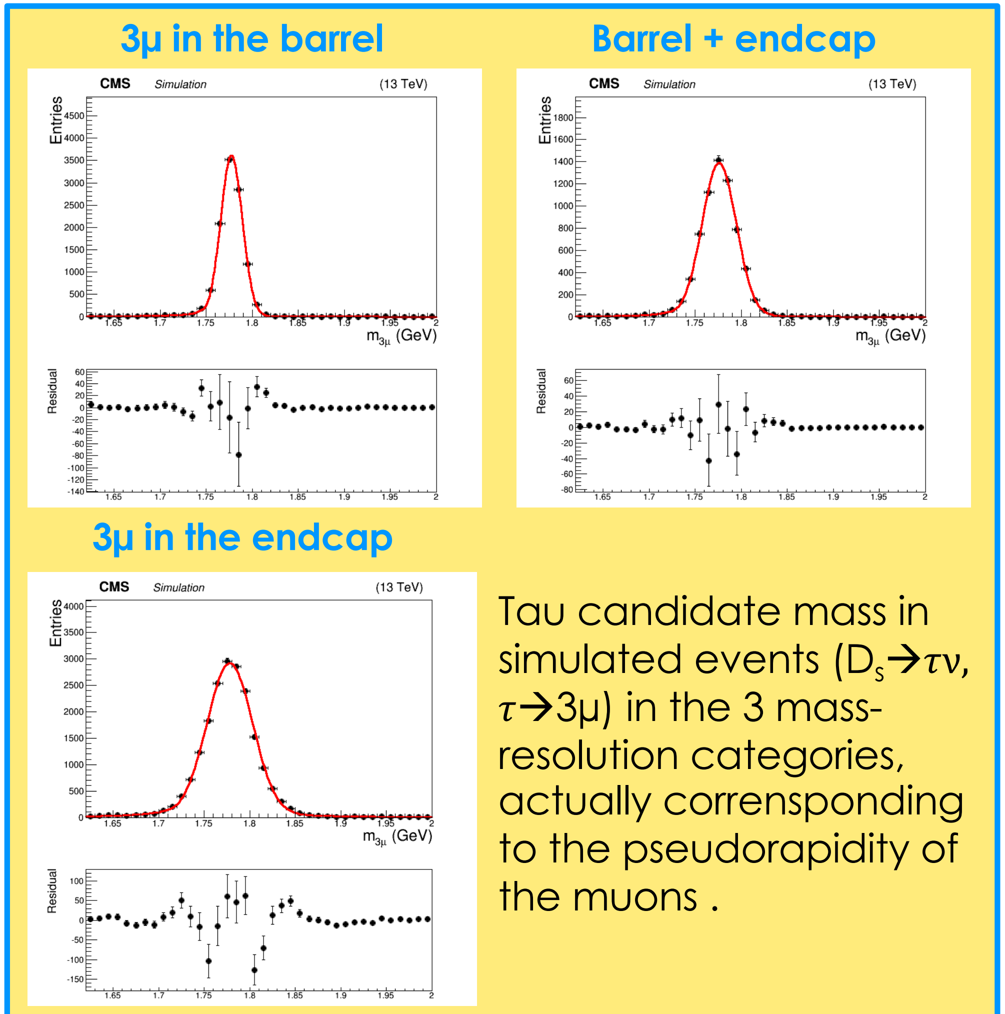
- <u>Muon Selections</u>
  - at least 3μ w/ $p_T > 2$ GeV per event, identified with Global algorithm
  - dR(2μ) < 0.8 & dz(2μ) < 0.5 cm
  - custom track-based isolation applied
- <u>3μ system selections</u>
  - charge = ±1
  - fiducial invariant mass window: [1.62-2.00] GeV
  - High quality secondary vertex
  - primary vertex refit removing the 3μ tracks
  - Veto on muon pairs with inv. mass close to Φ(1020)



Mass resolution of the 3μ system

- The uncertainty on the mass of 3μ system varies since the muon momentum resolution depends strongly on the muon pseudorapidity
- The method has been studied and calibrated in the H→ZZ→4μ search
- Event categorization based on the resolution of the 3μ system mass

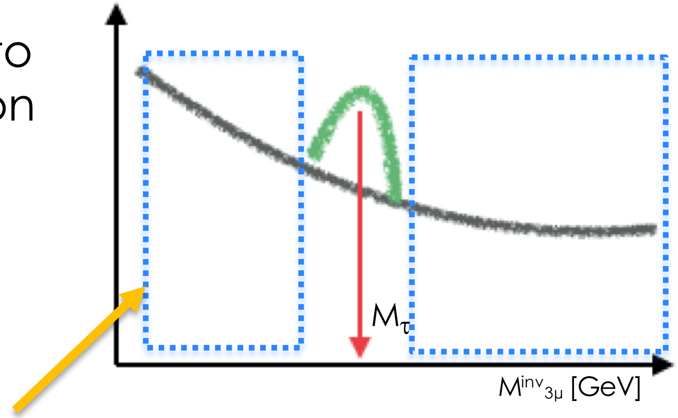




Tau candidate mass in simulated events ($D_s \to \tau\nu$, $\tau \to 3\mu$) in the 3 mass-resolution categories, actually corresponding to the pseudorapidity of the muons .

Background to signal discrimination

- Main source of background is the dacay of B mesons into resonance that decays in muon pairs, with the third muon coming from mis-identified pions or kaons
- <u>**Multivariate approach to discriminate signal to background**</u>→A BDT is trained
  – Signal: MC with properly mixed the D and B meson
  – Background from data using the 3μ-mass sidebands.

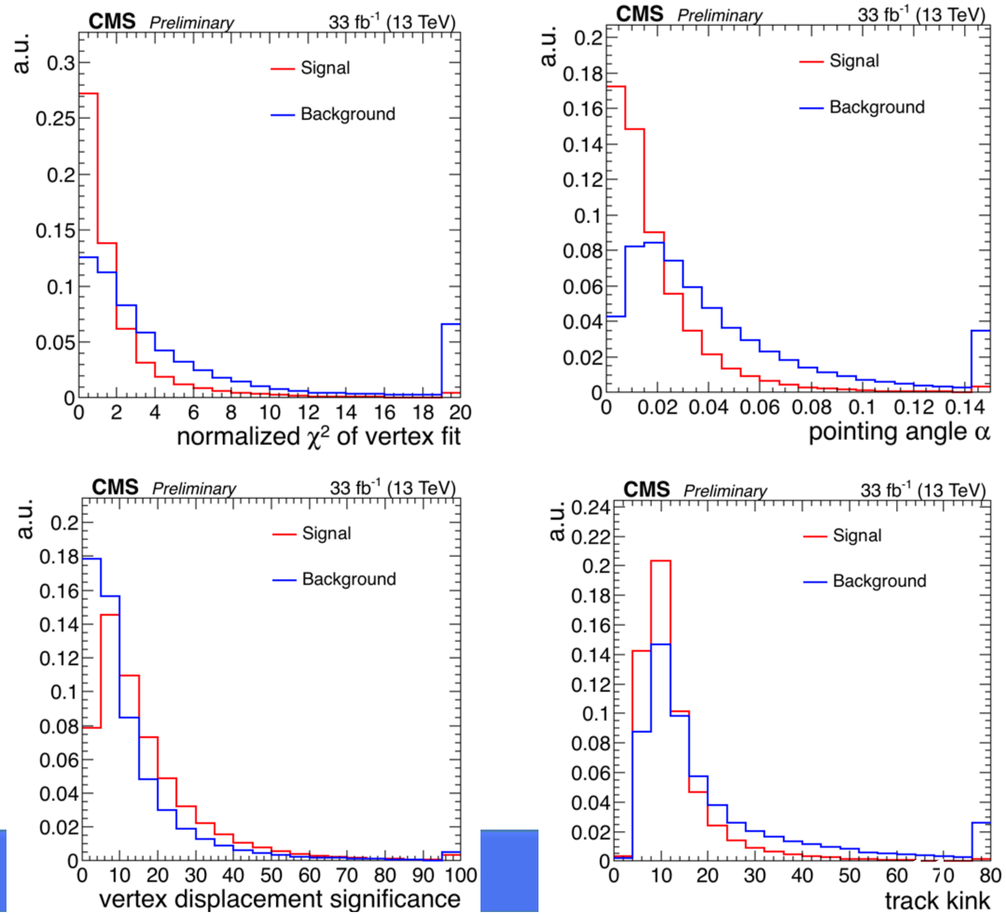


BDT Input variables

<u>3μ system variables</u>
- vertex fit chi²/ndof
- vertex displacement significance w.r.t PV
- angle between V(3μ)-PV and 3μ vector
- additional track closest distance to V(3μ)

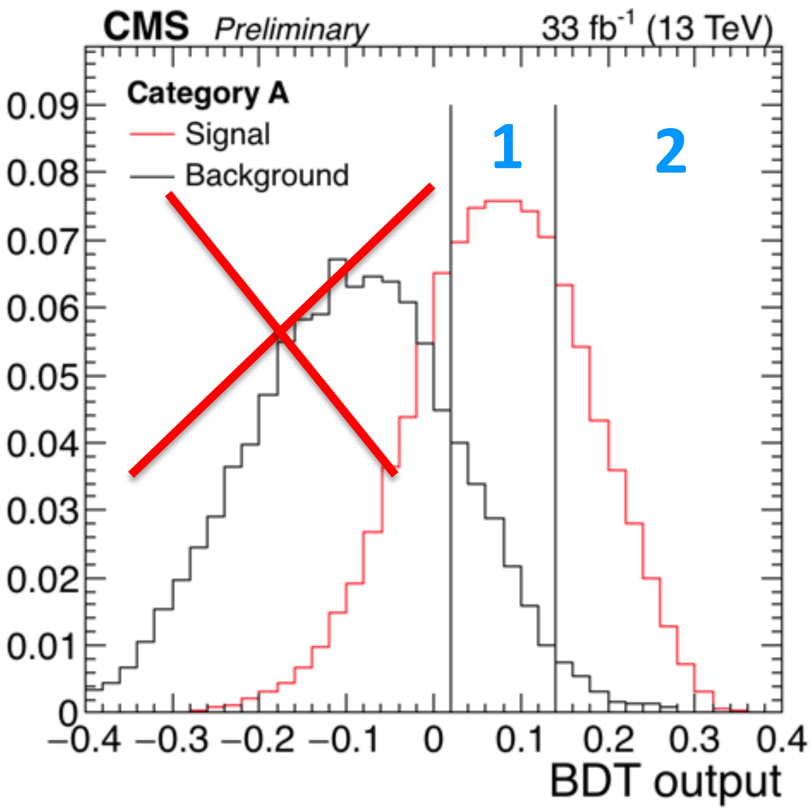
<u>Additional muon variables</u>
- Inner track "Kink"
- track and STA muon position matching chi²
- track and muon segment compatibility
- Relative isolation
- Transverse I.P. significance (*)
- muon momentum

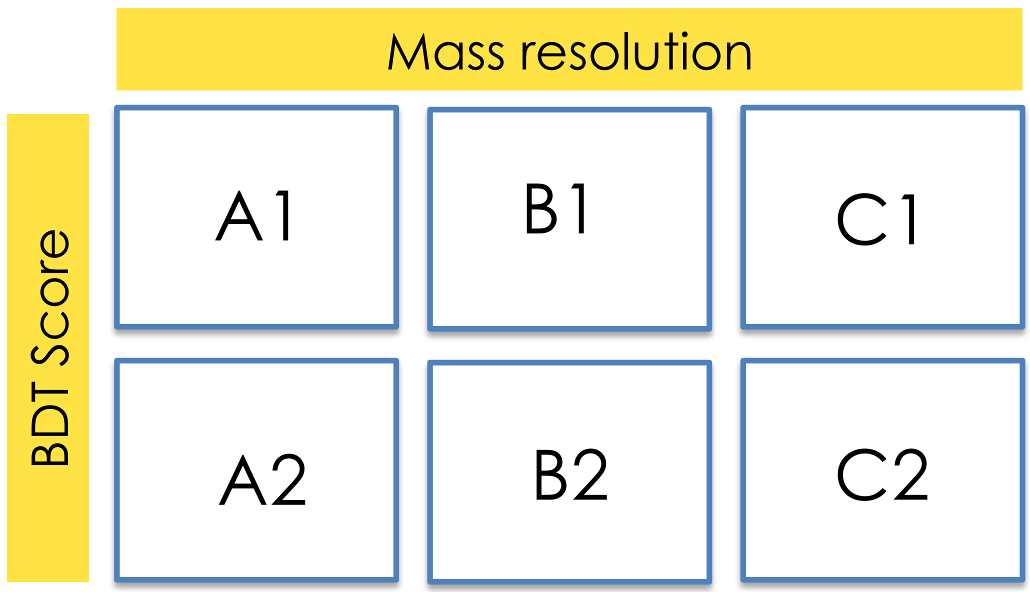
(*the smallest of the three)



Event categorization

- Additional categories introduced according to the BDT score.
- Keep the two categories with best signal-to-background purities, while excluding the background like phase space region.
- Category boundaries defined with a procedure based on the optimization of the signal significance simoultaneoulsy in all categories





Signal normalization – D_s channel

- The expected $\tau \to 3\mu$ signal event yield associated with D_s can be written as:

$$N_{\mathrm{sig(D)}} = \mathcal{L}\sigma(\mathrm{pp} \to \mathrm{D_s})\ \mathcal{B}(\mathrm{D_s} \to \tau\nu)\ \mathcal{B}(\tau \to 3\mu)\ \mathcal{A}_{3\mu(D)}\ \epsilon^{3\mu}_{\mathrm{reco}}\epsilon^{2\mu}_{\mathrm{trig(sig)}},$$

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Number of Ds. How to estimate?

BR from PDG

Acceptances and efficiencies from MC

Signal normalization – D_s channel

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Acceptances and efficiencies from MC

Estimate Ds → Φπ → μμπ events in data

$$\boxed{N} = \mathcal{L}\sigma(\mathrm{pp} \to \mathrm{D_s})\,\boxed{\mathcal{B}(\mathrm{D_s} \to \phi\pi \to \mu\mu\pi)}\,\boxed{\mathcal{A}_{2\mu\pi}\;\epsilon^{2\mu\pi}_{\mathrm{reco}}\;\epsilon^{2\mu}_{\mathrm{trig}(\mu\mu\pi)}},$$

Measured in data

BR from PDG

Acceptances and efficiencies from MC

Then we rewrite

$$N_{\mathrm{sig(D)}} = N\,\boxed{\frac{\mathcal{B}(\mathrm{D_s} \to \tau\nu)}{\mathcal{B}(\mathrm{D_s} \to \phi\pi \to \mu\mu\pi)}}\,\boxed{\frac{\mathcal{A}_{3\mu(D)}}{\mathcal{A}_{2\mu\pi}}\;\frac{\epsilon^{3\mu}_{\mathrm{reco}}}{\epsilon^{2\mu\pi}_{\mathrm{reco}}}\;\frac{\epsilon^{2\mu}_{\mathrm{trig,sig}}}{\epsilon^{2\mu}_{\mathrm{trig}(\mu\mu\pi)}}}\,\mathcal{B}(\tau \to 3\mu).$$

BR from PDG

MC

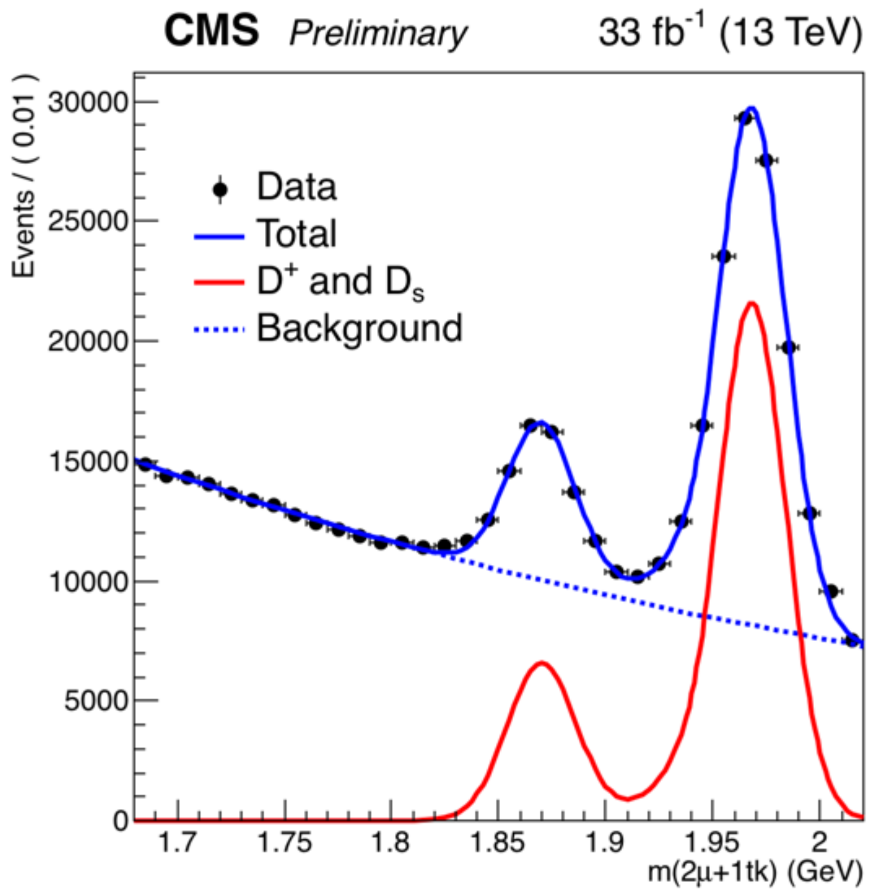
Signal normalization – D_s channel

- Number of produced Ds can be derived from data, by selecting events compatible with the **Ds→Φπ→μμπ**

- Same triggers and selections as in signal region excepts:
  - two opposite signs muons
  - di-muon invariant mass is in the range 1.00–1.04 GeV
  - 1 high quality track

- The number of Ds→Φπ →μμπ events, *N*, can be easily extracted from the area below the rightmost peak.

- Uncertainty computation
  - **10% statistics**
  - The ratio of the number of Ds →Φπ → μμπ events to the number of 3μ events in the sideband in seven different run periods has been measured
  - Max variations not exceeding 10%



Signal normalization – B channel

- Direct B→τ+… decays are the second largest source of τ leptons.

$$N_{\mathrm{sig(B)}} = \boxed{\mathcal{L}\sigma(pp \to B)}\, \mathcal{B}(\mathrm{B} \to \tau + ...)\ \mathcal{B}(\tau \to 3\mu)\ \mathcal{A}_{3\mu(B)}\ \epsilon^{3\mu}_{\mathrm{reco}}\ \epsilon^{2\mu}_{\mathrm{trig(sig)}}$$

$$f = \frac{\sigma(\mathrm{pp} \to \mathrm{B})\mathcal{B}(\mathrm{B} \to \mathrm{D_s} + ...)}{\sigma(\mathrm{pp} \to \mathrm{D_s})}$$

Fraction on D_s mesons produced from B decay and promptly (MC, normalization channel **f=0.24**)

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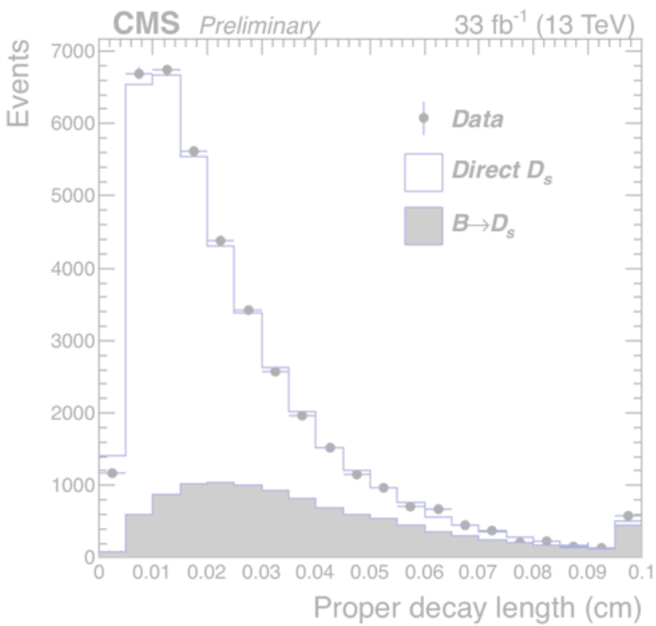

- *f* estimation validated in data, based on the B → D_s → Φπ → μμπ decay events
- Template fit method used, with the proper decay lenght distribution
- Events coming from B → Ds + … are expected to have a longer tail wrt directly-produced D_s mesons.
  - *Proper decay Lenght: L=L M/p*
- *Difference between data and MC is taken as sys.* ***(11%)***

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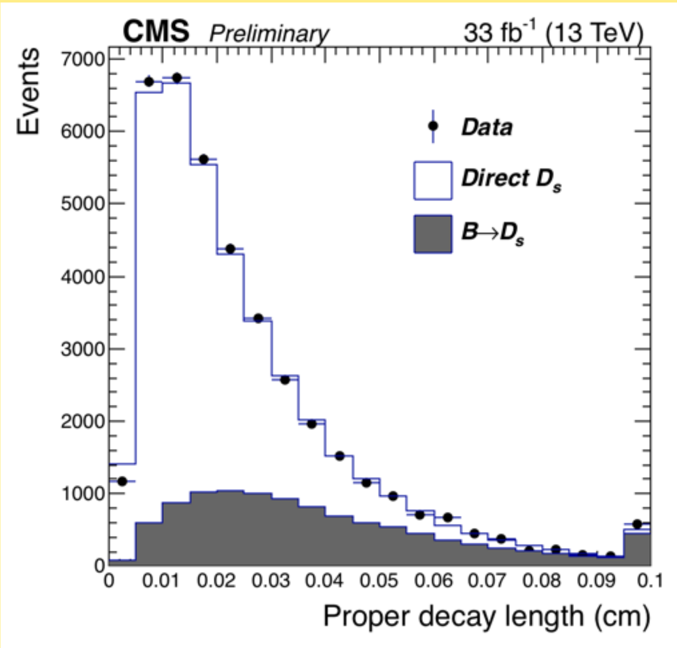

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Systematics

- **Signal modeling uncertainties**

Source of uncertainty	Yield	Shape
Uncertainty on D_s normalization [10%]	10%	
Relative uncertainty in $\mathcal{B}(D_s \to \tau\nu)$ [4%]	3%	
Relative uncertainty in $\mathcal{B}(D_s \to \phi\pi \to \mu\mu\pi)$ [8%]	8%	
Relative uncertainty in $\mathcal{B}(B \to D_s + ...)$ [16%]	5%	
Relative uncertainty in $\mathcal{B}(B \to \tau + ...)$ [11%]	3%	
Uncertainty in f (B/D ratio) [11%]	3%	
Uncertainty on D^+ as a source of τ [100%]	3%	
Uncertainty on B_s as a source of τ [100%]	4%	
Uncertainty in number of events triggered by trimuon trigger [8%]	2%	
Uncertainty in the ratio of acceptances $\mathcal{A}_{sig}/\mathcal{A}_{2\mu\pi}$ [1%]	1%	
Muon reconstruction efficiency [1.5%]	1.5%	
Charged pion reconstruction efficiency [2.3%]	2.3%	
BDT cut efficiency [5%]	5%	
Mass scale uncertainty [0.07%]	–	yes
Mass resolution uncertainty [2.5%]	–	yes

From PDG

Stability across different data taking periods of the ratio $N(Ds \to \Phi\pi \to \mu\mu\pi)/N(Ds \to \tau \to 3\mu)$

Difference from estimation in data an MC

Measured in the 3μ mass sidebands

Estimated by changing PDF sets in signal simulated events.

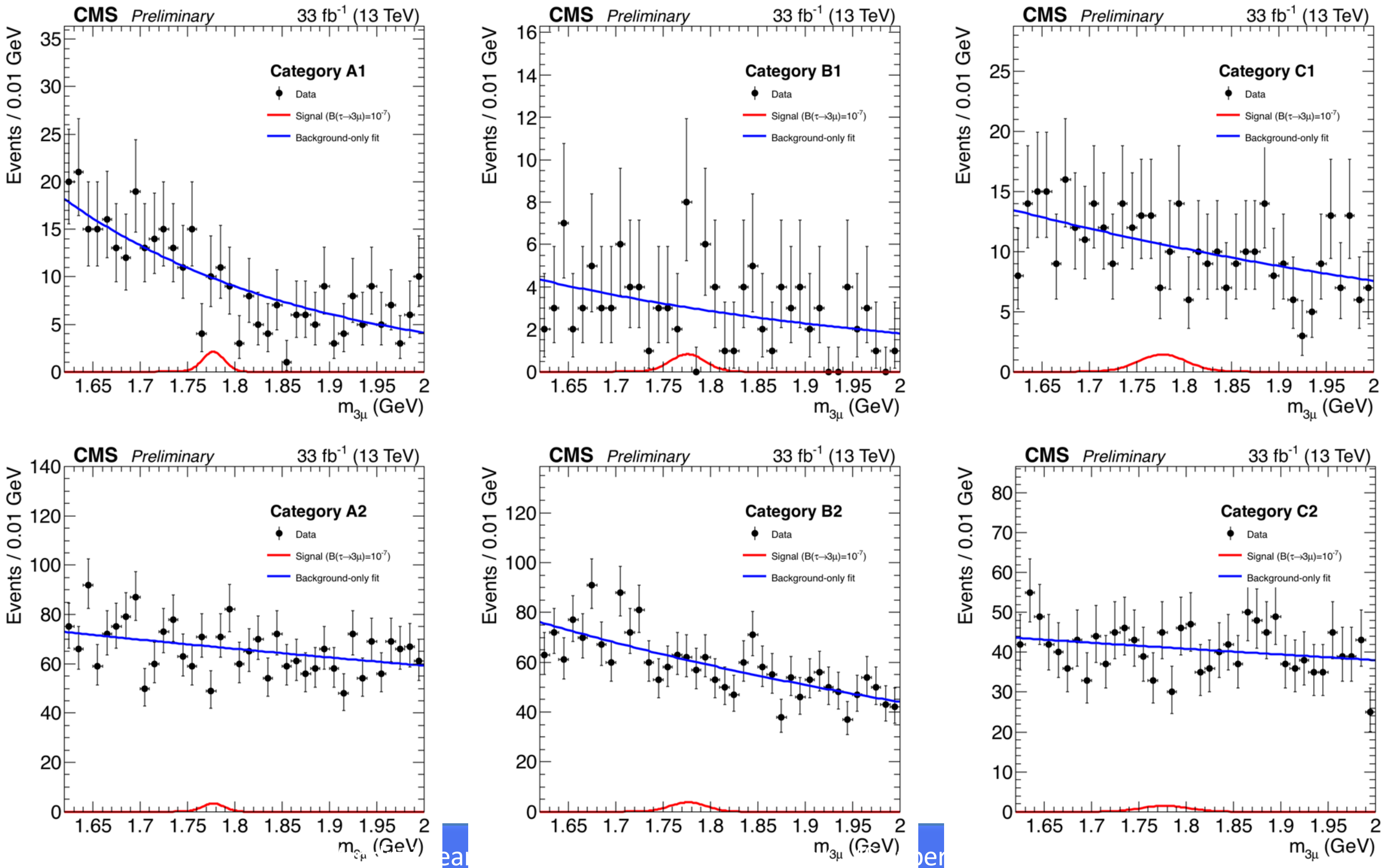
Estimated in $J/\psi \to \mu\mu$ events with Tag and Probe technique.

Estimated in $Ds \to \phi\pi \to \mu\mu\pi$ simulation and data

- **Background Modeling uncertainties**
  - The statistical uncertainties on the observed number of background events in the signal region vary from **3 to 15%,** depending on the event subcategry.
  - The systematic uncertainty is associated with the choice of the functional form →The net effect does not exceed **1%** among all event subcategories.

Signal extraction

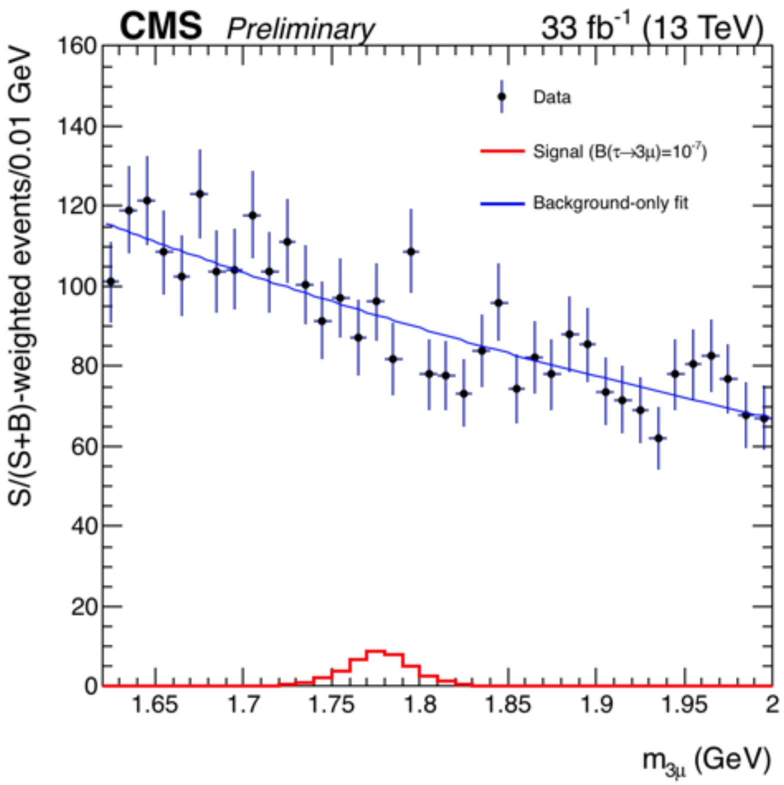
- Signal is extracted from a maximum likelihood fit to the 3μ system invariant mass, in each of the six event categories.
  - MC signal is parametrized with Crystal Ball functions
  - exponential plus a polynomial is used to model the background.
- Systematics uncertainties are treated as nuisance paramters in the fit.
- No signal excess is observed



In these plots BR($\tau \rightarrow 3\mu$)=10^{-7}

Results

- No significant event excess is observed in the signal region.



- *Qualitative representation of the analysis power to observe a signal over background*
- *Obtained by combining the mass distributions in the six categories, scaled by S/(S+ B) ratios in each category*
- *Expected signal (S) and background (B) event rates are extracted from the 3μ-mass distribution, assuming exactly the τ lepton mass.*

- Upper limits on the branching fraction BR($\tau \to 3\mu$) are set using the modified frequentist CLs criterion

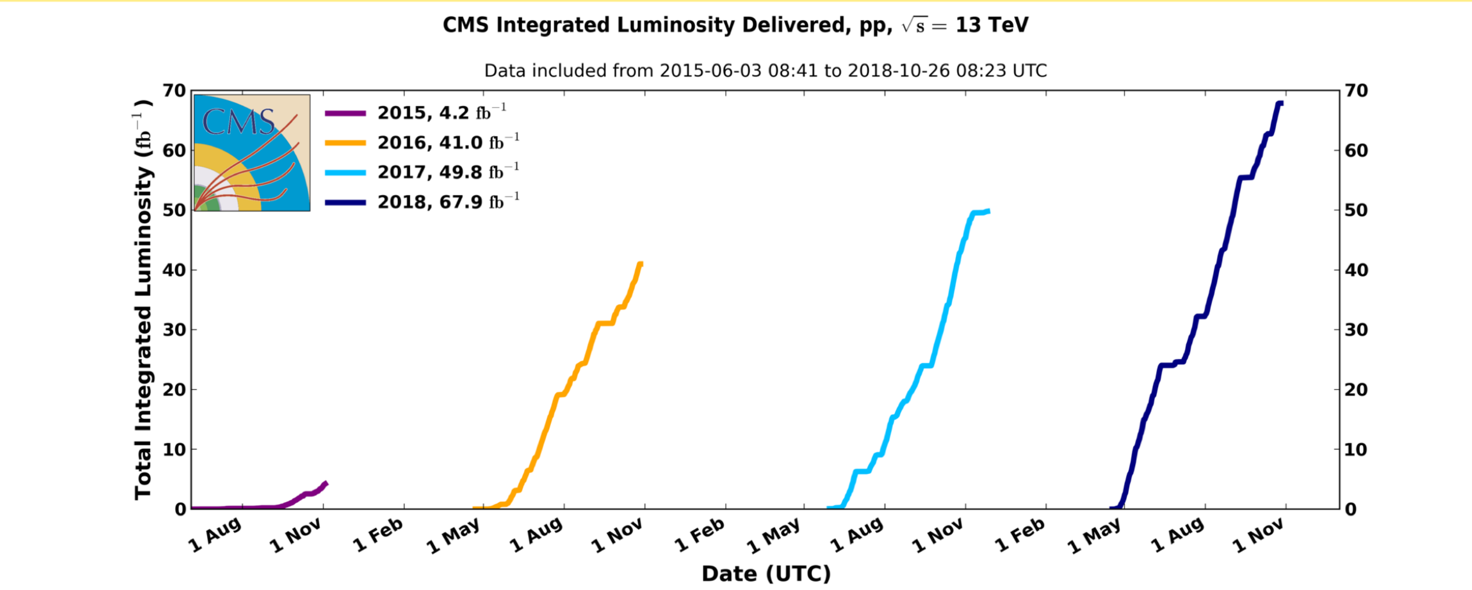
CL	Expected BR($\tau \to 3\mu$)	Observed BR($\tau \to 3\mu$)
90%	9.9×10^{-8}	8.9×10^{-8}
95%	1.2 × 10−7	1.1 × 10−7

Conclusions and perspectives

- Search for CLFV $\tau \longrightarrow 3\mu$ decay done for the first time at CMS
- 2016 pp collisions data analyzed, $\mathcal{L}$= 33/fb $\sqrt{s}$=13 TeV
- **Upper limits Br($\tau \rightarrow 3\mu$) < 8.9×10^{-8} at 90% CL.**

- Analysis in the W channel is ongoing → Combination of the results foreseen

Perspectives: 2017+2018 data



✓ x3 more statistics ($\mathcal{L}$=108/fb)
✓ new, more efficient, triggers for both HF and W channels

Thanks for your attention

Backup

D and B meson decay branching fractions

Process	Branching ratio	Reference
$D_s \to \tau\nu$	$5.48 \pm 0.23\%$	PDG [13]
$B^+ \to \tau + \nu + D^{0(*)}$	$2.7 \pm 0.3\%$	PDG [13]
Other $B^+ \to \tau + X$ decays	0.7%	PYTHIA [5]
$B^0 \to \tau + \nu + D^{+(*)}$	$2.7 \pm 0.3\%$	PDG [13]
Other $B^0 \to \tau + X$ decays	0.7%	PYTHIA [5]
$B^+ \to D_s + X$	$9.0 \pm 1.5\%$	PDG [13]
$B^0 \to D_s + X$	$10.3 \pm 2.1\%$	PDG [13]
$D_s \to \phi(\mu\mu)\pi$	$1.3(\pm 0.1) \times 10^{-5}$	PDG [13]

Expected number of tau leptons

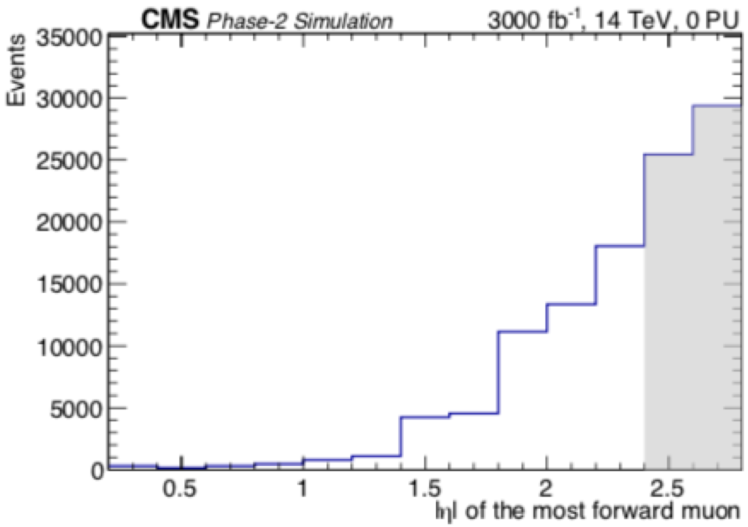
Process	Number of τ leptons ($33\,\mathrm{fb}^{-1}$)
$\mathrm{pp} \to c\,\bar{c} + \ldots$	
$\quad \mathrm{D} \to \tau\nu$	4.0×10^{12} (95% $\mathrm{D_s}$, 5% $\mathrm{D^{\pm}}$)
$\mathrm{pp} \to \mathrm{b\bar{b}} + \ldots$	
$\quad \mathrm{B} \to \tau\nu + \ldots$	1.5×10^{12} (44% $\mathrm{B^{\pm}}$, 45% $\mathrm{B^0}$, 11% $\mathrm{B_s^0}$, 0% $\mathrm{B_c^{\pm}}$)
$\quad \mathrm{B} \to \mathrm{D}(\tau\nu) + \ldots$	6.3×10^{11} (98% $\mathrm{D_s}$, 2% $\mathrm{D^{\pm}}$)

Signal and data yields

- The signal yields are shown for B($\tau \rightarrow 3\mu$) = 10−7.
- The data yields inside parentheses are in the mass ranges of 1.78 GeV ± 2σ, where σ is the mass resolution (12 MeV, 19 MeV, and 25 MeV for the category A, B, and C respectively).

	Signal		Data	
	sub-category 1	sub-category 2	sub-category 1	sub-category 2
Category A	6.3	10.3	360(44)	2502(319)
Category B	3.9	18.5	110(27)	2229(449)
Category C	9.4	9.6	389(107)	1549(400)

HF $\tau \rightarrow 3\mu$ Search @ HL-LHC



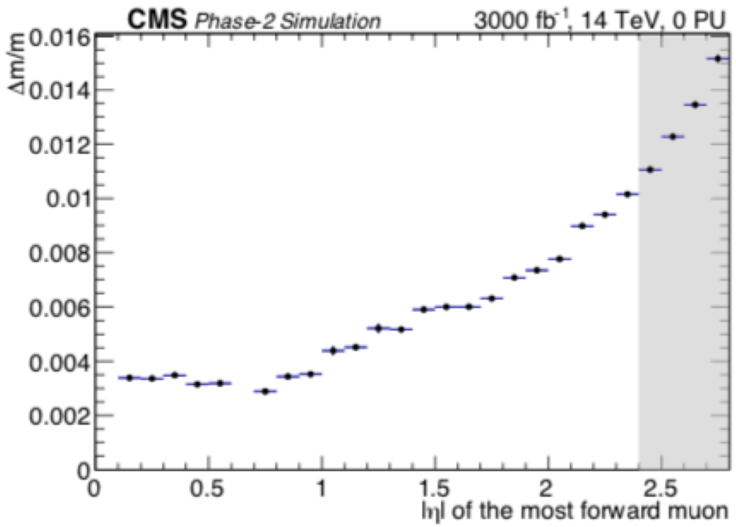


Table 8.3: The expected numbers of signal and background events in mass window 1.55–2.00 GeV for integrated luminosity L = 3000 fb^{-1} (for signal, $B(\tau \rightarrow 3\mu) = 2 \times 10^{-8}$ is assumed). In absence of a signal, the projected limits on $B(\tau \rightarrow 3\mu)$ are for 90% CL, which are obtained using the standard CL$_s$ methodology [140–142].

	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
$B(\tau \rightarrow 3\mu)$ limit per event category	4.3×10^{-9}	7.0×10^{-9}
$B(\tau \rightarrow 3\mu)$ 90%C.L. limit	3.7×10^{-9}	
$B(\tau \rightarrow 3\mu)$ for 3σ-evidence	6.7×10^{-9}	
$B(\tau \rightarrow 3\mu)$ for 5σ-observation	1.1×10^{-8}	

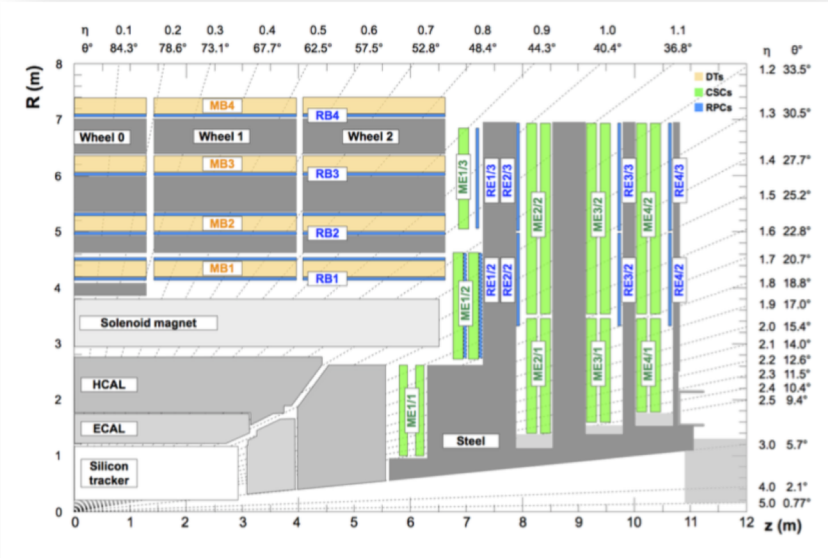
The CMS Forward Muon System Challenge

- The CMS Muon System performed excellently up to the end of the LHC Run2
- Nevertheless, the forward region is characterized by:
  1. Smaller magnetic field
  2. Higher neutron-induced background vs low hit multiplicity

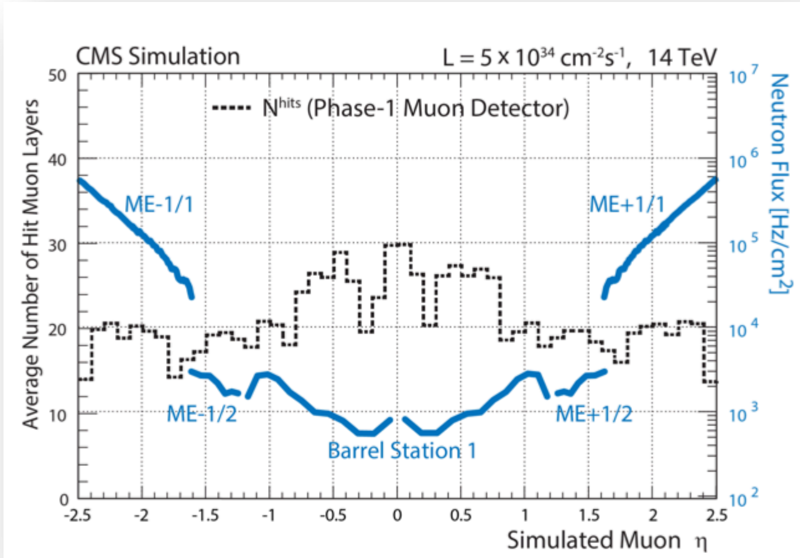
à trigger rate is dominated by soft muons reconstructed as high p_T muons

à This effect will be increased in the HL-LHC scenario (200 pile-up interactions per BX)

à **Adding a new muon station in front of ME1/1 could be a powerful tool to improve the muon p_T precision**



Present CMS Muon System slice,
JINST 13 (2018) P06015, 10.1088/1748-0221/13/06/P06015



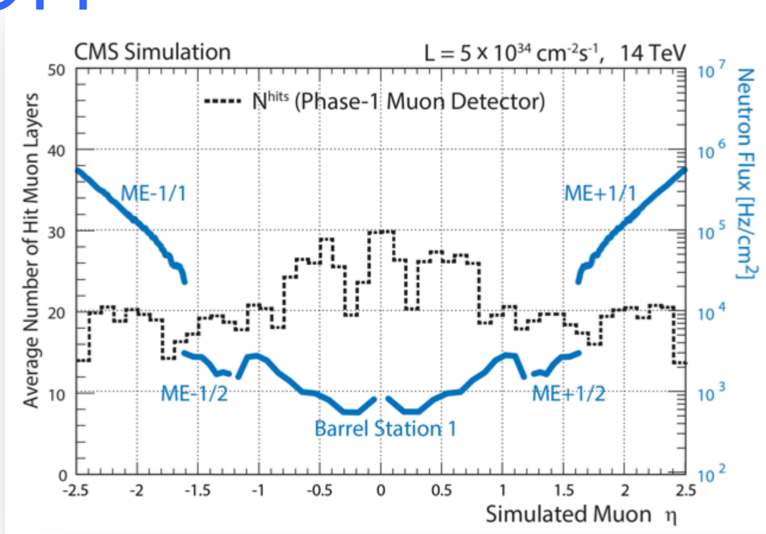
Neutron flux and average number of muon hits in the present CMS Muon System
CMS-TDR-013

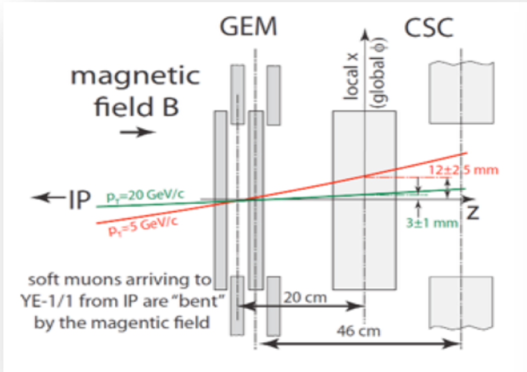
A new tool in the endcap Muon system: the GE1/1 Station

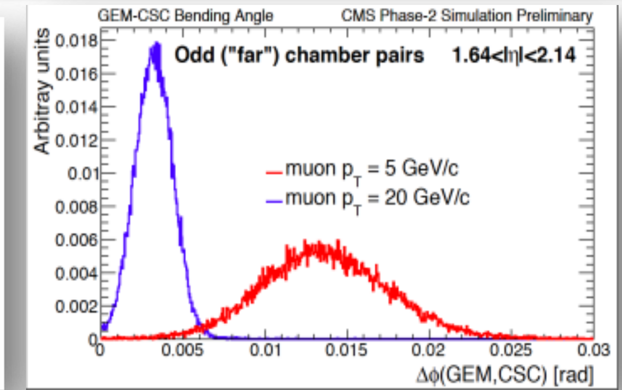
- Present forward muon system challenges:
    1. Small magnetic field
    2. High neutron-induced background vs low hit multiplicity
- Key role of the first muon station with small scattering and higher magnetic field→ muon p_T estimation presently **relies entirely on the CSC**

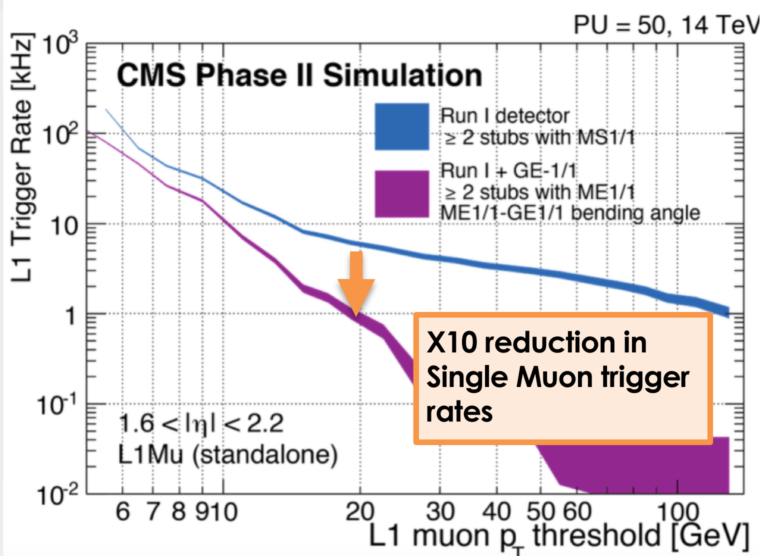
à trigger rate is dominated by junk muons reconstructed as high p_T muons

à **Adding a new muon station in front of ME1/1 could be a powerful tool to improve the muon p_T precision**



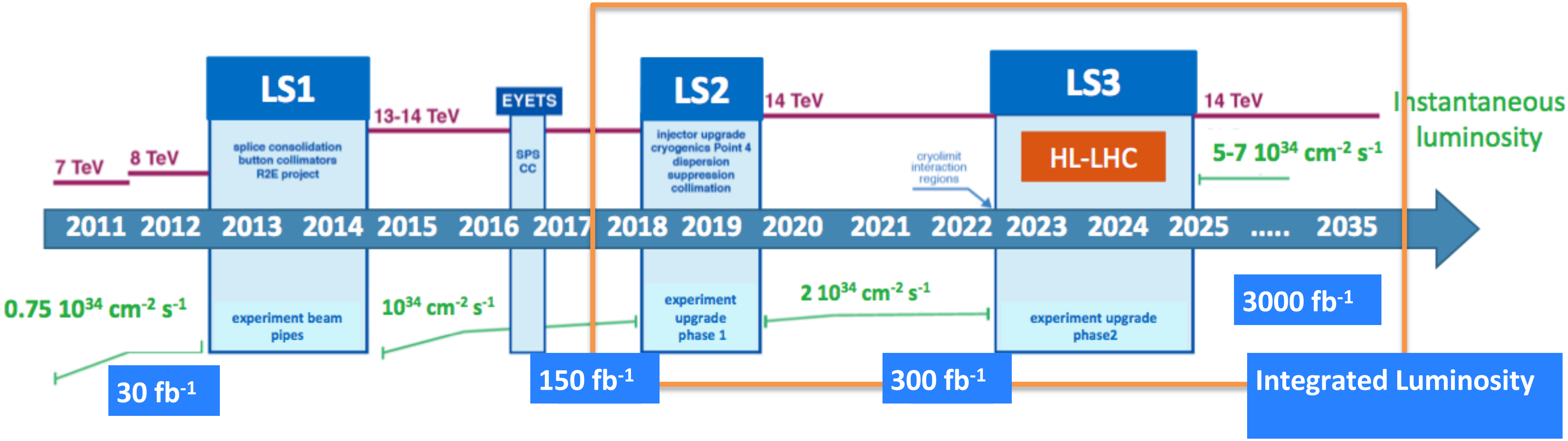






Large lever arm + magnetic field + good positions resolutions results in excellent discriminating power against soft muons from the bending angle

The CMS Experiment towards HL-LHC

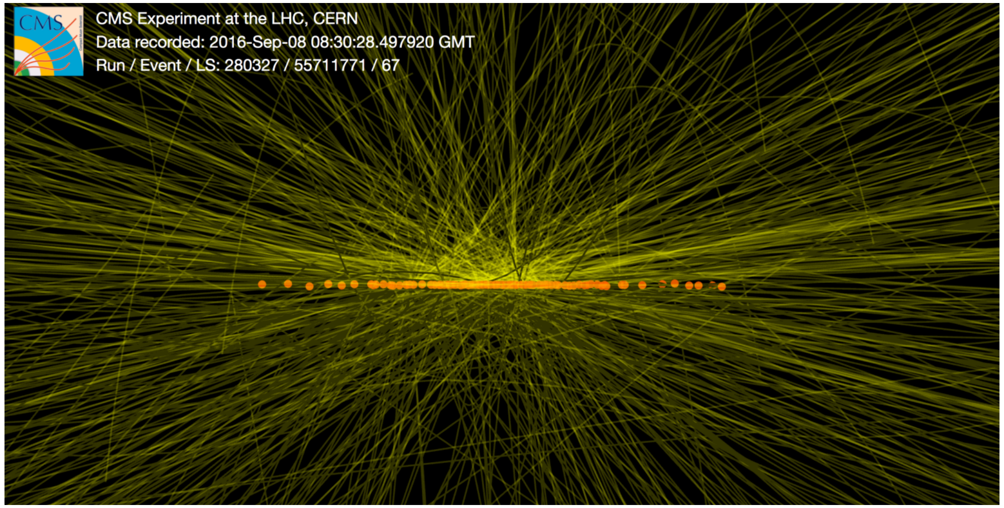


New phase space accessible for physics:

- Higgs precision era (properties and couplings)
- Electroweak precision measurement
- New physics: high mass resonance, displaced signatures dark matter
- Key role of muon final state signatures

The price to pay:

- Particle densities x5-10 →Radiation damage x10
- 50(200) pile-up interactions per BX



Intensive program of detector upgrade with the goal to keep the same performance as in Run2