Istituto Nazionale di Fisica Nucleare

DIPARTIMENTO DI FISICA MICHELANGELO MERLIN

Topical workshop on LFV decays of the tau

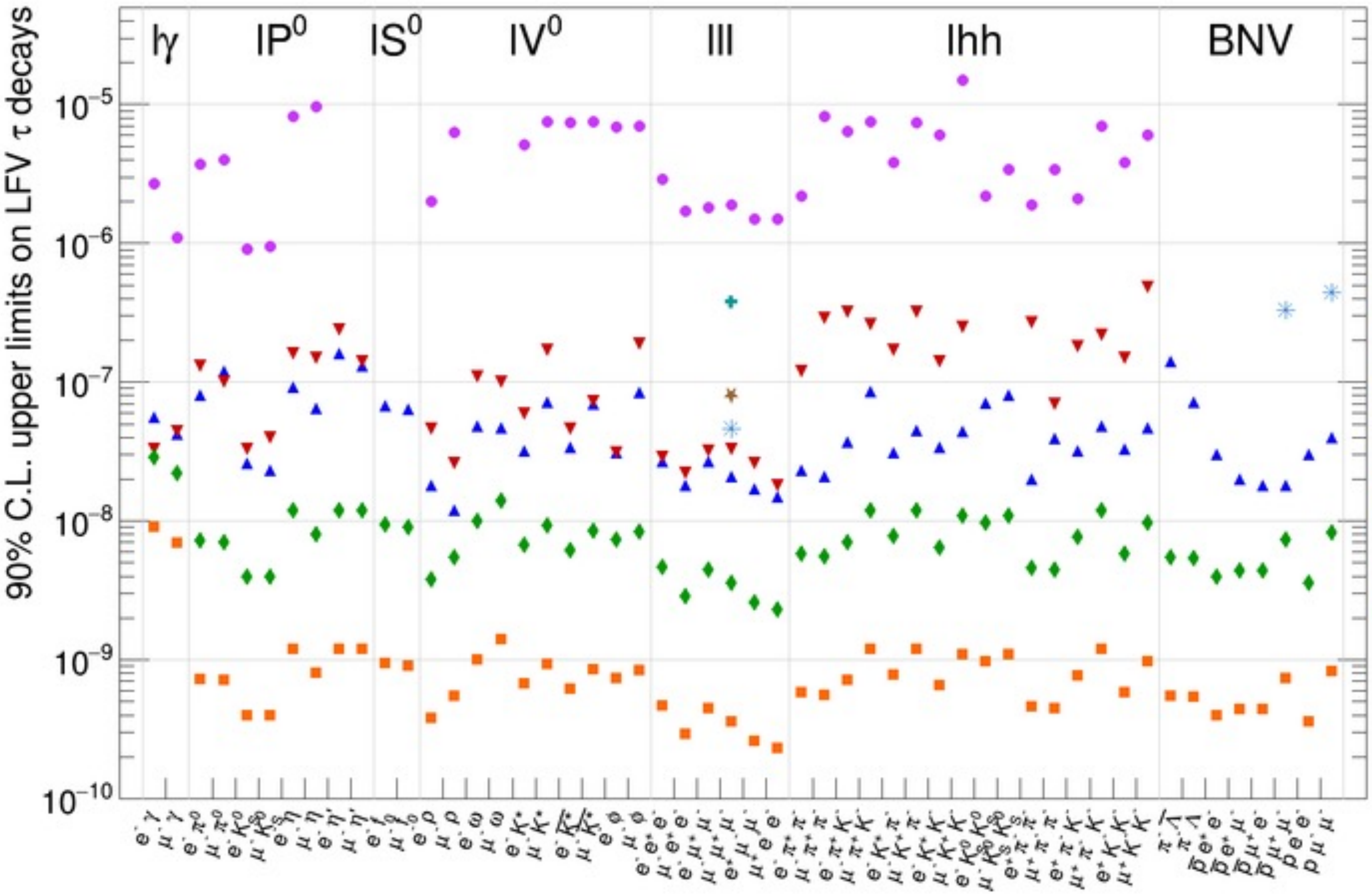
$\tau \to 3\ell$ at hadron colliders

Federica Simone[1] on behalf of the CMS, ATLAS and LHCb Collaborations

[1] Politecnico di Bari & INFN Bari

11 – 12 April 2024, IJCLab, Université Paris-Saclay (France)

τ LFV searches



$\int Ldt$ used

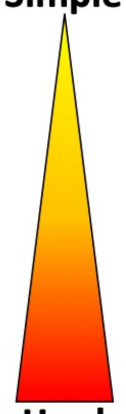
CLEO	$\sim 9\ fb^{-1}$
ATLAS	$\sim 20\ fb^{-1}$
CMS	$\sim 30\ fb^{-1}$ (superseded)
LHCb	$\sim 3\ fb^{-1}$
BaBar	$\sim 500\ fb^{-1}$
Belle	$\sim 800\ fb^{-1}$
Belle II (5 ab^{-1})	
Belle II (50 ab^{-1})	

10.48550/arXiv.2203.14919

Motivations for $\tau \to 3\ell$

Search various decay modes:

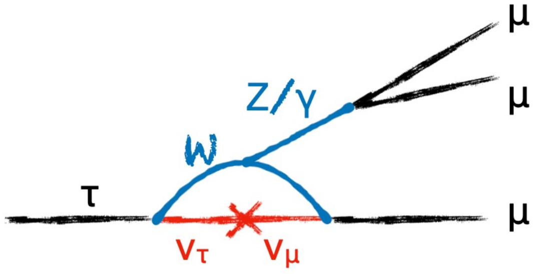
- $\tau \to \ell\ell\ell$
- $\tau \to \ell K_s, \Lambda h$
- $\tau \to \ell V_0(\to hh')$
- $\tau \to \ell P^0\ (\to \gamma\gamma)$
- $\tau \to \ell hh'$
- $\tau \to \ell\gamma$

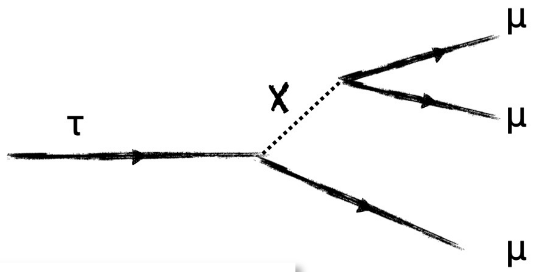


Difficulty of background reduction

$\tau \to 3\mu$: experimentally the most accessible

- fully reconstructed final state
- good muon momentum resolution allows precise determination of the τ lepton mass
- no irreducible SM backgrounds





Model	**Ref.**	$\mathcal{B}(\tau \to 3\mu)$
SM model + ν oscillation	10.1140/EPJC/S10052-020-8059-7	$10^{-56} \div 10^{-53}$
SM with right-handed heavy Dirac neutrino	10.1103/PhysRevD.89.059904	$< 10^{-18}$
SM with right-handed heavy Majorana neutrino	10.1103/PhysRevD.66.034008	$< 10^{-10}$
left-right SUSY	10.1016/J.NUCLPHYSB.2003.10.020	$< 10^{-10}$
SUSY with neutral Higgs	10.1016/S0370-2693(02)02900-3	$10^{-7} \div 10^{-10}$
SUSY with Higgs triplet	10.1016/S0920-5632(03)80316-X	10^{-7}
Non universal Z' (technicolor)	10.1103/PhysRevD.68.016004	10^{-8}

State of the art of $\boldsymbol{\tau \to 3\mu}$ searches

Year	Collab.	Process	Data	Expected [*]	Observed [*]
2010	Belle	$ee \to \tau\tau$	782 fb^{-1}	-	2.1
2010	BaBar	$ee \to \tau\tau$	468 fb^{-1}	4.0	3.3
2014	LHCb	$D/B \to \tau X$	3.0 fb^{-1} (pp 7-8 TeV)	5.0	4.6
2016	ATLAS	$W \to \tau\nu$	20.3 fb^{-1} (pp 8 TeV)	39	38
2023	CMS	$D/B \to \tau X$ and $W \to \tau\nu$	131 fb^{-1} (pp 13 TeV)	2.4	2.9
2024	Belle II	$ee \to \tau\tau$	424 fb-1	-	1.9

[*] $\times 10^{-8}$@ 90% C.L.

State of the art of $\tau \to 3\mu$ searches at hadron colliders

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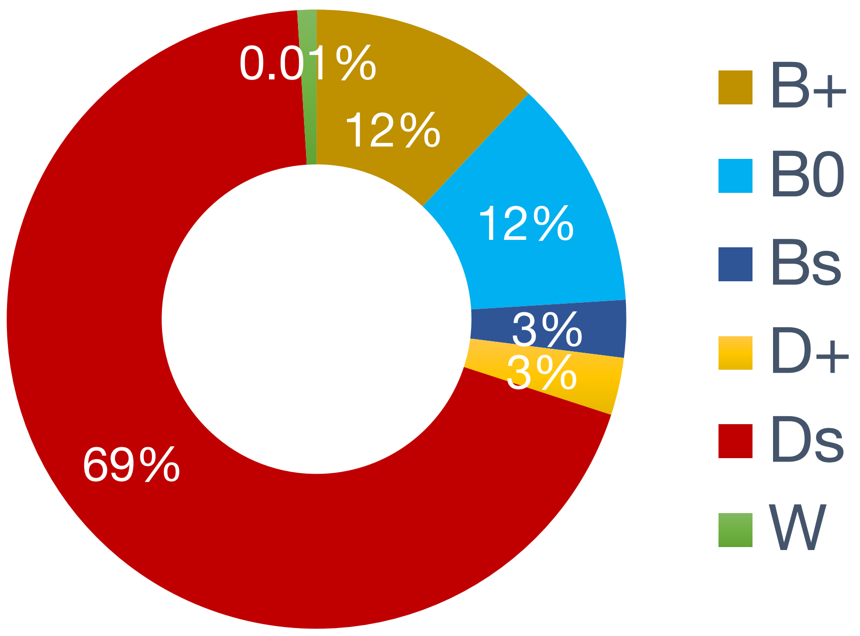
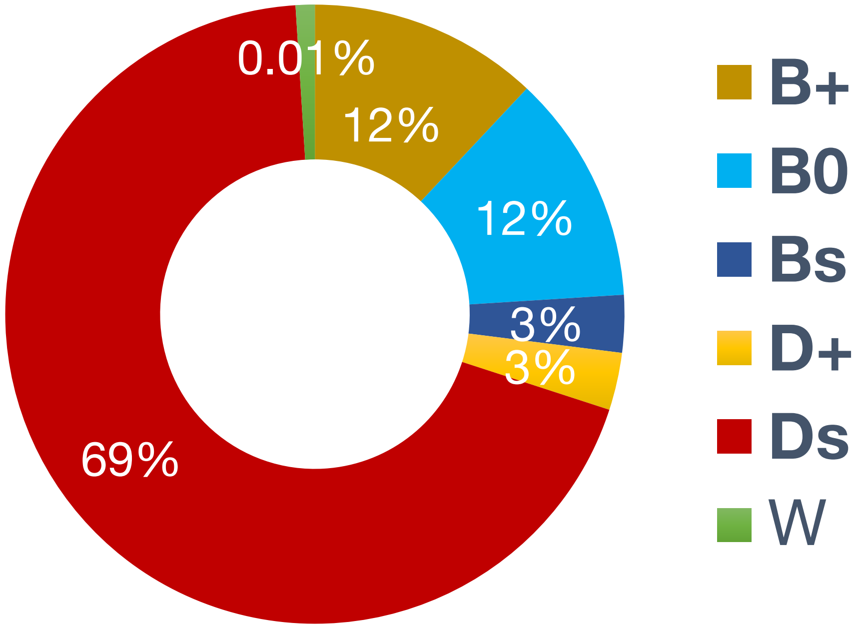
τ production at the LHC



τ production at the LHC



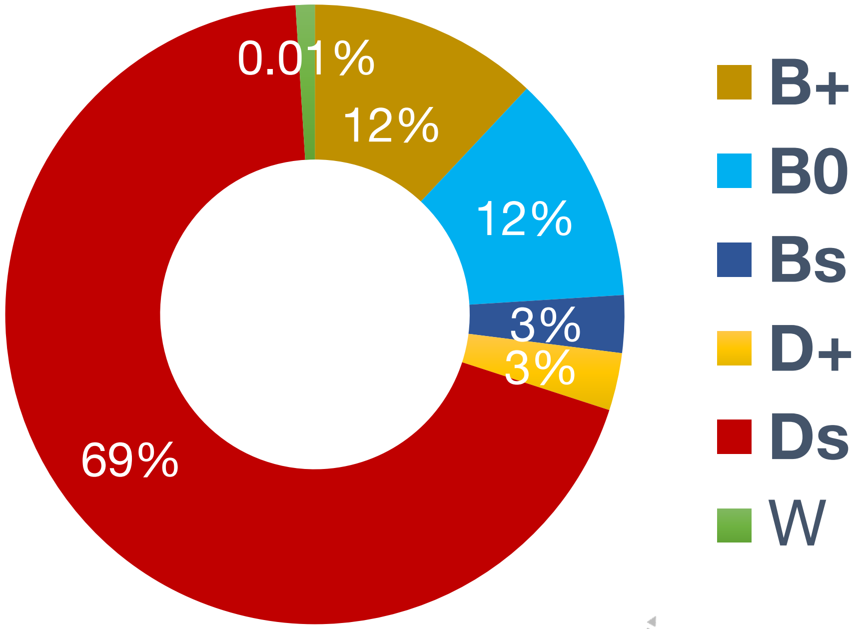
Decays of heavy flavour mesons

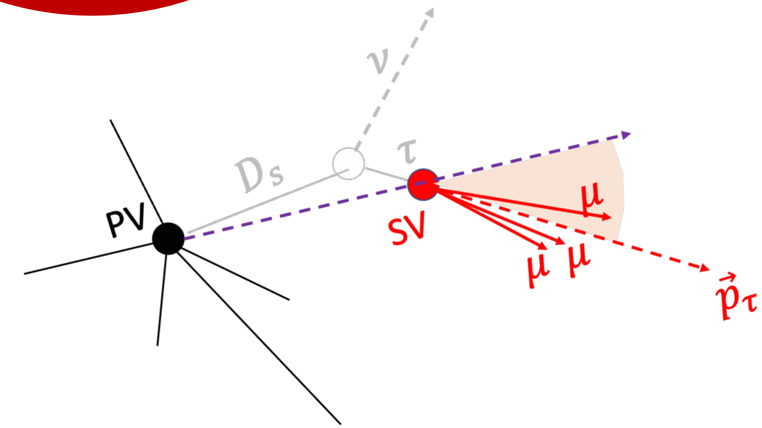
- 70% D, 25% B

Exp. number of produced τ per 10 /fb at $\sqrt{s} = 13\ TeV$ (PYTHIA8 LO)

Process 1	Process 2	No. of τ for $\mathcal{L} = 10\ fb^{-1}$
$pp \to c\bar{c} + \ldots$	$D \to \tau\nu_\tau$ (95% D_s, 5% $D^\pm$)	$1.2 \cdot 10^{12}$
$pp \to b\bar{b} + \ldots$	$B \to \tau\nu_\tau + \ldots$ (44% $B^\pm$, 45% B^0, 11% B_s^0)	$5.6 \cdot 10^{11}$
	$B \to D(\tau\nu_\tau) + \ldots$ (98% D_s, 2% $D^\pm$)	$1.9 \cdot 10^{11}$

τ production at the LHC





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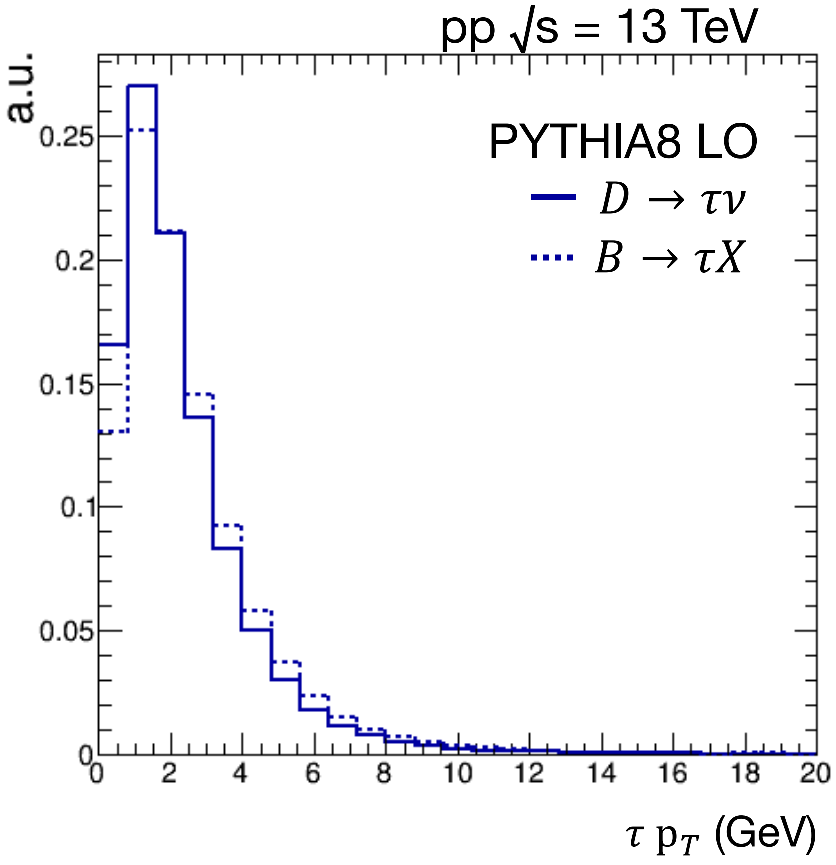
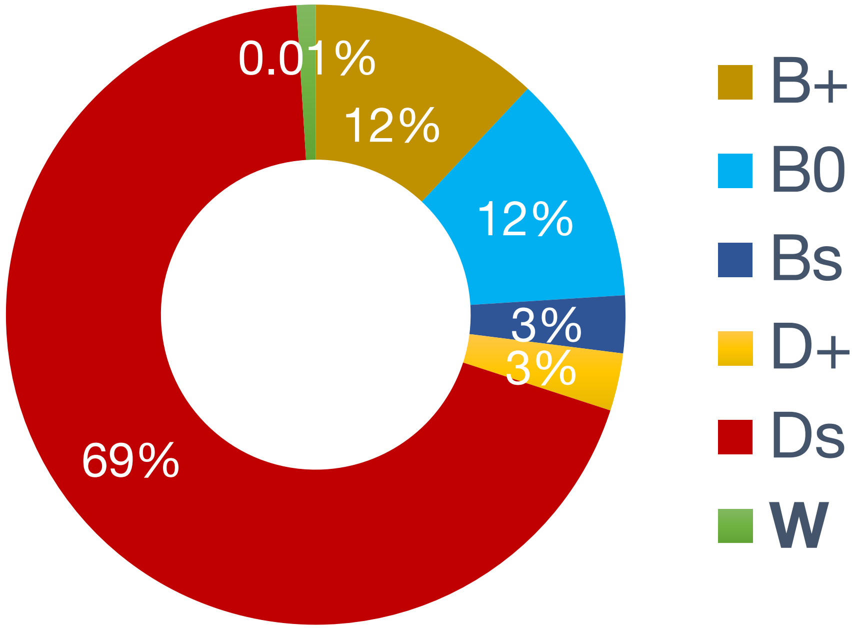


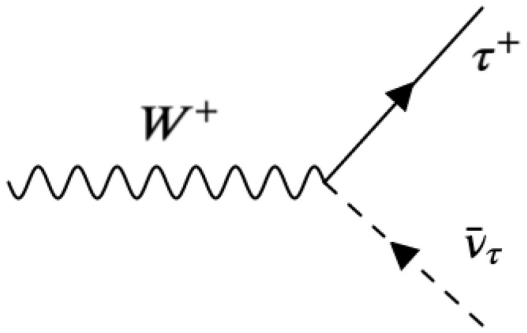
Low energy leptons in the final state

τ production at the LHC



Decays of EW bosons

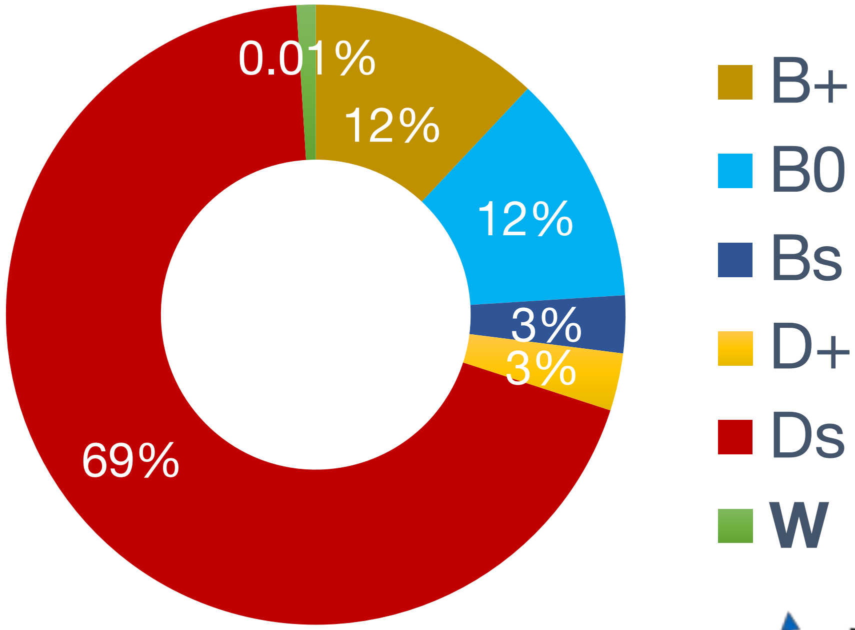
- 0.01% W, 0.002% Z

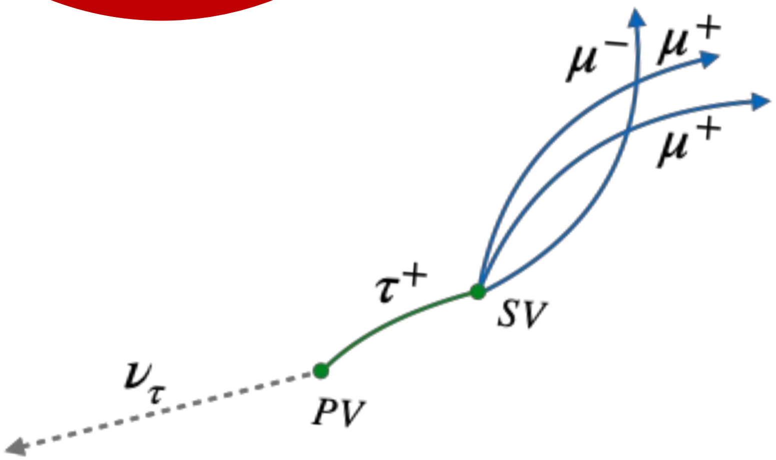


Exp. number of produced τ per 10 /fb at $\sqrt{s} = 13\ TeV$ (PYTHIA8 LO)

Process 1	Process 2	No. of τ for $\mathcal{L} = 10\ fb^{-1}$
$pp \to W + ...$	$W \to \tau\nu_\tau$	$2.0 \cdot 10^8$
$pp \to Z + ...$	$Z \to \tau\tau$	$3.9 \cdot 10^7$

τ production at the LHC





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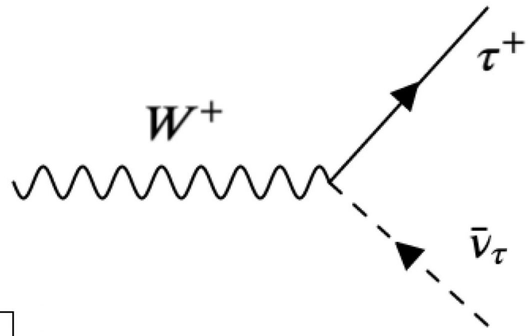
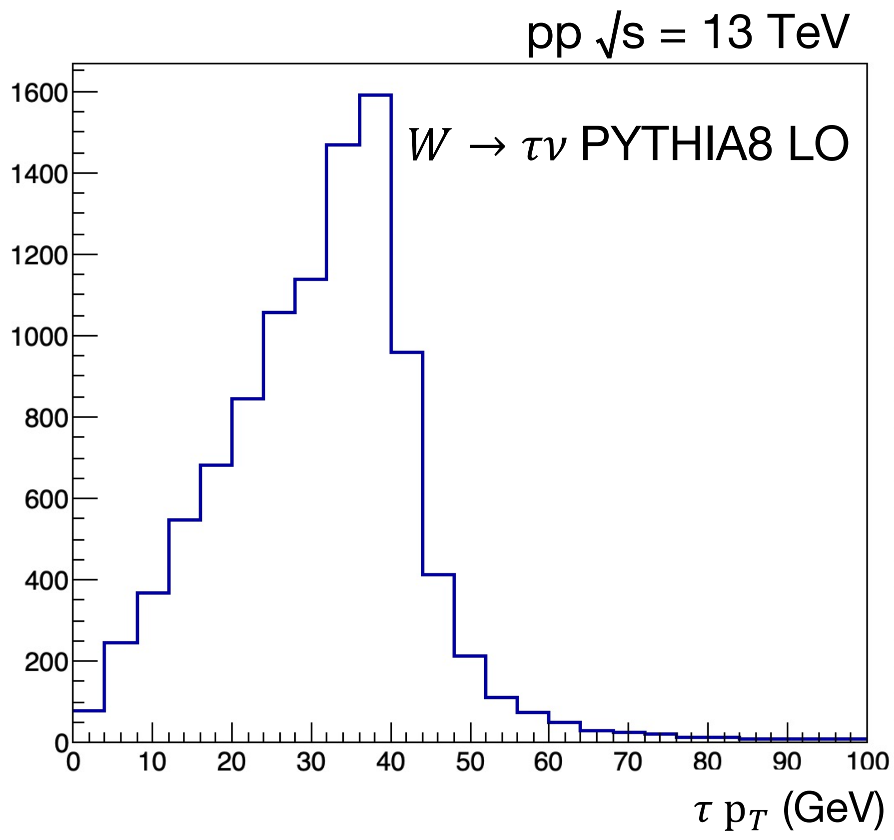
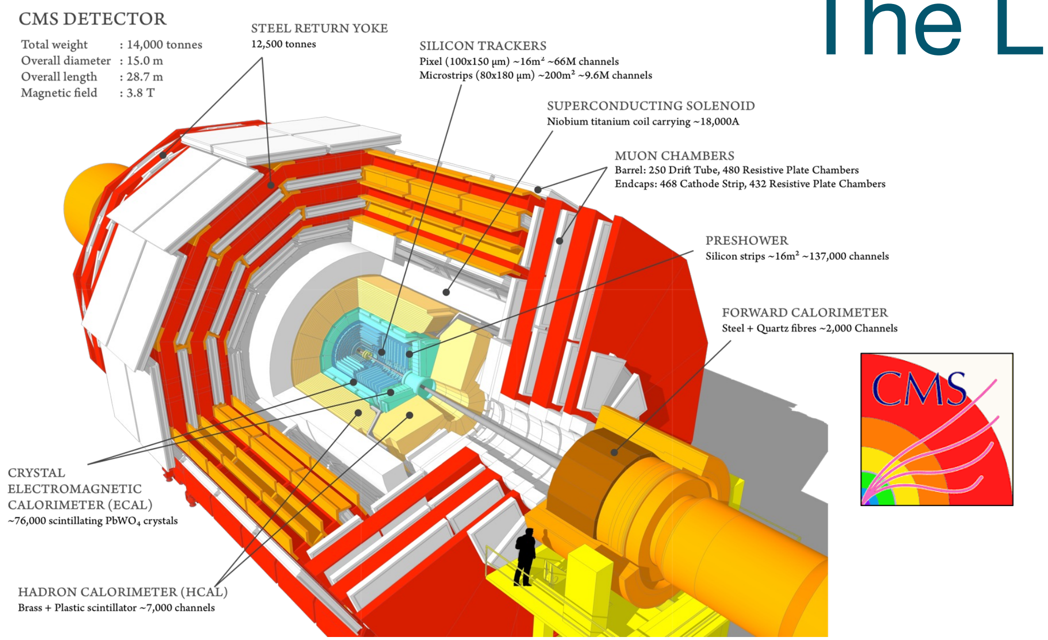


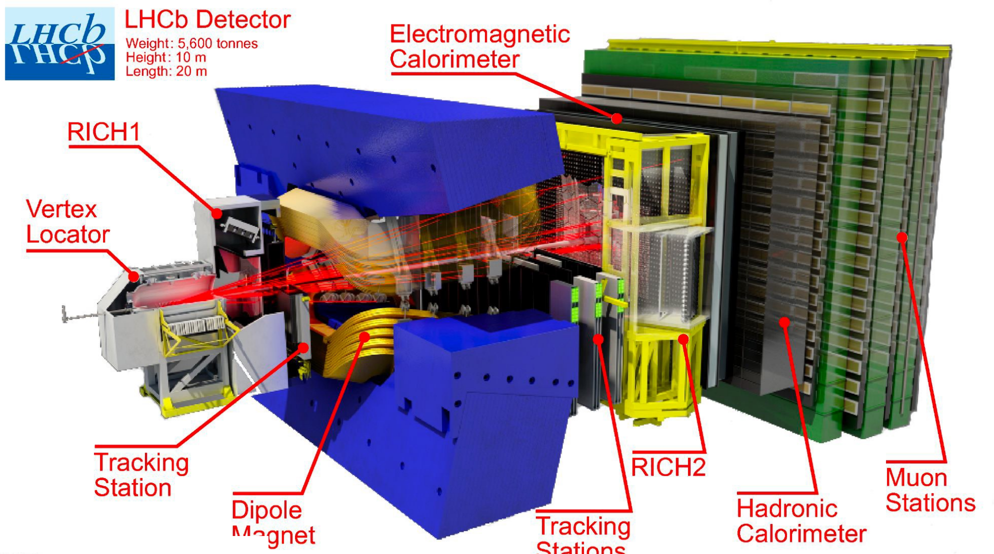


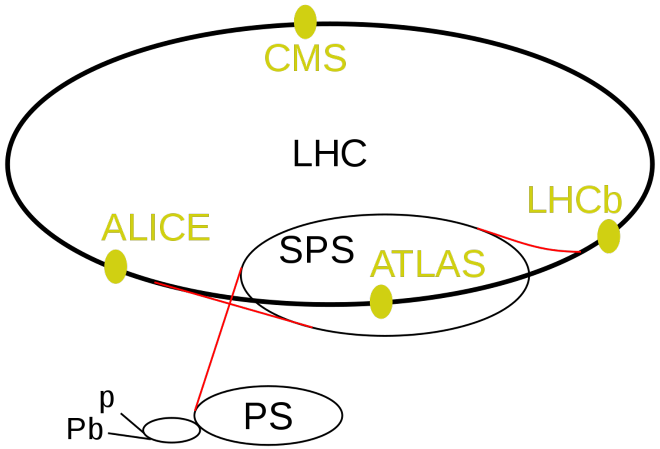
High energy final-state leptons

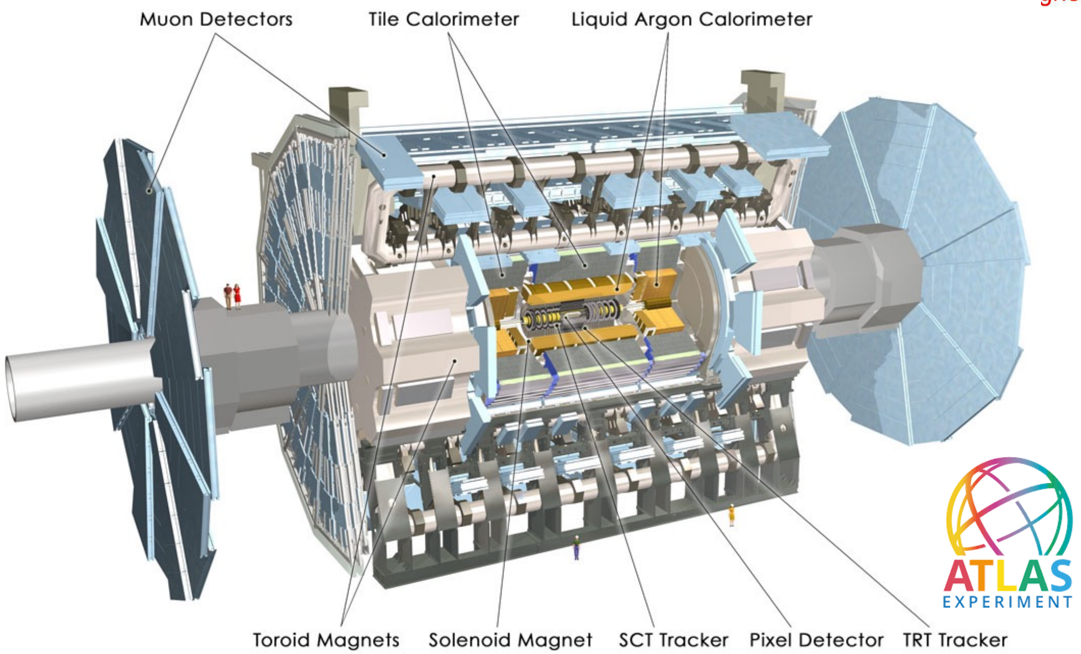
Missing energy

The LHC experiments





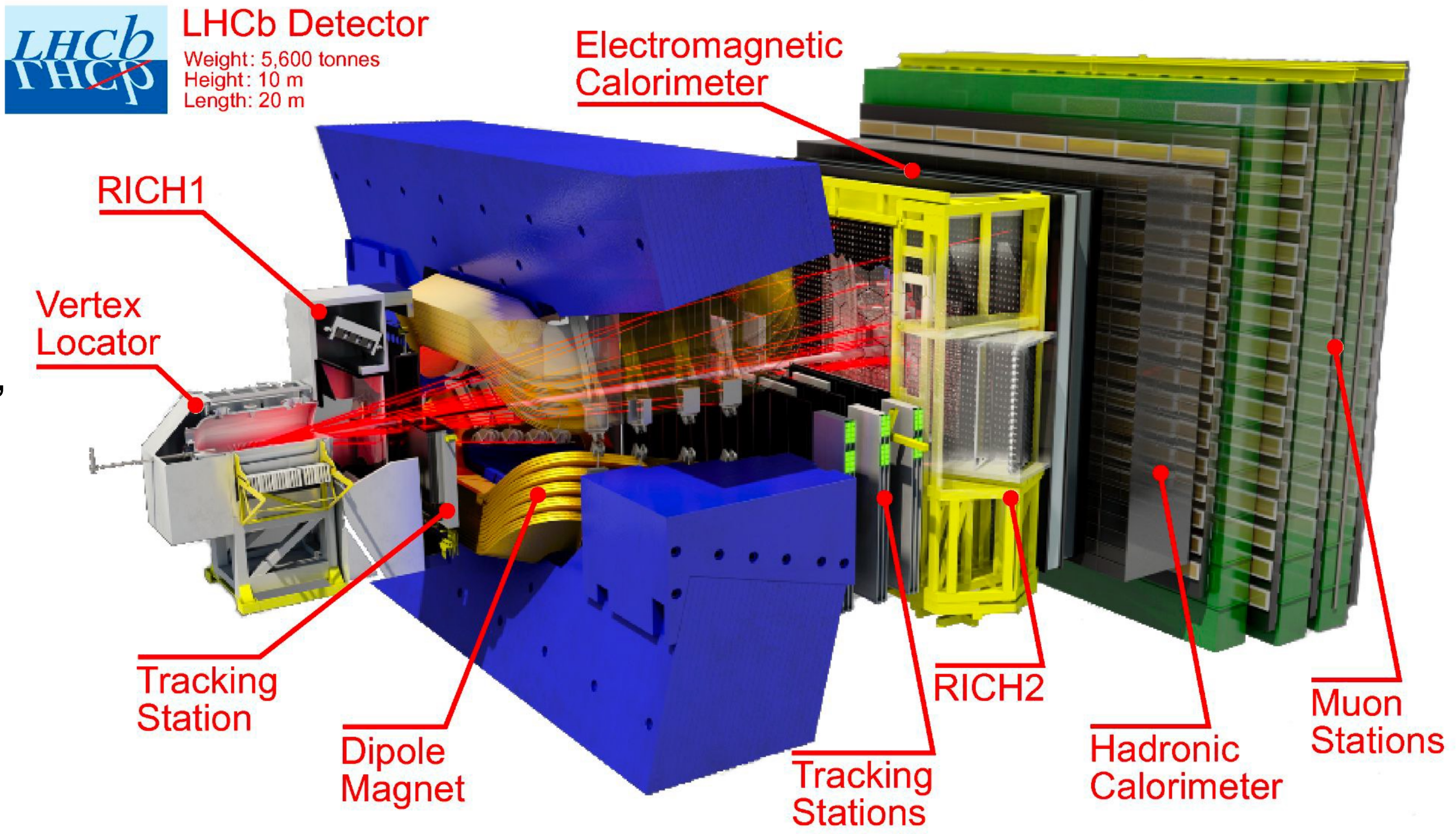




LHCb

Single-arm forward spectrometer covering $2 < \eta < 5$, featuring high beauty and charm production cross-sections.

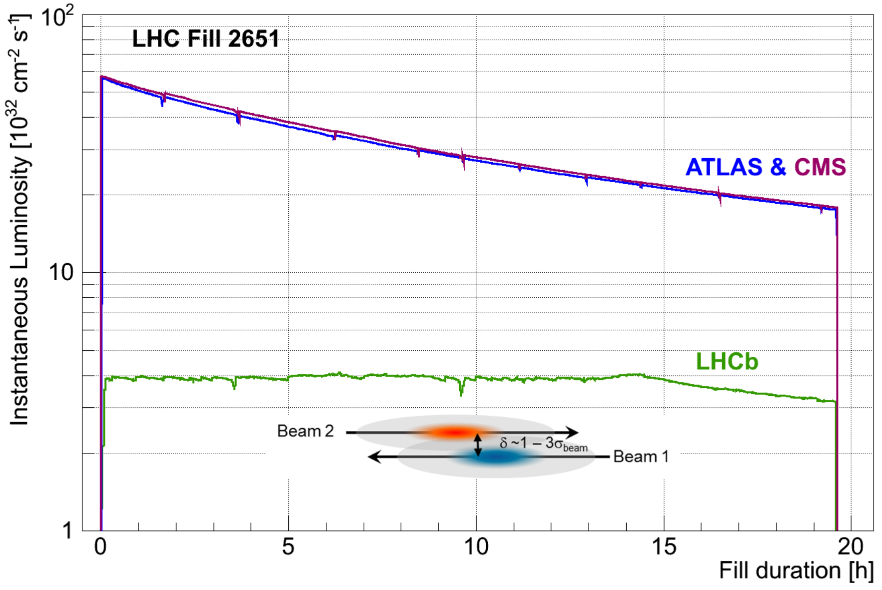
- Excellent particle identification,
- π / K separation for 2 < *p* < 100 GeV,
- μ misID ~ 2%.



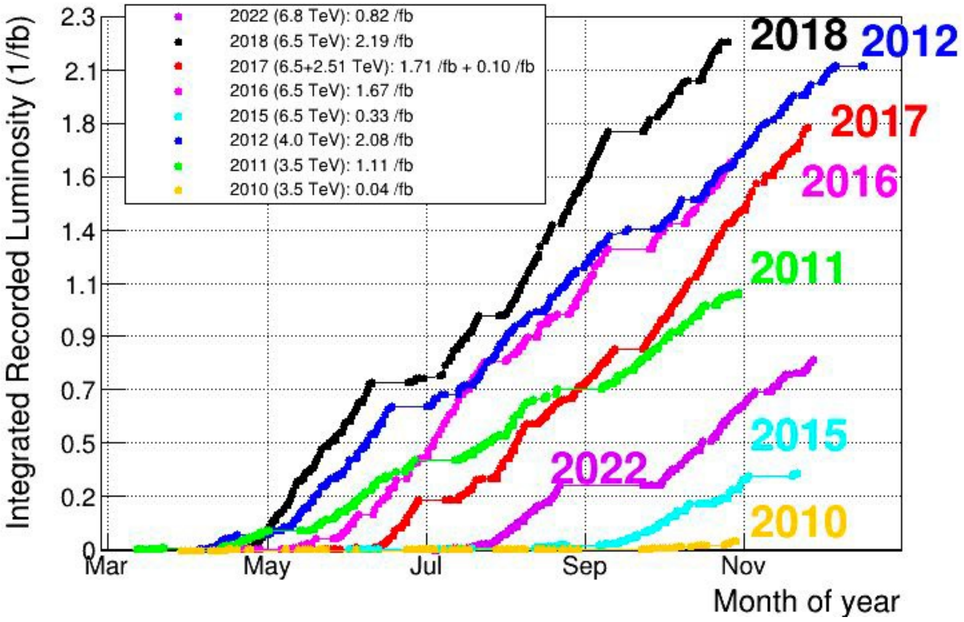
$$\sigma(pp \to b\bar{b}X)_{2<\eta<5} = 144 \pm 1 \pm 21 \mu\text{b}$$ [PRL 119, 169901 (2017)]

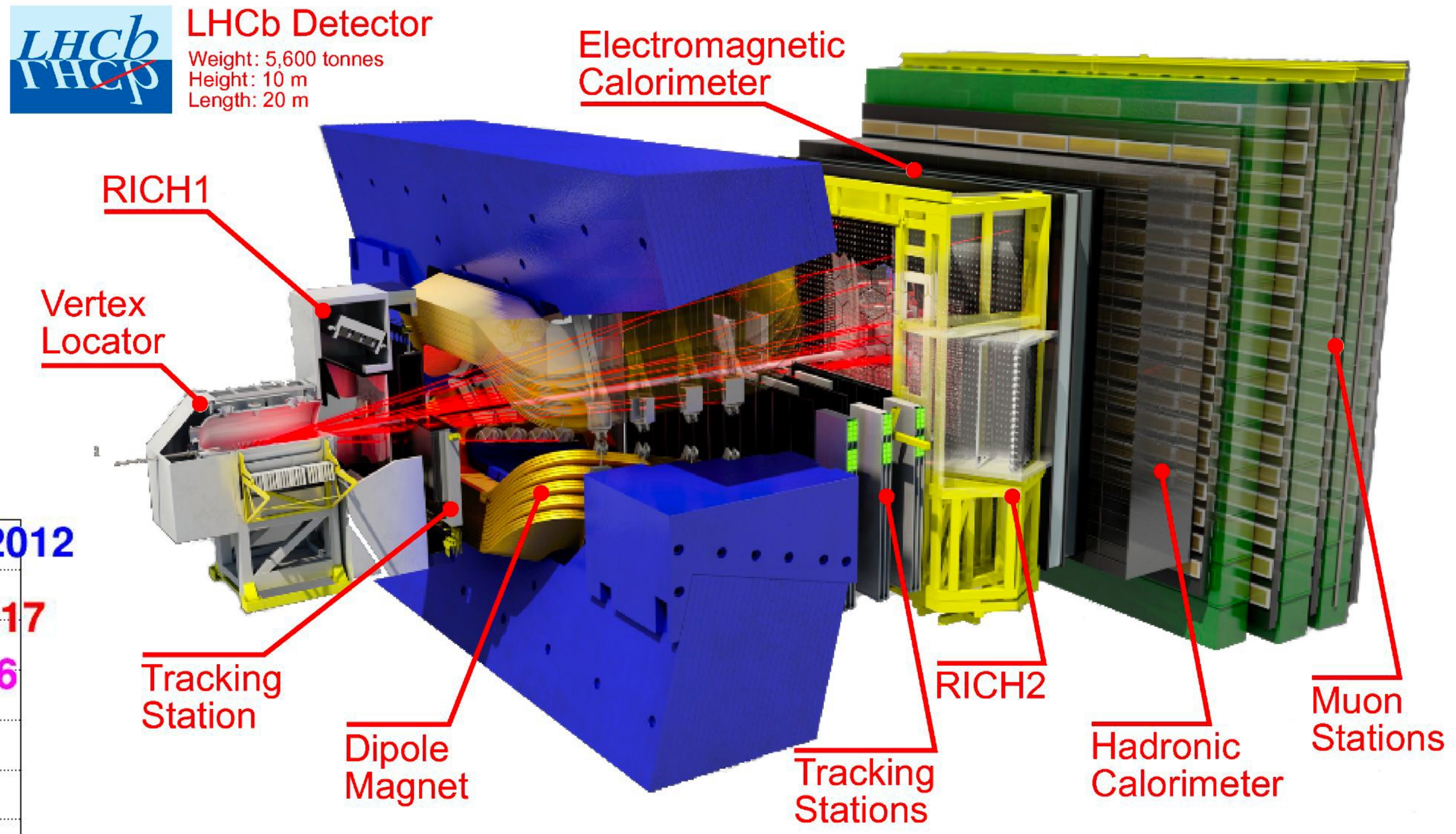
$$\sigma(pp \to c\bar{c}X)_{p_{\mathrm{T}} < 8\ \mathrm{GeV/c},\, 2.0 < y < 4.5} = 2369 \pm 3 \pm 152 \pm 118\ \mu\mathrm{b}$$ [JHEP 05 (2017) 074]

LHCb



[Int. J. Mod. Phys. A 30 (2015) 1530022]()

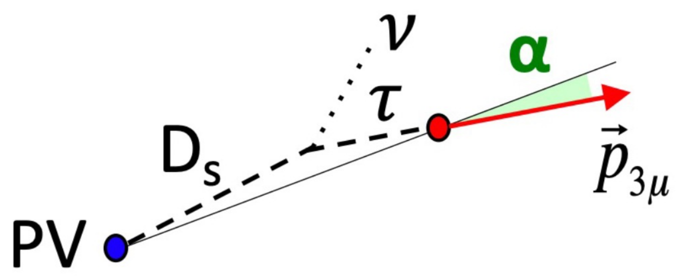




Search for $\tau \rightarrow 3\mu$ decays with the LHCb detector

Result based on 3 fb^{-1} at $\sqrt{s}$ = 8 TeV
Heavy flavour channel: $\mathbf{D/B} \rightarrow \boldsymbol{\tau(3\mu)X}$

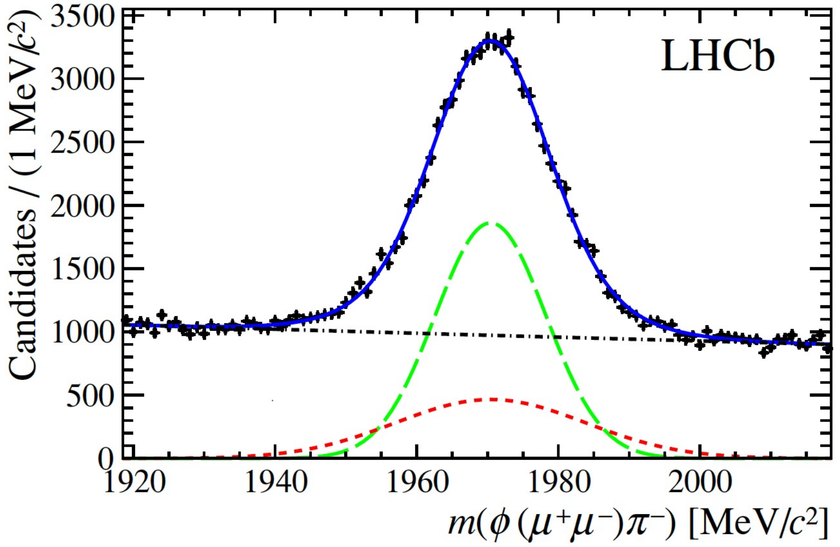
- Isolated and displaced 3μ signature
- Small pointing angle



Analysis strategy:

- Background described using data in the mass sidebands (SB)
- Normalisation channel $D_s \rightarrow \phi(\mu\mu)\pi$

$$\mathcal{B}(\tau^- \rightarrow \mu^-\mu^+\mu^-) = \frac{\mathcal{B}(D_s^- \rightarrow \phi(\rightarrow \mu^+\mu^-)\pi^-)}{\mathcal{B}(D_s^- \rightarrow \tau^-\bar{\nu}_\tau)} \times f_\tau^{D_s} \times \frac{\epsilon_{\text{cal}}}{\epsilon_{\text{sig}}} \times \frac{N_{\text{sig}}}{N_{\text{cal}}}$$



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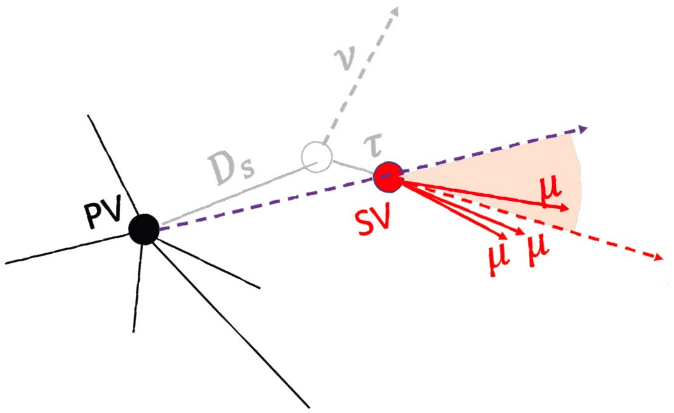
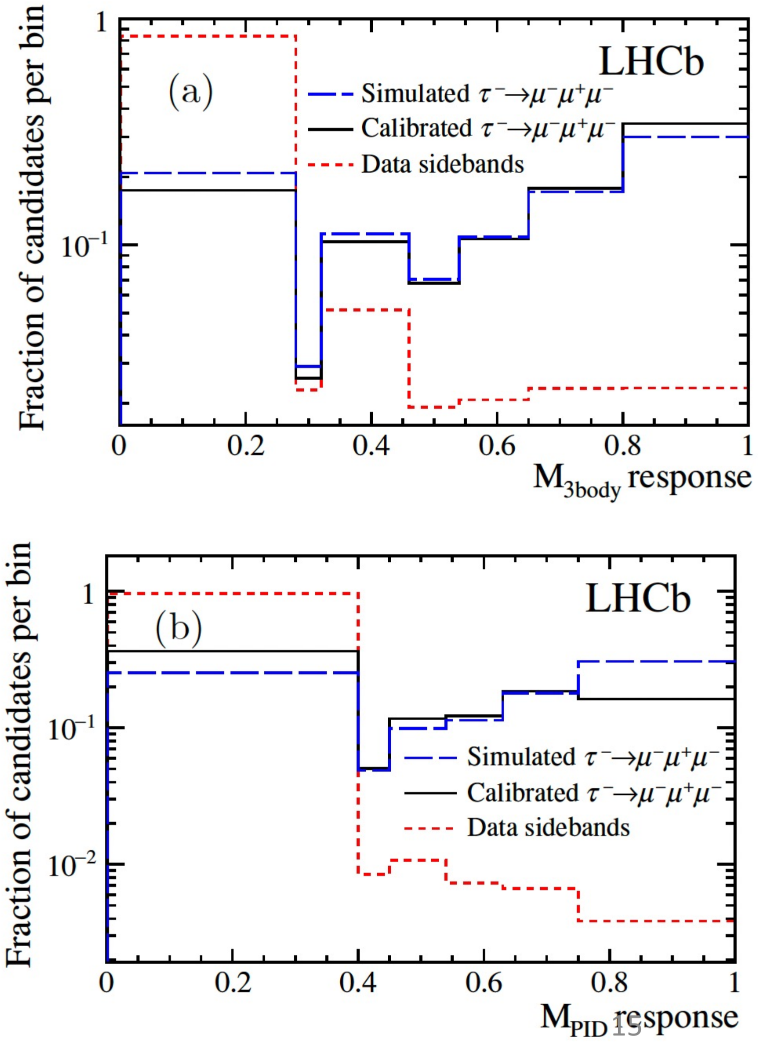


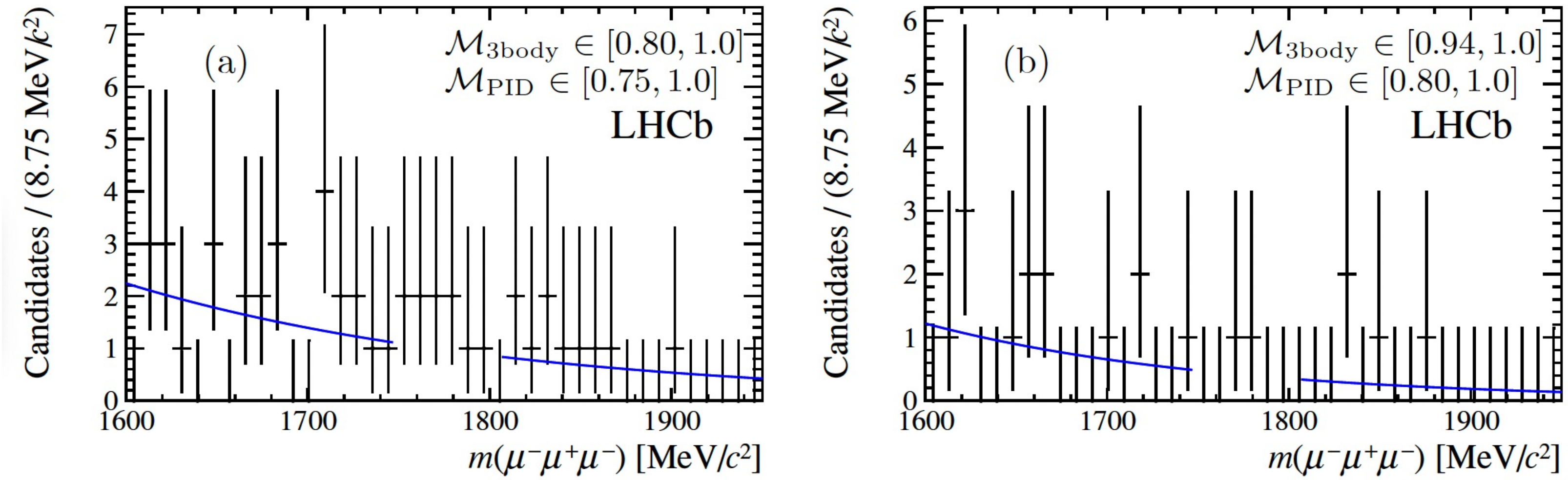
Analysis strategy:

- Background described using data in the mass sidebands (SB)
- Normalisation channel $D_s \rightarrow \phi(\mu\mu)\pi$
- Background rejection:
  - $m(3\mu)$ invariant mass of the τ candidate
  - $\mathcal{M}_{3body}$ BDT trained using three-body decay topology features
  - $\mathcal{M}_{PID}$ NN trained using inputs from the RICH detector to identify muons

→ Fit invariant $m(3\mu)$ in each bin of $\mathcal{M}_{3body} \times \mathcal{M}_{PID}$

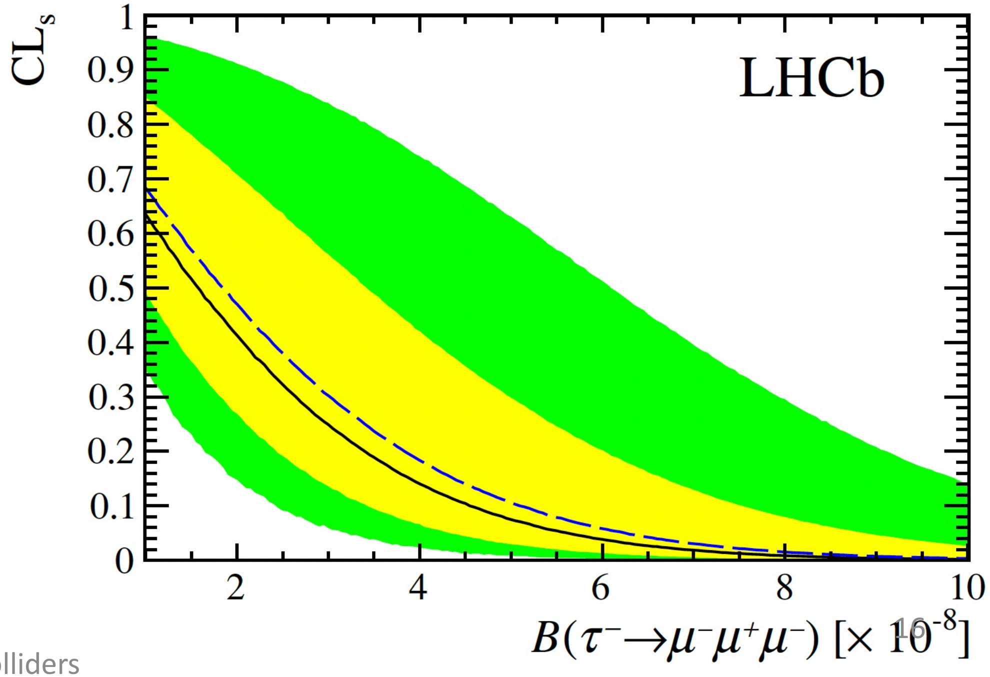


Search for $\tau \rightarrow 3\mu$ decays with the LHCb detector

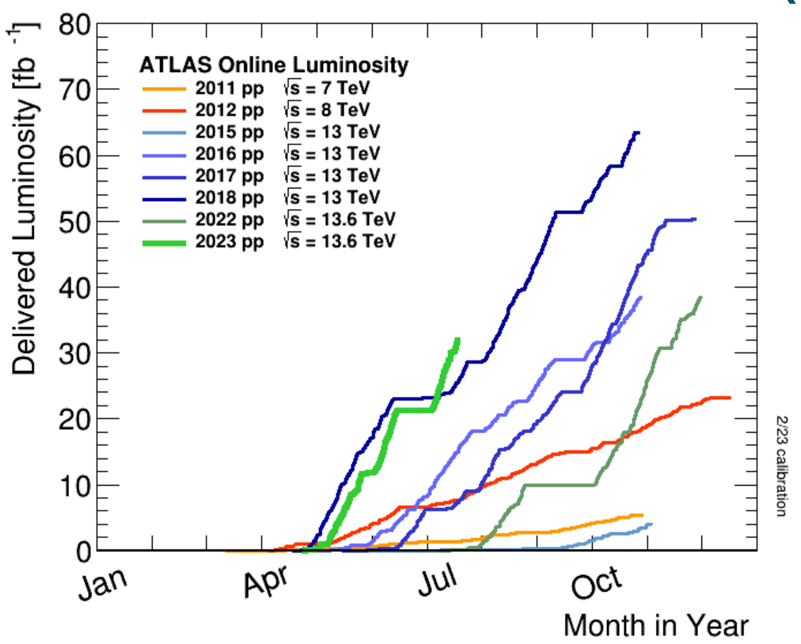


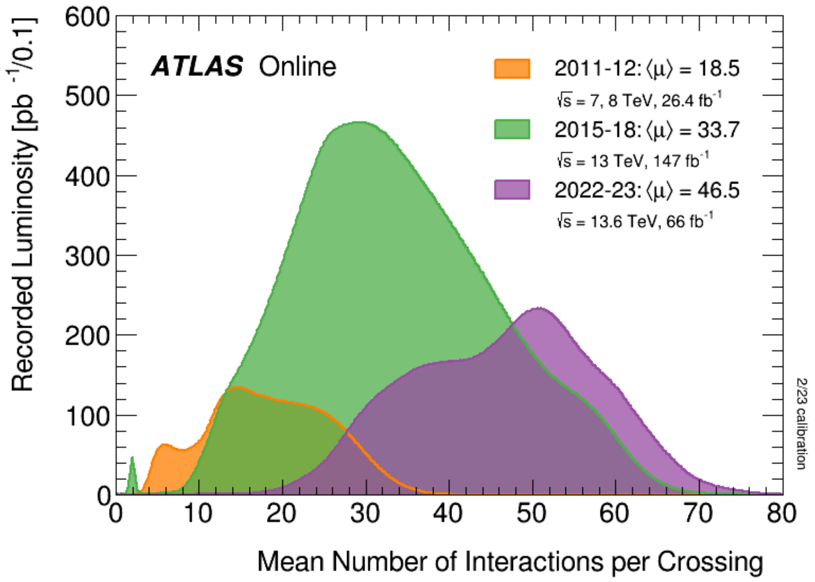
Results:

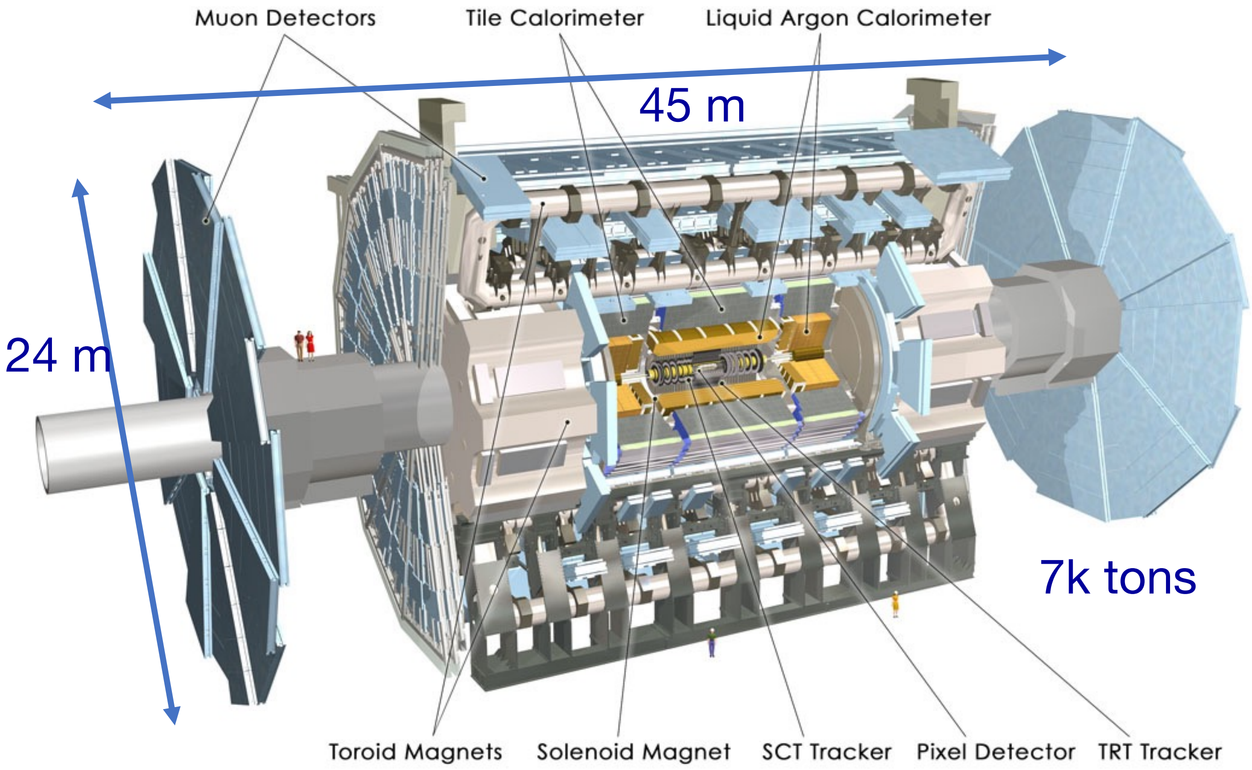
- All bins compatible with bkg-only hypothesis
- Observed (expected) upper limit of **4.6×10^{-8}** on. Br($\tau \rightarrow 3\mu$) at **90 % CL** using phase-space $\tau \rightarrow 3\mu$ simulation
- Model-independent analysis of the decay distributions in an EFT approach including BSM operators with different chirality structures → the observed limit varies within the **range (4.1 – 6.8) $\times$ 10^{-8}**



ATLAS (A Toroidal LHC ApparatuS)







Muon p_T resolution: ~3%

Muon acceptance: $|\eta| < 2.7, p_T > 3$ GeV

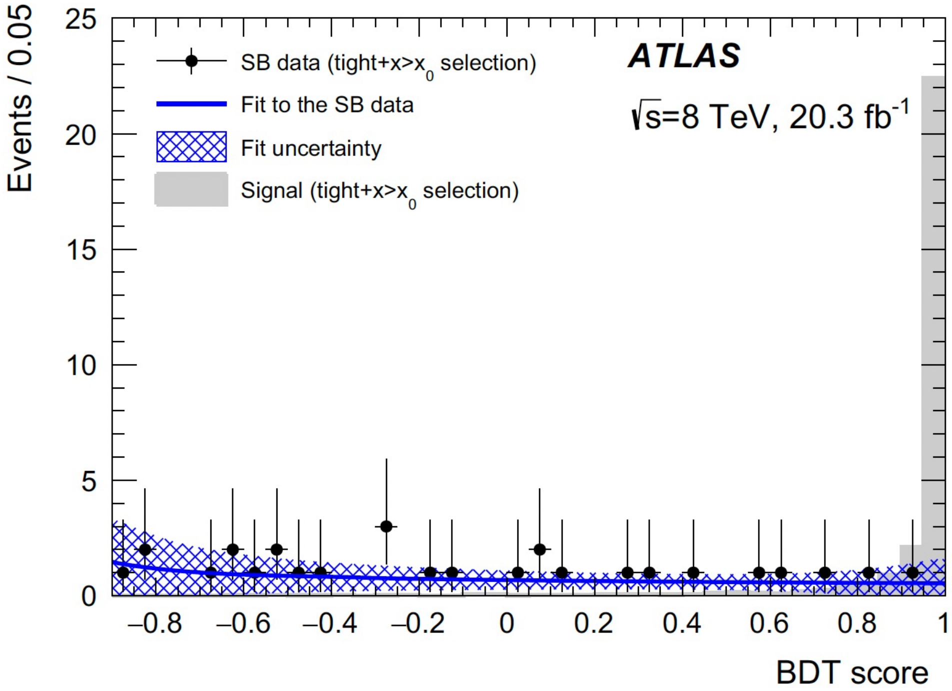
Search for $\tau \to 3\mu$ decays with the ATLAS detector

[EPJ C (2016) 76 232]

Result based on 20.3 fb^{-1} at $\sqrt{s}$ = 8 TeV
W channel only: $\mathbf{W \to \tau(3\mu)\nu_\tau}$
- Missing energy
- Isolated and displaced 3μ signature

$$\mathcal{B}(\tau^- \to \mu^-\mu^+\mu^-) = \frac{N_{\text{sig}}}{\epsilon_{\text{sig}} \times \sigma_{W^- \to \tau^-\bar{\nu}_\tau} \times \mathcal{L}}$$

Analysis strategy:
- Background described using data in the mass sidebands (SB)
- $\mathcal{B}(\tau \to 3\mu)$ estimated based on $W \to \mu\nu$ cross-section measurement (PRD 85 (2012) 072004)

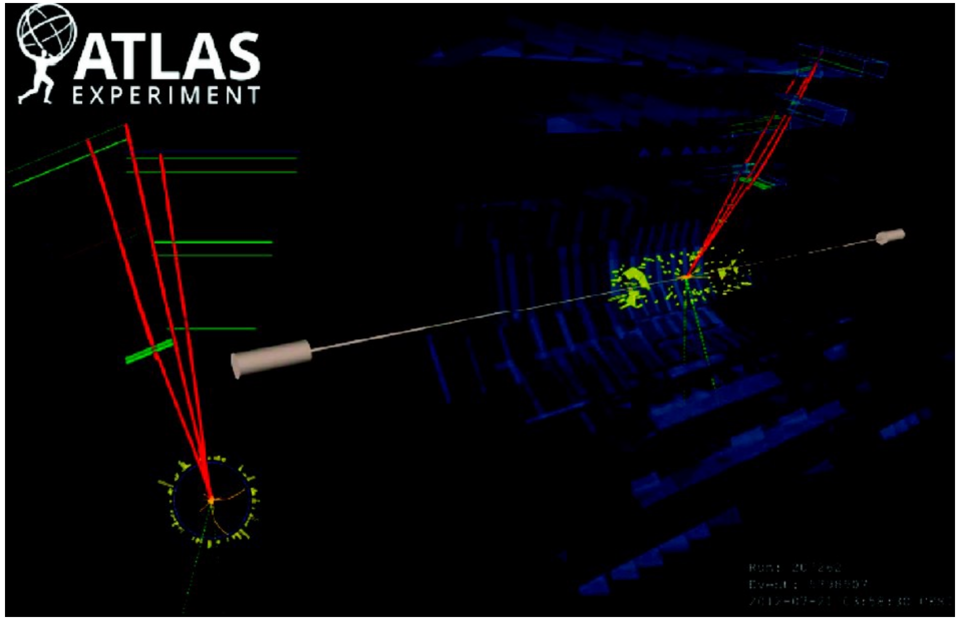


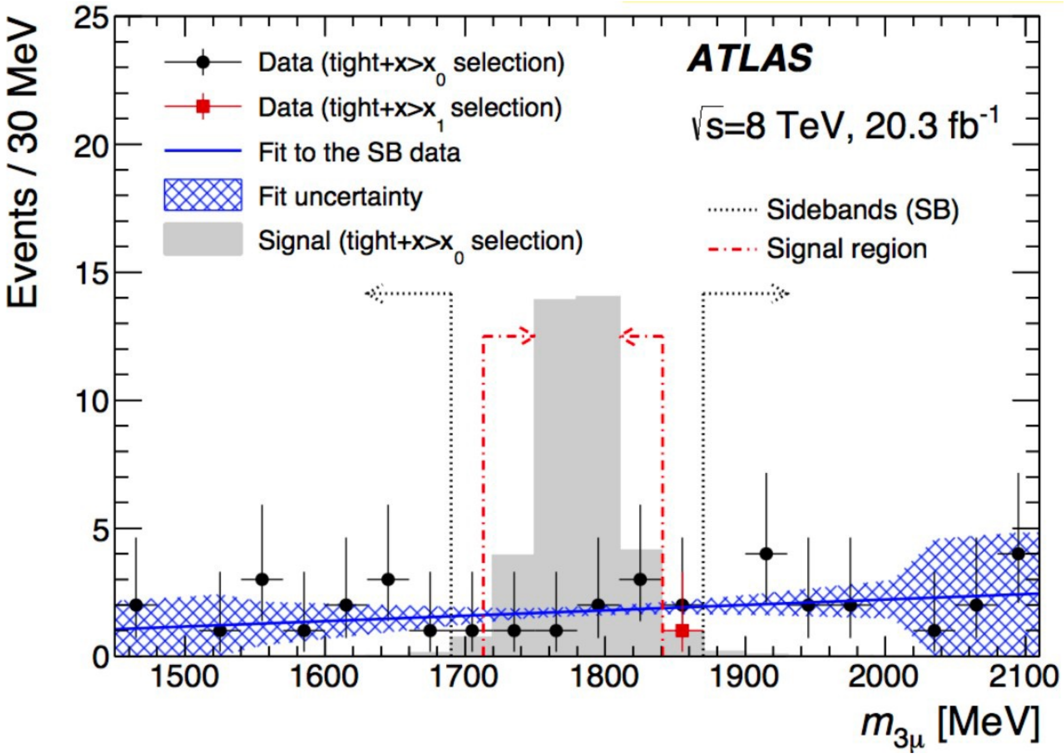
Workflow:
1. Train BDT and apply loose cut x_0 on BDT output x
2. Cut-based tight selection
3. Estimate bkg yield from mass SB using "tight + x > x_0"
4. Fit BDT output in region x > x_0

5. Apply tight cut x_1 on BDT output, optimising for the expected $\mathcal{B}$ limit
6. Extrapolate background yield for "tight + x > x_1"

Search for $\tau \to 3\mu$ decays with the ATLAS detector

[EPJ C (2016) 76 232]

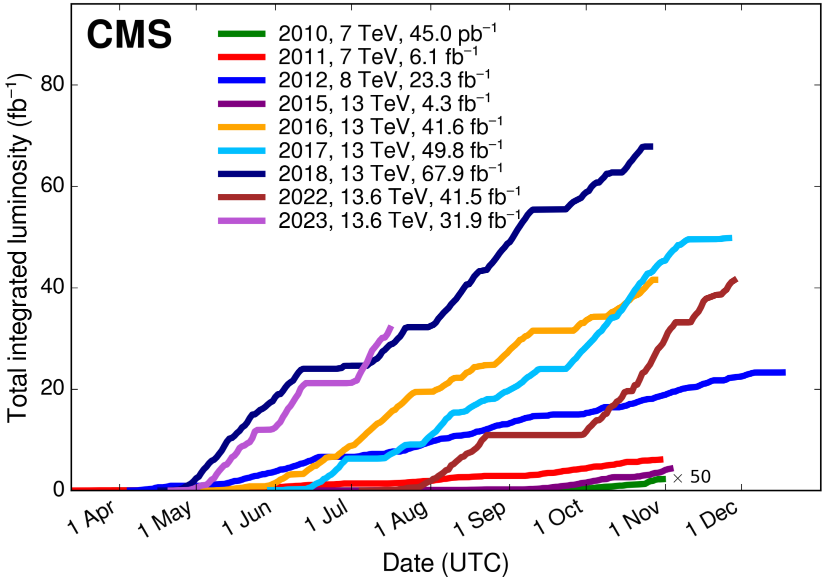


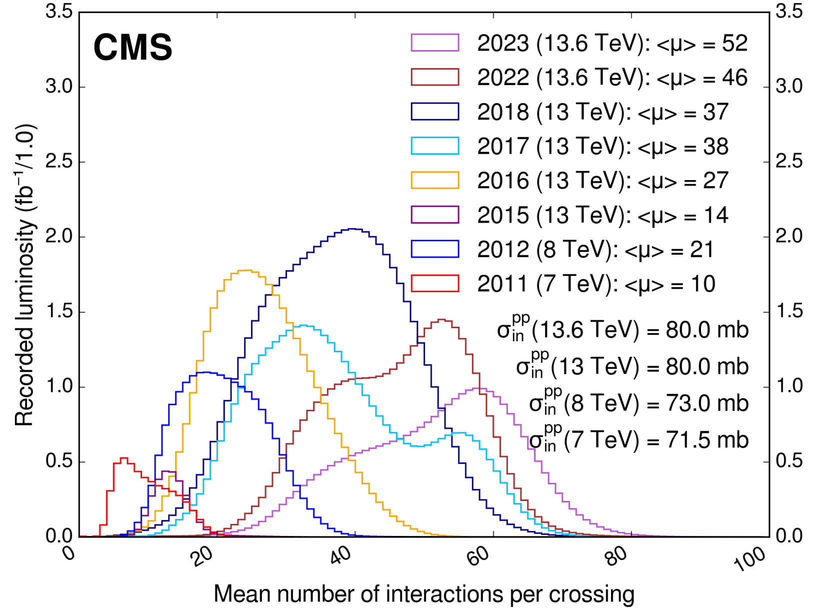


Results:

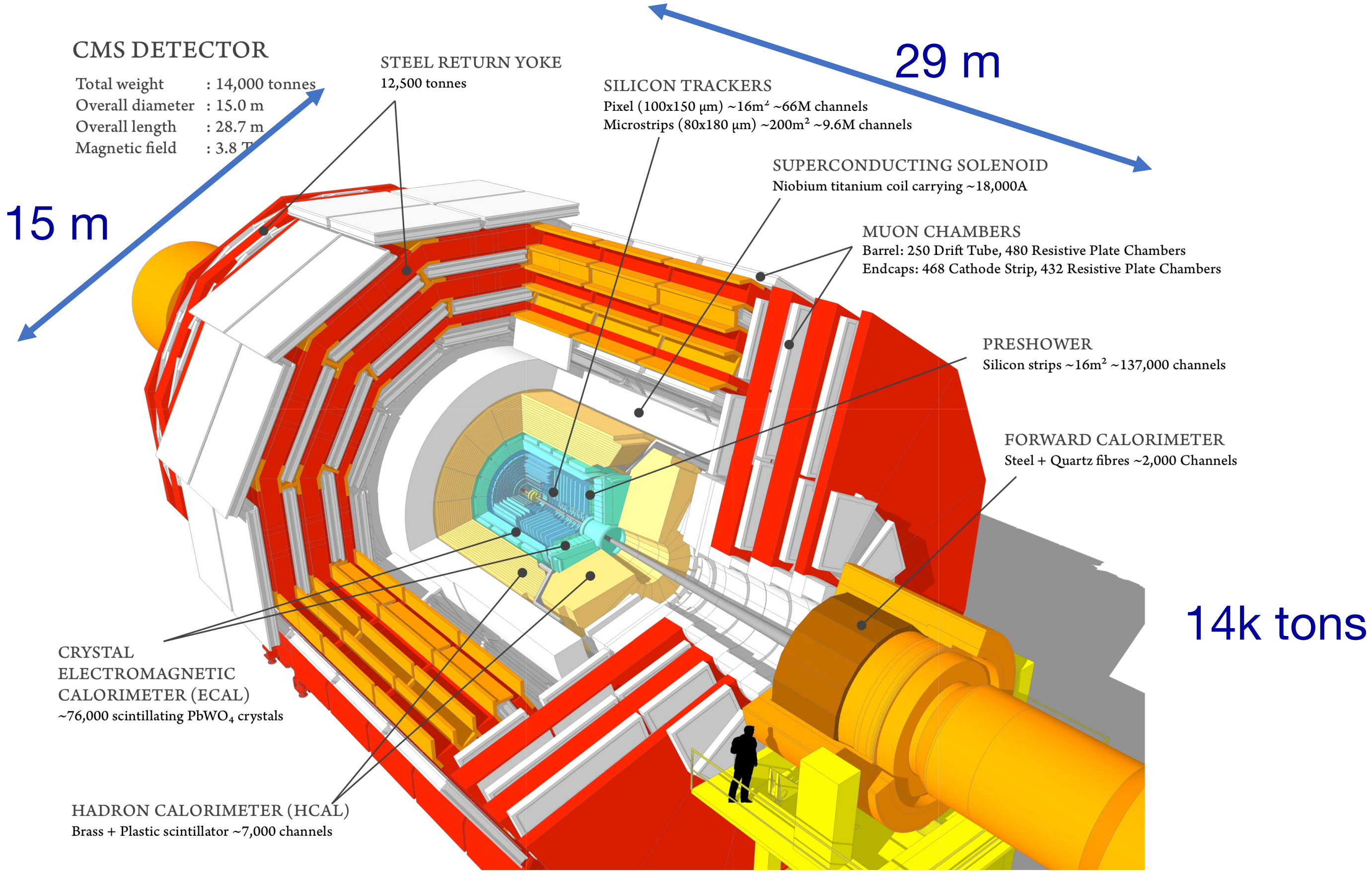
- No events found in signal region
- Expected background N_{bkg} = 0.193 ± 0.037 (stat) ± 0.131 (syst) (dominant uncertainty = extrapolation procedure)
- Efficiency ε_{sig} = 0.0231 ± 0.0005 (Jet) ± 0.0009 (MC) ± 0.0025 (trig) ± 0.0030 (reco)
- Limit: **observed** (expected) upper limit of **3.76×10^{-7}** (3.94×10^{-7}) on Br($\tau \to 3\mu$) at **90 % CL**

CMS (Compact Muon Solenoid)





Muon p_T resolution: 1% (3%) in barrel (endcaps)
Muon acceptance: $|\eta| < 2.4, p_T > 3.5\ (2.0)$ GeV in barrel (endcaps)



Search for $\tau \to 3\mu$ decays at CMS

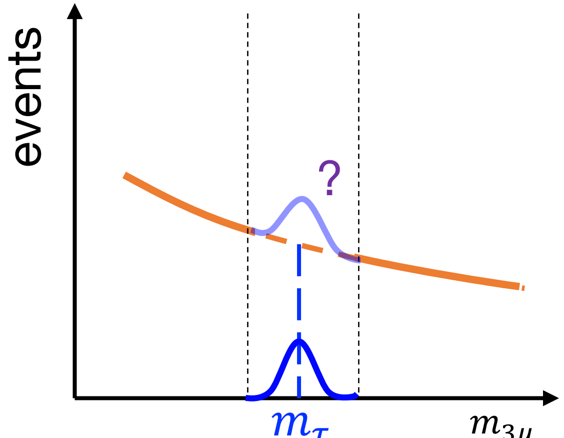
BPH-21-005 (2023) submitted to PLB

Result based on 131 fb^{-1} at $\sqrt{s}$ = 13 TeV (full Run 2)
Both W and HF channels exploited! Given the different topology, the analysis strategies are different, and the results are statistically combined

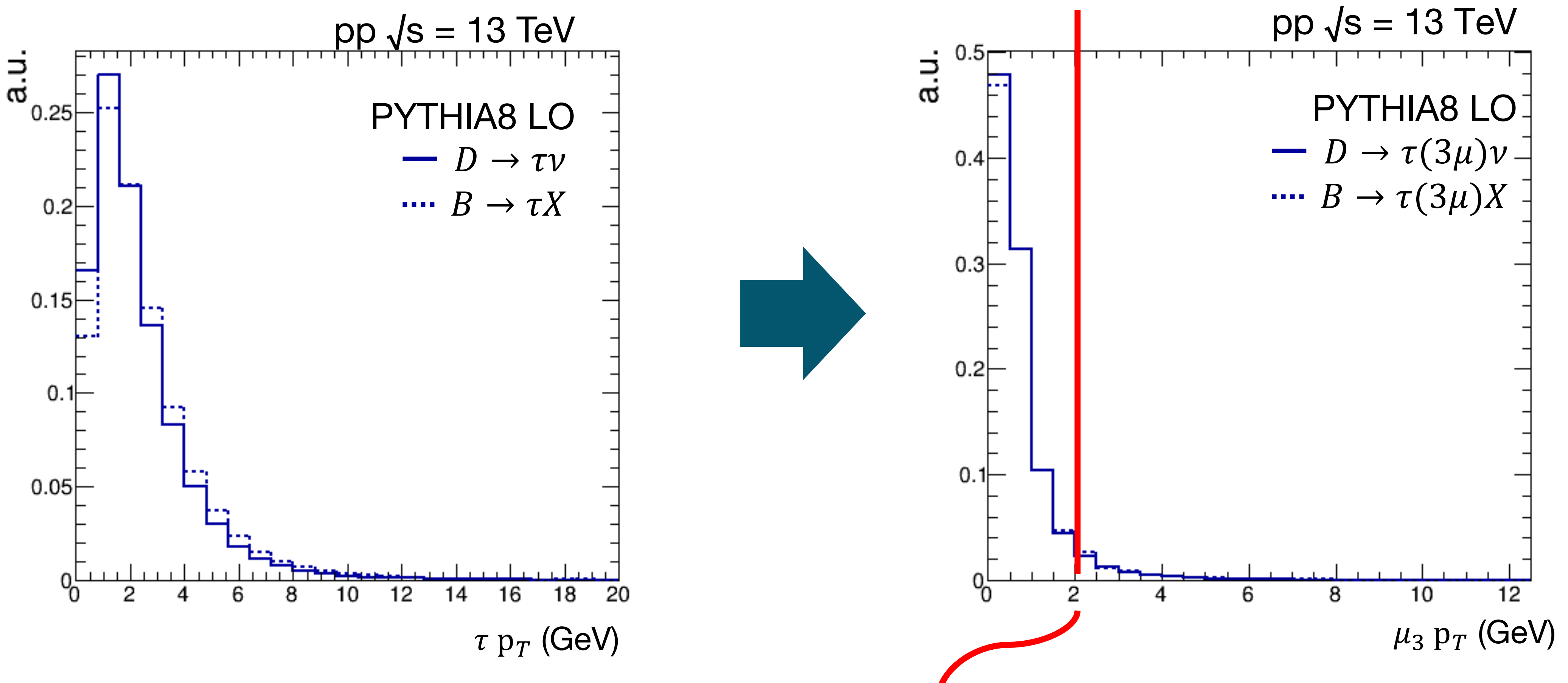
Analysis of 2016 data from previous paper: doi:10.1007/JHEP01(2021)163

2017+2018 data analysis overview:

- **online event selection:** dedicated trigger paths selects events with three muons or two muons and a track
- **offline signature:** charge-one three muon events from a displaced vertex
- **categorization** based on the invariant mass resolution and production channel
- **figure of merit**: three-muon invariant mass distribution

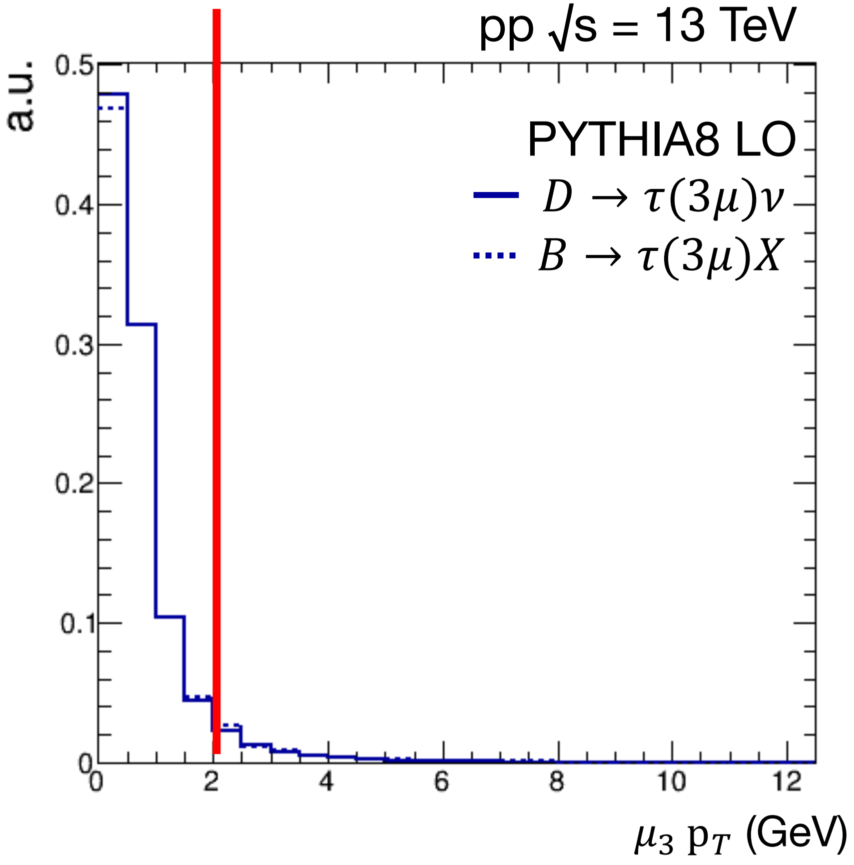


Search for $\tau \to 3\mu$ decays at CMS – HF channel



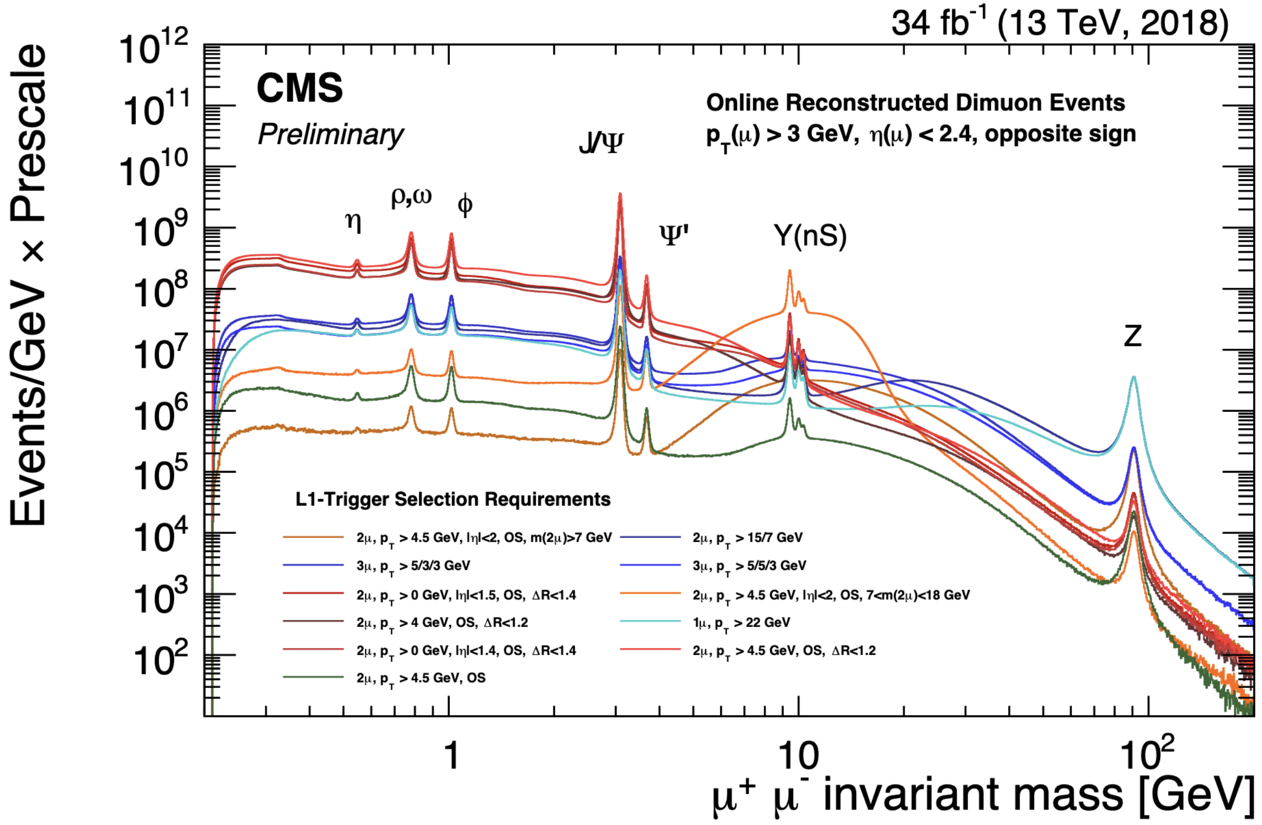
CMS muon acceptance $p_T > 2$ GeV → two orders of magnitude reduction of D/B → τ events

Search for $\tau \to 3\mu$ decays at CMS – HF channel



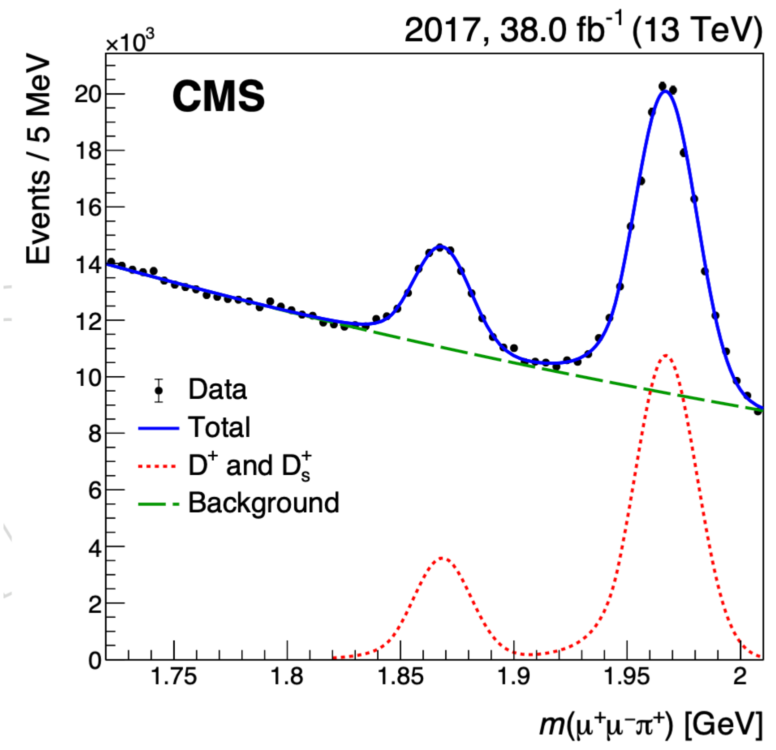
Flavour physics programme at CMS allowed by:

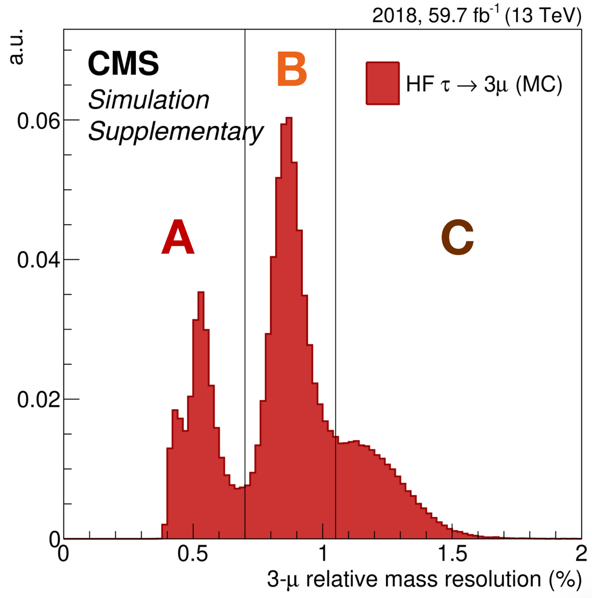
- Large trigger bandwidth for low p_T muons
- Dedicated trigger algorithms at low $m(2\mu)$ and $m(3\mu)$ masses



Search for $\tau \to 3\mu$ decays at CMS – HF channel

$$N_{3\mu(D)} = N_{\mu\mu\pi} \frac{\mathcal{B}(D_s^+ \to \tau^+\nu_\tau)}{\mathcal{B}(D_s^+ \to \phi\pi^+ \to \mu^+\mu^-\pi^+)} \frac{\mathcal{A}_{3\mu(D)}}{\mathcal{A}_{\mu\mu\pi}} \frac{\epsilon^{\text{reco}}_{3\mu(D)}}{\epsilon^{\text{reco}}_{\mu\mu\pi}} \frac{\epsilon^{2\mu\text{trig}}_{3\mu(D)}}{\epsilon^{2\mu\text{trig}}_{\mu\mu\pi}} \mathcal{B}(\tau \to 3\mu)$$





Online: dedicated trigger
2μ + 1 track forming displaced vertex

A: best reso. → ~ barrel

B: medium reso. → ~ overlap

C: low reso. → ~ endcap

cut-based loose selections

BDT training (MC vs data SB)

- Topology: displacement, vertex,iso etc
- muon reco. quality (MVA)

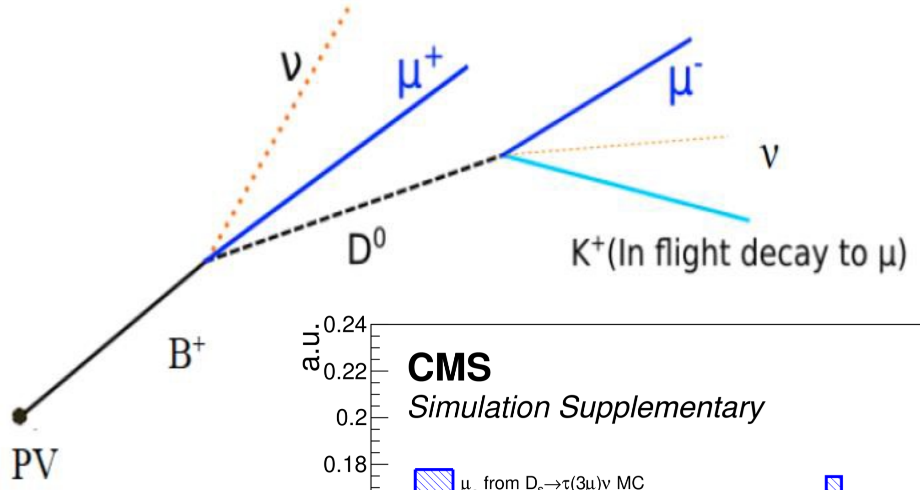
background rejection based on BDT score and **final categorisation**

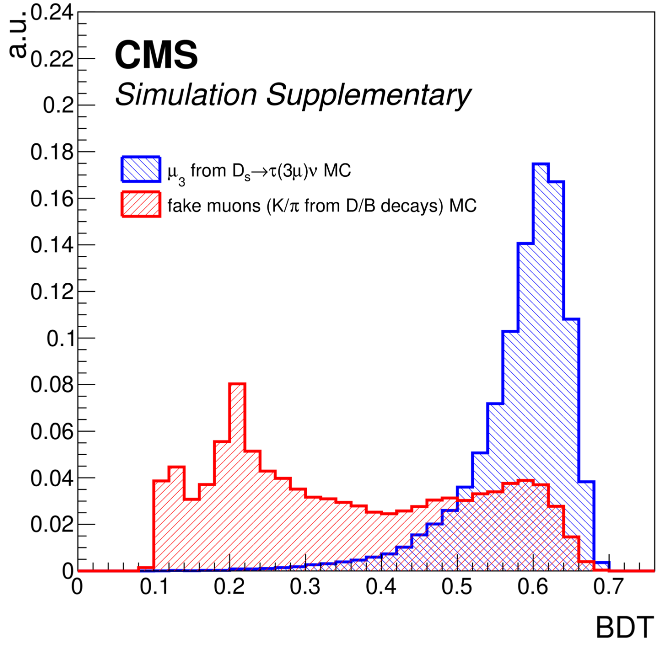
Search for $\tau \to 3\mu$ decays at CMS – HF channel

Background composition:
The dominant background is combinatorial of two real muons plus one fake (typically decay-in-flight)
Most common one is B→D cascade decay, for example
- B → D + μ + X
- D → μ + ν + Kaon
- Kaon fakes muon

The second source is background with 3 genuine muons two of which come from resonances
→ ϕ(1020) and omega(783)
→ Ds → η (μμγ) μν

No peaking background in the search region (1.6-2.0 GeV)
→ Data sidebands are used as proxies of background



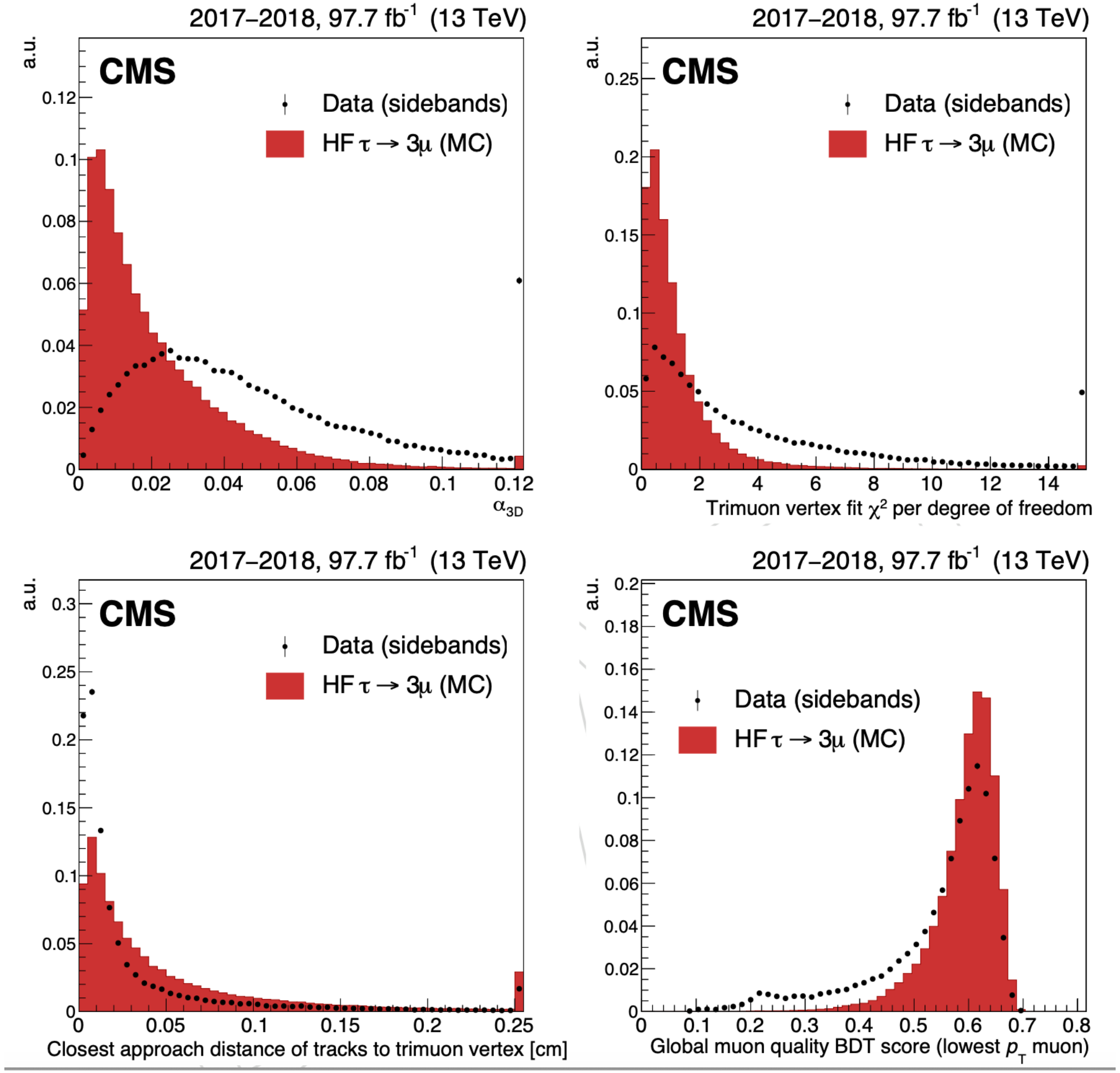


A BDT is used for low-p_T muon identification, trained on MC signal muons vs fake muons from pion/kaon decays using reconstruction quality features.

Search for $\tau \rightarrow 3\mu$ decays at CMS – HF channel

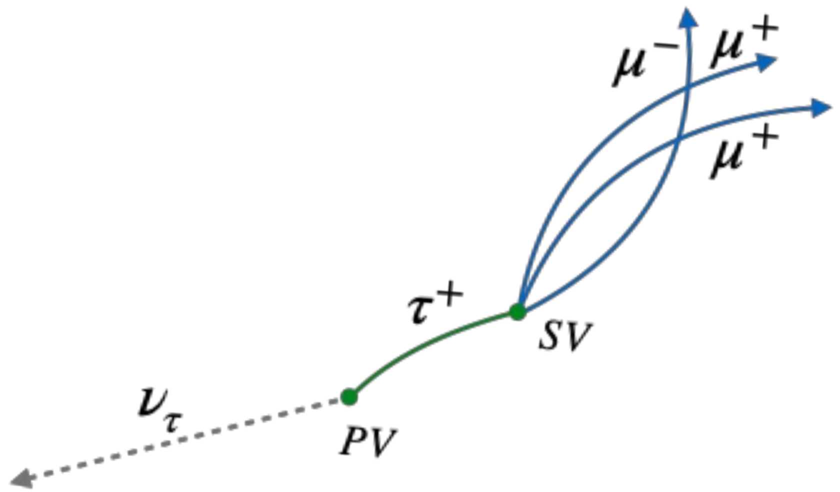
Background rejection:

- Cut-based preselections
- Additional categorisation based on the reconstruction of the lowest-p_T muon
- Multivariate analysis used to suppress dominant backgrounds
    - Signal MC vs data sideband
    - Features with highest importance:
        - α_{3D} pointing angle
        - 3μ vertex fit χ^2
        - the smallest distance of closest approach to the trimuon vertex of all the other tracks in the event with $p_T > 1$ GeV
        - muon reconstruction quality BDT score of the lowest p_T muon



Search for $\tau \rightarrow 3\mu$ decays at CMS – W channel

$$N_{3\mu(W)} = \mathcal{L}\,\sigma(pp \rightarrow W + X)\,\mathcal{B}(W \rightarrow \tau\nu_\tau)\,\mathcal{A}_{3\mu(W)}\,\epsilon_{3\mu(W)}\,\mathcal{B}(\tau \rightarrow 3\mu)$$



Online: dedicated trigger
3μ forming isolated tau candidate

Efficiency corrections (trigger, μID) applied to MC

Train Boosted Decision Tree for signal-background separation
- Signal: MC - Bkg: data in mass sidebands

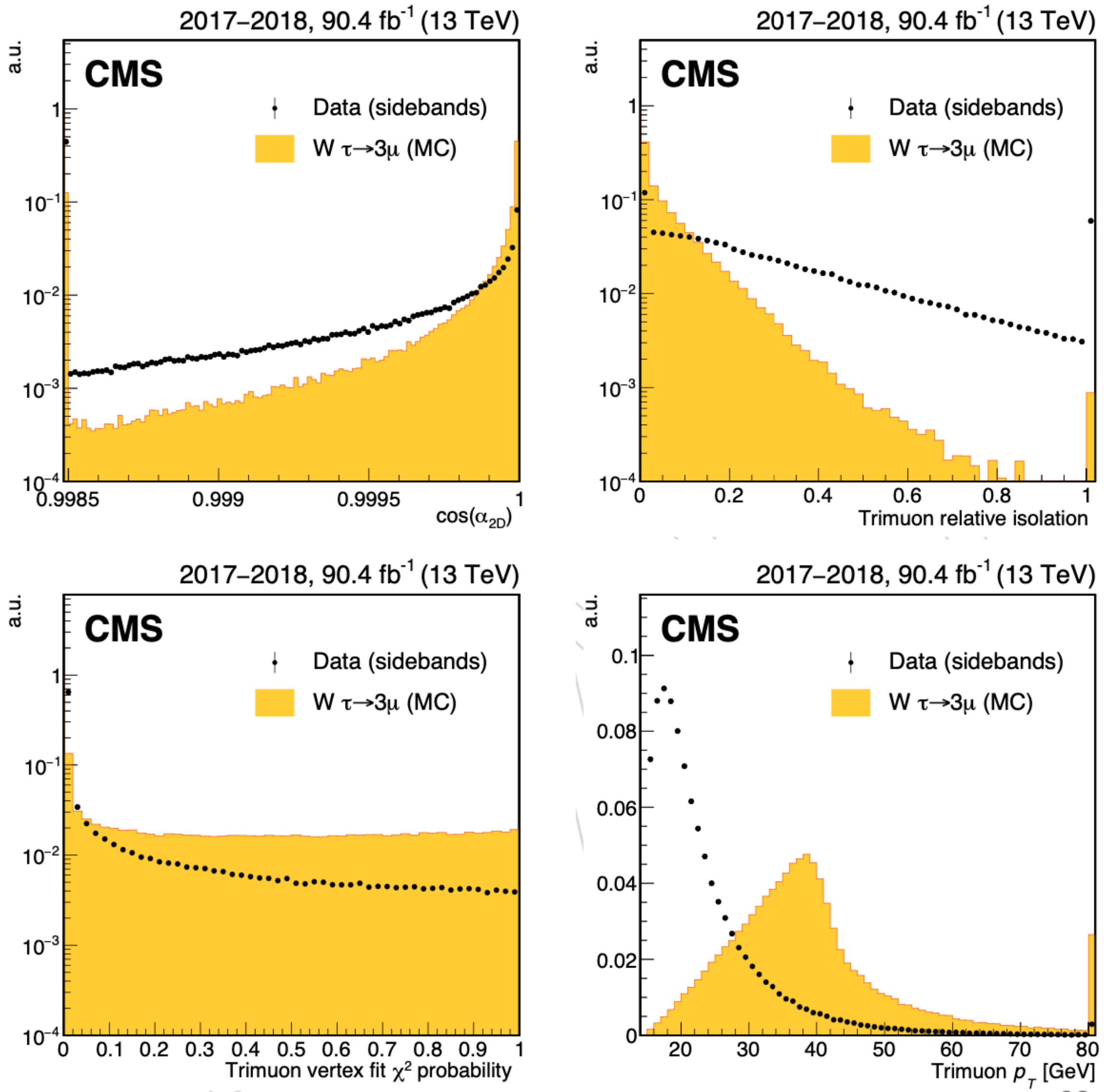
Event categories based on m(3μ) resolution ~ barrel, overlap, endcap

Search for $\tau \to 3\mu$ decays at CMS – W channel

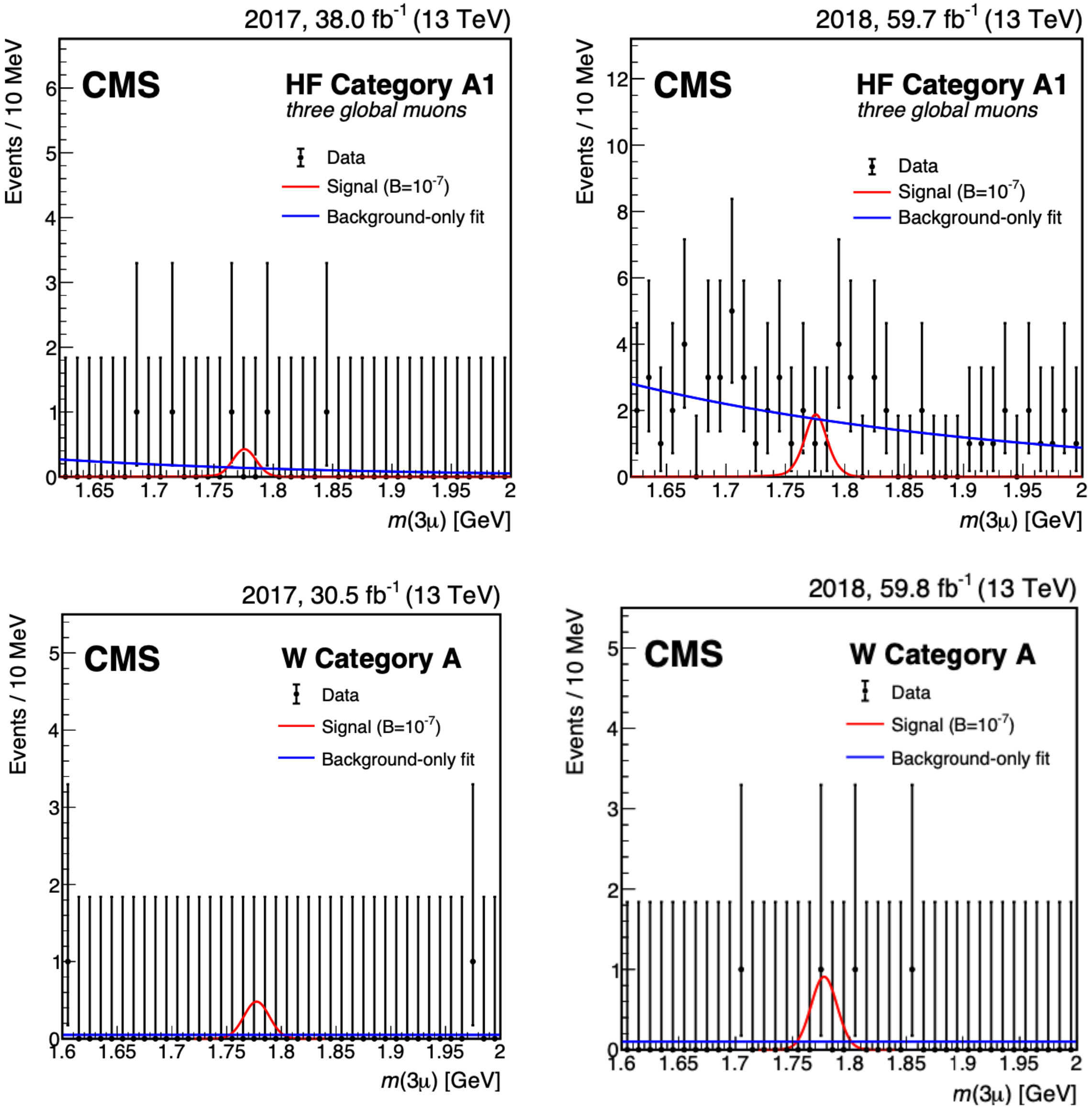
Background rejection:

- Cut-based loose preselections

- Multivariate analysis (BDT) to enhance signal sensitivity
  - Signal MC vs data sideband
  - Most discriminating features:
    - Pointing angle
    - Isolation of the tau candidate
    - p_T of the tau
  - Other useful observations include the transverse mass, trimuon vertex fit quality, trimuon vertex displacement ..



Search for $\tau \to 3\mu$ decays at CMS – Results



Dominant systematics related to signal normalisation, muon reconstruction and identification efficiencies etc

Results dominated by statistical uncertainty

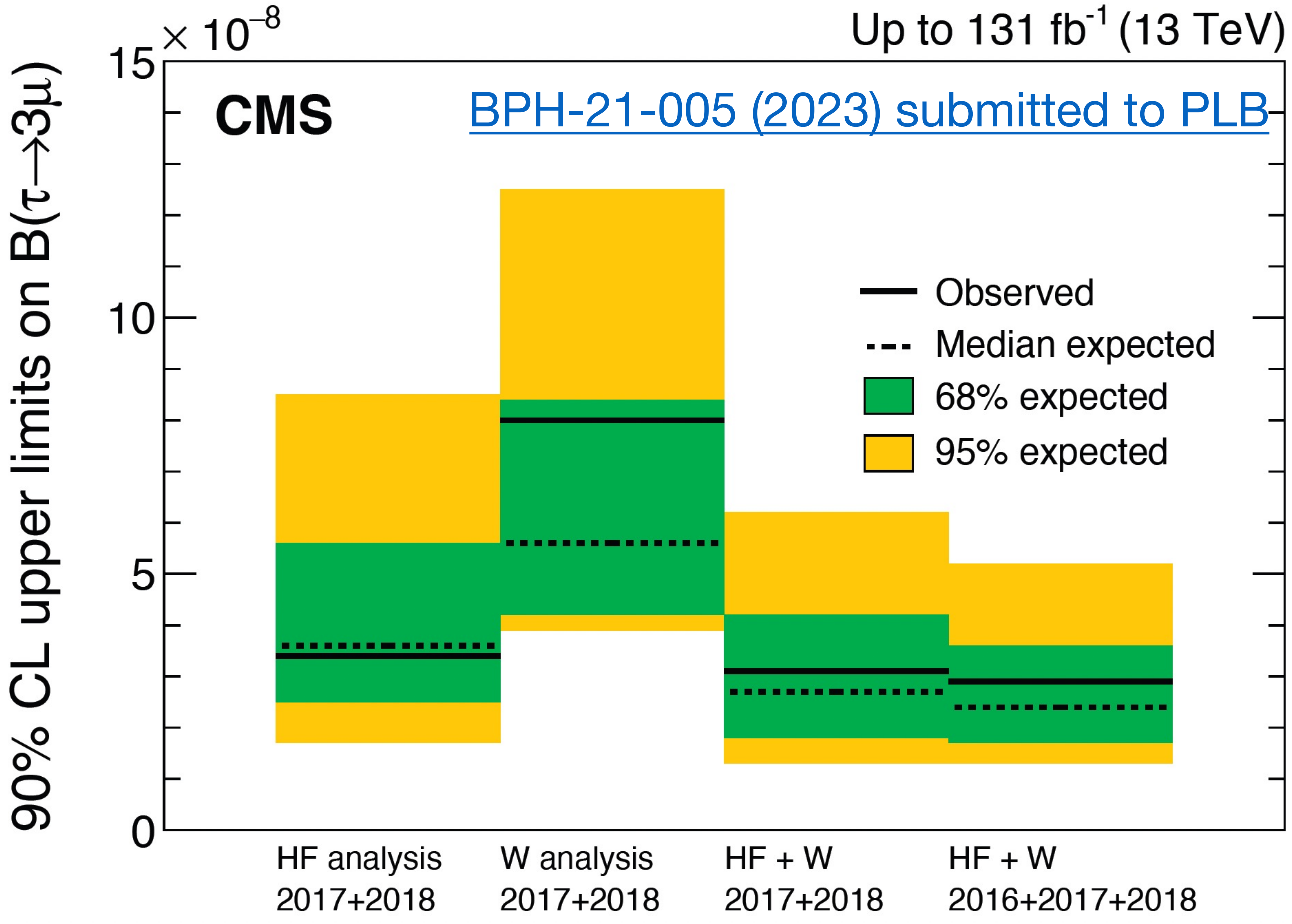
2017+2018 analysis results:

HF channel: observed (exp) upper limit:
3.4×10^{-8} (3.6×10^{-8}) 90% CL

W channel: observed (exp) upper limit:
8.0×10^{-8} (5.6×10^{-8}) 90% CL

BPH-21-005 (2023) submitted to PLB

Search for $\tau \rightarrow 3\mu$ decays at CMS – Results



Analysis of 2016 data from previous paper:
doi:10.1007/JHEP01(2021)163

New analysis of 2017+2018 data combined with 2016 for the full Run 2 result:

Observed (exp) upper limit:
2.9×10^{-8} (2.4×10^{-8}) 90% CL

Conclusions and perspectives

$\tau \rightarrow 3\mu$ decays as a golden channel for probing LFV in the charged sector

- clean experimental signature
- at hadron colliders: high number of tau lepton produced with different mechanisms (HF channel, W channel)

The ATLAS and LHCb experiments carried out this search using Run 1 data

CMS recently published the full Run 2 analysis, setting the best upper limit at LHC, but still far from Belle II

Conclusions and perspectives

What's next?

CMS Run 3: dedicated trigger strategies for low-energy muons are expected to further enhance the signal significance in the HF channel

LHCb Run 2 result expected to be in the same ballpark as Belle II → stay tuned

This search is mostly dominated by statistical uncertainties: HL-LHC is expected to give a major boost to LFV studies!

Backup

HF Branching fractions

Process	Branching ratio (BR)	Reference
$D_s \to \tau\nu_\tau$	$(5.48 \pm 0.23){\cdot}10^{-2}$	PDG [10]
$B^+ \to \tau\nu_\tau\bar{D}^0$	$(7.7 \pm 2.5){\cdot}10^{-3}$	PDG [10]
$B^+ \to \tau\nu_\tau D^{*0}$	$(1.88 \pm 0.20){\cdot}10^{-2}$	PDG [10]
$other B^+ \to \tau\nu_\tau X$	$0.7{\cdot}10^{-2}$	PYTHIA [84]
$B^0 \to \tau\nu_\tau D^{*-}$	$(1.57 \pm 0.09){\cdot}10^{-2}$	PDG [10]
$B^0 \to \tau\nu_\tau D^-$	$(1.08 \pm 0.23){\cdot}10^{-2}$	PDG [10]
$other B^0 \to \tau\nu_\tau X$	$0.7{\cdot}10^{-2}$	PYTHIA [84]
$D_s \to \phi(\mu\mu)\pi$	$(1.3 \pm 0.1)\ {\cdot}10^{-5}$	PDG [10]
$B^+ \to D_s X$	$(9.0 \pm 1.5){\cdot}10^{-2}$	PDG [10]
$B^0 \to D_s X$	$(10.3 \pm 2.1){\cdot}10^{-2}$	PDG [10]
$B_s^0 \to D_s X$	$(93 \pm 25){\cdot}10^{-2}$	PDG [10]

HL-LHC ATLAS Projections

ATL-PHYS-PUB-2018-032

Upper limits on BR($\tau \to 3\mu$) for different scenarios for an assumed luminosity of 3 ab^{-1} of pp collisions at $\sqrt{s}$ = 14 TeV

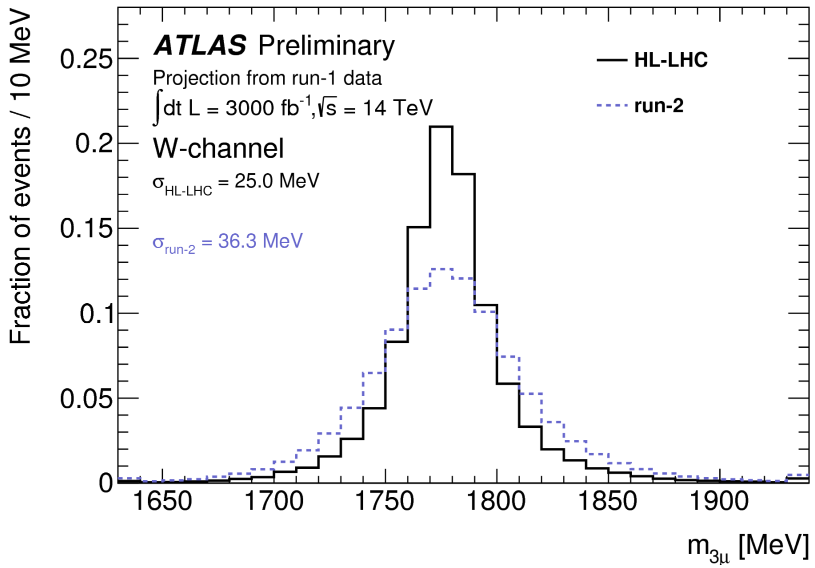
W channel

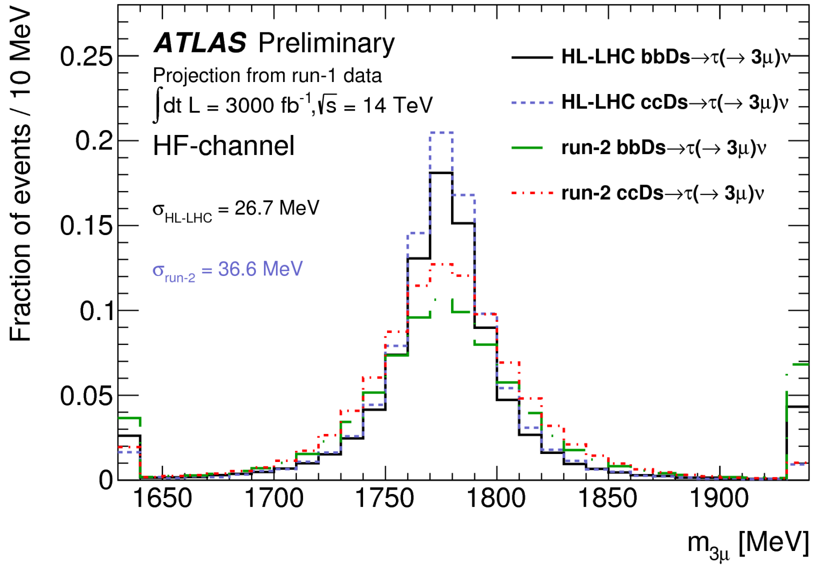
	Scenario	$\mathcal{A} \times \epsilon$ [%]	$N_{\text{bkg}}^{\text{exp}}$	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
	Run 1 result	2.31	0.19	276
	Non-improved	2.31	50.71	13.52
[1]	Intermediate	5.01	50.71	6.23
[2]	Improved	5.01	40.06	5.36

[1] Increased acceptance (trigger, reco) [2] Better S/B separation

HF channel

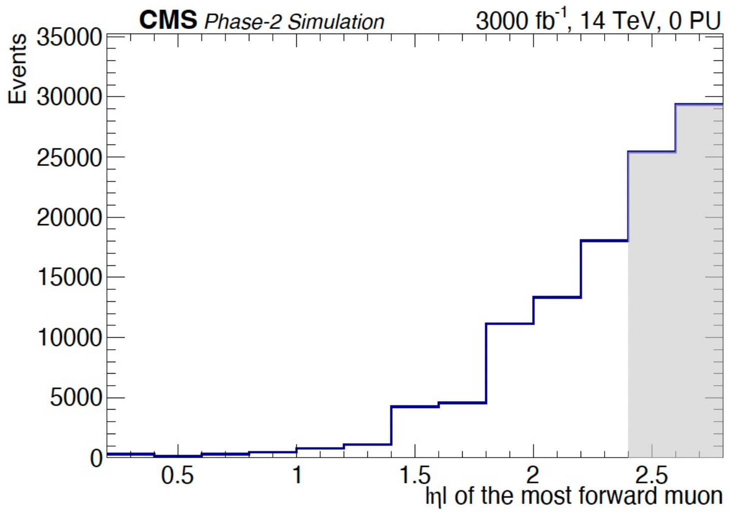
Scenario	$\mathcal{A} \times \epsilon$ [%]	$N_{\text{bkg}}^{\text{exp}}$	90% CL UL on BR($\tau \to 3\mu$) [10^{-9}]
High background	0.88	507.05	6.40
Medium background	0.88	152.12	2.31
Low background	0.88	50.71	1.03

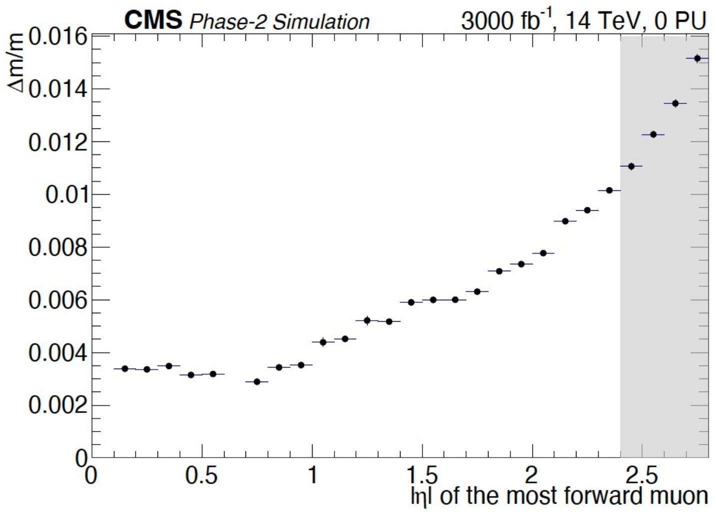


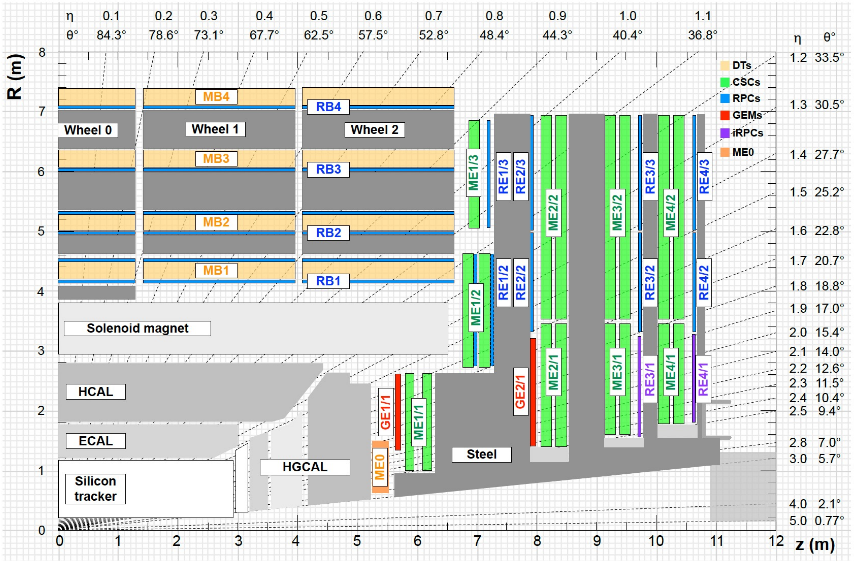


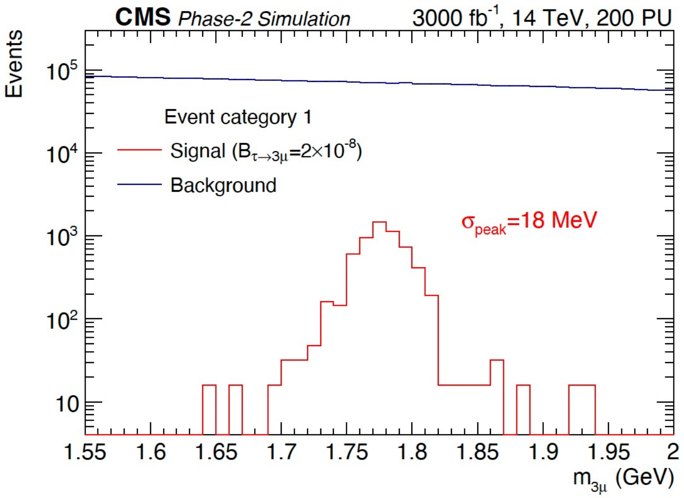
HL-LHC CMS Projections

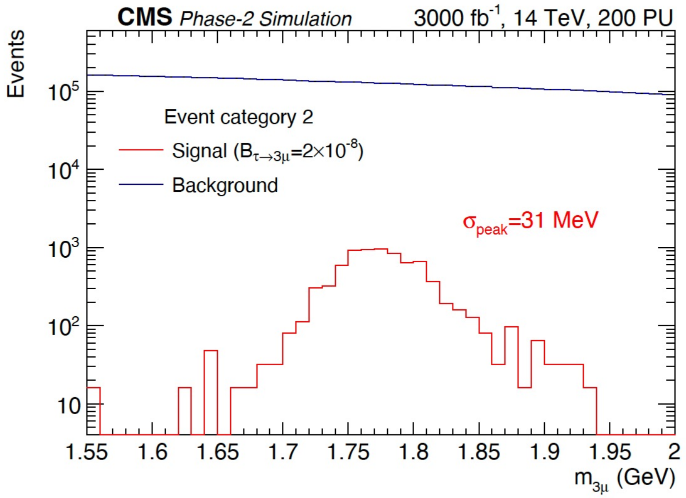
CMS-TDR-016











	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}	

Model independent analysis of LFV tau decays

https://doi.org/10.1088/1126-6708/2007/10/039

A model-independent study on $\tau \to 3\ell$ **decays based on EFT methods:**

- different operators possibly contributing to $\tau \to 3\ell$
- coupling constants are related to the lepton masses and PMNS matrix terms
- Dalitz distributions for the individual chirality structures appearing in the effective Hamiltonian → evaluate how different operators can impact the decay phenomenology

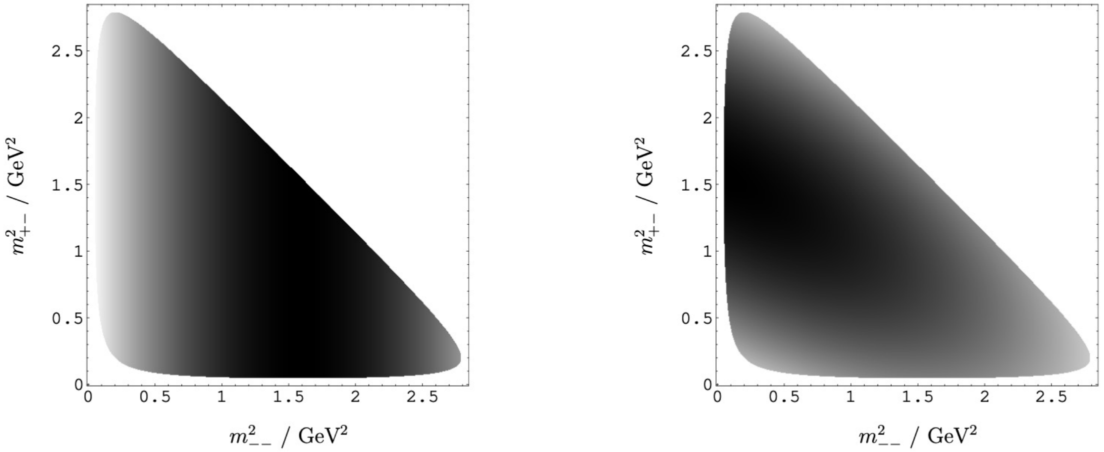


Figure 1: Dalitz plot for $d^2\Gamma_V^{(LL)(LL)}$ (left) and $d^2\Gamma_V^{(LL)(RR)}$ (right) in $\tau^- \to \mu^-\mu^-\mu^+$.

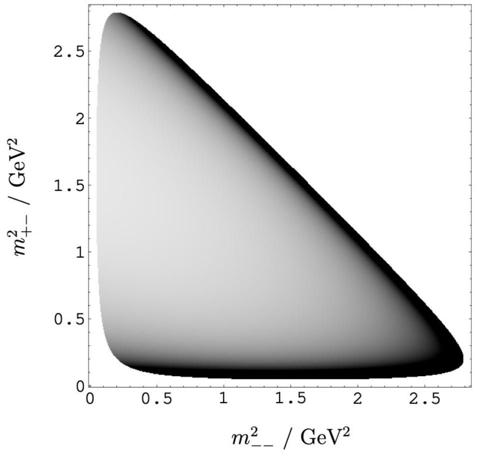


Figure 2: Dalitz plot for $d^2\Gamma_{\rm rad}^{(LR)}$ in $\tau^- \to \mu^-\mu^-\mu^+$.

$$H_{\rm eff}^{(LL)(LL)} = g_V^{(LL)(LL)} \frac{\left(\bar{\ell}_L \gamma_\mu \tau_L\right)\left(\bar{\ell}'_L \gamma^\mu \ell''_L\right)}{\Lambda^2}$$

$$H_{\rm eff}^{(LL)(RR)} = g_V^{(LL)(RR)} \frac{\left(\bar{\ell}_L \gamma_\mu \tau_L\right)\left(\bar{\ell}'_R \gamma^\mu \ell''_R\right)}{\Lambda^2}$$

$$H_{\rm eff}^{\rm rad} = \frac{e}{4\pi}\frac{v}{\Lambda^2}\sum_{h,s} g_{\rm rad}^{(s,h)} \left(\bar{\ell}_h \left(-i\sigma_{\mu\nu}\right)\tau_s\right) F^{\mu\nu}$$

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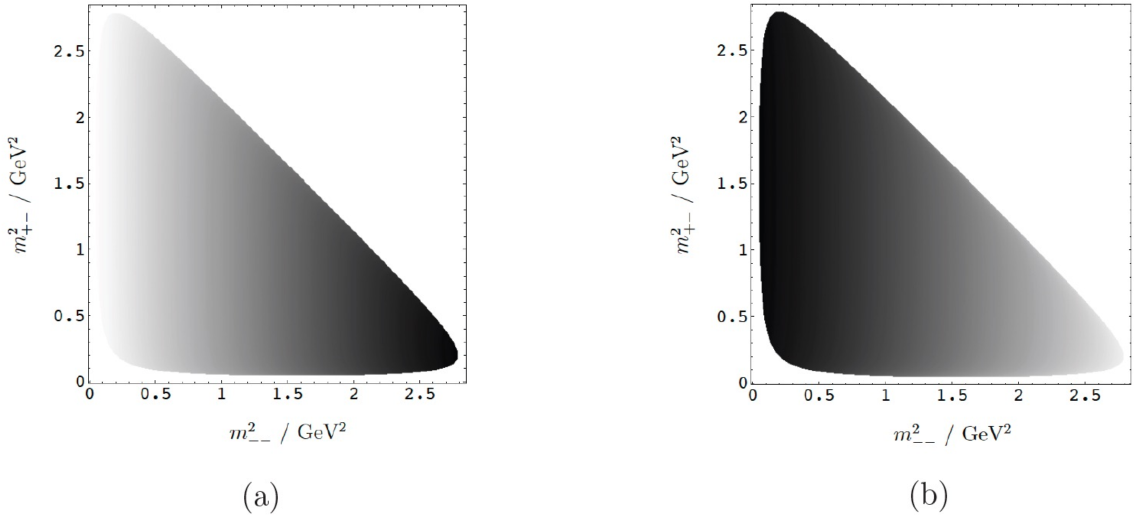


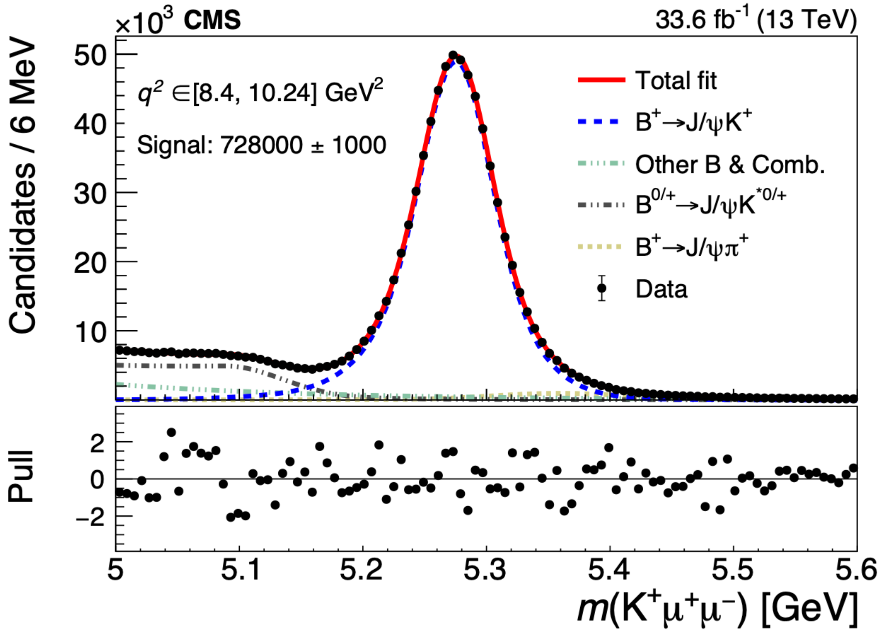
Figure 1.10: Dalitz plot for $d^2\Gamma^{(LL)(LL)}_{\text{mix}}$ (left) and $d^2\Gamma^{(LL)(RR)}_{\text{mix}}$ (right) [48].

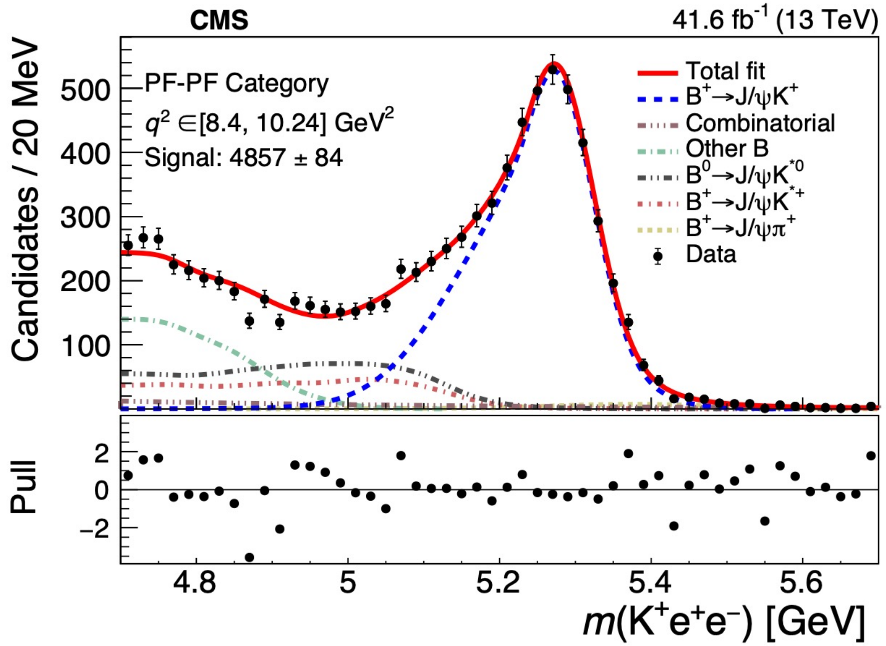
CMS: what about electrons?

- Electron energy resolution ranges from 3 to 5%
- No suitable electron triggers in Run 2
- Higher background expected

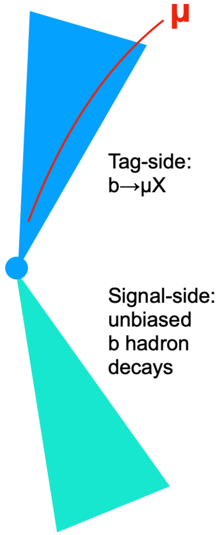
In Run3 → included a low-pT dielectron trigger potentially allowing for LFV searches

Feasibility studies needed



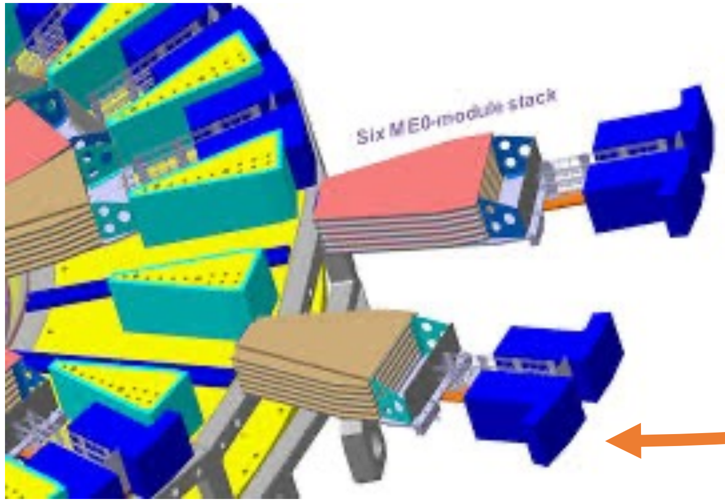


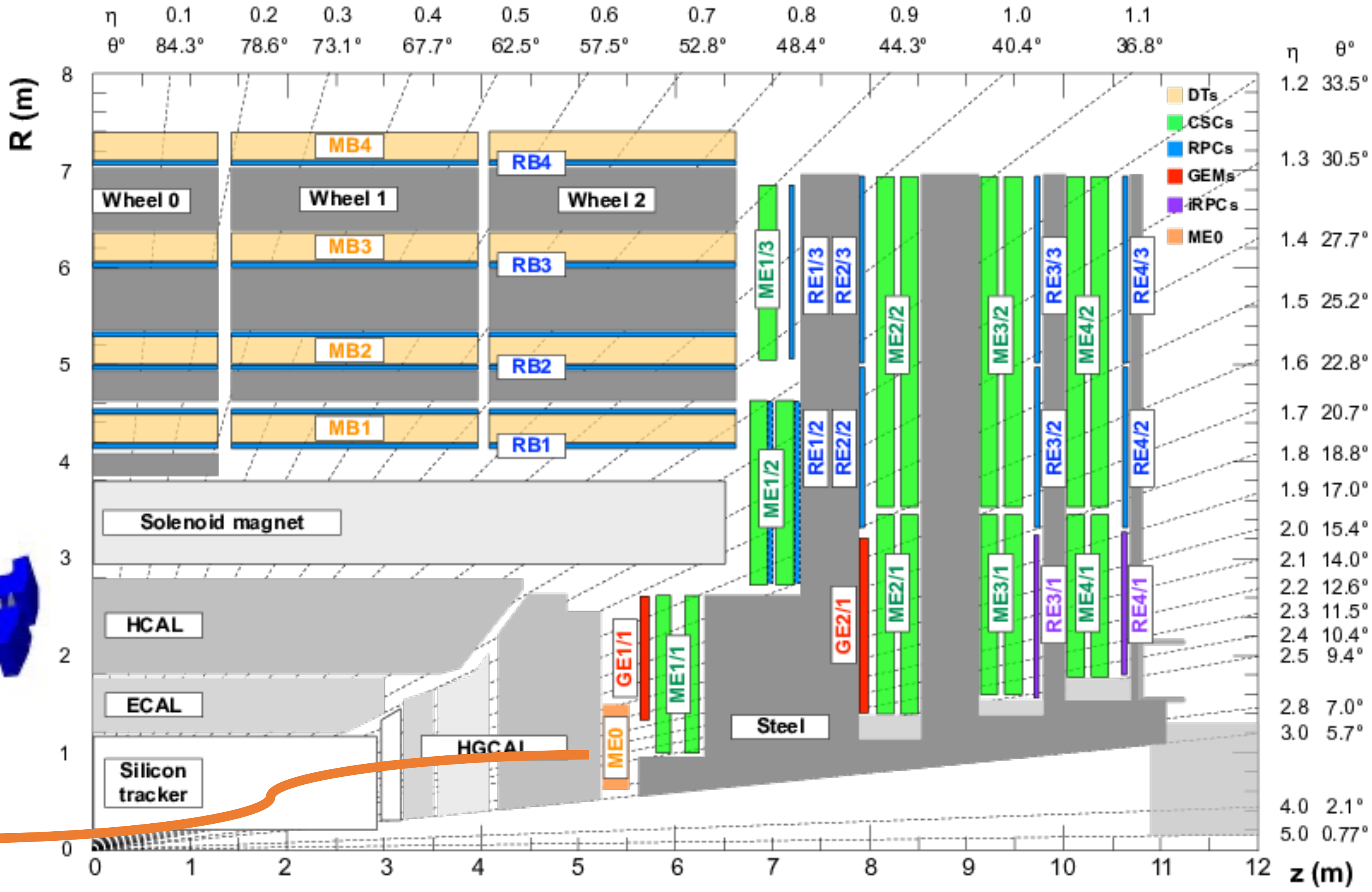
Test of LFU in $B \to K\ell\ell$ decays using 2018 "B-Parking" dataset
arXiv:2401.07090v1

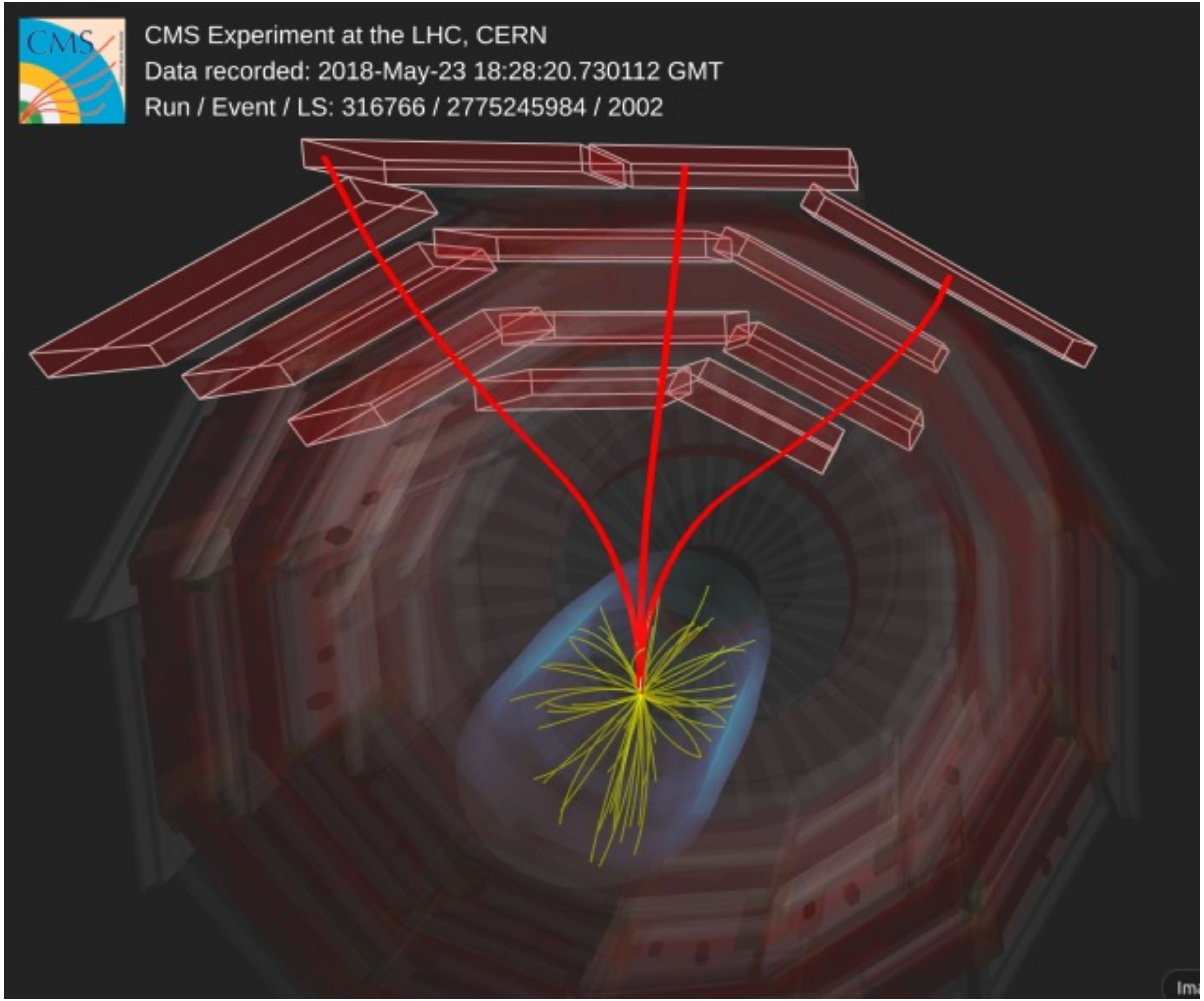


CMS: Phase 2 Muon system

Muon coverage
$|\eta| < 2.4 \rightarrow |\eta| < 2.8$






CMS Experiment at the LHC, CERN
Data recorded: 2018-May-23 18:28:20.730112 GMT
Run / Event / LS: 316766 / 2775245984 / 2002