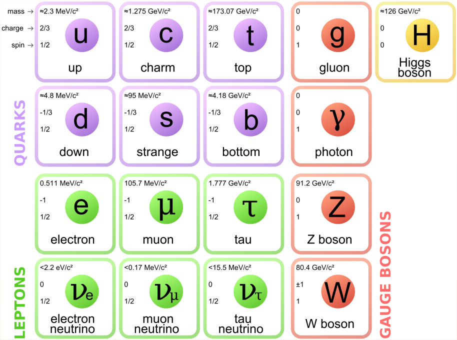
Search for lepton flavour violation in tau decays

Paul Seyfert

lepton content of the Standard Model



This is the Standard Model of Particle Physics!
. . . well, actually it's the list of fundamental particles in the Standard Model

illustration: Standard Model on Wikipedia

- u+u+d+glue = proton, u+d+d+glue = neutron.
- Sendung mit der Maus: alles was man im alltag so kennt sind protonen+neutronen+elektronen+licht

lepton content of the Standard Model

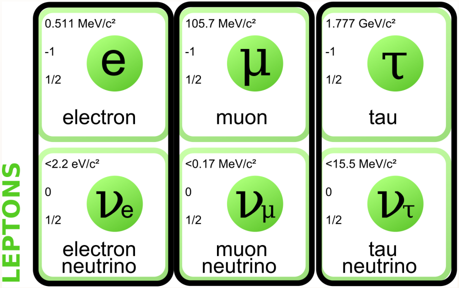


illustration: Standard Model on Wikipedia

- three flavours of leptons

lepton content of the Standard Model

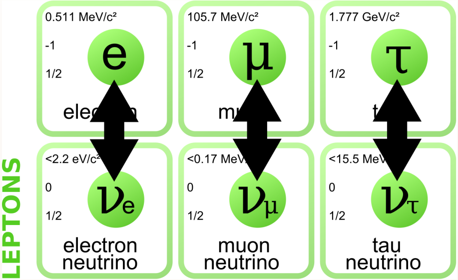
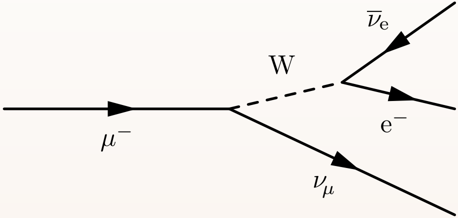


illustration: Standard Model on Wikipedia

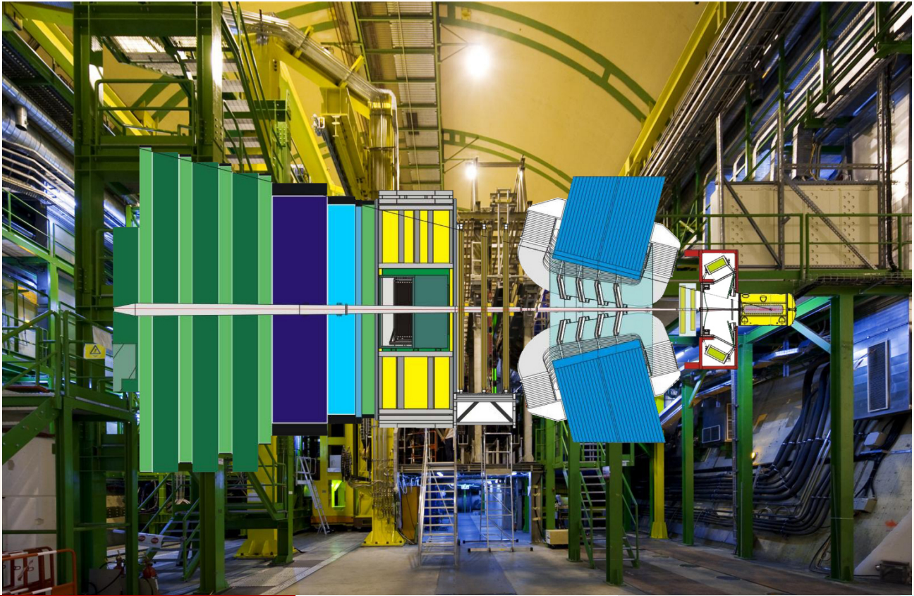
- three flavours of leptons
- transition within flavours through weak interaction



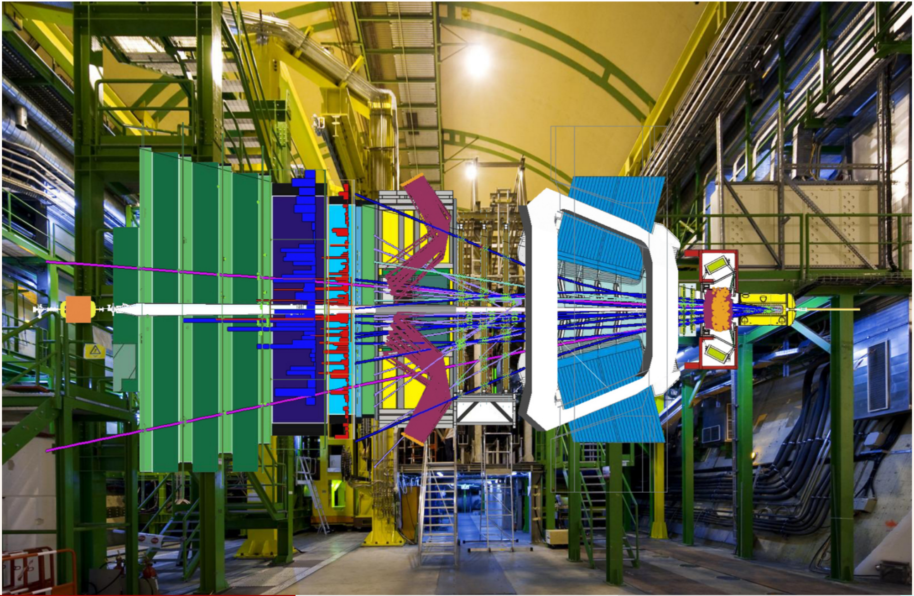
Und ich suche nach $\tau \to \mu\mu\mu$

the LHCb detector

the LHCb detector



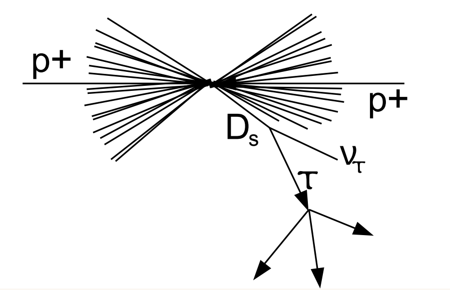
the LHCb detector



simple principle

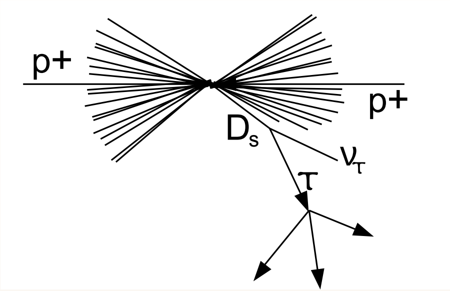
- produce many τ leptons
- check for $\tau \to \mu\mu\mu$ / fight backgrounds
- calculate branching fraction
- done.

τ production



- $\mathcal{O}(100)$ particles in the detector
- mainly hadrons
  = so Dinger, die von glue zusammen gehalten werden
- τ are produced as decay products of heavy mesons

τ production



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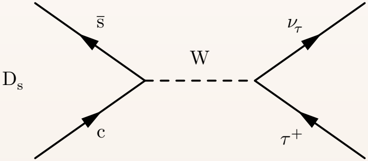
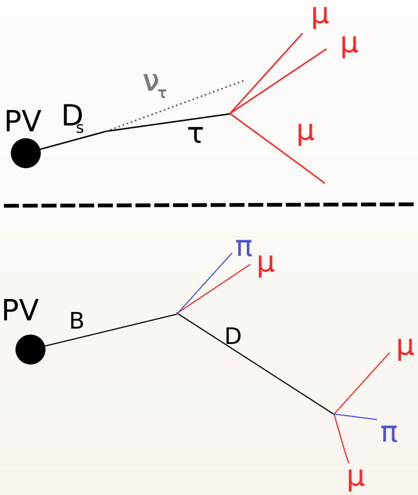


- 78 % from $D_s \to \tau\nu_\tau$ decays
- 17 % from $B \to \tau\nu_\tau(+X)$ decays

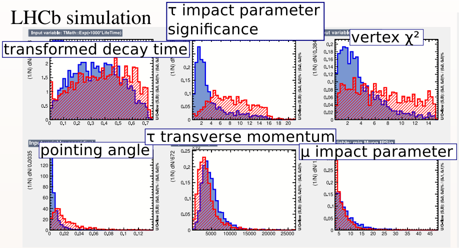
signal properties

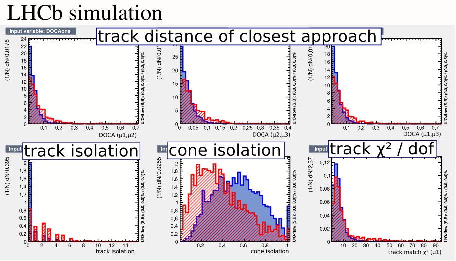
differences between signal and background

- vertex quality
- track quality
- separation from primary vertex
- compatibility with origin in the primary vertex
- vertex incompatible with other tracks in the event



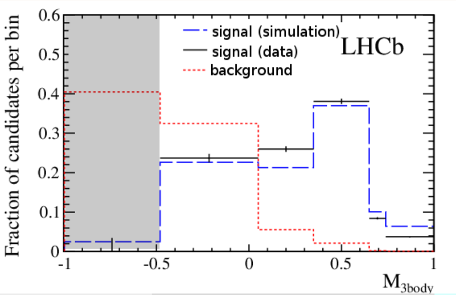
decay topology





multivariate classifier

response



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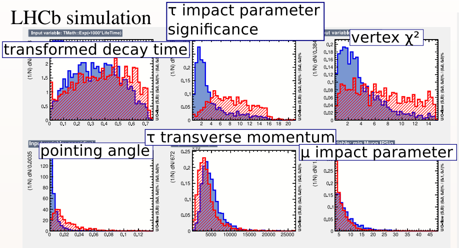
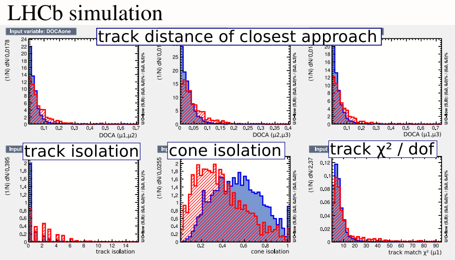
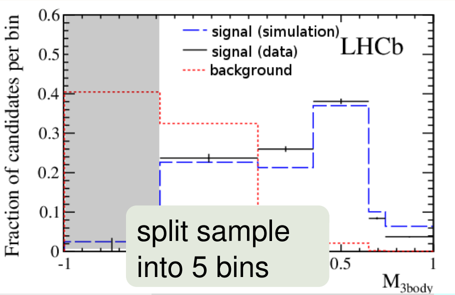


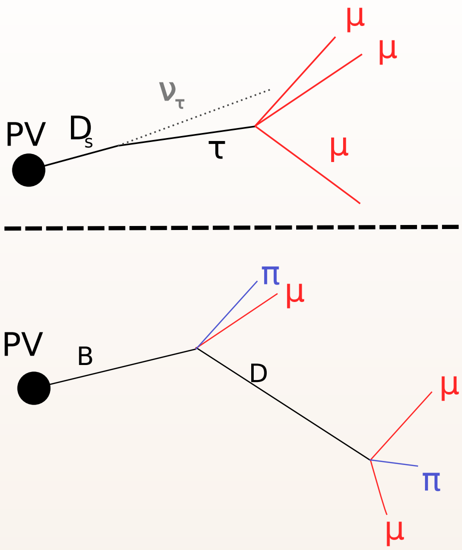


multivariate classifier → response

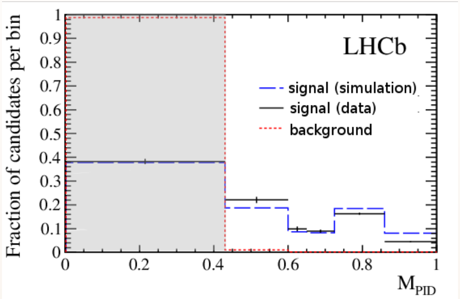


split sample into 5 bins

particle identification



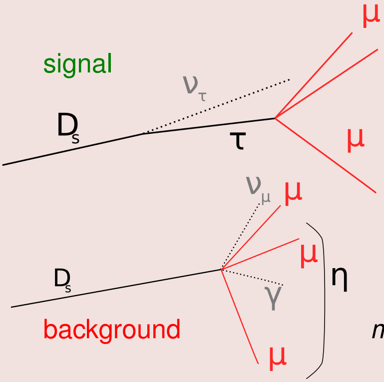
- use particle identification



split again into 5 bins

remaining background

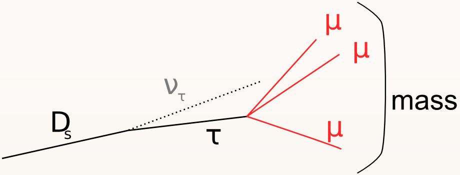
identical to signal in most properties

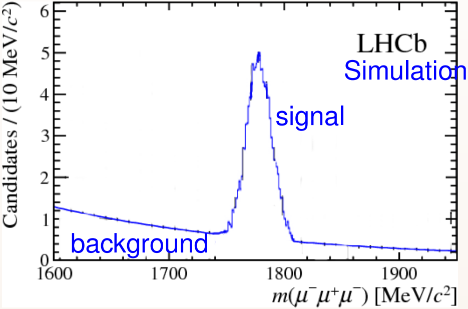


$m_{\mu^+\mu^-\gamma} = m_\eta$

$\rightarrow$ cut $m_{\mu^+\mu^-} > m_\eta$

distinguish signal from residual background





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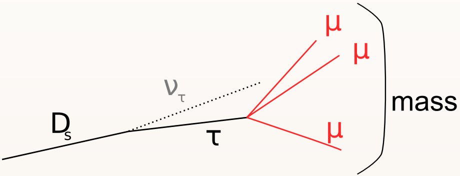

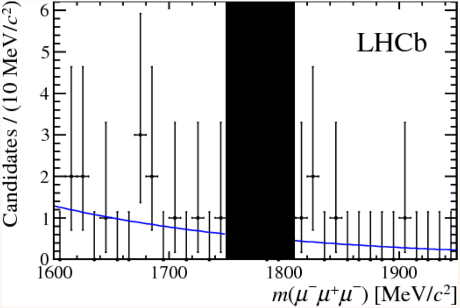

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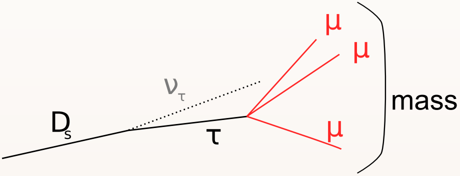
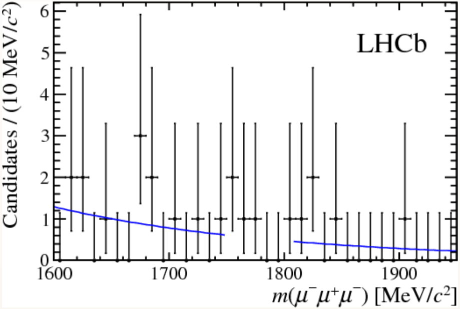
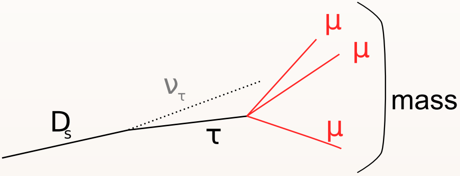




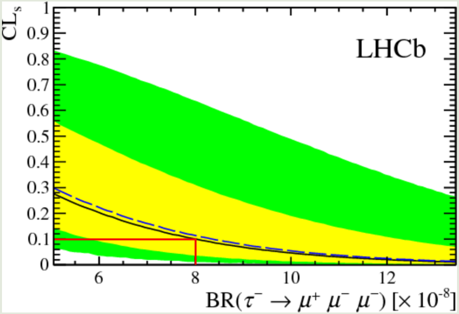
distinguish signal from residual background



das ganze 25 mal

stellt euch die letzte abbildung ganz oft vor. manchmal mit viel untergrund, manchmal mit wenig

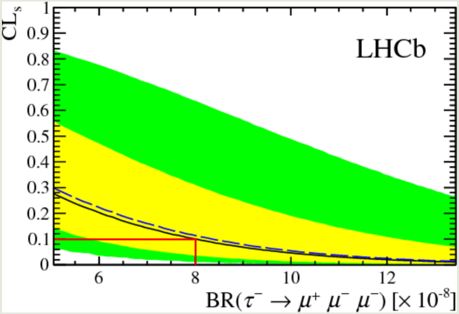
Result



$\mathcal{B}(\tau \to \mu\mu\mu) <$ 0.000008% @ 90 % CL (using 1 fb^{-1} from 2011)

$\to$ Phys.Lett. **B724** (2013) 36

Result



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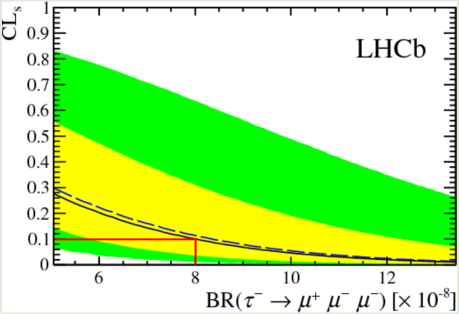
Belle	0.000002%	Phys.Lett. **B687** (2010) 139
BaBar	0.000003%	Phys.Rev. **D81** (2010) 111101

Result



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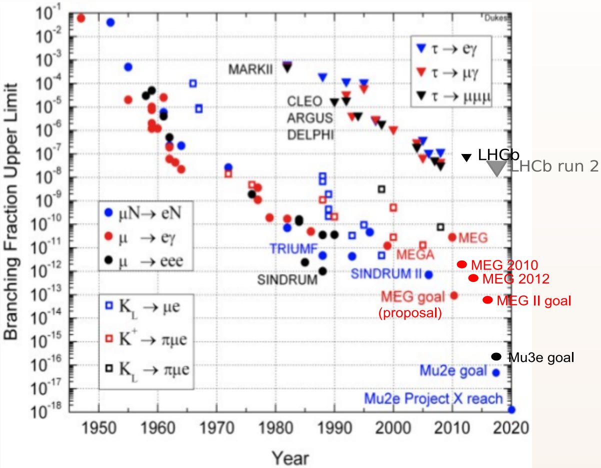
$\rightarrow$ Phys.Lett. **B724** (2013) 36

started with $\sim$ 100 times more τ
limit still 4 times worse
$\rightarrow$ lots of background at hadron collisions

Conclusion



compilation by E.C. Dukes @Tau2010
updated by F. Renga @FPCP2012
+my addition

BACKUP

Production modes

Mode	LHCb cross-section	p_T (GeV/c)	η	Reference
$\boldsymbol{\sigma(b\bar{b}X)}$	$288 \pm 4 \pm 48$ µb	$p_T < \infty$	4π	[10]
$\boldsymbol{\sigma(D_s^{\pm})}$	$194 \pm 23 \pm 3$ µb	$p_T < 8$	$2 < \eta < 4.5$	[11]
$\boldsymbol{\sigma(D^{\pm})}$	$717 \pm 39 \pm 15$ µb	$p_T < 8$	$2 < \eta < 4.5$	[11]
$\sigma(\psi(2S))$	$1.88 \pm 0.02 \pm 0.31^{+0.25}_{-0.48}$ µb	$p_T < 12$	$2 < \eta < 4.5$	[12]
$\sigma(\Upsilon(1S))$	$108.3 \pm 0.7^{+30.9}_{-25.8}$ nb	$p_T < 15$	$2 < \eta < 4.5$	[13]
$\sigma(Z)$	$73 \pm 4 \pm 7.3$ pb	$p_T > 20$	$2 < \eta < 4.5$	[14]
$\sigma(W^+)$	$1007 \pm 48 \pm 101$ pb	$p_T > 20$	$2 < \eta < 4.5$	[14]
$\sigma(W^-)$	$680 \pm 40 \pm 68$ pb	$p_T > 20$	$2 < \eta < 4.5$	[14]

Table 6: Production cross-sections measured at $\sqrt{s} = 7$ TeV at LHCb.

test statistics

$$Q = \frac{\text{probability for observed events assuming signal and background}}{\text{probability for observed events assuming background}}$$

blue

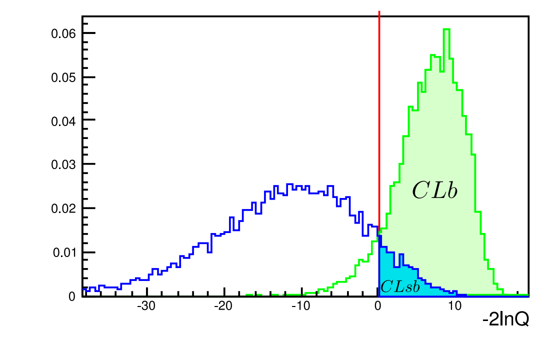
generate toy experiments for signal+background (depends on assumed $\mathcal{B}$)

green

generate toy experiments for background

red

observed Q value



$$CLs = CLsb/CLb$$

interpretation of CLs values

confidence level of exclusion = 1 - CLs

get a CLs value for each assumed branching ratio

advantages

- robust against downward fluctuations
- state of the art

“disadvantage”

- conservative
- unintuitive
- unnecessary complicated

(depending on who’s opinion you ask for)

theory predictions

Model	$\tau \to \ell\gamma$	$\tau \to \ell\ell\ell$
SM with lepton CKM	10^{-40}	10^{-14}
SM with left-handed heavy Dirac neutrino	$< 10^{-18}$	$< 10^{-18}$
SM with right-handed heavy Majorana neutrino	$< 10^{-9}$	$< 10^{-10}$
SM with left- and right-handed neutral singlets	10^{-8}	10^{-9}
MSSM with right-handed heavy Majorana neutrino	10^{-10}	10^{-9}
MSSM with seesaw	10^{-7}	
left-right SUSY	10^{-10}	10^{-10}
SUSY SO(10)	10^{-8}	
SUSY-GUT	10^{-8}	
SUSY with neutral Higgs	10^{-10}	$10^{-10} - 10^{-7}$
SUSY with Higgs triplet		10^{-7}
gauge mediated SUSY breaking	10^{-8}	
MSSM with universal soft SUSY breaking	10^{-7}	10^{-9}
MSSM with non-universal soft SUSY breaking	10^{-10}	10^{-6}
Non universal Z' (technicolor)	10^{-9}	10^{-8}
two Higgs doublet III	10^{-15}	10^{-17}
seesaw with extra dimensions	10^{-11}	

arXiv:hep-ph/0503261

τ production in detail

- $\sigma(\mathrm{pp} \to \mathrm{D_s} + X)$ measured at LHCb
- $\mathcal{B}(\mathrm{D_s} \to \tau\nu_\tau)$ measured at B factories

$\Rightarrow$ cross section for τ from $\mathrm{D_s}$

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$\Rightarrow$ cross section for τ from $\mathrm{D_s}$

- $\sigma(\mathrm{pp} \to \mathrm{B} + X)$ measured at LHCb
- $\mathcal{B}(\mathrm{B} \to \tau\nu_\tau X)$ measured at B factories

$\Rightarrow$ cross section for τ from B

more important

ratio has much smaller systematic uncertainty:

$$\frac{\sigma(\mathrm{pp} \to \mathrm{D_s}(\tau\nu_\tau)X)}{\sigma(\mathrm{pp} \to \tau X)} \approx (78.5 \pm 4.8)\,\%$$

5 τ production at LHCb

τ production

at the LHC

main contributions

- $\mathrm{b\overline{b}}$ and $\mathrm{B} \to \tau + X$
  $\to$ 13(3) µb
- $\mathrm{c\overline{c}}$ and $\mathrm{D_s} \to \tau + \overline{\nu}_\tau$
  $\to$ 57(10) µb
- $\mathrm{b\overline{b}}$ and $\mathrm{B} \to \mathrm{D}(\to \tau + \overline{\nu}_\tau) + X$
  $\to$ 8(2) µb

$\Rightarrow$ **already** 8×10^{10} τ **produced**

negligible contributions

- gauge bosons
- Drell-Yan

τ production

at the LHC

main contributions

- $\mathrm{b}\overline{\mathrm{b}}$ and $\mathrm{B} \rightarrow \tau + X$
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negligible contributions

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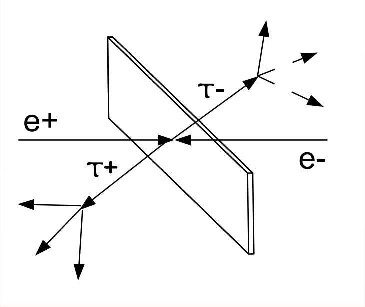
at B factories

pair production

$\mathrm{e}^-\mathrm{e}^+ \rightarrow \tau^-\tau^+$

10^9 τ pairs produced



challenges

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\#\tau\to\mu\mu\mu}{\#\tau \text{ produced}}$$

no pair production

unknown whether a τ has been produced in an event

no direct measurement of τ production

standard model τ signatures indistinguishable from D^+ signatures

e.g.:

$\tau^+ \to \pi^+\pi^+\pi^-\overline{\nu}_\tau$

$\mathrm{D}^+ \to \pi^+\pi^+\pi^-\pi^0$

absolute normalisation has large uncertainties

- luminosity measurement
- systematic uncertainties (trigger, reconstruction, PID)

normalisation

use knowledge on production channels

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\#\tau\to\mu\mu\mu}{\#\tau \text{ produced}}$$

step 1

- $\mathcal{B}(\mathrm{D_s} \to \tau\nu_\tau)$ is known (4 %)
- $\mathcal{B}(\mathrm{D_s} \to \phi\pi)$ is known (5 %)
- $\mathcal{B}(\phi \to \mu^-\mu^+)$ is known (6 %)
- $\mathrm{D_s} \to \phi(\mu^-\mu^+)\pi$ is well reconstructible

$\Rightarrow$ 9 % systematic uncertainty

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\mathcal{B}(\mathrm{D_s}\to\phi(\mu\mu)\pi)}{\mathcal{B}(\mathrm{D_s}\to\tau\nu_\tau)} \frac{\#\mathrm{D_s}\to\tau(\to\mu\mu\mu)\nu_\tau}{\#\mathrm{D_s}\to\phi(\mu\mu)\pi}$$

normalisation

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\mathcal{B}(\mathrm{D_s}\to\phi(\mu\mu)\pi)}{\mathcal{B}(\mathrm{D_s}\to\tau\nu_\tau)} \frac{\#\mathrm{D_s}\to\tau(\to\mu\mu\mu)\nu_\tau}{\#\mathrm{D_s}\to\phi(\mu\mu)\pi}$$

step 2

- $\sigma(pp \to \mathrm{D_s} + X)$ is known (3 %stat +11 %sys)
- $\sigma(pp \to \mathrm{B} + X)$ is known (1 %stat +17 %sys)
- $\mathcal{B}(\mathrm{B} \to \tau + X)$ is kown (9 %)

$\Rightarrow \frac{\sigma(pp\to\mathrm{D_s}(\tau\nu_\tau)+X)}{\sigma(pp\to\tau\nu_\tau+X)}$ is known (7 %)

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\sigma(pp\to\mathrm{D_s}(\tau\nu_\tau)+X)}{\sigma(pp\to\tau)} \frac{\mathcal{B}(\mathrm{D_s}\to\phi(\mu\mu)\pi)}{\mathcal{B}(\mathrm{D_s}\to\tau\nu_\tau)} \frac{\#\tau\to\mu\mu\mu}{\#\mathrm{D_s}\to\phi(\mu\mu)\pi}$$

normalisation

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\sigma(pp \to D_s(\tau\nu_\tau)+X)}{\sigma(pp \to \tau)} \frac{\mathcal{B}(D_s \to \phi(\mu\mu)\pi)}{\mathcal{B}(D_s \to \tau\nu_\tau)} \frac{\#\tau \to \mu\mu\mu}{\#D_s \to \phi(\mu\mu)\pi}$$

"real" decays

step 3

- correct for efficiencies (reconstruction, trigger, PID)
- most systematic uncertainties cancel in ratios (8 %)

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{\sigma(pp \to D_s(\tau\nu_\tau)+X)}{\sigma(pp \to \tau)} \frac{\mathcal{B}(D_s \to \phi(\mu\mu)\pi)}{\mathcal{B}(D_s \to \tau\nu_\tau)} \frac{\varepsilon_{norm}}{\varepsilon_{sig}} \frac{\#\tau \to \mu\mu\mu}{\#D_s \to \phi(\mu\mu)\pi}$$

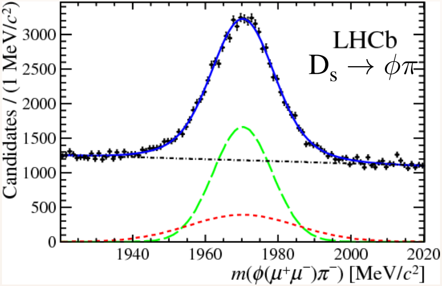
overall 13 % uncert.

reconstructed decays

reference channel for τ production

- $D_s \to \phi\pi$ is easy to reconstruct
- $\mathcal{B}(D_s \to \phi\pi)$ and $\mathcal{B}(D_s \to \tau\nu_\tau)$ known branching fractions

- $N(D_s \to \tau\nu_\tau) = \frac{\mathcal{B}(D_s\to\tau\nu_\tau)}{\mathcal{B}(D_s\to\phi\pi)} N(D_s \to \phi\pi)$



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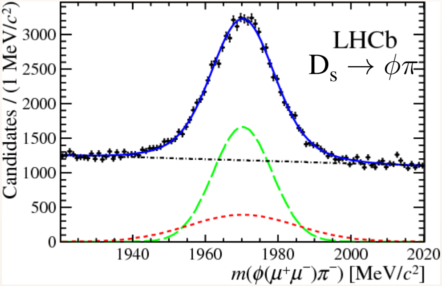

(not shown) correction of reconstruction efficiency

$\Rightarrow$

$\sim 6.2 \times 10^{10}$ τ from $\mathrm{D_s}$ in 1 fb^{-1} from 2011

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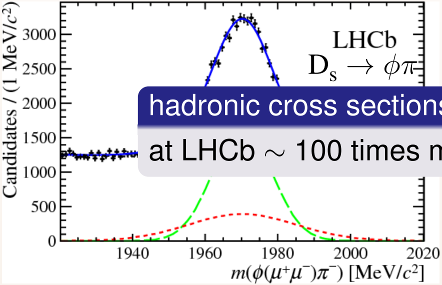

(not shown) correction of reconstruction efficiency

hadronic cross sections are large

at LHCb $\sim$ 100 times more τ than at B factories

$\sim 6.2 \times 10^{10}$ τ from D_s in 1 fb^{-1} from 2011

computing a branching fraction

central formula

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{N(\tau \to \mu\mu\mu)}{N(\tau)}$$

$$\mathrm{N}(\tau) = \frac{\mathcal{B}(\mathrm{D_s} \to \tau\nu_\tau)}{\mathcal{B}(\mathrm{D_s} \to \phi\pi)} \frac{\sigma(\mathrm{pp} \to \tau X)}{\sigma(\mathrm{pp} \to \mathrm{D_s}(\tau\nu_\tau)X)} N(\mathrm{D_s} \to \phi\pi) \approx 8 \times 10^{10}$$

computing a branching fraction

central formula

$$\mathcal{B}(\tau \to \mu\mu\mu) = \frac{N(\tau \to \mu\mu\mu)}{N(\tau)}$$

$$\mathrm{N}(\tau) = \frac{\mathcal{B}(\mathrm{D_s} \to \tau\nu_\tau)}{\mathcal{B}(\mathrm{D_s} \to \phi\pi)} \frac{\sigma(\mathrm{pp} \to \tau X)}{\sigma(\mathrm{pp} \to \mathrm{D_s}(\tau\nu_\tau)X)} N(\mathrm{D_s} \to \phi\pi) \approx 8 \times 10^{10}$$

Then determine how many τ decayed to $\mu\mu\mu$