Measurement of the UPC $\gamma\gamma \to \tau\tau$ cross-section in proton-proton collisions with the LHCb detector

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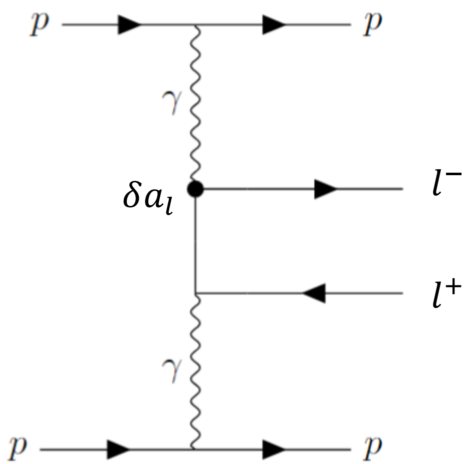
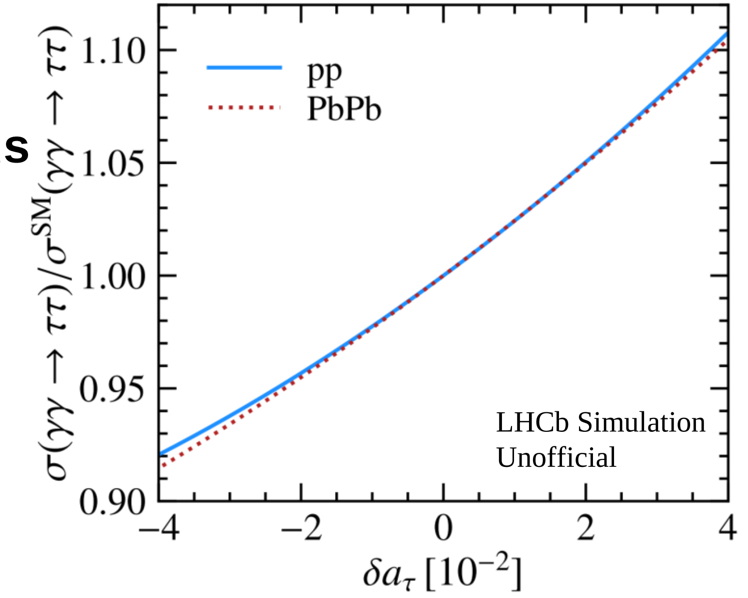
Ultraperipheral Collisions (UPCs)

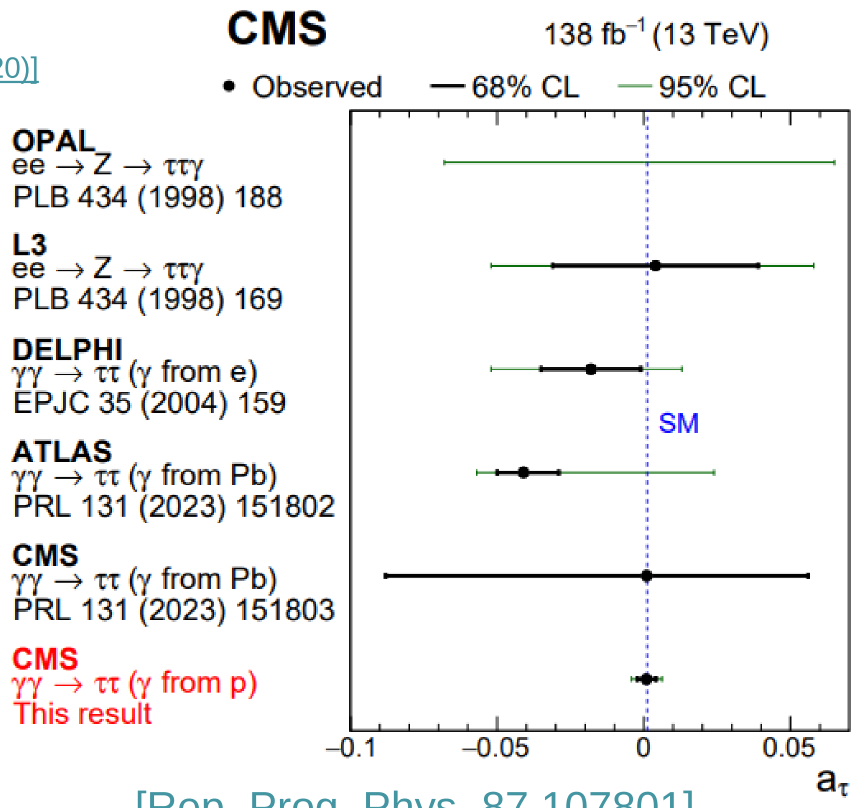
- In UPCs, two particles solely interact via their surrounding virtual propagator clouds, with an impact parameter larger than the sum of their radii.
- Two-photon interaction can produce a pair of leptons exclusively.
  - No primary vertex
  - In coherent collisions, the protons remain intact ⇒ **very low multiplicity**
  - The photons are nearly real ⇒ back-to-back leptons
- **The photon-lepton vertex is sensitive to the lepton's anomalous magnetic moment $\boldsymbol{a_l = (g_l - 2)/2}$**
  - The cross-section $\sigma_{\gamma\gamma\to ll}$ is dependent on $\delta a_l = a_l - a_l^{SM}$





Tau anomalous magnetic moment

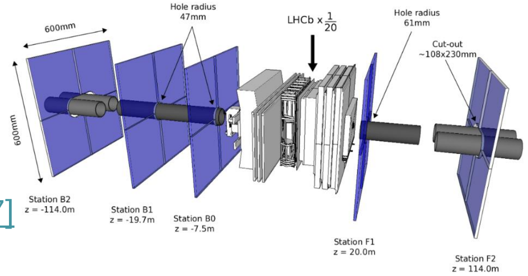
- Lepton's anomalous magnetic moment a_l tests Standard Model (SM) and probes new physics (NP)
  - a_e precise to 10^{-12}, consistent with SM [Phys.Rev.D102,113008(2020)]
  - a_μ precise to 10^{-7}, tension at $3\sim4\sigma \Rightarrow$ NP?
  - a_τ should be $\frac{m_\tau^2}{m_\mu^2}\sim280$ times more sensitive than a_μ to NP yet suffers from low experimental precision…
- Direct measurement of τ is difficult due to its short life time.
  - The **UPC $\gamma\gamma \to \tau\tau$** can provide a clean channel with an almost-empty detector.
- Recently, CMS reports the most precise measurement of a_τ to 10^{-3} with UPC $\gamma\gamma \to \tau\tau$ in pp collision proving the feasibility.
- The goal is to investigate the feasibility of measuring this process at the LHCb detector.



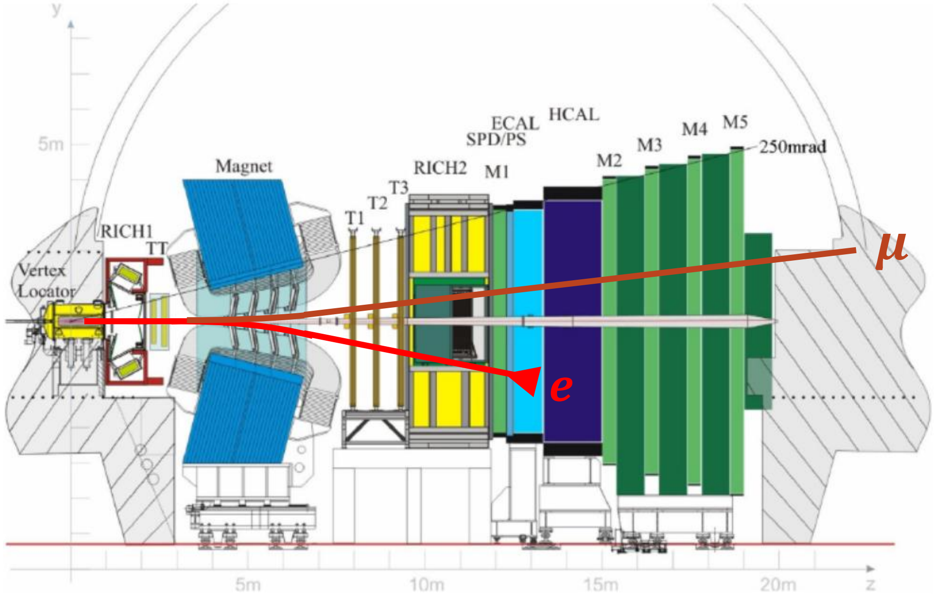
[Rep. Prog. Phys. 87 107801]

The LHCb experiment

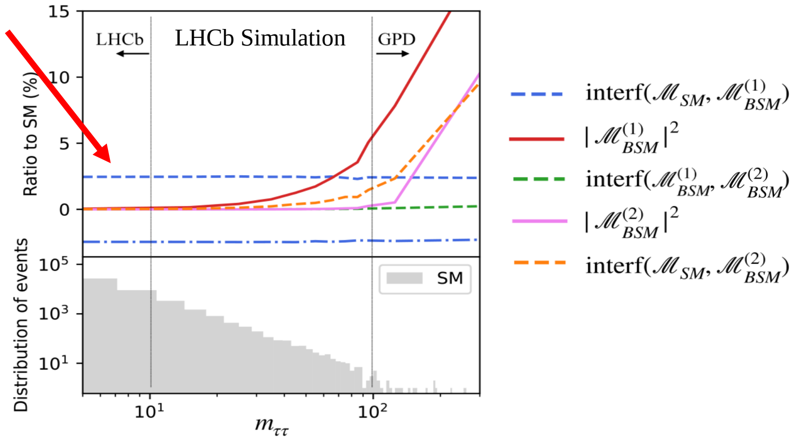
- Detector Layout:
  - Forward angle ⇒ rejecting massive non-diffractive-QCD background
  - Low pile-up ⇒ favours UPC studies
  - Special triggers to select UPC events
  - High Resolutions of muon and electron
  - **HeRSCheL Detector** ⇒ additional detector to distinguish UPC events with extended η coverage

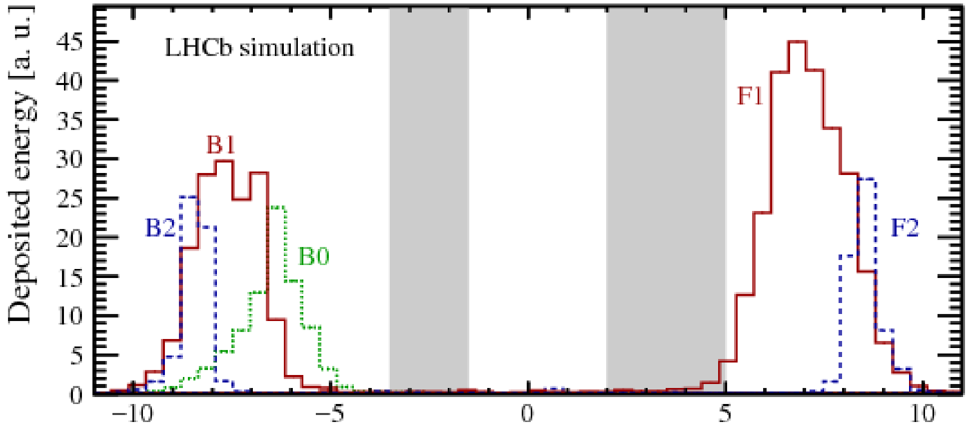


[JINST 13 (2018) no.04, P04017]



- Energy scale $\mathcal{O}(1\ \mathrm{GeV})$ ⇒ provide unique probes of NP interference term

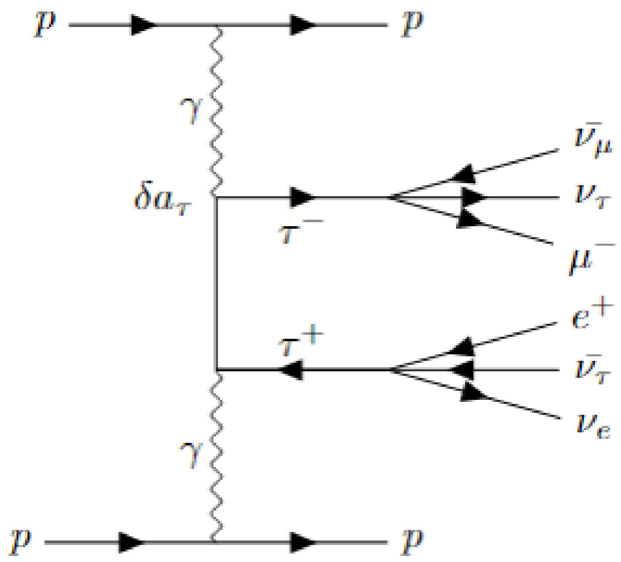




[JINST 13 (2018) no.04, P04017]

Proposed measurement

- The τ can only be measured through its decay product.
  - Unable to fully reconstruct because of neutrino production
- The decay channel $(\tau \to \mu\nu_\mu\nu_\tau)(\tau \to e\nu_e\nu_\tau)$ is chosen.
  - Pure leptonic channel
  - Distinct visible $e\mu$ pair ⇒ direct production is forbidden in SM, rejecting massive background
- Signal selection:
  - 1 muon + 1 electron, opposite charge
  - Strict Particle Identification (PID) ⇒ avoid mis-ID
  - Low **HeRSCheL** readout
  - Several Boosted Decision Trees (BDTs) to reject background

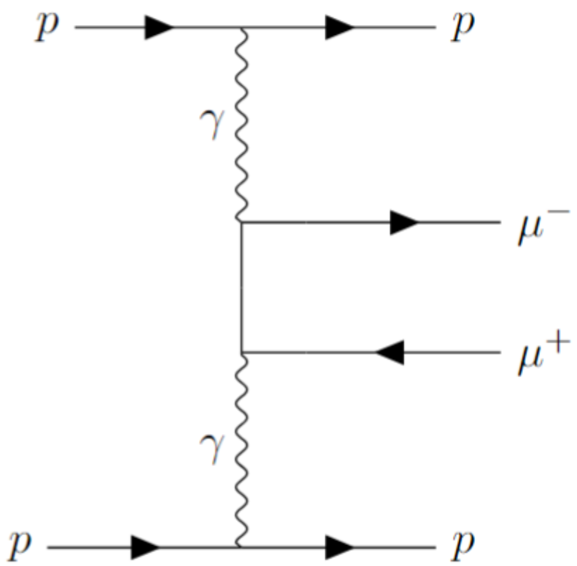


$\gamma\gamma \rightarrow \mu\mu$ calibration

- Extract $\gamma\gamma \rightarrow \mu\mu$ sample from data to calibrate the signal and efficiency
  - Much higher cross-section
  - Clear UPC feature
  - Easy reconstruction

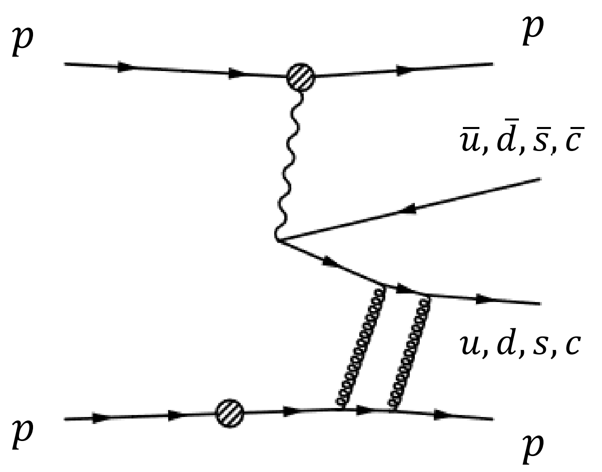
$\Rightarrow$ Clean isolation of $\mu\mu$ events

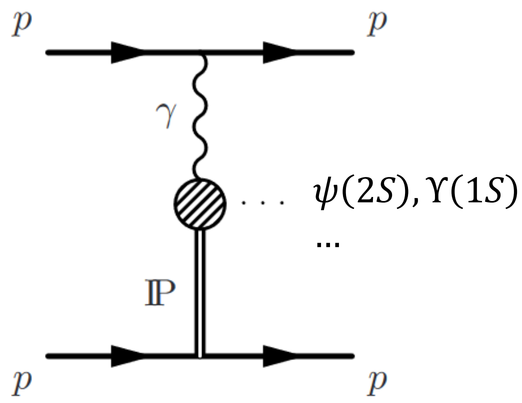
  - **Calibration of the $\gamma\gamma \rightarrow ll$ simulation**
  - PID calibration with well-identified μ
  - Study proton dissociation (PD), determine the **HeRSCheL** efficiency and optimise the selection



Background Origination

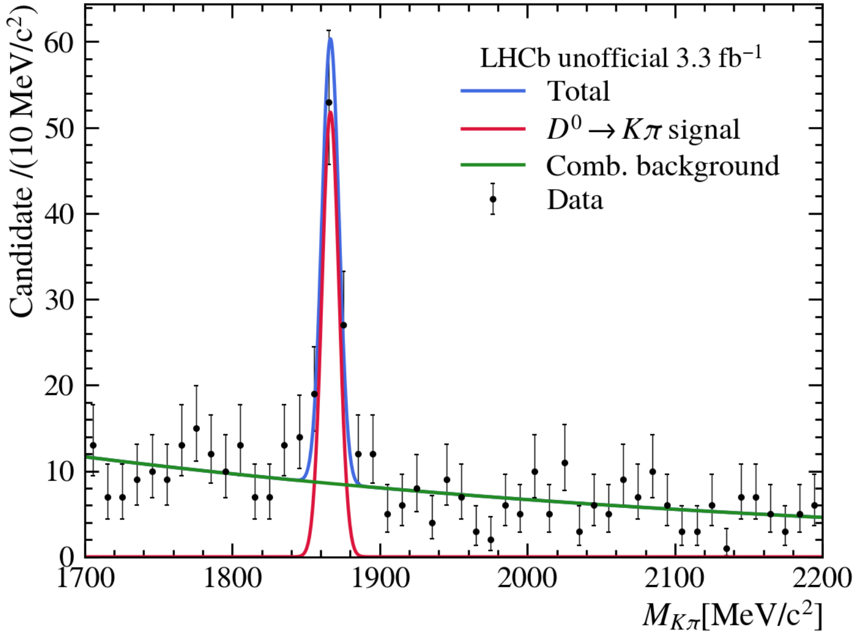
- The non-UPC background should be eliminated by the trigger and custom selections.
- Background should come from UPC photoproduction process:
  - Jet production
    - Charm-anticharm ($c\bar{c}$) pair ⇒ 2 D mesons decay to a visible $e\mu$ pair
    - Light-quark pair ⇒ mostly contribute through photon conversion and misID
  - Heavy quarkonia exclusive production and decay to $\tau\tau$
    - $eg.\ \psi(2S), \Upsilon(1S)$ ...
- $c\bar{c}$ production has similar mass window as $\tau\tau$ so should be dominant.
- The UPC $\psi(2S) \to \mu\mu$ has been measured by LHCb [SciPost Phys.18,071(2025)]
  - Simulation of $\psi(2S) \to \tau\tau$ shows very small contribution
  - Other heavy charmonia like χ_{cJ} has much less production rate so ignored

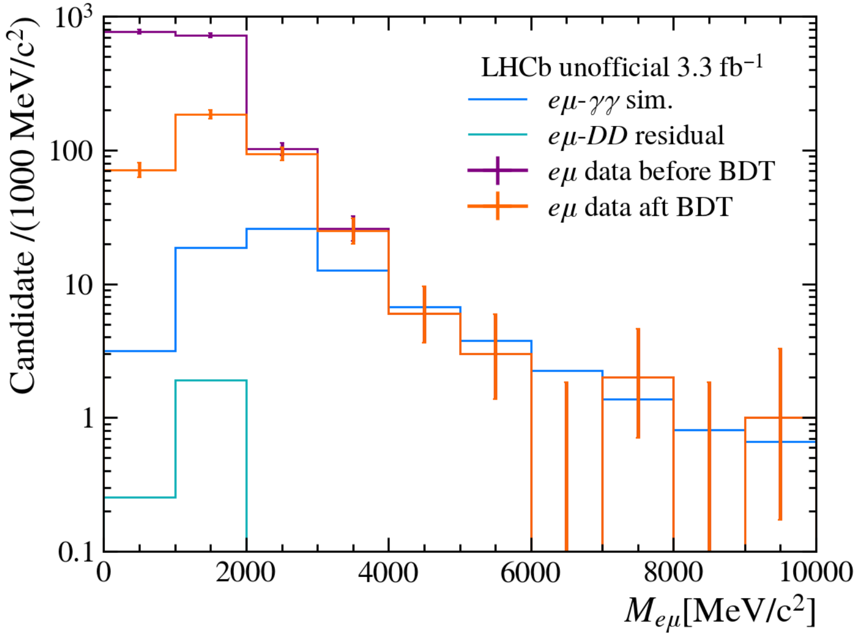




UPC $c\bar{c}$ backgrounds

- The jet production can contribute through 2 c-meson decay into a visible $e\mu$ pair, i.e. $(D^{+}\rightarrow K_L^0\mu^-\bar{\nu}_\mu)(D^{-}\rightarrow \bar{K}_L^0 e^+\nu_e)$.
- Analyse $(D^0\rightarrow K^+\mu^-\bar{\nu}_\mu)(\bar{D}^0\rightarrow K^-\pi^+)$ data to get the cross-section of UPC $c\bar{c}$ $\Rightarrow$ calculate D^+D^- yield
  - A muon requirement to fire the same trigger
  - A hadronic decay $\Rightarrow$ clear D^0 mass peak in $K\pi$ invariant mass spectrum
- The isolation of signal from D^+D^- background proceeds with a BDT.



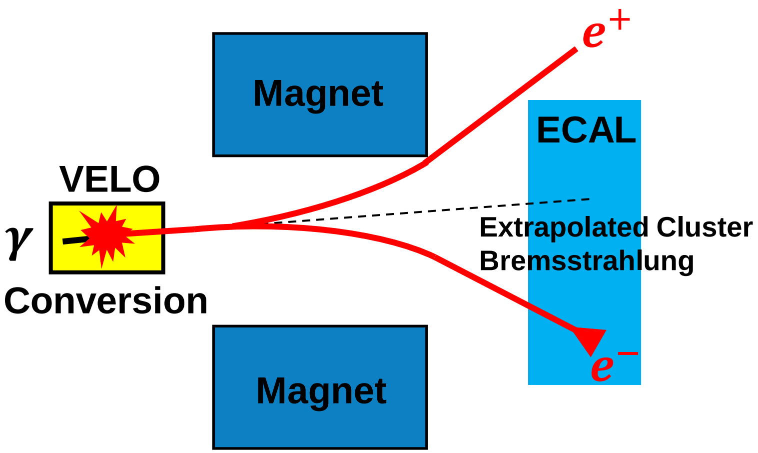


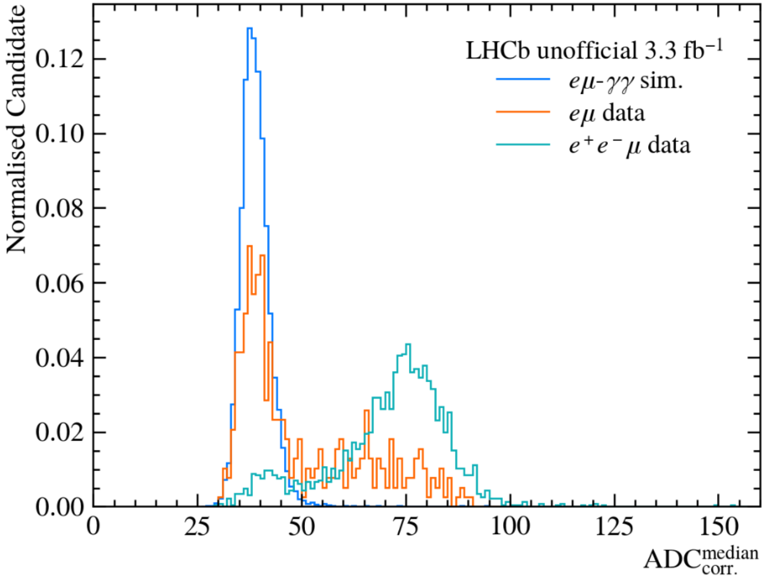
$\gamma \to ee$ conversion background

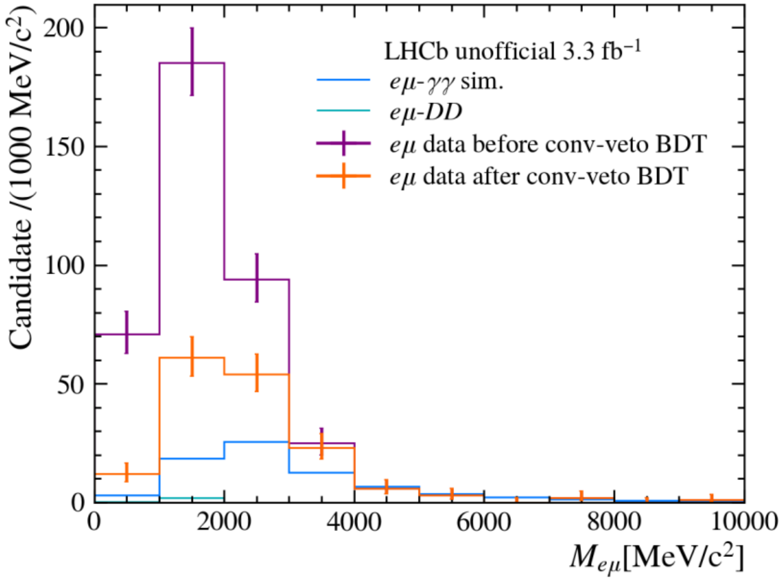
- The tracked electron can actually be a photon-converted one

$$\pi^0 \to \gamma(\gamma \to ee)$$

- If the photon converts inside VELO, the analog-to-digit count (ADC) can be an indicator
- Another BDT is trained to help eliminate the conversion
- Explicit $\pi^0 \to \gamma e(e)$ is also studied





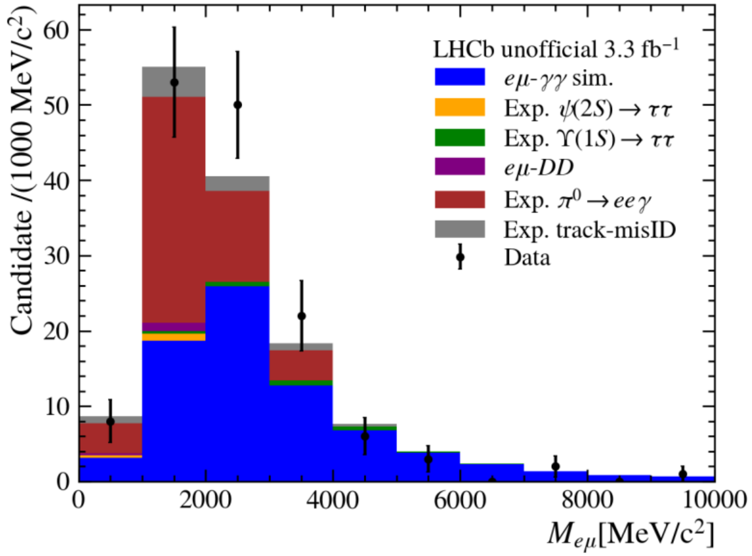


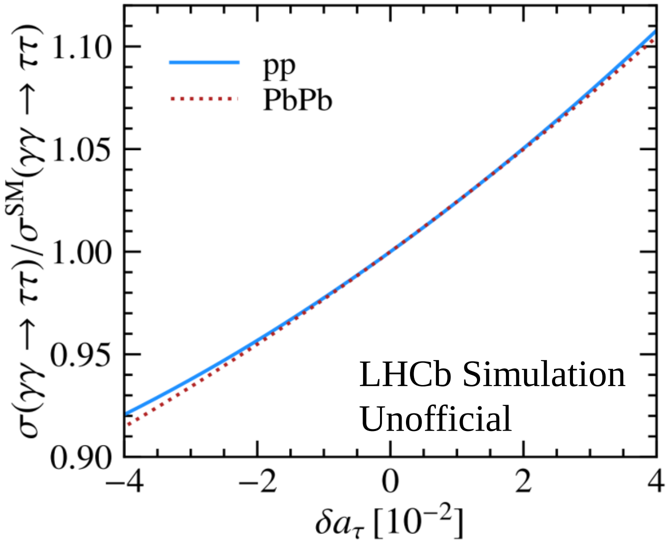
Residual Mis-ID

- The residual background is likely to come from track mis-ID
  - Possible π-μ decay-in-flight
  - Patterns observed in $\gamma\gamma \rightarrow \mu\mu$ control sample
- Model the misID with the data-driven *pass-fail* method [Phys. Rev. D 108 (2023) 032002]
  - Inverting PID to make an enriched misID area
  - Determining a transfer weight to extrapolate from the misID area to nominal PID area
  - Applying to data to estimate the number of misID

Signal extraction and $\sigma_{\gamma\gamma\to\tau\tau}$

- Currently finalising signal isolation
  - Further correction will be applied based on the stacked plot
- A fit of the $e\mu$ invariant mass spectrum can then be performed
  - The observed number of events N_{obs} will be obtained
  - Systematic and statistical uncertainty will be investigated
  - The cross-section $\sigma^{obs}_{\gamma\gamma\to\tau\tau}$ can be calculated with $\sigma^{obs}_{\gamma\gamma\to\tau\tau} = N_{obs}/\mathcal{L}^{eff}_{int}$
- Given the reference $\sigma^{SM}_{\gamma\gamma\to\tau\tau}$, the observed $\sigma^{obs}_{\gamma\gamma\to\tau\tau}$ can then give a constraint on the value of a_τ





Summary

- **Identifying components in UPC $e\mu$ spectrum in pp collisions**
- Cross-checking $\gamma\gamma \to \mu\mu$ process
- **Measuring the cross-section of $\gamma\gamma \to \tau\tau$ process**
- Constraining a_τ values

Thank you for your listening!

Backup

Theoretical Expectation

[Phys.Rev.D102,113008(2020)]

- The general form of photon-lepton vertex is

$$\Gamma^\mu = \gamma^\mu F_1(q^2) + \frac{\sigma^{\mu\nu} q_\nu}{2m_l}[iF_2(q^2) + F_3(q^2)\gamma_5]$$

  - $F_2(0) = a_l$, with a_l anomalous magnetic moment
  - $F_3(0) = -2m_l/e \cdot d_l$, with d_l electric dipole moment
- Under Standard Model Effective Field Theory (SMEFT), the vertex of $\tau\tau\gamma$ can be written as

$$V_{\tau\tau\gamma} = ie\gamma^\mu - \frac{v\sqrt{2}}{\Lambda^2}(\mathrm{Re}\left[C_{\tau\gamma}\right] + i\gamma_5 \mathrm{Im}\left[C_{\tau\gamma}\right])\sigma^{\mu\nu} q_\nu$$

  - $C_{\tau\gamma}$ is the Wilson Coefficient, $v = 246\ \mathrm{GeV}$, and Λ is the NP scale.
- The correction to δa_τ and δd_τ is respectively

$$\delta a_\tau = \frac{2m_\tau}{e}\frac{v\sqrt{2}}{\Lambda^2}\mathrm{Re}\left[C_{\tau\gamma}\right]$$

$$\delta d_\tau = \frac{v\sqrt{2}}{\Lambda^2}\mathrm{Im}\left[C_{\tau\gamma}\right]$$

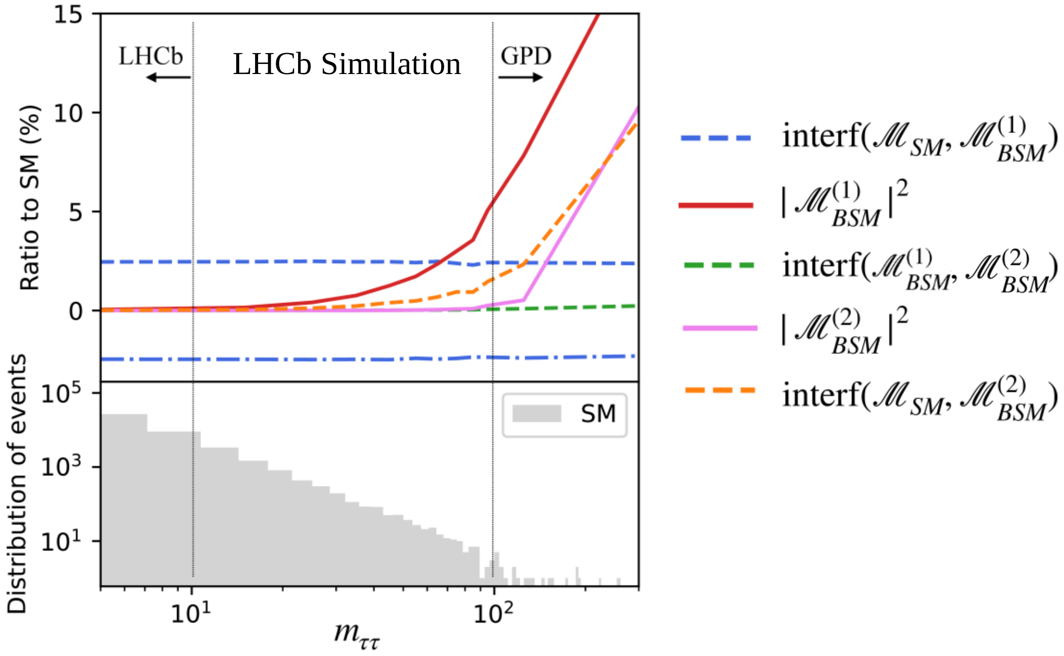
Theoretical Expectation

[Phys.Rev.D102,113008(2020)]

- The amplitude in expression of BSM (Beyond Standard Model) corrections can be written as

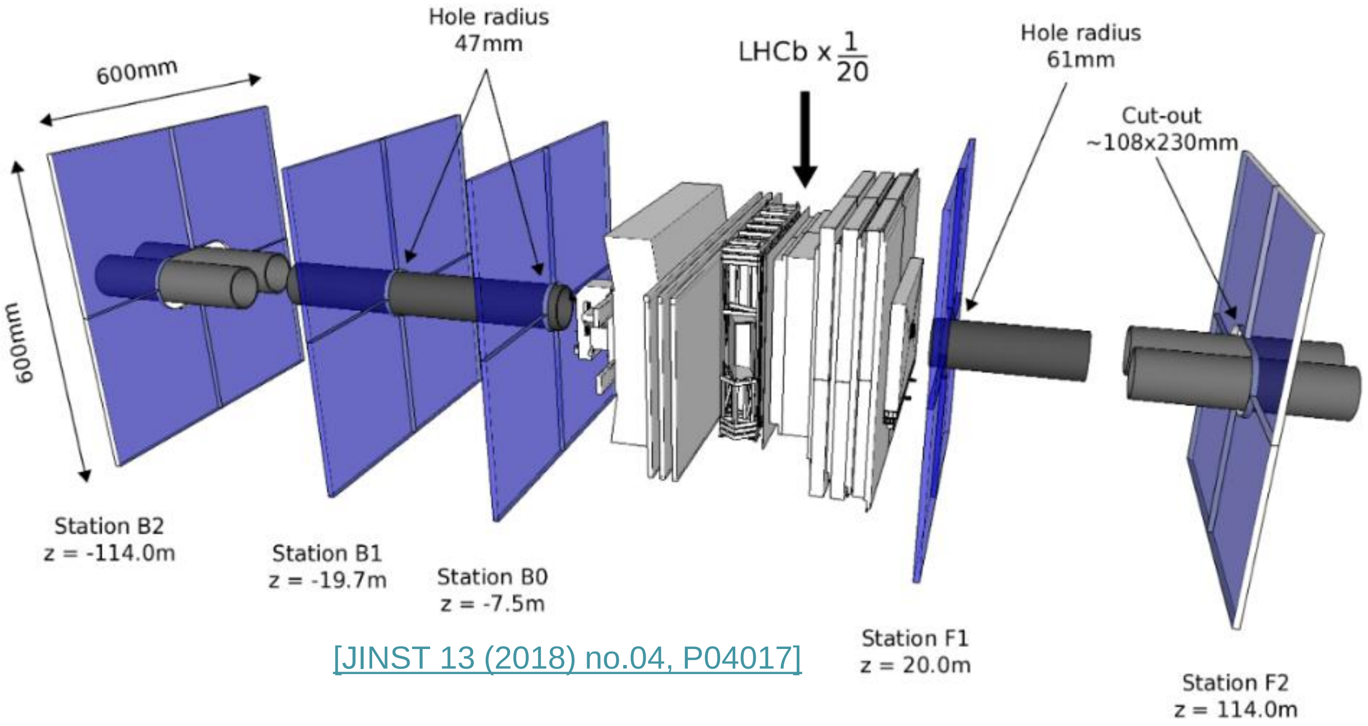
$$\mathcal{M}_{tot} = \mathcal{M}_{SM} + \mathcal{M}_{BSM}^{(1)}(\delta a_\tau) + \mathcal{M}_{BSM}^{(2)}(\delta d_\tau)$$

- The difference in amplitude square at different $m_{\tau\tau}$ indicates only contribution at $< \mathcal{O}(10\ \mathrm{GeV})$ is from δa_τ contribution



HeRSCheL detector

- The HeRSCheL (High Rapidity Shower Counters for LHCb) is a system of Forward Shower Counters (FSCs) located in the LHC tunnel
  - Expand pseudorapidity acceptance to $5 < |\eta| < 10$
  - 5 stations, each 4 quadrants ⇒ 20 scintillator planes detecting shower
  - A χ^2-like variable quantifies the activities on these planes
  - High activities imply proton dissociation ⇒ non-UPC events

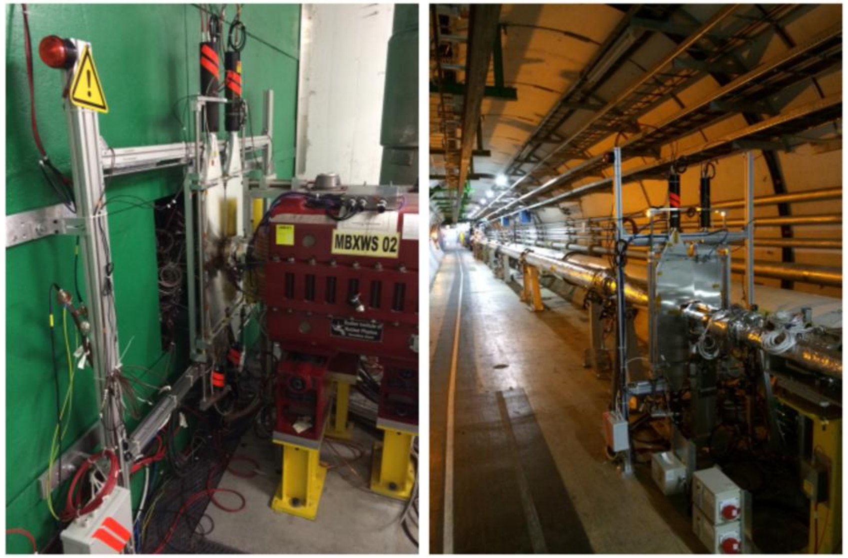


[JINST 13 (2018) no.04, P04017]

The HeRSCheL selection and efficiency are determined from the UPC J/ψ study [SciPost Phys.18,071(2025)].
Further optimisation is studied with $\gamma\gamma \to \mu\mu$.

HeRSCheL detector

[JINST 13 (2018) no.04, P04017]



Integrated Luminosity

- The 2017 and 2018 Run 2 datasets are analysed
  - Total integrated luminosity $\mathcal{L}_{int} = 3.30 \pm 0.07\ \text{fb}^{-1}$ [SciPost Phys.18,071(2025)]
- Low multiplicity requirement asks for only one visible pp interaction per event ⇒ lower effective luminosity
- The number of visible pp interaction per beam crossing follows a Poisson distribution

$$P(\mu, n) = \frac{\mu^n e^{-\mu}}{n!}$$

  - n: number of visible pp interaction
  - μ: mean, also known as pile-up, determined for each run with luminosity counters, $\mu \approx 1.2$ [2014 JINST 9 P12005]
- The effective integrated luminosity is

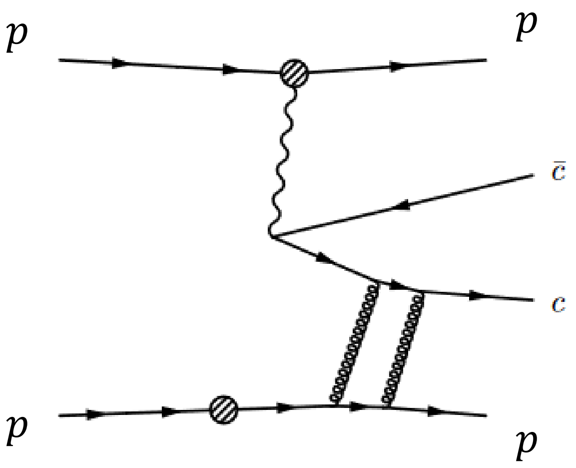
$$\mathcal{L}_{int}^{eff} = \frac{P(\mu, n=1)}{\Sigma_{n=0}^{\infty} nP(\mu, n)} \mathcal{L}_{int} = e^{-\mu} \mathcal{L}_{int} = 0.973 \pm 0.029\ \text{fb}^{-1}$$

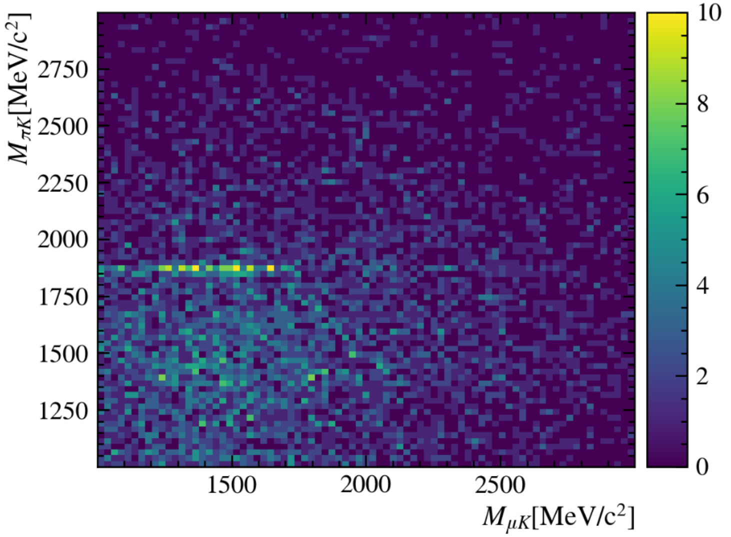
  - The uncertainty is from $\mathcal{L}_{int}$
- Signal comparison with $PbPb$ collisions

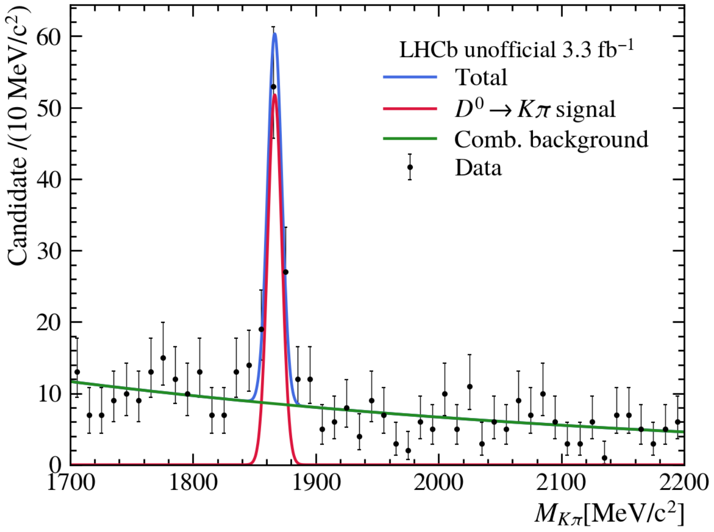
	pp Collision	$PbPb$ Collision
Effective Luminosity	$0.973\ \text{fb}^{-1}$	$\sim 50\ \mu\text{b}^{-1}$
Effective Cross-section (at $\delta a_\tau = \delta a_\tau^{\text{SM}}$)	$1.1 \times 10^3\ \text{fb}$	$10\ \mu\text{b}$
Expected events	$\sim 10^3$	~ 500

UPC $c\bar{c}$ backgrounds

- The jet production can contribute through 2 c-meson decay into a visible $e\mu$ pair, i.e. $(D^+ \to K_L^0 \mu^- \bar{\nu}_\mu)(D^- \to \bar{K}_L^0 e^+ \nu_e)$
- Not much research with UPC c-jets, so the cross-section $\sigma_{e\mu}^{DD}$ is measured from data
- A good control channel is $(D^0 \to K^+ \mu^- \bar{\nu}_\mu)(\bar{D}^0 \to K^- \pi^+)$
  - A muon requirement to fire the same trigger
  - A hadronic decay ⇒ clear D^0 mass peak in $K\pi$ invariant mass spectrum







- The 2D invariant mass plot indicates the presence of $D^0 \to K\pi$
- A sWeighted fit is applied to the $K\pi$ mass spectrum
  - Signal yield $N = 75$
  - The remaining $K\mu$ candidates is compatible with $D^0 \to K\mu\nu$ simulation ⇒ assume all $K\mu$ are real $D^0 \to K\mu\nu$

Detailed DD background σ

- The cross-section can be calculated as

$$\sigma_{e\mu}^{DD} = \frac{f(c\bar{c} \to D^+D^-)}{f(c\bar{c} \to D^0\bar{D}^0)} \frac{N_{K\pi K\mu\nu}^{D^0D^0}}{\mathcal{L}_{int}^{eff}\, \epsilon_{tot}^{D^0\bar{D}^0 \to K\pi K\mu\nu}} \epsilon_{tot}^{DD\to e\mu}$$

  - $N_{K\pi K\mu\nu}^{D^0D^0}$: the number of $(D^0 \to K^+\mu^-\bar{\nu}_\mu)(\bar{D}^0 \to K^-\pi^+)$ events
  - ϵ_{tot}^{i}: the efficiency of selection and the branching ratio of specific decay, determined from simulation
  - $\mathcal{L}_{int}^{eff}$: the effective integrated luminosity, calculated in previous slide
  - $f(c\bar{c} \to DD)$: the fraction of D appearance in the c-jets hadronization, determined with soft-QCD simulation

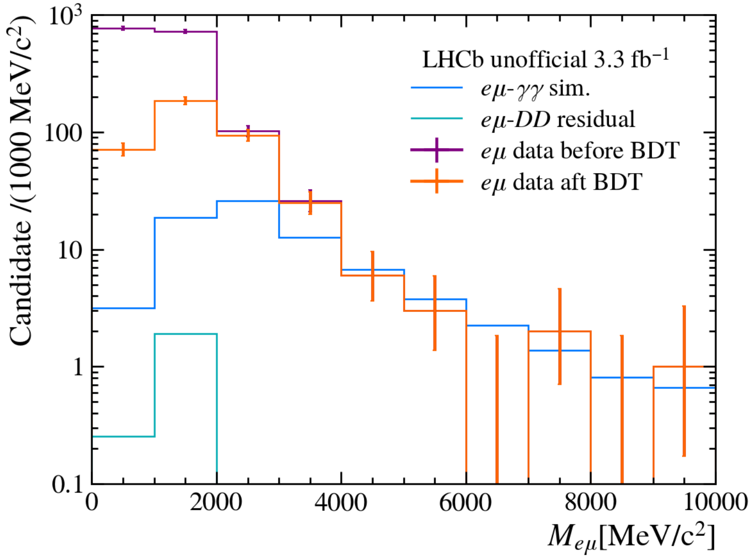
$$\frac{f(c\bar{c} \to D^+D^-)}{f(c\bar{c} \to D^0\bar{D}^0)} = \frac{0.34^2}{0.66^2}$$

UPC $c\bar{c}$ backgrounds

- The total number of $(D^0 \to K^+\mu^-\bar{\nu}_\mu)(\bar{D}^0 \to K^-\pi^+)$ event is thus $N_{K\pi K\mu}^{D^0 D^0} = 75$

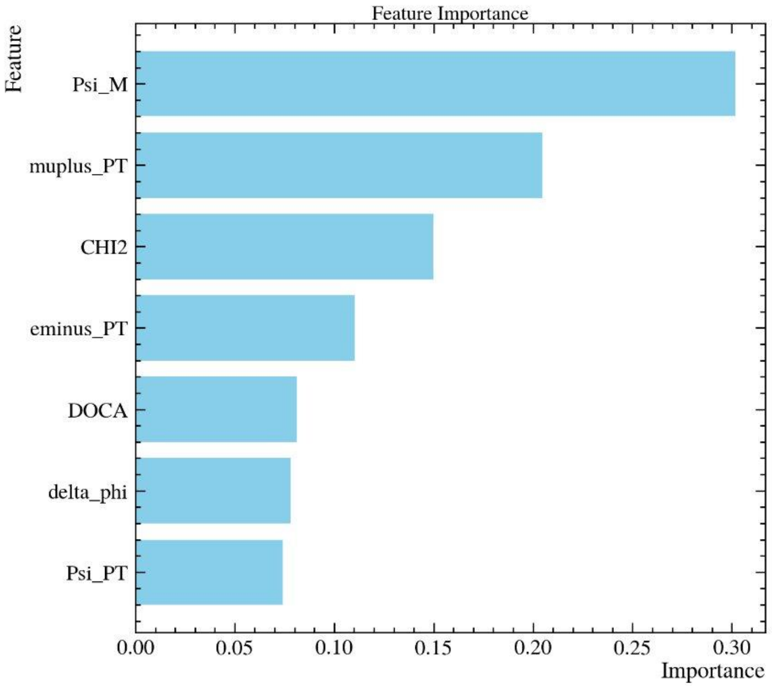
$$\Rightarrow \sigma_{e\mu}^{DD}(2 < \eta_{e,\mu} < 5) = 36.7 \text{ pb}$$

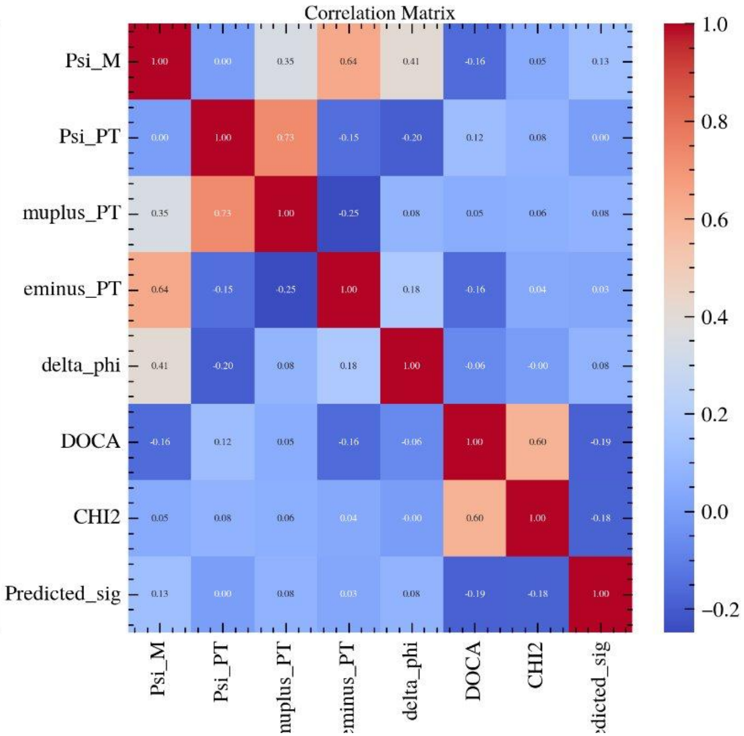
- The isolation of signal from D^+D^- background proceeds with a Boosted Decision Tree (BDT)
  - Hyperparameter optimisation is completed with Bayesian Optimisation
  - Signal: simulated $\gamma\gamma \to \tau\tau \to e\mu$ sample
  - Background: simulated $D^+D^- \to K^0\bar{K}^0 e\mu$ sample
  - Variables: kinetic variables of e, μ and their system



- The remaining data before and after BDT output is shown in the log-scaled figure
  - A massive background in low-mass region is eliminated
  - Residual DD background is about 1% the size of the signal

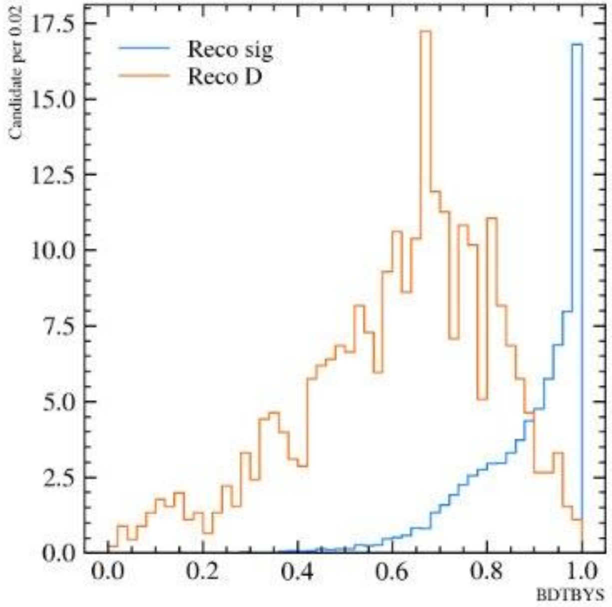
Trained Variables
p_T^e
p_T^μ
$M_{e\mu}$
$p_T^{e\mu}$
$DOCA$
χ^2_{ver}
$\Delta\phi(e,\mu)$

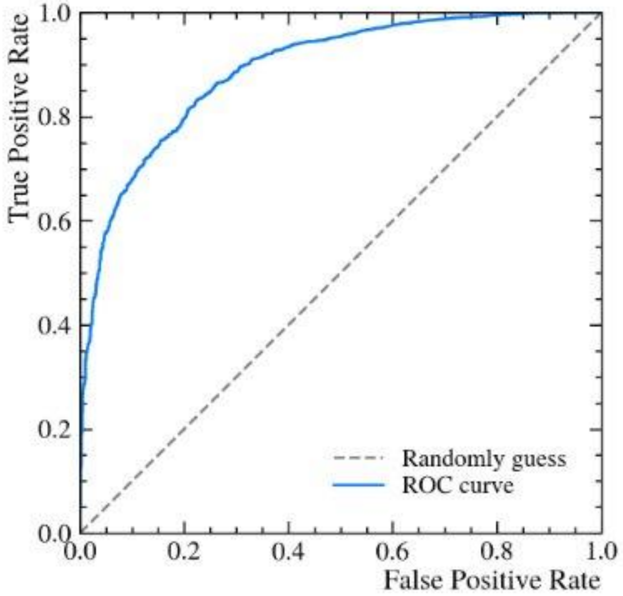


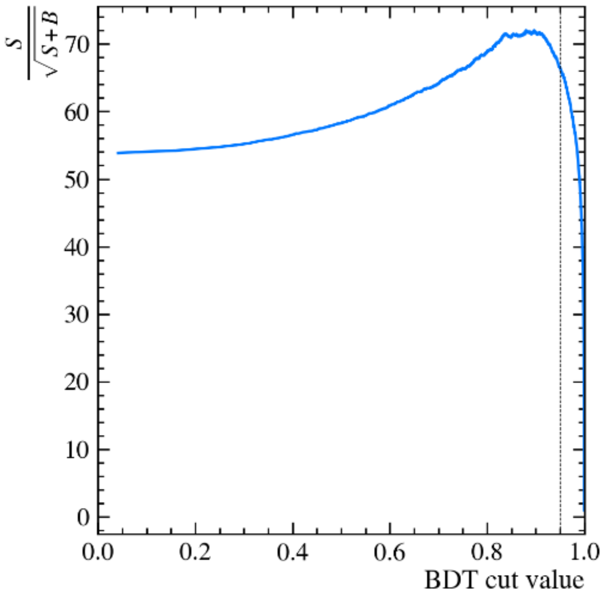


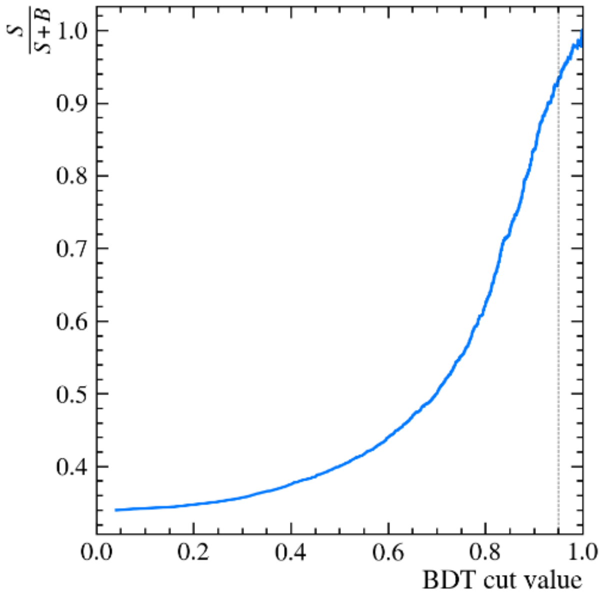
The Figure of Merit (FoM) is assessed with the significance $S/\sqrt{S+B}$ and the purity $\frac{S}{S+B}$

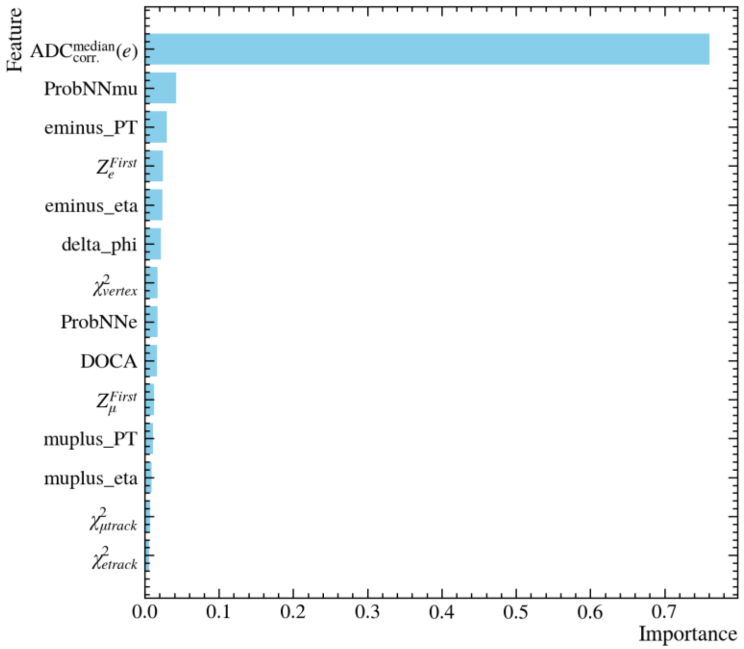
The cut value is selected to ensure the purity $> 95\%$ and with a relatively high significance







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ProbNNmu
eminus_PT
Z_e^{First}
eminus_eta
delta_phi
χ^2_{vertex}
ProbNNe
DOCA
Z_μ^{First}
muplus_PT
muplus_eta
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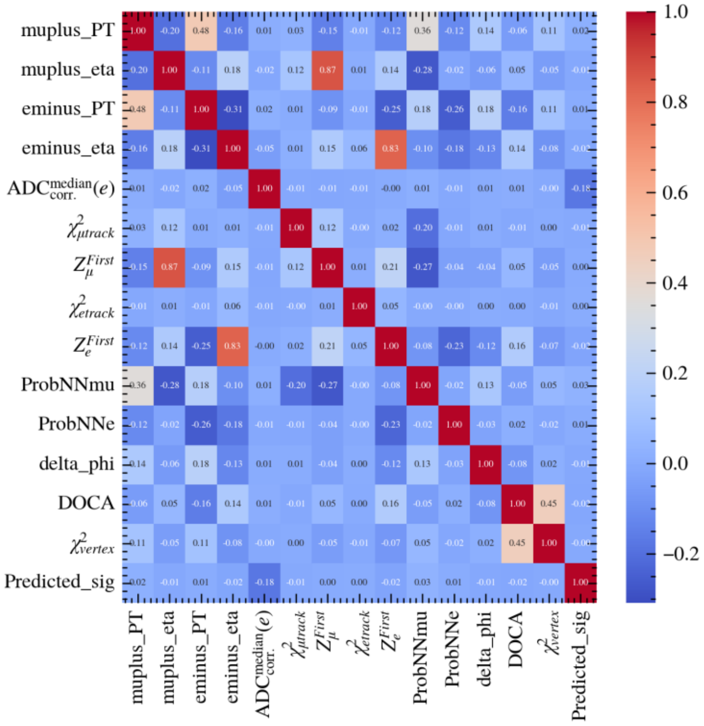
Importance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muplus_eta
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eminus_eta
$ADC^{median}_{corr.}(e)$
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Z_μ^{First}
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Z_e^{First}
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Predicted_sig
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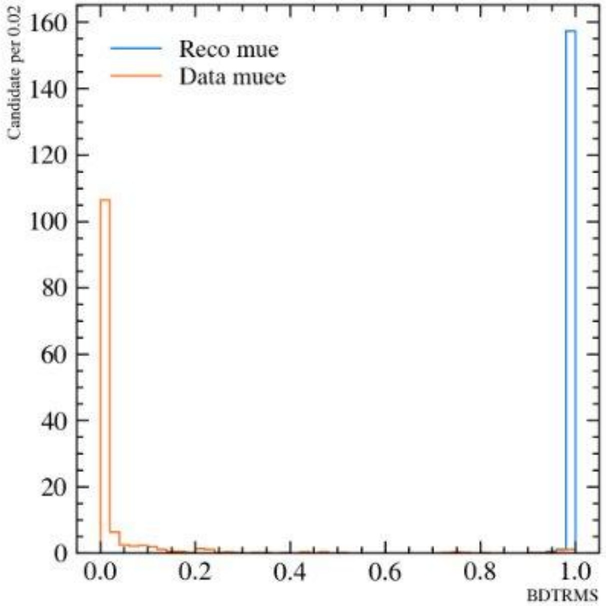
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Reco mue
Data muee
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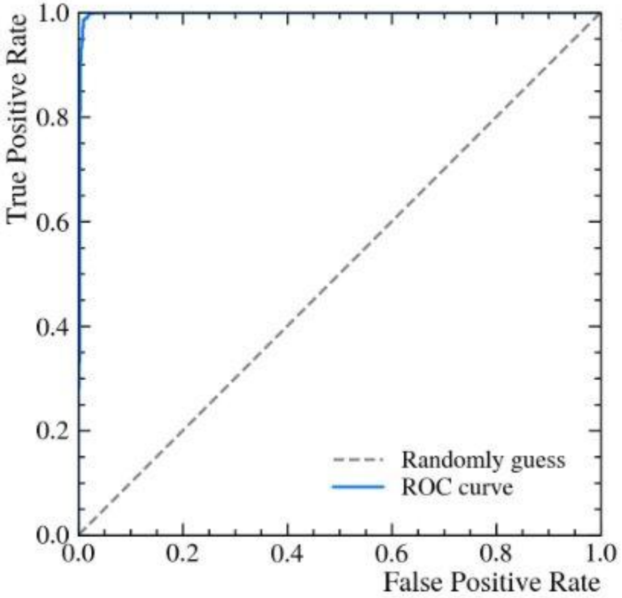
0.0 0.2 0.4 0.6 0.8 1.0
BDTRMS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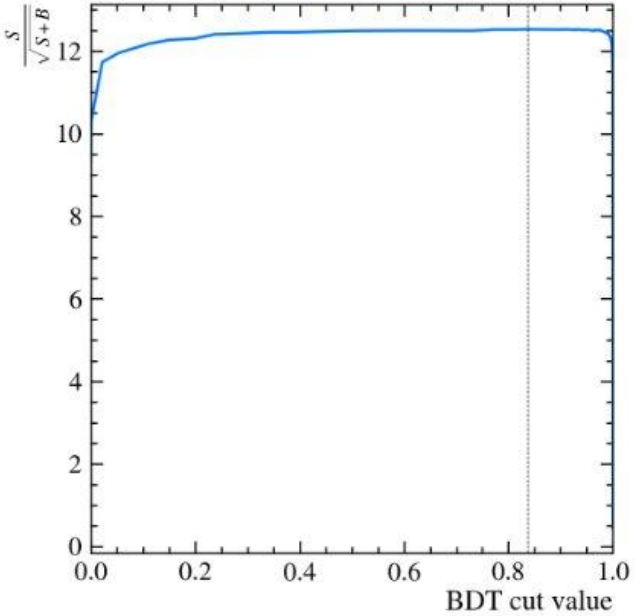
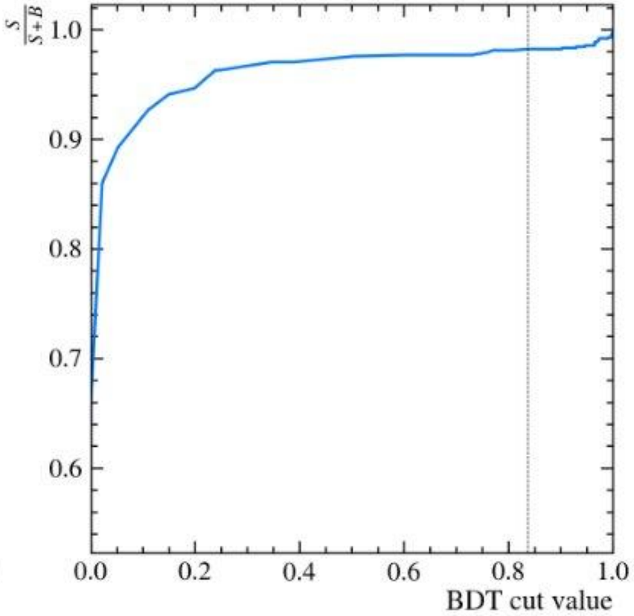
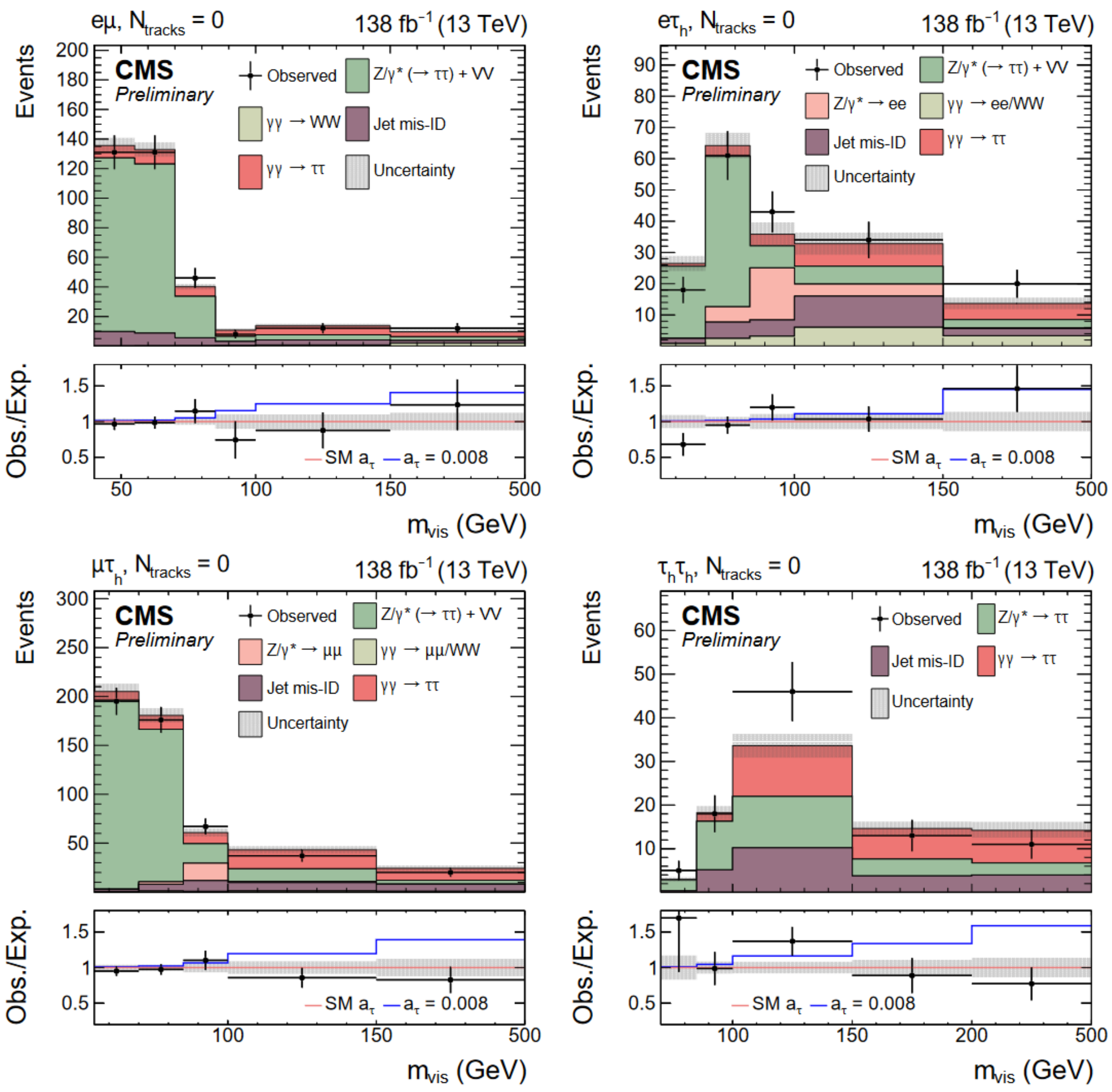
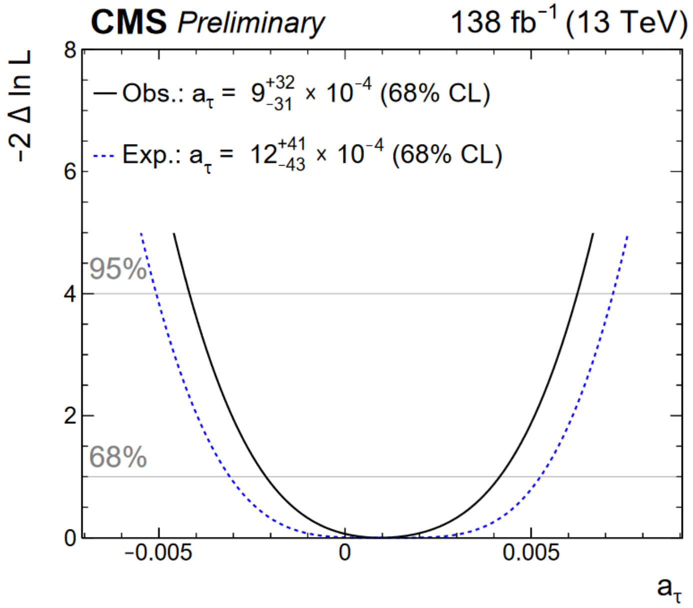
False Positive Rate
Randomly guess
ROC curve
0.0 0.2 0.4 0.6 0.8 1.0


$\frac{S}{\sqrt{S+B}}$
0 2 4 6 8 10 12
0.0 0.2 0.4 0.6 0.8 1.0
BDT cut value


$\frac{S}{S+B}$
0.6 0.7 0.8 0.9 1.0
0.0 0.2 0.4 0.6 0.8 1.0
BDT cut value





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Process	$e\mu$	$e\tau_h$	$\mu\tau_h$	$\tau_h\tau_h$
$Z/\gamma^* \to \tau\tau$	3.6 ± 0.5	9.0 ± 1.2	18.7 ± 2.9	20.2 ± 3.1
$Z/\gamma^* \to ee/\mu\mu$	—	3.9 ± 1.2	1.6 ± 0.6	—
Jet mis-ID	5.0 ± 0.8	11.4 ± 2.9	16.5 ± 3.6	17.5 ± 2.8
Inclusive VV	3.0 ± 0.3	0.2 ± 0.0	0.4 ± 0.0	—
$\gamma\gamma \to ee/\mu\mu$	—	8.1 ± 2.3	1.4 ± 0.2	—
$\gamma\gamma \to WW$	2.5 ± 0.6	0.1 ± 0.0	0.4 ± 0.1	—
Total bkg.	14.1 ± 1.3	32.8 ± 4.8	38.9 ± 4.4	37.7 ± 4.2
Signal	11.9 ± 4.2	15.8 ± 5.7	40.3 ± 14.2	33.4 ± 11.2
Total	26.0 ± 3.8	48.5 ± 4.7	79.2 ± 13.6	71.1 ± 9.3
Observed	24	54	57	70