Search for Non-thermal Dark Matter through Monojet Signatures Associated with a Bottom Quark

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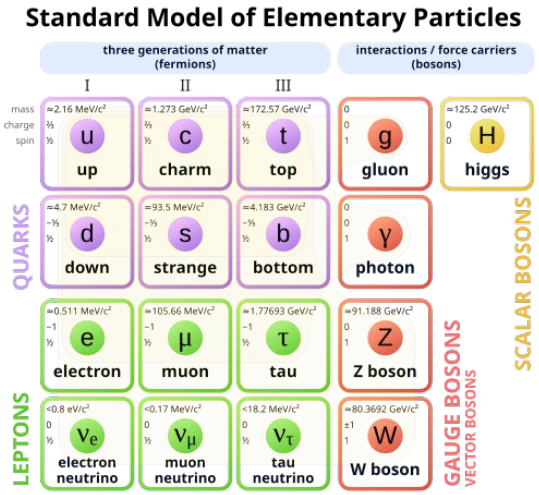
Introduction

The Standard Model

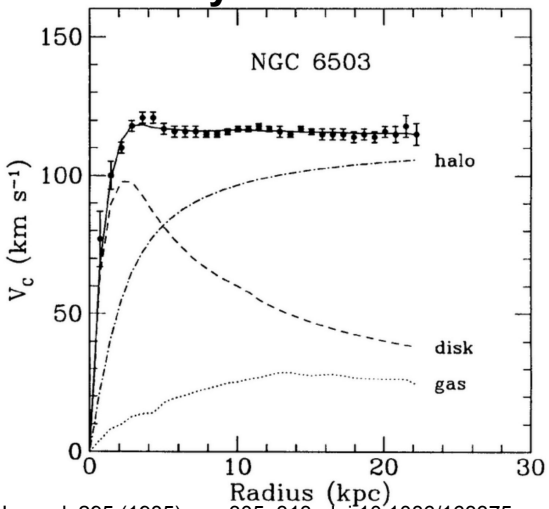
- Although the Standard Model (SM) is a successful theory describing fundamental particles, forces, and interactions, the SM has several limitations



Limitation of the Standard Model

- Baryon Asymmetry
  - Matter and Antimatter asymmetry
    ⇒ Theoretical prediction ≠ Observation
  - **Sakharov conditions**[1] to explain the asymmetry
  - BSM models proposed with the condition
- Dark Matter
  - galaxy rotation curves ⇒ dark matter (DM)[2]
  - various DM models have been proposed
    WIMPs, Axions, Sterile neutrinos, ect

Galaxy rotation curve[2]

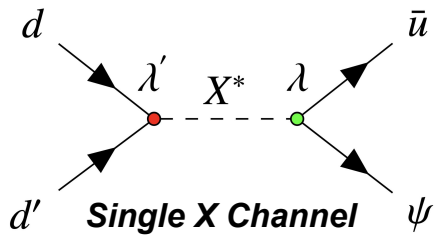


[1] A D Sakharov, Violation of CP in Variance, C Asymmetry, and Baryon Asymmetry of the Universe, 1991.
[2] T. S. van Albada, J. N. Bahcall, K. Begeman, and R. Sancisi, 'Distribution of Dark Matter in the Spiral Galaxy NGC 3198', Astrophysical Journal, 295 (1985), pp. 305–313, doi:10.1086/163375.

The Model Setup

Benchmark Model

- Interaction Lagrangian $\mathcal{L}_{int} \supset \lambda_{\alpha i} X_\alpha \psi u_i^c + \lambda'_{\alpha i j} X_\alpha^* d_i^c d_j^c + \frac{m_\psi}{2} \bar{\psi}^c \psi + \text{h.c.}$
  - X_α : Two iso-singlet color-triplet scalars (α =1,2)
  - ψ : Majorana fermion (hypercharge 0) | DM candidate
  - $X_\alpha^* d_i^c d_j^c$: Quark fusion interaction
  - $X_\alpha \psi u_i^c$: Interaction with up-type quark and DM candidate
  - $\lambda'_{\alpha i j}$ $\lambda_{\alpha i}$: coupling constant i, j flavour indices $i \neq j$



Monojet Signature

- Final state of monojet signature
  - One **b quark,** one **light quark**, and large **MET** from ψ
- Monojet signature

$$\mathcal{L}_{int} \supset \lambda_{\alpha i} X_\alpha \psi u_i^c + \lambda'_{\alpha i j} X_\alpha^* d_i^c d_j^c + \frac{m_\psi}{2} \bar{\psi}^c \psi + \text{h.c.}$$

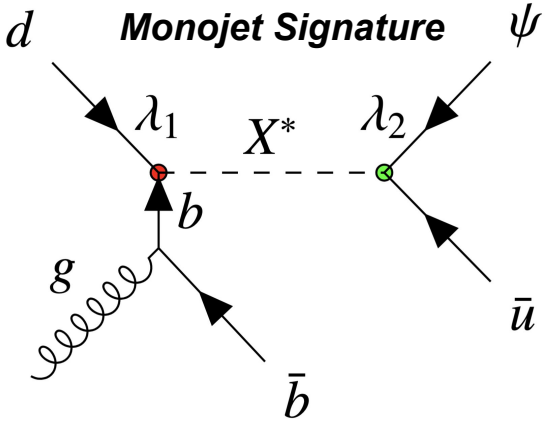
Coupling Condition

Allow : coupling of X to **u quark** only

The fusion of **d-b** and **s-b quarks**

$$\mathcal{L}_{monojet} \supset \lambda_{\psi u} X_1 \psi u^c + \lambda_{db} X_1^* d^c b^c + \lambda_{sb} X_1^* s^c b^c + \text{h.c.}$$

$\lambda_{\psi u} \rightarrow \lambda_2$, $\lambda_{db}, \lambda_{sb} \rightarrow \lambda_1$



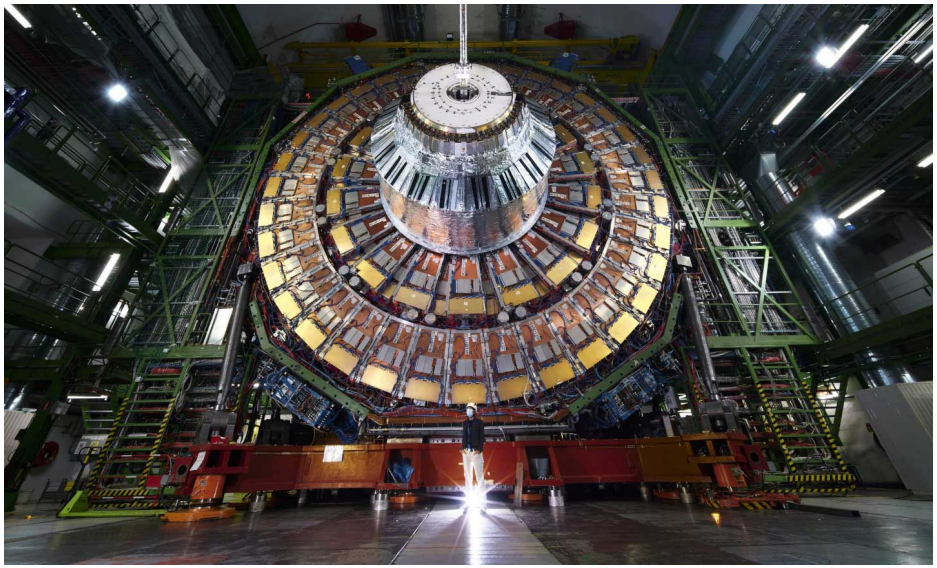
LHC and CMS

Large Hadron Collider (LHC)

"*The world's largest and highest-energy particle accelerator*"

Compact Muon Solenoid (CMS)

"one of two large general-purpose particle physics detectors built on LHC"



Simulation

Monte-Carlo Simulation Sample Production

- MadGraph5_aMC@NLO (v2.6.7) for ***pp* collisions at √s = 13 TeV**
  Parton showering and hadronization : PYTHIA8 (v8.244)
  Detector simulation : DELPHES (v3.4.2) Modified **CMS-like detector configuration**

- Signal Modeling and Coupling Grid
  - The m_{X_1} = **1.0, 1.5, and 2.0 TeV**
    with m_{X_2} = 10 TeV and m_{ψ} = 1 GeV
  - On a 2-dim coupling grid (15, 14) :
    λ_1 = {0.03, 0.05, …, 1.0}, λ_2 = {0.04, 0.06, …, 1.0}

cross section σ [fb]				
λ_1	λ_2			
	0.1	0.2	0.5	1.0
0.1	11.69	28.22	46.46	51.00
0.2	12.83	43.22	130.87	182.48
0.5	13.04	50.91	268.25	683.89
1.0	14.24	56.88	340.55	1159.29

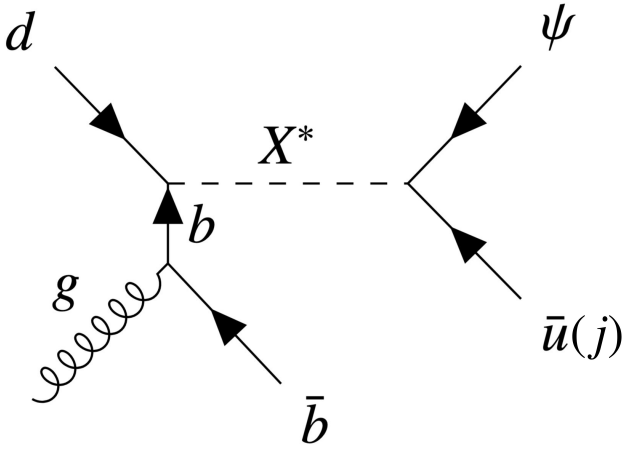
Several cross-section for production of X_1 with 1.0 TeV mass point

- Backgrounds information
  - Generated background processes:
    W+jets (WJ), Z+jets (DY), TTbar(TT), and Di-boson(VV)
  - *WJ, DY,* and *TT*
    ⇒ Generated with up to three additional ISR/FSR jets

Analysis

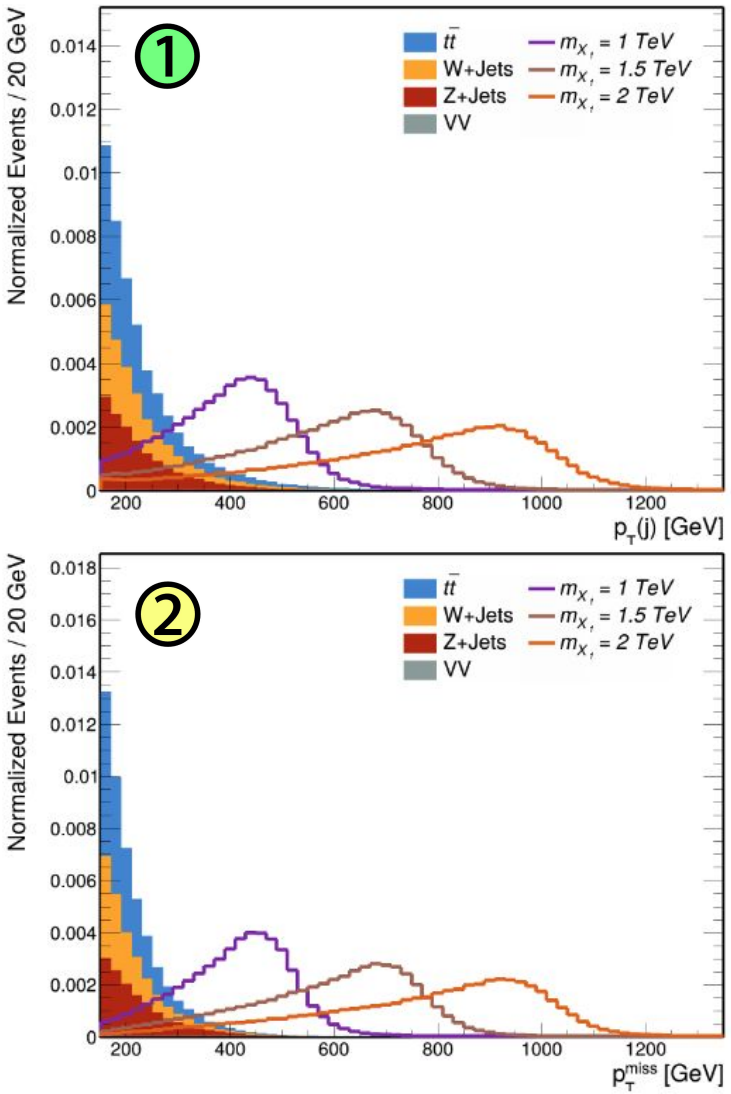
Object and Event Selections

- Signal topology (Remind)
  - One **b-tagged jet (b)**
  - One **light quark jet (j)** and
  - Large **transverse missing energy** (ψ)
    ⇔ DM candidate



- Selection description
  - One b-tagged jet selection :
    $p_T(b) > 20\ \mathrm{GeV} \quad |\eta(b)| < 2.4$
  - One light quark jet selection :
    $p_T(j) > 150\ \mathrm{GeV} \quad |\eta(j)| < 2.4$
  - Missing Transverse Energy :
    $p_{\mathrm{T}}^{\mathrm{miss}} > 150\ \mathrm{GeV}$
  - Lepton (e/μ) and τ tagged jet event veto :
    $p_T > 10\ \mathrm{GeV} \quad |\eta| < 2.4$
    applied to suppress backgrounds from $W(\rightarrow \ell\nu) + jets$ and $t\bar{t}$ with leptonic decays

Analysis



Kinematic distributions

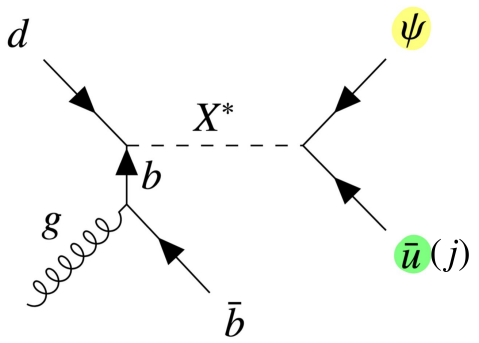
- Objects from mediator X
  - The light jet
  - $p_{\mathrm{T}}^{\mathrm{miss}}$: transverse missing momentum

    ⇒ Both carry much higher p_{T} than background

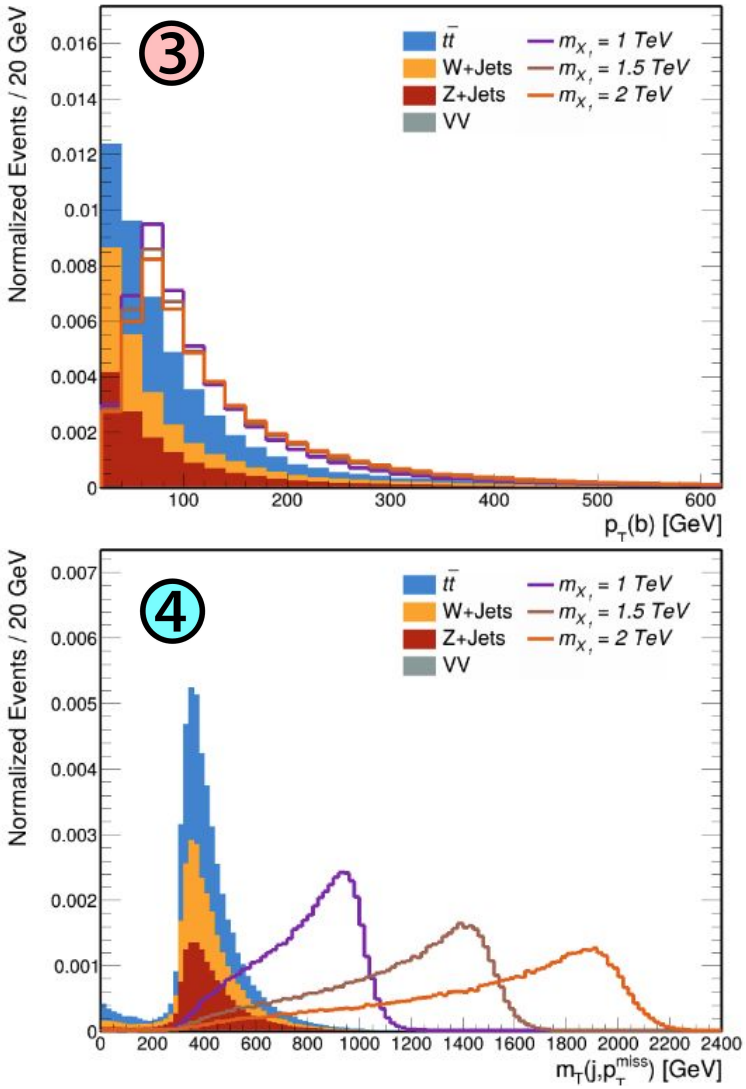
- Characteristic features
  - For each m_{X_1} both leading jet p_{T} and $p_{\mathrm{T}}^{\mathrm{miss}}$

    ⇒ Jacobian-like peak near $p_{\mathrm{T}} \sim m_{X_1}/2$

    ⇒ due to two-body decay kinematics of X

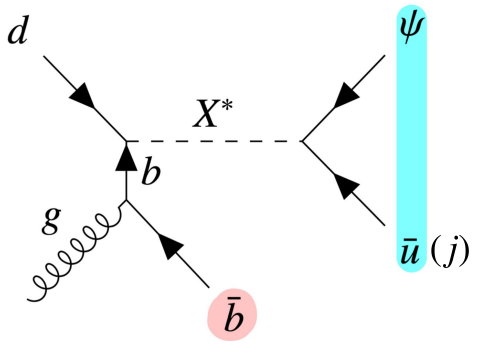


Analysis



Kinematic distributions

- Gluon splitting
  - The b-tagged jet arises from gluon splitting
    ⇒ soft b-jet concentrated at low p_{T}
- Transverse mass distribution
  - $m_{\mathrm{T}}(j, p_{\mathrm{T}}^{\mathrm{miss}})$ shows endpoint close to m_{X_1}
  - Signal produces harder m_{T} spectrum than background
  - As m_{X_1} increases, endpoint shifts to higher values



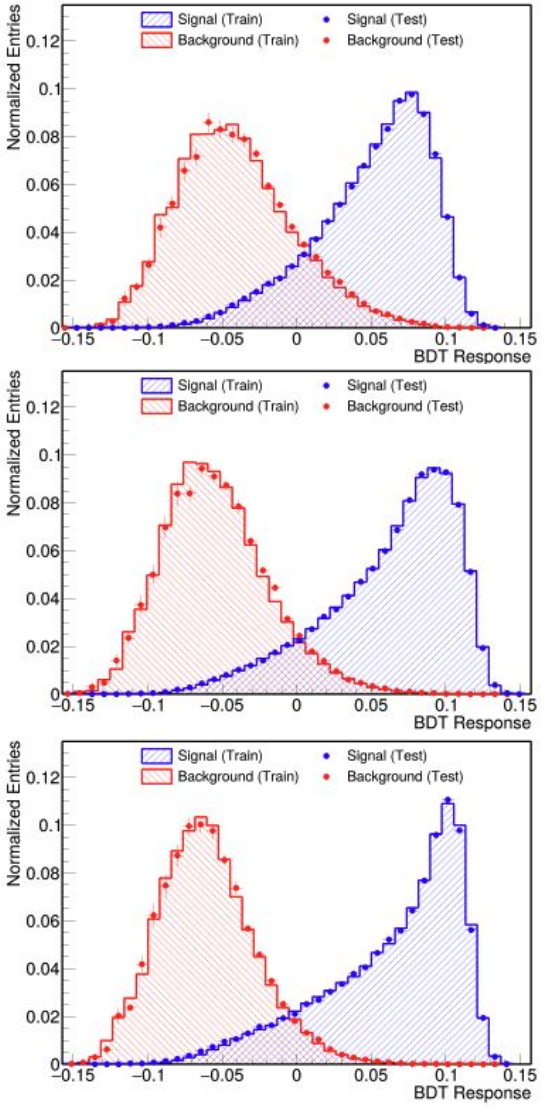
Analysis

BDT Training and Performance

- Boosted Decision Tree (BDT)
  - Machine-learning–based classifier trained
    ⇒ Lead to enhanced **signal–background discrimination**

- Training setup
  - Separate BDT model trained for each X_1 mass point
  - Signal : all combinations of $(\lambda_1, \lambda_2) \in \{0.1, 0.3, 1.0\}^2$
  - Background : all main background processes

- Input variables (total 10)
  - $p_{\mathrm{T}}(j),\ p_{\mathrm{T}}(b),\ p_{\mathrm{T}}^{\mathrm{miss}}$
  - $\eta(j),\ \eta(b)$
  - $\Delta\phi(j,b),\ \Delta\phi(b,p_T^{\mathrm{miss}}),\ \Delta\phi(p_T^{\mathrm{miss}},j)$
  - $\Delta R(j,b),\ m_T(p_{\mathrm{T}}^{\mathrm{miss}},j)$



Results

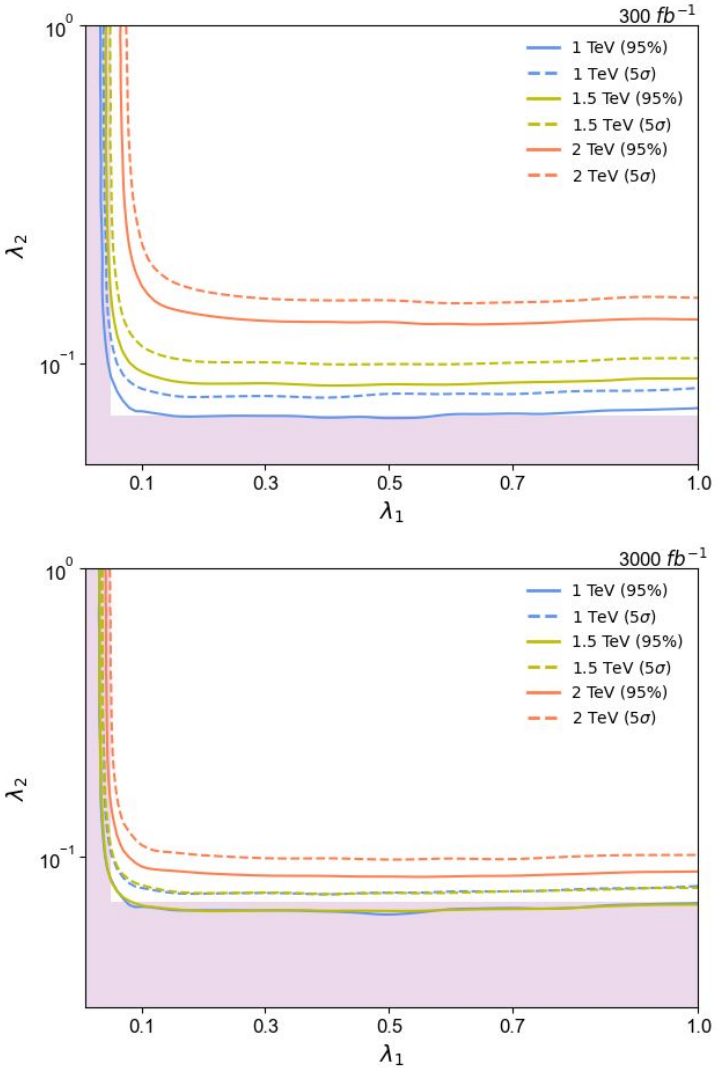
- **Statistical evaluation : Bayesian approach**
- MC Statistics : 1.84 - 3.64 %
  - Systematic error has become important
    → *Working in Progress*
- **95 % Confidence Level Exclusion Limit** and **5σ Discovery Potential Line**

- Exclusion region (95% CL)

Run 3 300 fb^{-1}	m_{X_1} [TeV]		
	1.0	**1.5**	**2.0**
λ_1	> 0.03	> 0.04	> 0.06
λ_2	> 0.07	> 0.09	> 0.13

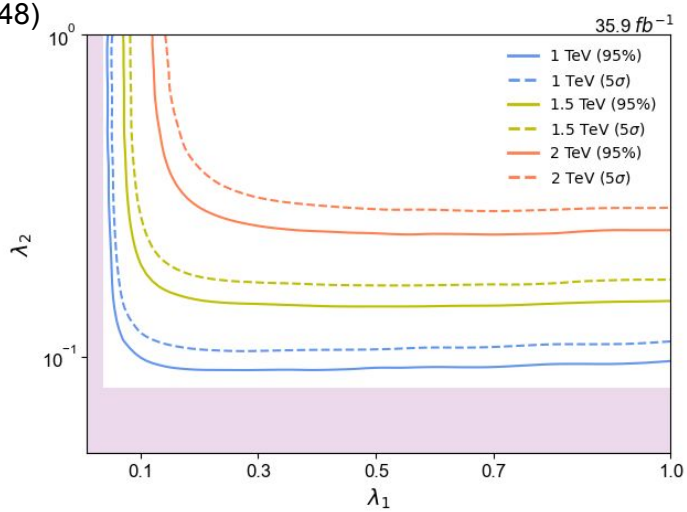
HL-LHC 3000 fb^{-1}	m_{X_1} [TeV]		
	1.0	**1.5**	**2.0**
λ_1	> 0.03	> 0.03	> 0.04
λ_2	> 0.06	> 0.06	> 0.09

  - If the coupling goes beyond **this limit**, the signal is excluded at 95% CL
  - Higher m_{X_1} → exclusion sensitivity decreased
  - Higher luminosity → stronger exclusion limits due to more signal events
  - Purple solid area ⇒ hadronization region



Results; Comparison with CMS analysis[7]

- CMS collaboration performed a monojet analysis(CMS-EXO-16-048)
- In that study, b-tagged jets were vetoed
  ⇒ **This study is comparably (**associated with a b quark)
- 35.9 fb^{-1} of data collected at $\sqrt{s}$ **= 13 TeV (2016 Run)**

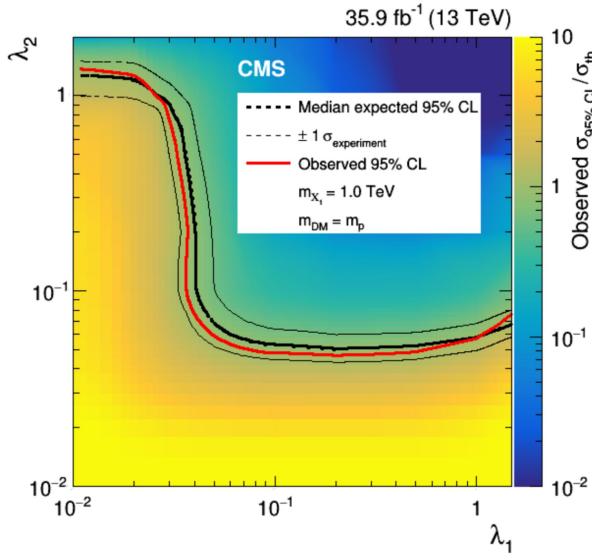


- Exclusion region (95% CL) **2016 Run (35.9 fb^{-1})**

monojet	m_{X_1} [TeV]
	1.0
λ_1	**> 0.04**
λ_2	**> 0.09**

CMS Monojet Analysis	m_{X_1} [TeV]
	1.0
λ_1	**> 0.04 (0.03)**
λ_2	**> 0.05 (0.05)**

  - The solid line in the CMS plot
    ⇒ the upper limit from the previous monojet analysis
  - The exclusion region for λ_1 is shown as similar level



[3] C. M. S. Collaboration, 'Search for New Physics in Final States with an Energetic Jet or a Hadronically Decaying W or Z Boson and Transverse Momentum Imbalance at $\sqrt{s} = $ 13 TeV', Physical Review D, 97.9 (2018), p. 092005, doi:10.1103/PhysRevD.97.092005.

Summary

- We presented a study on **the search potential for a baryon-number-violating dark matter (DM) candidate** using a **b-associated monojet channel** involving a bottom jet, light-quark jet, and DM candidates.

- To complement previous monojet, our analysis introduces an additional b-tagged jet in the final state, improving the sensitivity to this specific interaction topology.

- The results are shown in the parameter space with **95% CL exclusion limits** and **5σ discovery potential lines**, highlighting the experimental reach for given coupling and mass configurations.

- Compared to existing monojet analyses and b-associated monotop channel, this study provides **comparable coverage of the parameter space.**

Backup Slides

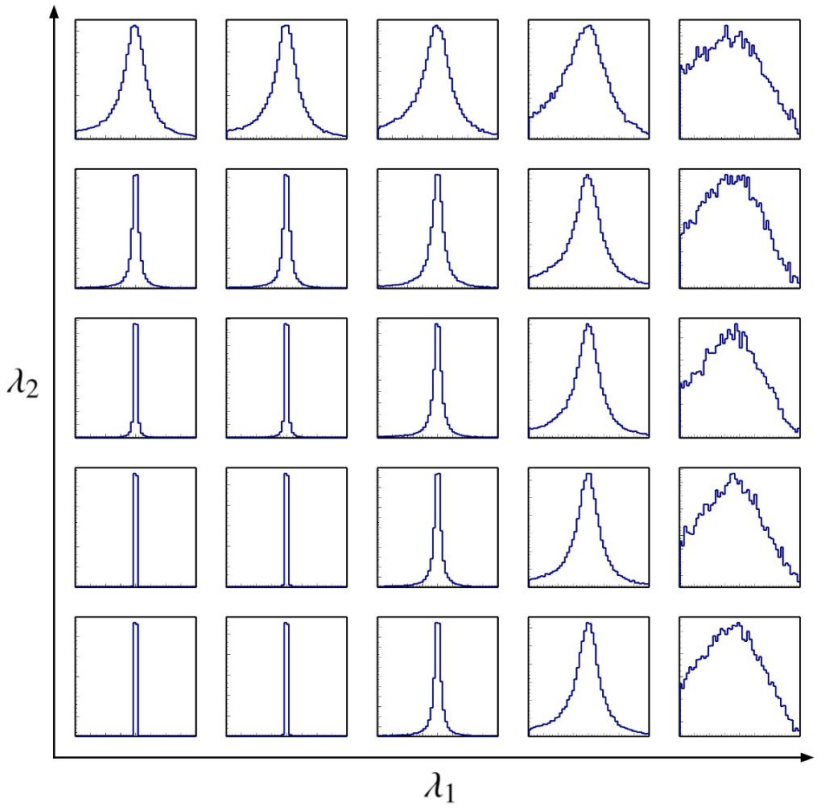
Simulation

Mass Distribution

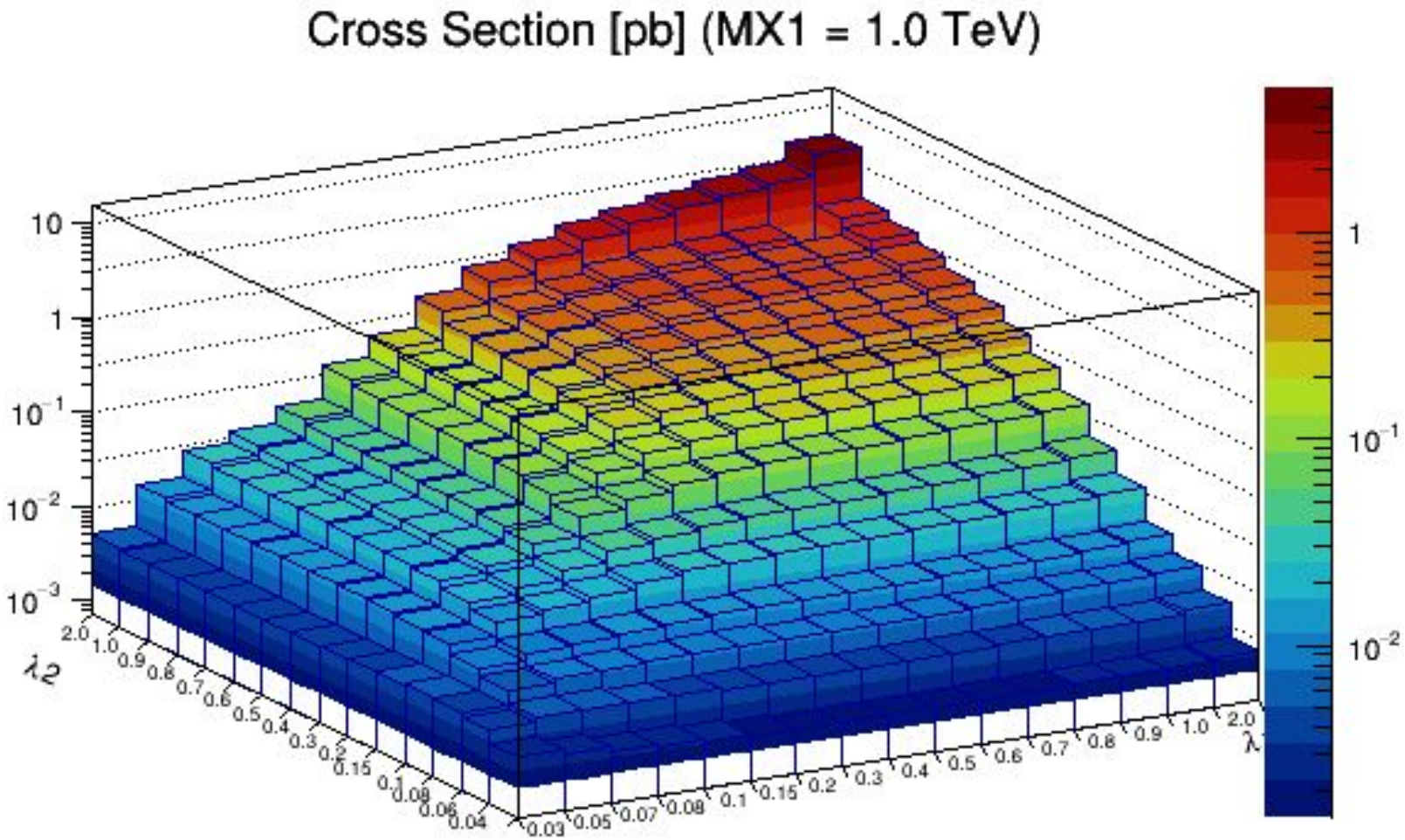
Generator level mass of x1 distributions for 1.0 TeV sample with several (λ_1, λ_2) values :
{0.08, 0.1, 0.5, 1.0, 2.0}.

Each plot shows the x-axis range of 800–1200 GeV divided into 50 bins,
while the y-axis represents the normalized event yield.

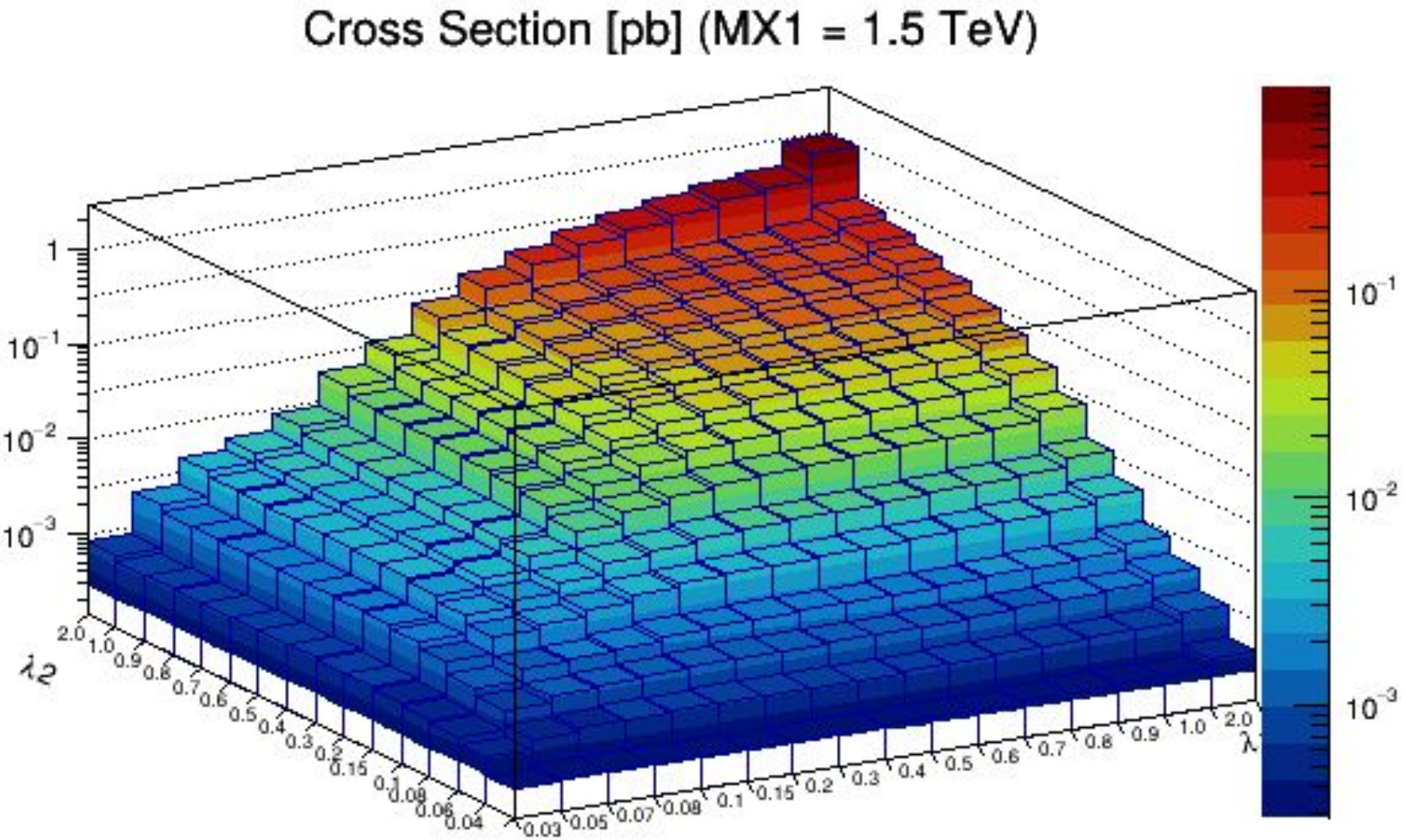
The case of (λ_1 = 2.0), It appears to show different kinematics from others.



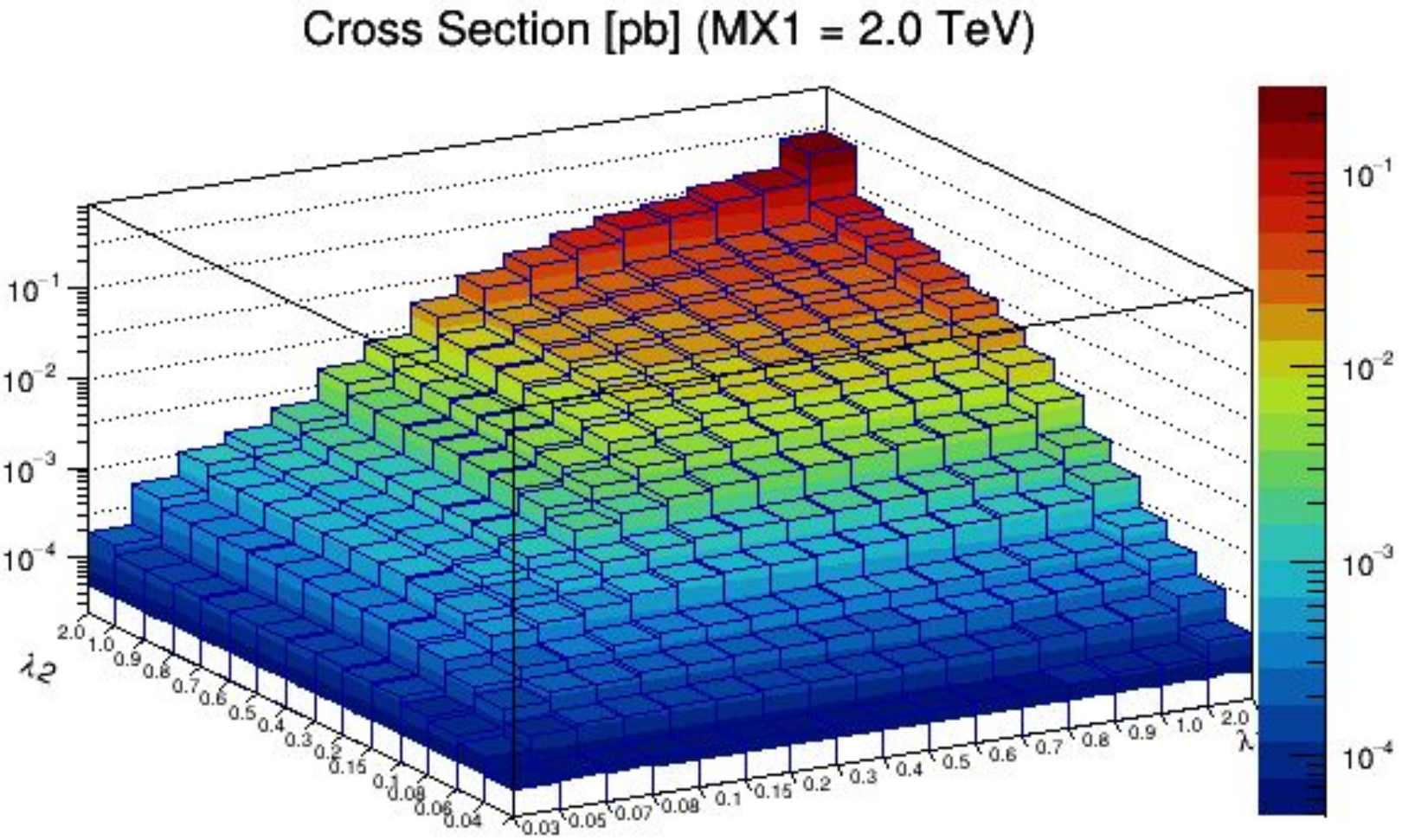
Cross-section 2D plot; 1.0 TeV signal



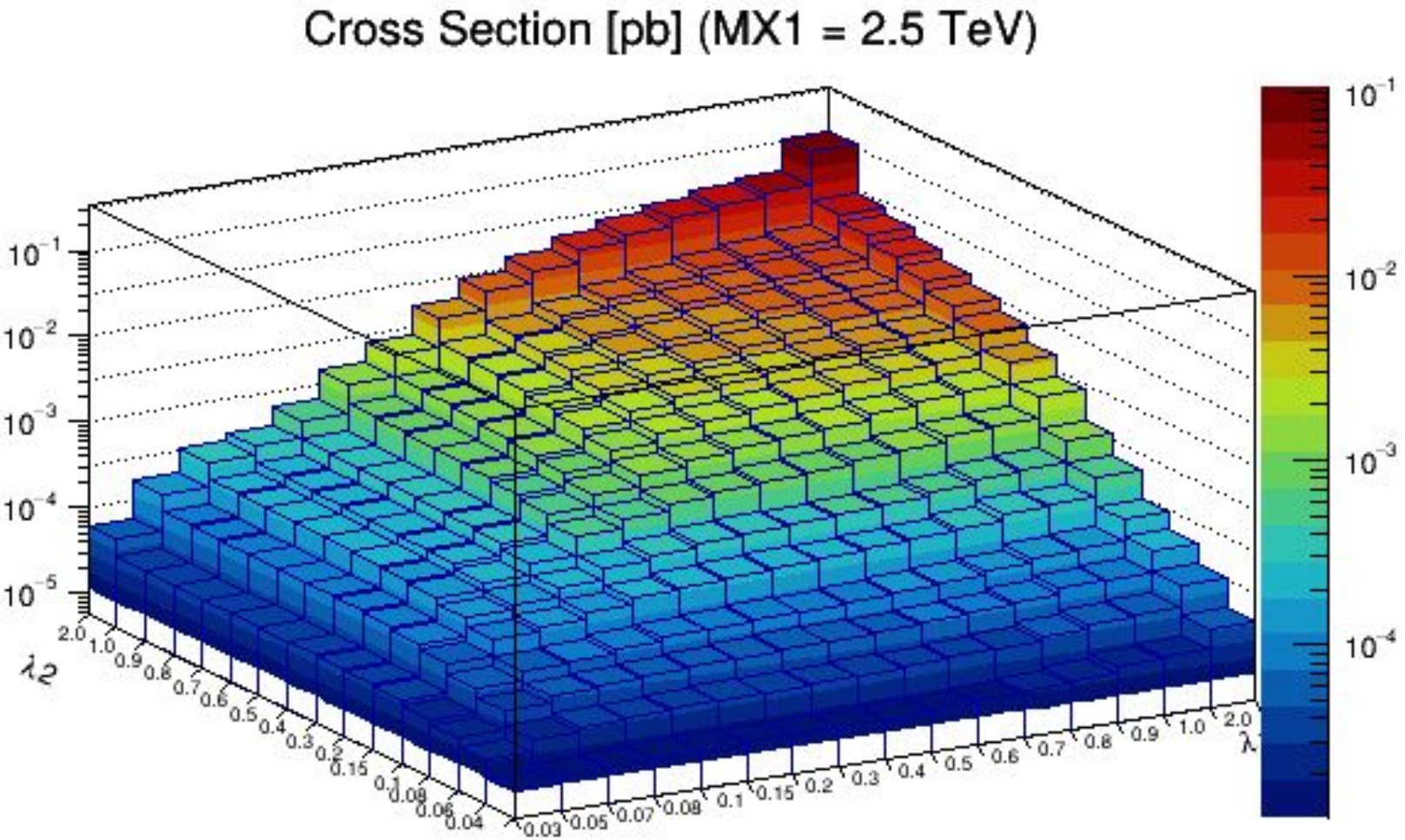
Cross-section 2D plot; 1.5 TeV signal



Cross-section 2D plot; 2.0 TeV signal



Cross-section 2D plot; 2.5 TeV signal



of events after selection

Backgrounds

Run3 Lumi	TT	DY	WJ	ZZ	Total
generated	165,137,700.0	67,059,895.4	305,904,769.0	13,173,705.8	551,276,070.0
l veto	97,875,346.6	65,331,800.8	148,834,524.0	6,394,586.6	318,436,259.0
ujet	12,627,962.2	10,842,621.0	20,479,855.5	165,958.8	44,116,397.5
bjet	5,927,747.5	662,997.1	1,250,993.0	21,757.3	7,863,495.0
met	351,373.9	236,314.1	225,546.8	2,657.9	**815,892.7**
Sel / Gen [%]	0.21%	0.35%	0.07%	0.02%	0.15%

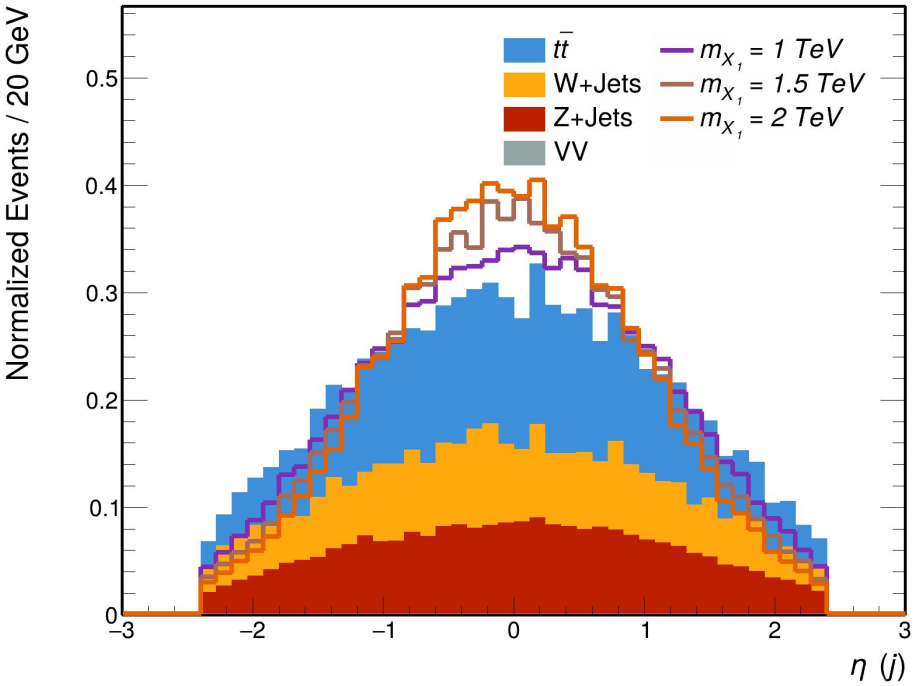
Signals

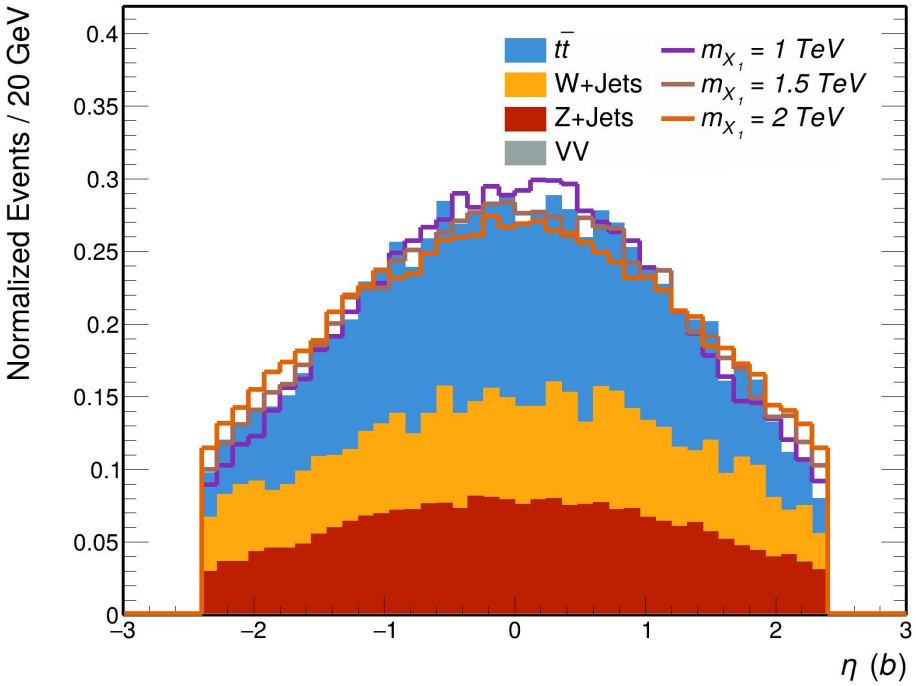
Run3 Lumi	1.0 (0.5, 0.5)	1.5 (0.5, 0.5)	2.0 (0.5, 0.5)
generated	80,475.3	11,979.9	2,549.0
l veto	75,684.1	11,242.1	2,387.8
ujet	51,881.2	7,313.4	1,465.5
bjet	30,598.9	4,288.3	849.2
met	29,620.6	4,230.4	842.6
Sel / Gen [%]	36.81%	35.31%	33.06%

Distribution

300 fb^{-1} (13 TeV)

- **Pseudorapidity (Eta or η) distribution**
  - η distribution of j on left plot in x ∈ [-3, 3]
  - η distribution of b on right plot in x ∈ [-3, 3]

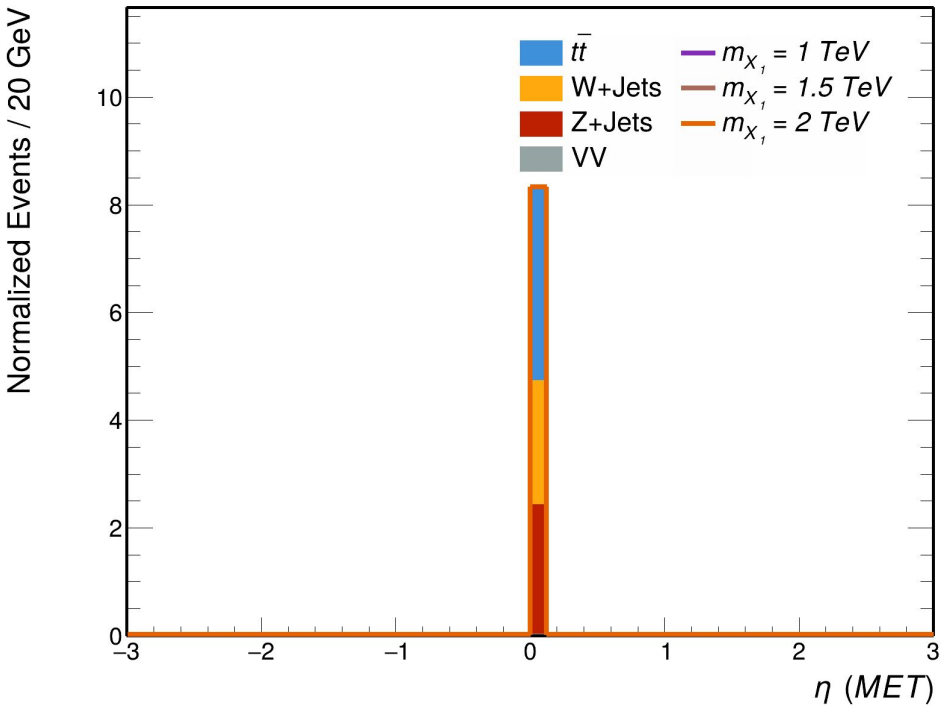




Distribution

300 fb^{-1} (13 TeV)

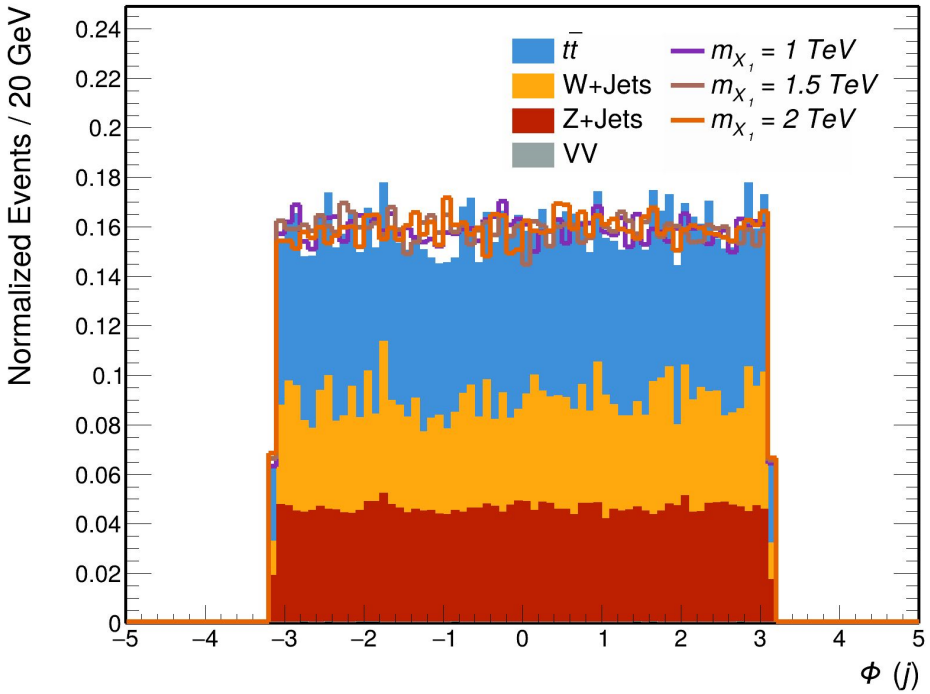
- **Pseudorapidity (Eta or η) distribution**
  - η distribution of MET in x ∈ [-3, 3] with normalized events
  - It's trivial result because η of MET is zero by definition

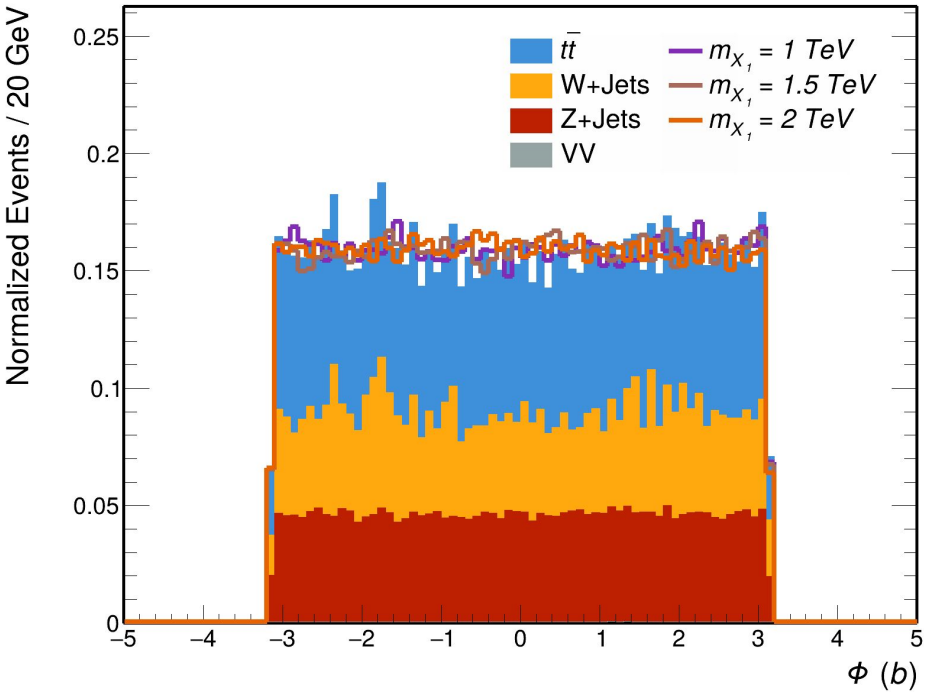


Distribution

300 fb^{-1} (13 TeV)

- **azimuthal angle (Phi or ϕ) distirbution**
  - ϕ distribution of j on left plot in x ∈ [-5, 5] with normalized events
  - ϕ distribution of b on right plot in x ∈ [-5, 5] with normalized events

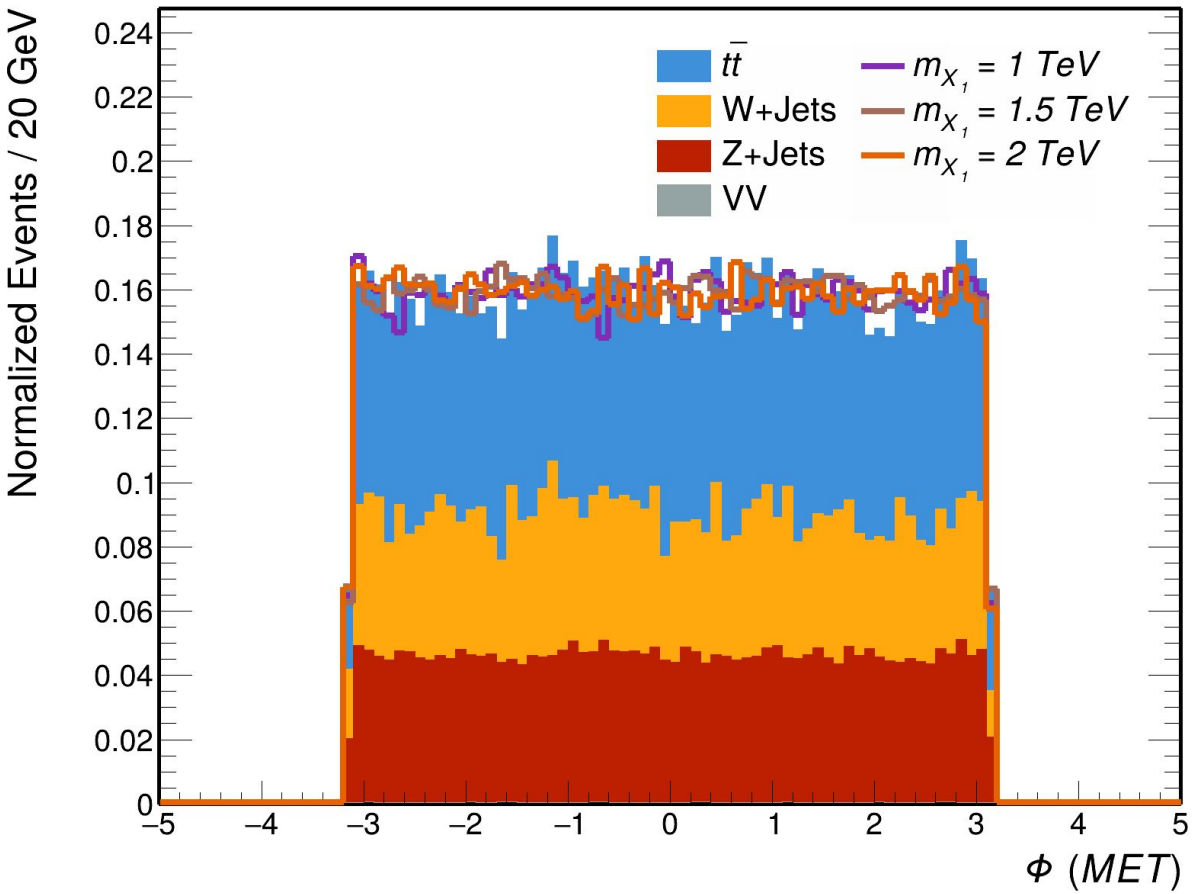




Distribution

300 fb^{-1} (13 TeV)

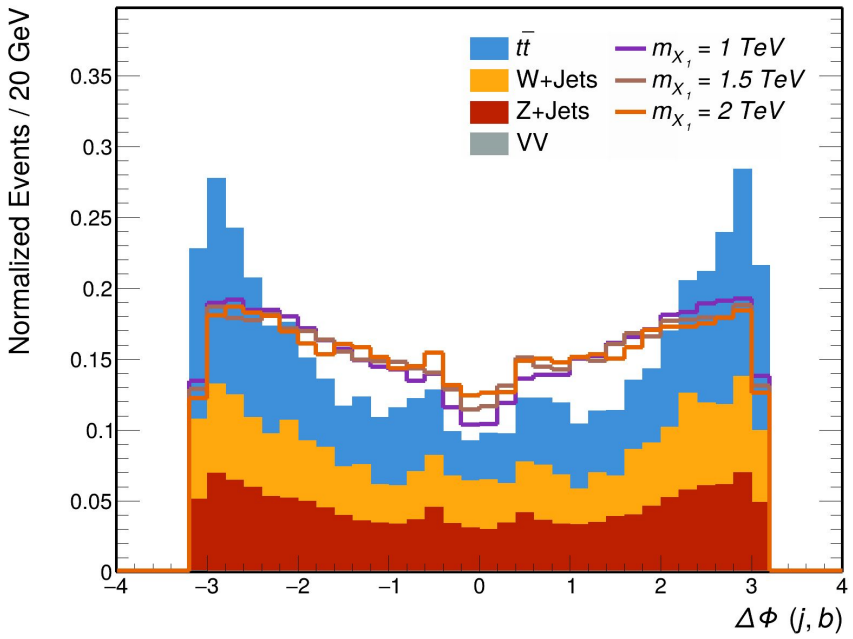
- **azimuthal angle (Phi or ϕ) distirbution**
  - ϕ distribution of MET in x ∈ [-5, 5] with normalized events

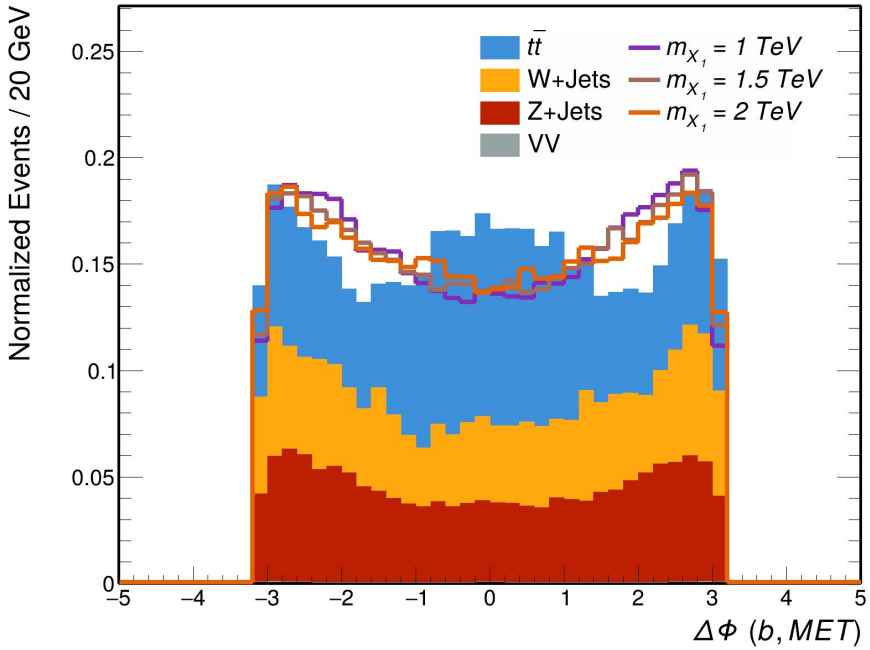


Distribution

300 fb^{-1} (13 TeV)

- **Azimuthal angle (Δϕ) distribution**
  - Δϕ distribution between j and b on left plot in x ∈ [-4, 4] with Normalized events per bin
  - Δϕ distribution between b and MET on right plot in x ∈ [-4, 4] with Normalized events per bin
  - Definition : $\Delta\phi = \arctan2(\sin(\phi_i - \phi_j), \cos(\phi_i - \phi_j))$

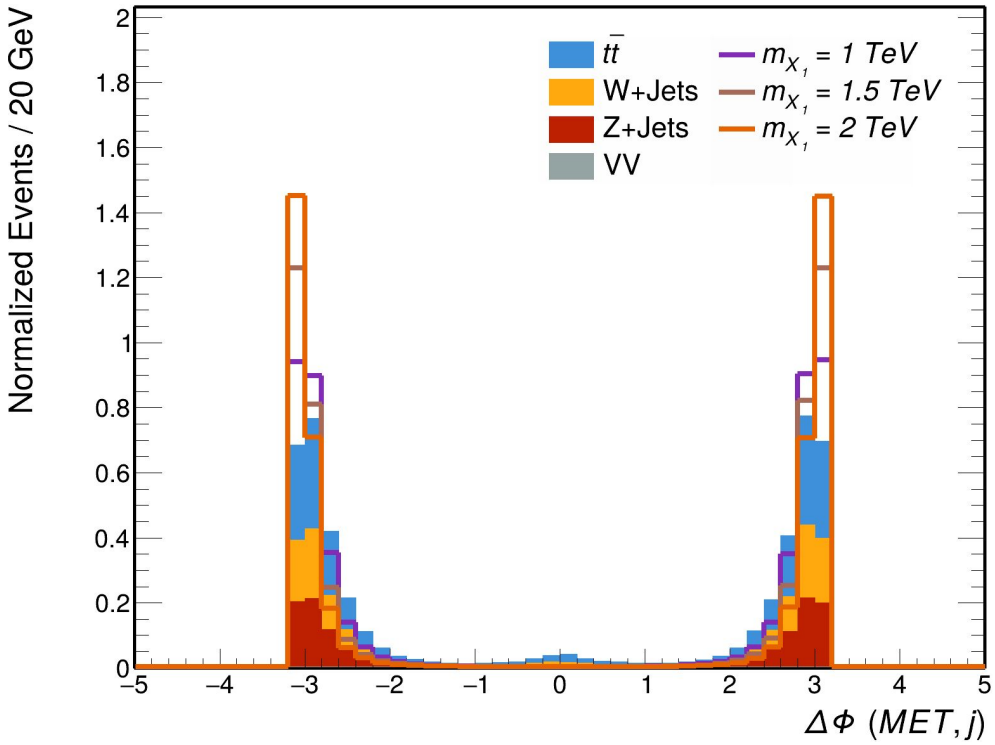




Distribution

300 fb^{-1} (13 TeV)

- **Azimuthal angle (Δϕ) distribution**
  - Δϕ distribution between MET and j on the plot in x ∈ [-4, 4] with Normalized events per bin
  - Definition : $\Delta\phi = \arctan2(\sin(\phi_i - \phi_j), \cos(\phi_i - \phi_j))$



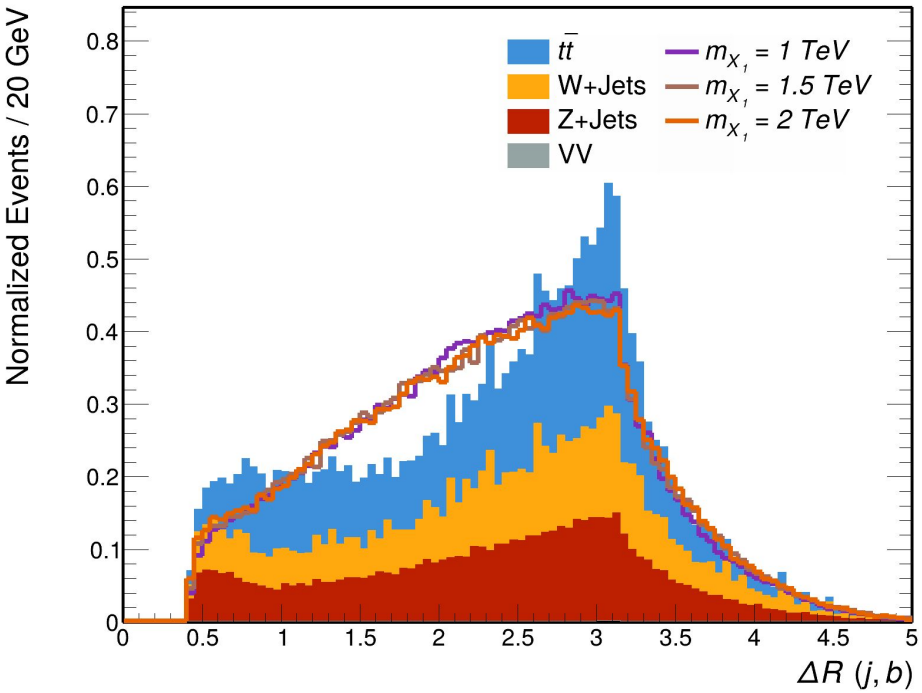
Distribution

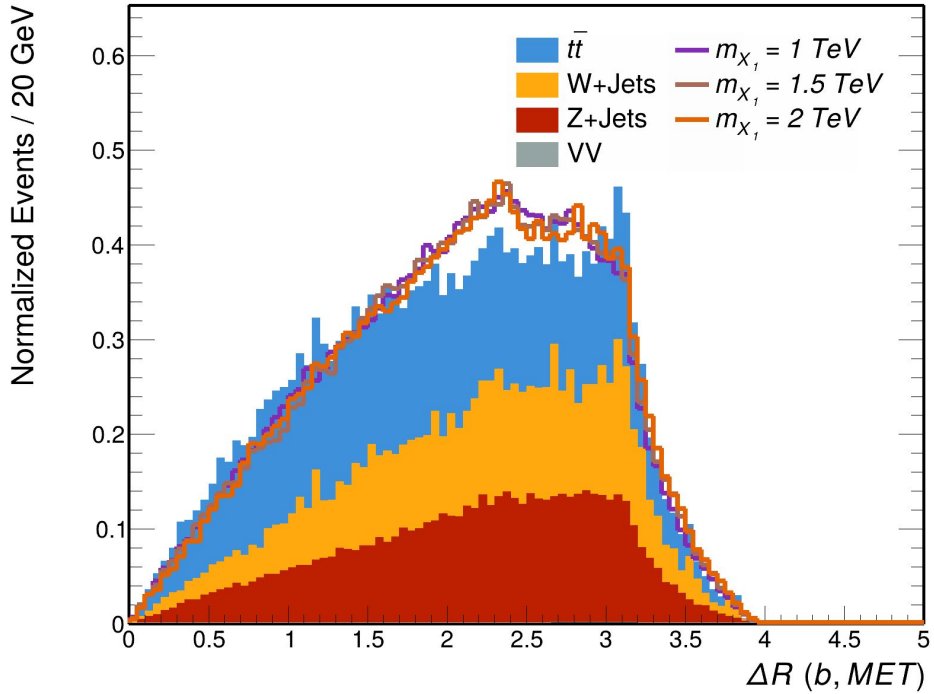
300 fb^{-1} (13 TeV)

- **Distance between two objects in the detector's η - ϕ angle plane (*ΔR*)**
  - *ΔR* distribution between j and b on left plot in x ∈ [0, 5] with Normalized events
  - *ΔR* distribution between b and MET on left plot in x ∈ [0, 5] with Normalized events
  - Definition : $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

    Where $\Delta\phi = \arctan2(\sin(\phi_i - \phi_j), \cos(\phi_i - \phi_j))$

    $\Delta\eta = \eta_i - \eta_j$





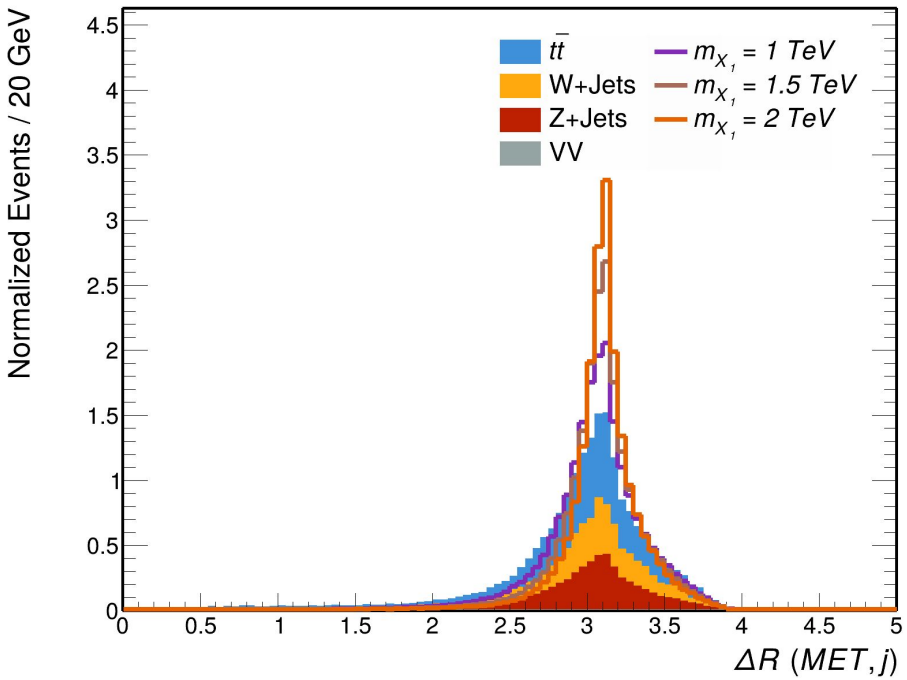
Distribution

300 fb^{-1} (13 TeV)

- **Distance between two objects in the detector's η - ϕ angle plane (*ΔR*)**
  - *ΔR* distribution between MET and j on left plot in x ∈ [0, 5] with Normalized events
  - Definition : $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$

    where $\Delta\phi = \arctan2(\sin(\phi_i - \phi_j), \cos(\phi_i - \phi_j))$

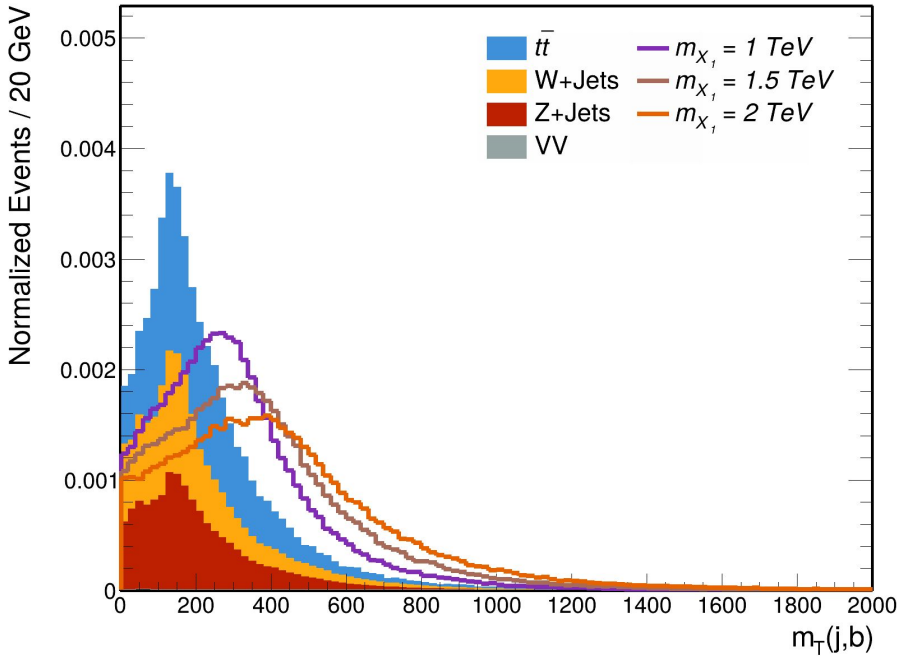
    $\Delta\eta = \eta_i - \eta_j$

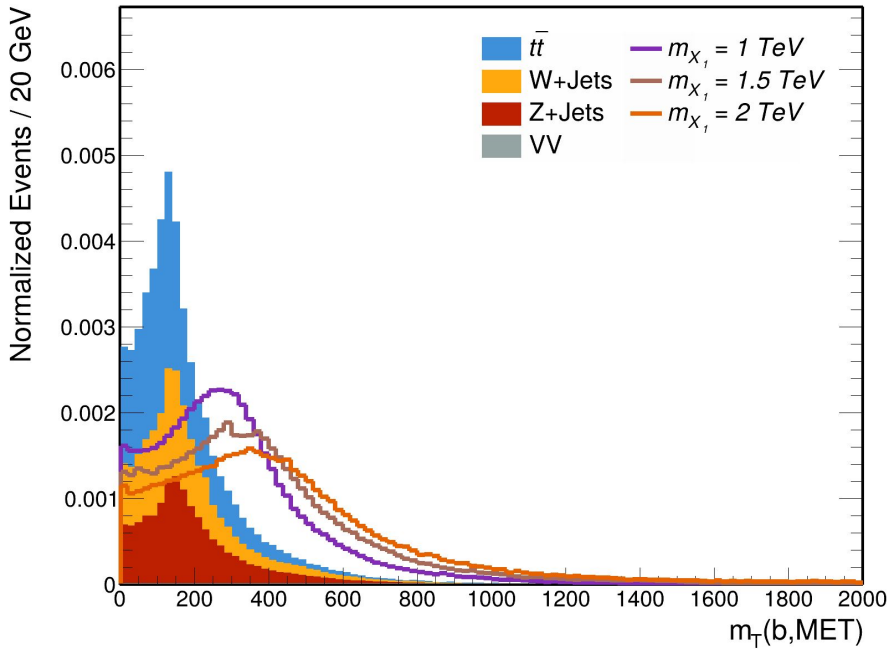


Distribution

300 fb^{-1} (13 TeV)

- **Transverse mass (M_T) distribution in two particle**
  - M_T distribution between j and b on left plot in x ∈ [0, 2000] with Normalized events per bin (20 GeV)
  - M_T distribution between b and MET on right plot in x ∈ [0, 2000] with Normalized events per bin (20 GeV)
  - Definition : $M_T(i,j) = \sqrt{2\, p_{T_i}\, p_{T_j}\, (1 - \cos\Delta\phi)}$





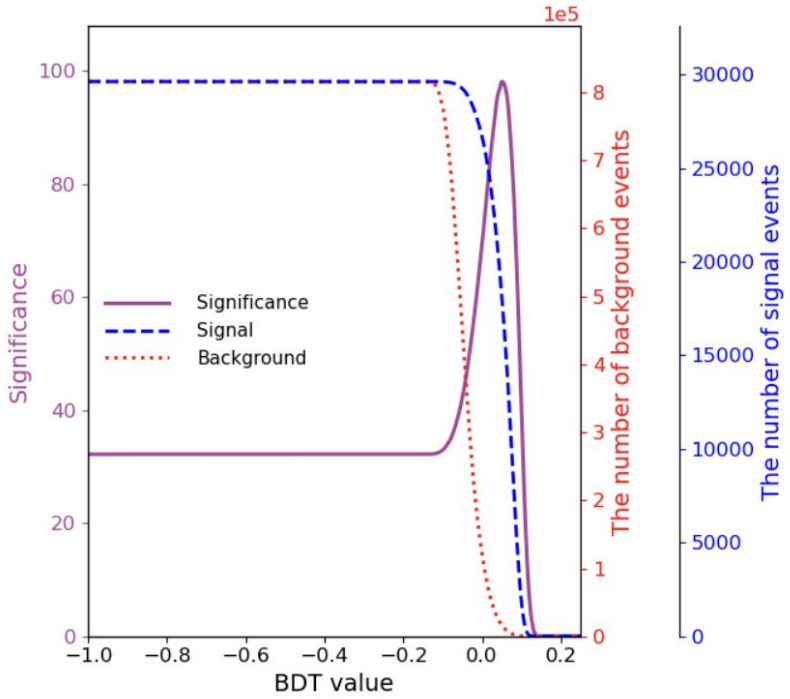
BDT Method

Boosted Decision Tree (BDT) Method

To determine appropriate candidate BDT cut values, significance is defined to: S/√(S+B). On the top plot: The distribution of signal (S) It can be observed that the maximum significance is attained at a specific BDT value.

Furthermore, the AUC of the ROC curve, one of the performance evaluation metrics in machine learning: 0.936, 0.965, and 0.970 for each mass point respectively.

This indicates that m_{X1} achieves better separation from the background for high-signal points.



Mass of x1 = 1.0 TeV with (0.5, 0.5)

BDT parameter information and ROC

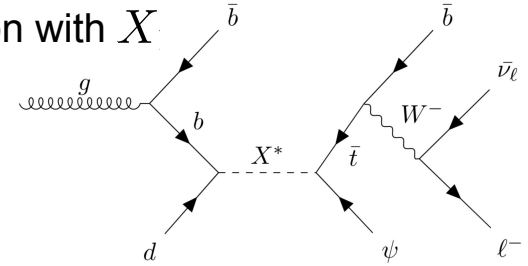
NTree, maxDepth = (4000, 6) for all mass point case

AUC of ROC : descried in the right-side table

m_{X1}	ROC AUC
1.0 TeV	0.936
1.5 TeV	0.965
2.0 TeV	0.970

Results; Comparison with Monotop channel[4]

- **Another search with b-associated monotop channel** provides a complementary probe to the monojet channel through **top–quark** production with X

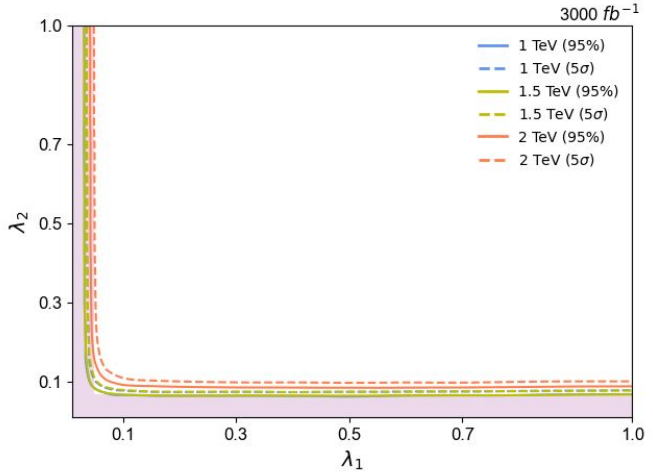


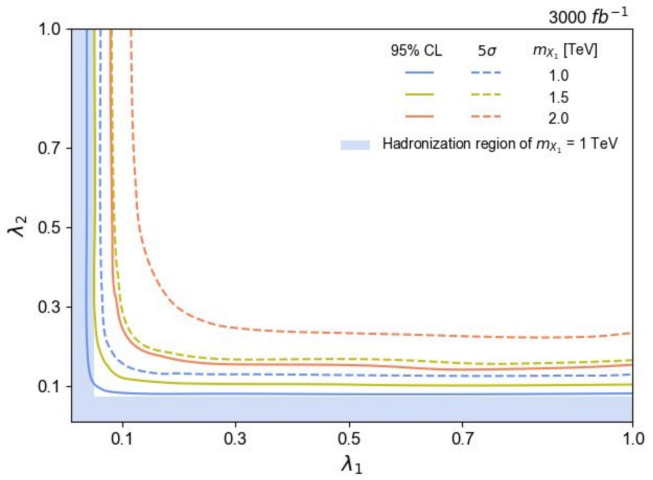
- Exclusion region (95% CL), **HL-LHC (3000 fb^{-1})**

monojet	m_{X_1} [TeV]		
	1.0	**1.5**	**2.0**
λ_1	0.03	0.03	0.04
λ_2	0.06	0.06	0.09

monotop	m_{X_1} [TeV]		
	1.0	**1.5**	**2.0**
λ_1	0.04	0.05	0.08
λ_2	0.08	0.11	0.15

- **Cross-section** for b-associated monojet channel enhanced by a **factor of five than the monotop channel**
  ⇒ Higher statistics extend the exclusion limit





[4] Amandeep Kaur Kalsi and others, 'Probing Bottom-Associated Production of a TeV Scale Scalar Decaying to a Top Quark and Dark Matter at the LHC', Journal of High Energy Physics, 2024.9 (2024), doi:10.1007/JHEP09(2024)203.