Search for Dark Matter from Baryon Number Violation Process in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV

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Outline

- Introduction & Motivation
- Model Signature
- Data & Monte Carlo Samples
- Event Selections
- Background Estimation
- Summary

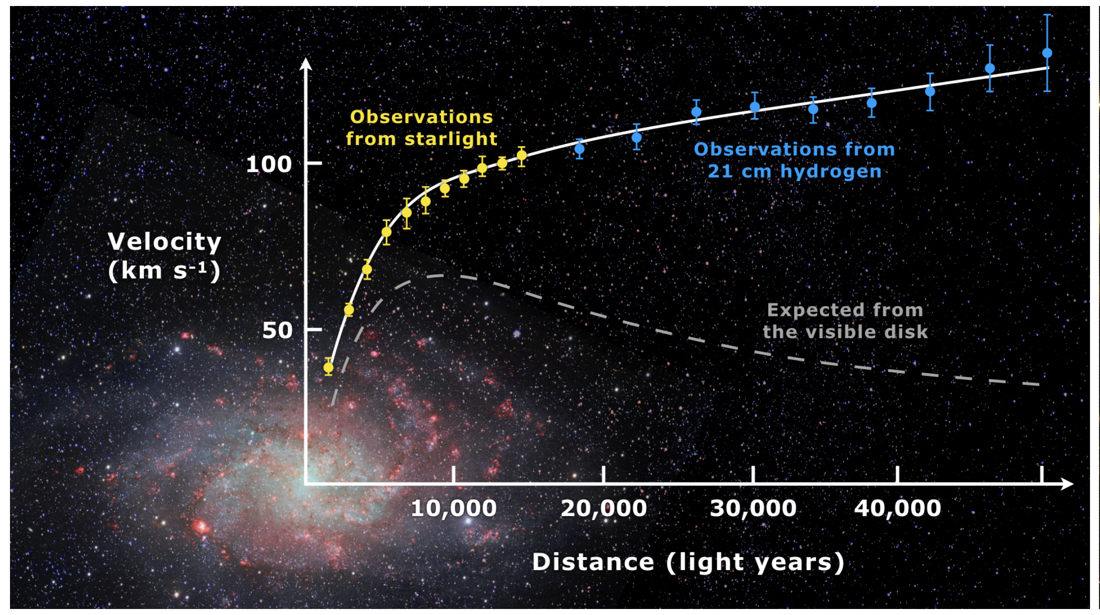
Dark Matter in Universe

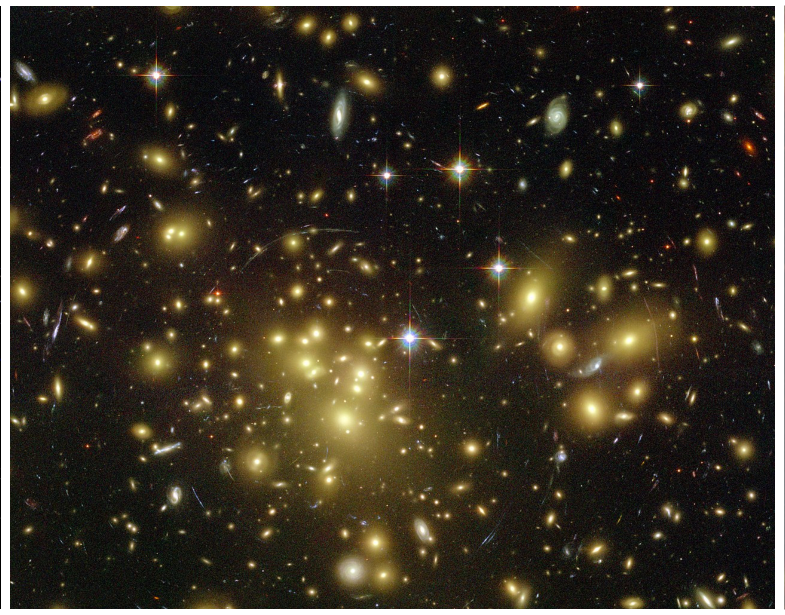
- **According to the well-established cosmological models**

Roughly 27% of the universe is made up of material known as **Dark Matter (DM)**.

- **Astrophysical evidence of the existence of DM**

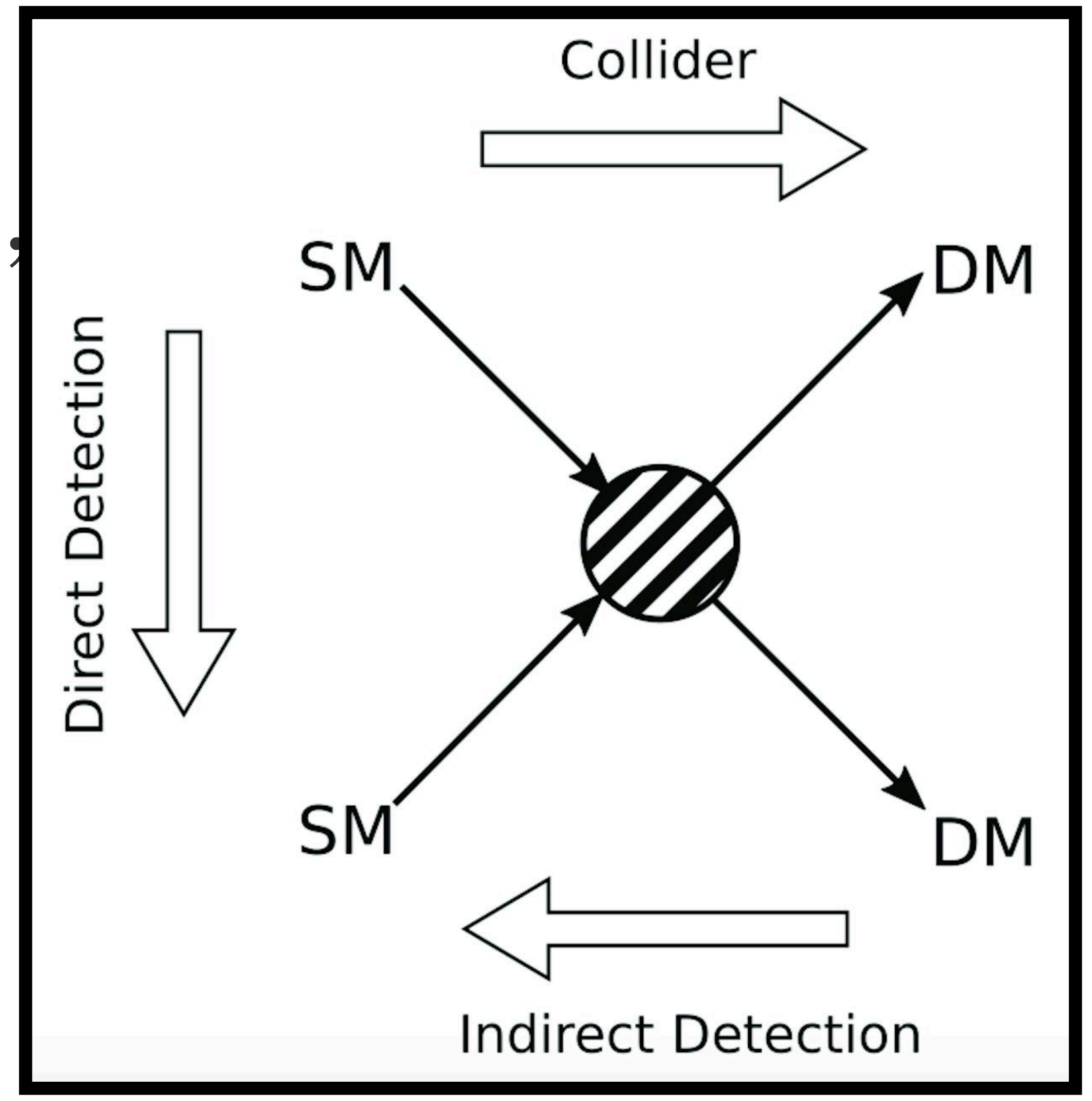
Galaxy Rotation Curve,
Gravitational Lensing,
Bullet Cluster etc..

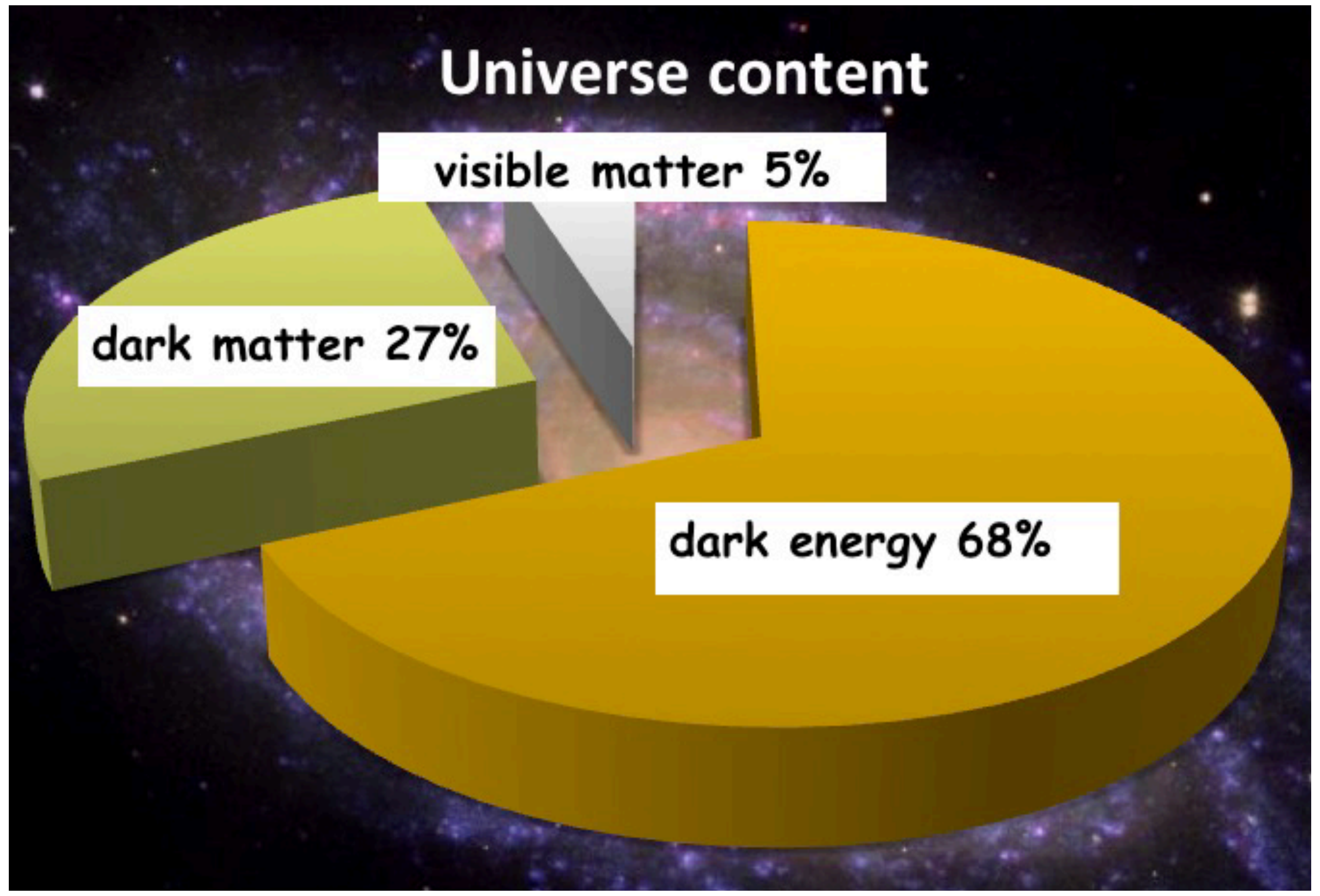




- **Possible Candidates of DM**

Weakly-Interacting Massive Particles (**WIMP**),
Axions, Gravitinos etc..





- **Techniques of DM Detection**

1. Direct Detection
2. Indirect Detection
3. Production at Colliders

Baryon and DM density coincidence

- Baryon and DM densities in the Universe are observed to be similar [1].

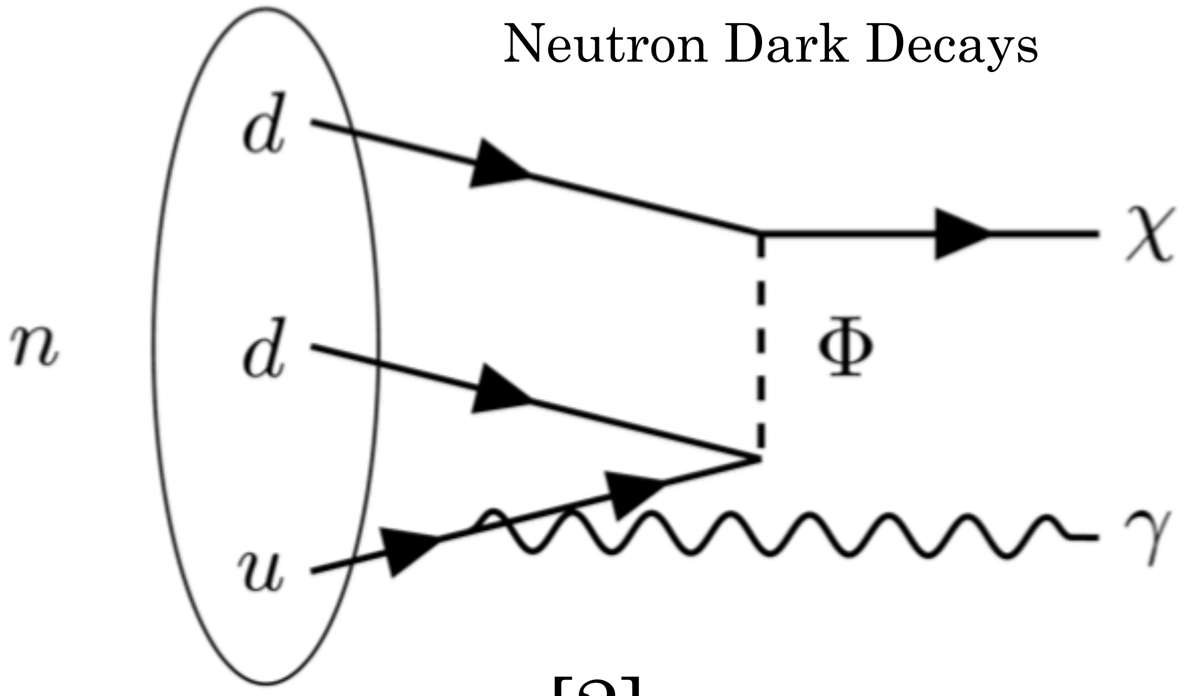
  - $R_{\frac{b}{dm}} = \frac{\Omega_b}{\Omega_{dm}} \cong 0.2$

- The visible content of the universe are made up of baryons and not anti-baryons.

- Perhaps the DM mass being close to the nucleon mass can explain the matter-antimatter asymmetry of the universe via a similar mechanism as in asymmetric DM models [2].

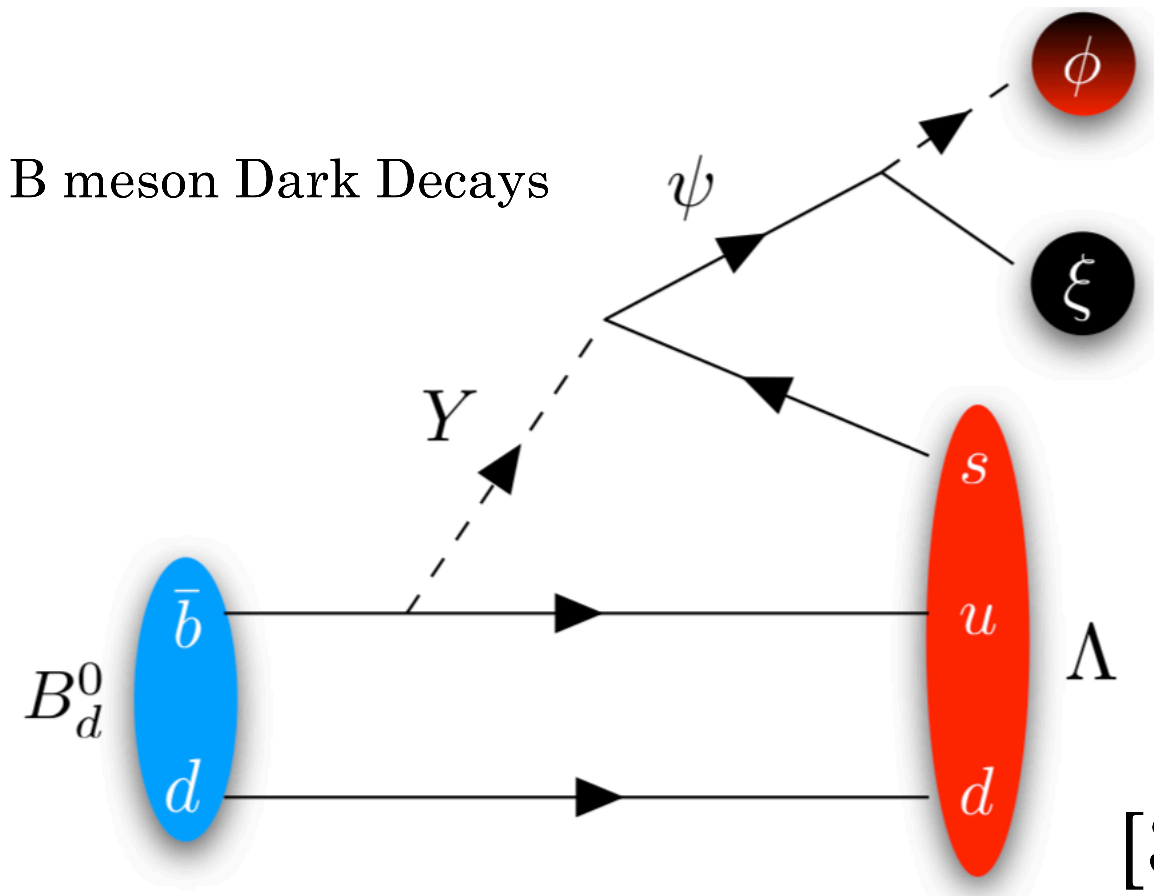
- There exist several possible DM models to relate the baryon productions (*baryogenesis*) and the DM productions in the early universe.

Neutron Dark Decays



[2]

B meson Dark Decays



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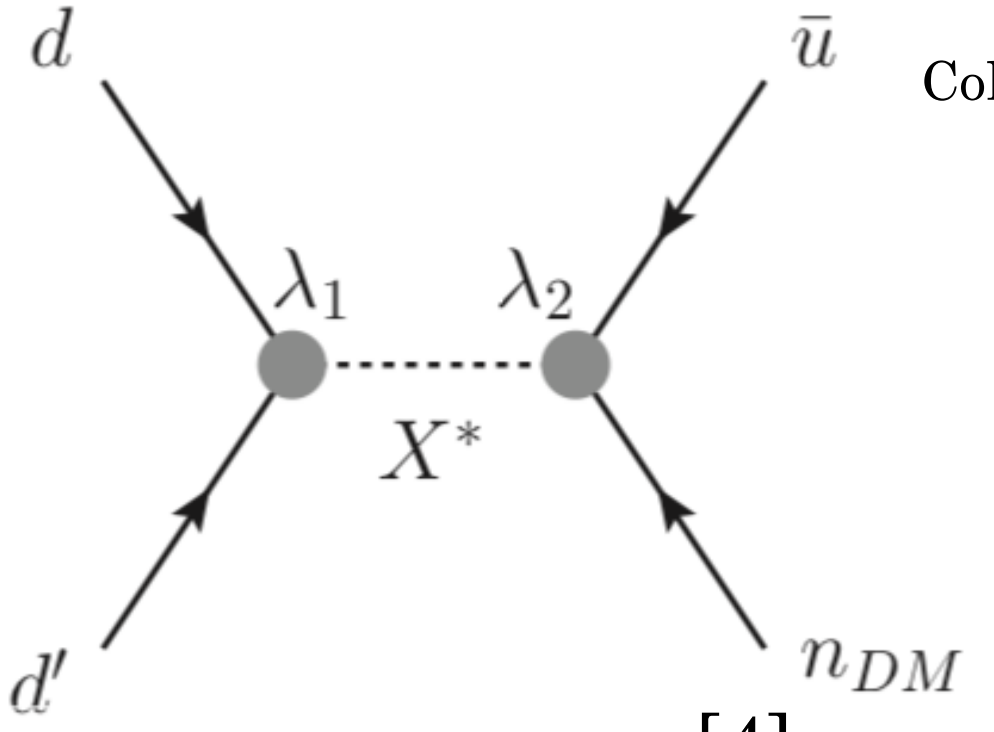


Collider/$n - \bar{n}$ oscillation

[4]

[1]: https://arxiv.org/pdf/1301.4189.pdf
[2]: https://arxiv.org/pdf/1801.01124.pdf
[3]: https://arxiv.org/pdf/1810.00880.pdf
[4]: https://arxiv.org/pdf/1401.1825.pdf

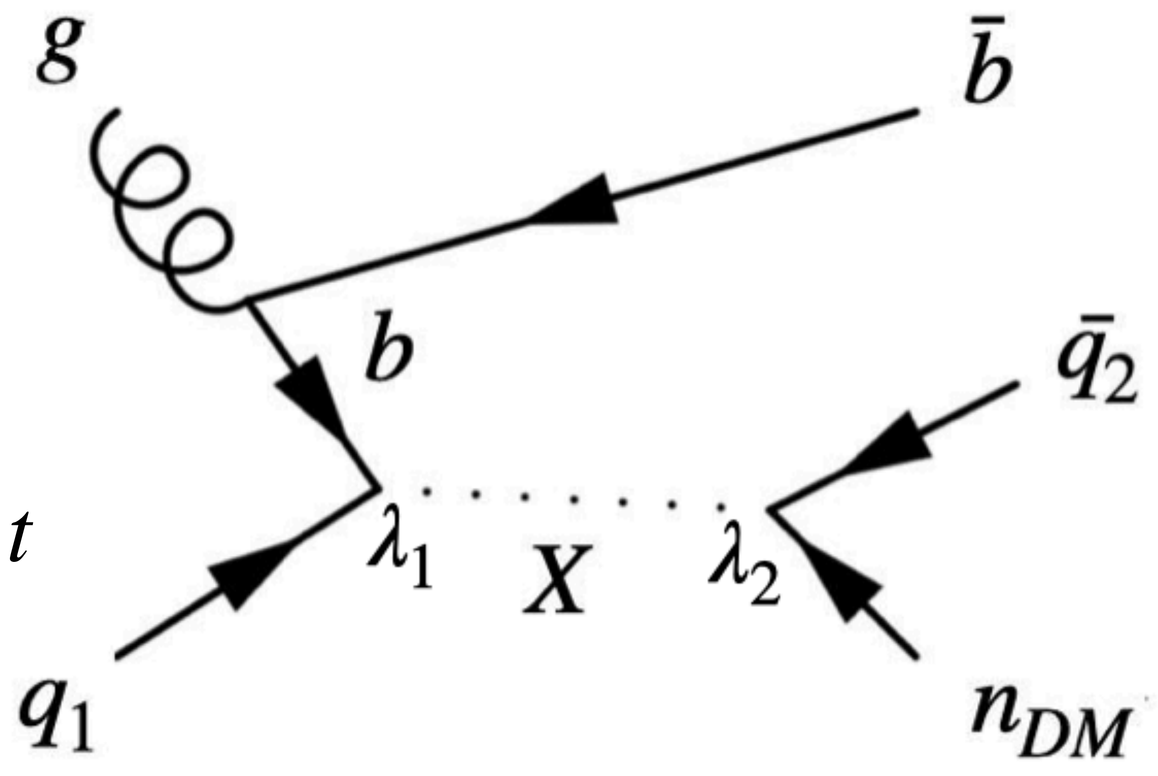
Model Signature

- This ***simple model of baryogenisis*** introduces **baryon number** violating interactions via a set of $\sim TeV$ color-triplet scalars (X) and a $\sim 1\, GeV$ singlet Majorana fermion (n_{DM}) that are coupled only to quarks

- The **model** is an example of *Simplified Model* and a set of four distinct parameters, which are (1): **DM Mass** ($M_{n_{DM}}$), (2): **Mediator Mass** (M_X), (3): **Coupling to SM** (λ_1) and (4): **Coupling to DM** (λ_2), can be scanned to search for DM.

- Jacobian-like peak for missing transverse energy (MET) distribution.

$q_1 \rightarrow d \; or \; s$
$q_2 \rightarrow u, c \; or \; t$



The Interaction Lagrangian is:

$$\mathcal{L}_{int} = \lambda_1^{\alpha,\rho\delta}\epsilon^{ijk}X_{\alpha,i}\bar{d}^c_{\rho,j}\mathbf{P}_R d_{\delta,k} + \lambda_2^{\alpha,\rho}X^*_\alpha \bar{n}_{\mathrm{DM}\rho}\mathbf{P}_R u + \mathrm{C.C.}$$

- Final states: one b-jet + up-type quarks + MET
  - b-jet + n_{DM} + u/c (~67%)
  - b-jet + n_{DM} + t (~33%)

Data & Monte Carlo Samples

Data Sample

MET dataset is used for SR study. This work is done using the data collected by CMS experiment in 2016, 2017 and 2018 at $\sqrt{s} = 13\ TeV$ with CMS detector at LHC, which corresponds to 137 fb^{-1}.
Electron, Muon and Photon datasets are used for the estimation of electroweak backgrounds.

DM Signal Samples

A **Signal Sample** has been privately generated with MadGraph5 and processed through CMS analysis framework.

$pp \rightarrow X + b \rightarrow n_{DM} q + b$ (q is an up-type quark)

Model parameters M_{X_1}, λ_1 and λ_2 will be allowed to as follows,

$M_{X_1}(GeV)$: [1000,1500,2000,2500,3000]
λ_1 : [0.01,0.02,0.03,0.04,0.05,0.06,0.07,0.08,0.09,0.1,0.2,0.5,1.0]
λ_2 : [0.01,0.02,0.03,0.04,0.05,0.06,0.07,0.08,0.09,0.1,0.2,0.5,1.0]

Background Samples

Major Backgrounds
$Z(\nu\nu) + jets$
$W(l\nu) + jets$
$Top\ (single\ top + t\bar{t})$

Minor Backgrounds
$Diboson\ (WW,\ WZ\ and\ ZZ)$
QCD
$\gamma + jets$
$Z(ll) + jets$

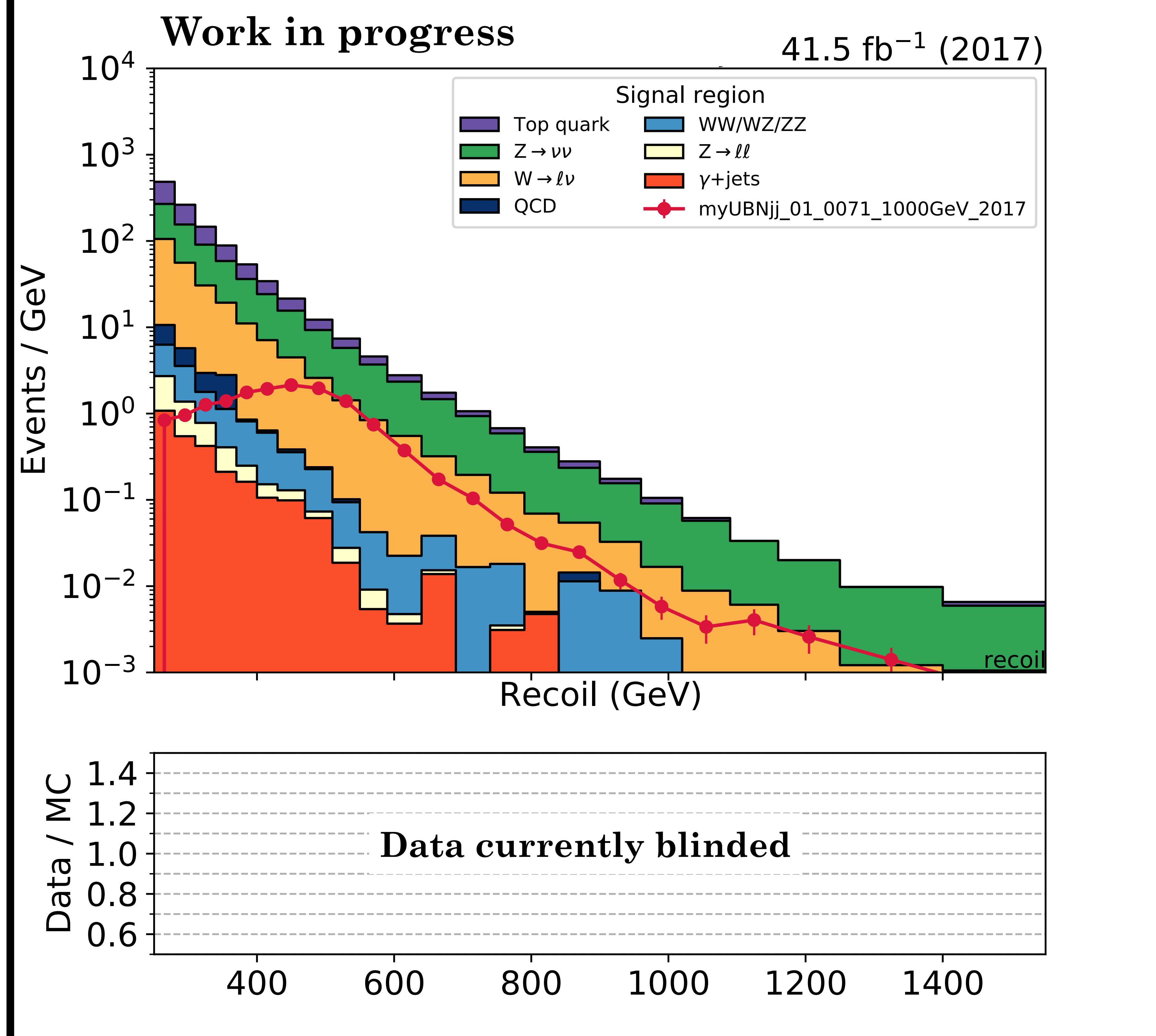
Event Selection of Signal Region (SR)

In this analysis, the selection criteria for the search of **DM** in **MET** **+jets channel**. The event selection of **Signal Region (SR)** can be written as follows,

- ✳ require the ak4 leading jet: $p_t > 100\ GeV$ & $|\eta| < 2.5$
- ✳ $\Delta\phi\,(jet, MET) > 0.5$ in order to reject the QCD events.
- ✳ veto the leptons (loose electrons, muons and taus) to suppress the EWK and top backgrounds.
- ✳ veto the photons (loose ones) to reject the EWK backgrounds — $Z(\nu\nu)\gamma + jets$, $W(l\nu)\gamma + jets$.
- ✳ MET cut > 250 GeV (consistent with trigger turn on).
- ✳ require events have only one b-tag.

Signal Region: MET

The **MET** distribution in **SR** is shown for a comparison between the predicted SM backgrounds & DM signal ($M_{X_1} = 1\,TeV, \lambda_1 = 0.1, \lambda_2 = 0.071$).



- The major backgrounds are $Z(\nu\nu) + jets$ (54%), $Top(single\ top + t\bar{t})$ (27%) and $W(l\nu) + jets$ (18%) [the sum of those 3 backgrounds 99%] for $MET > 400\,GeV$.

- The significance is calculated as,

$$Significance = \frac{S}{\sqrt{\Delta S^2 + \Delta B^2}}$$

S = The number of signal events

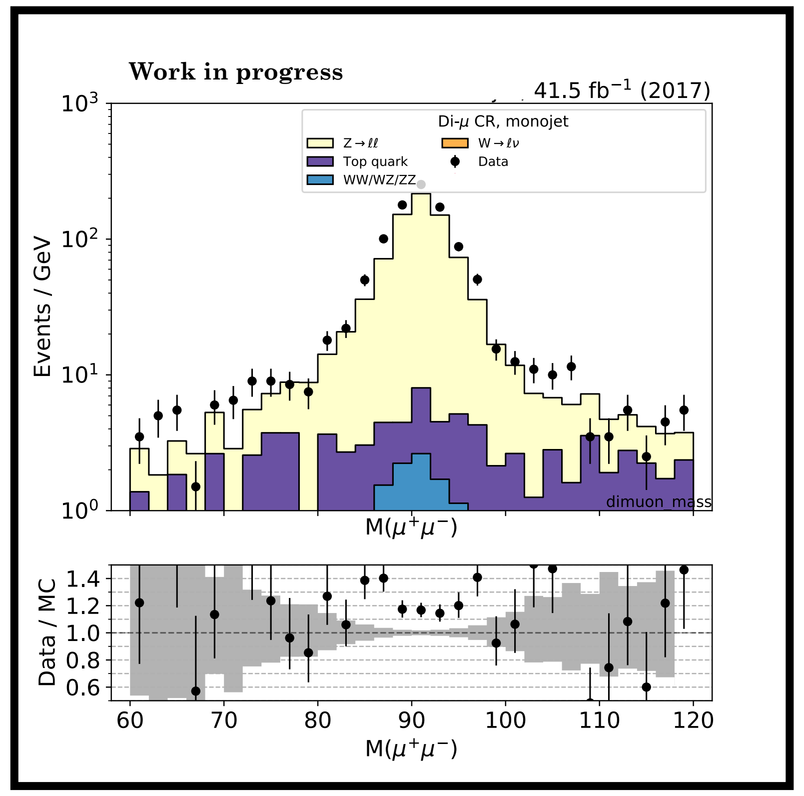
ΔS = The statistical error on signals

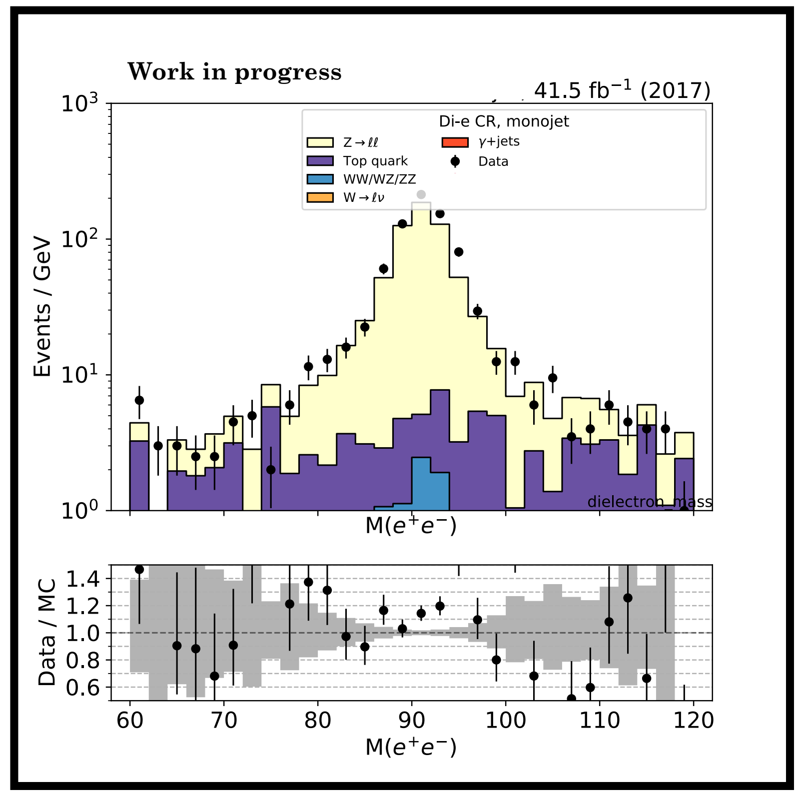
ΔB = The quadratic sum of the statistical error and the systematic error (2%) on background.

- The CMS has the sensitivity to detect a DM signal over the background at **5.8 sigma significance** in $b + d$ and $b + s$ productions modes for 400 – 500 GeV range.

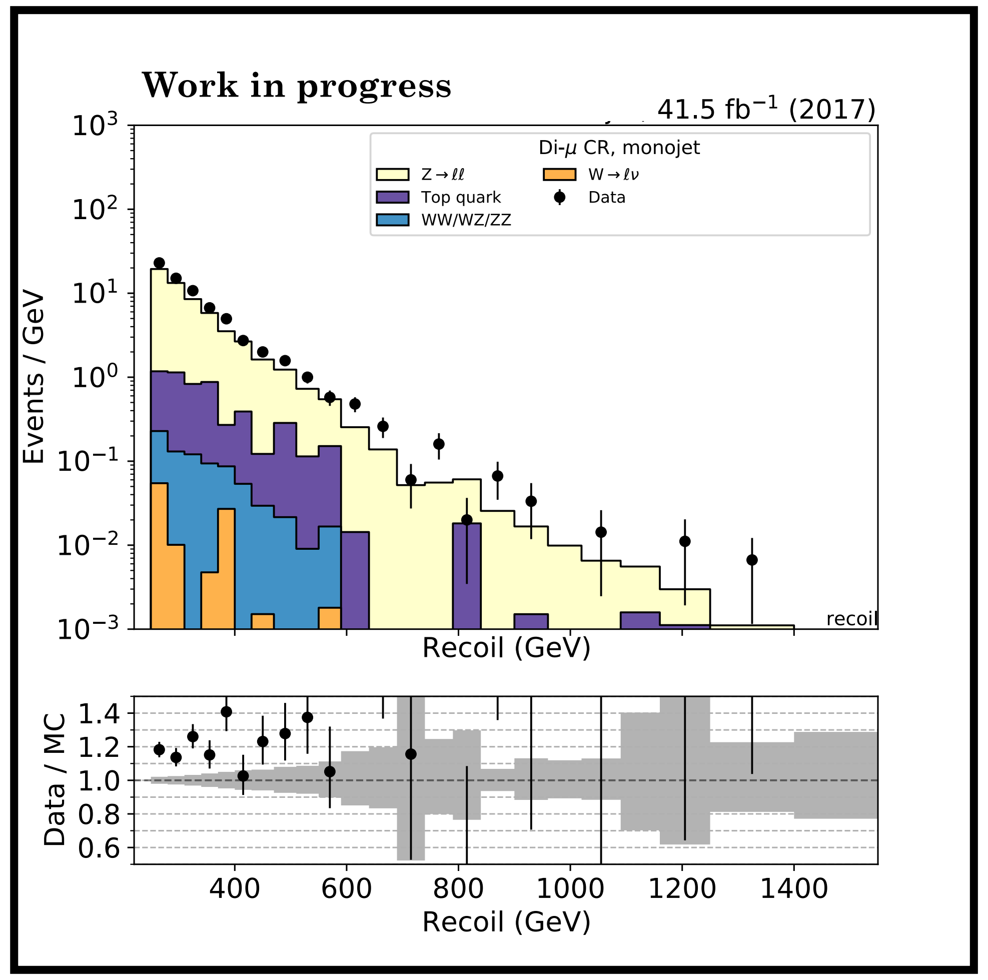
$Z \to \nu\nu$ Background Estimation

- The major background in this analysis comes from the $Z \to \nu\nu$ production.
- di-muon ($Z(\mu\mu) + jets$), di-electron ($Z(ee) + jets$) and single-photon ($\gamma + jets$) are used as control samples for estimating the $Z \to \nu\nu$ background.
- di-lepton mass cut (60 – 120 GeV) is applied to reduce the $Z(\mu\mu) + jets$ and $Z(ee) + jets$ background events.

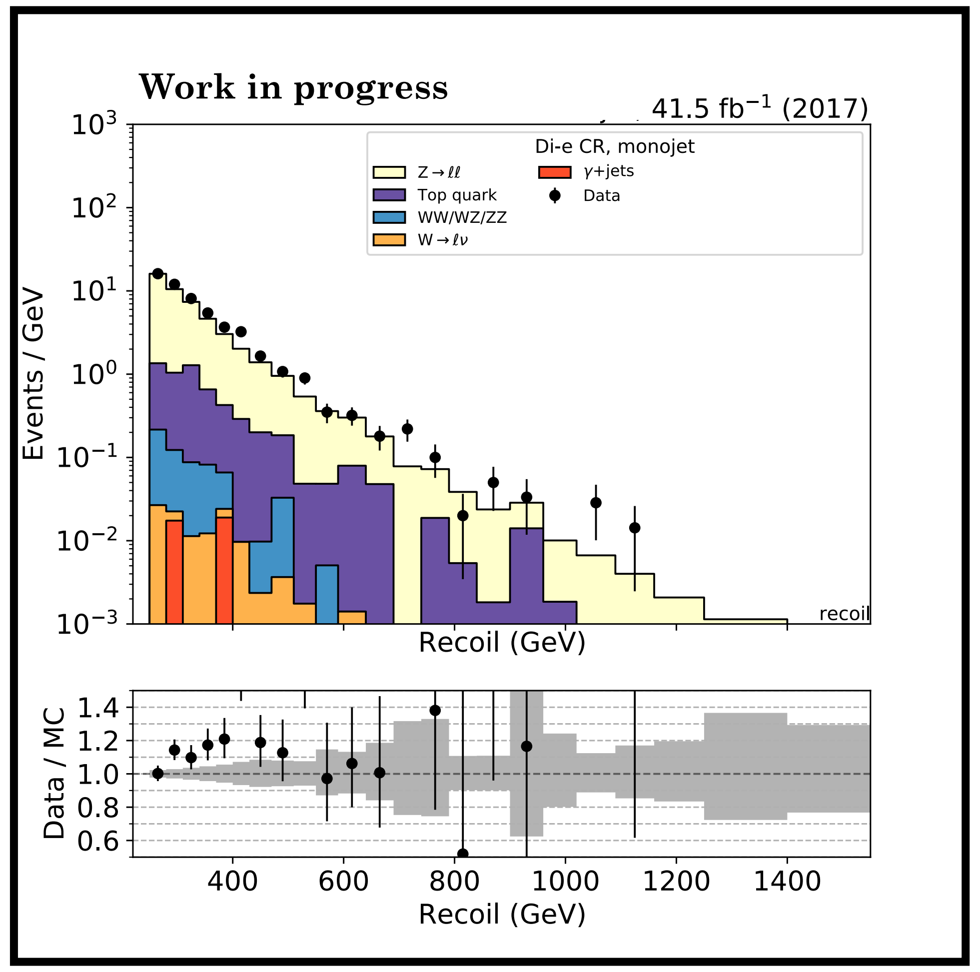




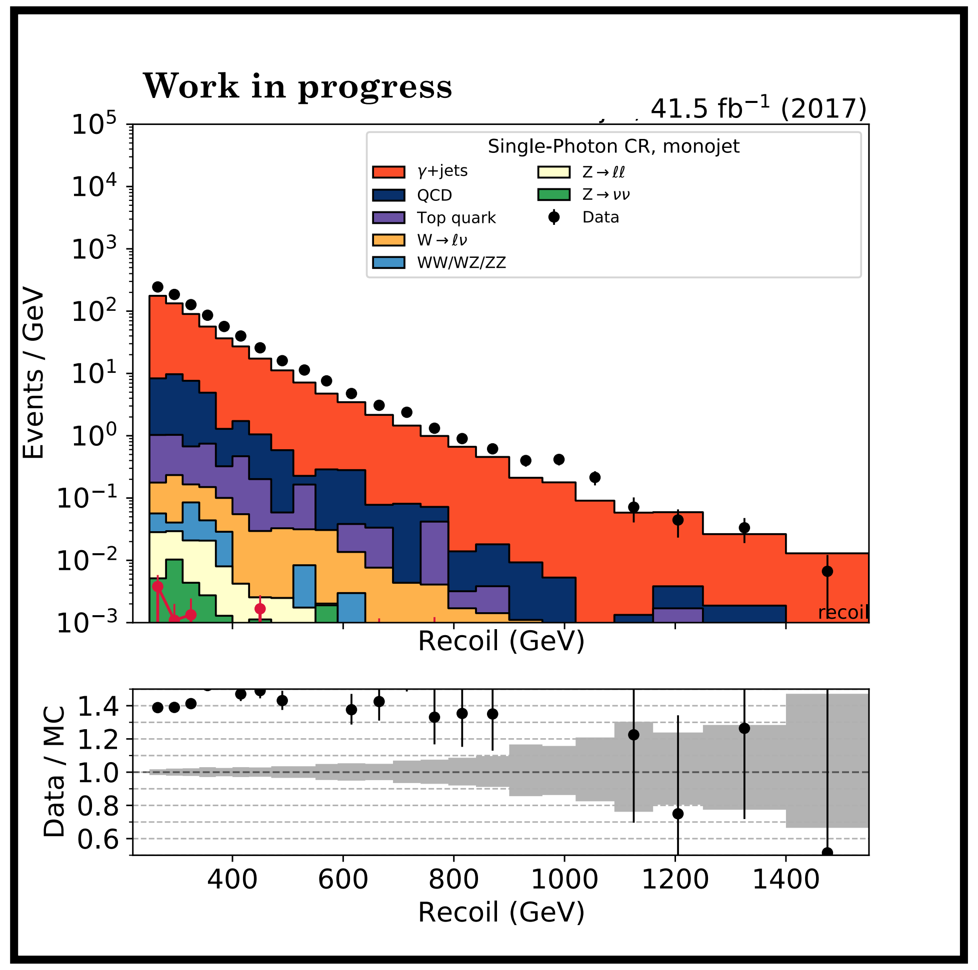
di-muon CR



di-electron CR



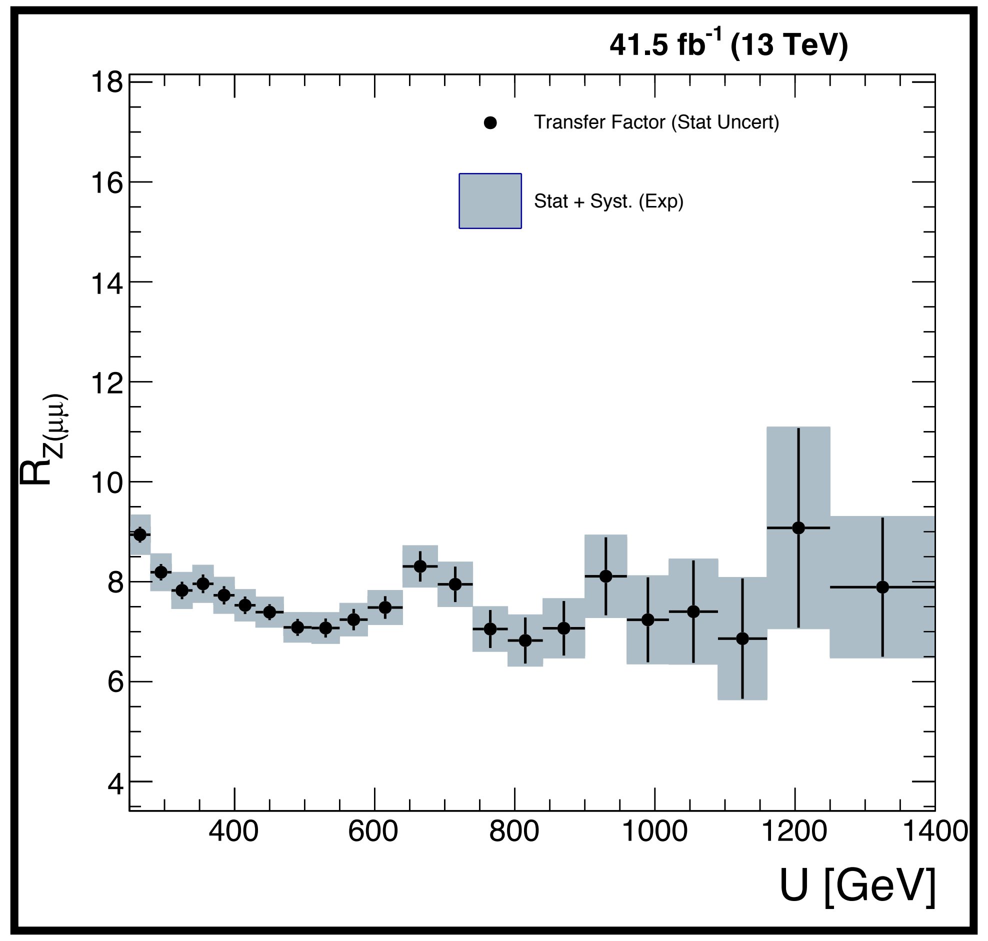
single-photon CR

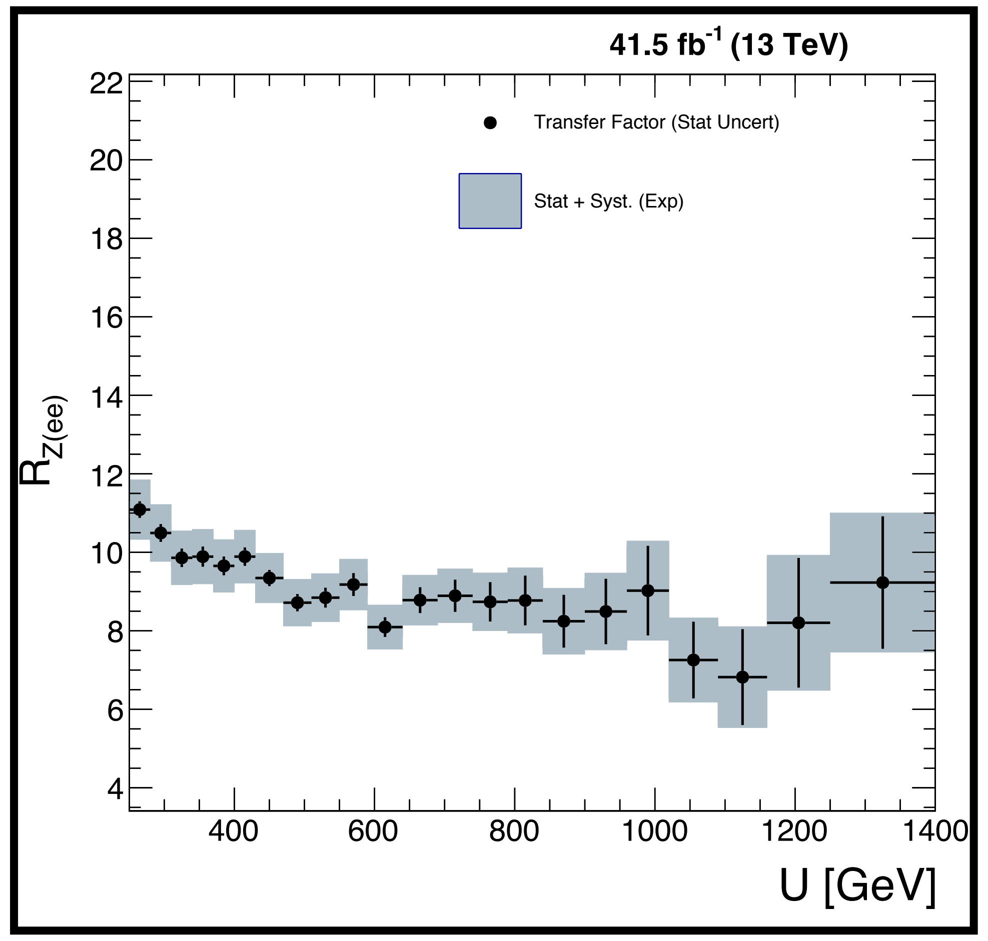


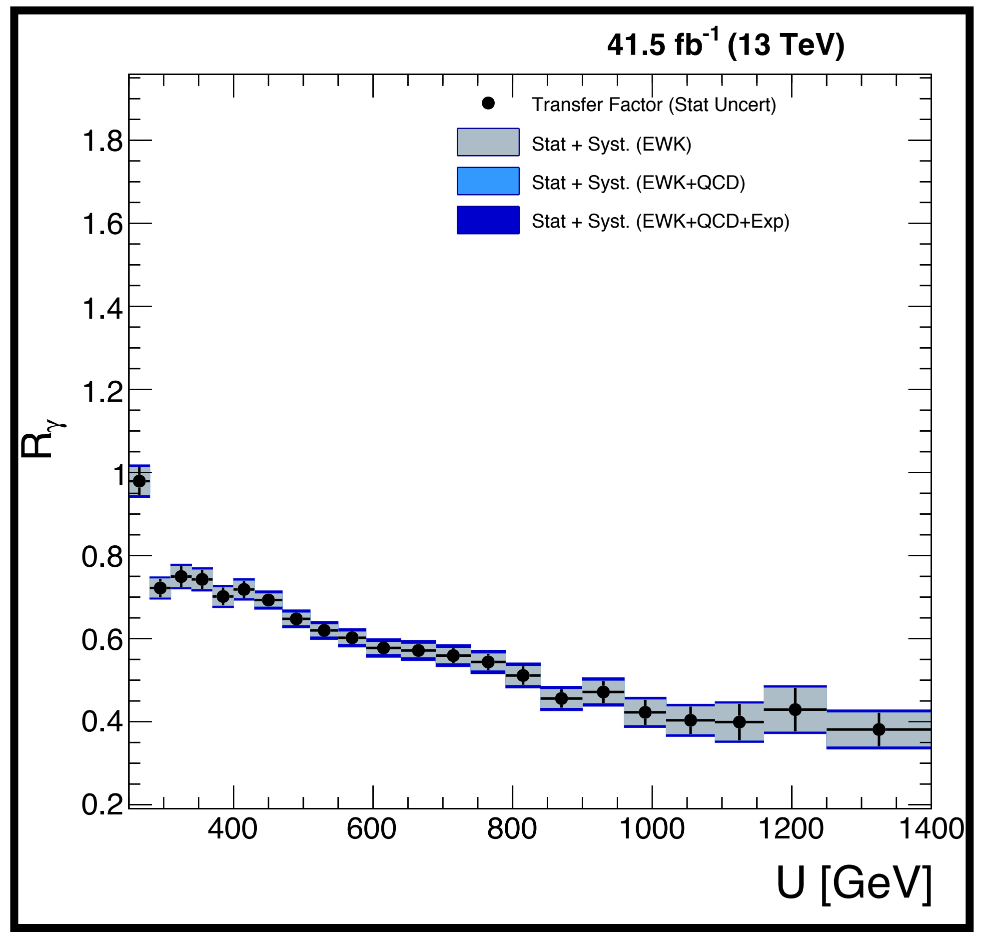
$$R_{Z(\mu\mu)} = \frac{N_i(Z(\nu\nu))_{[SR]}}{N_i(Z(\mu\mu))_{[CR]}}$$

$$R_{Z(ee)} = \frac{N_i(Z(\nu\nu))_{[SR]}}{N_i(Z(ee))_{[CR]}}$$

$$R_{\gamma} = \frac{N_i(Z(\nu\nu))_{[SR]}}{N_i(\gamma)_{[CR]}}$$



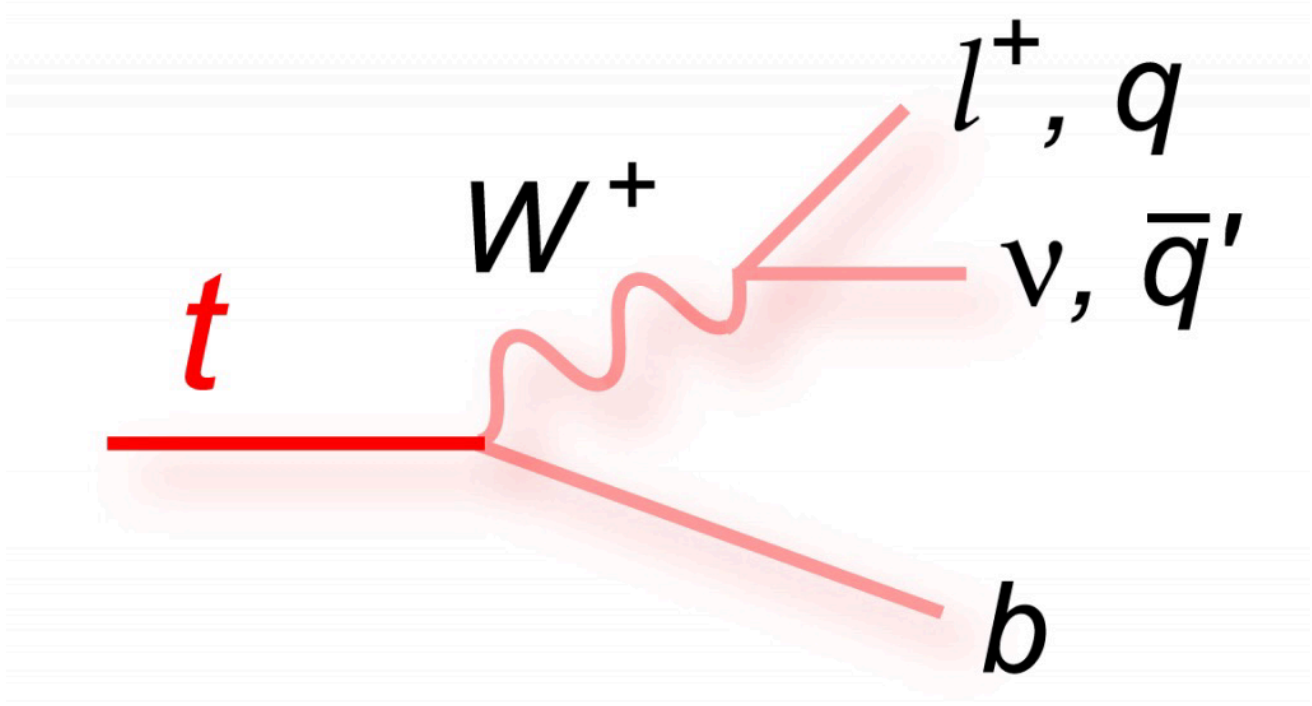




Lost Lepton ($W_{l\nu}$ + top) Background Estimation

- Some leptons are not reconstructed in the detector because the limited geometrical acceptance of the detector, minimum p_T requirements in muon and electron selection etc.. These leptons are called as "**Lost Leptons**".

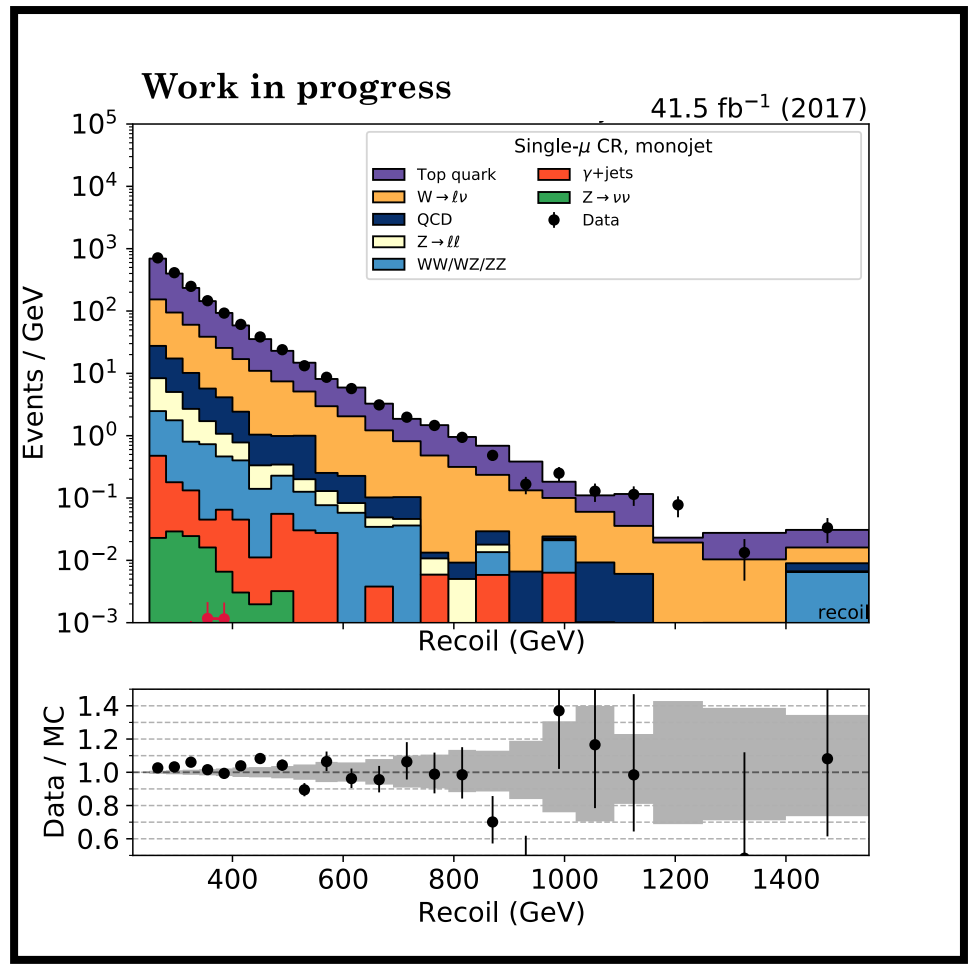
- $W \rightarrow l\nu$ and $Top\,(single\,top + t\bar{t})$ background samples are combined together because each processes arise when we have lost leptons from leptonic decays of the W boson.



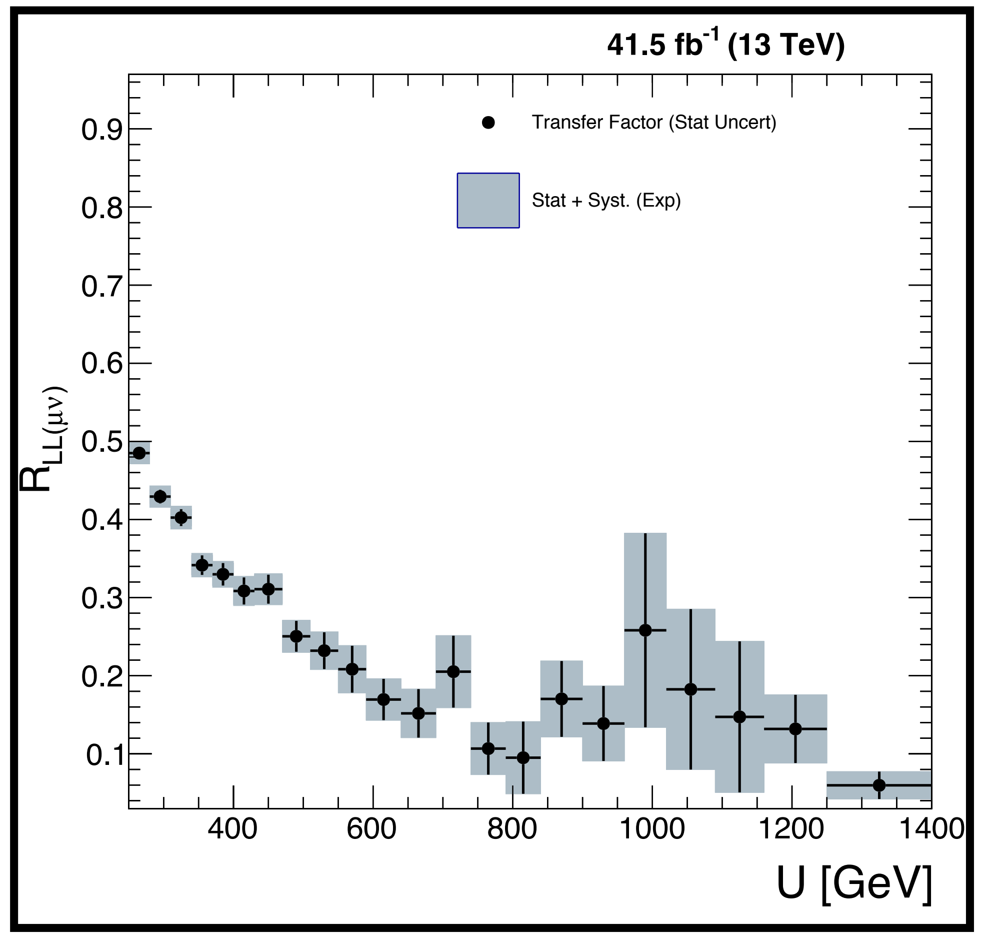
- The associated neutrino in Lost Lepton events will be generated large MET.

- **single-muon** and **single-electron** control regions are used to estimate Lost Lepton backgrounds.

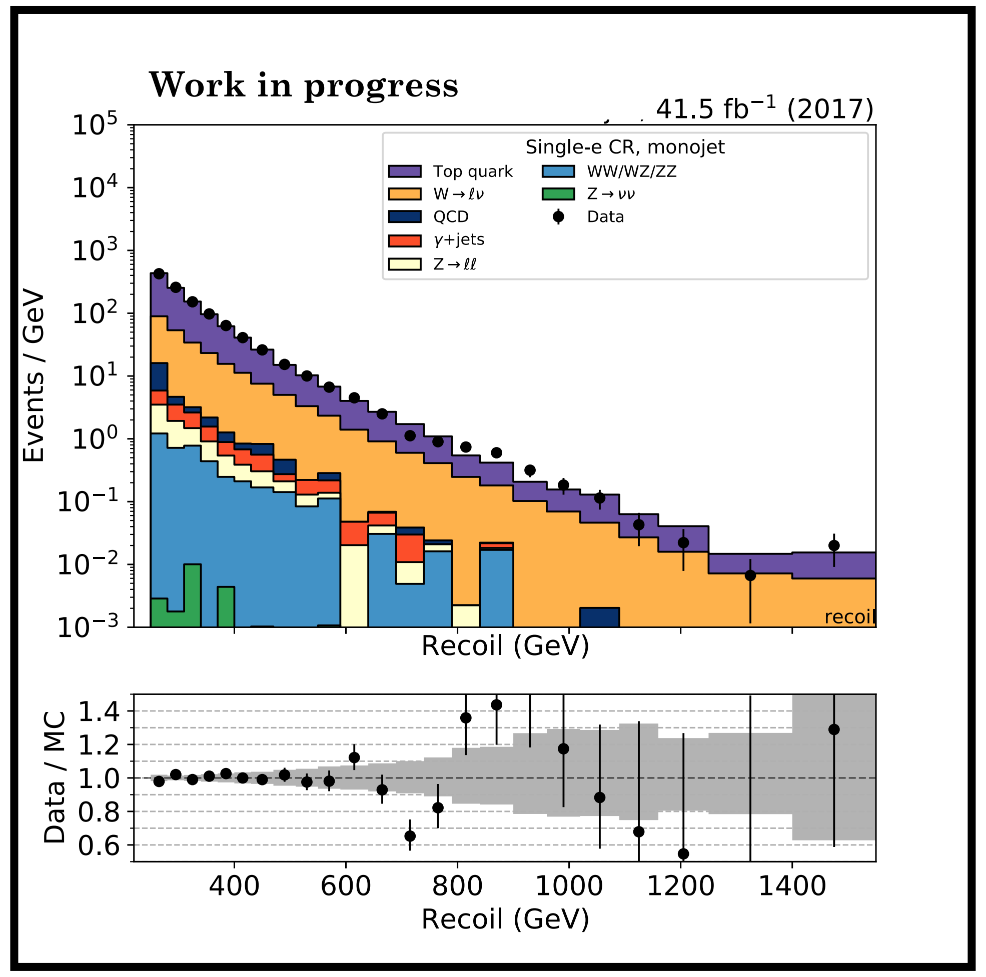
single-muon CR



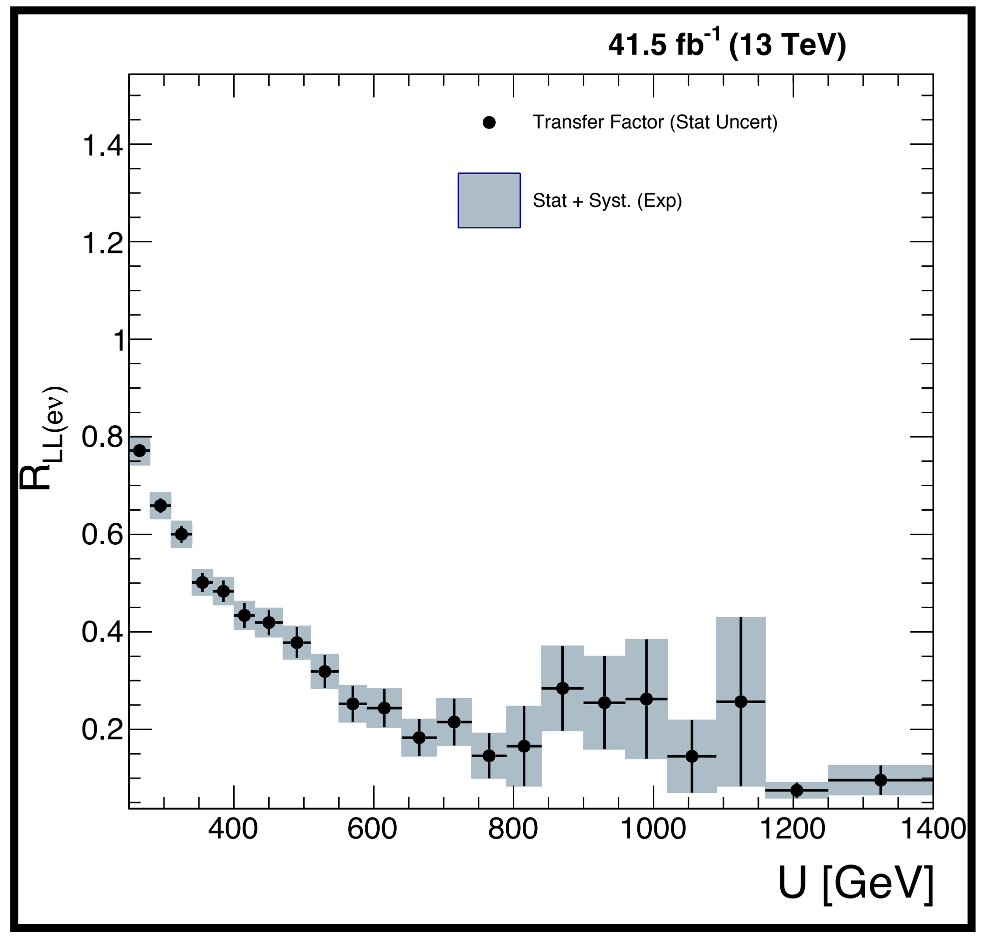
$$R_\mu = \frac{N_i(w_{l\nu} + st + t\bar{t})_{[SR]}}{N_i(w_{\mu\nu} + st + t\bar{t})_{[CR]}}$$



single-electron CR



$$R_e = \frac{N_i(w_{l\nu} + st + t\bar{t})_{[SR]}}{N_i(w_{e\nu} + st + t\bar{t})_{[CR]}}$$



Estimated Background

- Number of Estimated Background events for $MET > 400\,GeV$ can be calculated as follows:

Major Backgrounds	$N_i(MC)_{[SR]}$	Type of Control Region	$N_i(MC)_{[CR]}$	$R_i = \frac{N_i(MC)_{[SR]}}{N_i(MC)_{[CR]}}$	$N_i(DATA)_{[CR]}$	$Estimated\,BG = R_i\,.\,N_i(DATA)_{[CR]}$
$Z \rightarrow \nu\nu$	1766.8	di-muon	249.7	7.4	346.0	2550.6 ± 222.8
		di-electron	192.2	9.2	306.0	2813.2 ± 267.4
		single-photon	2703.1	0.6	4365.0	2853.0 ± 97.4
$Lost\,Lepton : W \rightarrow l\nu$ $(W_{l\nu} + Top)$	1480.3	single-muon	5555.3	0.3	5939.0	1582.6 ± 20.5
		single-electron	4024.3	0.4	4116.0	1514.1 ± 23.6

- Detail background estimation is in progress.

Summary

- We are testing a simple model of baryogenisis and DM production in early universe using data collected by CMS experiment in 2016, 2017 and 2018 at $\sqrt{s} = 13\ TeV$, which corresponds to 137 fb^{-1}.

- The model predicts events with large MET and a b-jet as signature of DM production from baryon number violation processes at LHC.

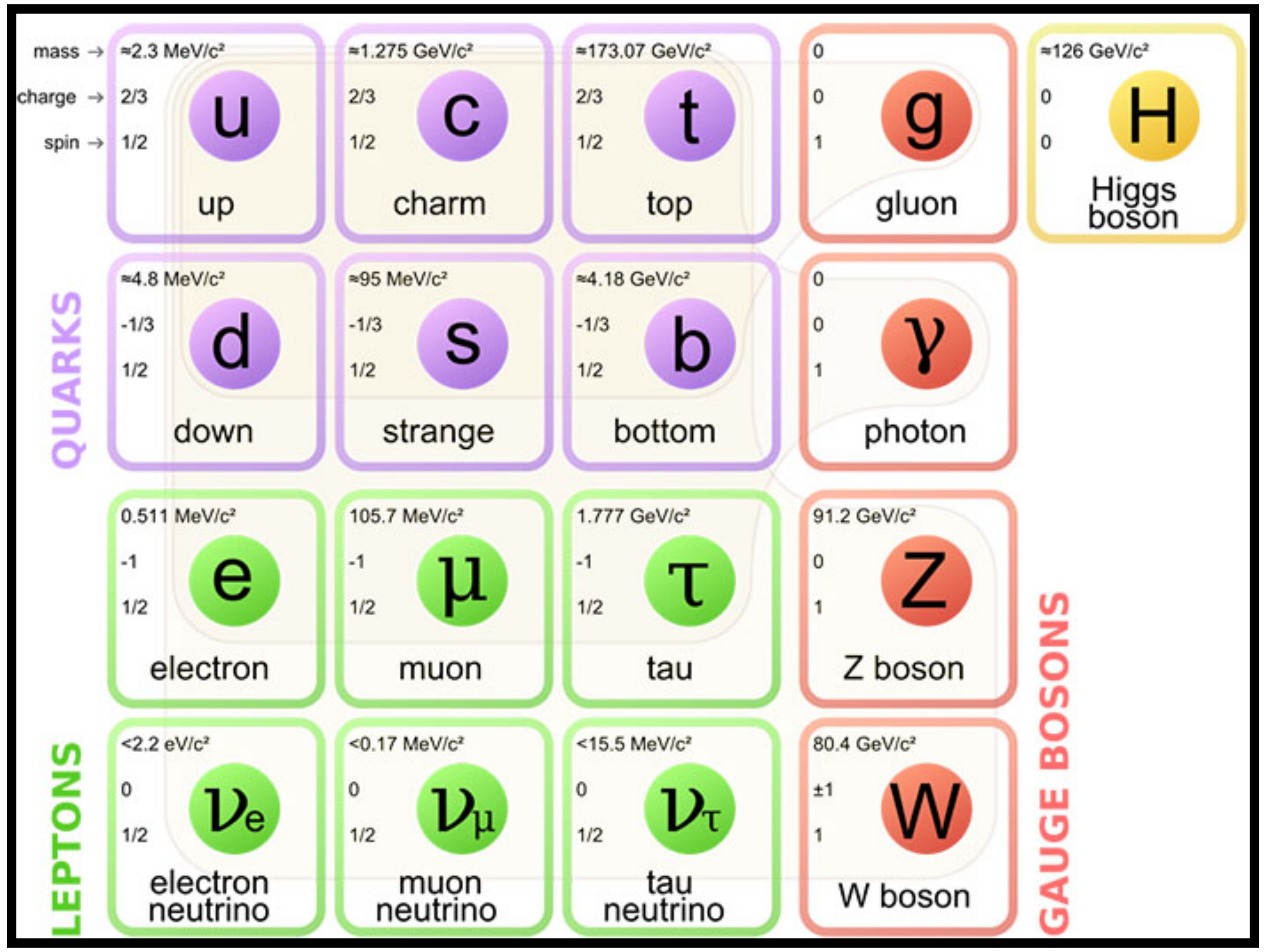
- Estimation of background is in progress using control samples and signal is still blinded.

Thank you!

Back Up

Standard Model (SM)

- Most successful Physic theory ever , That ability to predict and explain every aspect of the quantum world makes the Standard Model (SM) a bit of a superstar.



- **Fundamental particles: Quarks & Leptons (Fermions)**
- **Gauge Bosons: Force Carriers**
- **Higgs Boson**
- There are four **Fundamental Forces** in the universe: Strong, Weak, Electromagnetic, and Gravity. SM covers first three.

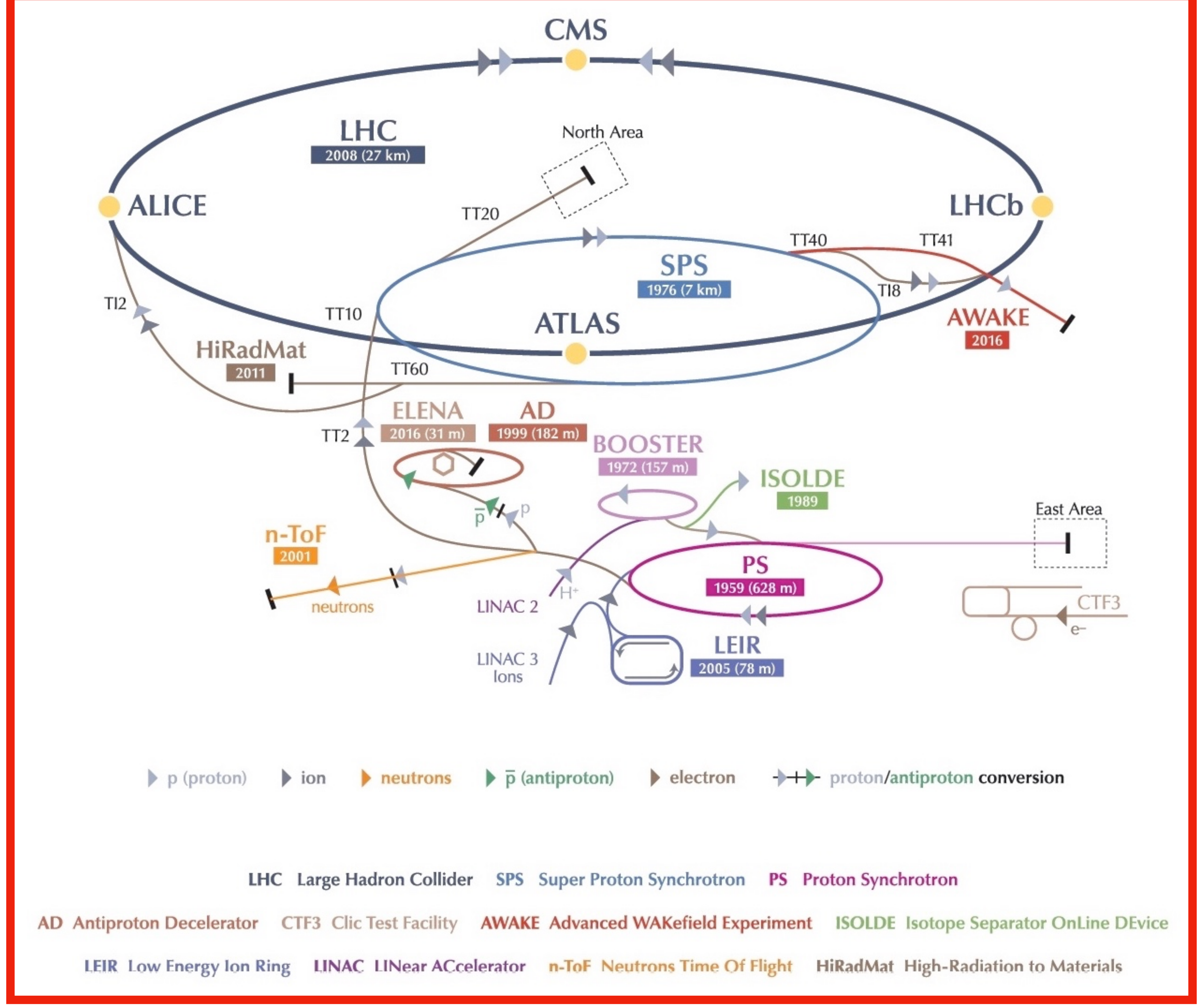
- But while it is incredible, it does not provides a complete picture of the Universe, for example it can not account for Gravity (G) and **Dark Matter (DM)** etc..

- Now, It is necessary to modify the SM, It is called as ***Beyond the SM (BSM)***

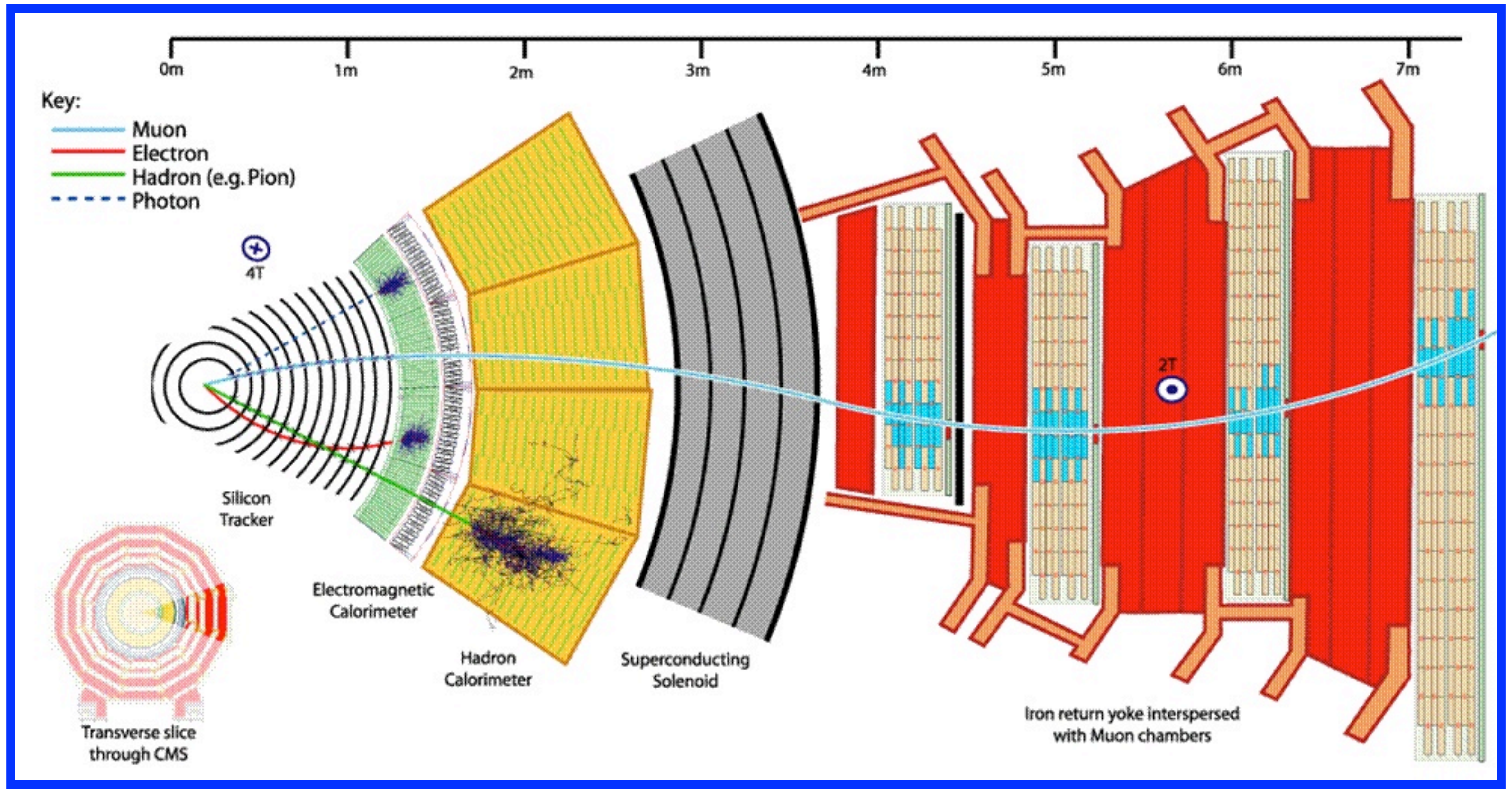
Experimental Apparatus

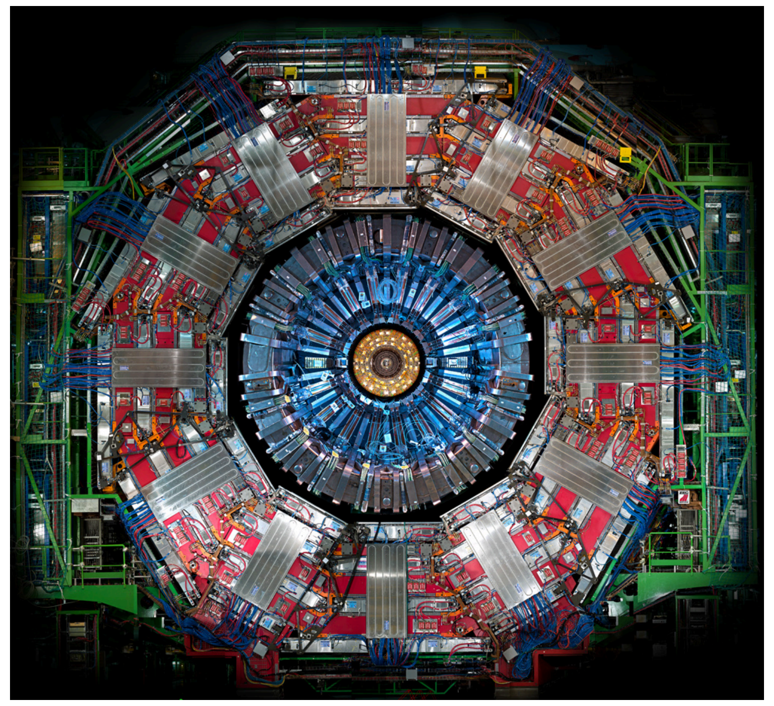
◆ Large Hadron Collider (LHC)

- The **LHC** is a succession of machines with increasingly higher energies.
- Each machine injects the beam into the next one, which takes over to bring the beam to an even higher energy, and so on.
- In the LHC the last element of this chain each particle beam is accelerated up to the record energy of 6.5 TeV.



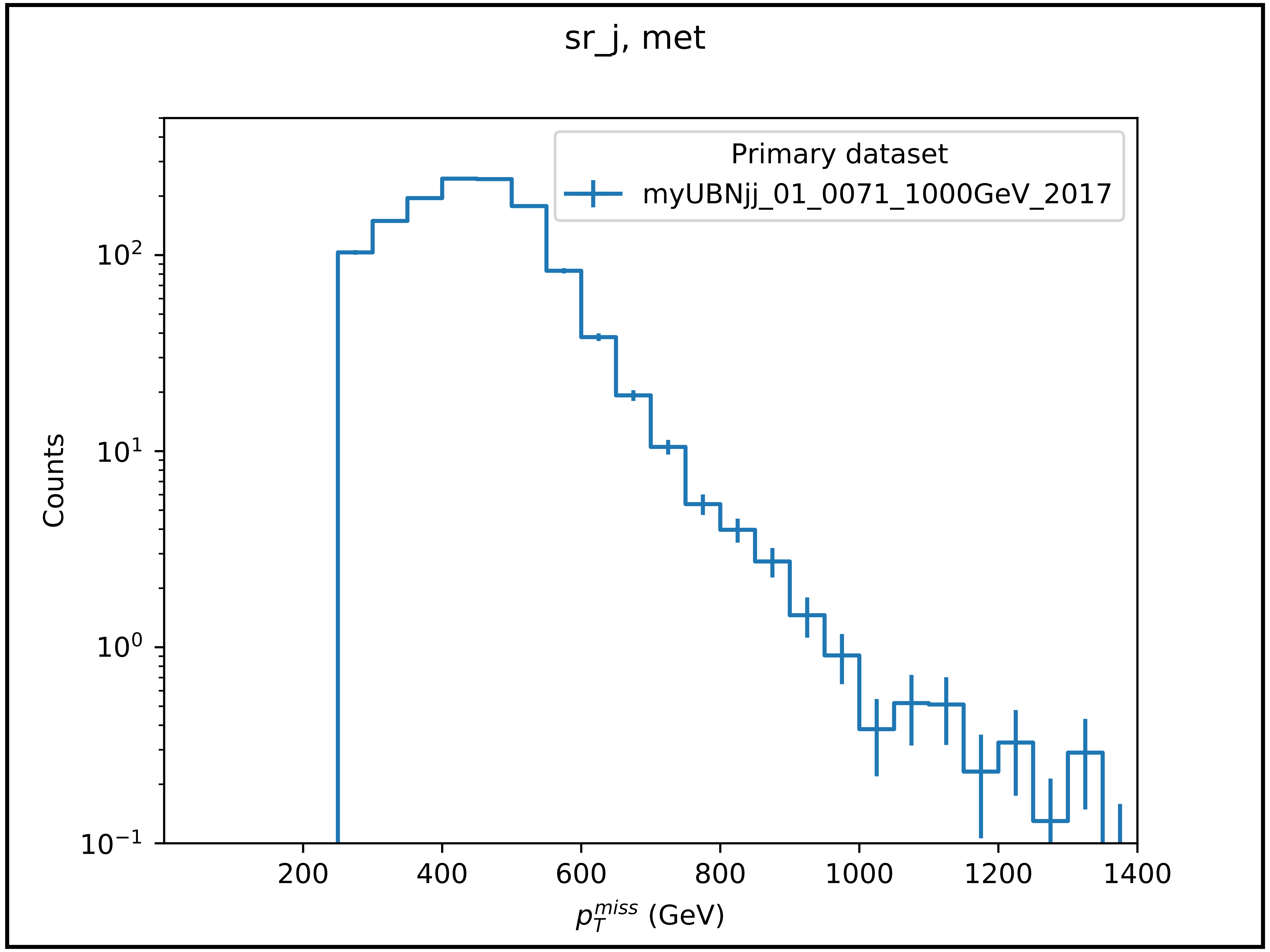
◆ Compact Muon Solenoid (CMS)

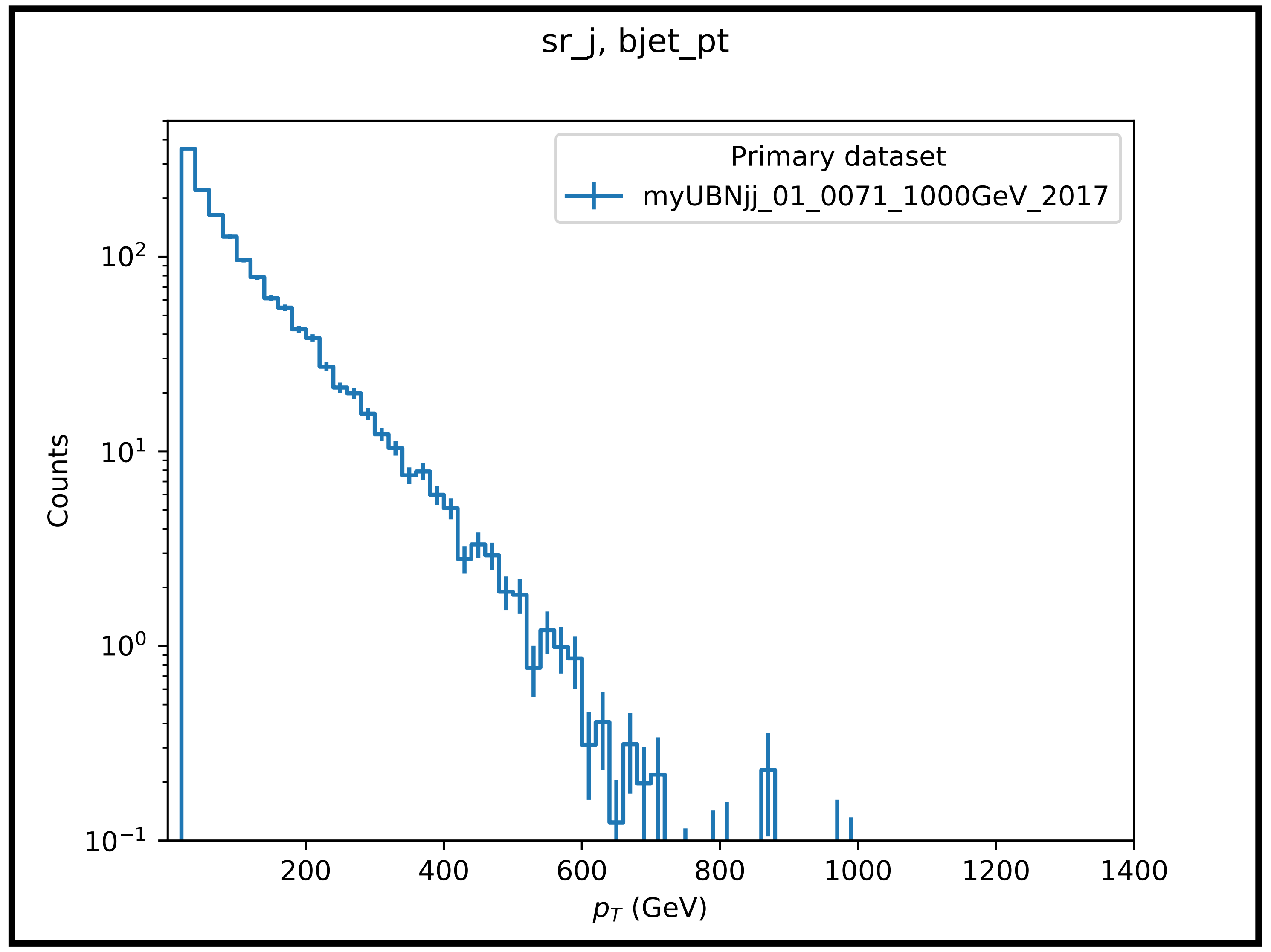


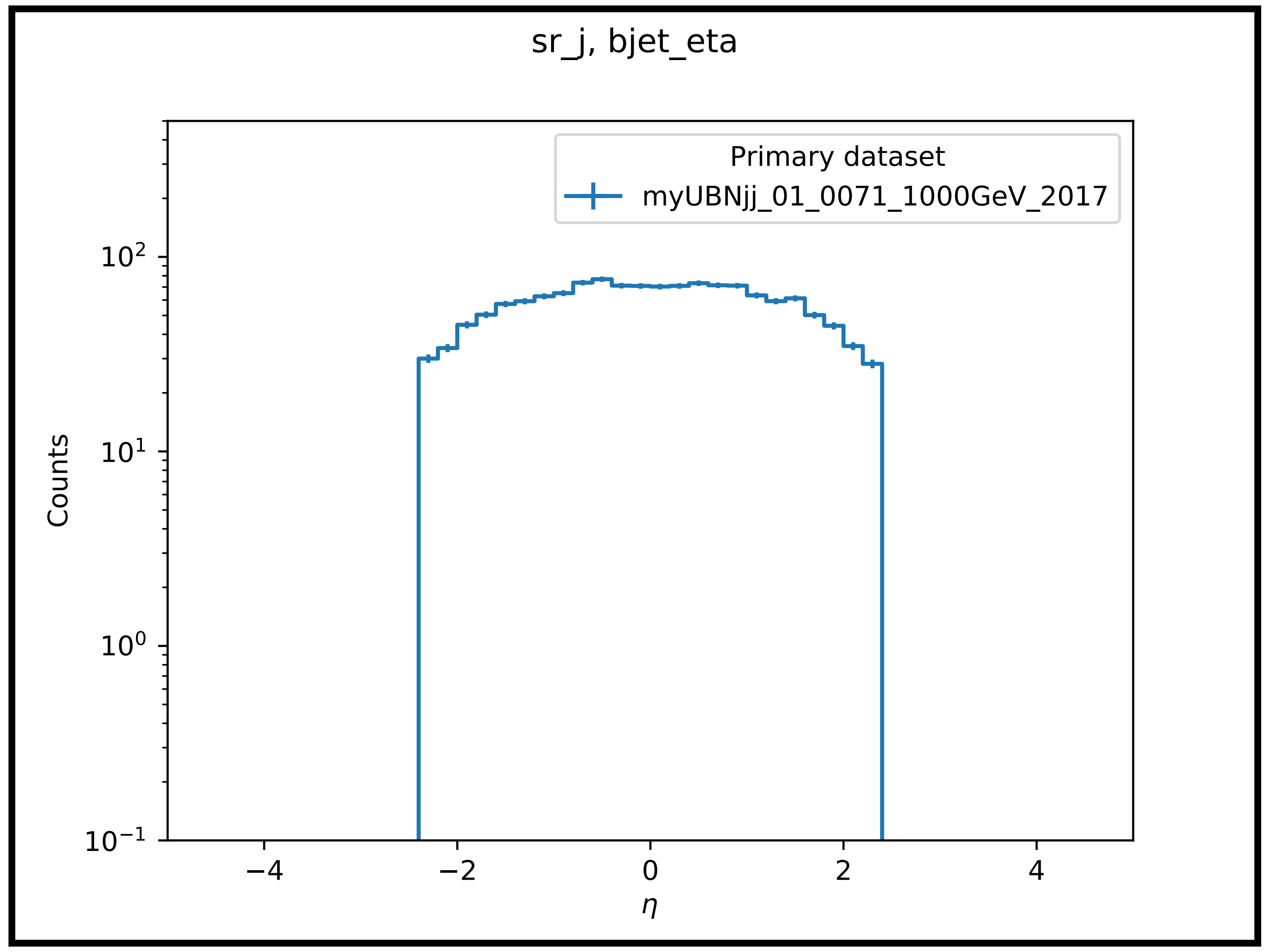


- The **CMS** detector is a large technologically advanced detector comprising many layers, each designed to perform a specific task.
- To identify and precisely measure the energies and momenta of all particles

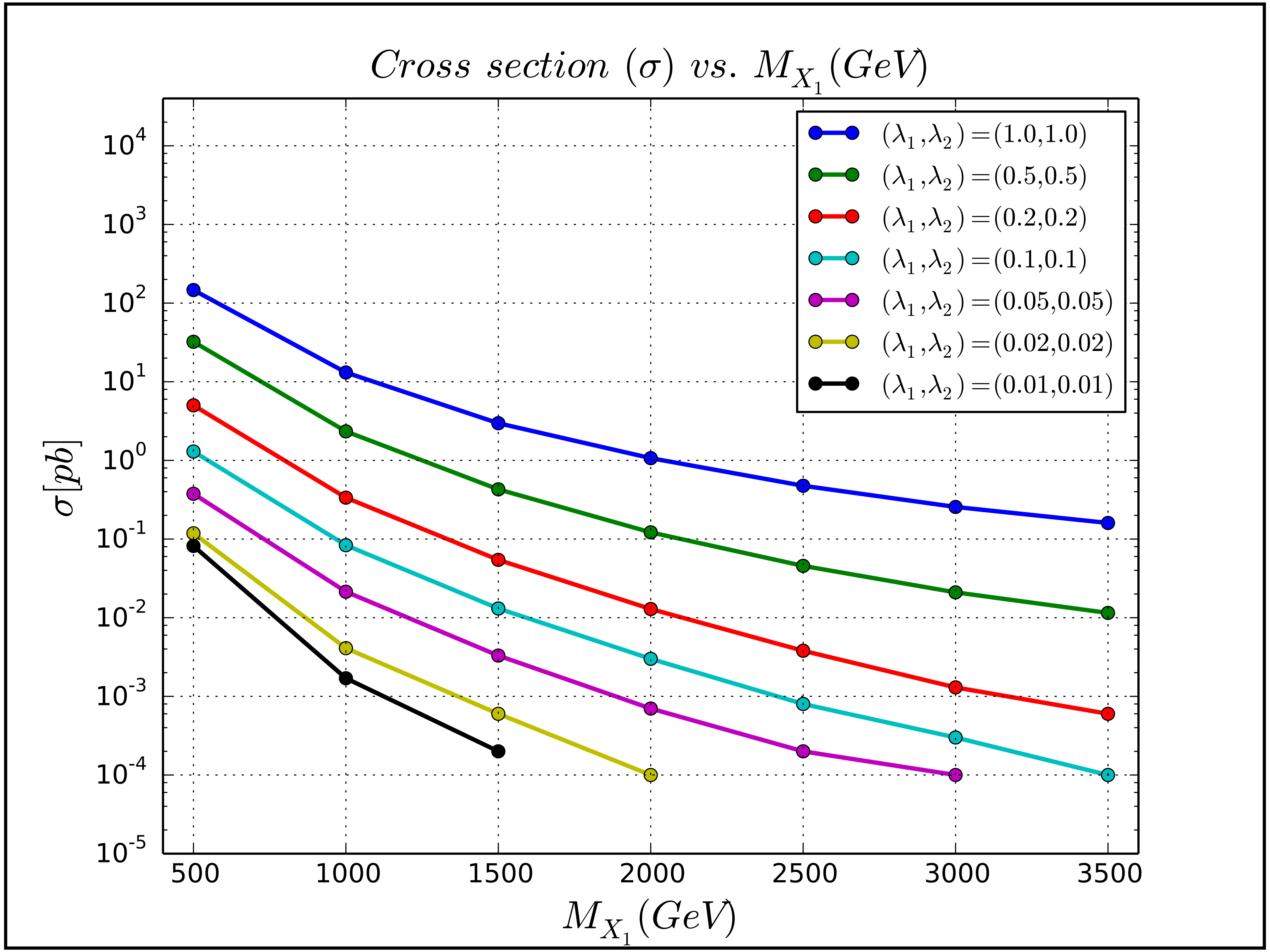
Kinematics: DM Signal Sample







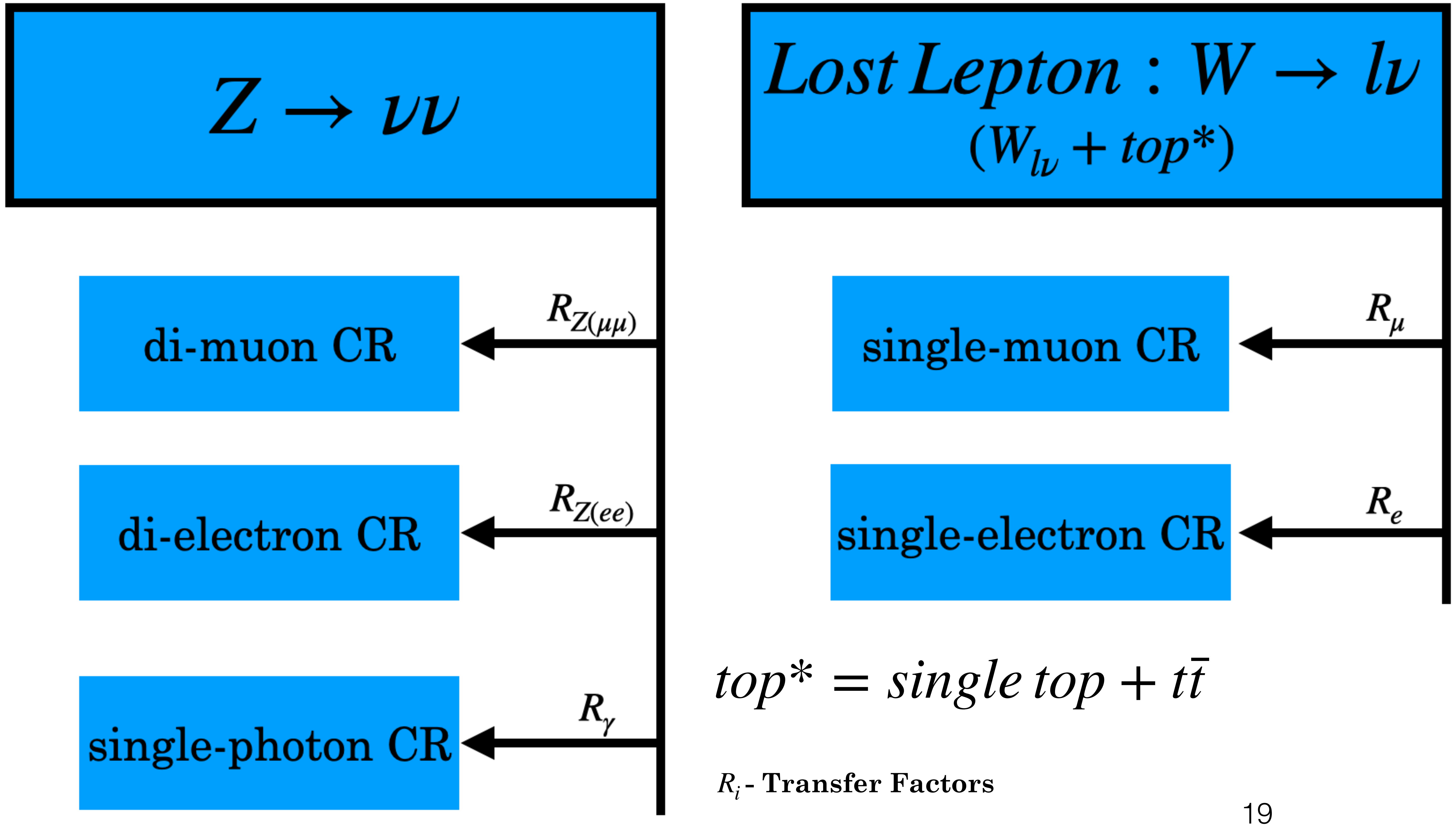
Cross section (σ) vs. M_{X_1}



Background Estimation

The **Major Backgrounds**, $Z \to \nu\nu$ and Lost Lepton ($W \to l\nu$), will be estimated from a **Combined Maximum Likelihood Fit** of the five control regions in data and as well as the signal region. Other **Minor Backgrounds** are estimated by the corresponding Monte Carlo samples.

Major Backgrounds



$top^* = single\ top + t\bar{t}$

R_i - **Transfer Factors**

- The number of estimated background (BG) events is obtained by,

$$Estimated\ BG = R_i \ . \ N_i(DATA)_{[CR]}$$

- The Transfer Factor (R_i) is calculated by,

$$R_i = \frac{N_i(MC)_{[SR]}}{N_i(MC)_{[CR]}}$$

The Interaction Lagrangian

$$\mathcal{L}_{int} = \lambda_1^{\alpha,\rho\delta} \epsilon^{ijk} X_{\alpha,i} \bar{d}^c_{\rho,j} \mathbf{P}_R d_{\delta,k} + \lambda_2^{\alpha,\rho} X^*_\alpha \bar{n}_{\mathrm{DM}\rho} \mathbf{P}_R u + \mathrm{C.C.}$$

- d^c is the charge-conjugate of the Dirac spinor.
- P_R is the right-handed projection operator.
- X_s are iso-single color triplet scalars with hypercharge 3/4.
- n_{DM} is a SM singlet which is dark matter candidate in this model.
- For the indices, $\rho, \delta = 1,2,3$ denote the three quark generations, and $i, j = 1,2,3$ are the SU(3) color indices.