Leptophilic Dark Matter in Single and Multicomponent Frameworks at Future Lepton Colliders

Bhavya Ashok Thacker

Supervisor: Dr. Subhaditya Bhattacharya

Department of Physics
Indian Institute of Technology Guwahati

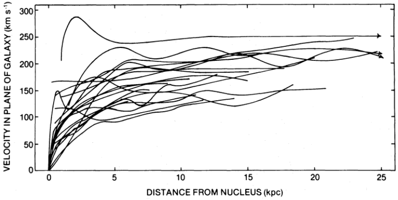
Outline

- Dark Matter and Where to find it?
- Effective Field Theory
- Collider Analysis Framework
- Effective Leptophilic WIMPs

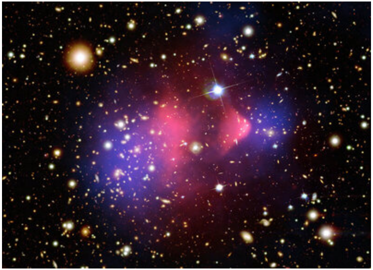
  Based on arXiv 2109.10936 [B.Barman, S.Bhattacharya, S.Girmohanta, S.Jahedi]
- Mono-X Signal and Two Component DM

  Based on arXiv 2211.10749 [S.Bhattacharya, P.Ghosh, J.Lahiri, B.Mukhopadhyaya]
- Future Prospects
- Summary

Evidences of Dark Matter



Vera C Rubin et al., Astrophysical Journal, Part 1, vol. 238, June 1, 1980

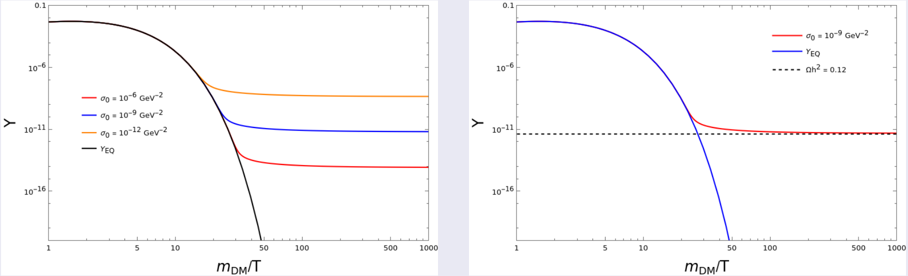


https://www.esa.int/ESA Multimedia/Images /2007/07/The Bullet Cluster2 [1]

$$v(r) \propto \sqrt{\frac{M(r)}{r}}$$

$$\delta\phi = \frac{4G_N M}{b}$$

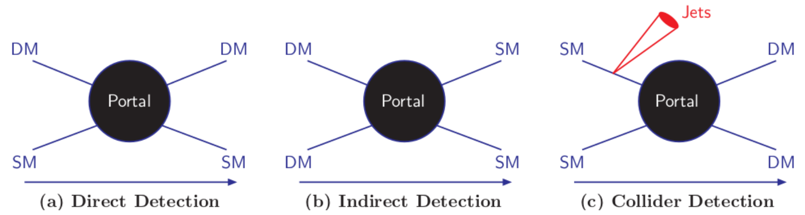
The WIMP Miracle



$$\Gamma \leq H(Decoupled) \qquad \Gamma \geq H(Coupled)$$

$$\frac{dY}{dX} = -\frac{\lambda}{x^{n+2}}[Y^2 - (Y^{eq})^2]$$

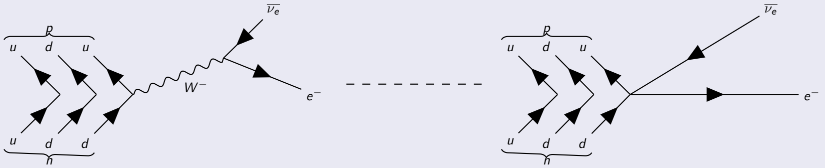
Dark Matter Search Stratagies



Dark Matter phenomenology: Pierre, Mathias, arXiv:1901.05822

- **Direct Search:** DM-nucleus scattering. `XENON1T`, `CRESST`, etc
- **Indirect Search:** DM Annhilation to SM particles. `Fermi-LAT`, `MAGIC`, etc.
- **Collider Search:** DM direct production. `ATLAS` and `CMS` at the `LHC`

Fermi's Theory of Weak Interaction



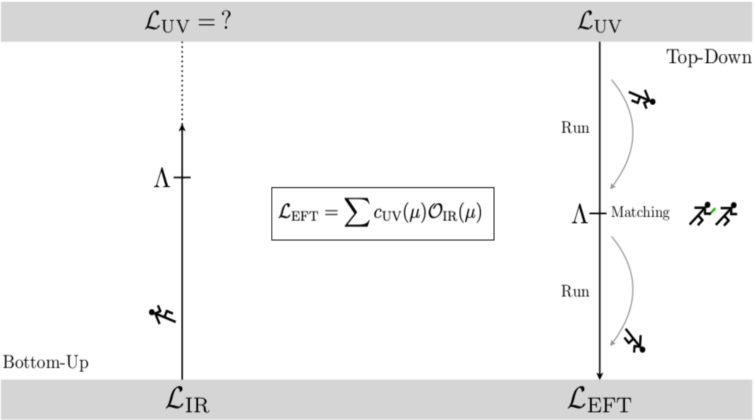
$$\mathcal{M} = \left(\frac{ig}{\sqrt{2}}\right)^2 V_{du}(\bar{d}\gamma^\mu P_L u)\left(\frac{-ig_{\mu\nu}}{p^2 - M_W^2}\right)(\bar{e}\gamma^\mu P_L \nu_e)$$

$$\mathcal{L}_{\text{effective}} = -\frac{4G_F}{\sqrt{2}} V_{du}(\bar{d}\gamma^\mu P_L u)(\bar{e}\gamma^\mu P_L \nu_e)$$

"In Limit $p << M_W$"

$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

Effective Theory Approachs



Effective Field Theory Phenomenology and Scattering Amplitudes, Aoude, Rafae: PhD thesis, Mainz U., 2020

Effective Theory Framework

- Model independent way to gauge effects of New Physics (that exist at a scale Λ) at current experiments using higher dimensional operators.

$$\mathcal{L} = \mathcal{L}_{SM} + \sum \frac{c_i \mathcal{O}_i^{(5)}}{\Lambda} + \sum \frac{c_i \mathcal{O}_i^{(6)}}{\Lambda^2} + \sum \frac{c_i \mathcal{O}_i^{(7)}}{\Lambda^3} + \sum \frac{c_i \mathcal{O}_i^{(8)}}{\Lambda^4} \ldots$$

- The DM-SM interactions can be described in the following way:

$$\mathcal{L}_{\text{int}} = \frac{c_{DM}}{\Lambda^{d+d'-4}} \mathcal{O}_{\text{SM}}^{(\text{d})} \mathcal{O}_{\text{DM}}^{(\text{d'})}$$

$\mathcal{O}_{\text{DM}}^{(\text{d'})}$: Invariant under $\mathcal{G}_{\text{DM}} = \mathbb{Z}_2$

$\mathcal{O}_{\text{SM}}^{(\text{d})}$: Invariant under $\mathcal{G}_{\text{SM}} = SU(3)_C \times SU(2)_L \times U(1)_Y$

$$\boxed{\mathcal{L}_{\text{DMEFT}} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{int}} + \mathcal{L}_{\text{DM}}}$$

- **Mono-X** + $\not{E}$ / MET, where X refers to γ, Jet, Z or H.
- **Multi-lepton/ Multi-Jet** channel: HDSP

Hadron Colliders

- $\sqrt{\hat{s}}$ Unknown. EFT Validation questionable $\sqrt{s} < \Lambda$
- QCD background
- Unpolarized beams (LHC)

Lepton Colliders

- Known $\sqrt{s}$. EFT applicable with $\sqrt{s} < \Lambda$
- Less QCD background
- Initial beam polarization

- **Invariant Mass:** $m_{ij}^2 = \sqrt{(E_i + E_j)^2 - (\vec{p}_i + \vec{p}_j)^2}$
- **MET:** $\not{E}_T = \sqrt{(\sum_{l,j,\gamma} p_x)^2 + (\sum_{l,j,\gamma} p_y)^2}$
- **Missing Energy ($\not{E}$)**: $\not{E} = \sqrt{s} - \sum_{l,j,\gamma}(E_{visible})$

Event Generation

`FeynRules` `LanHEP`	Model implementation. Generates mass spectrum.
`MaGraph5`	Event generation and Computations of cross-sections.
`Pythia8`	Parton showering. Multiparticle interaction.
`Delphes`	Detector simulation. Tagging Resolution.
`MicrOmegas`	Calculates Dark Matter properties.

`MadAnalysis5`	Histogramming. Cut-and-count. Signal significance.

Effective Leptophilic WIMPs

Dimension 5 Operators	
Name	**Description**
$\mathcal{O}^5_{D1}$	$\frac{c_{B1}}{\Lambda}(\bar{\chi}\sigma_{\mu\nu}\chi)B^{\mu\nu}$
$\mathcal{O}^5_{D2}$	$\frac{c_{B2}}{\Lambda}(\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi)B^{\mu\nu}$
$\mathcal{O}^5_{3}$	$\frac{c_{H1}}{\Lambda}(\bar{\chi}\chi)\left(H^\dagger H\right)$
$\mathcal{O}^5_{4}$	$\frac{c_{H2}}{\Lambda}(\bar{\chi}\gamma^5\chi)\left(H^\dagger H\right)$

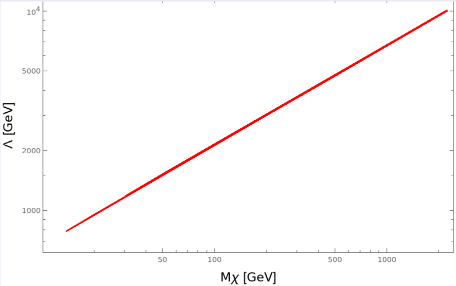
Dimension 6 Operators			
Leptohilic	**Description**	**Hadrophilic**	**Description**
$\mathcal{O}^6_{DL}$	$\frac{c_{l1}}{\Lambda^2}(\overline{\chi}\gamma_\mu\chi)(\bar{l}\gamma^\mu l)$	$\mathcal{O}^6_{DQ}$	$\frac{c_{q1}}{\Lambda^2}(\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu q)$
$\mathcal{O}^6_{L}$	$\frac{c_{l2}}{\Lambda^2}(\overline{\chi}\gamma_\mu\gamma^5\chi)(\bar{l}\gamma^\mu l)$	$\mathcal{O}^6_{Q}$	$\frac{c_{q2}}{\Lambda^2}(\overline{\chi}\gamma_\mu\gamma^5\chi)(\overline{q}\gamma^\mu q)$
$\mathcal{O}^6_{L1}$	$\frac{c_{l3}}{\Lambda^2}(\overline{\chi}\gamma_\mu\gamma^5\chi)(\bar{l}\gamma^\mu\gamma_5 l)$	$\mathcal{O}^6_{Q1}$	$\frac{c_{q3}}{\Lambda^2}(\overline{\chi}\gamma_\mu\gamma^5\chi)(\overline{q}\gamma^\mu\gamma_5 q)$
$\mathcal{O}^6_{DL}$	$\frac{c_{l4}}{\Lambda^2}(\overline{\chi}\gamma_\mu\chi)(\bar{l}\gamma^\mu\gamma_5 l)$	$\mathcal{O}^6_{DQ}$	$\frac{c_{q4}}{\Lambda^2}(\overline{\chi}\gamma_\mu\chi)(\overline{q}\gamma^\mu\gamma_5 q)$

χ: Dirac Fermion and obeys $\mathcal{G}_{\text{DM}} = \mathbb{Z}_2$ symmetry [3]

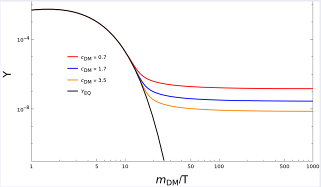
Relic Density Constraint

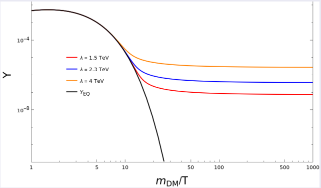
- Planck data [2] to constrain the parameter space: Λ, m_χ, C

$$\Omega h^2 = 0.11933 \pm 0.00091$$

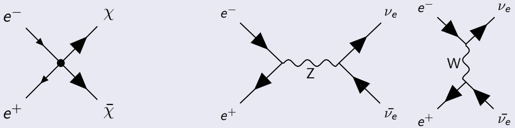


$$\Omega_\chi h^2 \approx 1/\langle \sigma V \rangle \approx \Lambda^4 / m_\chi^2$$





Collider Search: ILC

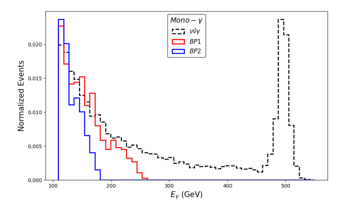


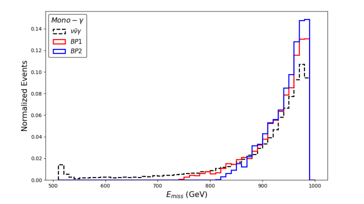
- Signal: $e^+e^- \to \chi\bar{\chi}\gamma \to ME + \gamma$.
- Background: $e^+e^- \to \nu\bar{\nu}\gamma \to ME + \gamma$
- Setup: ILC $\sqrt{s} = 1\,TeV \quad \mathcal{L} = 100\,fb^{-1}$

Points	m_χ **(GeV)**	Λ **(GeV)**
BP1	350	2800
BP2	400	3000

BP		**Signal(fb)**		**Bg**
P_{e^+}	P_{e^-}	BP1	BP2	(fb)
0	0	15.96	8.47	2380
0.3	-0.8	2.24	1.18	5570
-0.3	0.8	37.39	19.84	360

Event Distributions





Appropriate Cuts

- Efficiency factor: $\epsilon = \frac{S}{B}$ $\qquad$ $S = \sigma_S \mathcal{L}$
- Signal Significance: $\sigma = \frac{S}{\sqrt{S+B}}$ $\qquad$ $B = \sigma_B \mathcal{L}$

Mono-γ (ISR) + missing energy: Potential signal

Two Component Dark Matter

Multicomponent DM Features

- Coupled Boltzmann equations to determine relic contribution
- Interactions between DM components
- Modified Freeze-out/Freeze-In
- Modified Direct search and Indirect search constraints
- Large allowed parameter space

Can we distinguish two DM components at colliders? [5] [4]

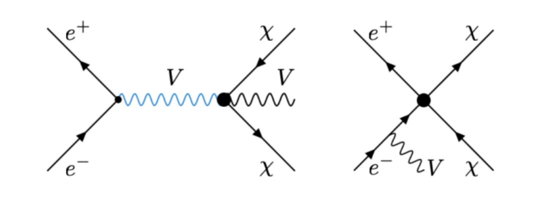
DM effective Operators

Type	Name	Operator
φ	$\mathcal{O}_s^1$	$\frac{1}{\Lambda^2}(\bar{L}\Phi l_R)(\varphi^2)$
φ	$\mathcal{O}_s^2$	$\frac{1}{\Lambda^4}(\bar{L}D_\mu\Phi l_R)(\varphi\partial^\mu\varphi)$
φ	$\mathcal{O}_s^3$	$\frac{1}{\Lambda^2}(B_{\mu\nu}B^{\mu\nu} + W_{\mu\nu}W^{\mu\nu})(\varphi^2)$
χ	$\mathcal{O}_f^1$	$\frac{1}{\Lambda^2}(\bar{L}\gamma^\mu L + \bar{l}_R\gamma^\mu l_R)(\overline{\chi}\gamma_\mu\chi)$
χ	$\mathcal{O}_f^2$	$\frac{1}{\Lambda^3}(\bar{L}\Phi l_R)(\overline{\chi}\chi)$
χ	$\mathcal{O}_f^3$	$\frac{1}{\Lambda^3}(B_{\mu\nu}B^{\mu\nu} + W_{\mu\nu}W^{\mu\nu})(\overline{\chi}\chi)$

ϕ: Scalar χ: Dirac Fermion

- Signal: $e^+e^- \to \chi\overline{\chi}(\varphi\varphi) + X \to ME + X$
- Background: $e^+e^- \to \nu\bar{\nu}X \to ME + X$
- $X = \gamma, Z, H$

Collider Analysis

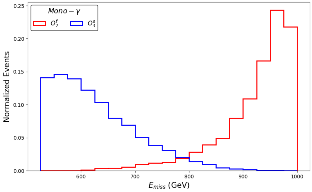


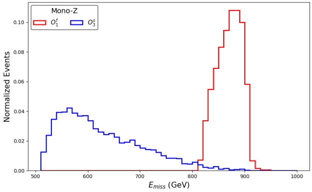
$2 \to 3$ and $2 \to 2$

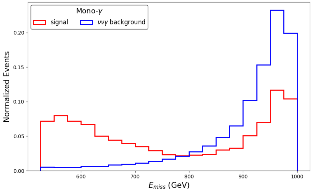
Double bump hunting in the $\not{E}$ distribution.

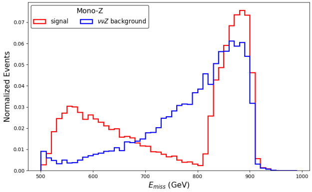
- Kinematics: Determines peak position ($\sqrt{s}, m_{DM}$)
- Dynamics: Distribution shape (Operator Structure)

$\not{E}$ Distributions









Can we rise above the Background?

Local Significance

$\mathcal{S} = S/\sqrt{B}$ against the $\not{E}$

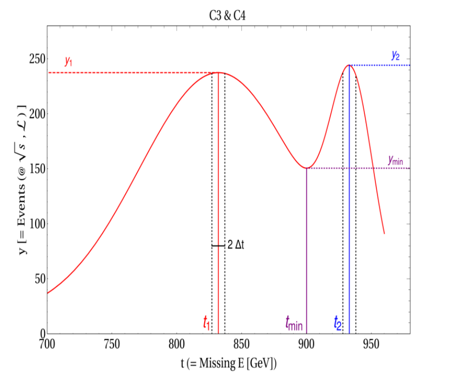
Quantifying two peaks

- $R_{C_3} = \dfrac{\int_{t_1-\Delta t}^{t_1+\Delta t} y\,dt - \int_{t_2-\Delta t}^{t_2+\Delta t} y\,dt}{\int_{t_1-\Delta t}^{t_1+\Delta t} y\,dt + \int_{t_2-\Delta t}^{t_2+\Delta t} y\,dt}$

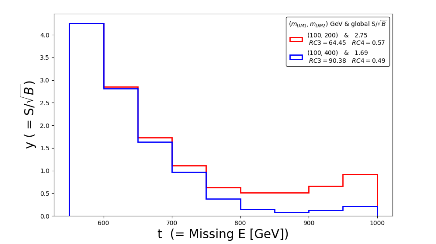
$$\boxed{R_{C_3} = \frac{y_1 - y_2}{y_1 + y_2}}$$

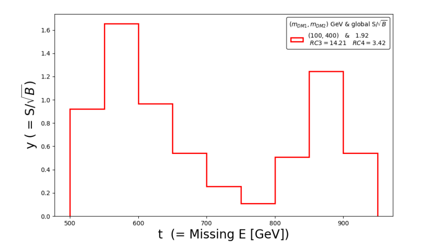
- $R_{C_4} = \dfrac{y(t) - y(t_{min})}{\sqrt{y(t_{min})}}$

$$\boxed{R_{C_4} = \frac{y(t) - y_{min}}{\sqrt{y_{min}}}}$$



Local Significance





Mono-X	Operators	$\{m_{\rm DM1}, m_{\rm DM2}\}$ (GeV)	$(\sigma_{\rm DM1}, \sigma_{\rm DM2})$ (fb)	L (fb^{-1})	S/$\sqrt{B}$	RC3	RC4
γ	$(\mathcal{O}_3^f, \mathcal{O}_2^f)$	{100, 200}	(2.41, 3.19)	100	2.24 σ	30.75	0.47
γ	$(\mathcal{O}_3^f, \mathcal{O}_2^f)$	{100, 400}	(2.41, 0.54)	100	1.18 σ	77.49	0.24
Z	$(\mathcal{O}_3^s, \mathcal{O}_1^f)$	{100, 400}	(0.15, 0.14)	1000	1.92 σ	14.21	3.42

Two peak behavior: $\mathcal{S}$ against $\not{E}$

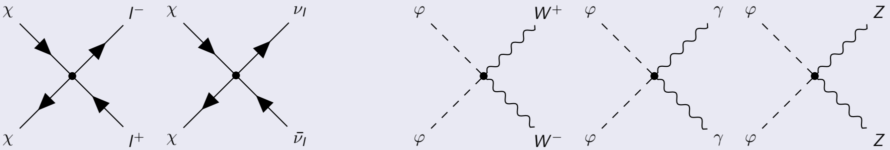
Future Prospects

- Validity of the analysis: Direct, Indirect and Relic Constraint.
- Two-Component DM setup:

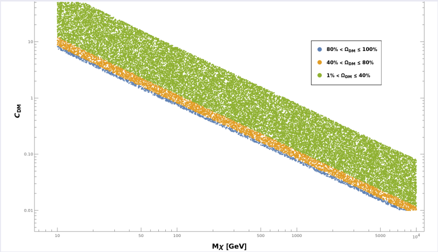
$$\Omega_{DM}h^2 = \Omega_{DM1}h^2 + \Omega_{DM2}h^2 = 0.11933 \pm 0.00091$$

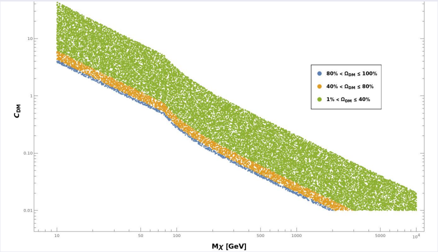
- Mono-Z EFT free parameters:

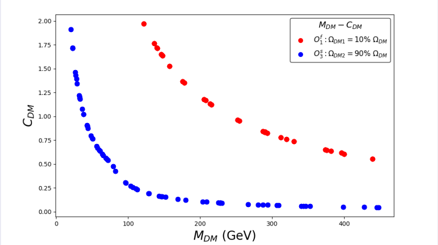
$$\mathcal{O}_f^1 : (m_{DM1}, C_1) \; \mathcal{O}_s^3 : (m_{DM2}, C_2)$$

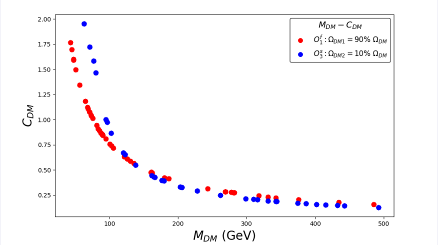


Relic Constraint









Summary

- DMEFT validity questionable to be probed at the LHC
- Leptophilic operators can be probed at the ILC and can hide from the null result from the direct search experiments.
- Peaks in the $\not{E}$ distribution.
- Distinguished two DM components in the local significance distribution using two statistical variables R_{C_3} and R_{C_4}

References

[1] The bullet cluster, 2007.

[2] Peter AR Ade, Nabila Aghanim, M Arnaud, Mark Ashdown, J Aumont, Carlo Baccigalupi, AJ Banday, RB Barreiro, JG Bartlett, N Bartolo, et al.
Planck 2015 results-xiii. cosmological parameters.
Astronomy & Astrophysics, 594:A13, 2016.

[3] Barman Basabendu, Bhattacharya Subhaditya, Girmohanta Sudhakantha, and Jahedi Sahabub.
Effective leptophilic wimps at the e+ e- collider.
Journal of High Energy Physics, 2022(4), 2022.

[4] Subhaditya Bhattacharya, Purusottam Ghosh, Jayita Lahiri, and Biswarup Mukhopadhyaya.
Distinguishing two dark matter component particles at e^+e colliders.
JHEP, 12:049, 2022.

[5] Subhaditya Bhattacharya, Purusottam Ghosh, Jayita Lahiri, and Biswarup Mukhopadhyaya.
Mono-x signal and two component dark matter: new distinction criteria.
arXiv preprint arXiv:2211.10749, 2022.

THANK YOU

Appendix

- Collider kinematics:

$$\vec{p_T} = (p_x, p_y)$$

$$p_T = \sqrt{p_x^2 + p_y^2}$$

$$\phi = \tan^{-1} \frac{p_x}{p_y}$$

$$y = \frac{1}{2} ln \frac{E + p_z}{E - p_z}$$

- Signal Significance

$$\mathcal{S} = \sqrt{\left[(S + B) \log \left(1 + \frac{S}{B} \right) - S \right]}$$