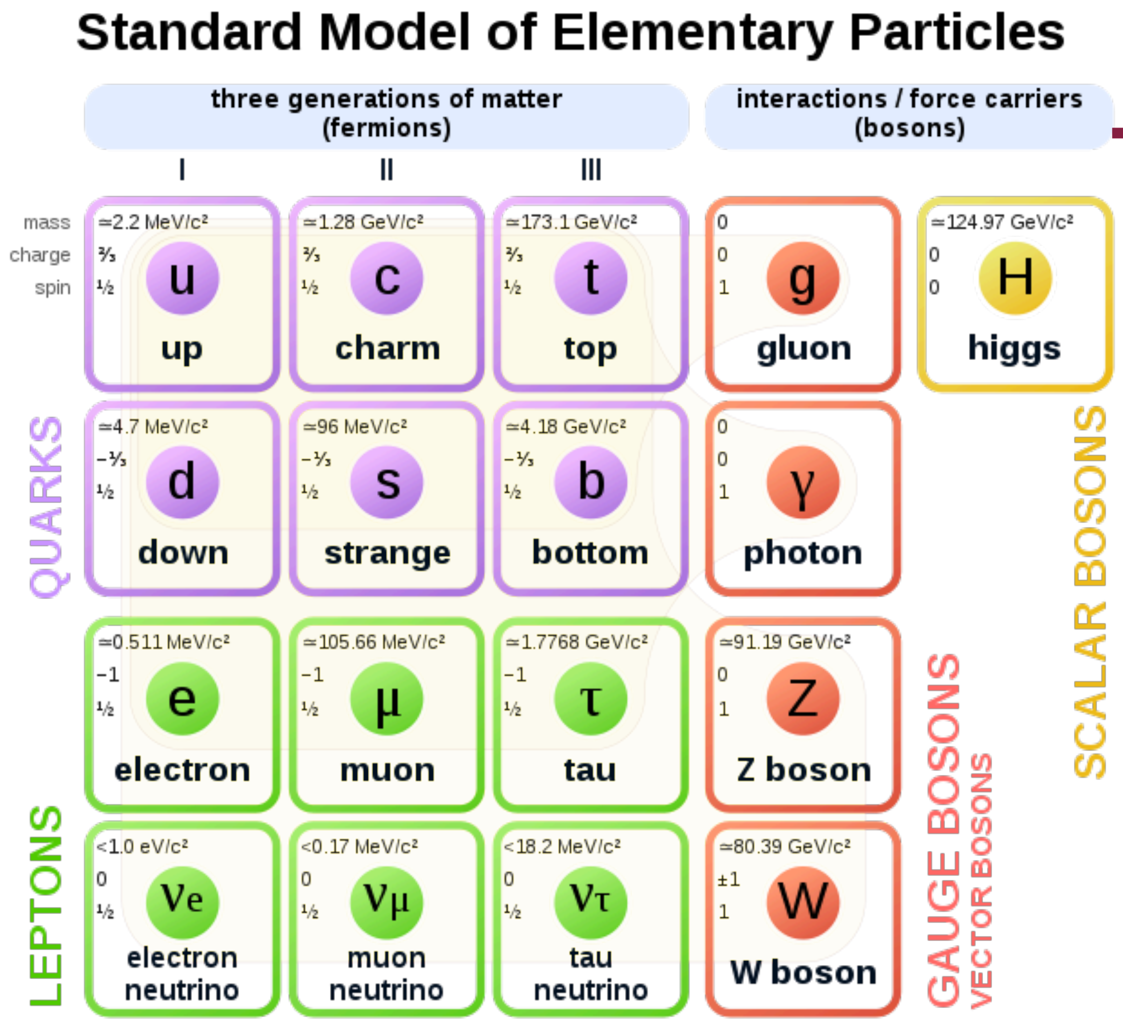
iDM Search

TOMMY LAM

2023 JULY 26

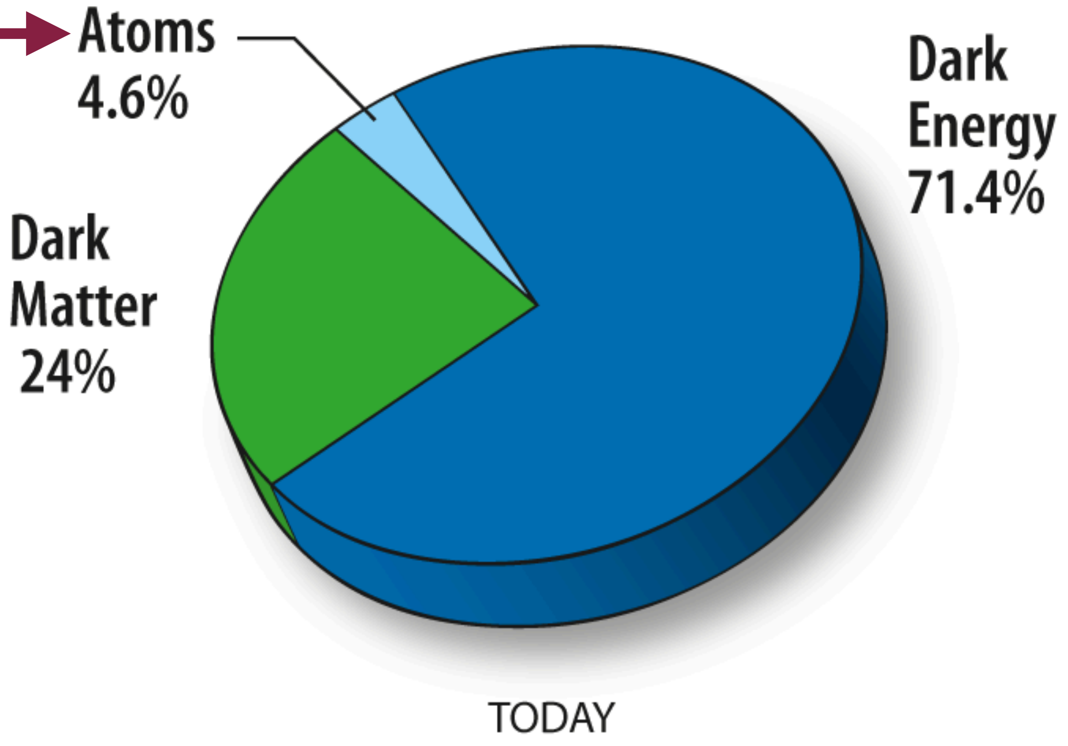
VIRGINIA TECH

Introduction



PC: [1]

PC: [2]

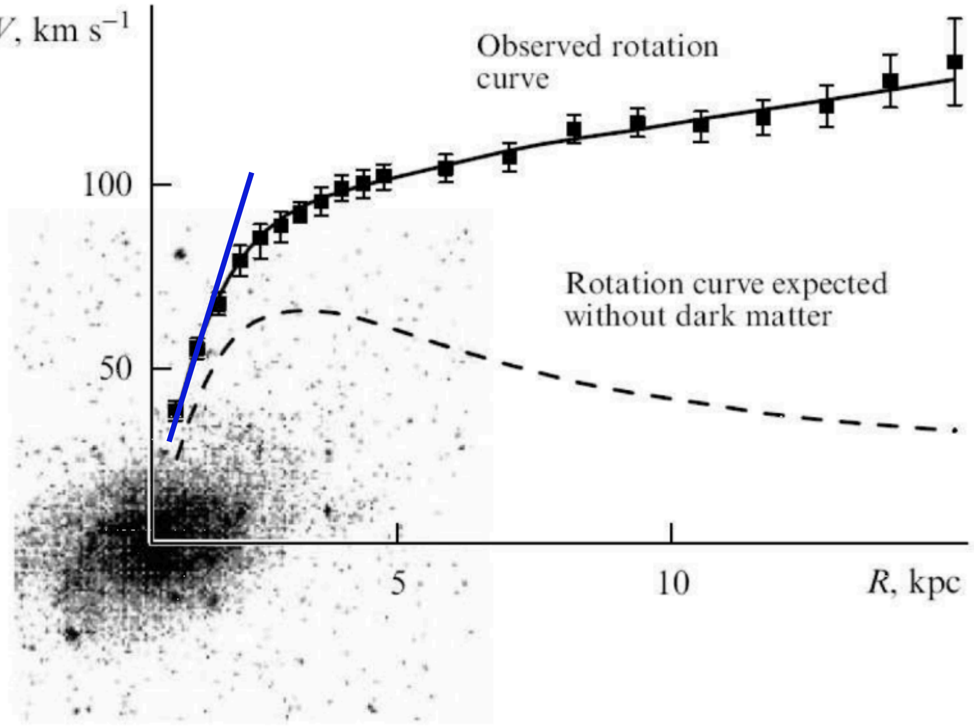


[1]: Wikipedia Commons. "File:Standard Model of Elementary Particles.svg-Wikimedia Commons, the free media repository" (2020)
[2]: https://wmap.gsfc.nasa.gov/universe/uni_matter.html

Evidence for Dark Matter

- From Astronomy/Cosmology [1]
  - Galaxy rotation curves [2]
  - Bullet Cluster
  - CMB Anisotropies

$$v^2 = \frac{GM(r)}{r}$$



M33 Galaxy's rotation curves [3]

constant density

$$v^2 = \frac{4\pi G\rho_0}{3} r^2$$

outside central density w/o DM

$$v^2 = \frac{GM_{tot}}{r}$$

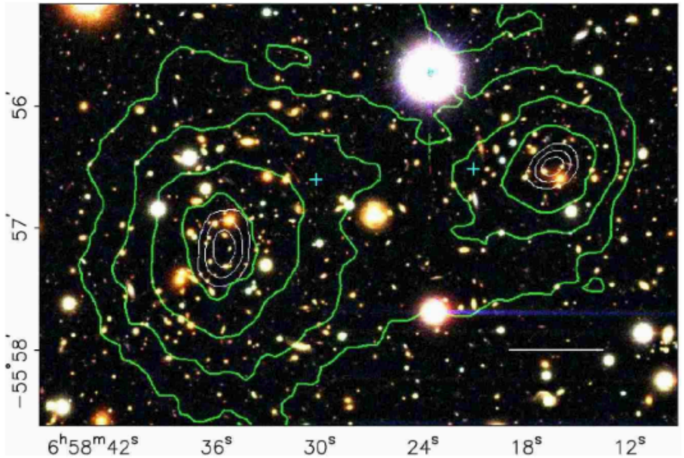
[1]: D. Gruen. "Cosmology Overview." SSI 2020:The Almost Invisibles: Exploring the Weakly Coupled Universe. (2020) (Slide 25)
[2]: V.C Rubin, W.K. Ford Jr. "Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions" (1970)
[3]: A.V. Zasov et al. "Dark Matter in galaxies." (2017) arxiv:1710.10630
[4]: D. Clowe et al. "A Direct Empirical Proof of the Existence of Dark matter." (2004) arxiv:0608407

Evidence for Dark Matter

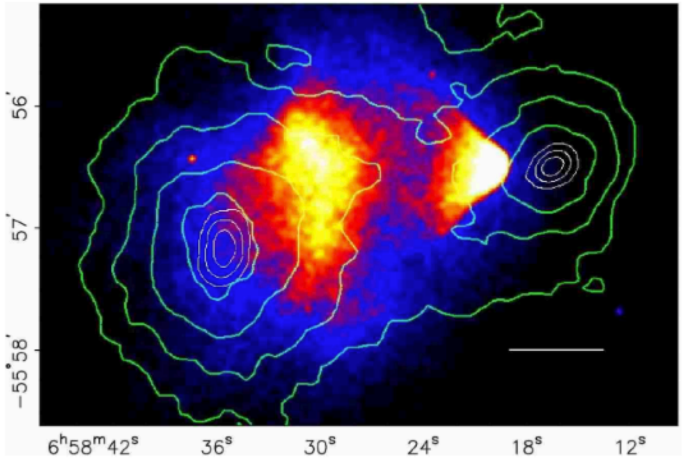
- From Astronomy/Cosmology [1]
  - Galaxy rotation curves
  - Bullet Cluster [2]
  - CMB Anisotropies

PC: [2]

Gravitational Lensing



Plasma Clouds

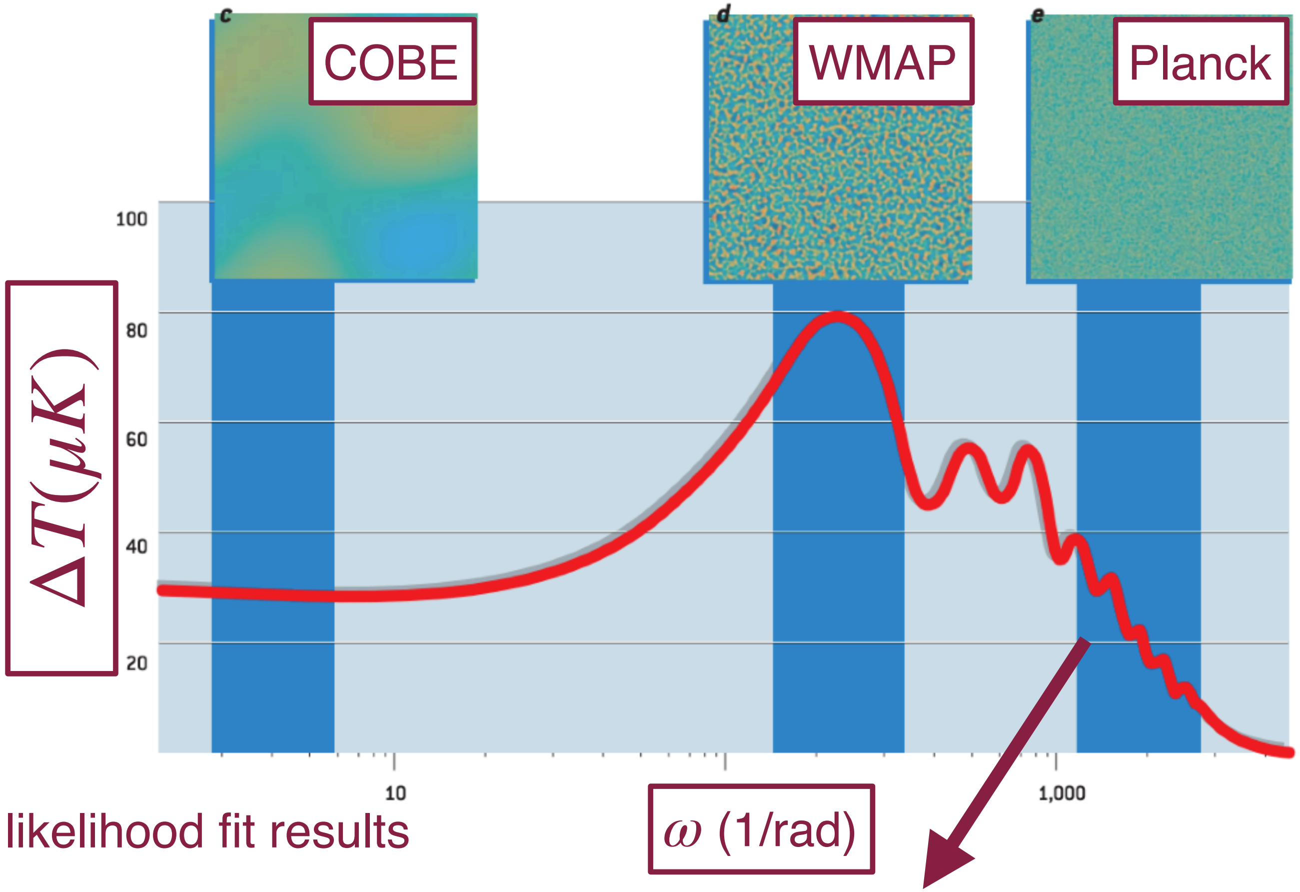


[1]: D. Gruen. “Cosmology Overview.” SSI 2020:The Almost Invisibles: Exploring the Weakly Coupled Universe. (2020) (Slide 25)
[2]: D. Clowe et al. “A Direct Empirical Proof of the Existence of Dark matter.” (2004) arxiv:0608407

Evidence for Dark Matter

PC: [3]

- From Astronomy/Cosmology [1]
  - Galaxy rotation curves
  - Bullet Cluster
  - CMB Anisotropies [4,5,6]

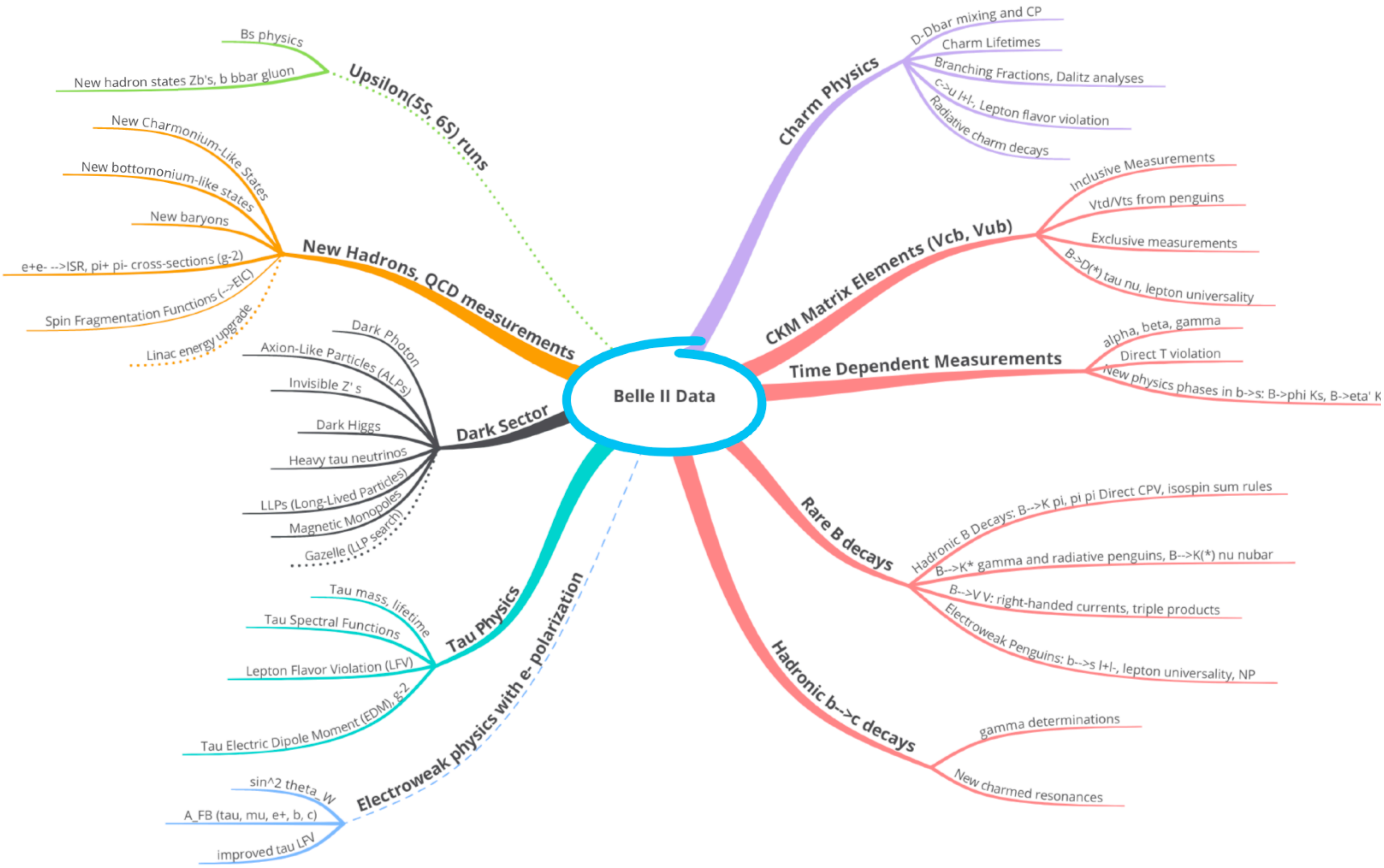


baryon $\Omega_b h^2 = 0.02237 \pm 0.00015$

cold DM $\Omega_c h^2 = 0.1200 \pm 0.0012$

total matter $\Omega_m h^2 = 0.1430 \pm 0.0011$

[1]: D. Gruen. "Cosmology Overview." SSI 2020:The Almost Invisibles: Exploring the Weakly Coupled Universe. (2020) (Slide 25)
[2]: https://www.nasa.gov/mission_pages/planck/multimedia/pia16874.html
[3]: W. Hu and M. White. "The Cosmic Symphony." http://background.uchicago.edu/~whu/Papers/HuWhi04.pdf
[4]: S. Das et al. PRL 107, 021301 (2011).
[5]: E. Komatsu et al. ApJS **192** 18 (2011)
[6]: Planck Collaboration. arxiv:1807.06209



PC: https://twitter.com/belle2collab/status/1324345141029527552

Inelastic Dark Matter

- Motivation: During early Universe, we might want to have a production channel for dark matter
- Features such a channel would need:
  - coupling to standard model for thermalization with SM
  - having enough annihilations to be consistent with the observed relic abundance

SOURCE: M. Duerr et al. "Invisible and displaced dark matter signatures at Belle II". https://arxiv.org/pdf/1911.03176.pdf

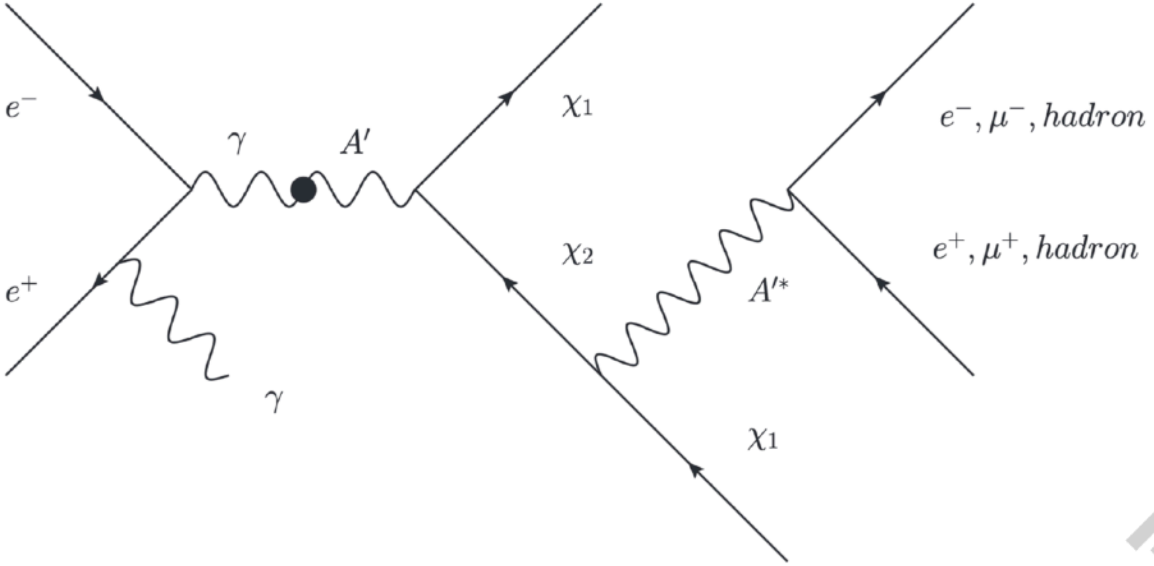
Inelastic Dark Matter

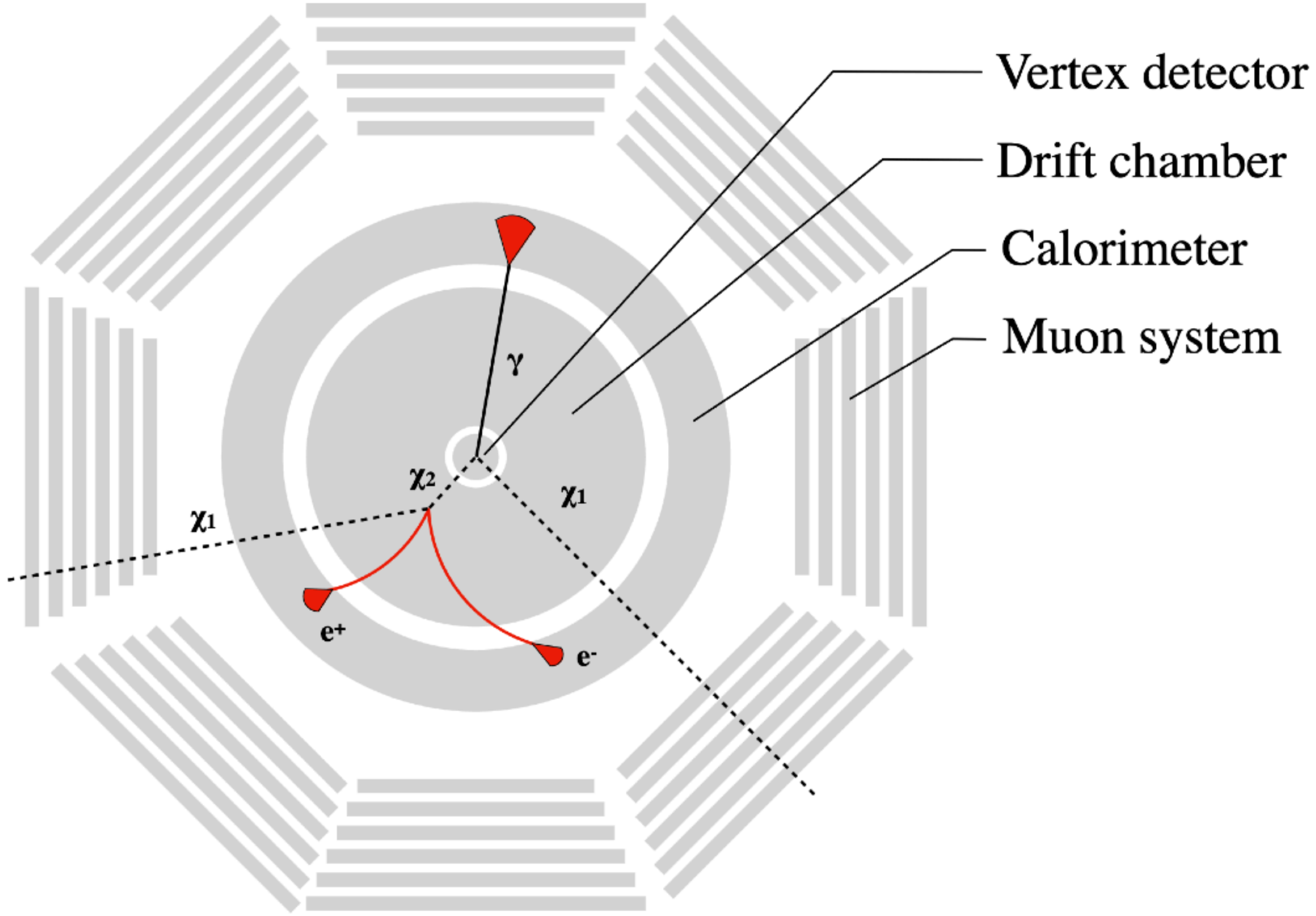
- Model Constituents
  - Dark Fermions (χ_1, χ_2), dark photon (A')
- Parameters:
  - kinetic mixing term (ϵ),
  - dark photon to dark fermions coupling ($\alpha_D = g_X^2/4\pi$)
  - stable dark fermion mass (m_{χ_1}), mass difference (Δm), and dark photon mass ($m_{A'}$ or m_X)

$$\mathcal{L} = \mathcal{L}_{\rm SM} - \frac{1}{4}\hat{X}_{\mu\nu}\hat{X}^{\mu\nu} + \frac{1}{2}m_{\hat{X}}^2\hat{X}_\mu\hat{X}^\mu - \frac{\epsilon}{2c_{\rm W}}\hat{X}_{\mu\nu}\hat{B}^{\mu\nu},$$

$$\mathcal{L}_\psi = i\overline{\chi_1}\not{\partial}\chi_1 + i\overline{\chi_2}\not{\partial}\chi_2 + \frac{i}{2}g_X\hat{X}_\mu\overline{\chi_2}\gamma^\mu\chi_1 - \frac{i}{2}g_X\hat{X}_\mu\overline{\chi_1}\gamma^\mu\chi_2 - \frac{1}{2}m_{\chi_1}\overline{\chi_1}\chi_1 - \frac{1}{2}m_{\chi_2}\overline{\chi_2}\chi_2.$$

SOURCE: M. Duerr et al. "Invisible and displaced dark matter signatures at Belle II". https://arxiv.org/pdf/1911.03176.pdf

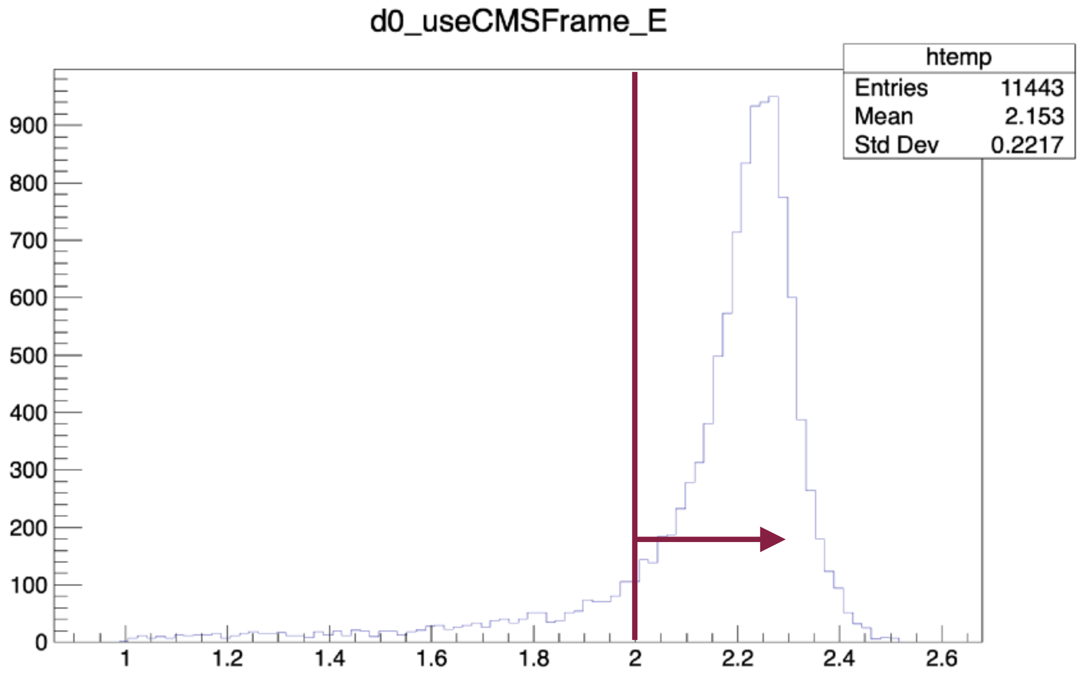


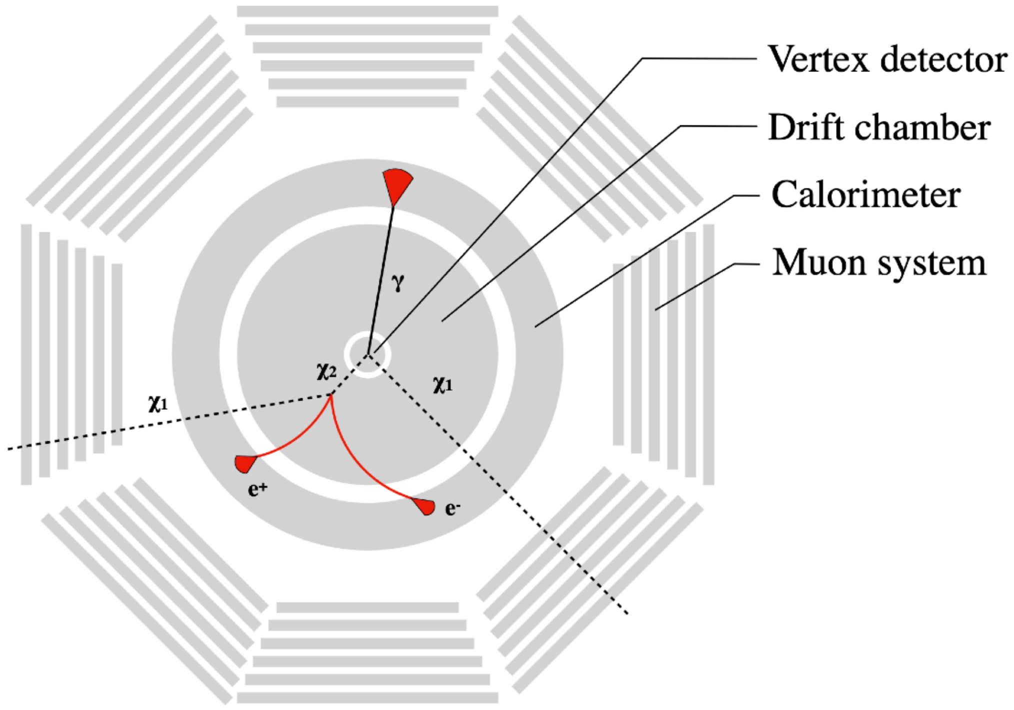


SOURCE: M. Duerr et al. “Invisible and displaced dark matter signatures at Belle II”. https://arxiv.org/pdf/1911.03176.pdf

Signal: ISR Photon

- Since this is our initial trigger, need to separate from background: an energetic photon (>2GeV), comes from the barrel, etc.



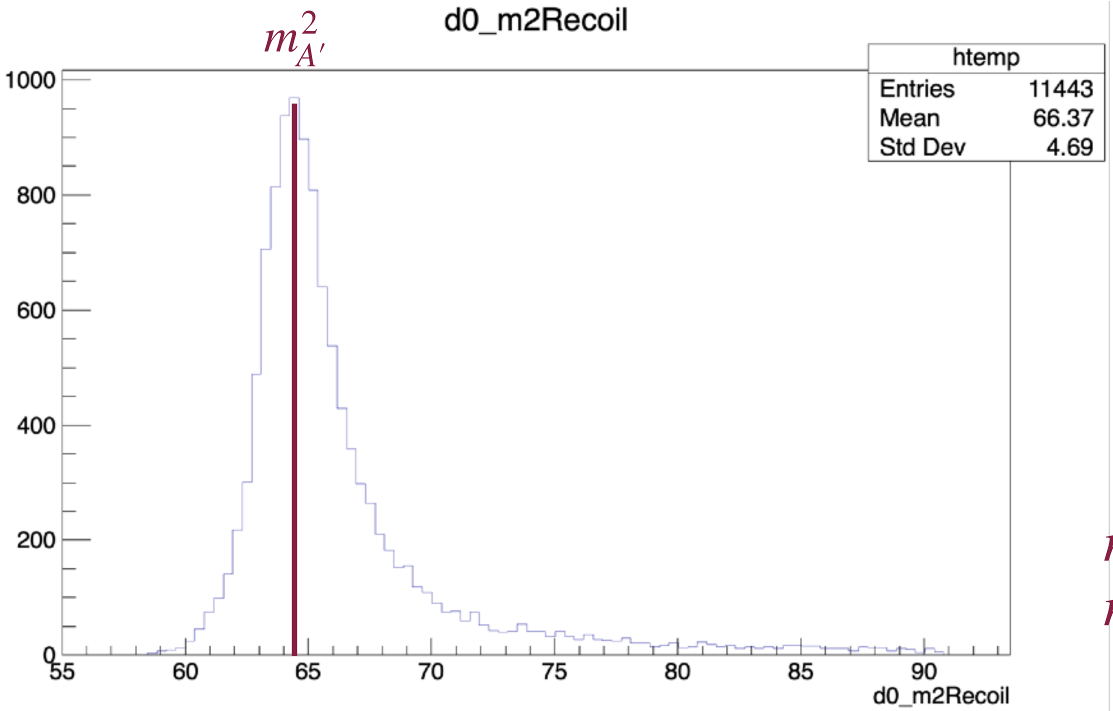


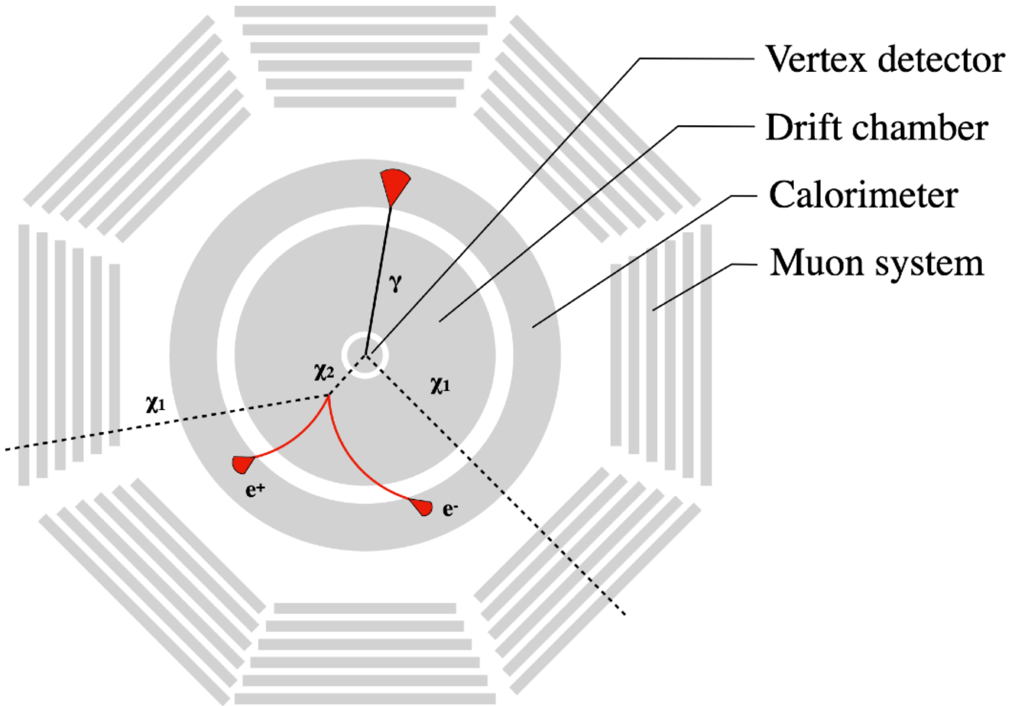
$m_{A'} = 8.0\text{GeV}, \Delta m = 1.28\text{GeV},$
$m_{\chi_1} = 3.2\text{GeV}, \epsilon = 10^{-4}, \alpha_D = 0.1$

SOURCE: M. Duerr et al. "Invisible and displaced dark matter signatures at Belle II". https://arxiv.org/pdf/1911.03176.pdf

Signal: A'

- Since we know the momentum and direction of the ISR photon + initial conditions, then $p_{ini} - p_\gamma = p_{A'}$



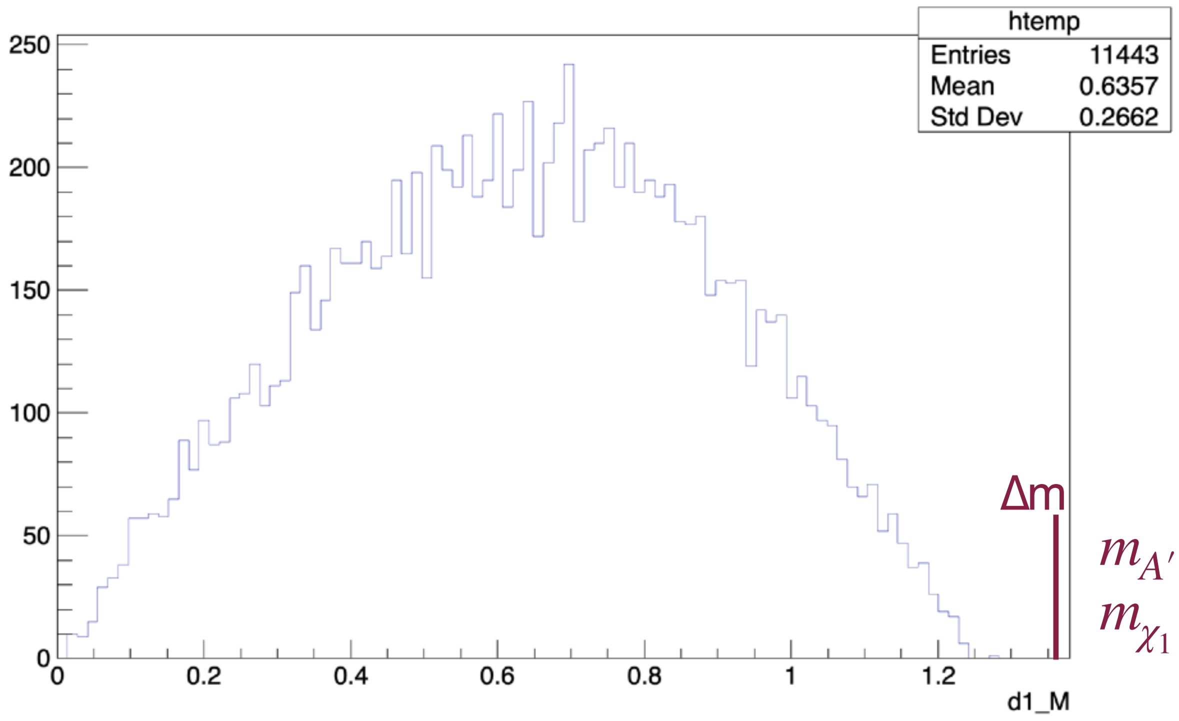


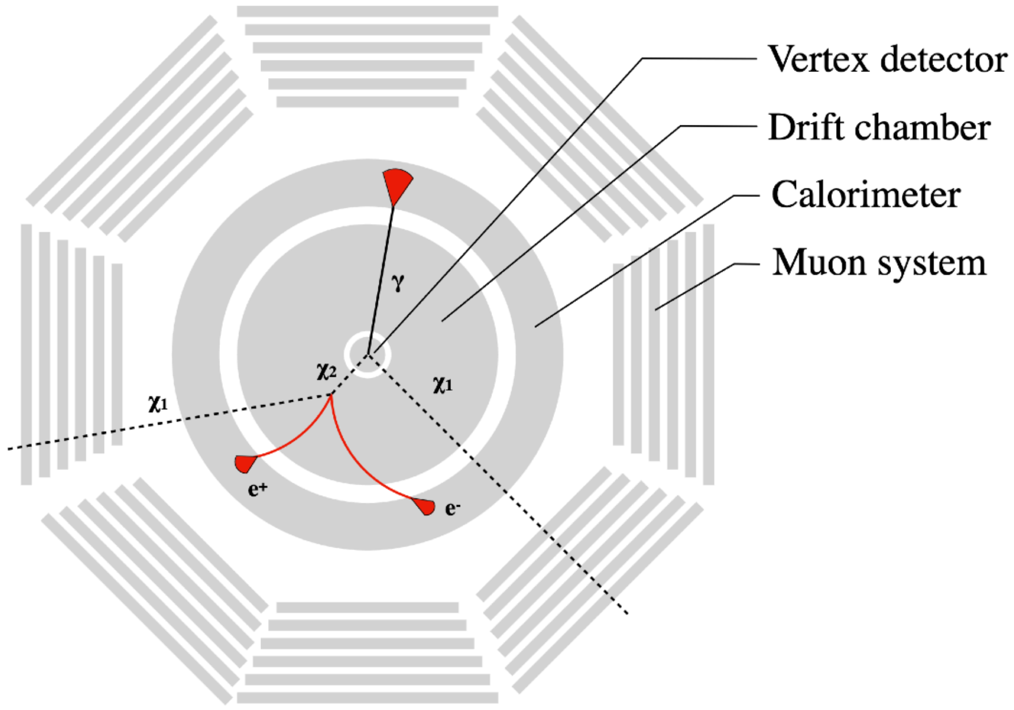
$m_{A'} = 8.0\text{GeV}, \Delta m = 1.28\text{GeV},$
$m_{\chi_1} = 3.2\text{GeV}, \epsilon = 10^{-4}, \alpha_D = 0.1$

SOURCE: M. Duerr et al. "Invisible and displaced dark matter signatures at Belle II". https://arxiv.org/pdf/1911.03176.pdf

Signal: Displaced Vertex Hunting

- With tree-fitted e+e- vertexing, providing m_{V^0} and V^0's dr
- Mass for reconstructed vertex < Δm

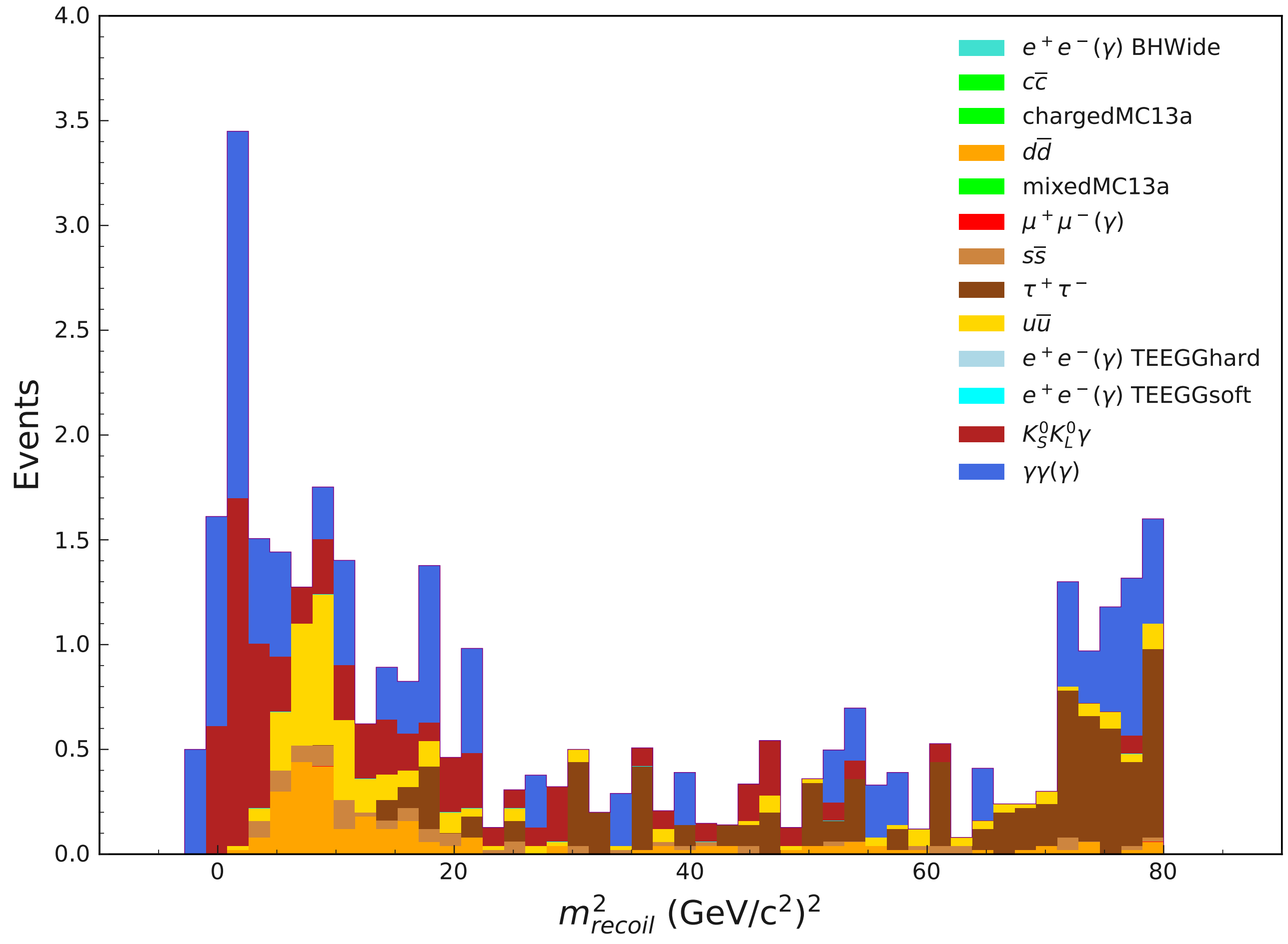




$m_{A'} = 8.0\text{GeV}, \Delta m = 1.28\text{GeV},$
$m_{\chi_1} = 3.2\text{GeV}, \epsilon = 10^{-4}, \alpha_D = 0.1$

Background: Sources (wanted list)

- $e^+e^- \to l^+l^-\gamma\gamma$ but we lose a photon out of detector acceptance (or the lepton pair w/ below)
- $e^+e^- \to \gamma\gamma(\to e^+e^-)$
- $e^+e^- \to \gamma K^0_S K^0_L$
- $e^+e^- \to \tau^+\tau^-$
- $e^+e^- \to \Sigma^+\Sigma^-$ (from uds)



Background: Mitigation

γ_{ISR}

- $E_{CMS} > 2$ GeV
- clusterReg=2 (barrel)
- ZernikeMVA > 0.7

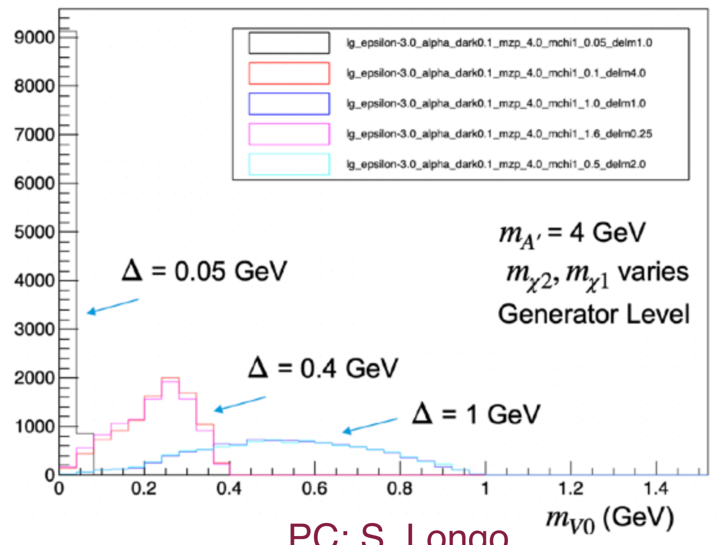
V^0 Tracks:

- nCDCHits>4
- $dr > 0.1$ cm
- clusterE < 2.0 GeV
- 3Dang($\vec{p}_{track}, \vec{p}_{ISR}$) > 0.5 rad

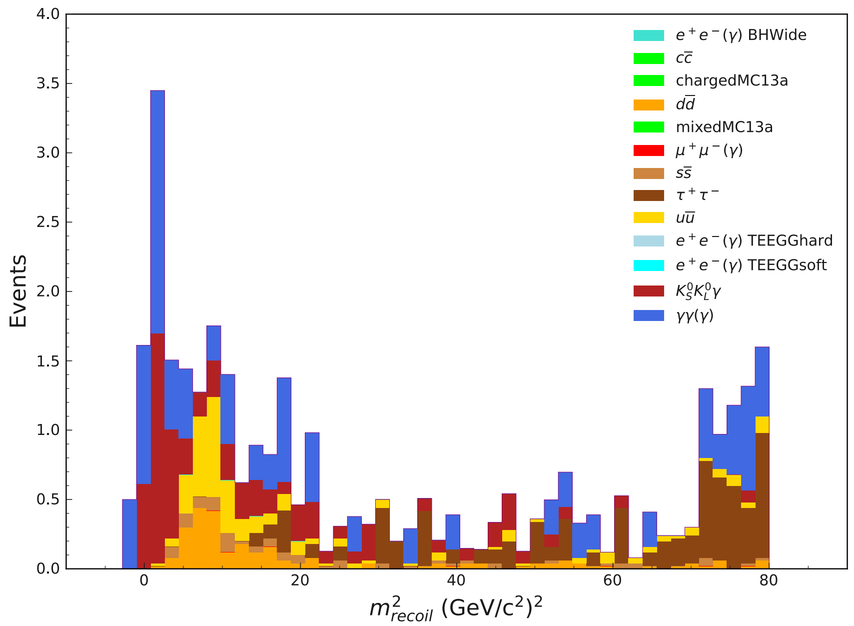
V^0:

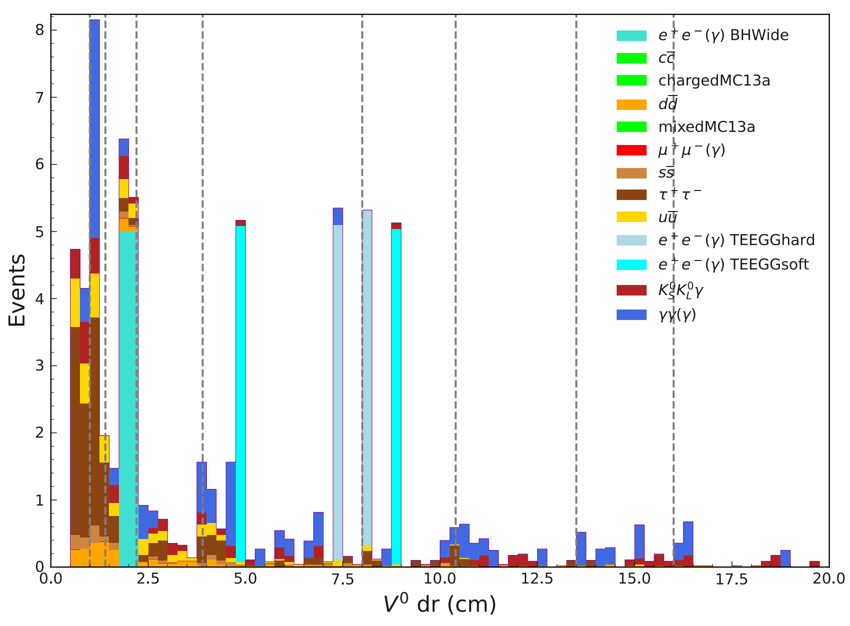
- Fit with treefit, $dr > 0.5$ cm, pval ≥ 0
- $|\Delta^{V^0}_{d_0}| < 1$ cm and $|\Delta^{V^0}_{d_z}| < 1$ cm
- $p_{lab} > 0.1$ GeV
- $p_{CMS} < 2.0$ GeV
- $\cos(\alpha_{PA}) < 0.999$ (α_{PA} = Pointing angle)
- $-0.6 < \cos(\theta_{vertex}) < 0.95$
- 3Dang($\vec{V}_{vertex}, \vec{p}_{ISR}$) > 0.5 rad

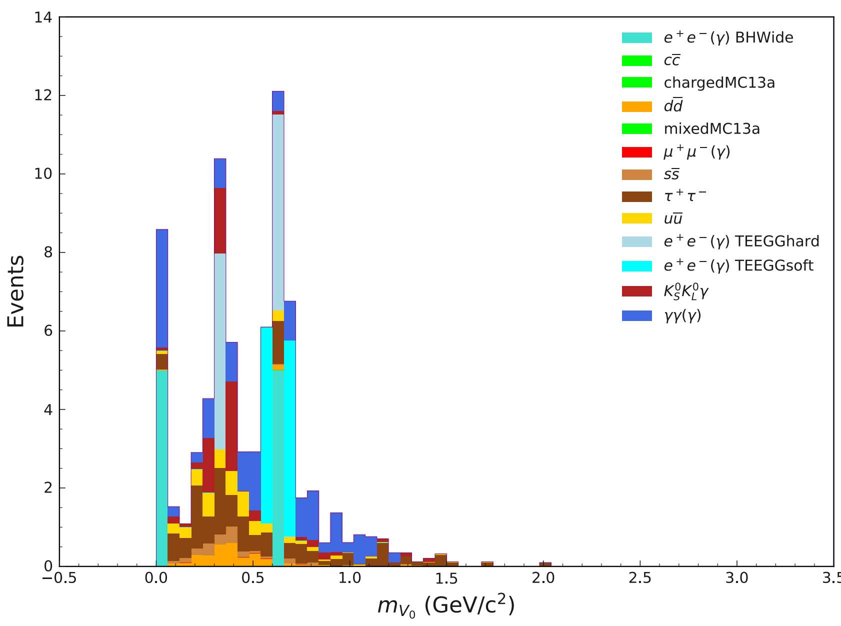
PC: S. Longo



PC: S. Longo

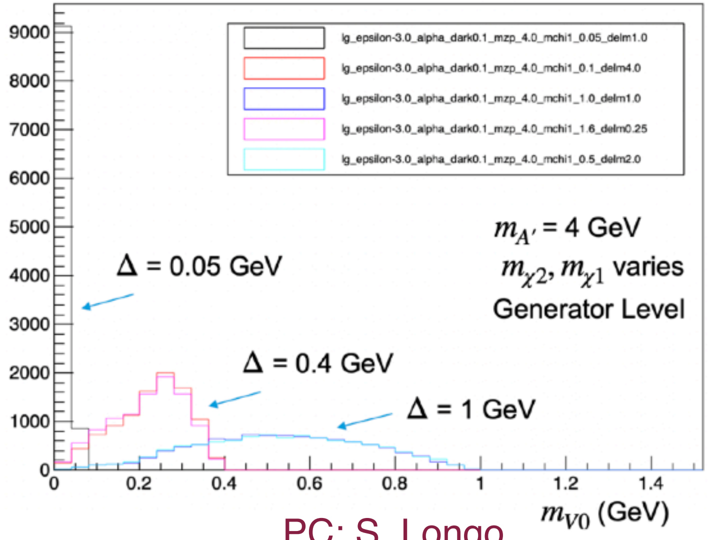




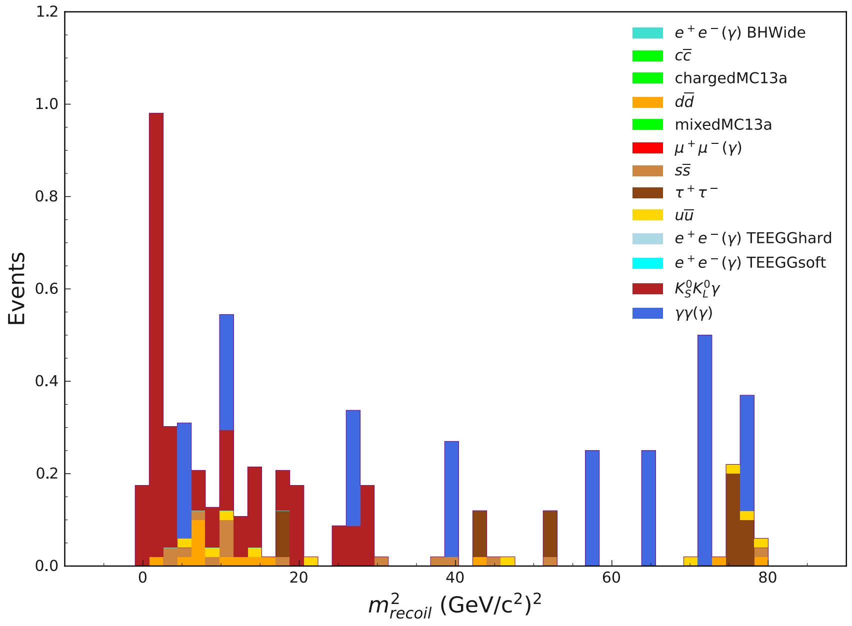


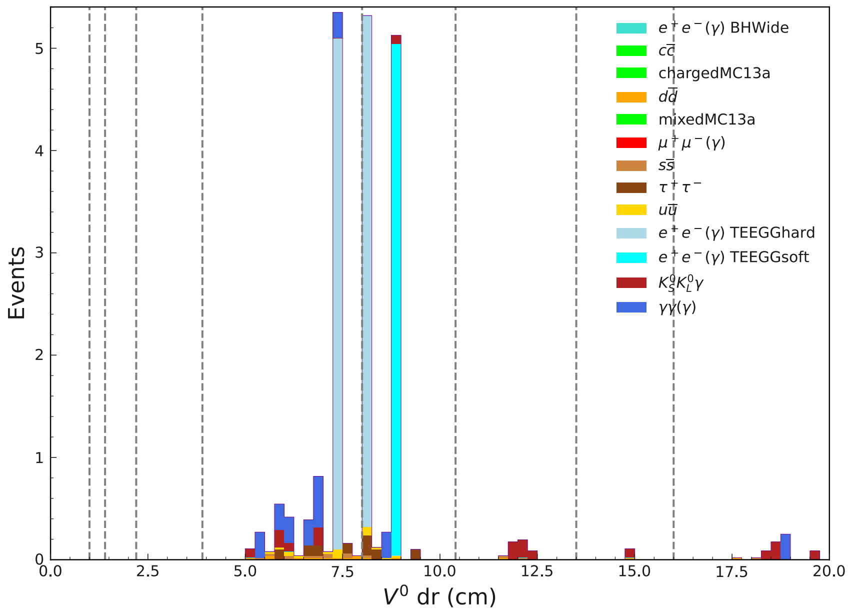
Background: Mitigation

- Further cuts:
  - For m_{V^0}, we can set a limit to range of models we want to investigate (<2GeV)
  - V^0 dr cuts (away from IP and VXD layers)



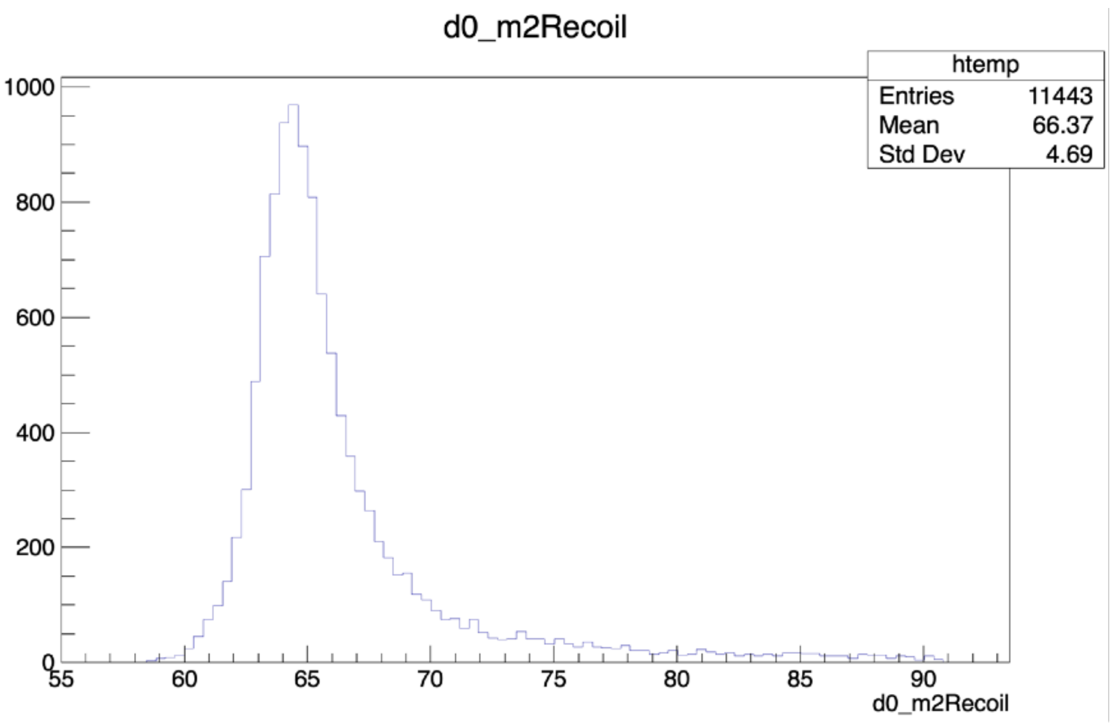
PC: S. Longo

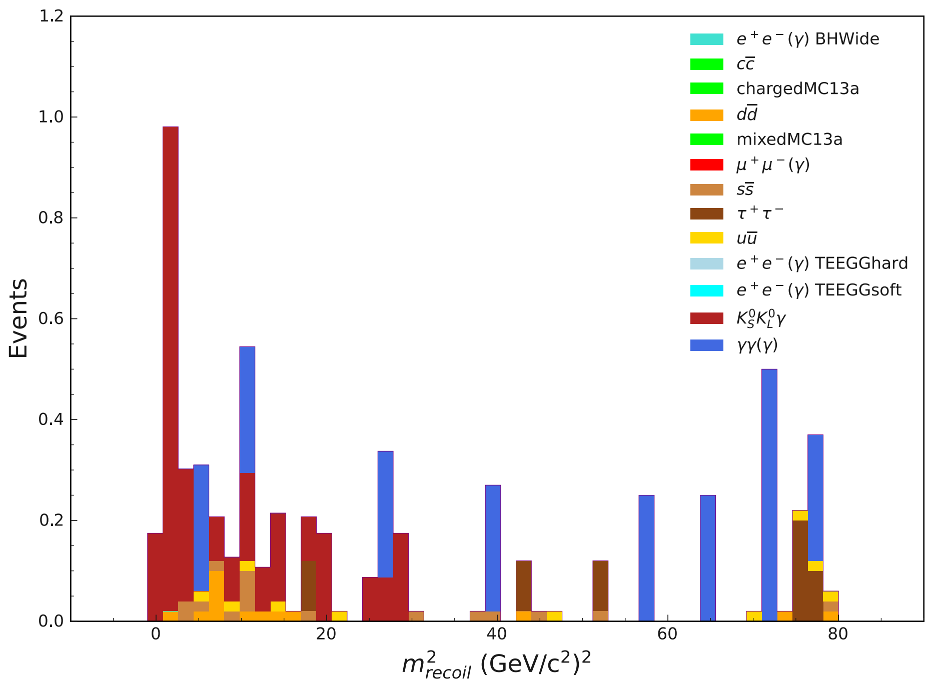




Putting the pieces together

- So we know what our signal looks like and quite a bit of effort has been put into cutting on backgrounds. Let's go digging





Signal Hunting

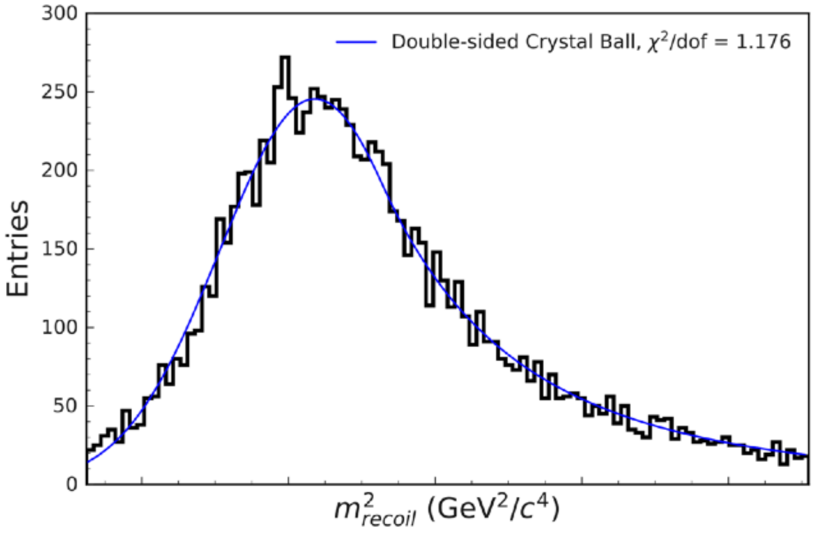
$$f(m; m_0, \sigma, \alpha_L, n_L, \alpha_R, n_R) = \begin{cases} A_L \cdot (B_L - \frac{m-m_0}{\sigma_L})^{-n_L}, & \text{for } \frac{m-m_0}{\sigma_L} < -\alpha_L \\ \exp\left(-\frac{1}{2} \cdot \left[\frac{m-m_0}{\sigma_L}\right]^2\right), & \text{for } \frac{m-m_0}{\sigma_L} \leq 0 \\ \exp\left(-\frac{1}{2} \cdot \left[\frac{m-m_0}{\sigma_R}\right]^2\right), & \text{for } \frac{m-m_0}{\sigma_R} \leq \alpha_R \\ A_R \cdot (B_R + \frac{m-m_0}{\sigma_R})^{-n_R}, & \text{otherwise,} \end{cases}$$

$$A_i = \left(\frac{n_i}{|\alpha_i|}\right)^{n_i} \cdot \exp\left(-\frac{|\alpha_i|^2}{2}\right)$$

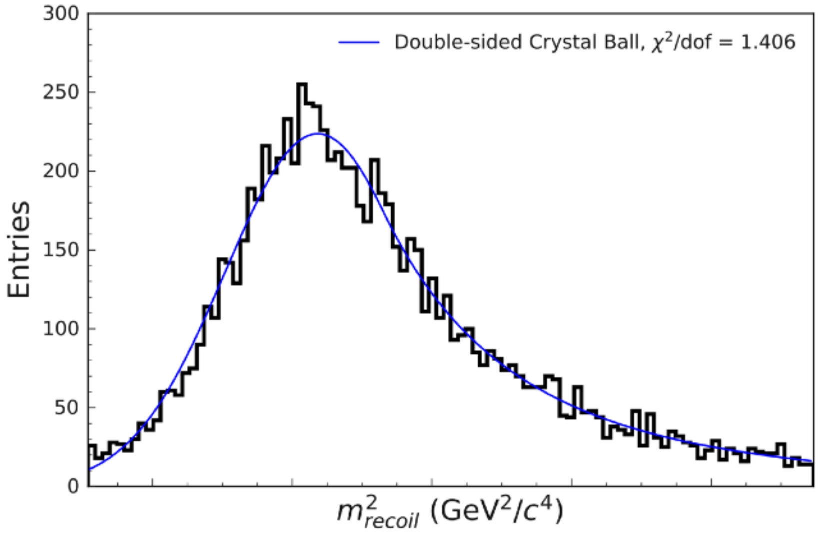
$$B_i = \frac{n_i}{|\alpha_i|} - |\alpha_i|$$

- Using DCSB to fit signal shape
- While other parameters might affect yield, the main shape parameters should $m_{A'}$

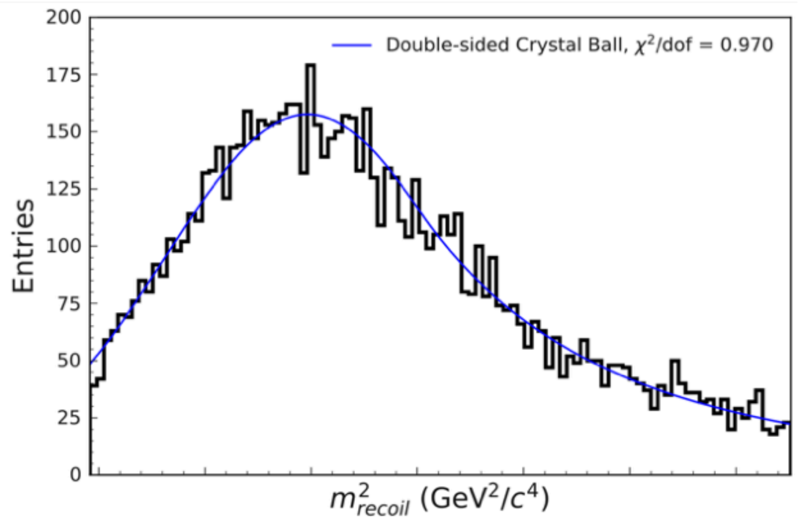
$m_{A'} = 8.0\text{GeV}, \Delta m = 1.28\text{GeV}, m_{\chi_1} = 3.2\text{GeV}, \epsilon = 10^{-4}, \alpha_D = 0.1$



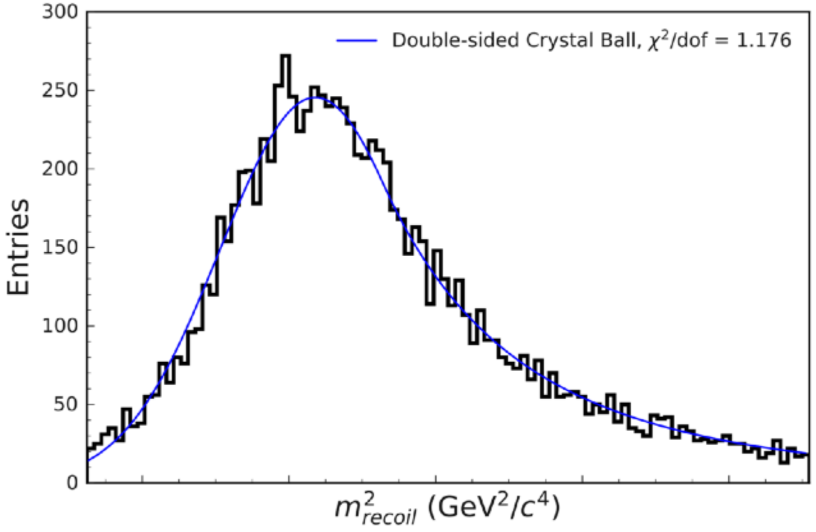
$m_{A'} = 8.0\text{GeV}, \Delta m = 1.28\text{GeV}, m_{\chi_1} = 3.2\text{GeV}, \epsilon = 10^{-3}, \alpha_D = 0.1$



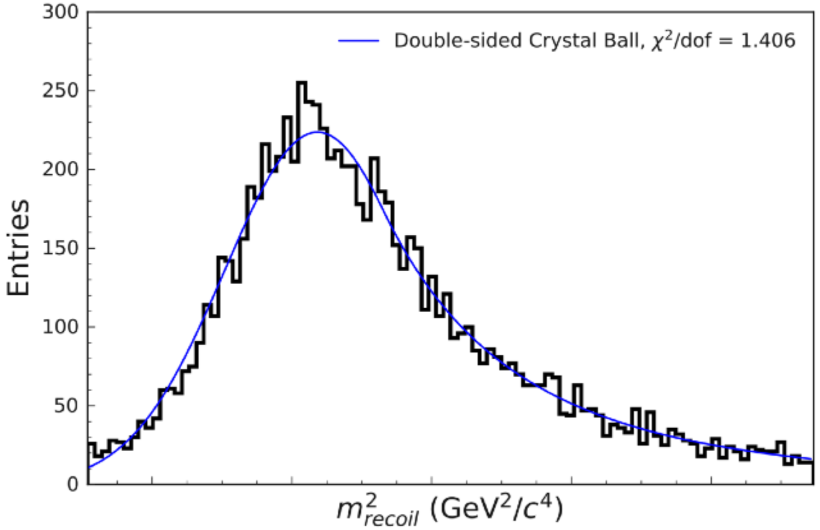
$m_{A'} = 8.75\text{GeV}, \Delta m = 1.4\text{GeV}, m_{\chi_1} = 3.5\text{GeV}, \epsilon = 10^{-4}, \alpha_D = 0.1$

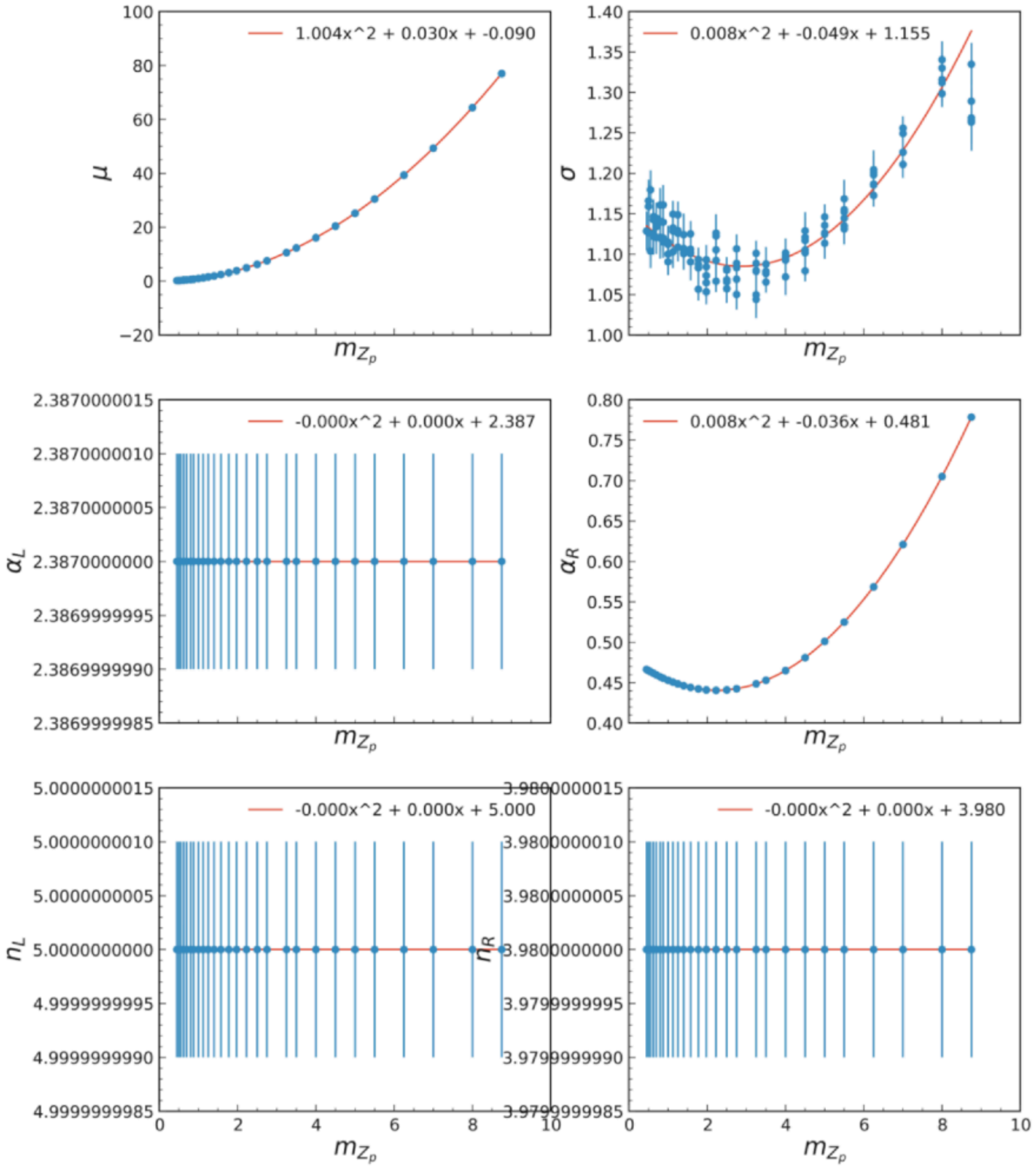


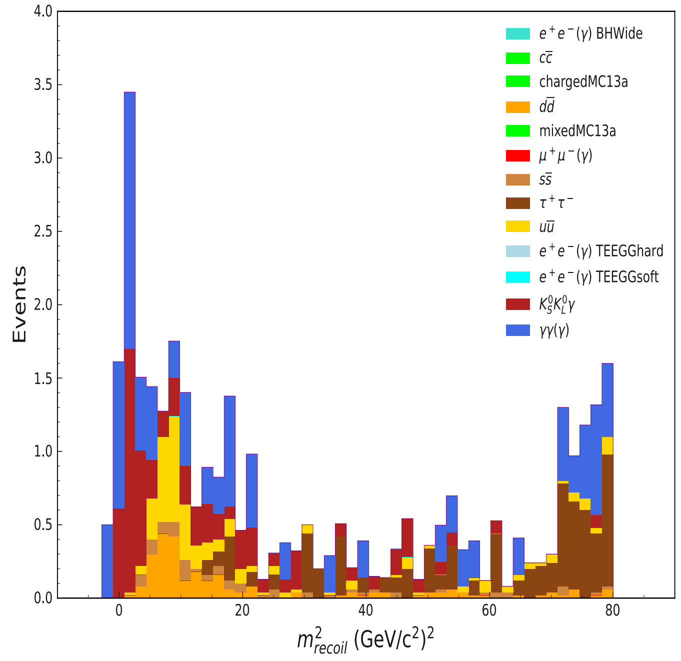
$m_{A'} = 8.0\text{GeV}, \Delta m = 1.28\text{GeV},$
$m_{\chi_1} = 3.2\text{GeV}, \epsilon = 10^{-4}, \alpha_D = 0.1$

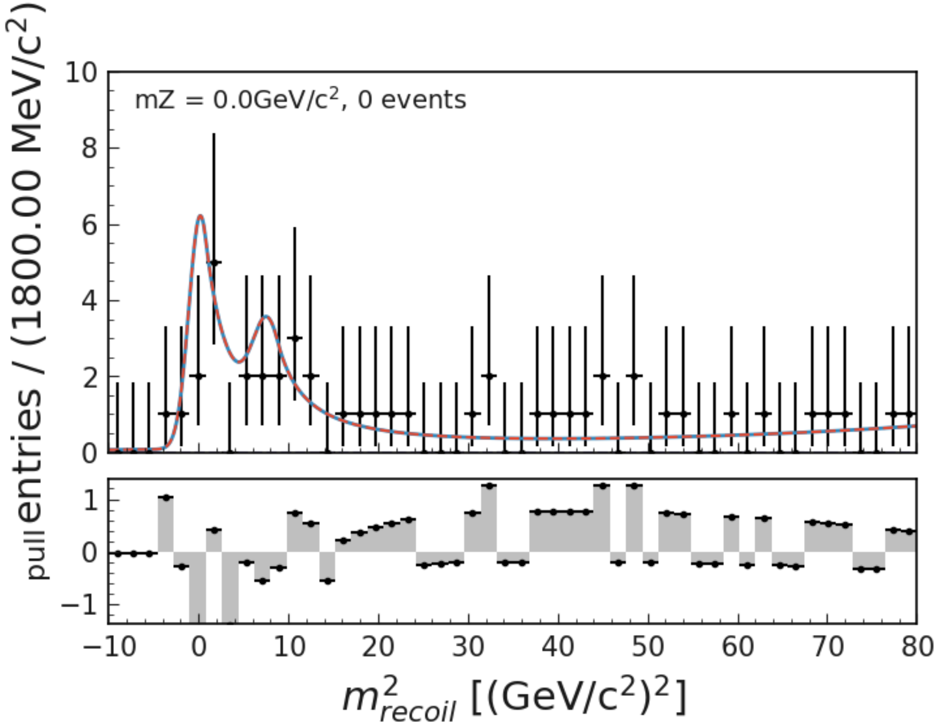


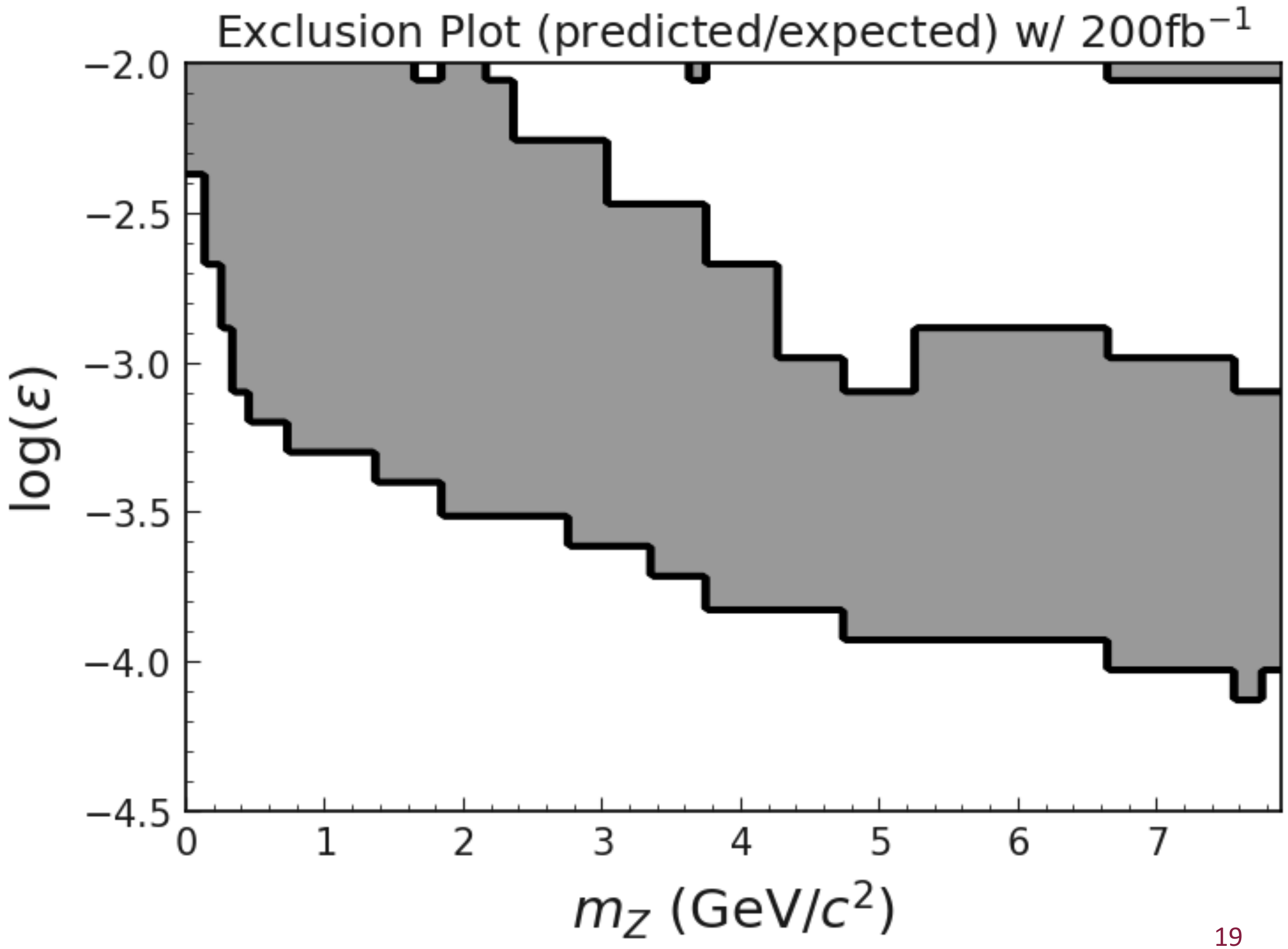
$m_{A'} = 8.0\text{GeV}, \Delta m = 1.28\text{GeV},$
$m_{\chi_1} = 3.2\text{GeV}, \epsilon = 10^{-3}, \alpha_D = 0.1$





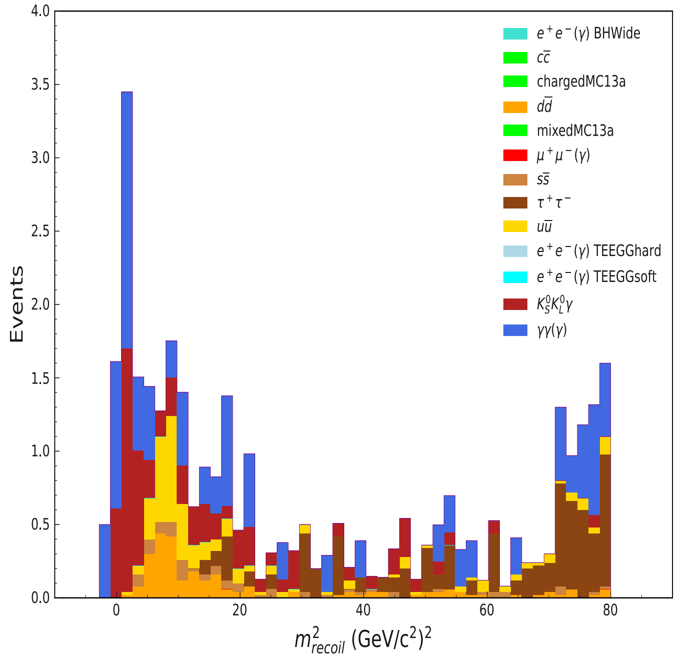

$e^+e^-(\gamma)$ BHWide
$c\bar{c}$
chargedMC13a
$d\bar{d}$
mixedMC13a
$\mu^+\mu^-(\gamma)$
$s\bar{s}$
$\tau^+\tau^-$
$u\bar{u}$
$e^+e^-(\gamma)$ TEEGGhard
$e^+e^-(\gamma)$ TEEGGsoft
$K_S^0K_L^0\gamma$
$\gamma\gamma(\gamma)$
Events
m^2_{recoil} (GeV/c^2)^2

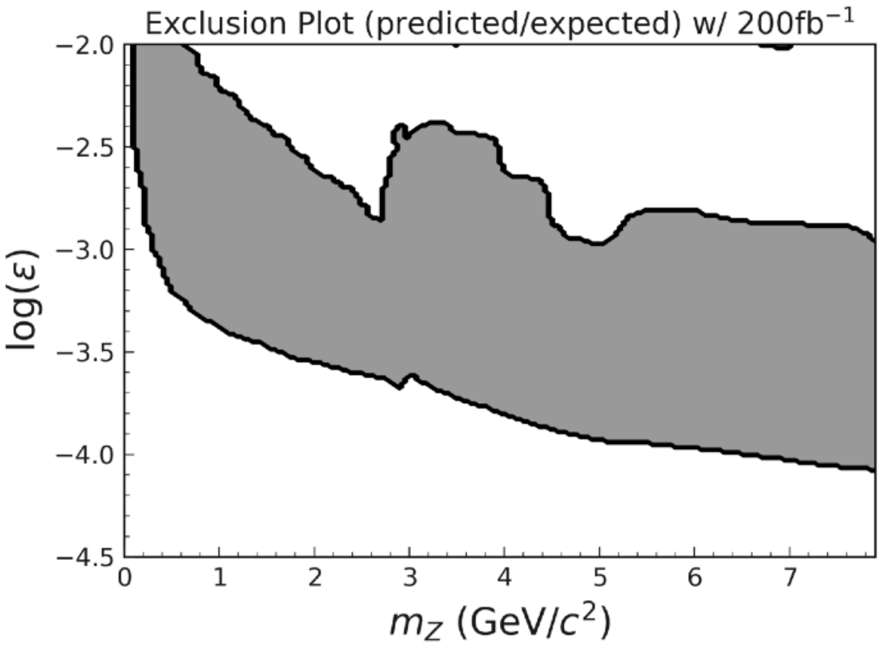

mZ = 0.0GeV/c^2, 0 events
entries / (1800.00 MeV/c^2)
pull
m^2_{recoil} [(GeV/c^2)^2]


Exclusion Plot (predicted/expected) w/ 200fb^{-1}
log(ε)
m_Z (GeV/c^2)

Where are we now?

- Run on MC15 and see what the background levels are like
  - Trying to work on skims rather than collections but potentially found a missing cut
  - Need to reproduce signal ntuples



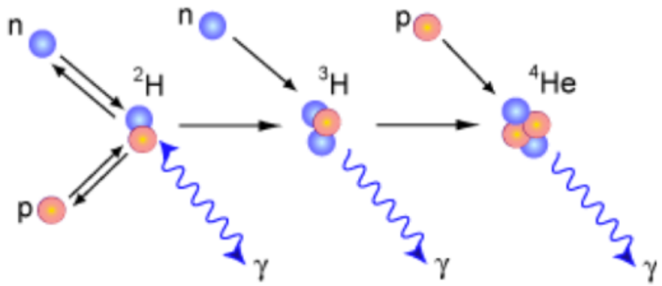


Much Thanks!

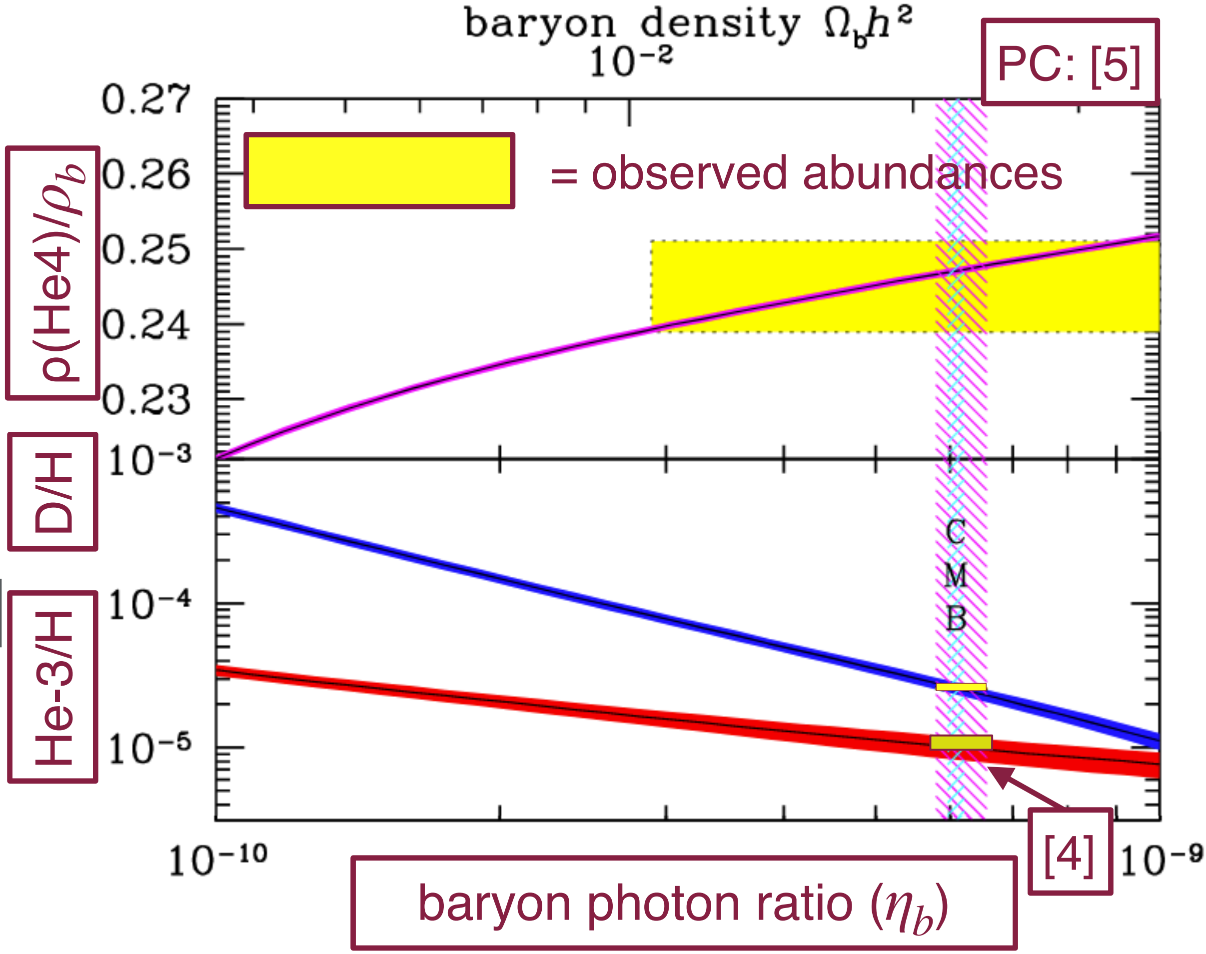
Backup

Evidence for Dark Matter

- From Astronomy/Cosmology [1]
  - Galaxy rotation curves
  - Bullet Cluster
  - CMB Anisotropies
  - Primordial Nucleosynthesis [2, 3, 4]



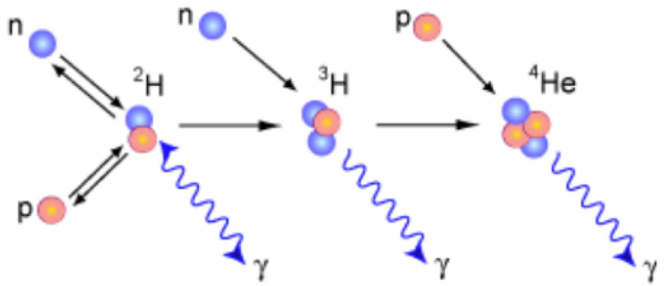
PC: [6]



[1]: D. Gruen. "Cosmology Overview." SSI 2020:The Almost Invisibles: Exploring the Weakly Coupled Universe. (2020) (Slide 25)
[2]: A. Dar et al. "Dark Matter and the Big Bang Nucleosynthesis." arxiv:9405010.
[3]: K. Jedamzik and M. Pospelov. "Big Bang nucleosynthesis and particle dark matter." arXiv:0906.2087
[4]: G. Steigman. "Primordial Nucleosynthesis: The Predicted and Observed Abundances and Their Consequences." arxiv:1008.4765.
[5]: B.D. Fields et al. "Big Bang Nucleosynthesis." arxiv:1412.1408. (updated 2017).
[6]: https://www.atnf.csiro.au/outreach/education/senior/cosmicengine/bigbang.html

Evidence for Dark Matter

- From Astronomy/Cosmology [1]
  - Galaxy rotation curves
  - Bullet Cluster
  - CMB Anisotropies
  - Primordial Nucleosynthesis [2, 3, 4]



PC: [6]

SBBN: Standard Big Bang Nucleosynthesis

SBBN prediction

Source: [5]

$$0.021 \leq \Omega_b h^2 \leq 0.024 \ (95\,\%\ CL)$$

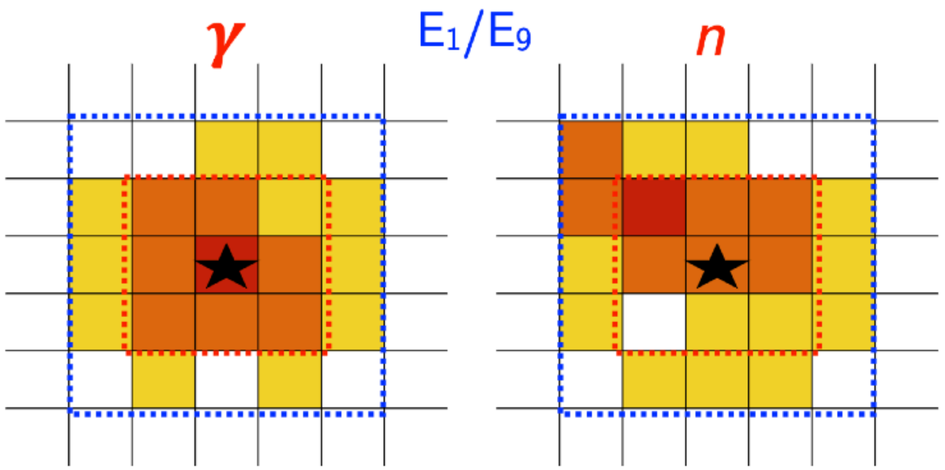
Planck CMB measurement

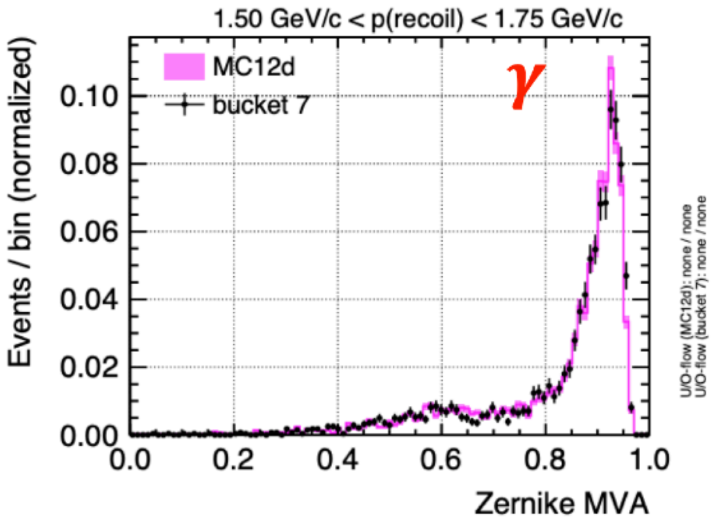
$$\Omega_b h^2 = 0.02237 \pm 0.00015$$

Source: [7]

[1]: D. Gruen. "Cosmology Overview." SSI 2020:The Almost Invisibles: Exploring the Weakly Coupled Universe. (2020) (Slide 25)
[2]: A. Dar et al. "Dark Matter and the Big Bang Nucleosynthesis." arxiv:9405010.
[3]: K. Jedamzik and M. Pospelov. "Big Bang nucleosynthesis and particle dark matter." arXiv:0906.2087
[4]: G. Steigman. "Primordial Nucleosynthesis: The Predicted and Observed Abundances and Their Consequences." arxiv:1008.4765.
[5]: B.D. Fields et al. "Big Bang Nucleosynthesis." arxiv:1412.1408. (updated 2017).
[6]: https://www.atnf.csiro.au/outreach/education/senior/cosmicengine/bigbang.html
[7]: Planck Collaboration. arxiv:1807.06209

Several variables probe in different ways how the energy is distributed between the crystals within a cluster.





"Shower shape variables" measure how the energy is distributed in the clusters.

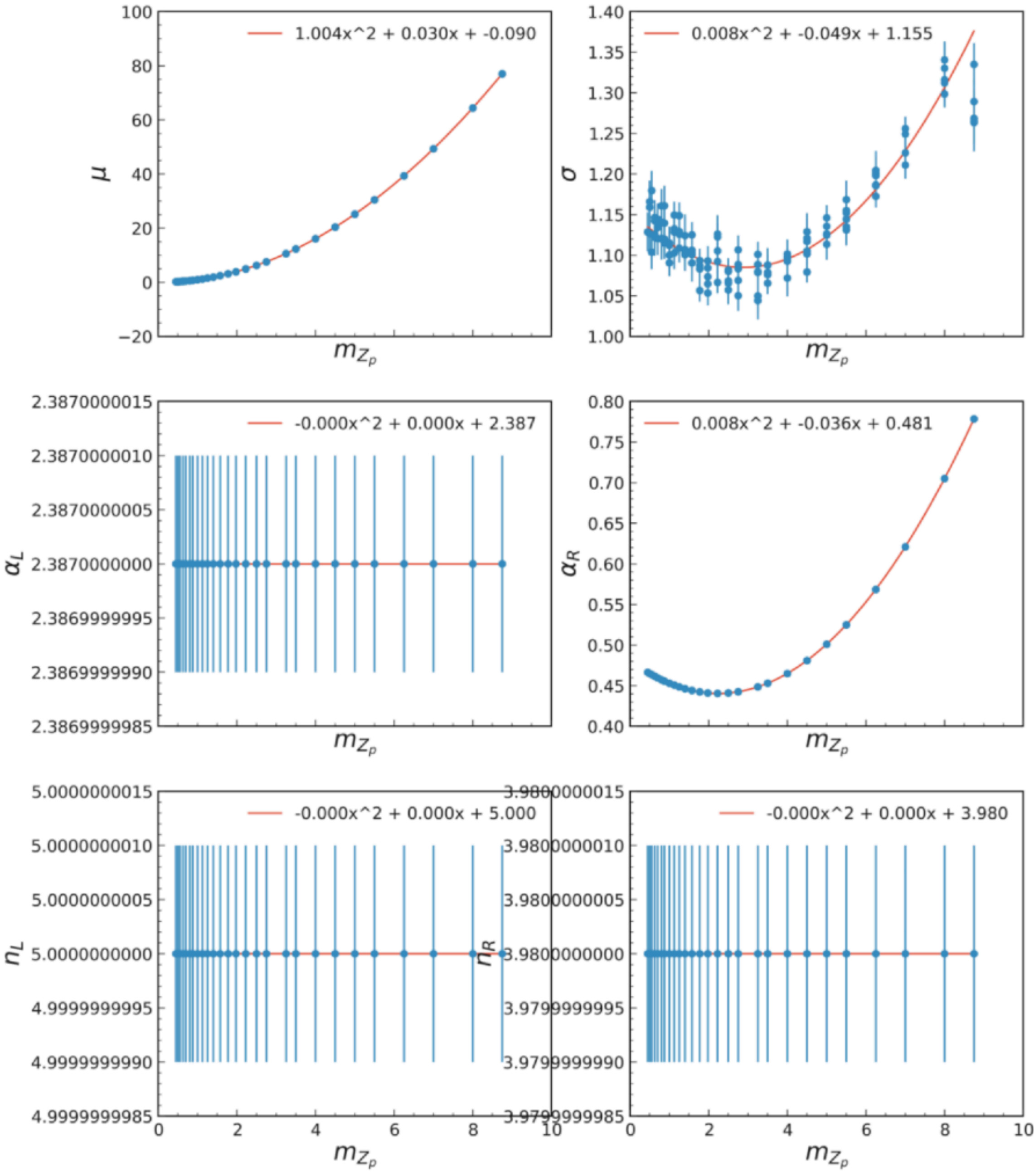
- Photons have most of their energy in the central crystal, E_1
- Ratios of energies probes radial energy dependence on energy ($\sim$ shower width).
  e.g. E_1/E_9, E_9/E_{21} etc.
- Newer variables like Zernike MVA measure how the energy is distributed as a function of an angular rotation around the central crystal.
- "Lateral energy distribution" measure of how the energy is distributed both radially and angularly.

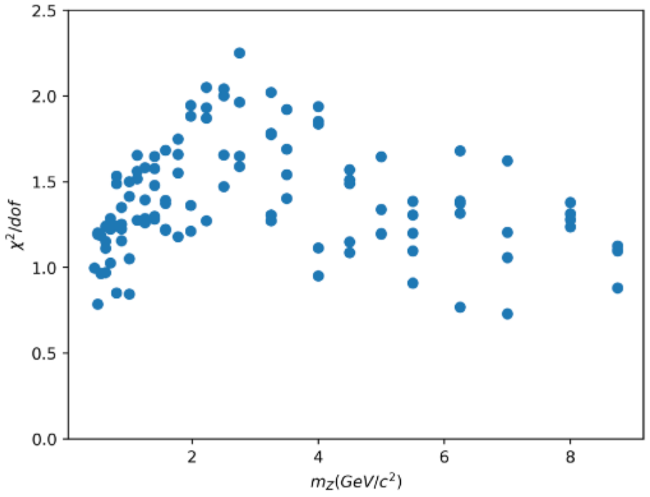
SOURCE: https://indico.belle2.org/event/3812/contributions/23440/attachments/12165/18610/EwanHill_2021_07_July_16__BelleIIsummerWorkshop__ECLpid_v03.pdf
Details on Zernike MVA: https://docs.belle2.org/record/454/files/BELLE2-NOTE-TE-2017-001.pdf

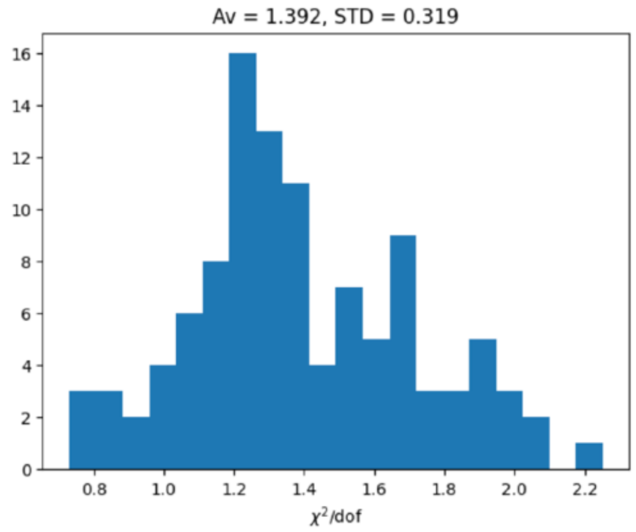
Interpolator Detail

‘Recent’ attempt

- In trying to get a handle for this interpolator, trying to get a measure of decency by looking ash the χ^2/dof after pinning down 3 of the DCS parameters

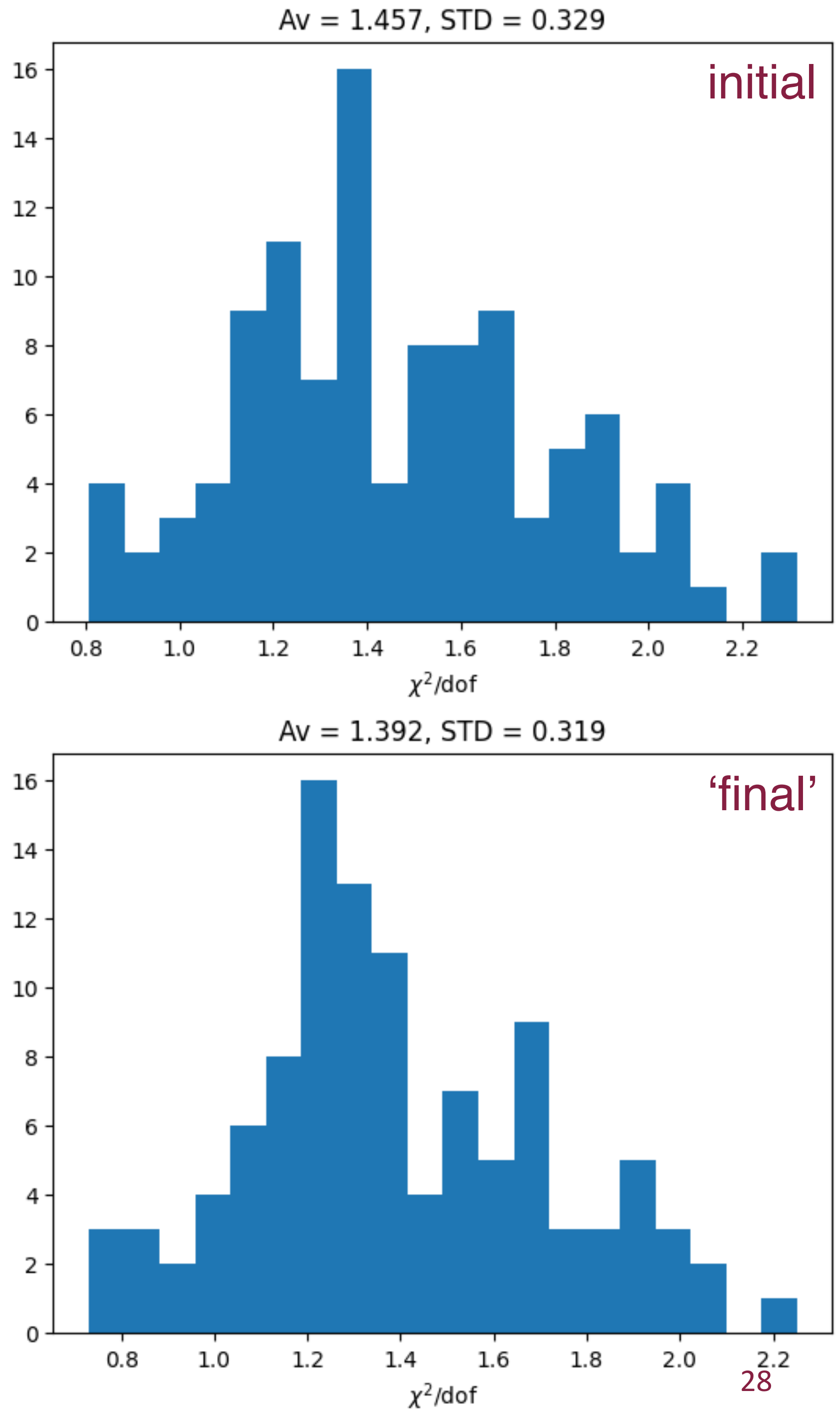






Summary

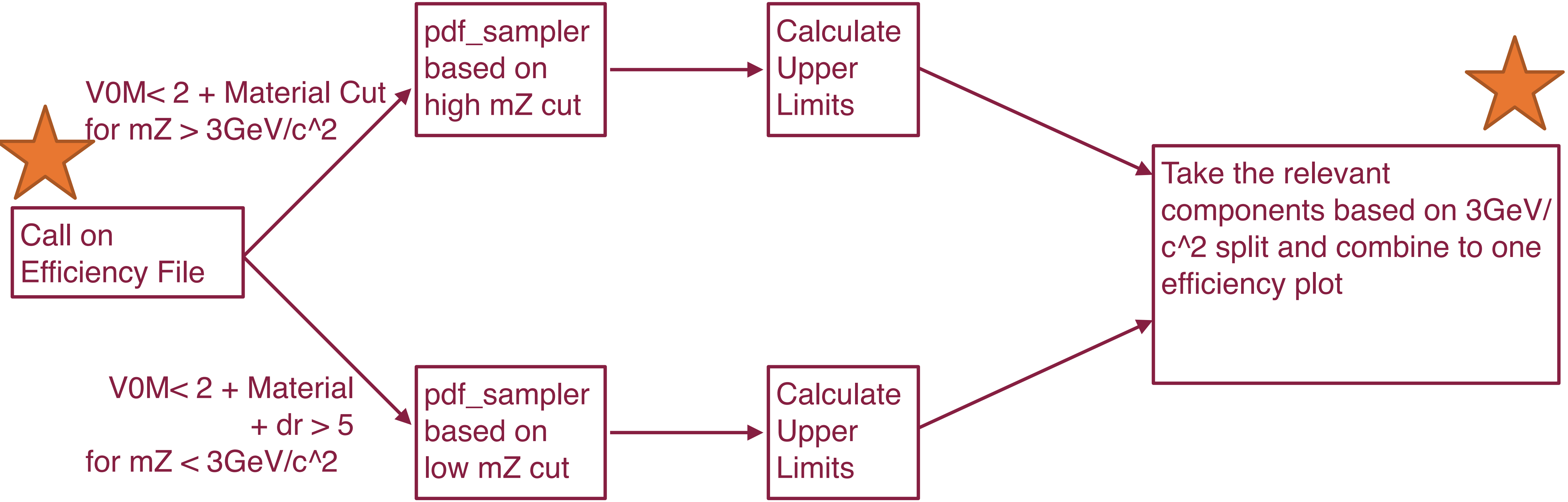
- Initial: Pinning one parameter
- Final (shown few slides ago)
- was able to get some minor improvement so maybe alright to continue for now until systematic studies

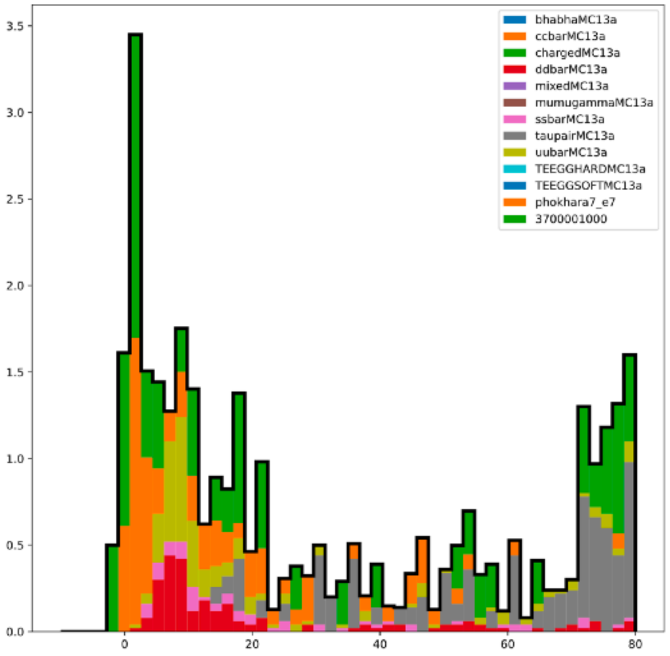


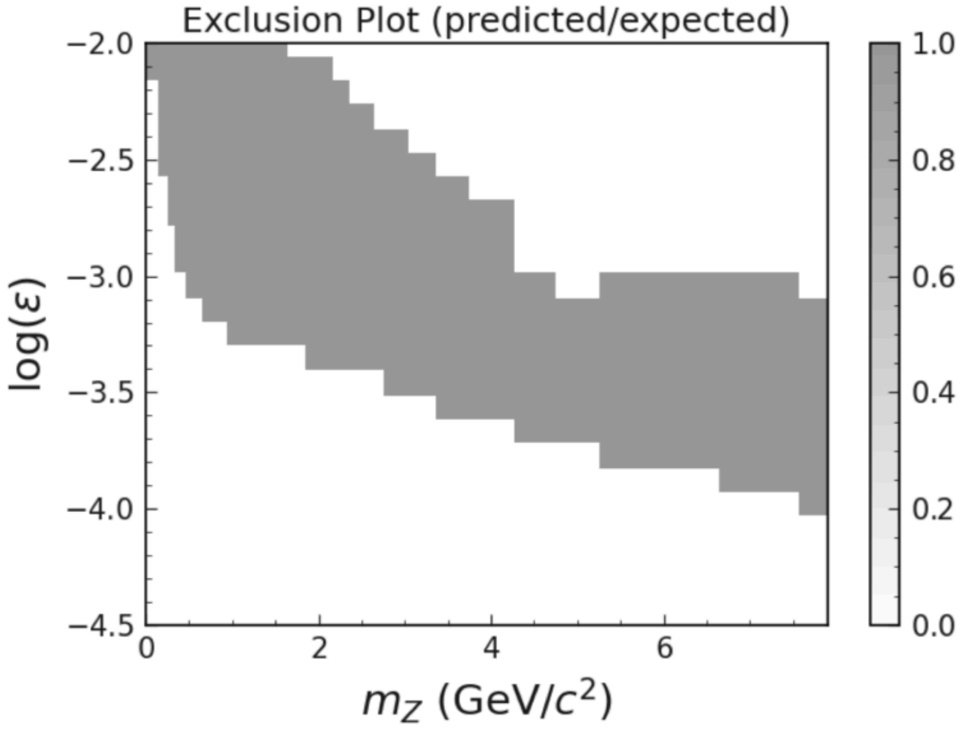
Exclusion

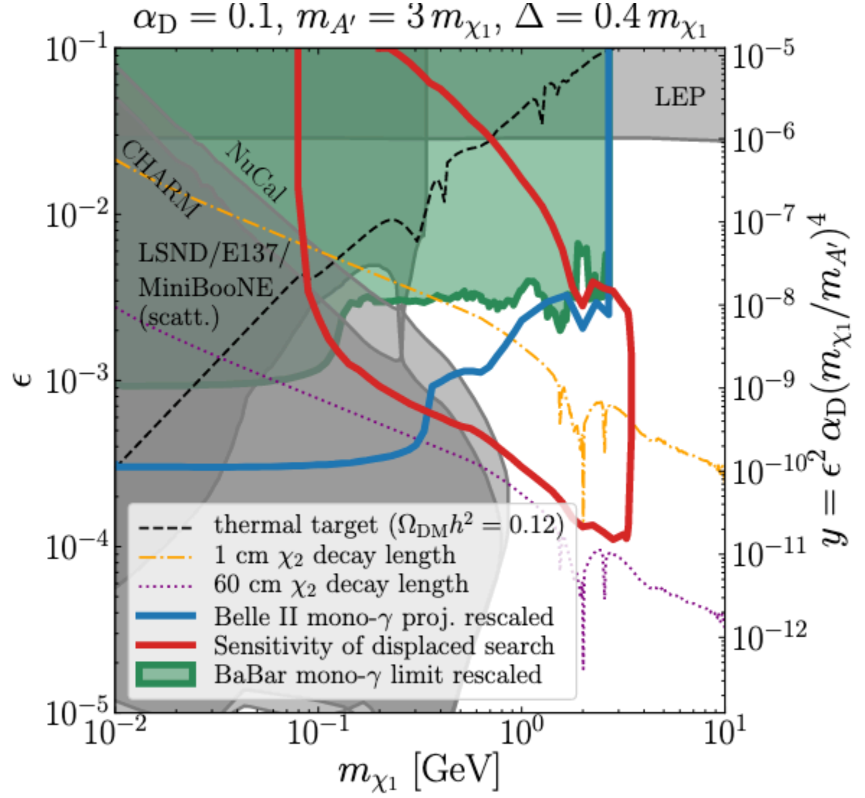
Splitting Cuts:Pipeline

= needed change to include split of mZ

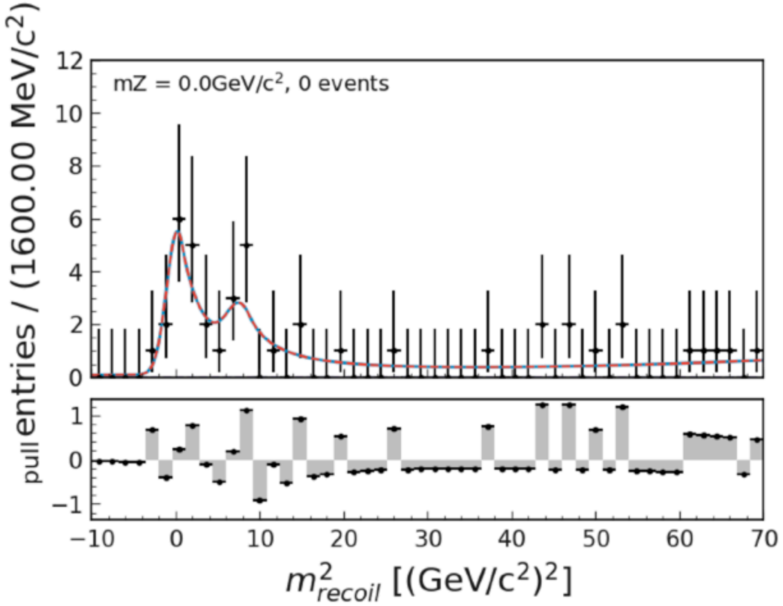


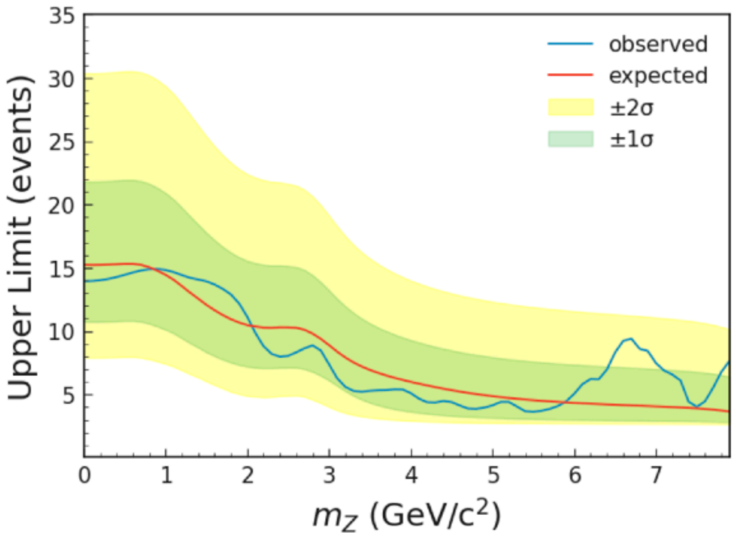




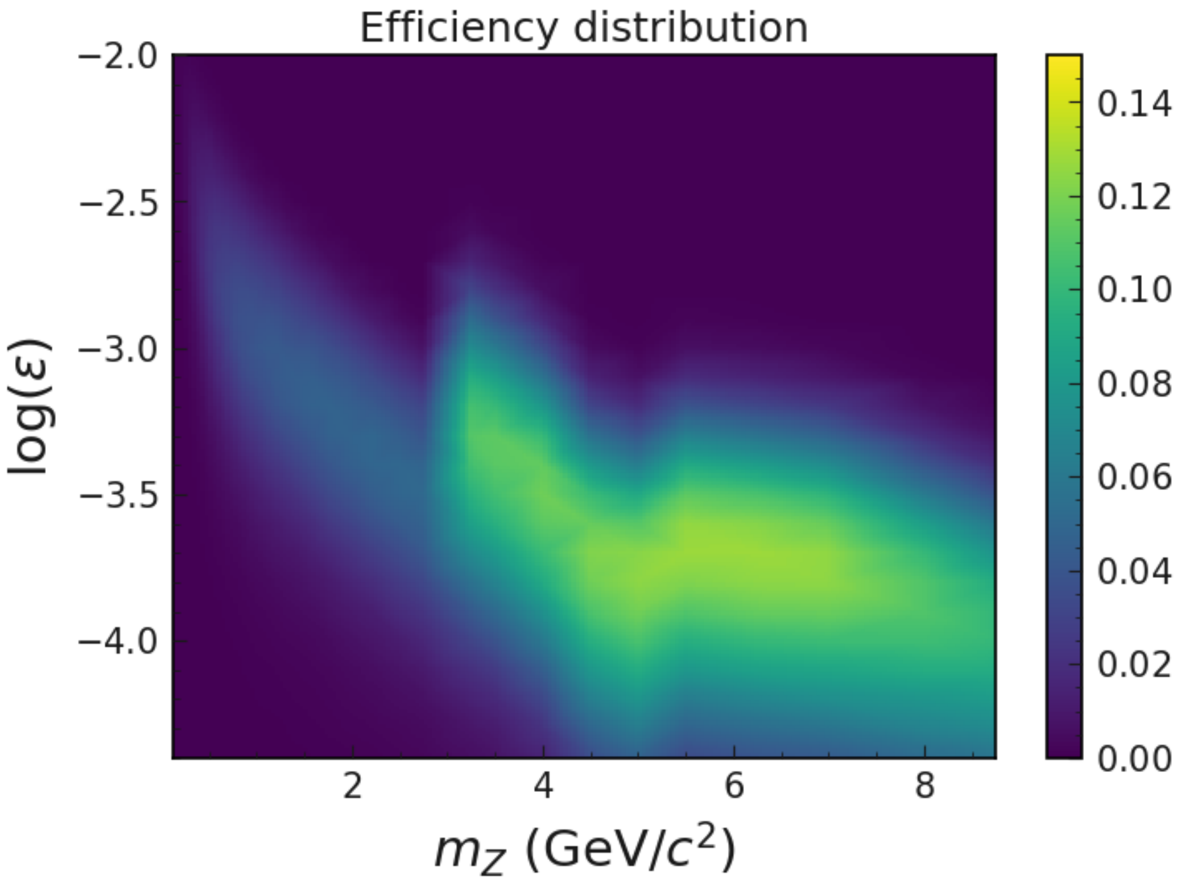


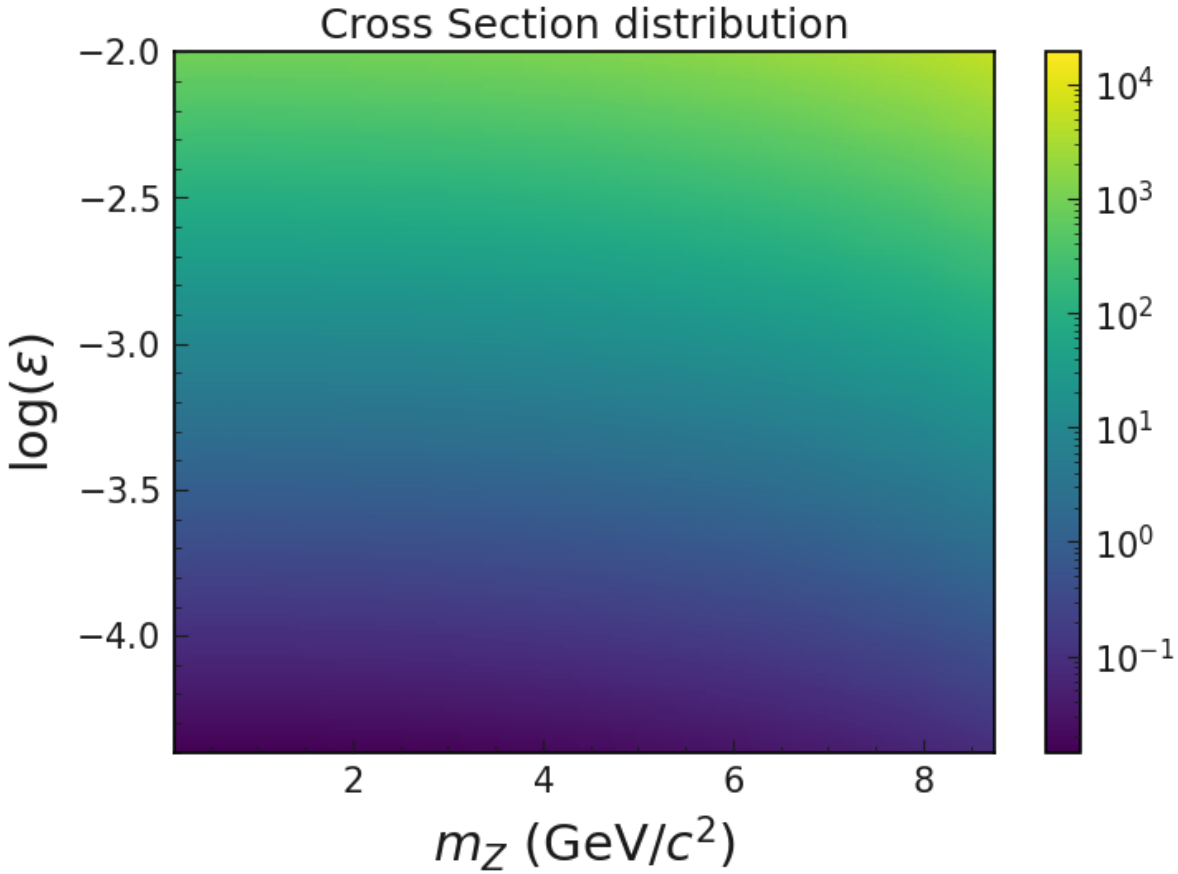
Source: https://arxiv.org/pdf/1911.03176.pdf





$$\sigma^{observed} = U/\eta L$$


Efficiency distribution
−2.0
−2.5
−3.0
−3.5
−4.0
log(ε)
2
4
6
8
m_Z (GeV/c^2)
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00


Cross Section distribution
−2.0
−2.5
−3.0
−3.5
−4.0
log(ε)
2
4
6
8
m_Z (GeV/c^2)
10^4
10^3
10^2
10^1
10^0
10^{-1}