Rencontres de Moriond Electroweak 2023
(La Thuile)

Recent results on DM, ALPs, and Heavy Neutral Leptons searches by *BABAR*

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on behalf of the *BABAR* Collaboration

March 2023

New Physics Searches at *BABAR*

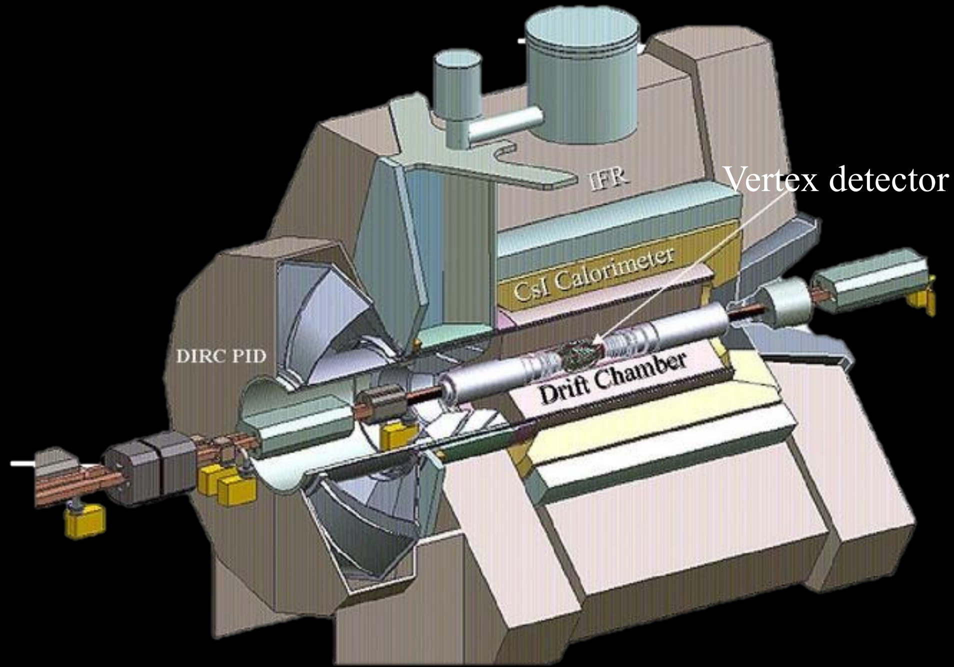
I will present the following new results from *BABAR*:

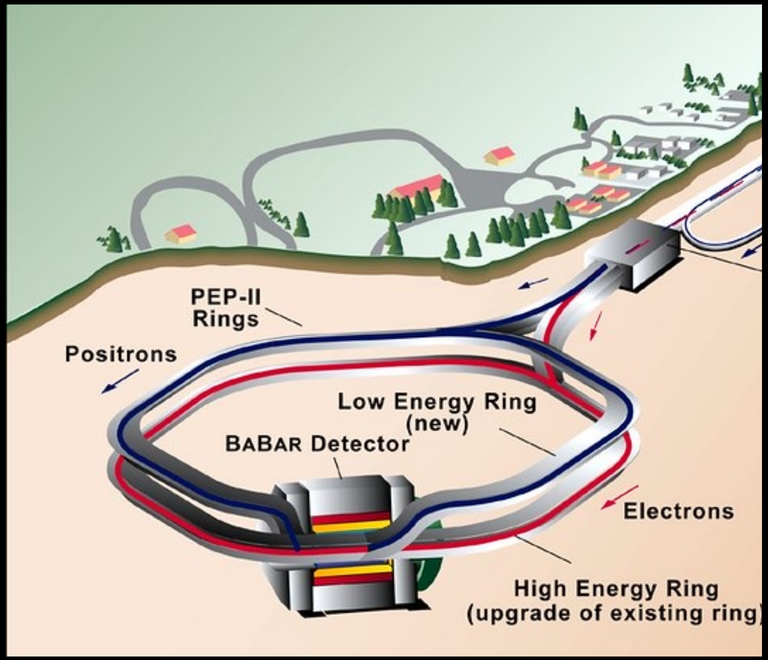
- **Search for Heavy Neutral Leptons from Taus:**
  - arXiv:2207.09575v1 (Accepted Phys. Rev. D, Sept. 2022)
- **Two Searches for Dark Matter & Baryogenesis in B Decays:**
  - arXiv:2302.00208v1 (Submitted to Phys. Rev. D Feb. 2023)
- **Search for an Axionlike Particle in B Meson Decays:**
  - Phys Rev Lett.128.131802 (Published April 2022)

Outline

BABAR

- For overview of experiment: **Nucl. Instrum. Meth. A 729, 615 (2013)**.
- Asymmetric e^+e^- collider with $\sqrt{s}$ = 10.58 GeV/c^2 i.e. Υ(4S) resonance: 9 GeV electrons collide with 3 GeV positrons.
- **Total luminosity: 432 fb^{-1} (4.7 x 10^8 $\overline{B}B$) on peak.**





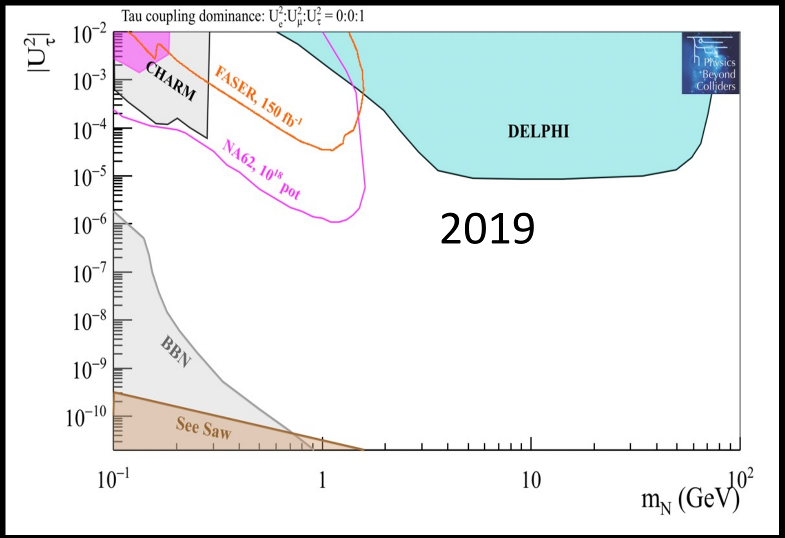
Detectors:

- **Reconstruct tracks:** Silicon Vertex Tracker (SVT) + 40-layer Drift Chamber (DCH), in 1.5-T solenoid.
  - Momentum resolution = 0.47% at 1 GeV/c
- **Measure energy:** ElectroMagnetic Calorimeter (EMC)
  - Energy resolution = 3% at 1 GeV.
- **PID:**
  - Identify charged pions, kaons and electrons using Ring Imaging Cherenkov detector (DIRC) + ionization loss measurements in the SVT and DCH.
  - Instrumented flux return of solenoid used to identify muons.

A Search for Heavy Neutral Leptons from Taus:

arXiv:2207.09575v1 (accepted to Phys Rev D Sept 2022)

Motivations



J. Beacham et al., Journal of Physics G: Nuc. and Part.1075 Phys. 47, 010501 (2019)

- Heavy Neutral Leptons (HNLs) are additional neutrino states. Could be produced in experiments only via mixing with active neutrinos.

- HNLs are proposed by several beyond Standard Model (BSM) theories to explain three major observational phenomena:
  - Neutrino oscillations and origins of their mass via seesaw models etc. (Phys. Rev. D 23,165);
  - Baryonic asymmetry of Universe (Phys. Rev. Lett. 81, 1359);
  - Dark matter candidate (Phys. Lett. B 631, 151–156).

$\sigma(e^+e^- \to \tau^+\tau^-) = 0.919 \pm 0.003$ **nb**

Integrated luminosity in runs used **= 432 fb $^{-1}$**

→ $N_{\tau\tau} \sim 4 \times 10^8$ events

BaBar has high stats. needed to improve limits on

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_s \\ \vdots \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & U_{e4} & \cdots \\ U_{\mu1} & U_{\mu2} & U_{\mu3} & U_{\mu4} & \cdots \\ U_{\tau1} & U_{\tau2} & U_{\tau3} & U_{\tau4} & \cdots \\ U_{s1} & U_{s2} & U_{s3} & U_{s4} & \cdots \\ \vdots & \vdots & \vdots & & \ddots \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \vdots \end{pmatrix}.$$

- Experiments generally quote results in parameter space of elements $|U_{ln}|^2$ .v. HNL mass hypothesis.
- Tau sector historically less explored…

The BABAR Search

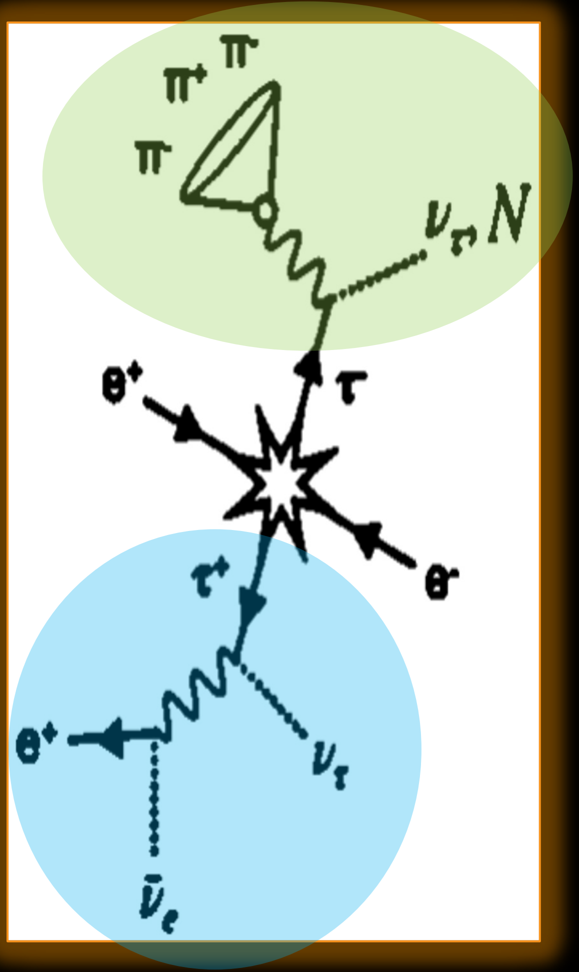
$\sigma(e^+e^- \rightarrow \tau^+\tau^-) = \mathbf{0.919 \pm 0.003}$ **nb**
Integrated luminosity in runs used **= 424 fb** $^{-1}$
$\rightarrow$ **$N_{\tau\tau}$ = 4.6 × 10^8 events**

arXiv:2207.09575 (2022)

- ***BABAR*** 2022 analysis used the kinematics of hadronic tau decays based on ALEPH technique (Eur. Phys. J.1137C 2, 395).
- Looks only at kinematics, no assumptions on underlying model, except that there must be some small mixing with tau sector.:
  - "signal side" : three pronged pionic tau decay ($\tau^- \rightarrow \pi^-\pi^-\pi^+\upsilon_\tau$) as it allows access to region $100 < m_4 < 1360$ MeV/c² where current limits are loose.

  - "tag side" : Second tau decay must be leptonic, due to cleaner environment.

Branching Fractions:
1-prong (electron or muon) ~ 34 %
3-prong (3 pion) ~ 9%



Method

arXiv:2207.09575 (2022)

Templates for each mass in the form of 2D plots of E_h.v. m_h. Boundary of curved region in this plot due to massive neutrino if present.

SM Tau Decay | **BSM Tau Decay**

$$\frac{d\Gamma_{\rm tot}(\tau^- \to \nu h^-)}{dm_h dE_h} = (1-|U_{\tau 4}|^2)\left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{m_\nu=0} + |U_{\tau 4}|^2 \left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{m_\nu=m_4}.$$

- Model 3-pronged decay as 2-body with outgoing HNL and hadronic system (h).
- Define E_h as reconstructed energy and m_h as the invariant mass of the visible, hadronic products.
- $E_\tau = \frac{E_{cms}}{2}$ in the limit of no ISR. The value of E_h and m_h can exist, in principle, in the ranges:

$$3m_{\pi^\pm} < m_h < m_\tau - m_4$$

and

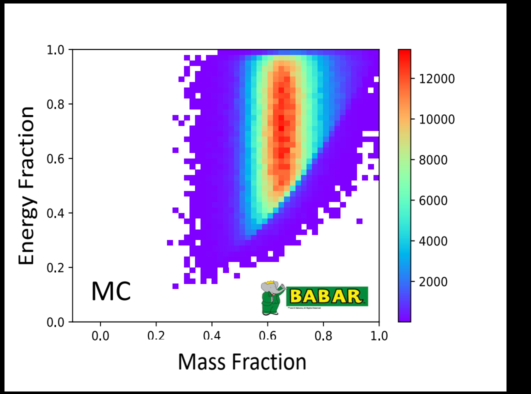
$$E_\tau - \sqrt{m_4^2 + q_+^2} < E_h < E_\tau - \sqrt{m_4^2 + q_-^2},$$

where

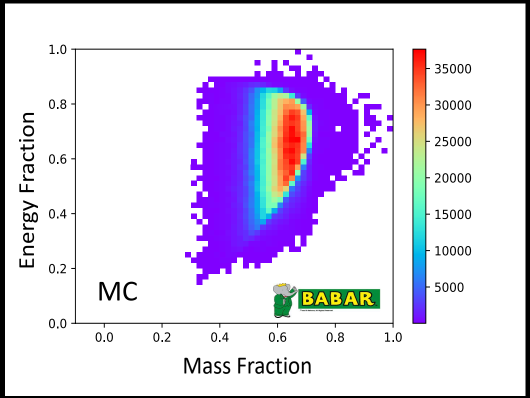
$$q_\pm = \frac{m_\tau}{2}\left(\frac{m_h^2 - m_\tau^2 - m_4^2}{m_\tau^2}\right)\sqrt{\frac{E_\tau^2}{m_\tau^2} - 1} \pm \frac{E_\tau}{2}\sqrt{\left(1 - \frac{(m_h+m_4)^2}{m_\tau^2}\right)\left(1 - \frac{(m_h-m_4)^2}{m_\tau^2}\right)};$$

Signal samples made in modified TAUOLA, and passed through G4 + BABAR reco. alg.

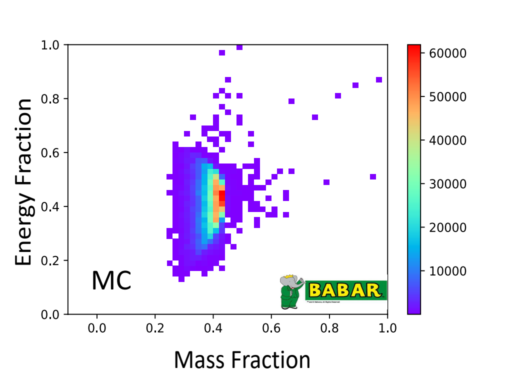
$m_4 = 100\ MeV/c^2$



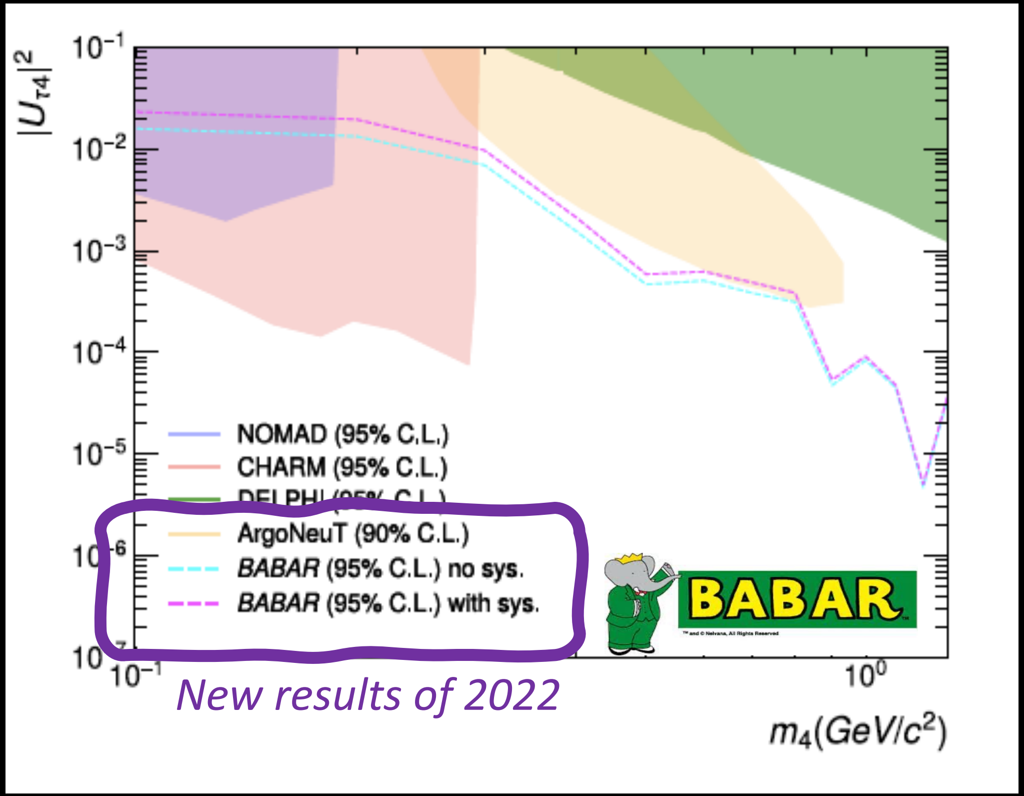
$m_4 = 500\ MeV/c^2$



$m_4 = 1000\ MeV/c^2$



Result



arXiv:2207.09575 (2022)

- Binned profile likelihood approach used to find 95% C.L. on $|U_{\tau 4}|^2$.
- Considers both lepton tags and + and – signal tau channels.
- Nuisance parameters include:
  - Luminosity (0.44%),
  - Cross-section (0.31%),
  - Branching Fractions (0.2-0.5%),
  - PID (1-2%).
- Background yields taken from MC.
- ***Largest systematics come from MC modelling of hadronic tau decay.***

- Presents new upper limits on $|U_{\tau 4}|^2$ at 95 % *C.L.* between 100 MeV/c^2 – 1300 MeV/c^2 :
  - Competitive with upcoming projections.
  - Novel technique used.
  - Published in Phys Rev. D.

Search for Dark Matter & Baryogenesis:

arXiv:2302.00208v1 (more to follow)

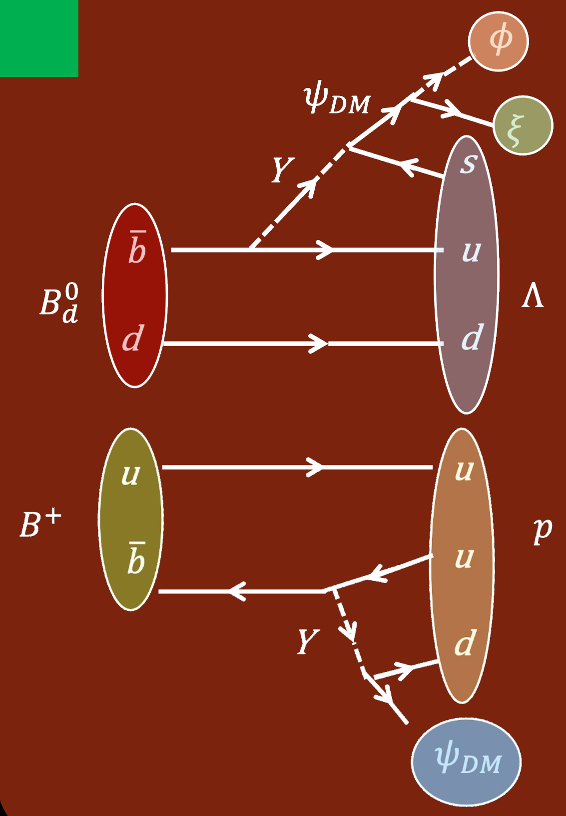
New Physics from B mesons

arXiv:2302.00208v1 (2023) + NEW RESULT FOR MORIOND EW 23

Mechanism proposed to explain dark matter (DM) abundance and Baryon Asymmetry of the Universe (BAU):

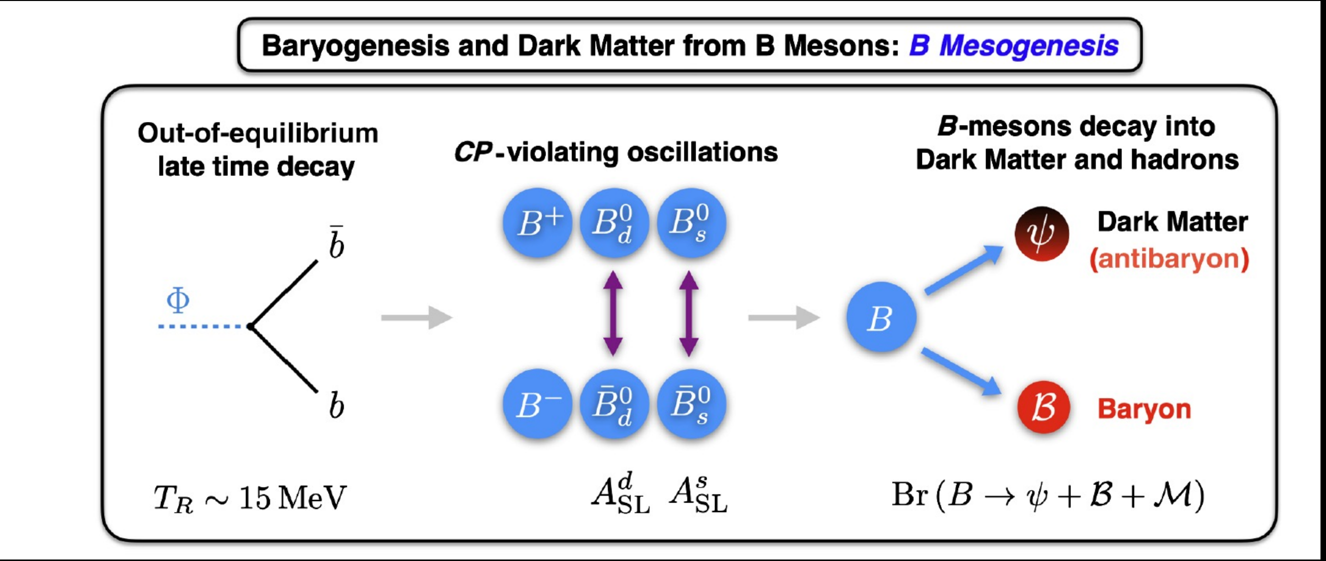
- DM: Light, unstable dark-sector fermion (ψ_D) and a TeV-scale color-triplet bosonic mediator (Y);
- BAU: CP violation from $B^0 - \bar{B}^0$ oscillations generates a matter-antimatter asymmetry. B^0 decays slightly dominate over $\bar{B}^0$ decays into anti-baryons, same for DM-anti-DM.
- Visible and dark sectors have equal but opposite matter anti-matter asymmetries, but total baryon number is conserved.

Example channels:



Φ = heavy scalar field;
ψ_D = dark fermion;
Y = TeV scale mediator;
ξ = Majorana Fermion;
ϕ = scalar baryon.

G. Elor, M. Escudero and A. E. Nelson, Phys. Rev. D 99, 035031 (2019).
G. Alonso-Alvarez, G. Elorand, and M. Escudero, Phys. Rev. D 104, 035028 (2021).



Overview

- Need to explore channels which have access to all operators $O_{i,j} = (\psi_D\ b)\ (ij)$ $(i = u, c\ and\ \ j = d, s)$.
- Flavor constraints on Y imply that only one of these operators can be active in the early Universe

→ one dominates, not a combination of operators.
- *Phys. Rev. D 104, 035028 (2021):*
  - Previous limits have been provided from recast of LEP data $BF(B \rightarrow\ \psi_D\ \ + \ p)\ <\ 10^{-4}$ (95 % C.L)
  - Searches for TeV-scale color-triplet scalars at the LHC require 0.94 < $m_{\psi D}$ < 3.5 GeV/c^2.
- ΔM corresponds to the kinematic upper bound on the mass of the dark particle.

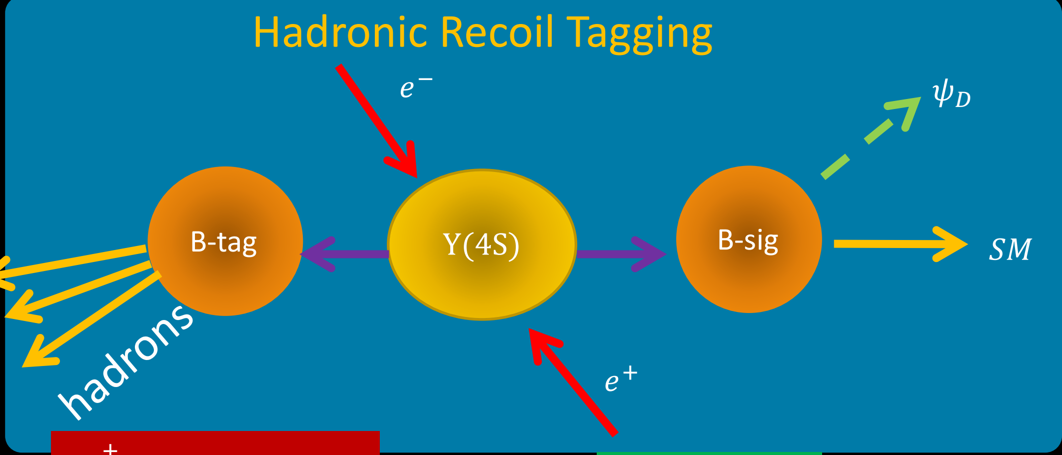
Initial State	Final State	Operators	ΔM (MeV/c^2)
B^0	$\psi_D + \Lambda$	O_{us}	4163.95
B^0	$\psi_D + \Xi_c^0$	O_{cd}	2807.76
B^0	$\psi_D + \Lambda_c^+ + \pi^-$	O_{cd}	2853.60
B^+	$\psi_D + p$	O_{ud}	4341.05
B^+	$\psi_D + \Sigma^+$	O_{us}	4089.95
B^+	$\psi_D + \Lambda_c^+$	O_{cd}	2992.86
B^+	$\psi_D + \Xi_c^+$	O_{cs}	2810.36

arXiv:2302.00208v1 (2023)

Preliminary result shown at Moriond EW 2023

Method

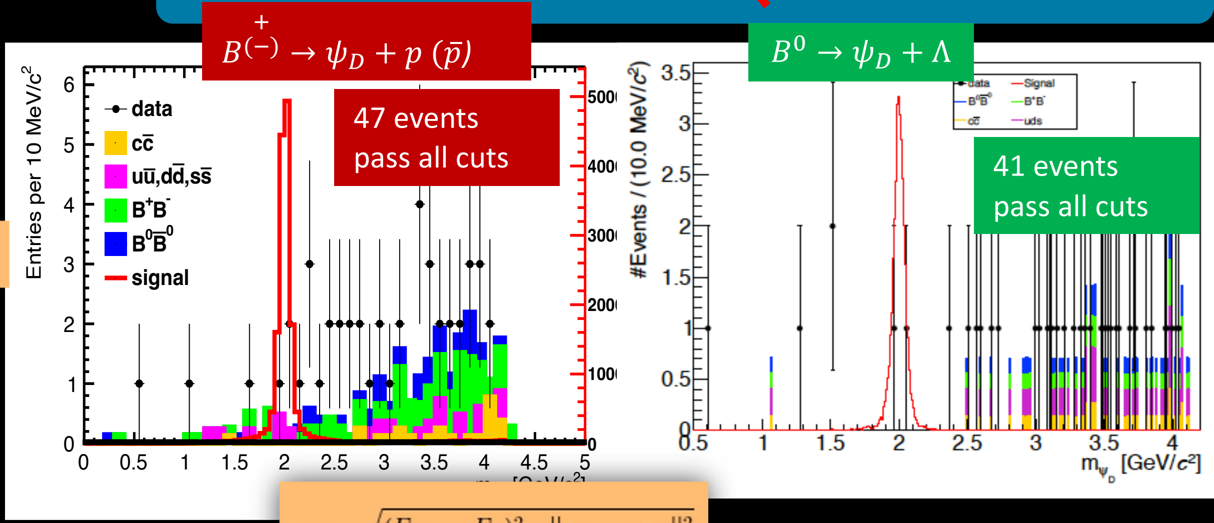
arXiv:2302.00208v1 (2023) + NEW RESULT FOR MORIOND EW 23



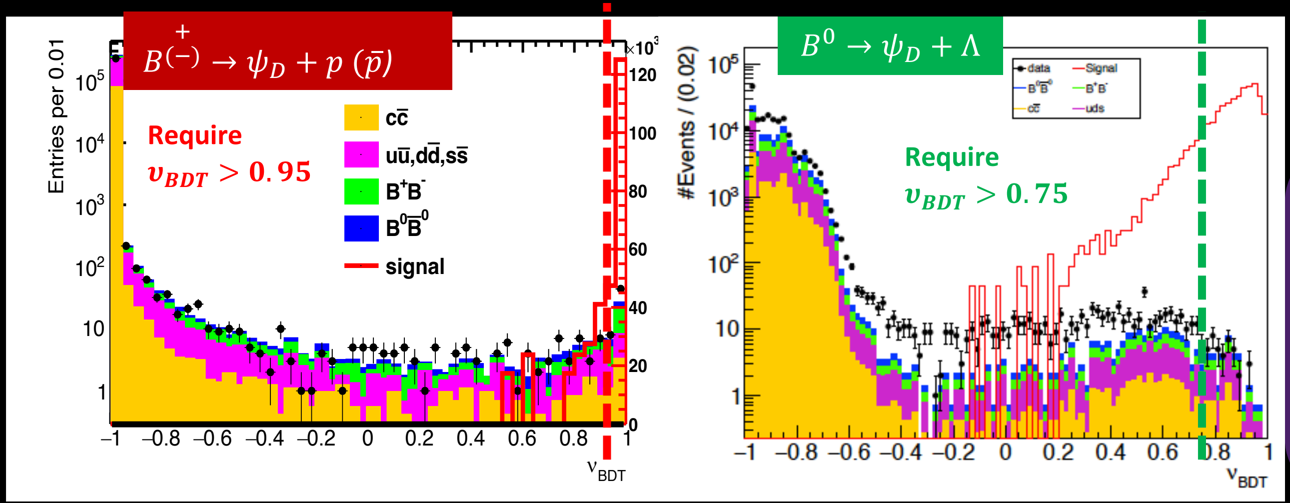
- Dark sector particle, ψ_D, escapes detection --> missing mass?
- Hadronic Recoil Tagging: Reconstruct B-tag and look for signal signature in the remainder of the event (B-sig).
- Reconstruct ψ_D from the missing energy 4-vector on signal side.
- Pre-selections and PID requirements are channel dependent.
- Some common criteria:

$-0.2\text{GeV} < \Delta E < 0.2\text{GeV}$, $5.2\text{GeV}/c^2 < m_{ES} < 5.3\text{GeV}/c^2$, where $\Delta E = E_{beam} - E_{B_{tag}}$, $m_{ES} = \sqrt{E^2_{beam} - p^2_{B_{tag}}}$,

- BDTs suppress backgrounds from SM $q\bar{q}$ and $B\bar{B}$ decays.



$m_{mis} = \sqrt{(E_{B_{sig}} - E_{\Lambda})^2 - \|\mathbf{p}_{B_{sig}} - \mathbf{p}_{\Lambda}\|^2}$,



- 8 signal samples made using EVTGEN: 1.0 < $m_{\psi D}$ < 4.2 GeV.
- Scan method used across missing mass, data-driven background yields from control regions.
- Signal efficiency interpolated from polynomial fits;
- Resolution interpolated from exponential fits.
- Both charge conjugates considered.

Results

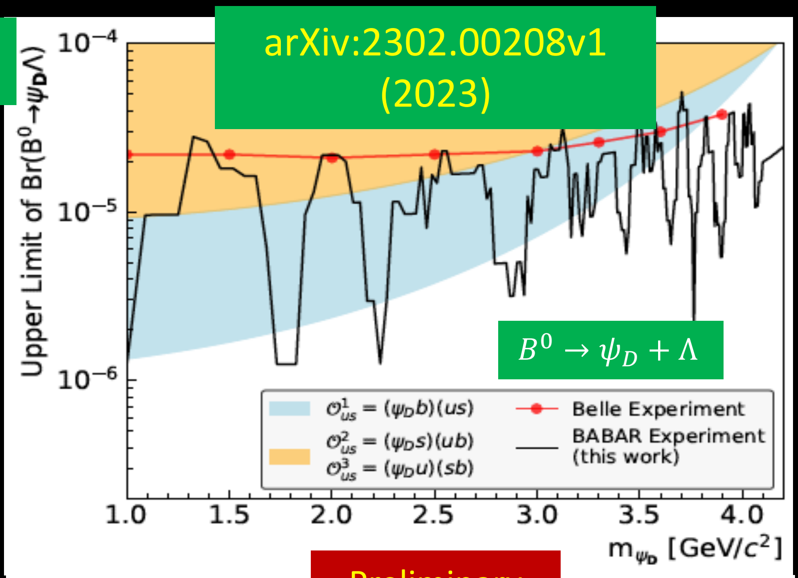
Presented analysis uses scan method compared to Belle method which looks at discreet signal mass hypotheses.

Belle Collaboration:
Phys. Rev. D 105, L051101 (2022).

Results for 398fb^{-1}

$B^0 \rightarrow \psi_D + \Lambda$ (probes O_{us})

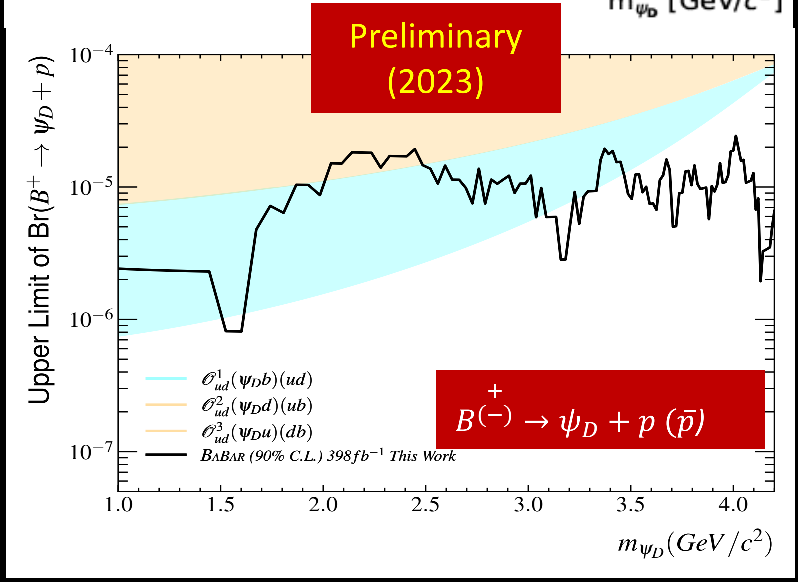
- Search for $B^0 \rightarrow \psi_D + \Lambda$ followed by $\Lambda \rightarrow p\pi^-$.
- Uncertainties come from: branching fraction (0.6%) luminosity (0.8%), limit signal MC stats (0.7-4.6%)
- The largest local significance is 2.3σ at m = 3.7 GeV, corresponding to global significance of 0.4 σ, consistent with the null hypothesis.
- BABAR result improves on Belle result at several mass hypotheses, tight constraints on O_{us} across the mass range.



Theory projections direct from:
miguel.escudero@tum.de
Phys. Rev. D. 99.035031 (2019)

$B^{(-)+} \rightarrow \psi_D + p\ (\bar{p})$ (probes O_{ud})

- Also includes uncertainties from proton PID (1%).
- Results show tight constraints on the O_{ud} operators.
- First direct limit on this process!
- Results also useful to constrain SUSY model (Journal of High Energy Physics 2023 jhep02(2023)224) – see back-up



Search for an Axionlike Particle in B Meson Decays:

Phys. Rev. Lett.128.131802

Axion-like particles at BABAR

coupling $SU(2)_W$ *field strength tensor*

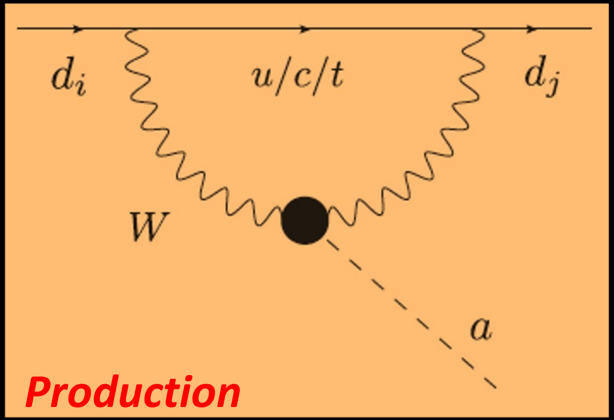
$$\mathcal{L} = -\frac{g_{aW}}{4} a W^b_{\mu\nu} \tilde{W}^{b\mu\nu},$$

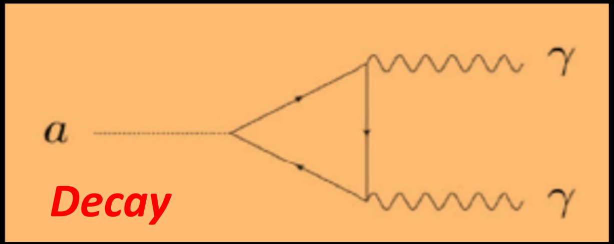
- Many BSM models include spontaneously-broken global symmetries, resulting in Axion-Like Particles (ALPs):
  - Can help resolve issues of naturalness of SM parameters but may also serve as mediators to dark sectors.
  - ALPs (a) couple primarily to pairs of SM gauge bosons.
- Can be produced in FCNC B decay processes, specifically $B^{\pm} \rightarrow K^{\pm} a$:
  - $a \rightarrow \gamma\gamma$ with nearly 100% BF for $m(a) < m(W)$.
  - For low axion mass and small coupling, the axion lifetime can become "long", i.e. non-prompt:

$$\tau \sim 1 / m_a^3 \, g_{aW}^2$$

Phys. Rev. Lett. 128.131802 (2022)

E. Izaguirre et al., PRL 118 (2017) 111802



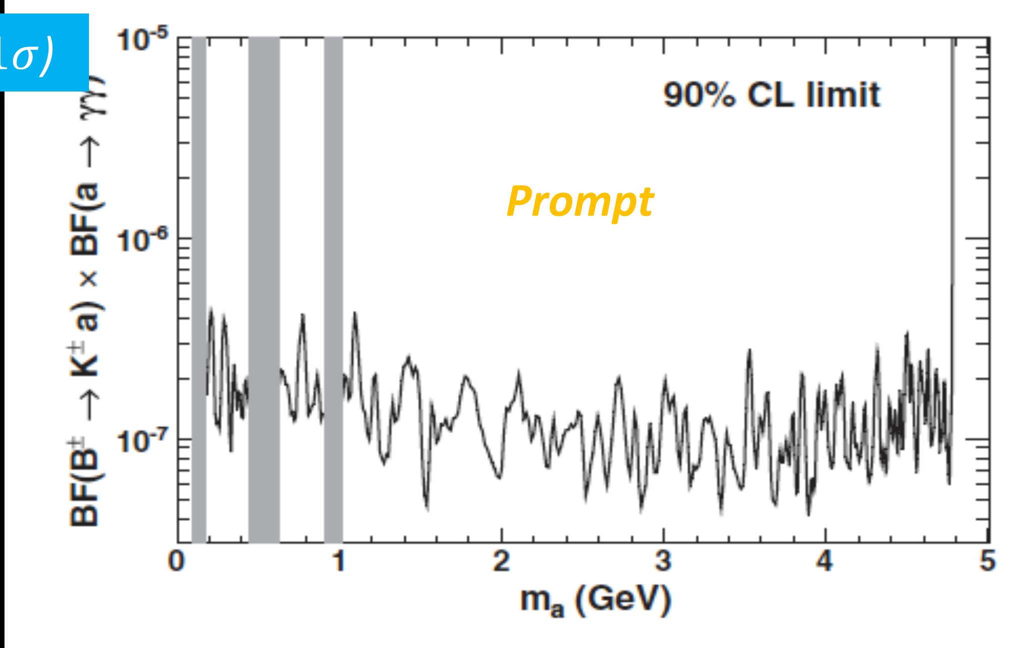


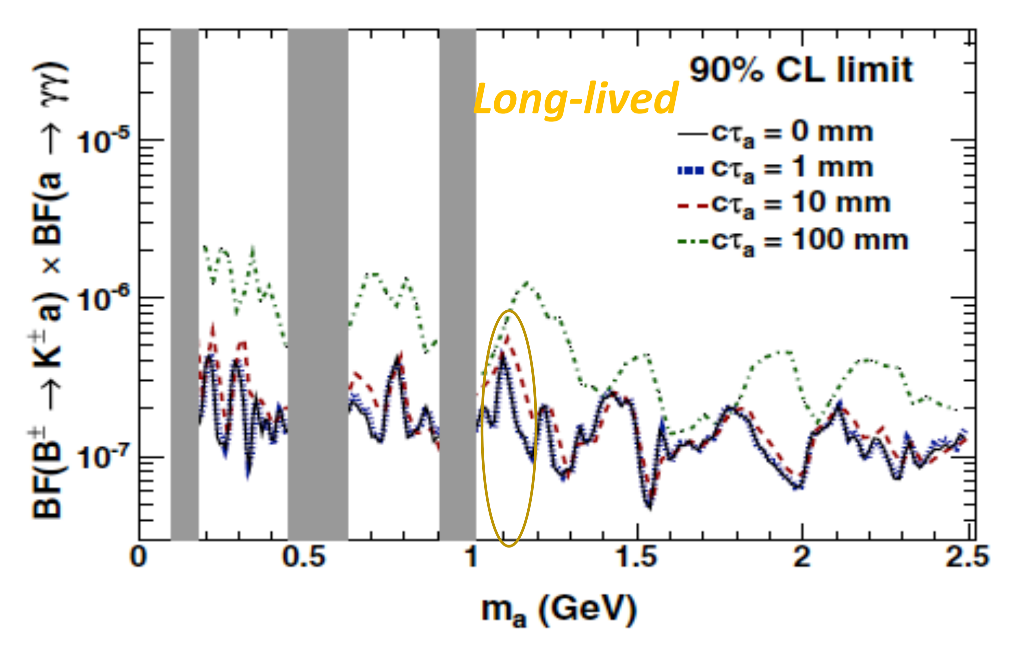
Results

Largest local significance near 1.1GeV (<1σ)

- BABAR search for ALPs in $B^{\pm} \to K^{\pm}a$ (+$a \to \gamma\gamma$) in 4.72 x 10^8 $B\bar{B}$ pairs collected at the Υ(4S) energy.
- Scan $m_{\gamma\gamma}$ with steps equal to the signal mass resolution (~ 8 – 14 MeV).
- Each signal mass hypothesis fit with unbinned maximum likelihood with a hypothetical signal peak + smooth background.
- In low mass region ($m_{\gamma\gamma}$ < 2.5 GeV) the signal sensitivity is also assessed for non-prompt signal hypotheses: $c\tau$ = 1, 10, 100mm:
  - Displaced vertex not reconstructed, but ALP resolution degraded;
  - No significant excess observed.
- $c\tau$ dependence is smaller at larger masses because ALP is less boosted, leading to shorter decay length in the detector.

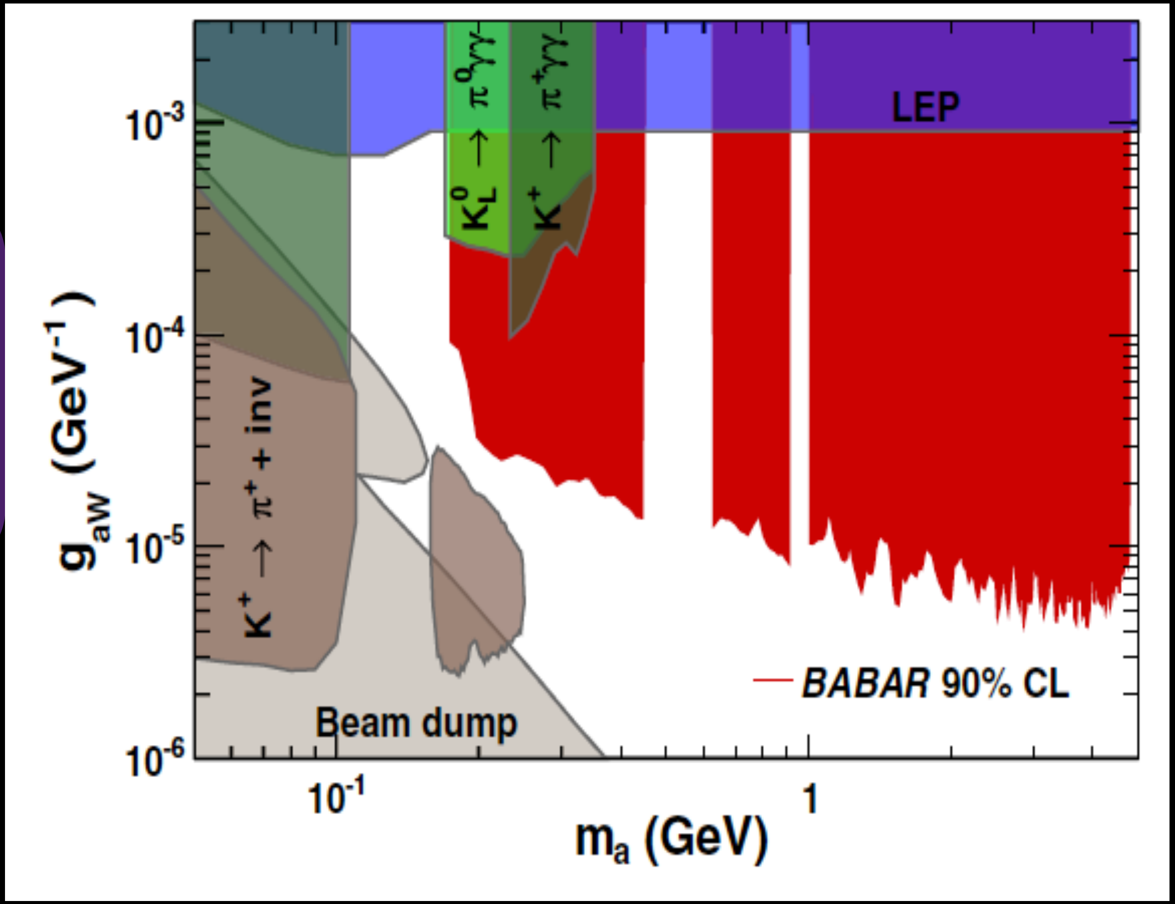
Phys. Rev. Lett. 128.131802 (2022)





Result

Phys. Rev. Lett. 128.131802 (2022)



- Results show new limits on g_{aW} at 90% C.L. which vastly improve on previous limits.
- Combination of results for all mass hypotheses and lifetimes.
- First search for visibly decaying ALPs produced in B meson decays.

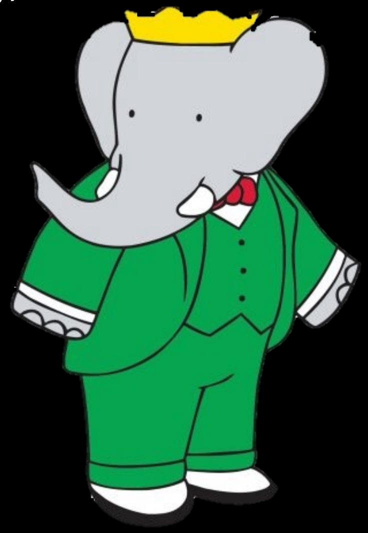
Final thoughts

- *BaBar* continues to provide tight constraints on possible new physics scenarios, including on models proposing:
  - Heavy Neutral Leptons (arXiv:2207.09575 (2022));
  - Dark matter scenarios (arXiv:2302.00208v1 (2023) + Preliminary Result shown here (2023));
  - Axion-like particles (Phys. Rev. Lett. 128.131802 (2022)).
- Other recent results not covered here include:
  - Search for Darkonium (Phys. Rev. Lett. 128 021802 (2022));
  - Search for LFV in Υ(3S) →eμ (Phys. Rev. Lett. 128, 091804 (2022));
  - ISR/hadronic cross-section results (arXiv 2207.10340 [hep-ex] (2022), Phys. Rev. D 104 (2021) , Phys. Rev. D 104 (2021,) Phys.Rev.D 103 (2021));
  - Light meson spectroscopy from Dalitz plot analyses of ηc decays **(** Phys. Rev.D 104 (2021));

  +++ more.
- ***We anticipate more new results in 2023.***

Thank You for the Invitation and for Listening

Any Questions?



Fit Model

Assume each bin (i, j) in 2D plots can be represented by a Poisson sampling function:

$$\mathcal{L} = \prod_{ij} f(n_{ij}; n_{\text{obs}}, \vec{\theta}) = \prod_{ij} \frac{(\nu_{\text{HNL}} + \nu_{\tau-\text{SM}} + \nu_{\text{BKG}})_{ij}^{(n_{\text{obs}})_{ij}} e^{-(\nu_{\text{HNL}}+\nu_{\text{BKG}}+\nu_{\tau-\text{SM}})_{ij}}}{(n_{\text{obs}})_{ij}!} \times \prod_k f(\theta_k, \tilde{\theta}_k),$$

Where:

Nuisance parameters

Potential signal events: $\hat{\nu}_{\text{HNL},ij} = n^{\text{reco}}_{\text{HNL},ij} = N_{\tau,\text{gen}} \cdot (|U_{\tau 4}|^2) \cdot p_{\text{HNL},ij},$

Expected tau SM background events: $\hat{\nu}_{\tau-\text{SM},ij} = n^{\text{reco}}_{\tau-SM,ij} = N_{\tau,\text{gen}} \cdot (1-|U_{\tau 4}|^2) \cdot p_{\tau-SM,ij},$

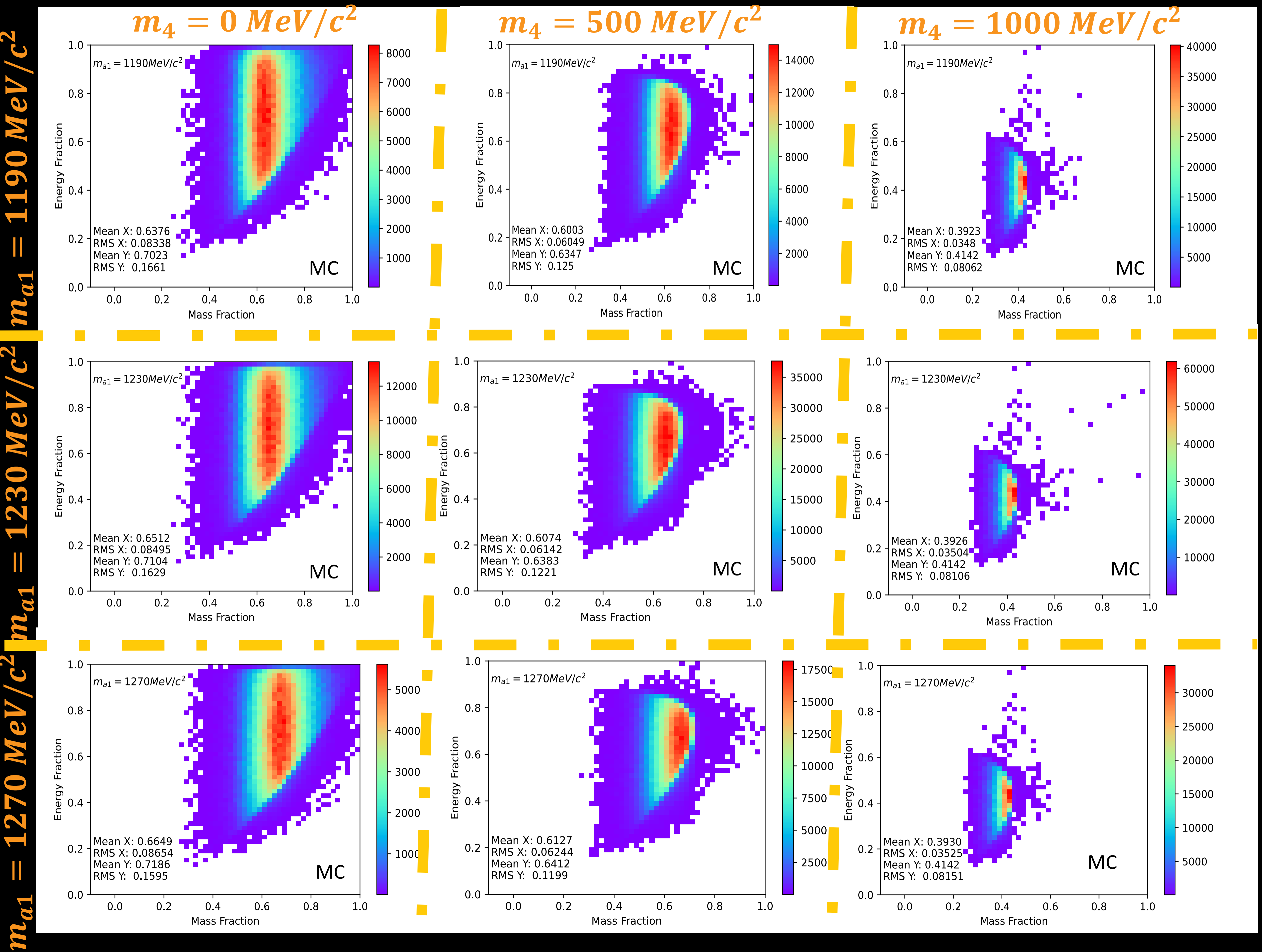
Expected non-tau SM background events: $\hat{\nu}_{\text{BKG},ij} = n^{\text{reco}}_{BKG,ij} = n^{\text{reco}}_{\tau-\text{other},ij} + n^{\text{reco}}_{\text{non}-\tau,ij},$

Use Wilk's theorem to find limits: $q = -2\ln\left(\frac{\mathcal{L}_{H_0}(|U_{\tau 4}|^2_0; \hat{\hat{\theta}}_0, \text{data})}{\mathcal{L}_{H_1}(|\hat{U}_{\tau 4}|^2; \hat{\theta}, \text{data})}\right) = -2\ln(\Delta\mathcal{L}).$

arXiv:2207.09575 (2022)

Back-up

Systematic Shape Uncertainties



- Dominant shape systematic from modelling of the hadronic tau decays in TAUOLA
- $\tau^- \rightarrow \pi^-\pi^-\pi^+\upsilon_\tau$ is mediated by the a_1 resonance 97% of the time.
- $m_{a_1} = 1230 \pm 40$ MeV/c² and $\Gamma_{a_1} = 420 \pm 35$ MeV/c² (PDG estimates 250 – 600 MeV/c²)

arXiv:2207.09575 (2022)

Back-up

Heavy Neutral Leptons: Results

Mass [MeV]	No Sys.	With Sys.
100	1.58×10^{-2}	2.31×10^{-2}
200	1.33×10^{-2}	1.95×10^{-2}
300	6.91×10^{-3}	9.67×10^{-3}
400	1.57×10^{-3}	2.14×10^{-3}
500	4.65×10^{-4}	5.85×10^{-4}
600	5.06×10^{-4}	6.22×10^{-4}
700	3.82×10^{-4}	4.85×10^{-4}
800	3.12×10^{-4}	3.58×10^{-4}
900	4.70×10^{-5}	5.28×10^{-5}
1000	8.34×10^{-5}	9.11×10^{-5}
1100	4.49×10^{-5}	4.78×10^{-5}
1200	4.70×10^{-6}	5.04×10^{-6}
1300	3.85×10^{-5}	4.09×10^{-5}

arXiv:2207.09575 (2022)

Back-up

BDT Features (Proton)

DM/Baryogenesis

- In order to further improve signal and background separation a BDT was developed and a cut made at post-selection
- The features which are used as input were chosen carefully, the list may be modified as I move forward:

Recoil B^- Features	Signal B^+ Features
Decay mode - the hadronic decay channel of B meson decay.	**signPiZ**– number of pions on signal side
B_{tag} Purity - the fraction of B_{tag} mesons that are correctly reconstructed for a given decay mode.	**SBQtot** – total charge in the signal side
ΔE - the difference of beam energy and the reconstructed B_{tag} energy.	**SBNNeut** – number of neutral particles in the signal side
M_{ES} - recoil B meson mass distribution.	**sigMissCosTheta**– cosine of the missing momentum
Thrust, ThrustZ - The B_{tag} thrust axis is defined as the axis which maximizes the longitudinal momenta of all the particle for B_{tag} reconstruction.	**sigClusETotCM** - The total extra neutral energy238 on the signal side in the center-of-mass fram

Plus:
r2All - the ratio of the second to zeroth Fox-Wolfram moment for all tracks and neutral clusters
cosT - the cosine of the thrust vector

BDT Features (lambda)

DM/Baryogenesis

- In order to further improve signal and background separation a BDT was developed and a cut made at post-selection
- The features which are used as input were chosen carefully, the list may be modified as I move forward:

Recoil B^- Features	Signal B^+ Features
Decay mode - the hadronic decay channel of B meson decay.	**signPiZ**– number of pions on signal side
B_{tag} Purity - the fraction of B_{tag} mesons that are correctly reconstructed for a given decay mode.	**SNClusters** – number of calorimeter clusters
ΔE - the difference of beam energy and the reconstructed B_{tag} energy.	**SBNNeut** – number of neutral particles in the signal side
M_{ES} - recoil B meson mass distribution.	**Chi2 –** of kinemtatic fit of lambda decay
Thrust, ThrustZ - The B_{tag} thrust axis is defined as the axis which maximizes the longitudinal momenta of all the particle for B_{tag} reconstruction.	**LambdaFlightlen** – lambda flight length

Plus:
r2All - the ratio of the second to zeroth Fox-Wolfram moment for all tracks and neutral clusters
cosT - the cosine of the thrust vector

SUSY constraints from $B^{+(-)} \rightarrow p(\bar{p}) + inv.$

- ***Susy model:*** (Journal of High Energy Physics 2023 - jhep02(2023)224) also constrained by this result: