SUSY 2024

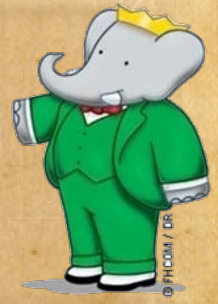
Theory meets Experiment

Madrid, 10 – 14 June 2024

Pre-SUSY school: 3 – 7 June 2024

https://indico.cern.ch/e/susy2024

Recent Dark Matter searches at BaBar and implications on some SUSY models



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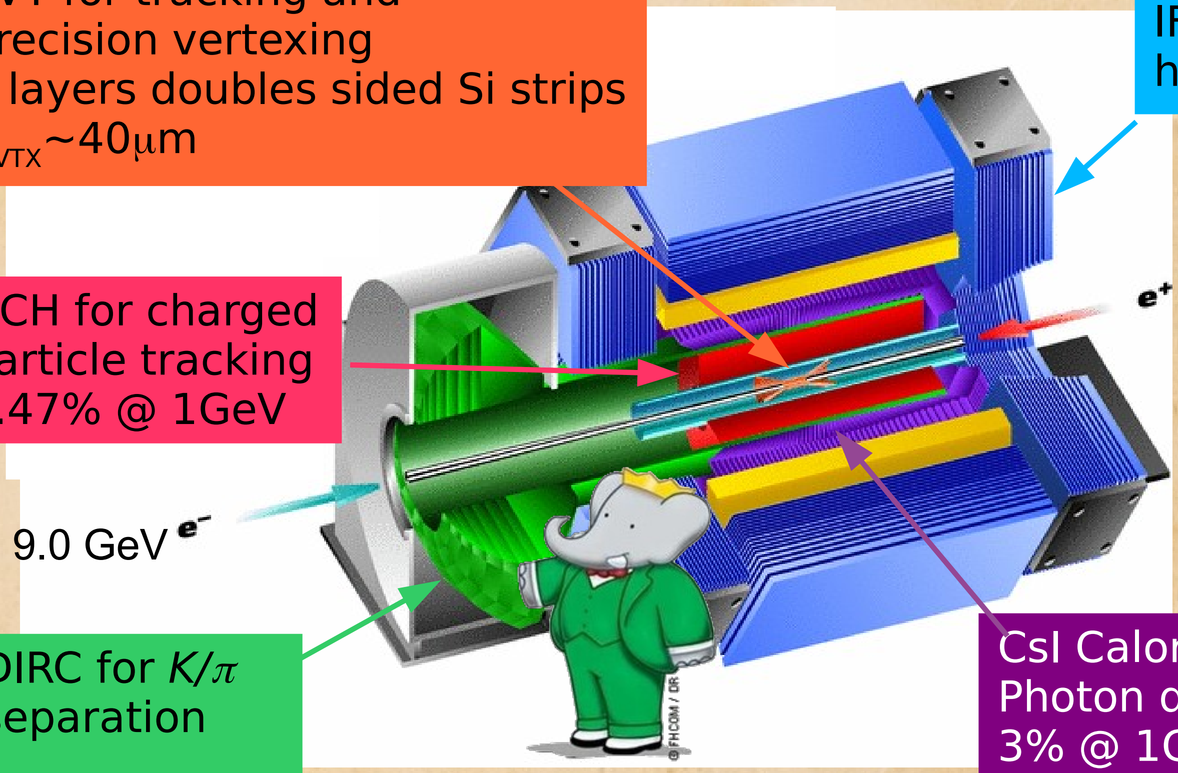
On behalf of the BaBar collaboration

Overview

- BaBar experiment
- Introduction
- Search for Heavy Neutral Leptons in tau decays
  - Phys.Rev.D 107 (2023) 5, 052009 (BABAR)
- Search for Baryogenesis and Dark Matter
  - Phys.Rev.Lett. 131 (2023) 20, 201801 (BABAR)
  - Phys.Rev.D 107 (2023) 9, 092001 (BABAR)
- Implications for some SUSY models
  - JHEP 2023, 224 (2023)
  - Phys. Rev.Lett. 131 (2023) 20, 201801 (BABAR)

BaBar Experiment at PEPII

Nucl. Instrum. Meth. A 729, 615 (2013).



- Well suited for dark sector searches
  - Quasi hermetic reconstruction of events
  - Very efficient trigger (98%)
  - Clean e+e- environment
  - Excellent Particle ID
  - Accurate Missing Energy reconstruction

On-Peak	432 fb^{-1} ~470 MBB
Off-Peak	44 fb^{-1},

100M Υ(2S), 120M Υ(3S),

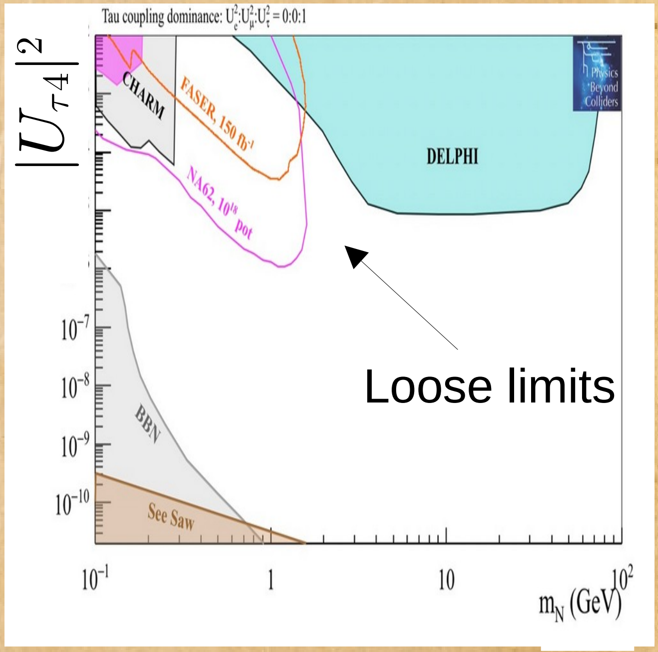
4fb^{-1} above Υ(4S)

Dark Matter (DM) Portals

- To understand the nature of dark matter an effective theory approach provides several portals
- At B-Factories DM can be produced in e^+e^- interactions or in B meson decays
- Searches can access different operators, constrain masses and couplings

Search For HNL: Motivation

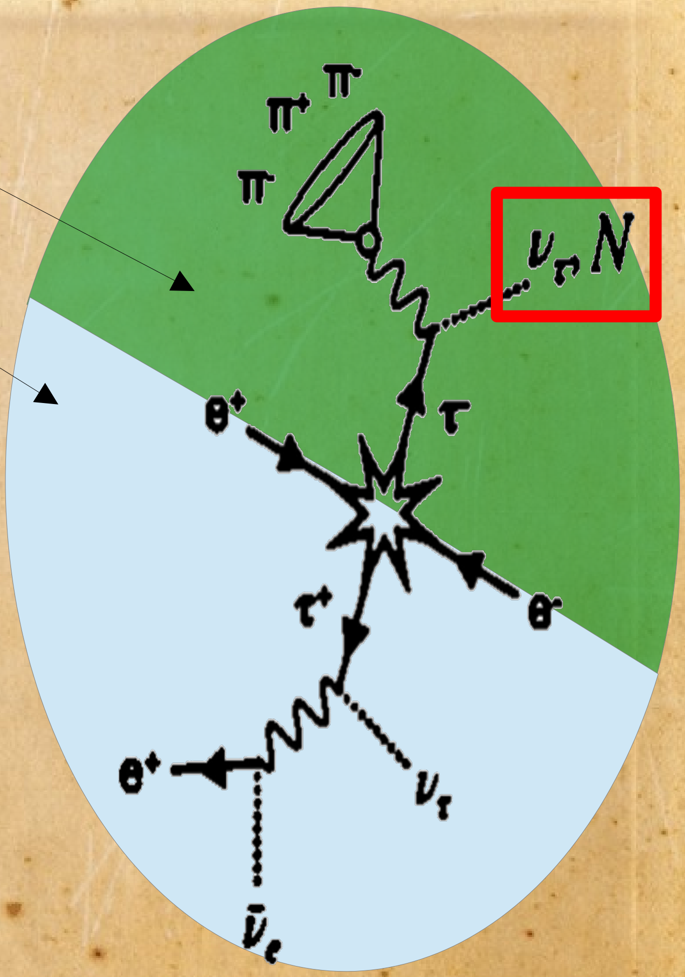
- Several Beyond Standard Model theories introduce Heavy Neutral Leptons (HNL)
- HNL are massive additional neutrino states which have no other charges, and can explain several phenomena
  - Neutrino small mass (seesaw mechanism) and oscillations
  - Baryon asymmetry in the universe
  - The origin of dark matter
- The ν-MSM has three HNL in the keV-GeV range
- HNL can be produced in lepton decays and the τ sector is the less constrained
- BaBar produces copious amounts of τ in a clean environment
  - $\mathcal{L}=424\,fb^{-1}$, $N_{\tau\tau}=400M$
  - $\sigma\,(e^+e^-)\rightarrow\tau^+\tau^-=0.92\,nb,\ \sigma_{tot}\simeq 5.4\,nb+bhabha$
- BaBar can search for a HNL that is capable of mixing with τ with strength $|U_{\tau 4}|^2$ in the mass range 100 MeV/c^2 < m$_4$ < 1300 MeV/c^2



$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\\ \nu_L\end{pmatrix} = \begin{pmatrix}U_{e1} & U_{e2} & U_{e3} & U_{e4}\\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & U_{\mu 4}\\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} & \boxed{U_{\tau 4}}\\ U_{L1} & U_{L2} & U_{L3} & U_{L4}\end{pmatrix}\begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\\ \nu_4\end{pmatrix}$$

Serach for HNL: strategy

- Selection
  - Signal side: three prong pionic decay ($\tau \rightarrow \pi\pi\pi\nu_\tau$)
  - Tag side one prong τ decay to reduce bkg
  - Signal and tag identified in different hemispheres (3+1 topology), thrust>0.85
  - P_T, P^{miss}_{CM}>0.9%$\sqrt{S}$ to suppress non tau bkg
  - DIRC acceptance and PID requirements for e and μ
  - Neutral and conversion veto for tag side
- Signal extraction: same strategy used in previous analysis in BaBar using only variables sensitive to the kinematics
  - if the decay products of the τ have recoiled against a heavy neutrino, the phase space and the kinematics of the visible particles would be modified with respect to SM τ decay with a massless neutrino: **no model assumptions**
  -

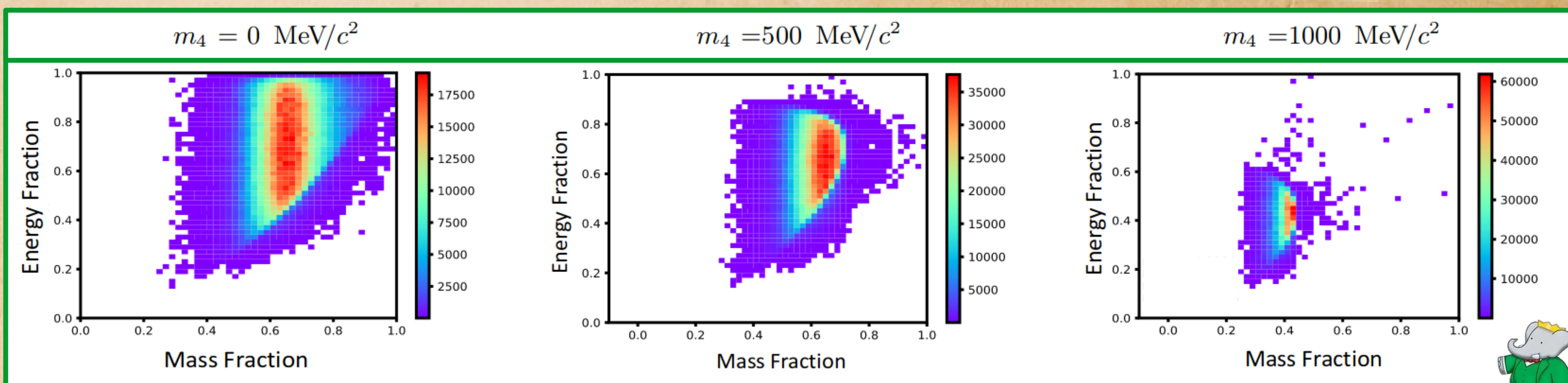


HNL Signal

- Consider the process as a two body decay $\tau \rightarrow h^{-}(E_h, m_h)\,\nu_\tau$
- The signal is searched in the 2D plane of the hadron mass and energy (m_h, E_h)
- Tau decay gets separate contributions from SM and BSM decay

$$\left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{\text{Total}} = |U_{\tau 4}|^2 \left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{\text{HNL}} + (1-|U_{\tau 4}|^2)\left.\frac{d\Gamma(\tau^- \to \nu h^-)}{dm_h dE_h}\right|_{\text{SM}}.$$

- 2D templates are built for each different m_4 mass. The hadronic system available phase space reduces as m_4 increases
- Signal samples from modified KK2F+TAUOLA+GEANT4 in the range $100\ MeV/c^2 < m_4 < 1300\ Mev/c^2$



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

HNL: Signal extraction

- Background from MC simulation
  - Misidentified SM τ decays
  - SM non τ bkg: B decays, light quarks, $e^+e^- \to \mu^+\mu^-(\gamma)$
- Signal (ν_{HNL}) extracted from binned ML fit assuming each bin has Poisson distribution with mean $\nu_{HNL}+\nu_{\tau-SM}+\nu_{BKG}$

  $\nu_{HNL} \propto |U_{\tau 4}|^2, \quad \nu_{\tau-SM} \propto (1-|U_{\tau 4}|^2)$
- Limits include nuisance parameters
- Dominant systematic from shape uncertainty

Mass [MeV/c^2]	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}	3.85×10^{-4}
900	4.70×10^{-5}	5.38×10^{-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}

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

Nuisance parameters

- For each mass re-weighted 2D templates for signal are used

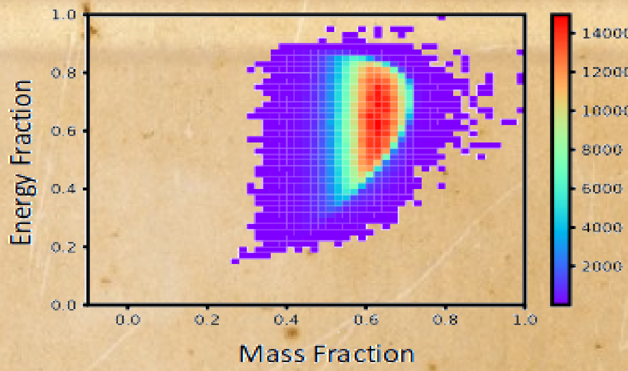
HNL: systematic uncertainties

- Normalization uncertainties
  - Affect all bins uniformly
  - Have small effect on the yield (<3%)
    - Biggest contribution from PID efficiency
  - Characterized by Gaussian nuisance parameters
- Shape uncertainties
  - $\tau \to$ 3-prong BF through a_1 resonance = 97%
  - **Large uncertainties** on a_1 parameters mass (+/-3%) and Γ_{a1} (250 MeV/c^2 – 600 MeV/c^2)
  - **Modeling of signal and bkg shape in TAUOLA affected by these uncertainties**
  - To account for this looked at **templates** with **mass and width varied** to these extremes (re-weighted MC) and **re-calculated** the likelihood
  - Γ_{a1} has the largest effect, especially on the RMS of m_h

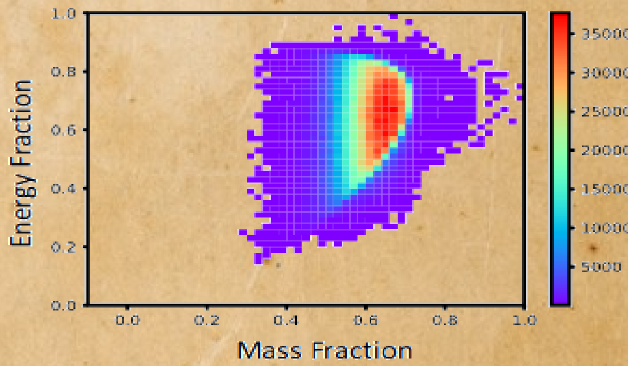
	E_h	m_h
RMS shift	1%-3%	6%-7%
Mean shift	1%-2%	1%-2%

$m_4 = 500$ MeV/c^2

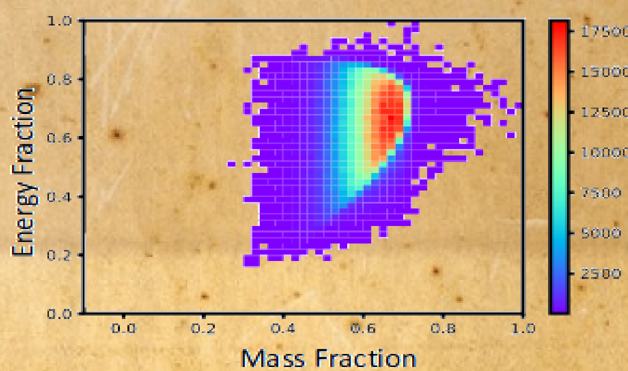
M_{a1}=1190 Mev/c^2



M_{a1}=1230 Mev/c^2



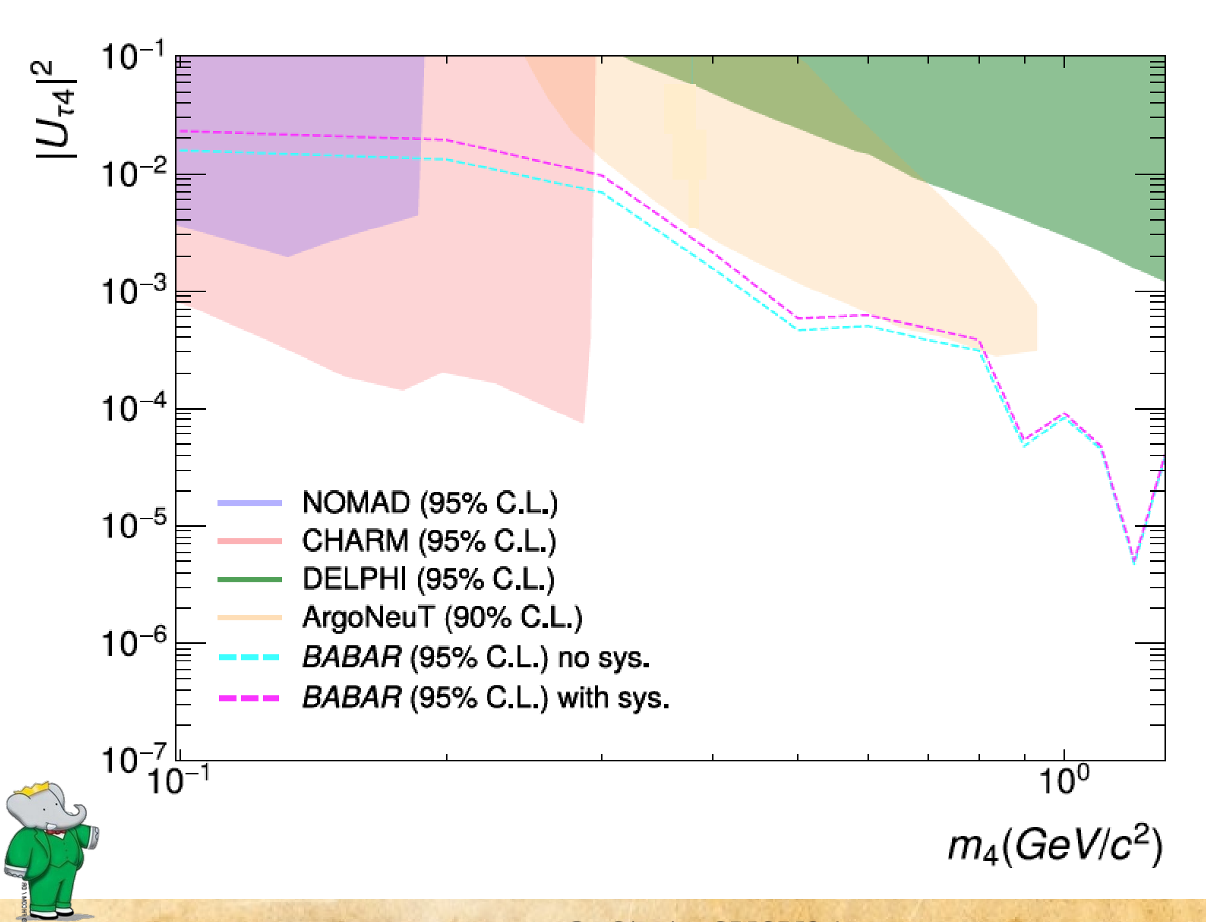
M_{a1}=1270 Mev/c^2



Phys.Rev.D 107 (2023) 5, 052009 (BABAR)

HNL: Results

- Result is expressed as an upper limit on $|U_{\tau 4}|^2 \, vs \, m_4$
- Covers nicely region around 1 GeV/c^2
- World leading constraint at time of publication

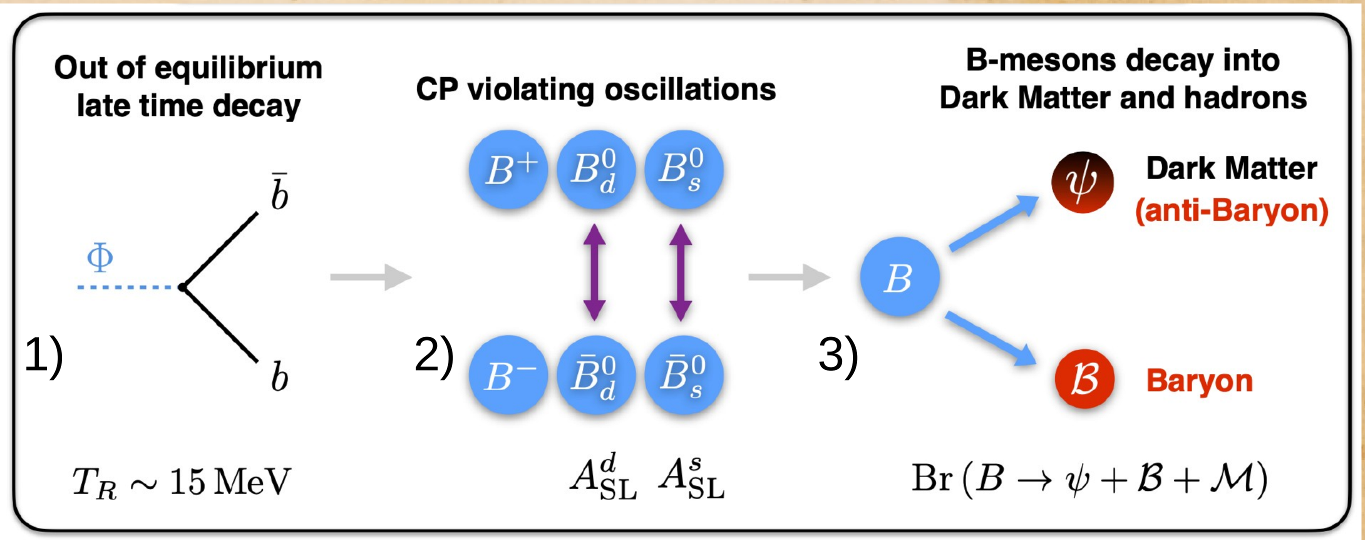


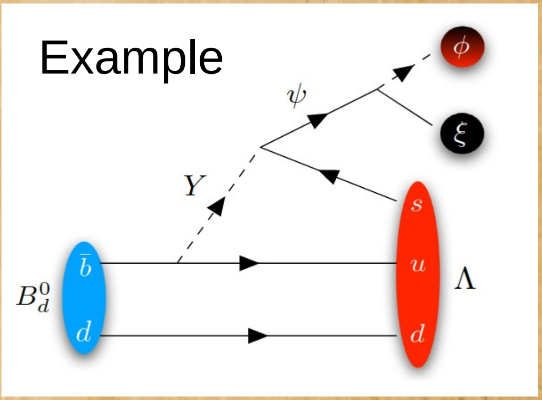
Phys.Rev.D 107 (2023) 5, 052009 (BABAR)

Baryogenesys and dark matter: Introduction

Phys. Rev. D 99, 035031 (2019)

- A new dark sector anti-baryon has been proposed to simultaneously explain both the **dark matter (DM) abundance** and the **Baryon Asymmetry in the Universe (BAU)**
- Baryon asymmetry generated via
  - 1) Production of bb pairs
- 2) CPV in B oscillations generates more B^0 than anti-B^0
- 3) B meson decay into a baryon $\mathcal{B}$ ($=\Lambda$ or p in this search) and a dark sector anti-baryon (Ψ_D) + additional mesons ($\mathcal{M}$) generated visible asymmetry





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

Phys. Rev. D 99, 035031 (2019)

Operators sensitivity and Reconstruction Technique

- Decay described by effective operators O_{ij} corresponding to transitions $b \to q_i q_j$ where $i = u, c$ $j = d, s$

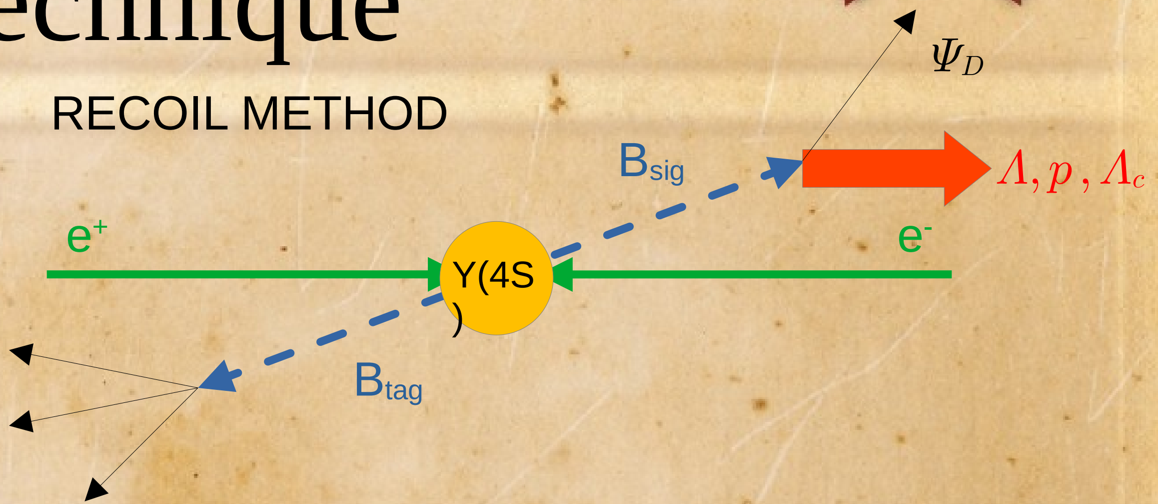
- Different decay channels are sensitive to different effective operators

In this talk

In preparation

Meson	Decay	Operator	M_{max} [MeV]
B^0	$\Psi_D + \Lambda$	O_{us}	4163.95
B^+	$\Psi_D + p$	O_{ud}	4341.05
B^+	$\Psi_D + \Lambda_c$	O_{cd}	2992.86
...	...	...	...

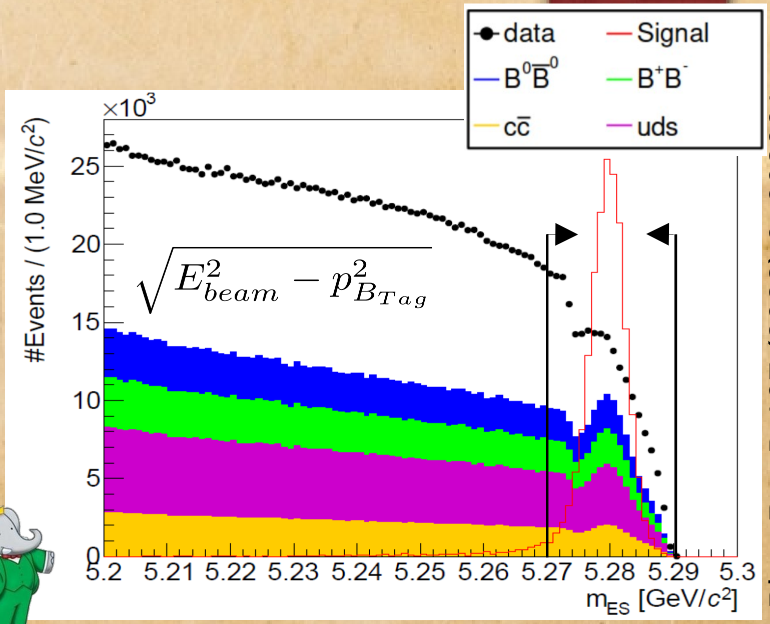
RECOIL METHOD



- B_{tag}: fully reconstructed hadronic B-decays (mostly charmed)
- B_{sig}: the rest of the event = a single reconstructed baryon
- Ψ_D: Missing momentum since dark-sector particles escape detection
- Kinematic constraints limit the search for $0.94\,GeV < m_{\Psi_D} < 4.34\,GeV$

Selection

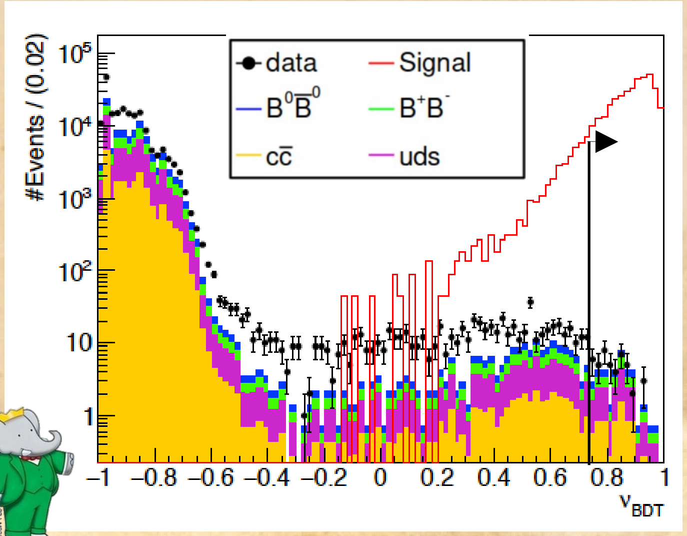
- B_{Tag}
  - Beam Energy substituted mass
  - $\Delta E = E_{beam} - E_{BTag}$
  - Spherical event topology



Phys.Rev.D 107 (2023) 9, 092001

- Signal Baryon
  - BDT built from bkg rejection variables, baryon (and B_{Tag} and) reconstruction quality variables with small correlation with missing mass

$B^0 \rightarrow \Lambda \Psi_D$



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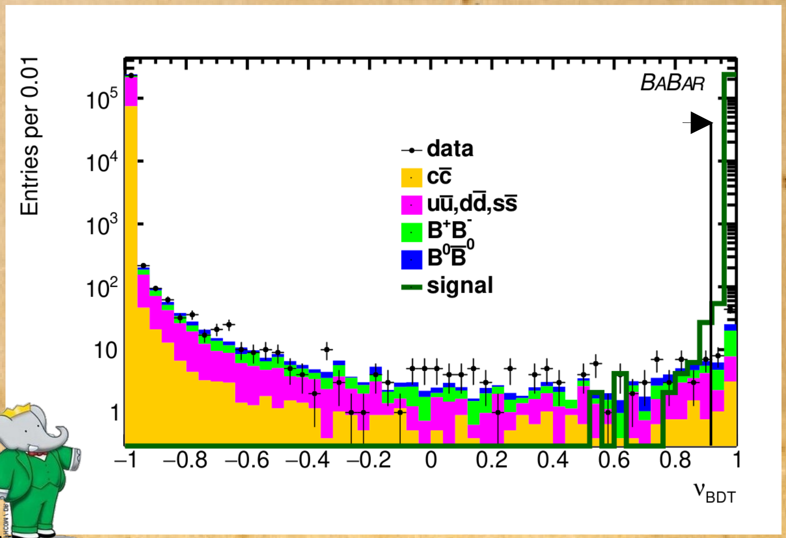
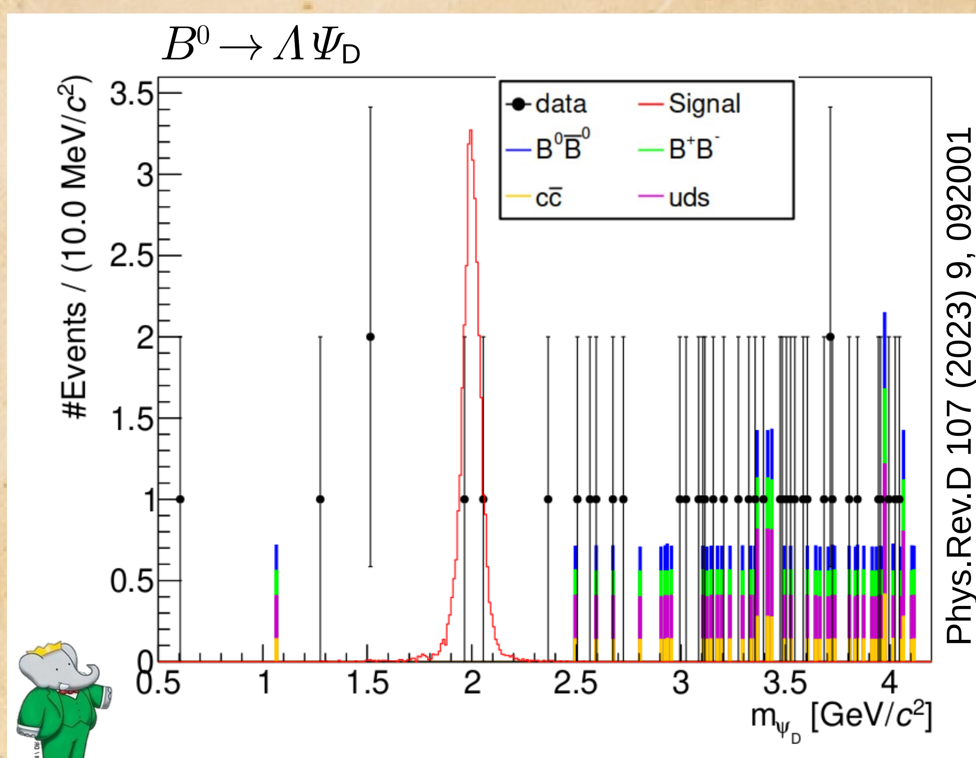
$B^+ \rightarrow p^+ \Psi_D$



Phys.Rev.Lett. 131 (2023) 20, 201801

Results

- Total data used 389ifb
- 10% of data used to optimize analysis
- Signal is extracted from the missing mass distribution fitted to a Crystal Ball
- Scan is performed on the missing mass with step size equal to the resolution
- Largest systematic uncertainty from data/MC corrections (efficiency)



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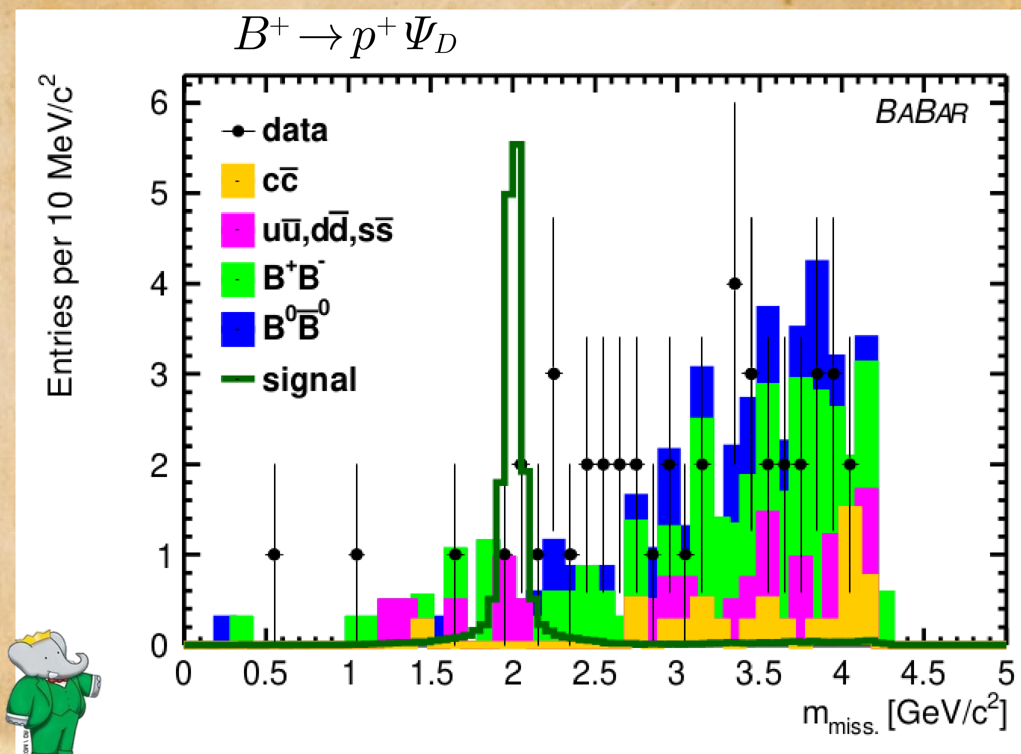

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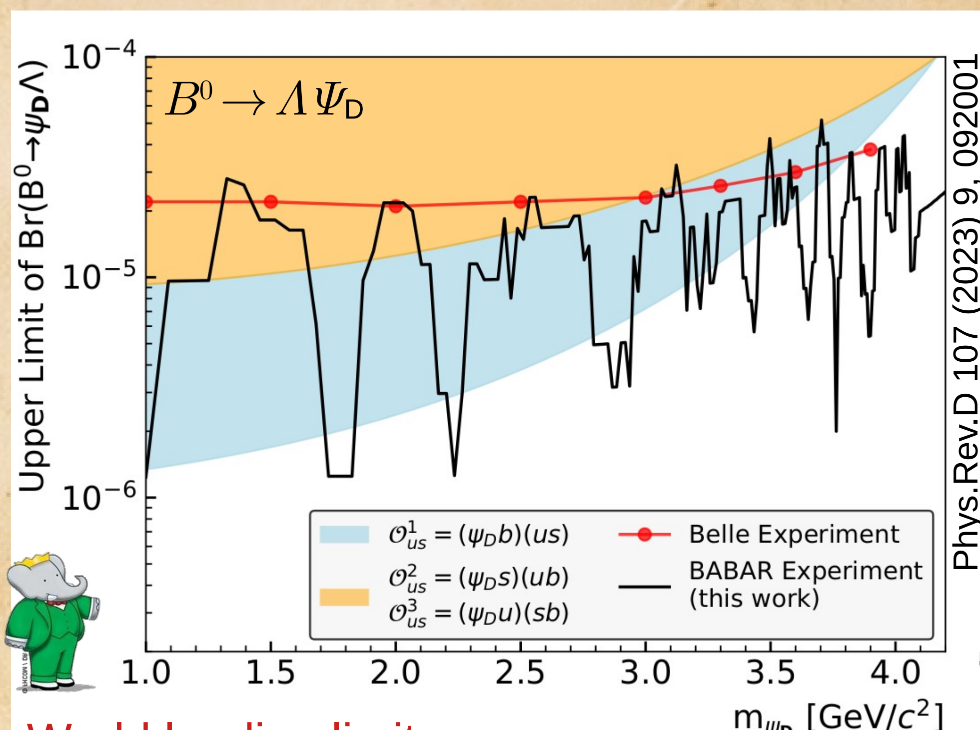
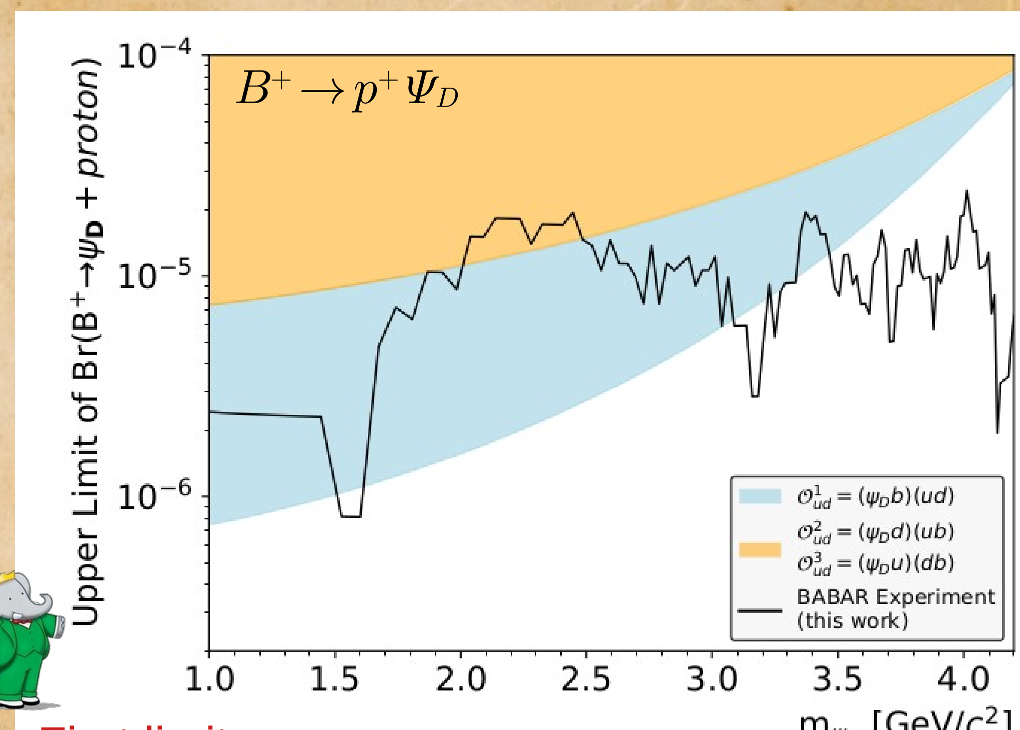
Results

- Upper limits (black line) computed assuming Poisson distribution
- 95% exclusion limits (black line) obtained scanning the missing mass distribution for many values

- Global significance at 1σ level
- Colored bands are the allowed regions consistent with observed baryon asymmetry: large regions excluded



World leading limit



First limit

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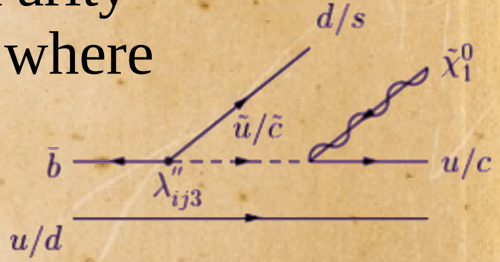
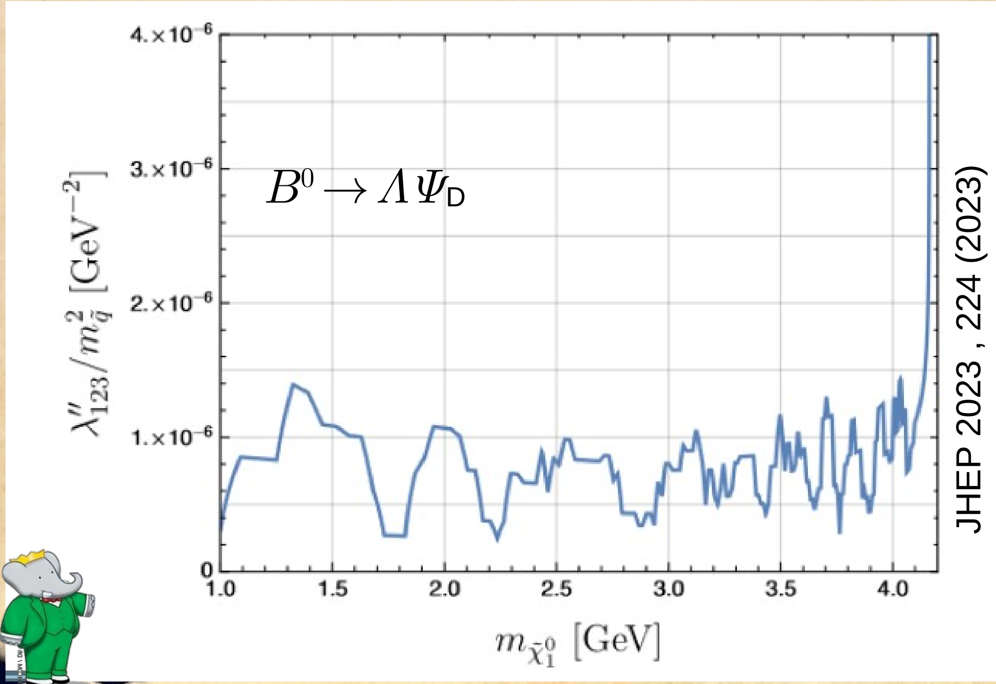
Results: limits on RPV SUSY models

JHEP 2023, 224 (2023)

- Since all we are requiring is missing mass these results can be reinterpreted to constrain other models, including the R Parity Violating (RPV) supersymmetry process $B^+ \to \tilde{\chi}_0 + p$ where $\tilde{\chi}_0$ is the lightest neutralino. It violates R parity since it produces only one neutralino.



- BF bounds are interpreted as limits on λ''_{113} vs neutralino mass



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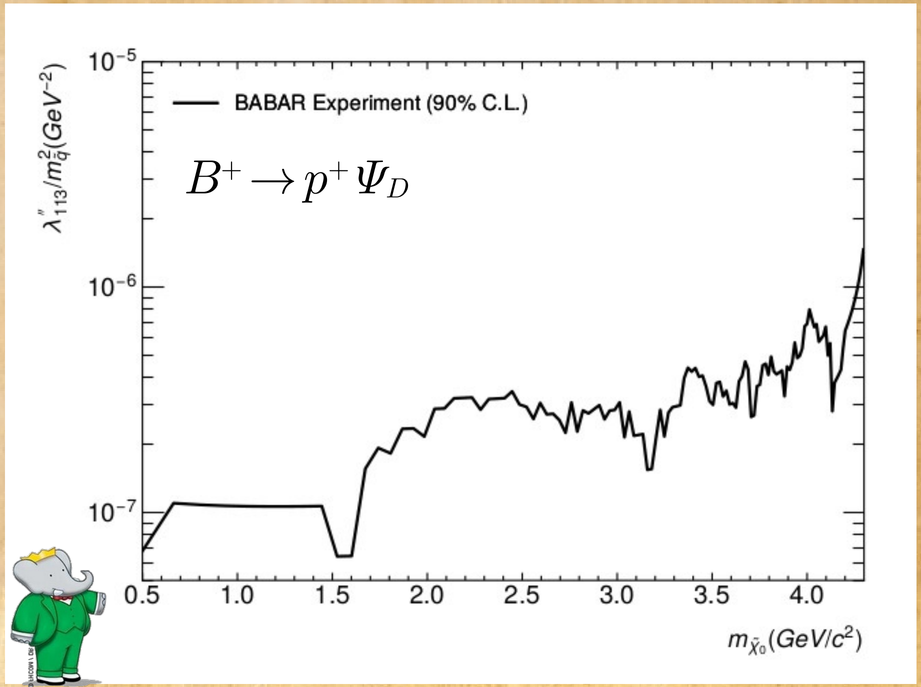


Phys.Rev.Lett. 131 (2023) 20, 201801

Conclusions

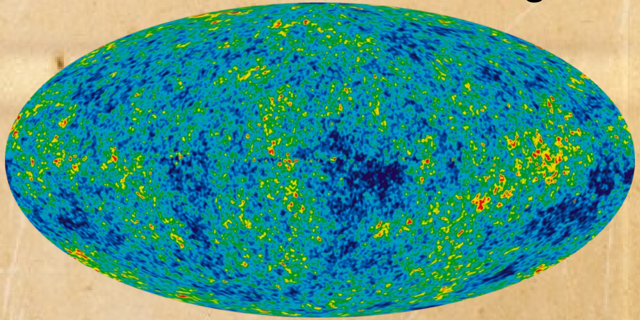
- BaBar continues to produce excellent physics results and is well suited to search for dark matter candidates
- We performed a model independent search searched for Heavy Neutral Leptons (mostly sterile)
  - Could explain simultaneously BAU and DM origin
  - No signal observed but set the world leading limits for the mixing strength with the tau in the region around 1 GeV/c^2
  - Largest systematic coming from hadronic tau decays
- We performed a search for dark matter candidates in exotic B decays to a baryon a dark sector anti-baryon
  - No signal is observed and we put limits on the BF
  - In the context of DM and BAU B-mesogenesys models we have put stringent limits on some operators
  - In the context of SUSY these limits can be recast as limits on RPV SUSY models

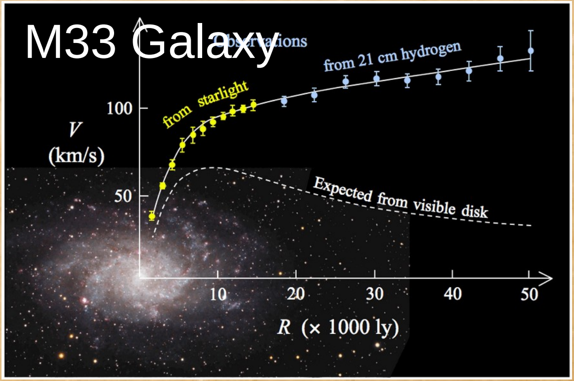
BACKUP

Dark Matter in the Universe

- Many experimental evidences of Dark matter
  - Lambda CDM: 5% Baryonic Matter, 27% Dark Matter, 68% Dark Energy
  - Rotational curve of galaxies
  - Large scale structure formation
  - Bullet galaxy cluster
  - Gravitational lensing

Cosmic microwave bkg





lensing

Dark matter Bullet cluster

[simulated] structure formation