T violation and other results from BaBar

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Outline

- Violation of time-reversal symmetry
- Searches for light Higgs
- $\bar{B} \to D^{(*)}\tau^{-}\bar{\nu}_{\tau}$

Observation of time-reversal violation in the B^0 system

Phys. Rev. Lett. 109, 211801 (2012)

T symmetry violation

- Not related to the macroscopic arrow of time.
  - Second law of thermodynamics
- Not related to time travel.

- Time-reversal is, however, a fundamental symmetry of the laws of physics.

CPT, CP, T

- Actually, we believe that T is not a good symmetry of the weak force.
- Physics is invariant under CPT, and not under CP

  $\Rightarrow$ T must be violated.
- But no clear experimental evidence.

CP violation

- Establishing our understanding of the violation of these fundamental symmetries has been the core of the B-factory physics program. Its importance was recognized in the 2008 Nobel prize.

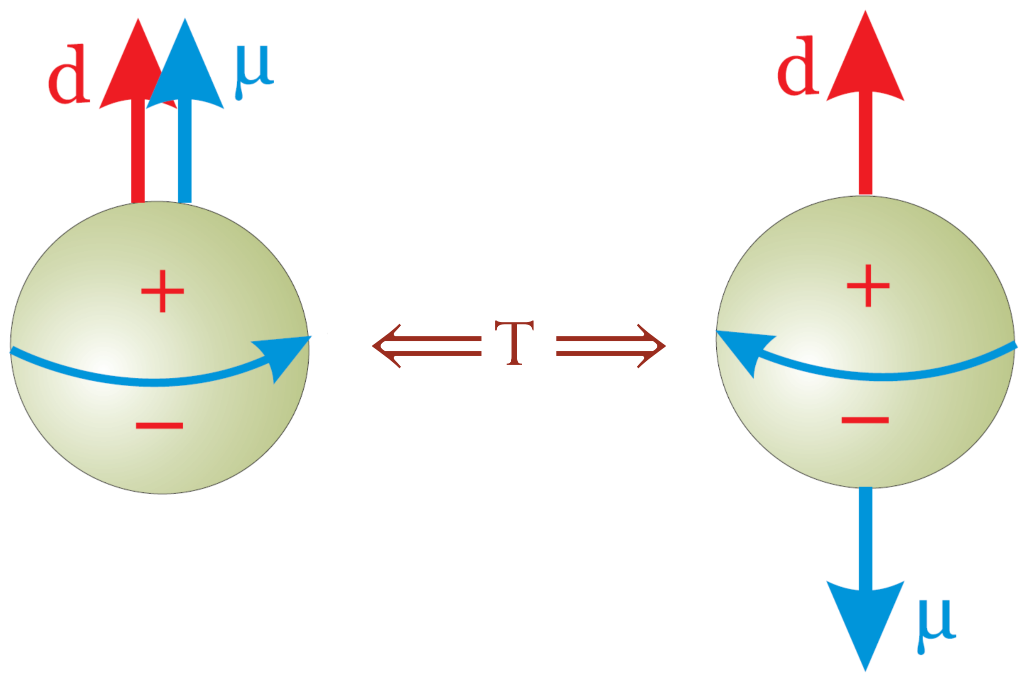
From the prize announcement:

As late as 2001, the two particle detectors BaBar at Stanford, USA and Belle at Tsukuba, Japan, both detected broken symmetries independently of each other. The results were exactly as Kobayashi and Maskawa had predicted almost three decades earlier.

Electric dipole moment

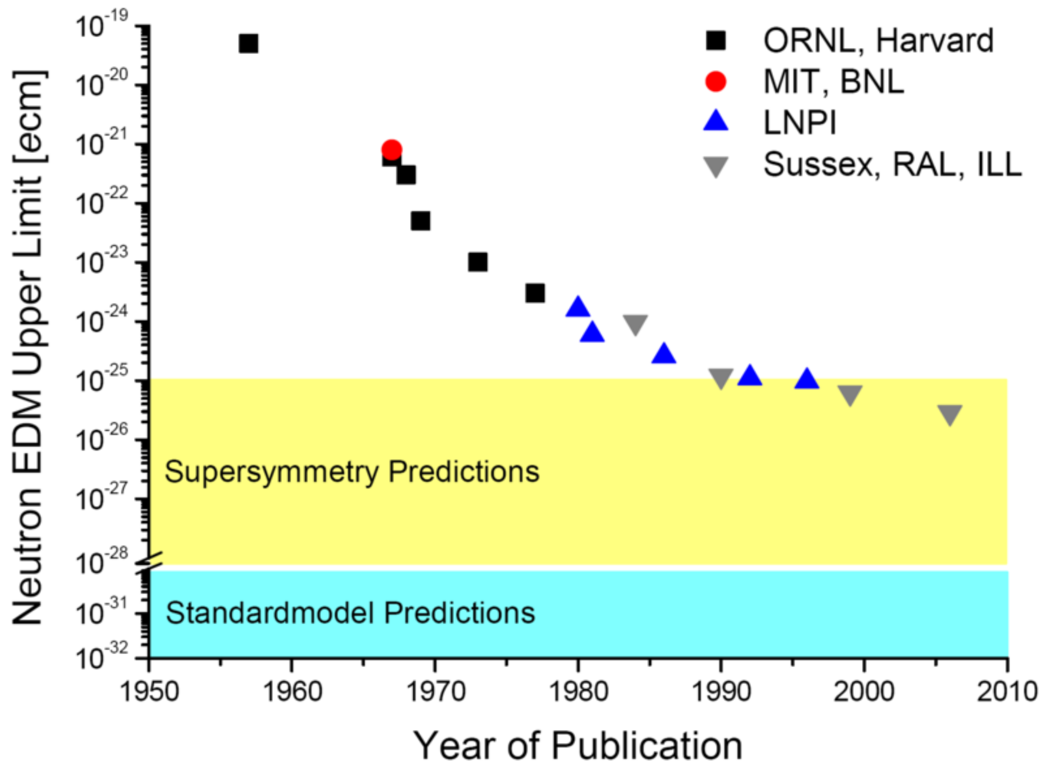
- An electric dipole moment in a particle with spin inherently violates time-reversal symmetry.
  - magnetic dipole changes direction under T; electric dipole does not.

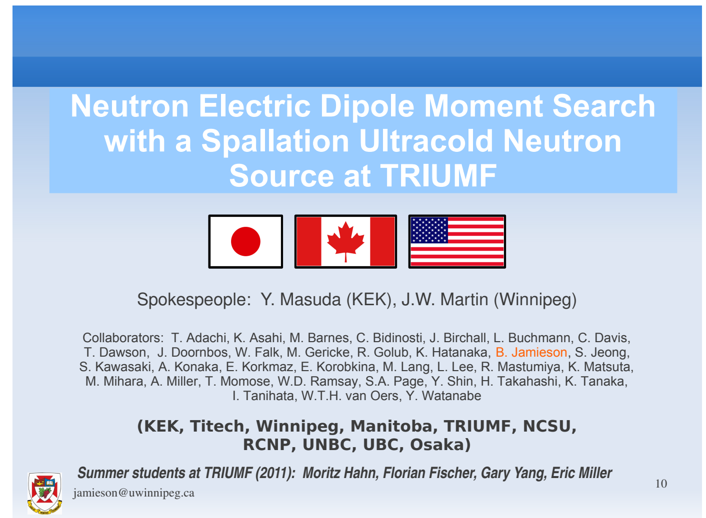
Electric and magnetic dipoles are parallel



Electric and magnetic dipoles are antiparallel

- But no evidence for dipole moment of the electron or neutron. And none expected in SM for current sensitivity.

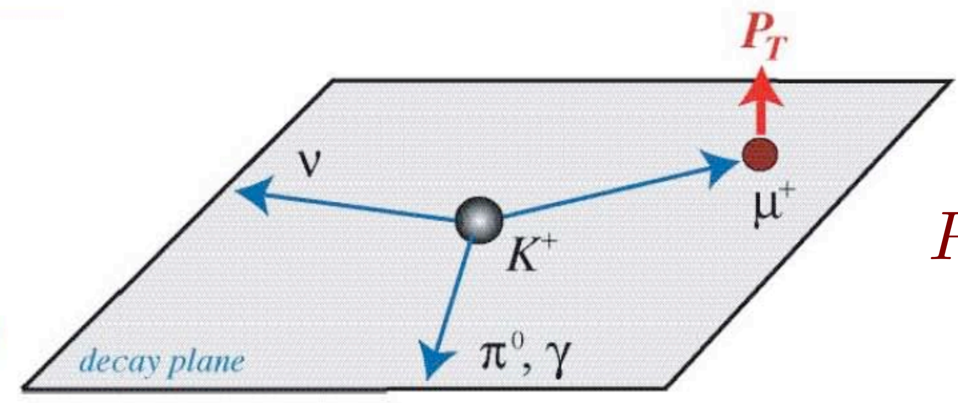




- TRIUMF/KEK is aiming to develop the world's most intense source of UCN, with the goal of constraining neutron EDM $< 1 \times 10^{-28}$ ecm (>2018).

TREK J-PARC E06

- Look for muon transverse polarization in $K^+ \to \pi^0 \mu^+ \nu_\mu$



$$P_T = \frac{\hat{\sigma}_\mu \cdot (\vec{p}_{\pi^0} \times \vec{p}_\mu)}{|\vec{p}_{\pi^0} \times \vec{p}_\mu|}$$

- Under T, $P_T \longrightarrow -P_T$, so a non-zero value implies T violation.
- SM $P_T \sim 10^{-7}$; FSI $P_T \sim$ few $\times 10^{-6}$; SUSY $P_T \sim 10^{-4}$
- KEK E246 $P_T < 5 \times 10^{-3}$ @ 90% CL
  TREK goal $P_T <$ few $\times 10^{-4}$.

CPLEAR

- CPLEAR presented 4σ evidence for asymmetry in
  $K^0 \to \bar{K}^0$ vs $\bar{K}^0 \to K^0$ Phys. Lett. B444, 43 (1998)
- Tag initial flavor via production,
  $p\bar{p} \to K^-\pi^+K^0$ vs $p\bar{p} \to K^+\pi^-\bar{K}^0$
- Tag final flavor via semileptonic decay

$$\left\langle \frac{R(\overline{\mathrm{K}}^0_{t=0} \to \mathrm{e}^+\pi^-\nu_{t=\tau}) - R(\mathrm{K}^0_{t=0} \to \mathrm{e}^-\pi^+\bar{\nu}_{t=\tau})}{R(\overline{\mathrm{K}}^0_{t=0} \to \mathrm{e}^+\pi^-\nu_{t=\tau}) + R(\mathrm{K}^0_{t=0} \to \mathrm{e}^-\pi^+\bar{\nu}_{t=\tau})} \right\rangle = (6.6 \pm 1.3_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}}) \times 10^{-3}$$

- Both CP and T violation; both lead to same observation.
- Some controversy in interpreting this as direct T violation; PDG says the measurement “is related to T violation”.

  Wolfenstein, Int. Jour. Mod. Phys. E8, 501 (1999)

Our measurement

- Concepts and methodology from
  J. Bernabeu, F. Martinez-Vidal, and P. Villanueva-Perez,
  J. High Energy Phys. 08 (2012) 64.
- Uses the same event sample (almost) as the sin2β measurement, but a different data treatment.
- Terminology requires a bit of care!

- We could have made this measurement years ago.

Entangled state

- The basis for this measurement (and that of CPV) is that the two neutral B's produced in Y(4S) decay are entangled.

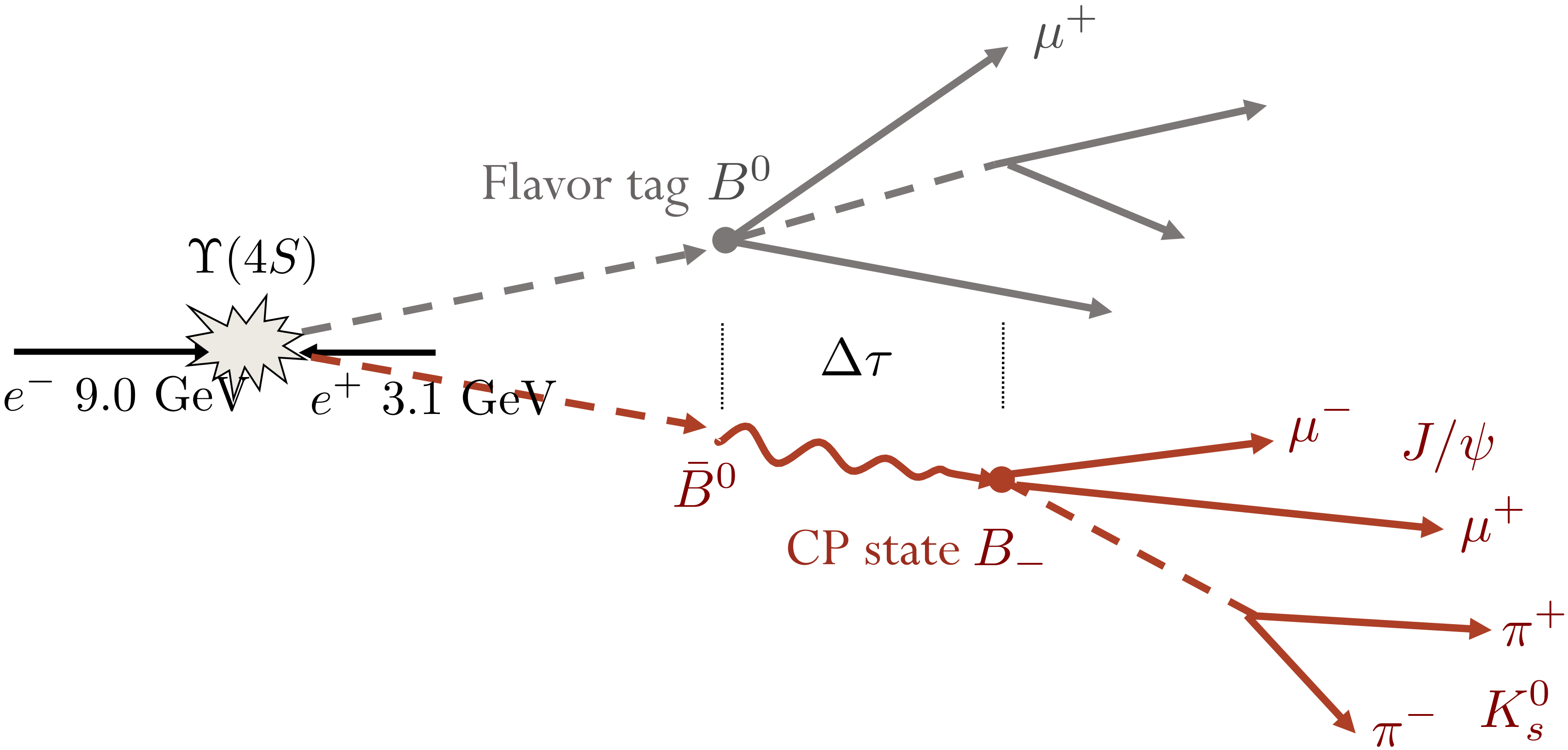
- *Flavor basis* $B^0\bar{B}^0$
  - states of definite quark content
- Or *CP basis* B_+B_-
  - CP even $\quad B_+ = (B^0 + \bar{B}^0)/\sqrt(2)$
    CP odd $\quad B_- = (B^0 - \bar{B}^0)/\sqrt(2)$
  - The use of + and – to refer to neutral B states can be unfortunately confusing.

Time evolution

- When the first B decays, it establishes ("tags") the nature of the second B at that time.
- We are studying the evolution of the second B from when it was tagged to when it decays at later time $\Delta\tau$.
- The events of interest have one B decay in which we can identify the flavor, and the other where we can identify the CP state.
- Tagging:

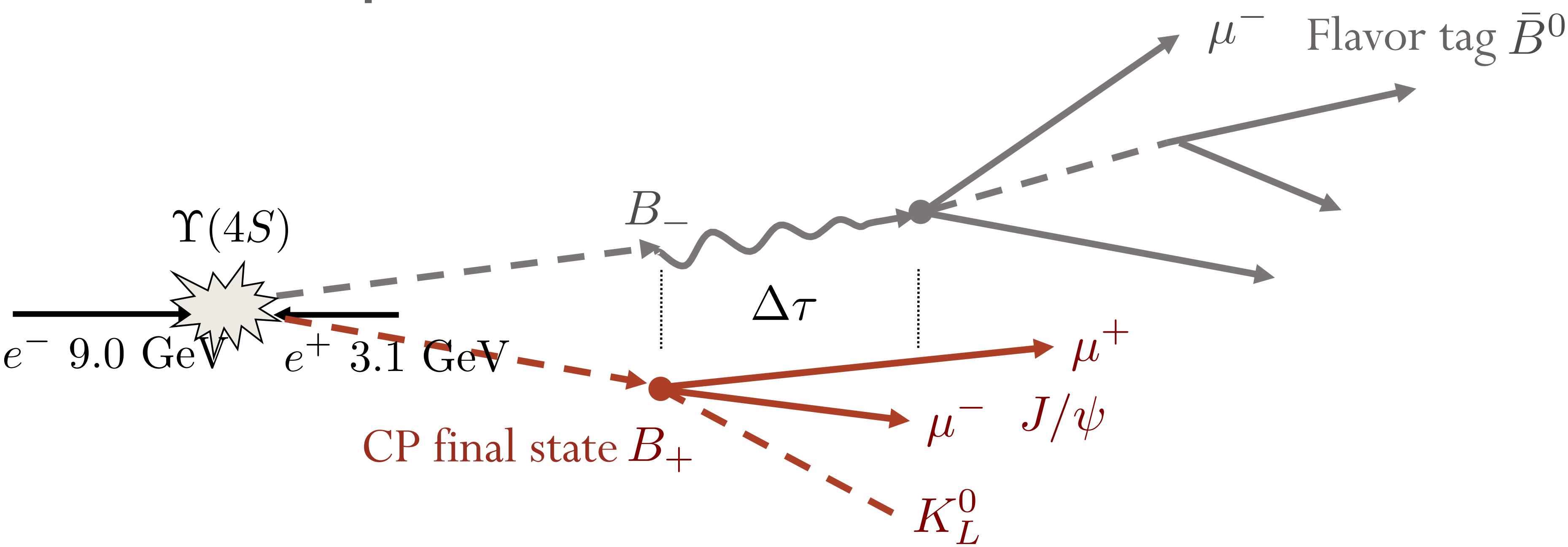
$$\begin{aligned} \ell^- X &\Rightarrow \bar{B}^0 \\ \ell^+ X &\Rightarrow B^0 \\ J/\psi K_L^0 &\Rightarrow B_+ \\ J/\psi K_s^0 &\Rightarrow B_- \end{aligned}$$

Example of T symmetry observable



- 1^{st} B decays to $\ell^+ X \ \ (B^0) \Rightarrow 2^{\text{nd}}$ B was a $\bar{B}^0$ at that moment.
- 2^{nd} B decays at later time $\Delta\tau$ to $J/\psi K_s^0 \ \ (B_-)$
- Time-ordered reconstructed event is $(\ell^+, J/\psi K_s^0)$
- Transition was $\bar{B}^0 \to B_-$

Example continued



- 1^{st} B decays to $J/\psi K_L^0$ $(B_+) \Rightarrow$ 2^{nd} B was a B_- at that moment.
- 2^{nd} B decays at later time $\Delta\tau$ to $\ell^- X$ $(\bar{B}^0)$
- Reconstructed event is $(J\psi K_L^0, \ell^-)$
- Transition was $B_- \to \bar{B}^0$, related by T symmetry to 1^{st} case.
- A difference between these rates implies T symmetry violation

$$\bar{B}^0 \to B_- \quad \Leftarrow T \Rightarrow \quad B_- \to \bar{B}^0$$

- Eight different transitions related by different symmetries.
- First pair is the T symmetry example I just showed.

$$\bar{B}^0 \to B_- \quad \Leftarrow T \Rightarrow \quad B_- \to \bar{B}^0$$

$$B^0 \to B_- \quad \Leftarrow T \Rightarrow \quad B_- \to B^0$$

$$\bar{B}^0 \to B_+ \quad \Leftarrow T \Rightarrow \quad B_+ \to \bar{B}^0$$

$$B^0 \to B_+ \quad \Leftarrow T \Rightarrow \quad B_+ \to B^0$$

- Eight different transitions related by different symmetries.
- Three other pairs of transitions related by T.

$$\begin{array}{ccc}
\bar{B}^0 \to B_- & \Leftarrow T \Rightarrow & B_- \to \bar{B}^0 \\
\Uparrow & \nwarrow \quad \nearrow & \Uparrow \\
CP & CPT & CP \\
\Downarrow & \swarrow \quad \searrow & \Downarrow \\
B^0 \to B_- & \Leftarrow T \Rightarrow & B_- \to B^0
\end{array}$$

$$\begin{array}{ccc}
\bar{B}^0 \to B_+ & \Leftarrow T \Rightarrow & B_+ \to \bar{B}^0 \\
\Uparrow & \nwarrow \quad \nearrow & \Uparrow \\
CP & CPT & CP \\
\Downarrow & \swarrow \quad \searrow & \Downarrow \\
B^0 \to B_+ & \Leftarrow T \Rightarrow & B_+ \to B^0
\end{array}$$

- Eight different transitions related by different symmetries.
- These transitions are related by CP and CPT as well.
- Each transition represents a separate set of events.

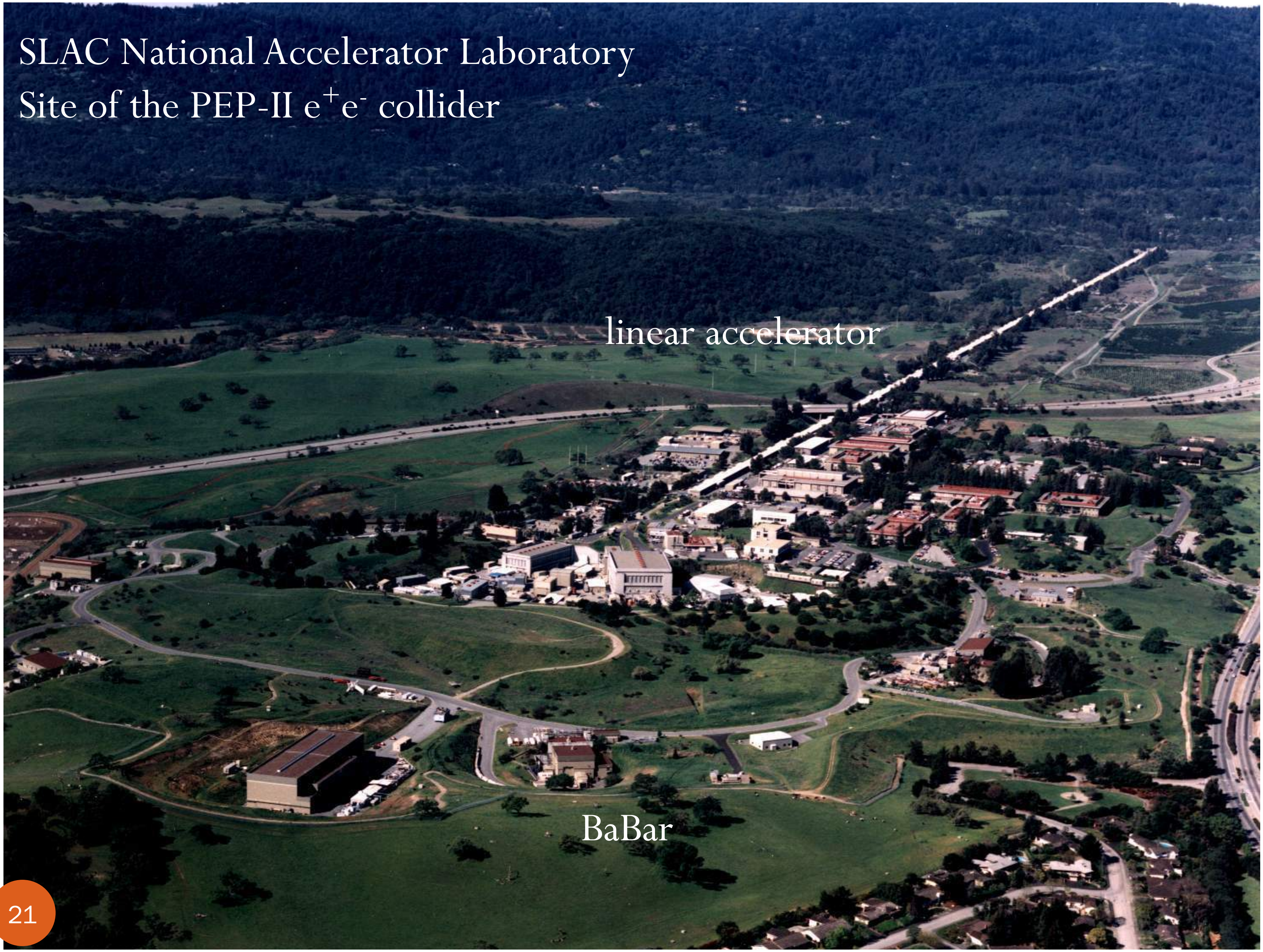
$$
\begin{array}{ccc}
\bar{B}^0 \to B_- & \Leftarrow T \Rightarrow & B_- \to \bar{B}^0 \\
\Uparrow & \nwarrow & \\
CP & CPT & \\
\Downarrow & \searrow & \\
B^0 \to B_- & & B_- \to B^0 \\
 & & \\
\bar{B}^0 \to B_+ & & B_+ \to \bar{B}^0 \\
 & \nwarrow & \Uparrow \\
 & CPT & CP \\
 & \searrow & \Downarrow \\
B^0 \to B_+ & \Leftarrow T \Rightarrow & B_+ \to B^0
\end{array}
$$

- Analysis consists of comparing the time dependence of the transitions related by the various transitions.
- Not all independent – show results for six.

$$
\begin{array}{ccc}
(\ell^+, K_s^0) & \Leftarrow T \Rightarrow & (K_L^0, \ell^-) \\
\Uparrow & & \\
CP & \Leftarrow\!\!\!\nwarrow\; CPT \;\searrow\!\!\!\Rightarrow & \\
\Downarrow & & \\
(\ell^-, K_s^0) & & (K_L^0, \ell^+)
\end{array}
$$

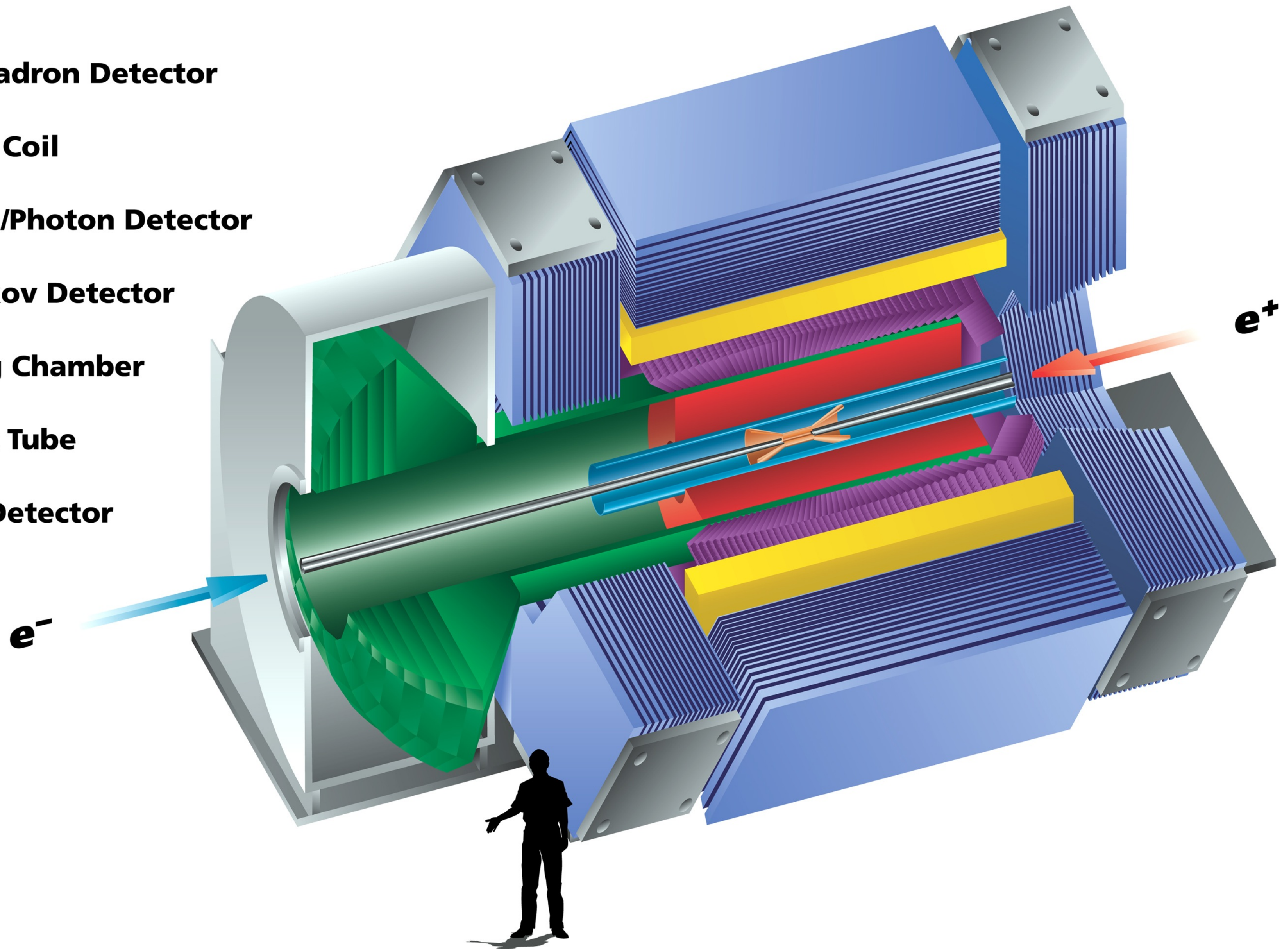
$$
\begin{array}{ccc}
(\ell^+, K_L^0) & & (K_s^0, \ell^-) \\
& & \Uparrow \\
& \Leftarrow\!\!\!\nwarrow\; CPT \;\searrow\!\!\!\Rightarrow & CP \\
& & \Downarrow \\
(\ell^-, K_L^0) & \Leftarrow T \Rightarrow & (K_s^0, \ell^+)
\end{array}
$$

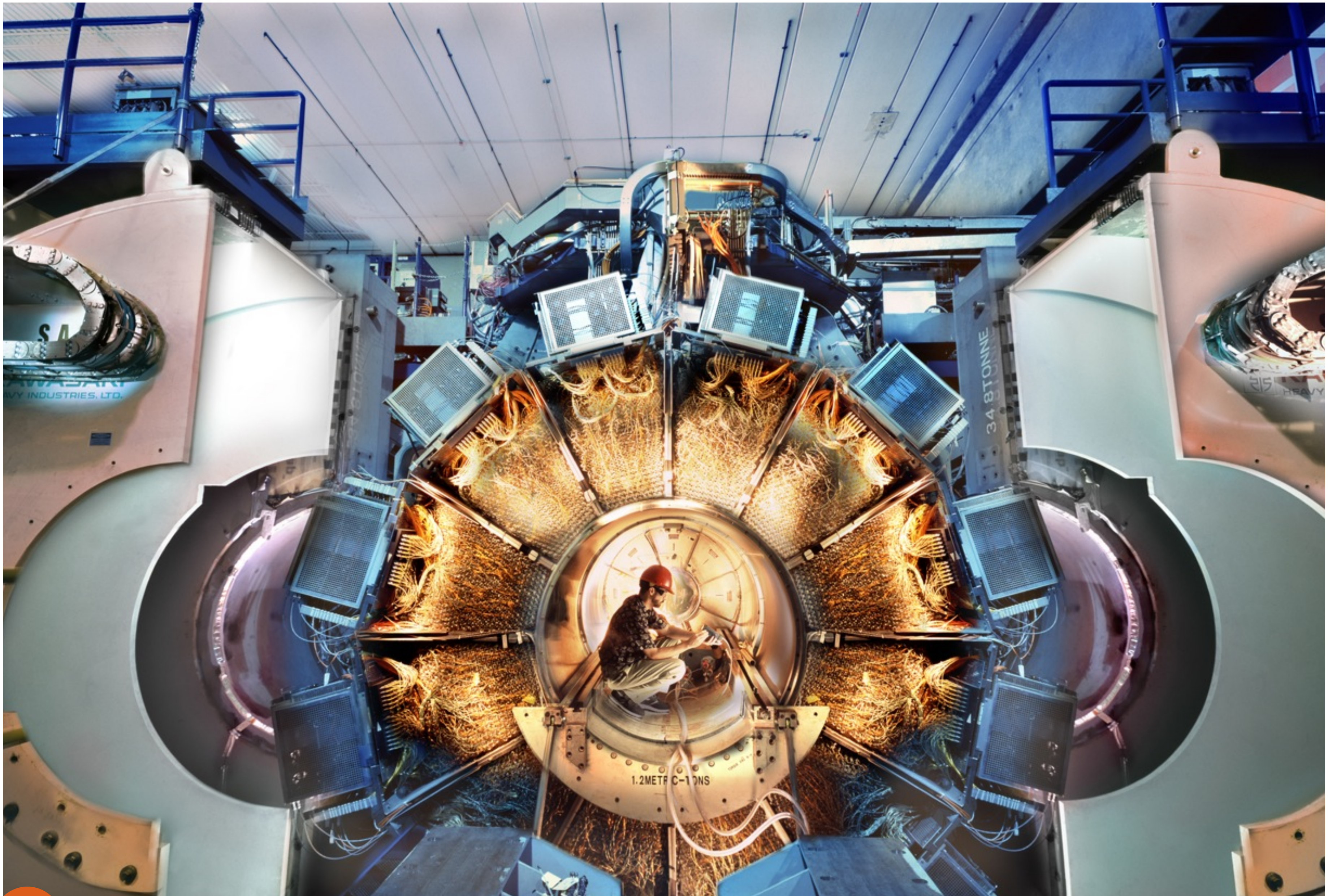
- Same transitions, labeled by the B decays.


SLAC National Accelerator Laboratory
Site of the PEP-II e^+e^- collider
linear accelerator
BaBar

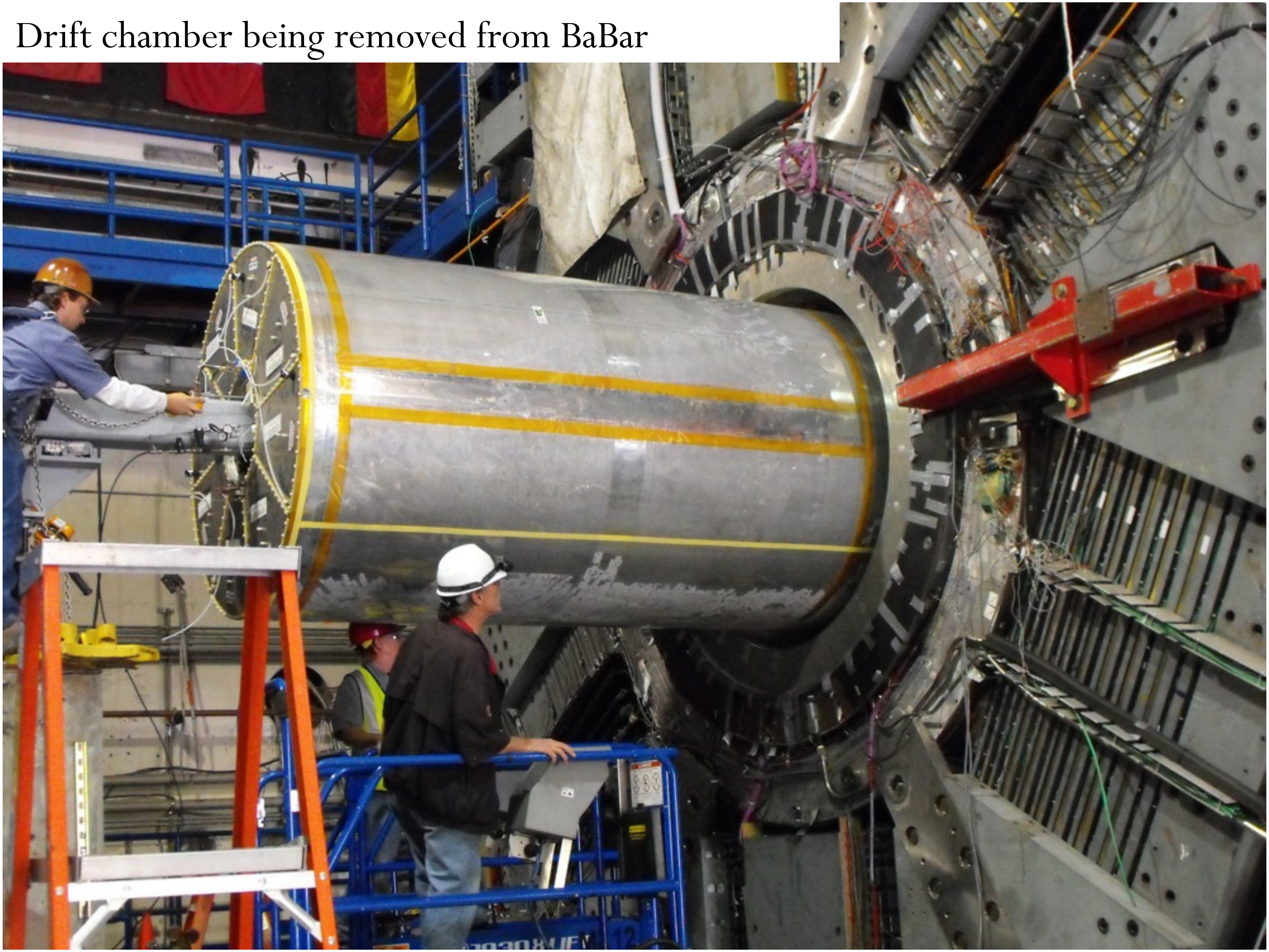
BABAR Detector

- Muon/Hadron Detector
- Magnet Coil
- Electron/Photon Detector
- Cherenkov Detector
- Tracking Chamber
- Support Tube
- Vertex Detector

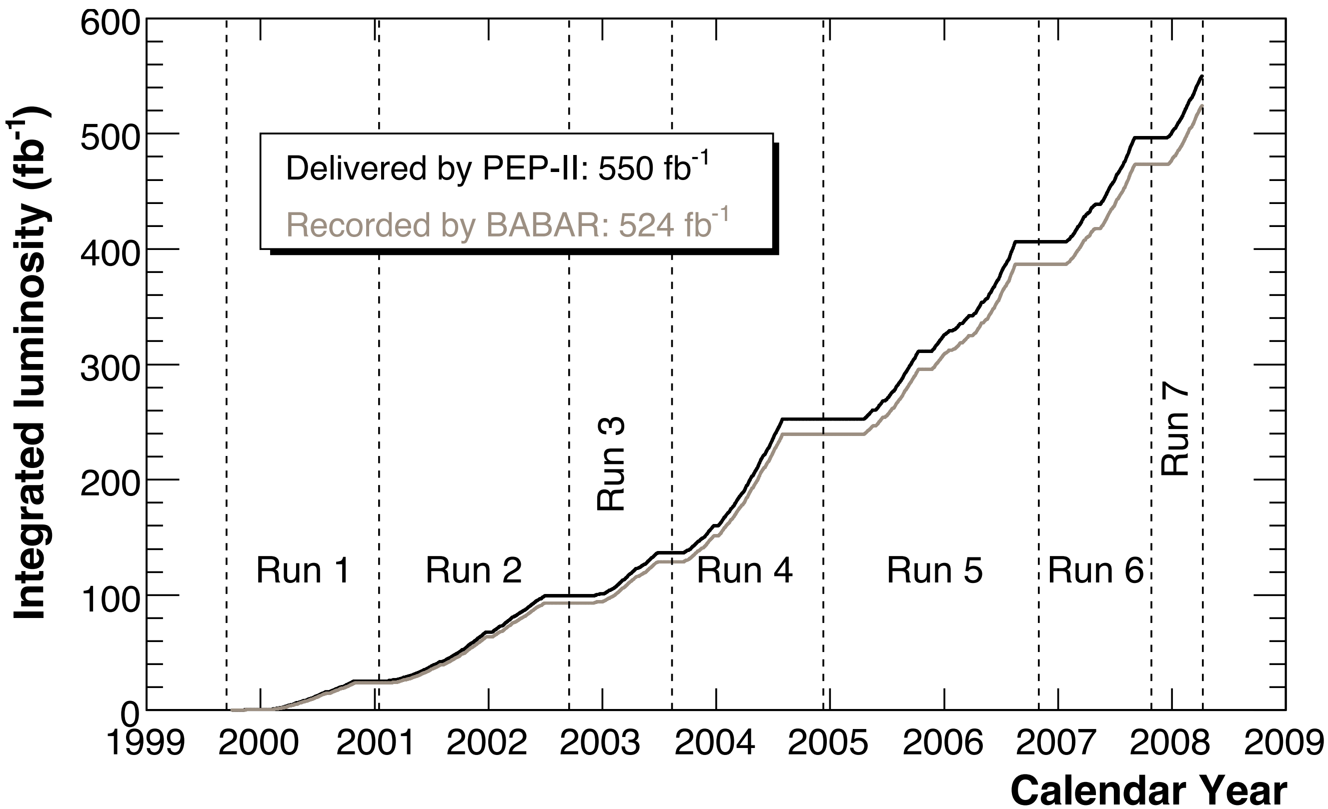




Drift chamber being removed from BaBar



Luminosity



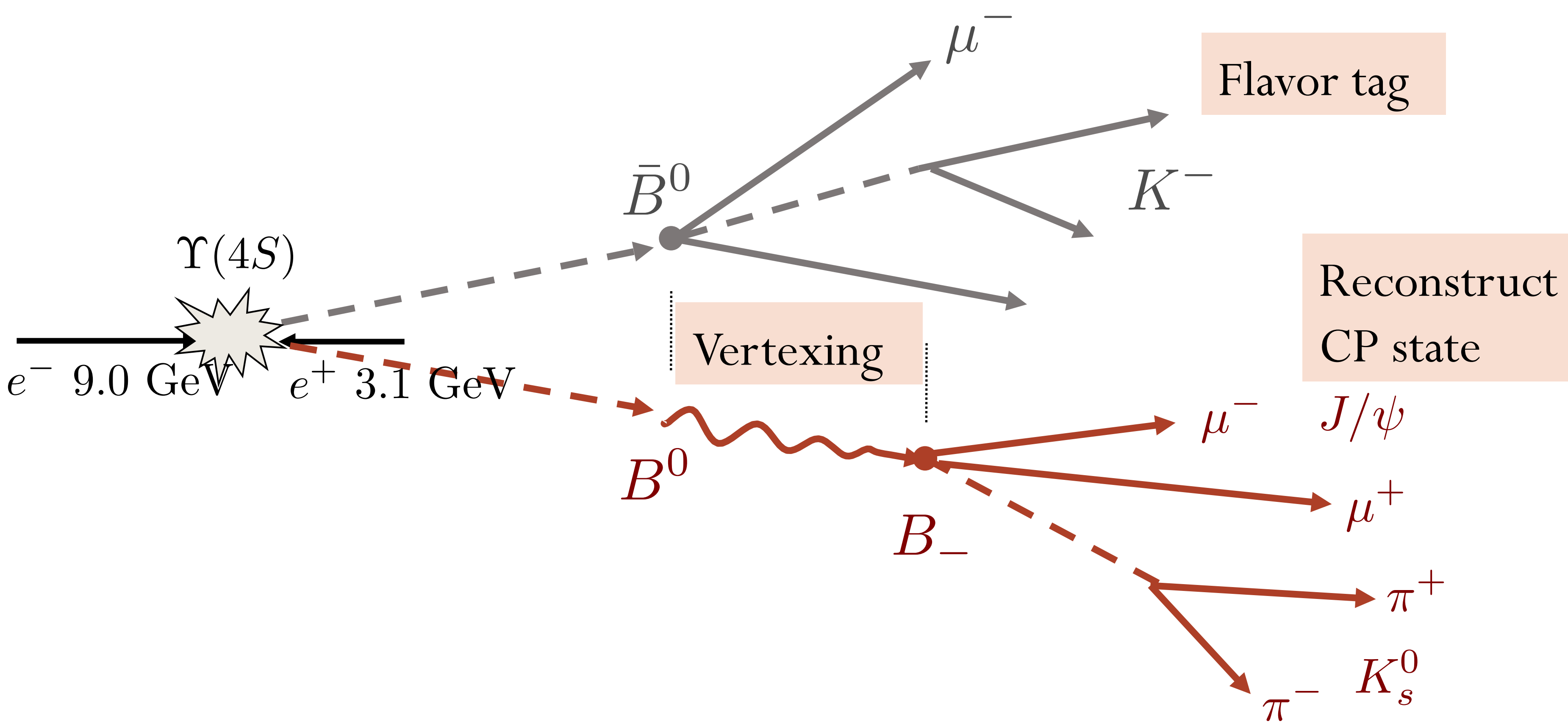
- 424 fb^{-1} at the Υ(4S) = 471M $B\bar{B}$
- 44 fb^{-1} 40 MeV below the Υ(4S)

Runs 1–6

- 121M Υ(3S)
- 98M Υ(2S)

Run 7

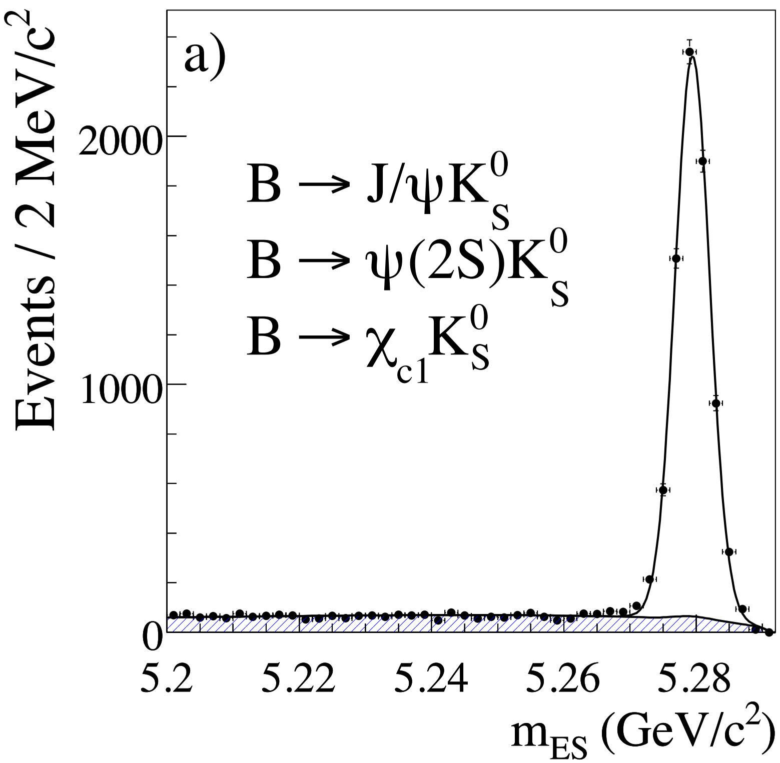
Experimental issues

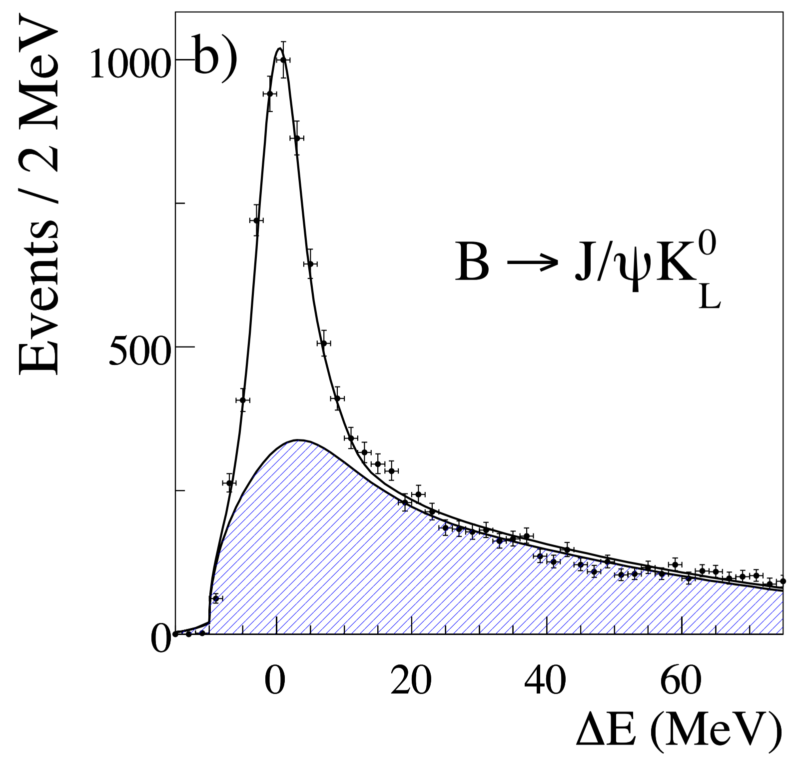


- Vertexing: $\Delta Z \approx \beta\gamma c\Delta\tau \sim 250\mu\mathrm{m}$
  Experimental resolution dominated by flavor tag vertex.

CP samples

- Same events as last sin2β paper, excluding $\eta_C K_s$ and $J/\psi\ K^{*0}$ ($\longrightarrow K_s\pi^0$)
  Phys. Rev. D79 (2009) 072009





7796 events
purity 87–96%

5813 events
purity 56%

Flavor tagging

- Use a neural net to combine information about prompt leptons, kaons, soft π^+ from D^{*+} decays, and high-momentum tracks.
  - train on MC.
- Evaluate flavor tagging performance and obtain vertex resolution function using a high-statistics "B-flavor" sample.

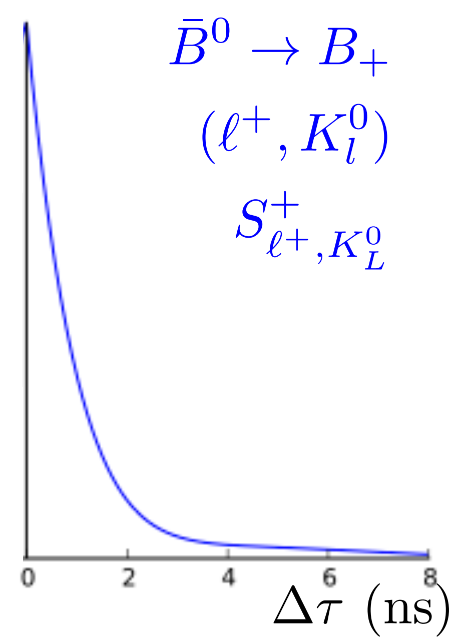
$$
\begin{aligned}
B^0 \to & D^{(*)-}\pi^+ \\
& D^{(*)-}\rho(770)^+ \\
& D^{(*)-}a_1(1260)^+ \\
& J\psi K^{*0}\ \ (\to K^+\pi^-)
\end{aligned}
$$

Signal PDF

- The time dependence of each of the eight transformations is parameterized as:

$$e^{-\Gamma_d \Delta\tau}\{1 + S^{\pm}_{\alpha,\beta}\sin(\Delta m_d \Delta\tau) + C^{\pm}_{\alpha,\beta}\cos(\Delta m_d \Delta\tau)\}$$

- α labels the observed flavor decay = ℓ^+ or ℓ^-
- β labels the observed CP decay K^0_s or K^0_L
- + = flavor decay occurs before CP decay
  − = flavor decay occurs after CP decay



- e.g. $\bar{B}^0 \to B_- \;\; (\ell^+, K_s^0)$ is characterized by $S^+_{\ell^+, K_s^0}$
- T-reversed transition is $B_- \to \bar{B}^0 \;\; (K_L^0, \ell^-)$, characterized by $S^-_{\ell^-, K_L^0}$
- If T were a good symmetry, $S^+_{\ell^+, K_s^0}$ and $S^-_{\ell^-, K_L^0}$ would be equal.
- Quantify T violation by their difference, $\Delta S_T^+ \equiv S^-_{\ell^-, K_L^0} - S^+_{\ell^+, K_s^0}$
- In the SM, $\Delta S_T^+ = -2\sin 2\beta = -1.4$

  $\Delta C_T^+ = 0$

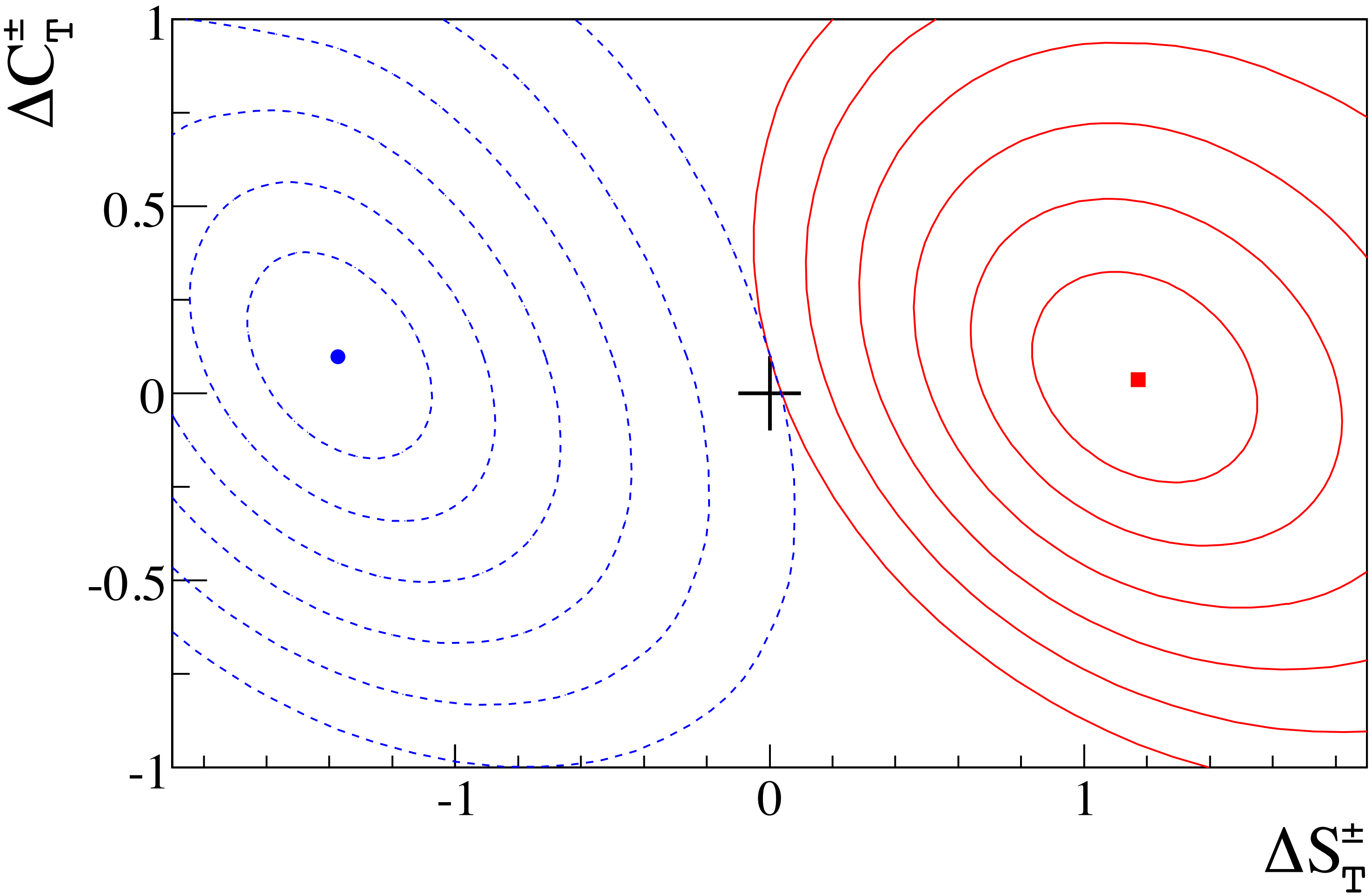
Fit

- Simultaneous unbinned maximum likelihood fit to the eight $\Delta\tau$ distributions.
- 16 signal parameters: $8 \times (S^{\pm}_{\alpha,\beta}, C^{\pm}_{\alpha,\beta})$
- 11 background parameters. Many more fixed using control samples, background samples, world averages.
  - as per sin2β analysis.

Results

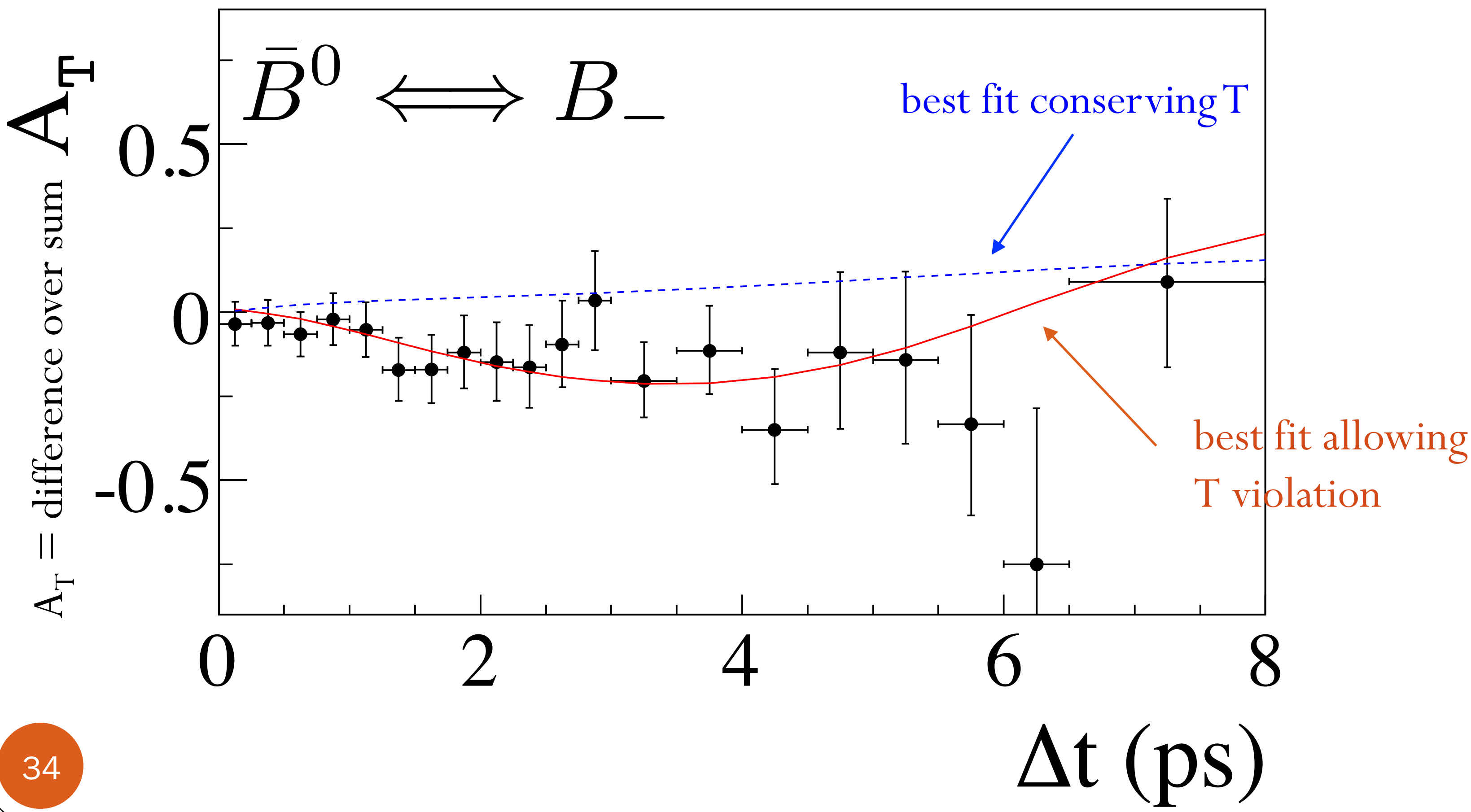
$\Delta S_T^+ = S^-_{\ell^-,K_L^0} - S^+_{\ell^+,K_S^0}$	$-1.37 \pm 0.14 \pm 0.06$	T is violated
$\Delta S_T^- = S^+_{\ell^-,K_L^0} - S^-_{\ell^+,K_S^0}$	$1.17 \pm 0.18 \pm 0.11$	
$\Delta C_T^+ = C^-_{\ell^-,K_L^0} - C^+_{\ell^+,K_S^0}$	$0.10 \pm 0.14 \pm 0.08$	
$\Delta C_T^- = C^+_{\ell^-,K_L^0} - C^-_{\ell^+,K_S^0}$	$0.04 \pm 0.14 \pm 0.08$	
$\Delta S_{CP}^+ = S^+_{\ell^-,K_S^0} - S^+_{\ell^+,K_S^0}$	$-1.30 \pm 0.11 \pm 0.07$	CP is violated
$\Delta S_{CP}^- = S^-_{\ell^-,K_S^0} - S^-_{\ell^+,K_S^0}$	$1.33 \pm 0.12 \pm 0.06$	
$\Delta C_{CP}^+ = C^+_{\ell^-,K_S^0} - C^+_{\ell^+,K_S^0}$	$0.07 \pm 0.09 \pm 0.03$	
$\Delta C_{CP}^- = C^-_{\ell^-,K_S^0} - C^-_{\ell^+,K_S^0}$	$0.08 \pm 0.10 \pm 0.04$	
$\Delta S_{CPT}^+ = S^-_{\ell^+,K_L^0} - S^+_{\ell^+,K_S^0}$	$0.16 \pm 0.21 \pm 0.09$	CPT is not violated
$\Delta S_{CPT}^- = S^+_{\ell^+,K_L^0} - S^-_{\ell^+,K_S^0}$	$-0.03 \pm 0.13 \pm 0.06$	
$\Delta C_{CPT}^+ = C^-_{\ell^+,K_L^0} - C^+_{\ell^+,K_S^0}$	$0.14 \pm 0.15 \pm 0.07$	
$\Delta C_{CPT}^- = C^+_{\ell^+,K_L^0} - C^-_{\ell^+,K_S^0}$	$0.03 \pm 0.12 \pm 0.08$	

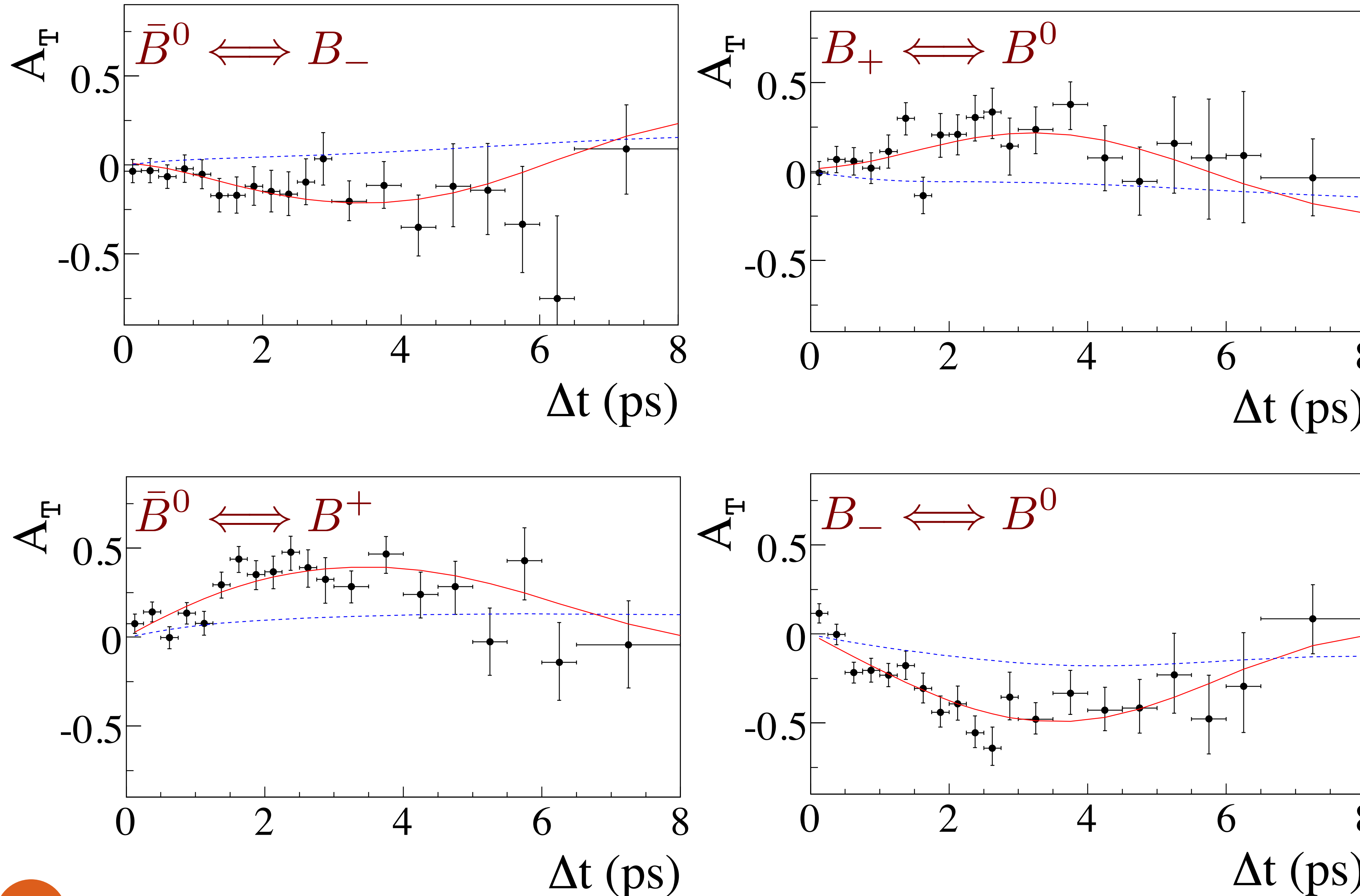
T violation has significance > 10σ



Raw asymmetry

- Illustrate asymmetry using events in cleanest signal region, purest flavor tags only.





A_T
$\bar{B}^0 \Longleftrightarrow B_-$
$B_+ \Longleftrightarrow B^0$
$\bar{B}^0 \Longleftrightarrow B^+$
$B_- \Longleftrightarrow B^0$
0.5
0
-0.5
0 2 4 6 8
Δt (ps)

Systematic errors

Systematic source	ΔS_T^+	ΔS_T^-
Interaction region	0.011	0.035
Flavor misID probabilities	0.022	0.042
Δt resolution	0.030	0.050
$J/\psi K_L^0$ background	0.033	0.038
Background fractions and CP content	0.029	0.021
m_{ES} parameterization	0.011	0.002
Γ_d and Δm_d	0.001	0.005
CP violation for flavor ID categories	0.018	0.019
Fit bias	0.010	0.072
$\Delta\Gamma_d/\Gamma_d$	0.004	0.003
PDF normalization	0.013	0.019
Total	0.064	0.112

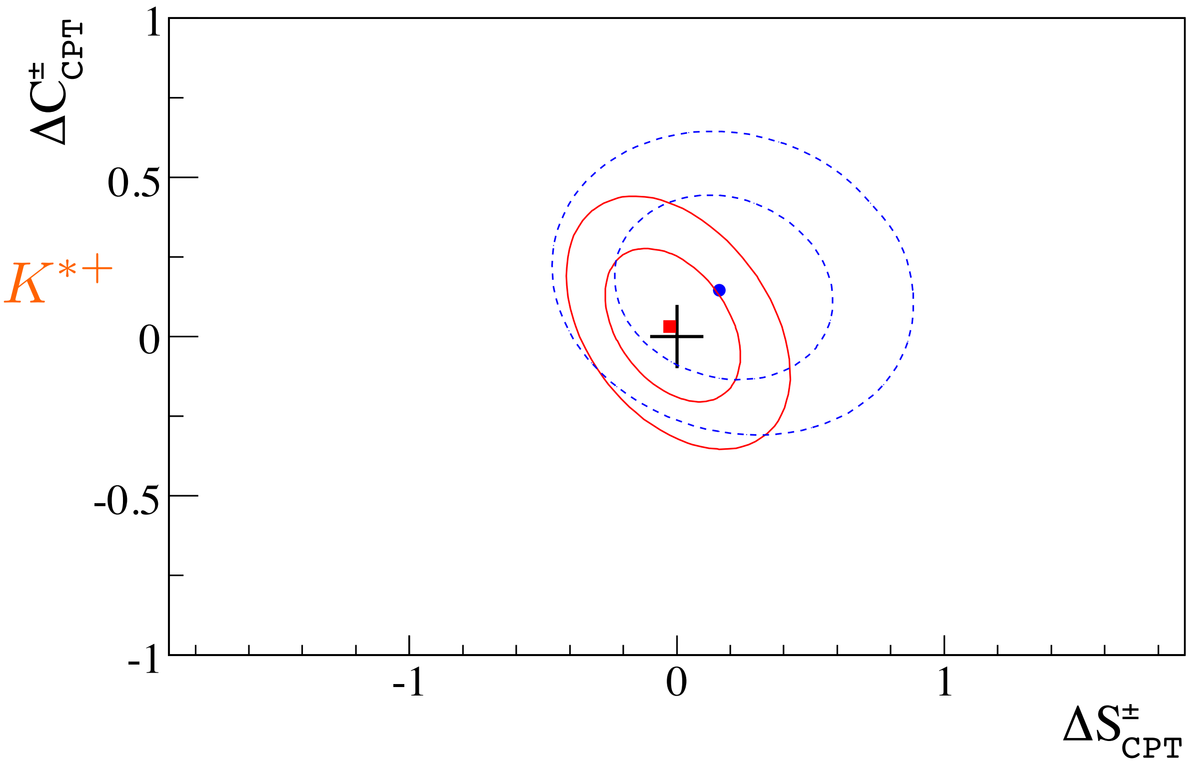
- CPV in K system $\Rightarrow$ J/ψ K_s and J/ψ K_L are not strictly orthogonal, but effect is small compared to others listed here.

Cross checks

- Get same values for S and C as last sin2β paper when fitting a single S and C pair.
- Using charged B control samples gives null result.

replace $c\bar{c}K_s^0$ with $c\bar{c}K^+$

replace $J/\psi K_L^0$ with $J/\psi K^{*+}$



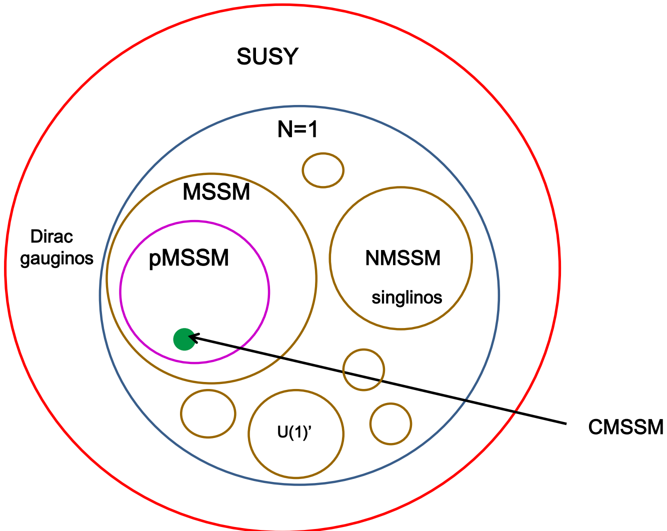
Light Higgs searches

arXiv:1210.5669 [hex-ex]

arXiv:1210.0287 [hex-ex]

Introduction

- A light Higgs A^0 is predicted by extensions to SUSY such as Next-to-Minimal SUSY.
  - NMSSM is meant to be the smallest SUSY extension that avoids parameter fine-tuning.
  - R. Dermisek and J. F. Gunion, Phys. Rev. Lett. 95, 041801 (2005).



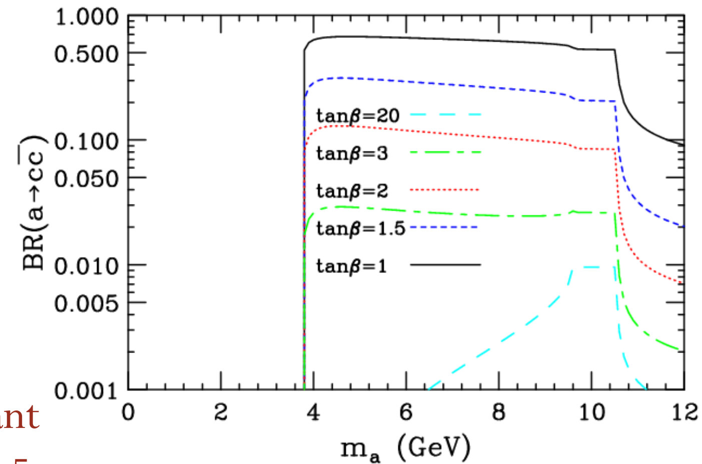
T. Rizzo

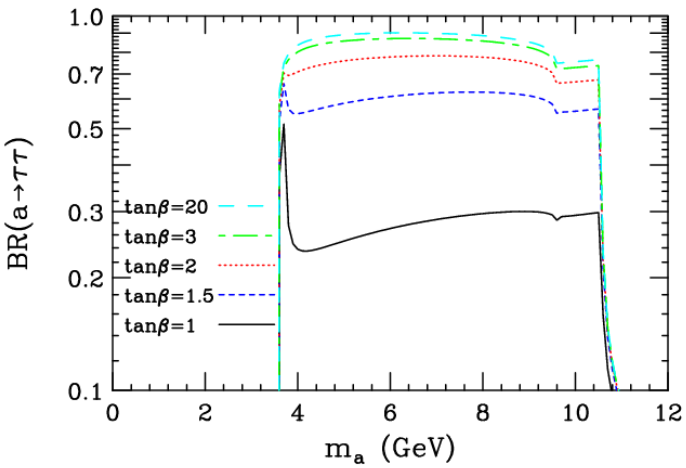
- Would be produced via $\Upsilon \rightarrow \gamma A^0$ with BF in the range 10^{-6} to few 10^{-4}
  - $\Upsilon(1S)$, $\Upsilon(2S)$, or $\Upsilon(3S)$

Higgs decay BF

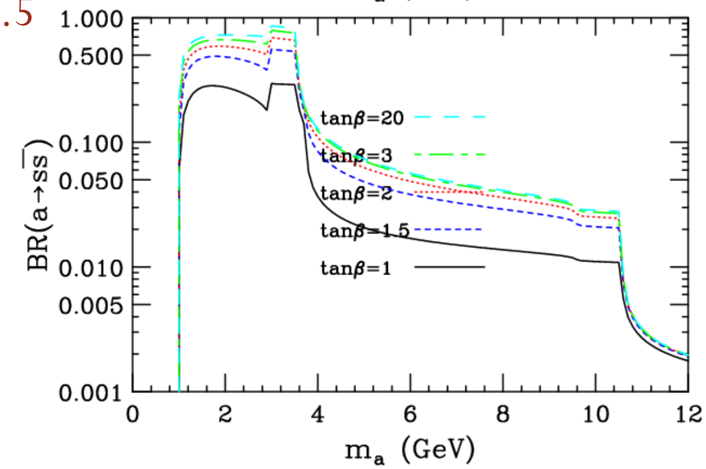
$$\mathcal{B}(A^0 \to f\bar{f}) \propto m_f^2/\tan^2\beta \ \text{ up-type fermion}$$

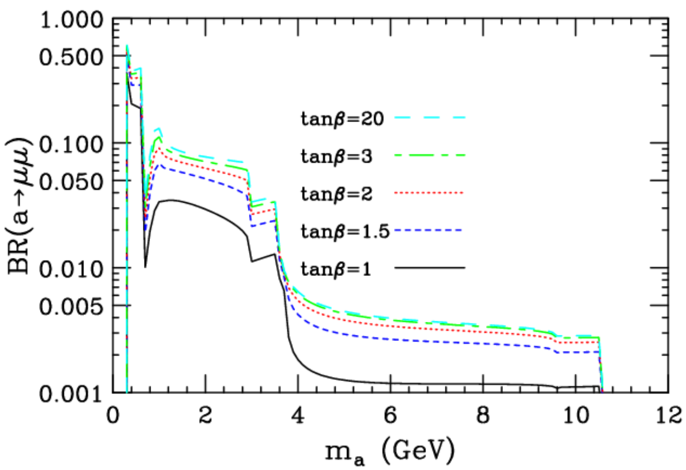
$$\mathcal{B}(A^0 \to f\bar{f}) \propto m_f^2 \tan^2\beta \ \text{ down-type fermion}$$

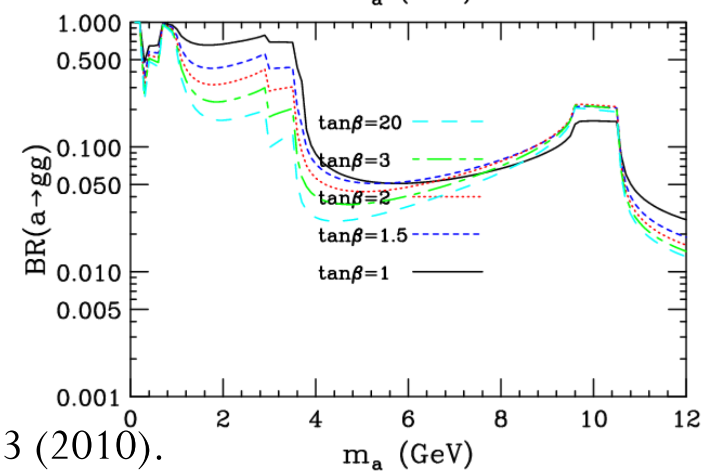




$\tau^+\tau^-$ dominant for $\tan\beta > 1.5$







R. Dermisek and J. F. Gunion, Phys. Rev. D 81, 075003 (2010).

Previous results

- $\Upsilon(2S,3S) \to \gamma A^0,\ A^0 \to \mu^+\mu^-$ Phys. Rev. Lett. 103, 081803 (2009)
- $\Upsilon(3S) \to \gamma A^0,\ A^0 \to \tau^+\tau^-$ Phys. Rev. Lett. 103, 181801 (2009)
- $\Upsilon(2S,3S) \to \gamma A^0,\ A^0 \to \text{hadrons}$ Phys. Rev. Lett. 107, 221803 (2011)
- $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S),\ \Upsilon(1S) \to \gamma A^0,\ A^0 \to \ \text{invisible}$

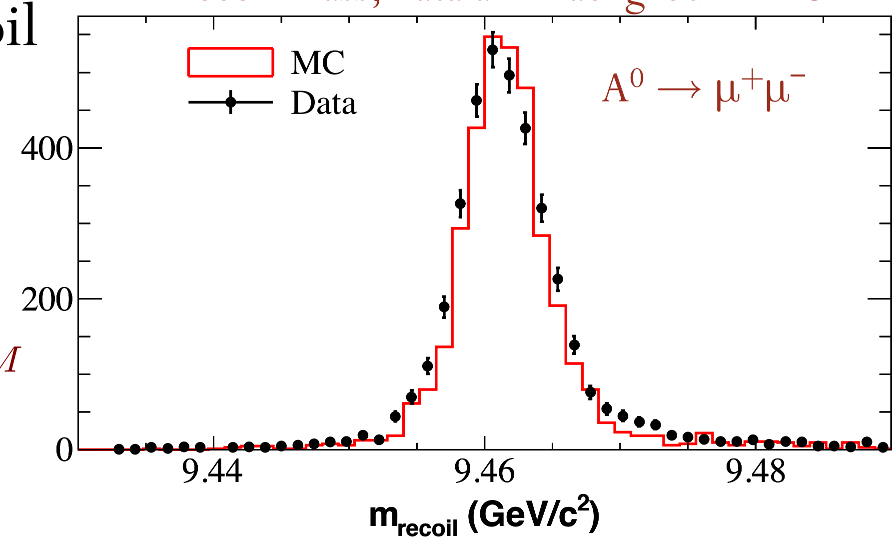
  Phys. Rev. Lett. 107, 021804 (2011)

- Today:
  - $\Upsilon(1S) \to \gamma A^0,\ A^0 \to \tau^+\tau^-$ arXiv:1210.5669 [hex-ex]
  - $\Upsilon(1S) \to \gamma A^0,\ A^0 \to \mu^+\mu^-$ arXiv:1210.0287 [hex-ex]

Method

- $\Upsilon(2S) \to \pi^+\pi^-\Upsilon(1S)$ (BF = 18%) produces a sample of Υ(1S) with essentially no e^+e^- annihilation background.
- $\Upsilon(3S) \to \pi^+\pi^-\Upsilon(1S)$ (BF = 4.4%) is almost as good.
- Contrast to Υ(2S,3S) direct decay, where $e^+e^- \to \gamma\ell^+\ell^-$ has the same final state as signal.
- Variety of kinematic variables to select the $\pi^+\pi^-$, but the recoil mass is most powerful.

Recoil mass, data and background MC



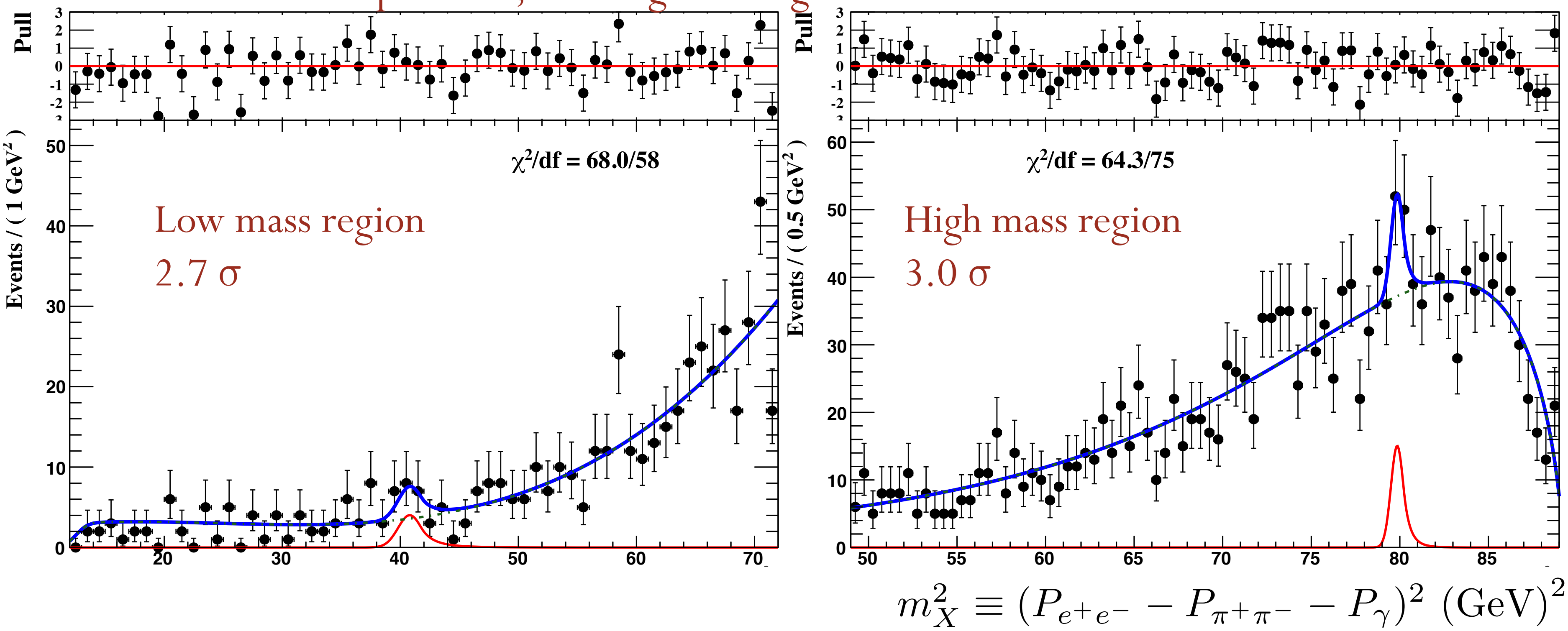
$$m^2_{\rm recoil} = M^2_{\Upsilon}(2S) + m^2_{\pi\pi} - 2M_{\Upsilon(2S)}E^{CM}_{\pi\pi}$$

$A^0 \rightarrow \tau^+ \tau^-$

- Both taus decay to single tracks, including at least 1 lepton.
- Optimize selection criteria separately for $3.6 < M_A < 8.0$ GeV/c^2 and $8.0 < M_A < 9.2$ GeV.
  - low energy photon background is very different
  - NN to select the $\tau^+\tau^-$.
- Look for a peak in mass recoiling against the $\pi^+\pi^-$ and the monochromatic photon.

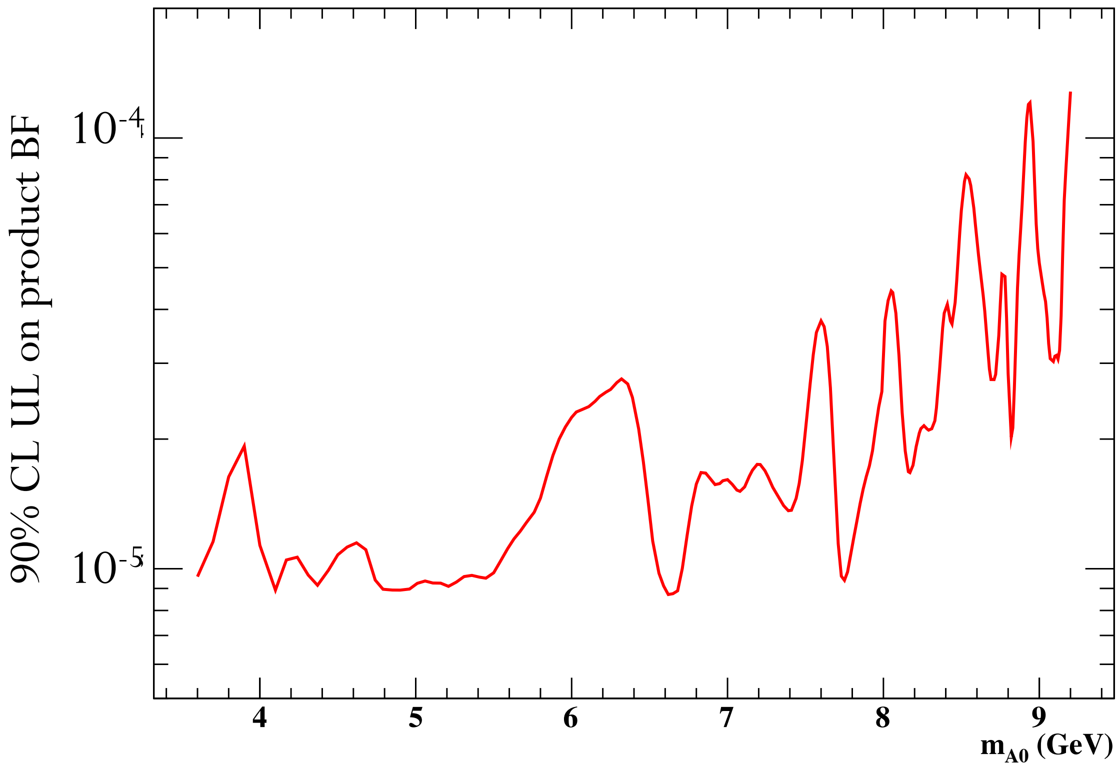
$A^0 \to \tau^+ \tau^-$ mass spectrum

A^0 candidate mass spectrum, showing most significant fluctuations



- Test 201 different A^0 mass hypotheses.
- 7.5% of Toy experiments see $\geq 3.0\sigma$ fluctuation. No signal.

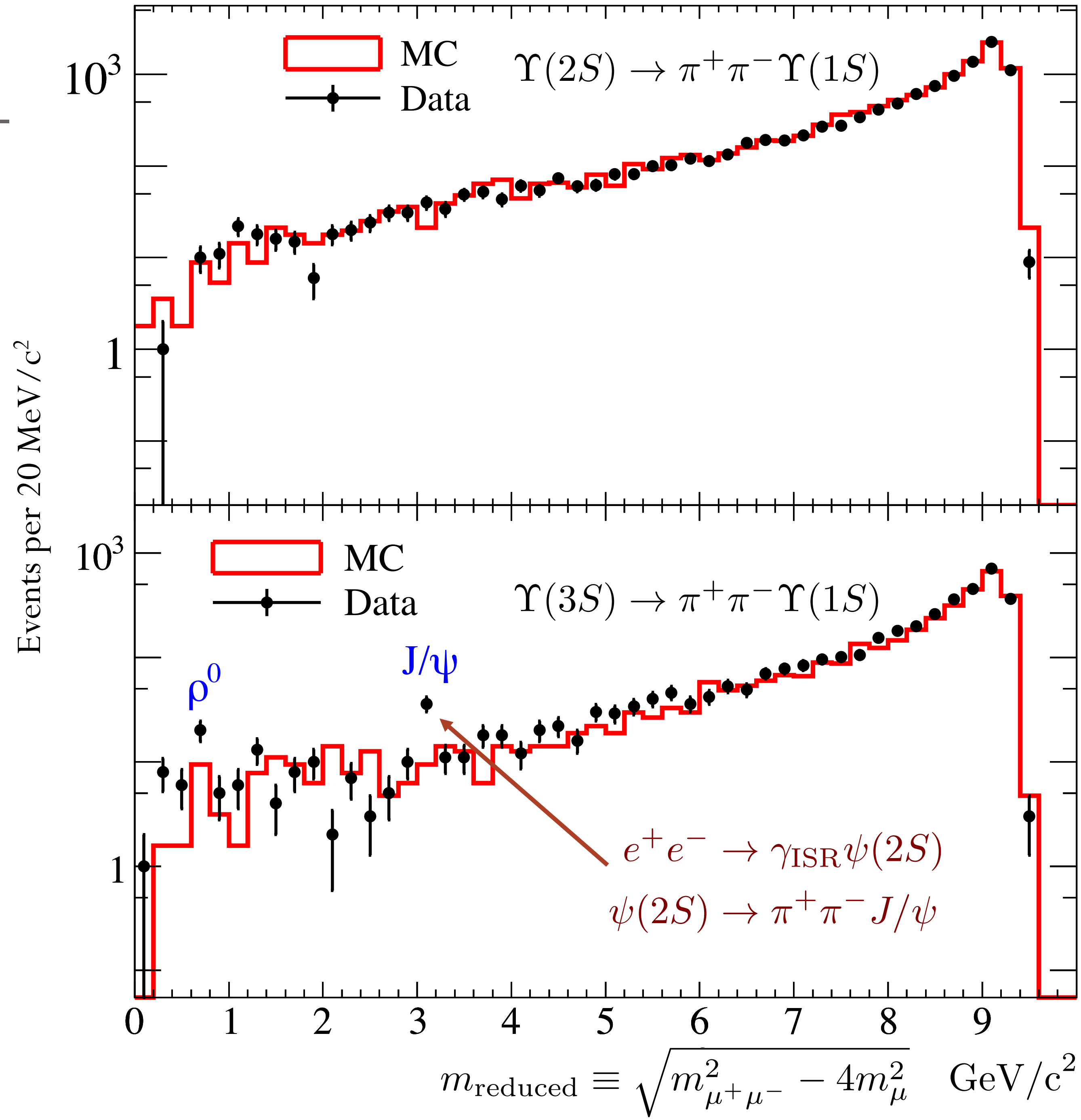
Upper limits on $\mathcal{B}(\Upsilon(1S)) \to \gamma A^0)\mathcal{B}(A^0 \to \tau^+\tau^-)$



- Generally comparable or better limits than $\Upsilon(3S) \to \gamma A^0$ analysis.

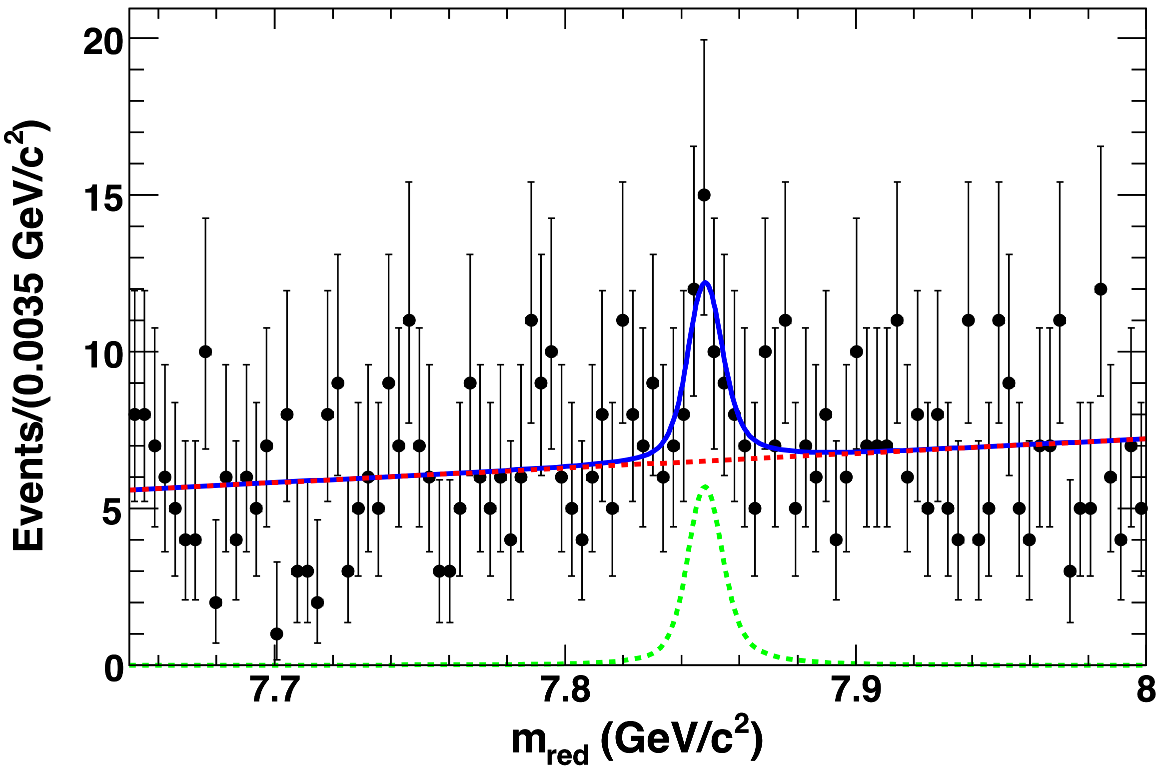
$A^0 \to \mu^+\mu^-$

Not a fit, just MC overlaid on data



$A^0 \rightarrow \mu^+ \mu^-$

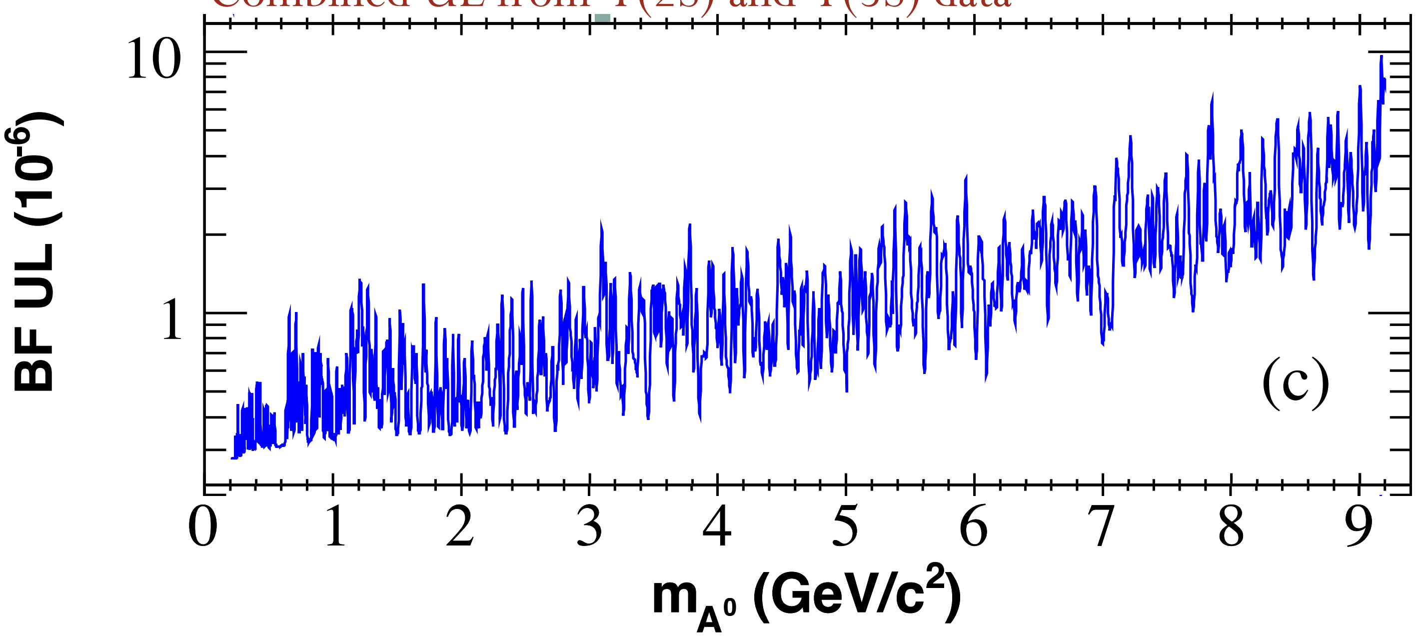
Largest A^0 “signal”, 3.62 σ



- 4585 A^0 mass hypotheses.
- 18% of Toy experiments see $\geq 3.62\sigma$. No signal.

Upper limits on $\mathcal{B}(\Upsilon(1S)) \to \gamma A^0)\mathcal{B}(A^0 \to \mu^+\mu^-)$

Combined UL from Y(2S) and Y(3S) data



- Y(2S) data has most of the statistical power.

Combined limit on product branching fractions $\mathcal{B}\left(\Upsilon(3S) \to \gamma A^0\right) \mathcal{B}\left(A^0 \to \ell^+\ell^-\right)$

- Combine $\Upsilon(1S) \to \gamma A^0$, $\Upsilon(2S) \to \gamma A^0$, and $\Upsilon(3S) \to \gamma A^0$ limits via an effective Yukawa coupling f_Υ^2, where

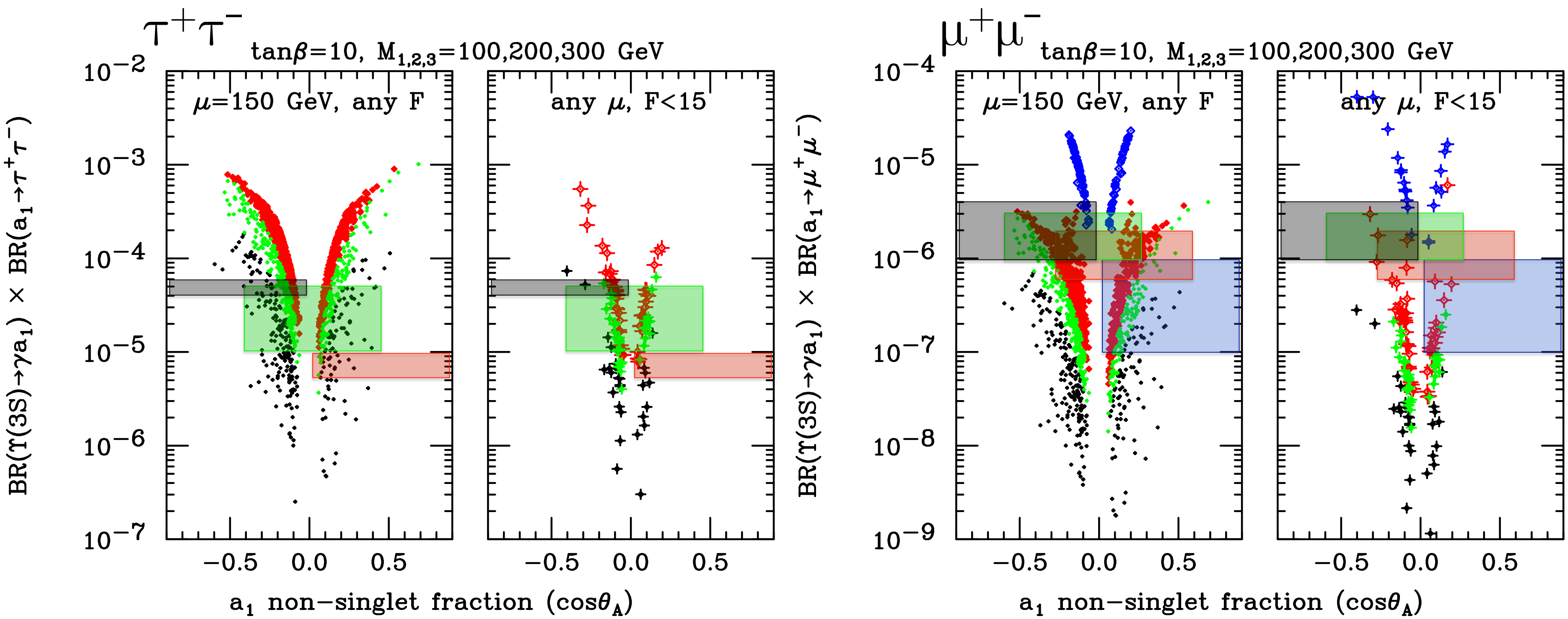
$$\frac{\mathcal{B}(\Upsilon(nS) \to \gamma A^0)}{\mathcal{B}(\Upsilon(nS) \to \ell^+\ell^-)} = \frac{f_\Upsilon^2}{2\pi\alpha}\left(1 - \frac{m_{A^0}^2}{m_{\Upsilon(nS)}^2}\right)$$

- Then translate limit on f_Υ^2 into limit on $\Upsilon(3S)$ product branching fraction for comparison to NMSSM predictions, Dermisek and Gunion, Phys. Rev. D81, 075003 (2010).

Blue: $0 < m_A < 2\ m_\tau$
Red: $2\ m_\tau < m_A < 7.5$ GeV
Green: $7.5 < m_A < 8.8$ GeV
Black: $8.8 < m_A < 9.2$ GeV

Colored boxes show the range of upper limits in the corresponding mass range

$\tan\beta = 10$

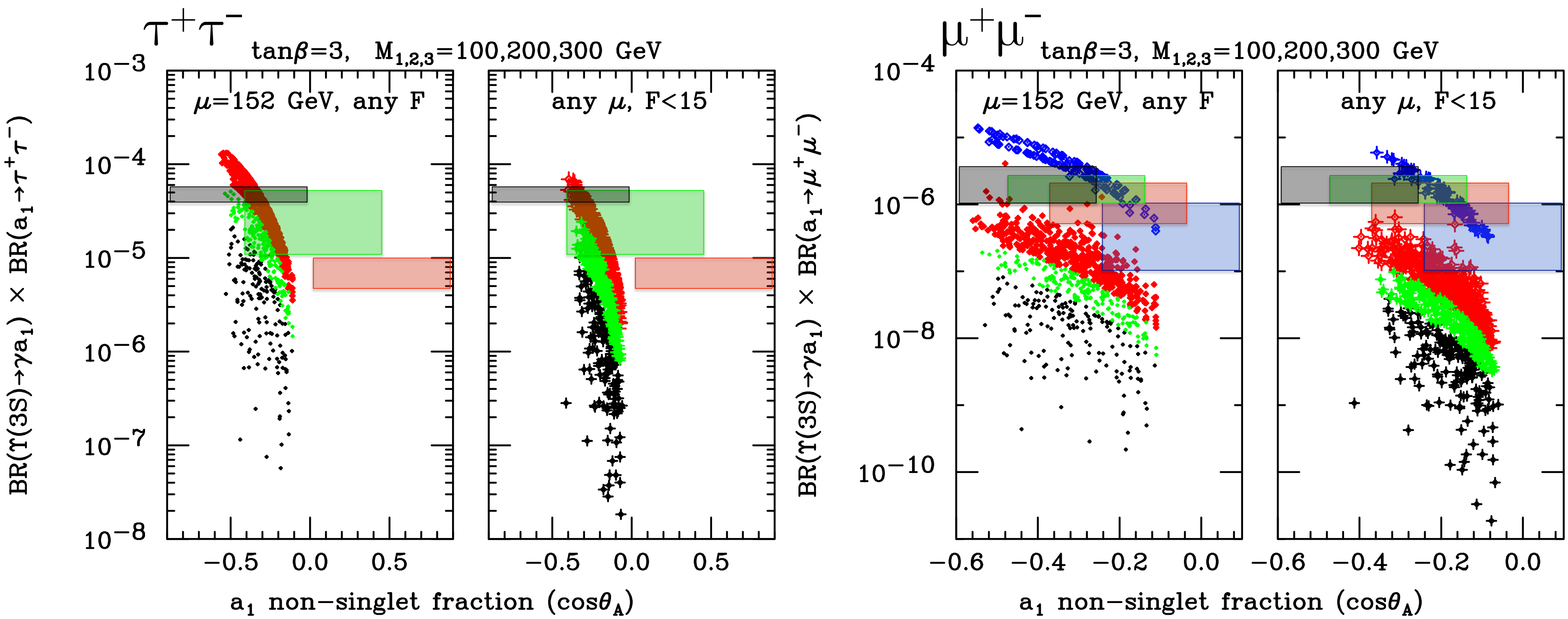


- For $\tan\beta = 10$, the muon data excludes essentially all parameter space below $2m_\tau$. The tau data excludes most parameter space up to 8.8 GeV. Higher masses are difficult.

Blue: $0 < m_A < 2\ m_\tau$
Red: $2\ m_\tau < m_A < 7.5$ GeV
Green: $7.5 < m_A < 8.8$ GeV
Black: $8.8 < m_A < 9.2$ GeV

Colored boxes show the range of upper limits in the corresponding mass range

$\tan\beta = 3$



- For $\tan\beta = 3$, exclusion region decreases to ~7.5 GeV. Some parameter space available below the tau mass.

$\bar{B} \to D^{(*)}\tau^- \bar{\nu}_\tau$

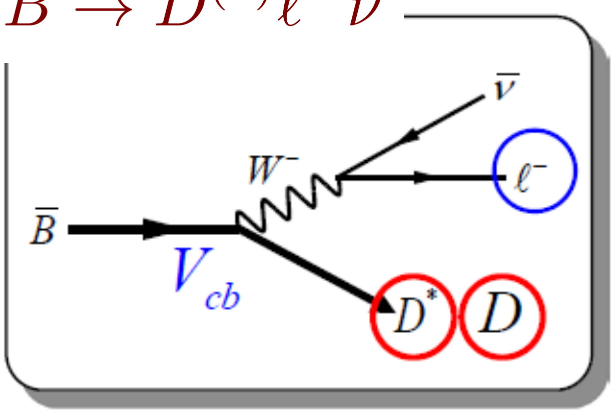
Phys. Rev. Lett 109, 101802 (2012)

Introduction

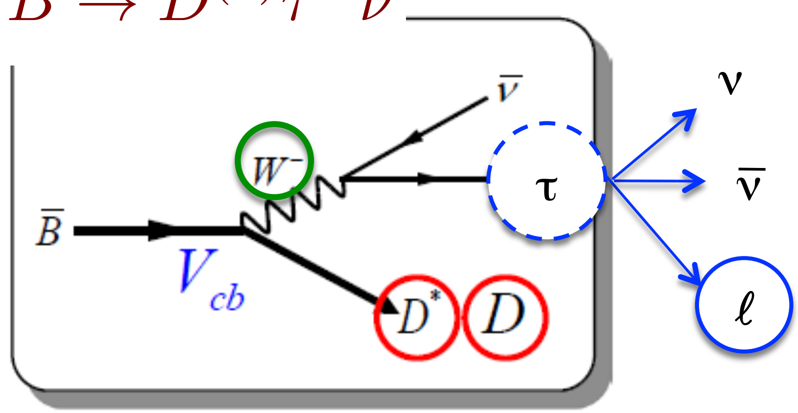
- $\mathcal{R}(D) \equiv \mathcal{B}(\bar{B} \to D\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D\ell^-\bar{\nu}_\ell)$ and $\mathcal{R}(D^*) \equiv \mathcal{B}(\bar{B} \to D^*\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^*\ell^-\bar{\nu}_\ell)$ can be calculated with low uncertainty in the SM.
  - ℓ^- is e^- or μ^- ; $D = D^0$ or D^+

H^- will contribute only to τ final state

$\bar{B} \to D^{(*)}\ell^-\nu$



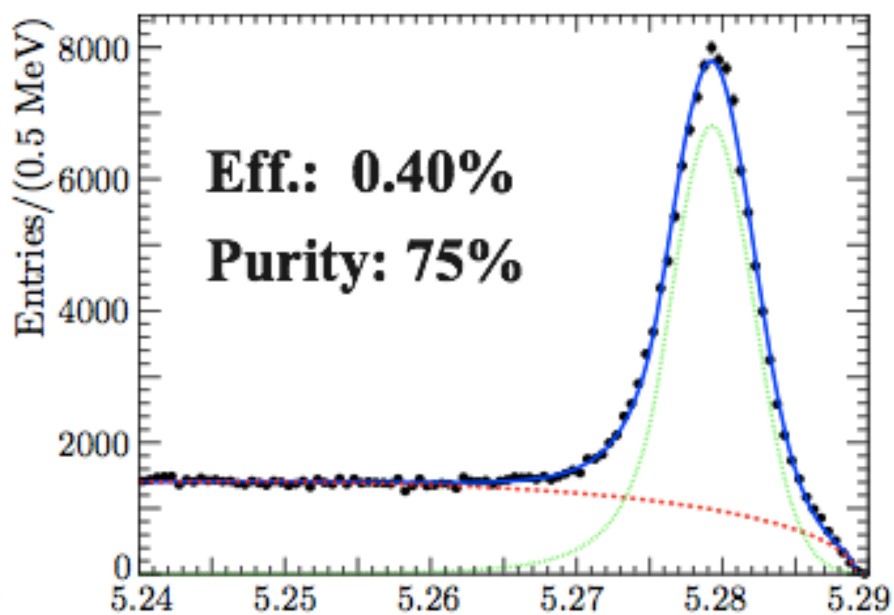
$\bar{B} \to D^{(*)}\tau^-\nu$



Use only $\tau^- \to \ell^-\nu_\tau\bar{\nu}_\ell$

Method

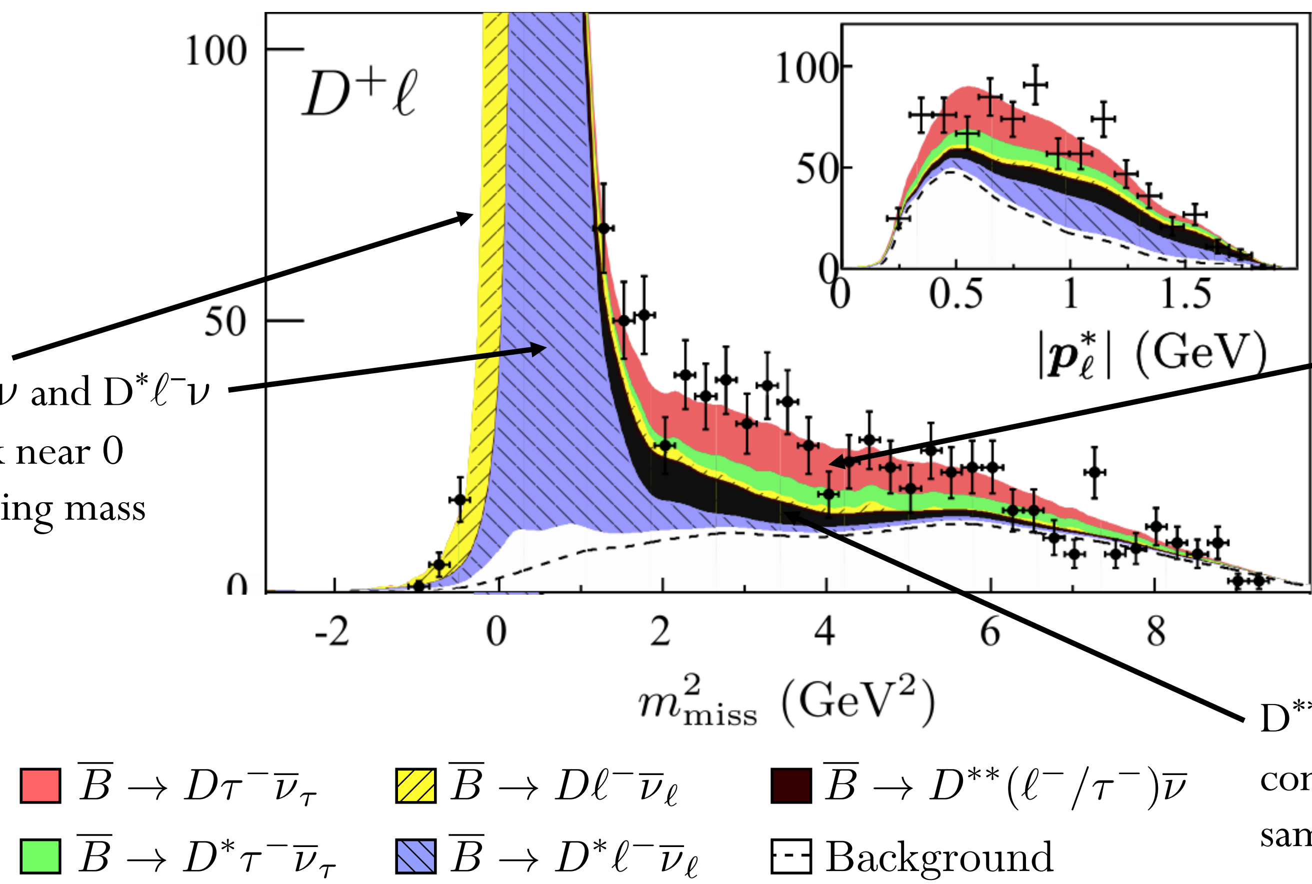
- Fully reconstruct one B using 1680 hadronic final states.
- Remainder of event must be consistent with $D^{(*)}\ell^- \nu(\nu\nu)$ or $D^{(*)}\ell^- \pi^0 \nu(\nu\nu)$ (control sample).
  - Use E_{extra} and other quantities to suppress backgrounds.



$$m_{ES} = \sqrt{E_{beam}^2 - p_{tag}^2}$$

Fit

- Simultaneous 2D fit to missing mass and lepton momentum, $D^{(*)}\ell$ and $D^{(*)}\ell\ \pi^0$ samples.

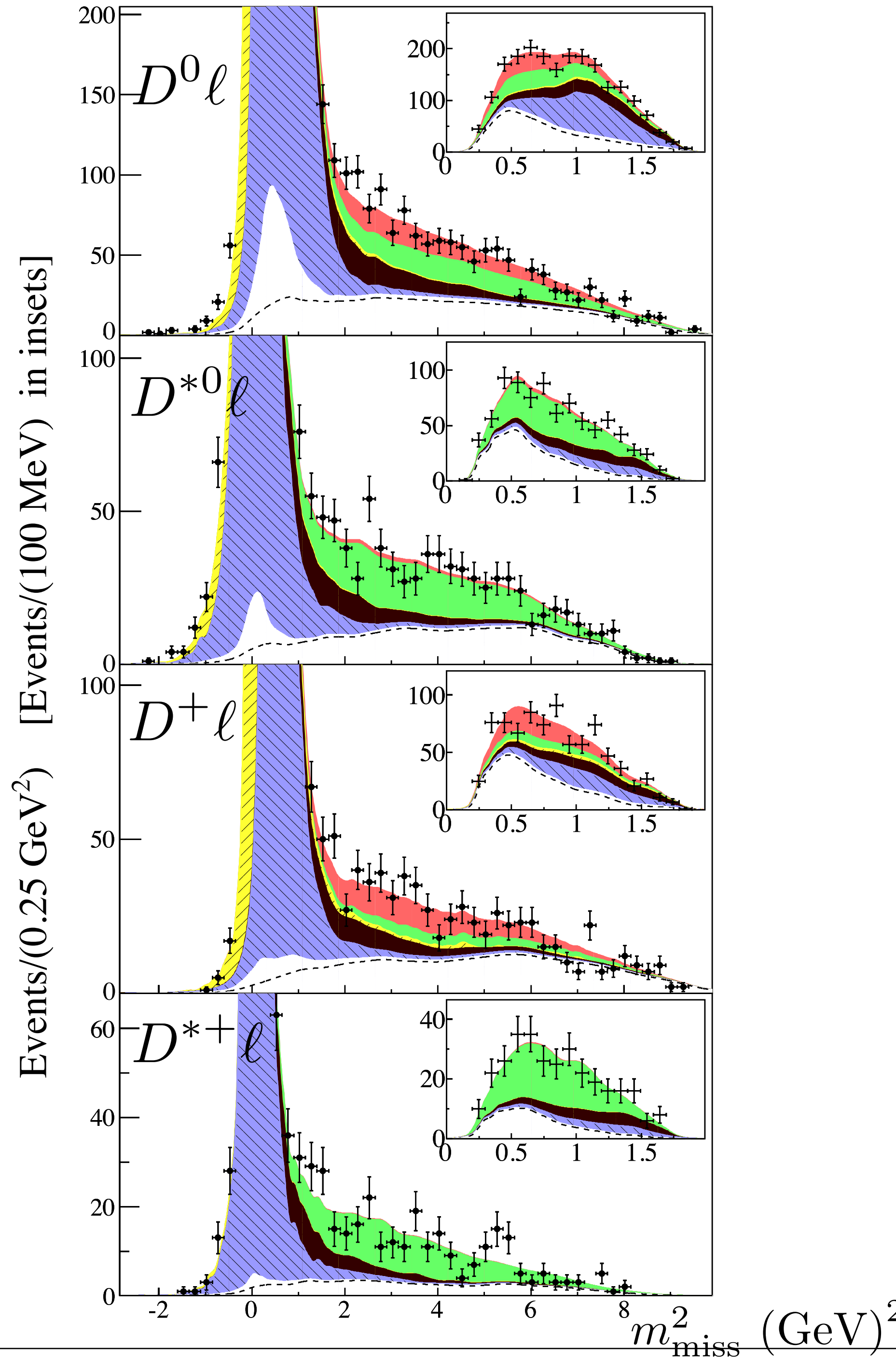


$D\ell^-\nu$ and $D^*\ell^-\nu$ peak near 0 missing mass

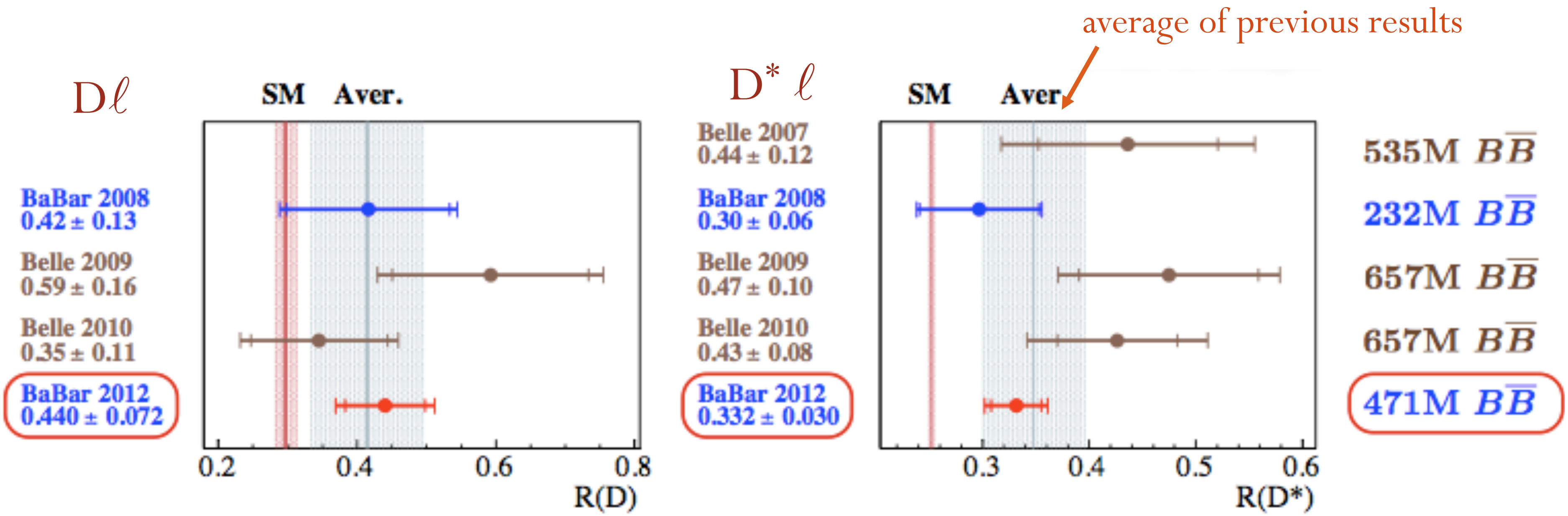
$D\tau^-\nu$ has larger missing mass (3 ν)

$D^{**}\ell^-\nu$ component constrained by π^0 sample

- $\overline{B} \to D\tau^-\overline{\nu}_\tau$
- $\overline{B} \to D\ell^-\overline{\nu}_\ell$
- $\overline{B} \to D^*\tau^-\overline{\nu}_\tau$
- $\overline{B} \to D^*\ell^-\overline{\nu}_\ell$
- $\overline{B} \to D^{**}(\ell^-/\tau^-)\overline{\nu}$
- Background

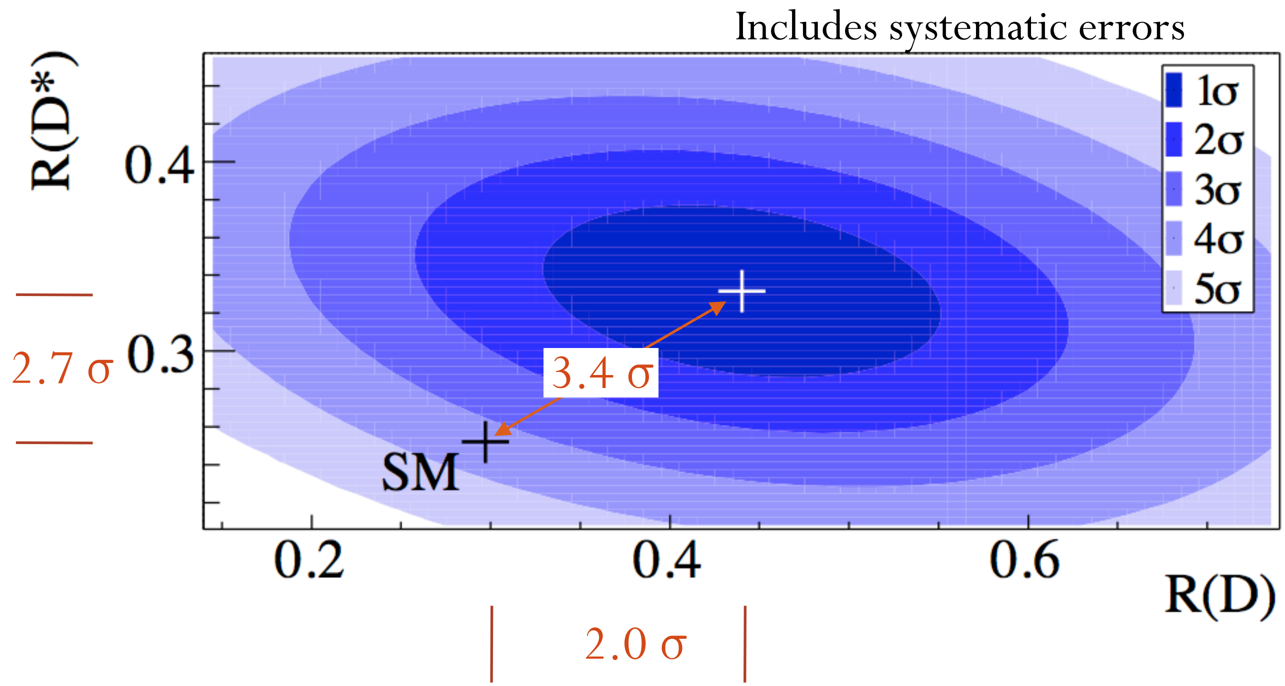


Results



- Efficiency ~3× larger than previous BaBar analysis.
- First $\bar{B} \rightarrow D\tau^- \bar{\nu}_\tau$ result with >5σ significance.

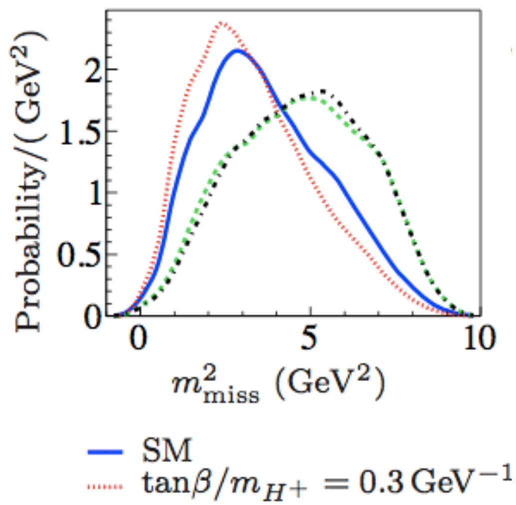
Comparison to SM

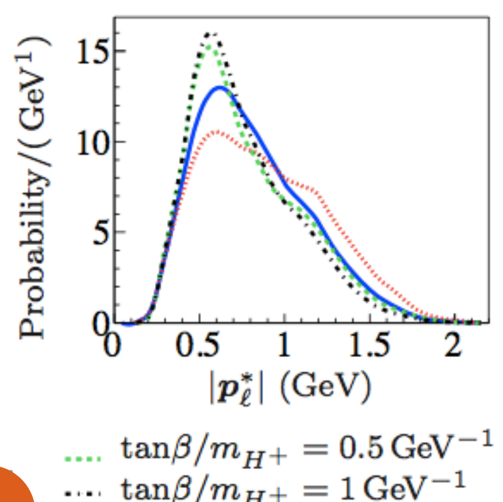


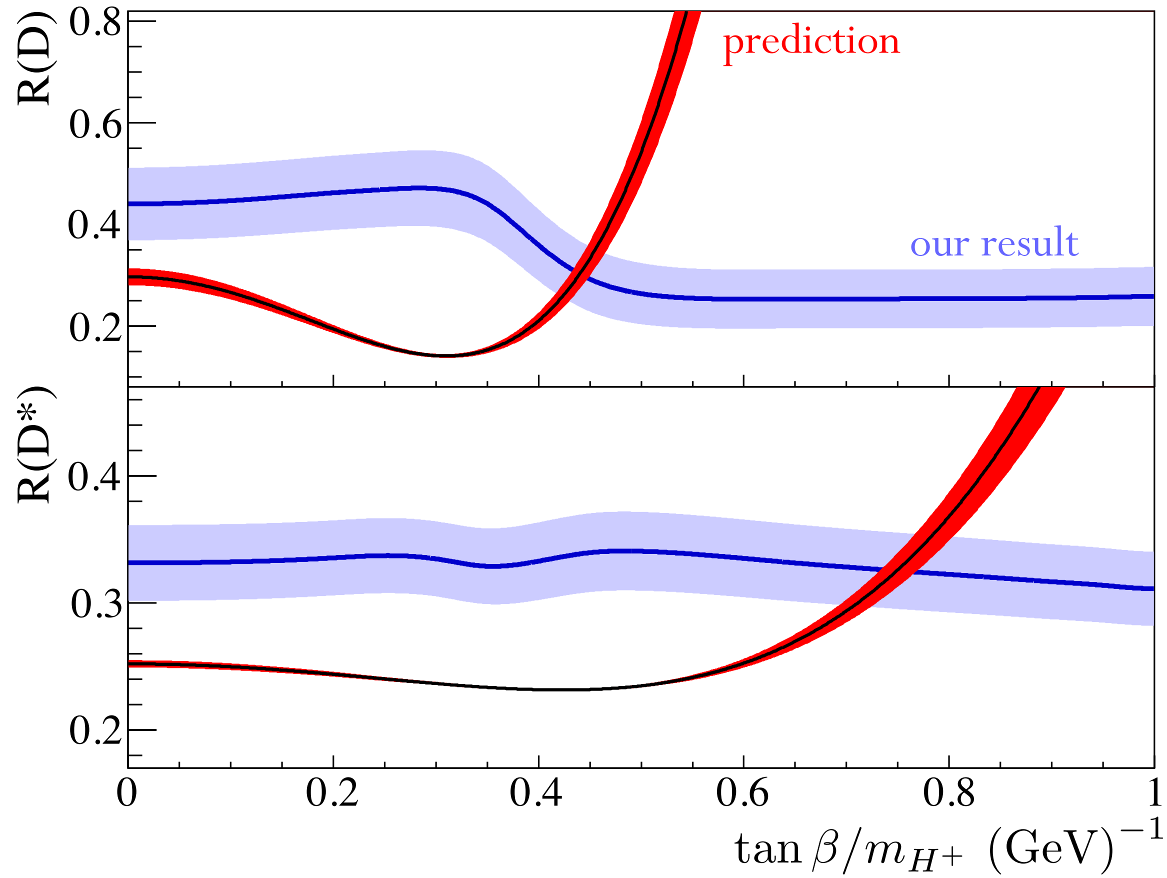
R(D) and R(D*) measurements are anticorrelated due to D* $\longrightarrow$ D feeddown

- Largest systematic is modeling of D** background. Also uncertainties on continuum and other $B\overline{B}$ backgrounds.

Comparison with type II two Higgs doublet model







- Not consistent with type-II 2HDM.
  - Fit quality is also poorer.

Summary

- Time reversal symmetry is directly observed to be violated in the B system, in good agreement with SM expectations.
- No evidence for a light Higgs (so far!)
- Hints of tension with the SM in $\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau$.
  It will be interesting to see Belle's final results in this area.

- I personally am looking forward to continuing this physics program on Belle-II.