Searching for baryon number violation in the BaBar dataset and elsewhere

LEPP Journal Club

Cornell University

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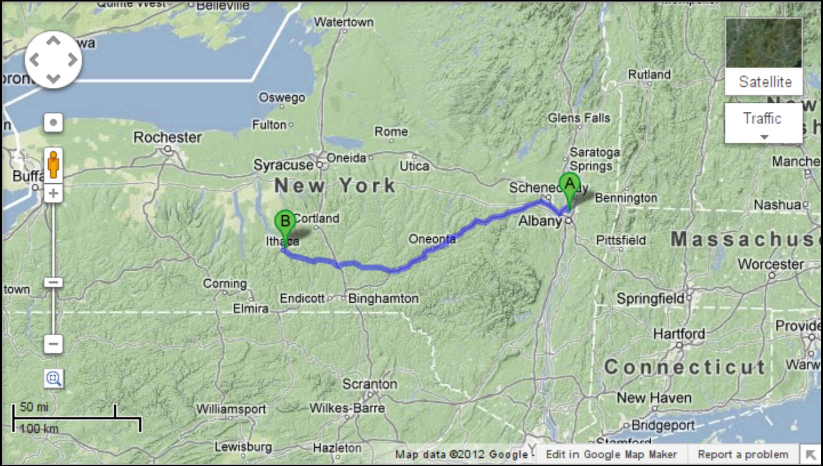
Aug. 24th, 2012

Siena College

Katherine Ollier / Flickr

http://www.techvalleyconnect.com



http://maps.google.com

Jim was my thesis advisor.

Outline

Motivation

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- Our universe is matter...not anti-matter.

NASA/ESA [JMA]

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- $t =$ early universe:
  - matter $=$ anti-matter

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Motivation

- Our universe is matter...not anti-matter.
- $t =$ early universe:
  - matter $=$ anti-matter
- $t =$ now:
  - matter $\neq$ anti-matter
- How do we know?
  - Cosmic ray's are mostly matter.
  - γ-ray spectrum.
- Universe is compartmentalized?
  - *Very* difficult theoretically.

NASA/ESA [JMA]

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- "*Violation of CP Invariance, c Asymmetry, and Baryon Asymmetry of the Universe.*"
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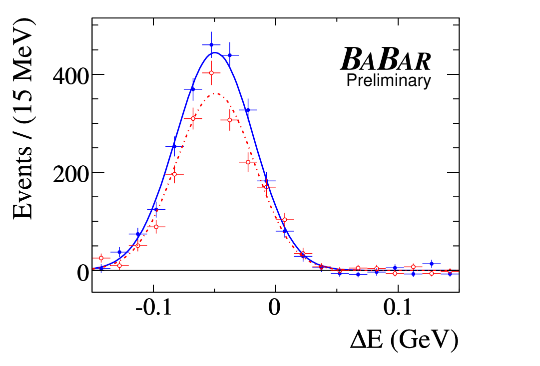
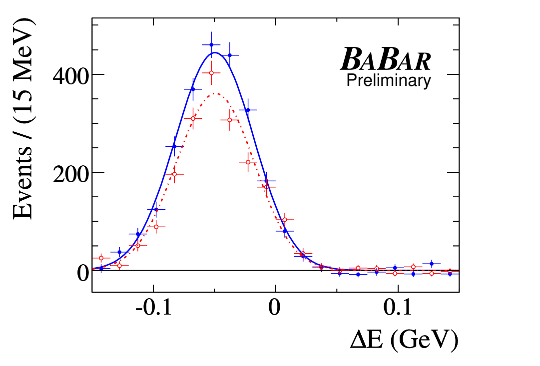
  2. *C* and *CP*-violation
     - Decay rates are different for *matter* and *anti-matter*.
  3. Baryon number violation
     - Implies sum of baryons + anti-baryons is a *non-conserved quantity*.
- Let's look at these last two...

- Direct CP-violation
  - $B^0 \to K^+\pi^-$
  - $\bar{B}^0 \to K^-\pi^+$



- Direct CP-violation
  - $B^0 \to K^+\pi^-$
  - $\bar{B}^0 \to K^-\pi^+$
- *Decay rates are different!*
- $A_{CP} \approx -0.1$
- Sakharov condition # 2!



- Baryon number violation actually *does* exist in the Standard Model.
  - Sphaleron, a non-perturbative process.
  - Occurs at *very* high temperatures. $T = 100$GeV. $(10^{15}$K)
  - Only found immediately after the big bang.
- Sakharov condition # 3!

Motivation

- Does this predict our asymmetric universe?
  - B for *baryon*
  - $B + \bar{B}$ annihilations in the early universe produced photons.
  - Asymmetry parameter (η).

$$\eta = \frac{N_B - N_{\bar{B}}}{N_\gamma} \approx 10^{-9}$$

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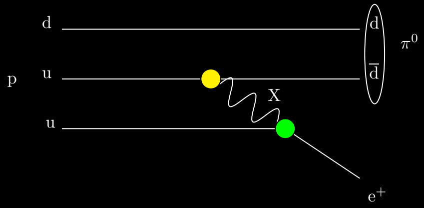
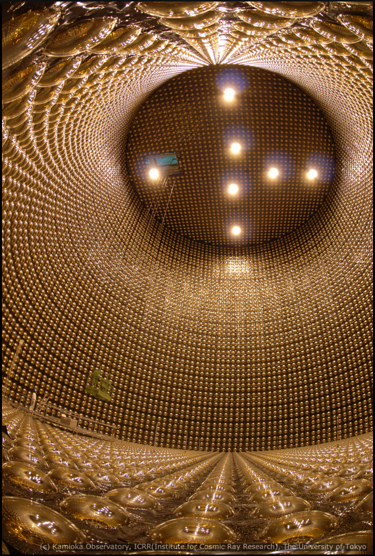
- Combination of observed *CP*-violation and and theoretical BNV in Standard Model is insufficient by 10 orders of magnitude!!!
- Additional CP violation? *Much work out there...no smoking gun.*
- Additional BNV?
- 1974, "*Unity of All Elementary Particle Forces.*", Georgi and Glashow
  - Proton decay mediated by heavy bosons (X & Y) which couple to *quarks* and *leptons*.
- Many Grand Unified Theories ⇒ BNV
- How would proton decay work?

New interaction with new *gauge bosons*.

- X has charge $q = +\frac{1}{3}$
  - $X \rightarrow q + q$
  - $X \rightarrow q + \ell$
- **B-L is the conserved quantity**



Experimental work
Super-Kamiokande
Proton lifetime $> 10^{29}$ years!



Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo[KO]

Proton decay

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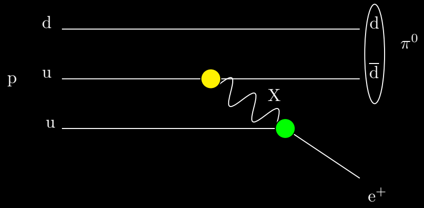
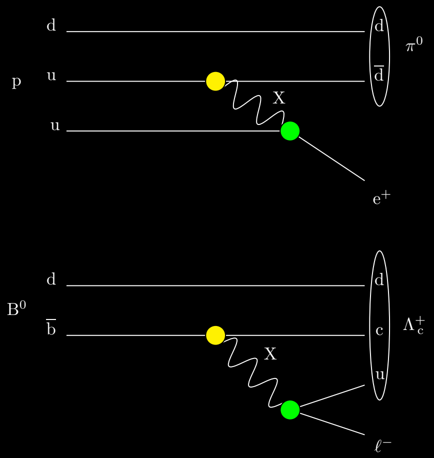


- X is $q = \frac{1}{3}$
  - $X \to q + q$
  - $X \to q + \ell$
- **B-L is conserved quantity.**
- Hypothesize a flavour/generation dependance to this interaction...

$$\begin{pmatrix} X_{u\bar{d}} & X_{c\bar{d}} & X_{t\bar{d}} \\ X_{u\bar{s}} & X_{c\bar{s}} & X_{t\bar{s}} \\ X_{u\bar{b}} & X_{c\bar{b}} & X_{t\bar{b}} \end{pmatrix}$$

$$\begin{pmatrix} X_{\bar{u}e^-} & X_{\bar{c}e^-} & X_{\bar{t}e^-} \\ X_{\bar{u}\mu^-} & X_{\bar{c}\mu^-} & X_{\bar{t}\mu^-} \\ X_{\bar{u}\tau^-} & X_{\bar{c}\tau^-} & X_{\bar{t}\tau^-} \end{pmatrix}$$

- $B^0 \to \Lambda_c^+ \ell^-$
- $B^+ \to \Lambda^0 \ell^+$
  $\ell = \mu$ or e



Experimental work

- Tevatron, HERA, LHC searches for leptoquarks.
  $M_{LQ} > 300 - 1000$ GeV/c^2

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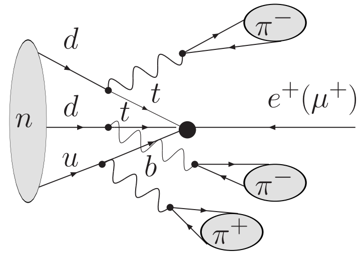
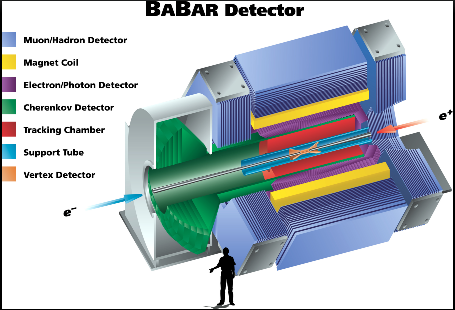
Theoretical work

- *"Baryon number violation involving higher generations."*, Hou, et.al.[HNS05]
  - Uses proton decay to constrain upper limits.
  - $\mathcal{B}(B^0) \rightarrow \Lambda_c^+ \ell^- < 4 \times 10^{-29}$
  - "Despite our findings, we believe it is still worth to look for BNV processes in τ, charm, B, and maybe in the future in top decays."

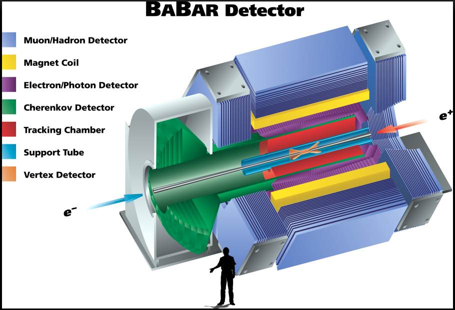


BaBar and SLAC

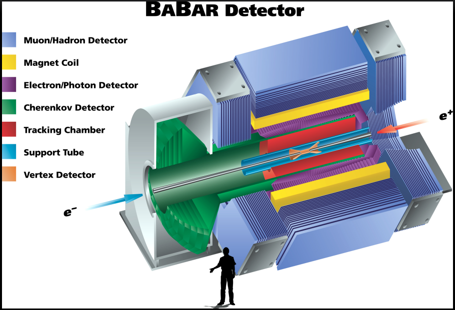
SLAC and BaBar



- BaBar at SLAC
- 1999-2008



- BaBar at SLAC
- 1999-2008
- PEP-II asymmetric e^+e^- collider
  - Ran on $\Upsilon(4S)$
  - Instantaneous $\mathcal{L} = 10^{-34}$ cm^{-2} s^{-1}
- 1 billion B mesons



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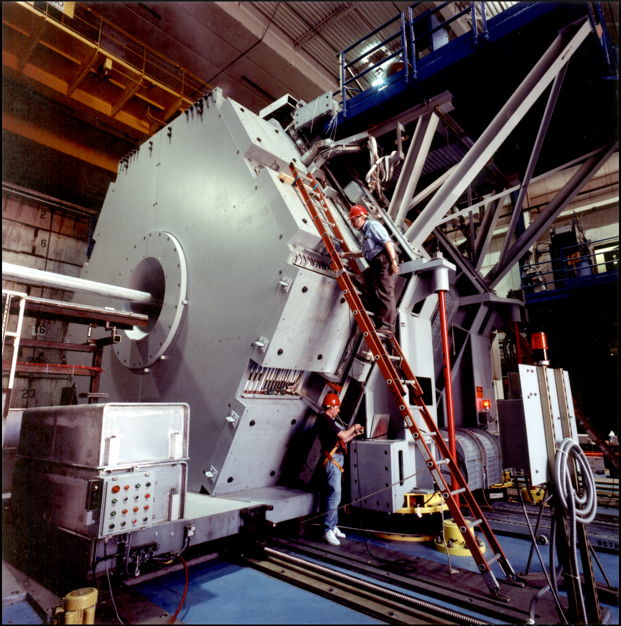
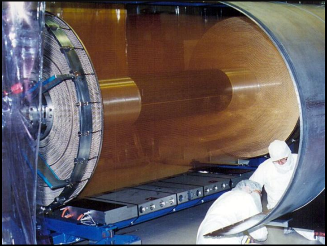
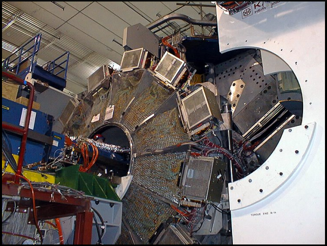
  - Ran on $\Upsilon(4S)$
  - Instantaneous $\mathcal{L} = 10^{-34}$ cm^{-2} s^{-1}
- 1 billion B mesons
- *Backgrounds (or other physics!)*
  - $e^+e^- \rightarrow u\bar{u}/d\bar{d}/s\bar{s}/c\bar{c}$
  - $e^+e^- \rightarrow e^+e^-/\mu^+\mu^-/\tau^+\tau^-$
- 400+ papers and counting.
- Excellent momentum and spatial resolution.

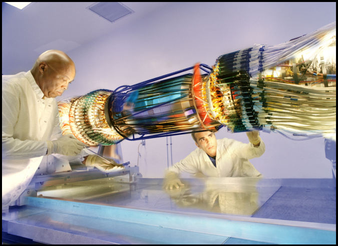
BaBar at SLAC

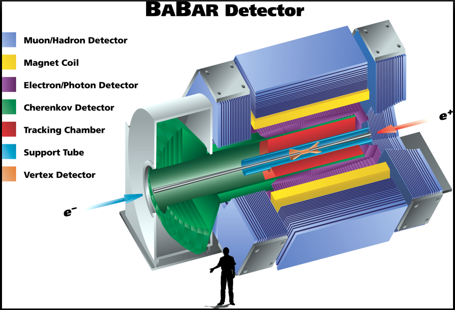




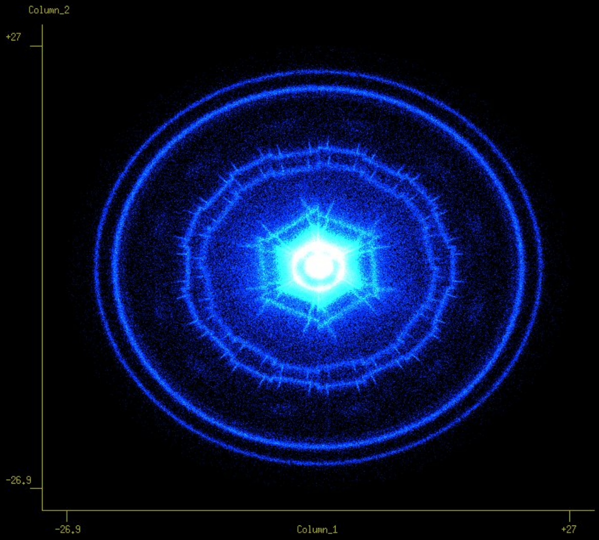


Layers of detectors

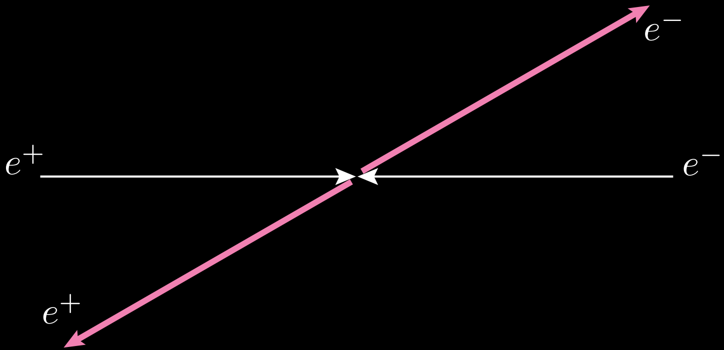




- Sophisticated particle ID.
- Inner silicon vertex detector.
  - Energy, spatial position (momentum)
- Drift chambers.
  - Energy, momentum
- Cerenkov detector (DIRC)
  - Velocity (π/K ID)
- Muon detection in outer region
  - Timing, spatial position
- All fed into a neural net algorithm.
- Gives analysts 6 levels.
  - For each particle type (e, μ, p, π, K)
  - Vary purity/efficiency.
  - Function of kinematics.


Column_2
+27
-26.9
-26.9
Column_1
+27

b quark production at an e^+e^- collider


e^-
e^+
e^-
e^+

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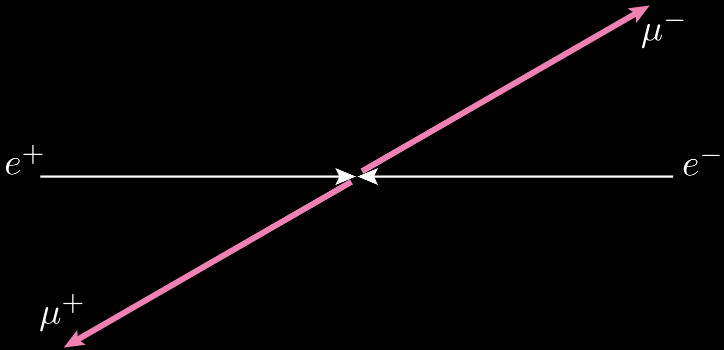

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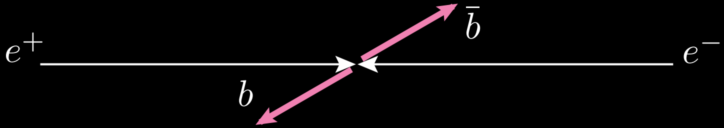
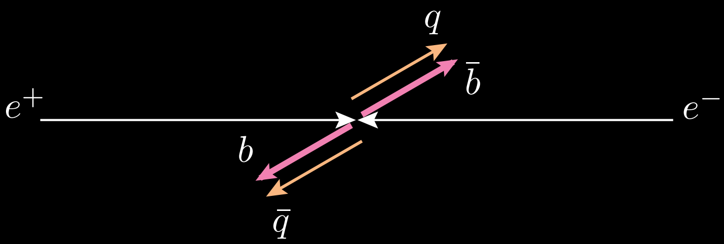
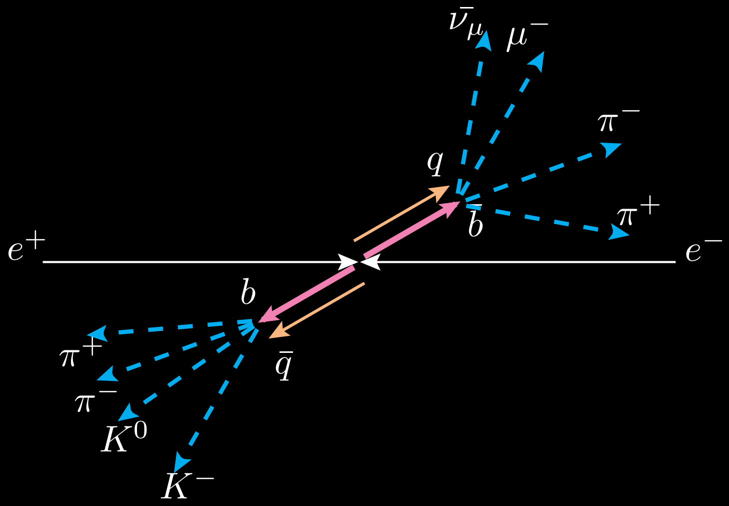



q
$\bar{b}$
e^+
e^-
b
$\bar{q}$


$\bar{\nu}_\mu$
μ^-
π^-
q
$\bar{b}$
π^+
e^+
e^-
b
$\bar{q}$
π^+
π^-
K^0
K^-

$$B^0 \to \Lambda_c \ell^-$$

$$B^- \to \Lambda \ell^-$$

$$B^- \to \bar{\Lambda} \ell^-$$

Our search

$\ell = \mu$ or e

$B^0 \rightarrow \Lambda_c^+ \ell^-$

$\rightarrow$

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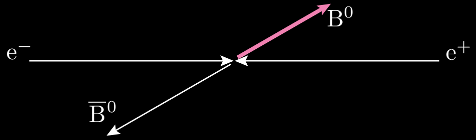

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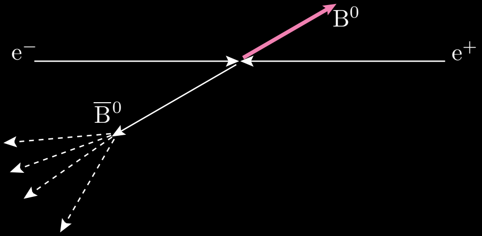
$\to$



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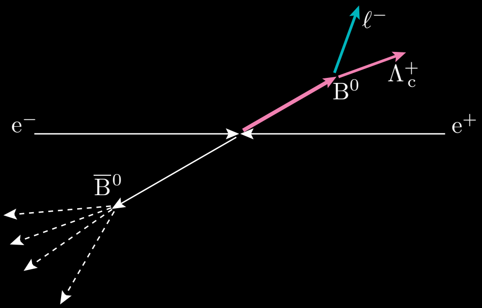
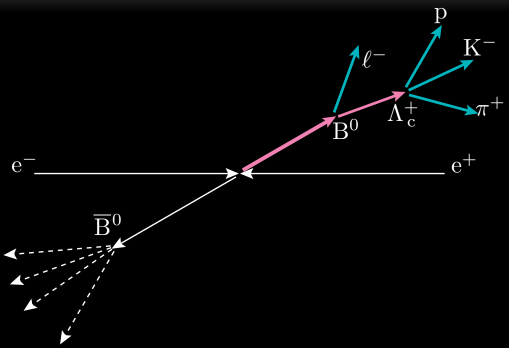


Our search

$\ell = \mu$ or e

$B^0 \to \Lambda_c^+ \ell^-$

$\Lambda_c^+ \to pK^- \pi^+$



$\ell = \mu$ or e

$B^0 \rightarrow \Lambda_c^+ \ell^-$

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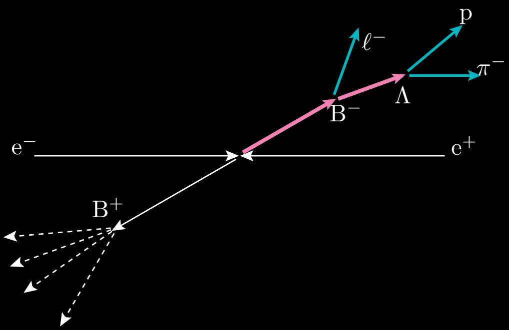
$B^- \rightarrow \Lambda^0 \ell^-$

$\Lambda^0 \rightarrow p\pi^-$

$B^- \rightarrow \bar{\Lambda}^0 \ell^-$

$\bar{\Lambda}^0 \rightarrow \bar{p}\pi^-$



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$\Lambda_c^+ \to pK^-\pi^+$

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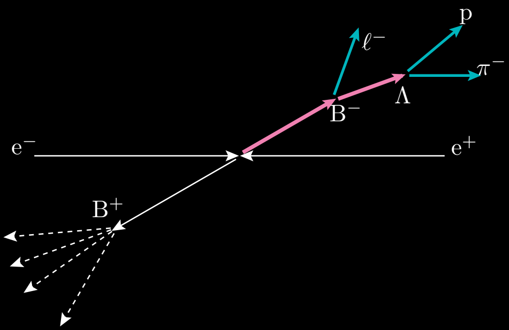
$\Lambda^0 \to p\pi^-$

$B^- \to \bar{\Lambda}^0 \ell^-$

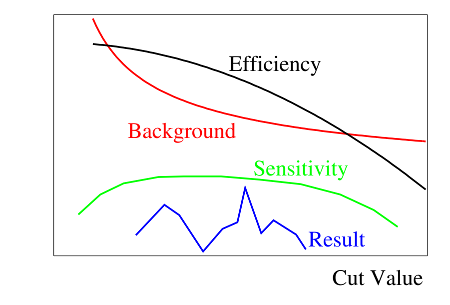
$\bar{\Lambda}^0 \to \bar{p}\pi^-$



- Experimental requirements:
  - Cleanly identify **3-4** charged particles.
  - Demonstrate they came from a B meson.

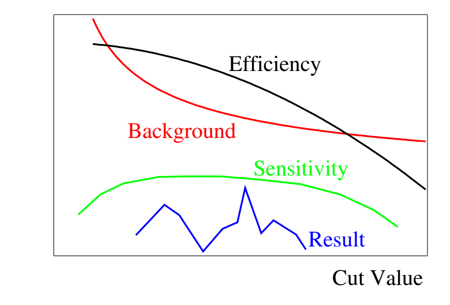
Blind analyses

Blind searches (Roodman, [Roo03])



Blind searches (Roodman, [Roo03])

- *Experimenter's bias.*



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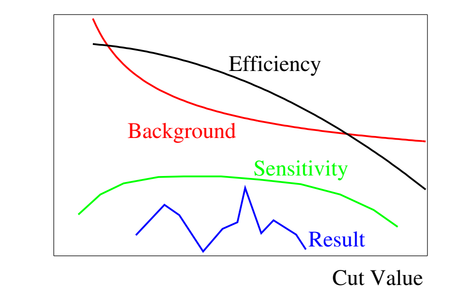
- *Experimenter's bias.*
- Medical field: double blind trials.
- Electron e/m, Dunnington (1933)



Blind searches (Roodman, [Roo03])

- *Experimenter's bias.*
- Medical field: double blind trials.
- Electron e/m, Dunnington (1933)
- *History of measurements?*
- How do you guard against this?
- Don't look!

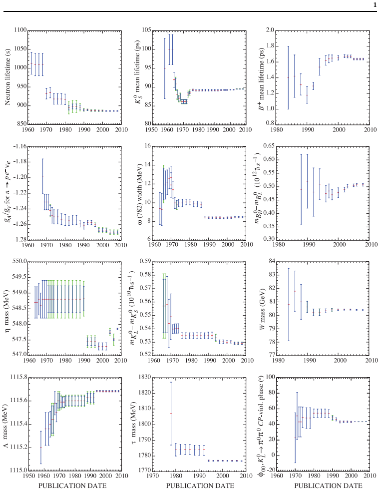


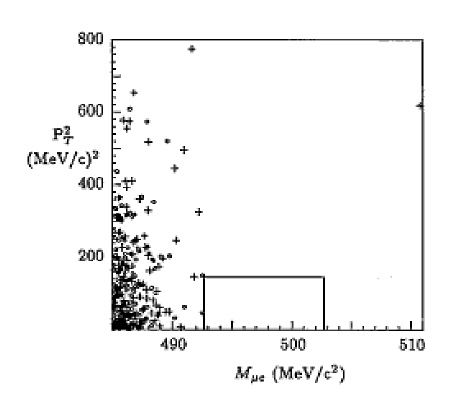
Figure 2: A historical perspective of values of a few particle properties tabulated in this *Review* as a function of date of publication of the *Review*. A full error bar indicates the quoted error; a thick-lined portion indicates the same but without the "scale factor."

Hidden signal box.

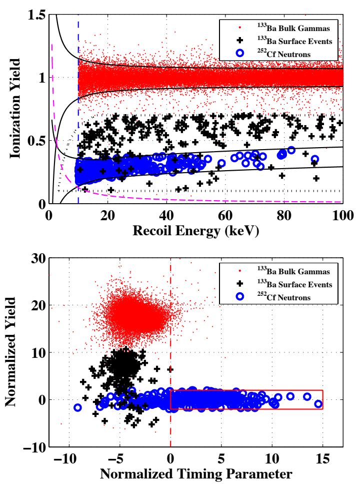
- $K_L^0 \to \mu^\pm e^\mp$
- Ariska, **PRL 70**, 1993
- FNAL, E791

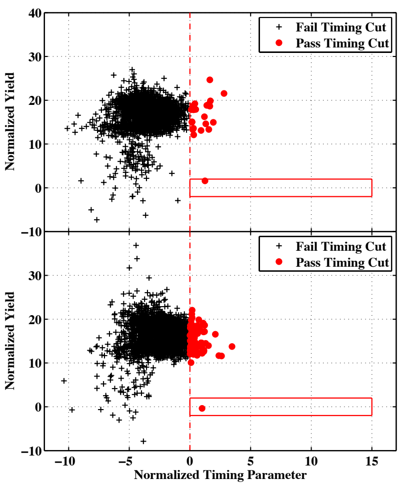
Kinematics dictates region of interest.

Other approaches: hidden answer, random noise.

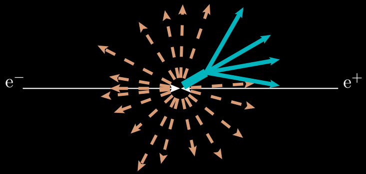


CDMS (2009), dark matter search





Our search

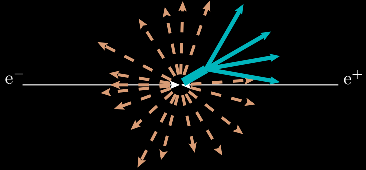


Signal

$e^+e^- \rightarrow B\bar{B}$

$B \rightarrow \Lambda_{(c)}\ell$

Signal and backgrounds



Signal

$$e^+e^- \rightarrow B\bar{B}$$
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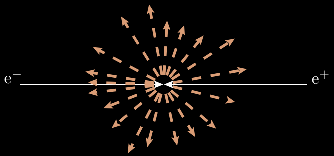
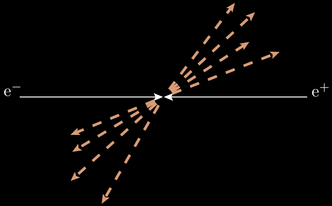
Backgrounds



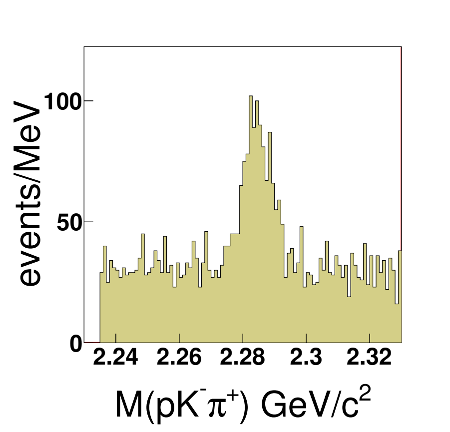


$$e^+e^- \rightarrow B\bar{B}$$
$B \rightarrow$ Standard Model decays

$$e^+e^- \rightarrow q\bar{q} \quad (q = c, s, u, d)$$
$$e^+e^- \rightarrow \ell^+\ell^- \quad (\ell = \tau, \mu, e)$$

Particle Identification (PID)

- Optimize PID for kinematics.
- e.g. $\Lambda_c^+ \to pK^-\pi^+$
- Loose PID



Particle Identification (PID)

- Optimize PID for kinematics.
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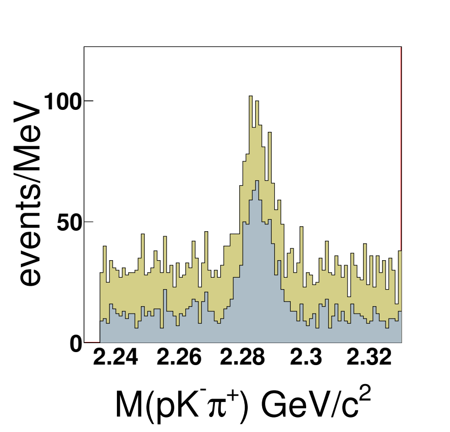
- Loose PID
- Some set of PID criteria.



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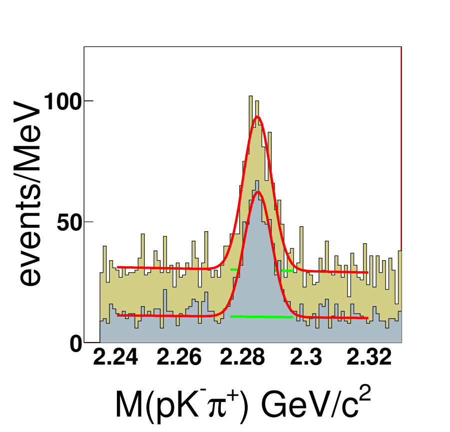
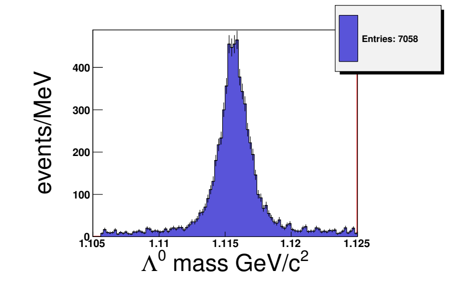
- Optimize PID for kinematics.
- e.g. $\Lambda_c^+ \to pK^-\pi^+$
- Loose PID
- Some set of PID criteria.
- Use Λ_c^+ *efficiency* and *background rejection* to optimize selection.



Particle Identification (PID)

- Optimize PID for kinematics.
- e.g. $\Lambda_c^+ \rightarrow pK^-\pi^+$
- Loose PID
- Some set of PID criteria.
- Use Λ_c^+ *efficiency* and *background rejection* to optimize selection.
- Λ: $c\tau = 7.89$ cm
- Select transverse flight length > 0.2cm and loose PID criteria.



Multivariate discriminator

TMVA http://tmva.sourceforge.net/

- Six variables: $B\ \cos(\theta)$ CM and 5 shape variables
- Neural network algorithm was used.

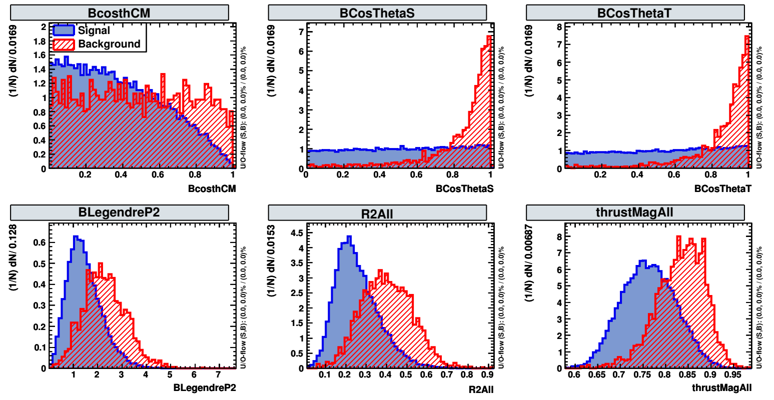


Figure: $\Lambda_c \mu^-$ Comparison between signal MC and $q\bar{q}$ MC.

Optimization of candidate selection.

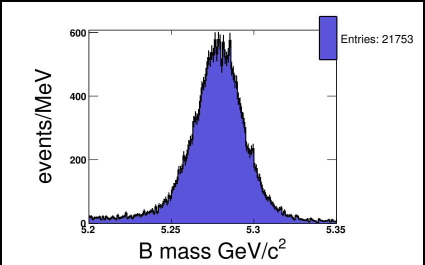
- Punzi figure of merit. (*PHYSTAT 2003*) [?]
    - Strike a balance between *setting upper limit for null results* and *observation of a small signal*.

$$\text{f.o.m.} = \frac{\epsilon_S}{\sqrt{B} + a/2}$$

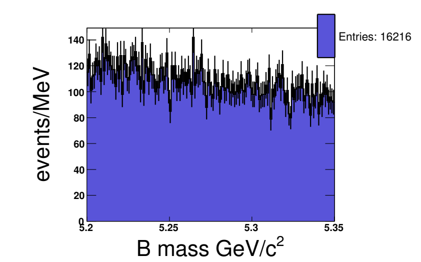
    - a is significance ($\#$ of σ).
        - For this analysis, $a = 5$.
    - ϵ_S is the efficiency of the signal.
    - B is the number of background candidates.

- *B* mass
- Beam energy resolution is better than *B* energy.

Signal process (Monte Carlo)

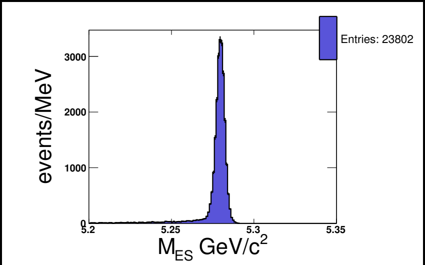


All background processes (Monte Carlo)



- B mass
- Beam energy resolution is better than B energy.
- $m_{ES} = \sqrt{\frac{1}{4}s - (p_B^*)^2}$

Signal process (Monte Carlo)



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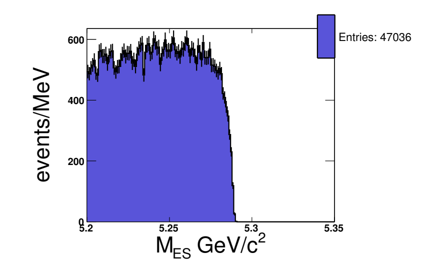

- B mass
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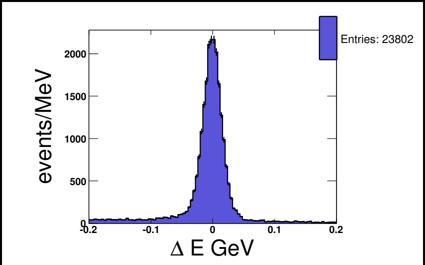
- $m_{ES} = \sqrt{\frac{1}{4}s - (p_B^*)^2}$
- $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$

Signal process (Monte Carlo)



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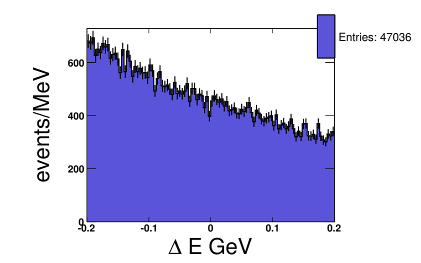
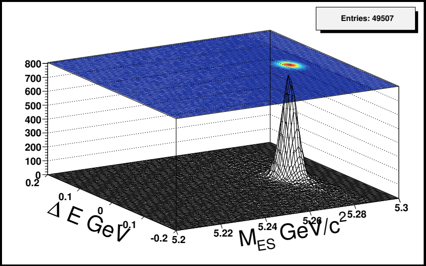


- B mass
- Beam energy resolution is better than B energy.
- $m_{ES} = \sqrt{\frac{1}{4}s - (p_B^*)^2}$
- $\Delta E = E_B^* - \frac{1}{2}\sqrt{s}$
- **Discriminating power in 2D plane.**
- **Signal region is blinded during candidate selection optimization!**

Signal process (Monte Carlo)



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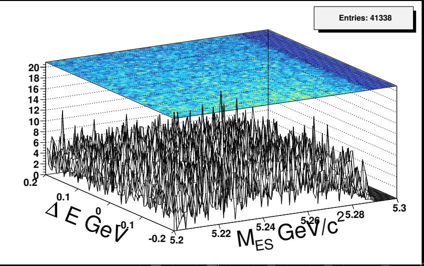


Fitting procedure

- Optimized PID selection and neural net selection with *blinded data* and *MC samples*.
- Determine *probability density functions (PDFs)* used to describe signal and background.
- Fit using *unbinned extended likelihood method*
- Define criteria for quoting upper limits and significance of signal.
- Many ($\sim$ 100k) Monte Carlo studies to determine sensitivity and possible bias.

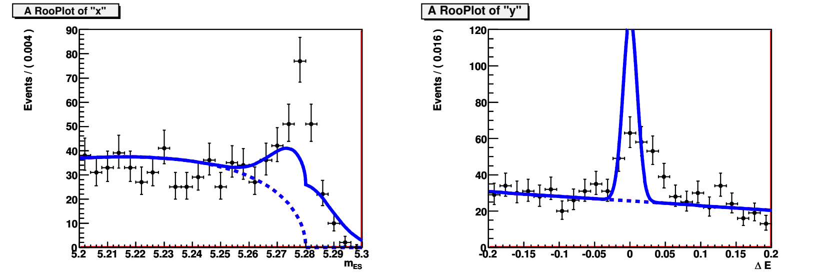
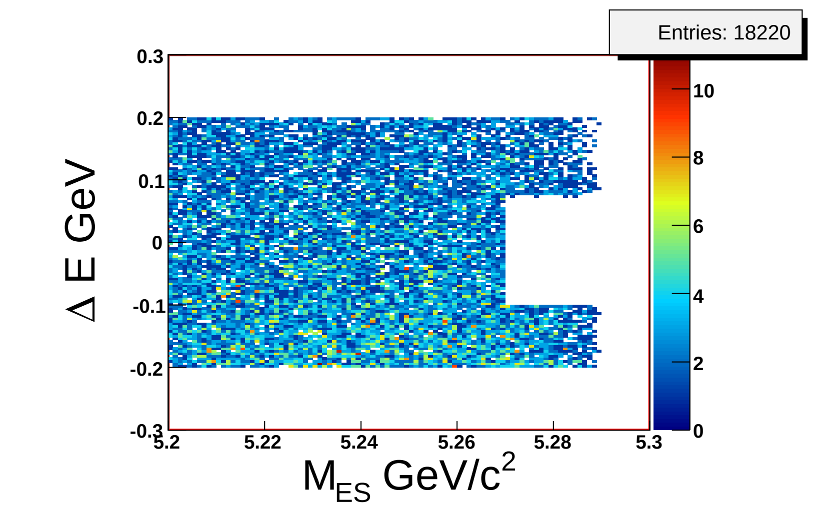


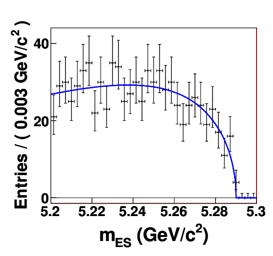
Figure: Fit to simulated data

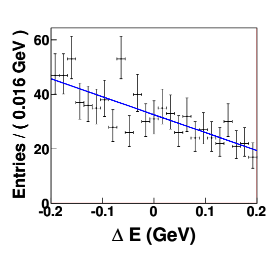
Our blind data



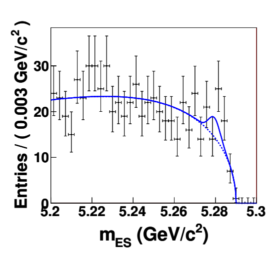
Results!

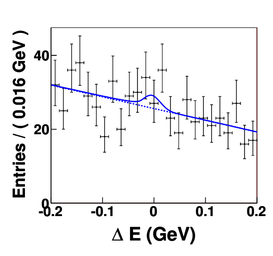
$B \to \Lambda_c^+ \mu^-$



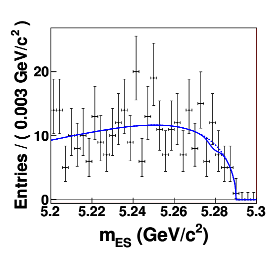


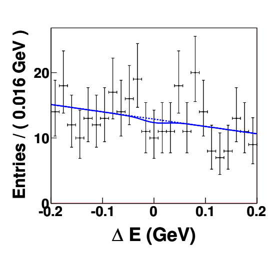
$B \to \Lambda_c^+ e^-$





$B \to \Lambda^0 \mu^-$





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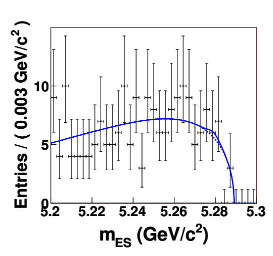
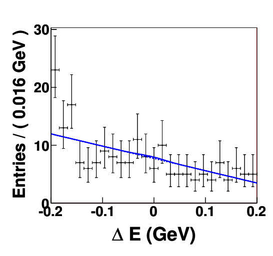
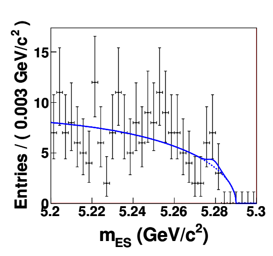
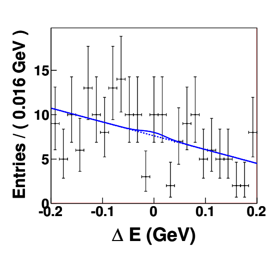


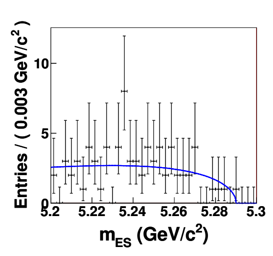


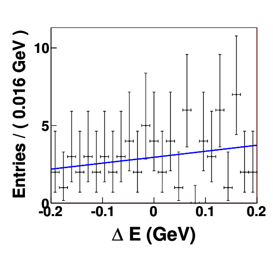
$B \to \bar{\Lambda}^0 \mu^-$





$B \to \bar{\Lambda}^0 e^-$





No significant signal is observed

Decay mode	Upper limit (90% CL)
$B^0 \to \Lambda_c^+ \mu$	180×10^{-8}
$B^0 \to \Lambda_c^+ e$	520×10^{-8}
$B^- \to \Lambda^0 \mu$	6.2×10^{-8}
$B^- \to \Lambda^0 e$	8.1×10^{-8}
$B^- \to \bar{\Lambda}^0 \mu$	6.1×10^{-8}
$B^- \to \bar{\Lambda}^0 e$	3.2×10^{-8}

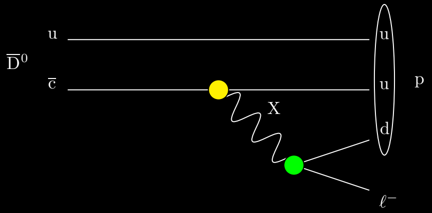
Most signficant branching fraction:

$$\mathcal{B}(B^0 \to \Lambda_c^+ e^-) = (190^{+130}_{-90}) \times 10^{-8} \text{ at } 2.4\sigma$$

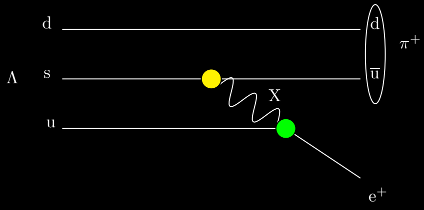
First *experimental* upper limits on these processes. [dAS+11]

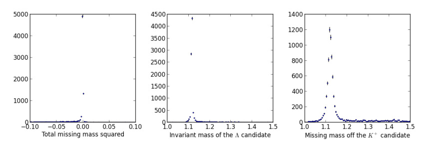
Other places to look

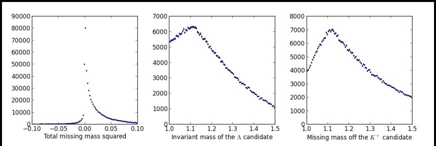
Rubin, et al. (CLEO Collaboration, 2009)
"*Search for* $D^0 \to \bar{p}e^+$ *and* $D^0 \to pe^-$" [R+09]



Current analysis...







- Jefferson Lab (CLAS)
- $\gamma p \to K^+ \Lambda$
  $\Lambda \to \text{meson} + \text{lepton}$
- Mike McCracken at Washington & Jefferson College, and CMU colleagues.
  Blind analysis!
- Parallel analysis: ROOT and python
  `https://github.com/mattbellis/lichen`

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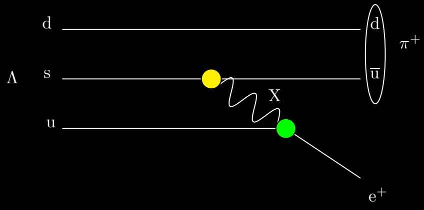

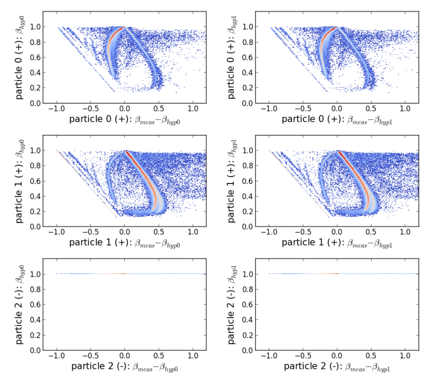

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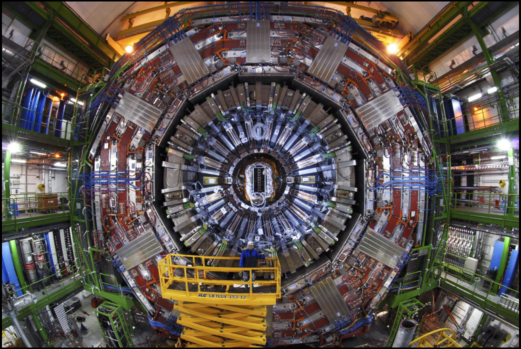
t-quark decays (LHC)

Davidson and Verdier, (2011)
"*Leptoquarks decaying to a top quark and a charged lepton at hadron colliders*"[DV11]

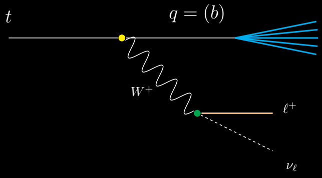
Dong, et al. (2011)
"*Baryon number violation at the LHC: the top option*"[DDG+12]

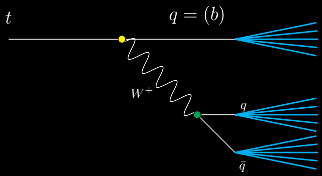


Decays of top quark to leptoquarks?

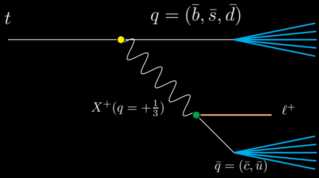
t-quark decays (LHC)

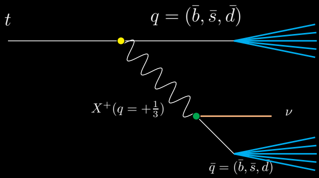
Standard Model decays





Baryon-/Lepton-number violating decays





Summary

- Does *New Physics* have a more complicated flavour structure? *Something* is missing in our picture.
- Experimentally, there's still a lot of places left to look!

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Thanks for your time!

P. del Amo Sanchez et al.
Searches for the baryon- and lepton-number violating decays $B^0 \to \Lambda_c^+ \ell^-$, $B^- \to \Lambda \ell^-$, and $B^- \to \bar{\Lambda} \ell^-$.
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Backup slides