JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TRIUMF — Canada's national laboratory for particle and nuclear physics and accelerator-based science

Search for New Physics with Pion Decays

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Napoli, Oct 2017

Outline

- General Context
- Motivation
- Experimental Technique
- Data Analysis
- Results
- Conclusions & Outlook

PI E NU

The Standard Model

Families 1 2 3

Quarks

Leptons

Gauge Bosons

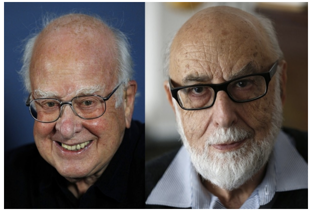
The Standard Model

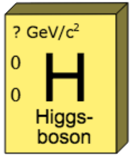
Families 1 2 3

Quarks

Leptons

Gauge Bosons





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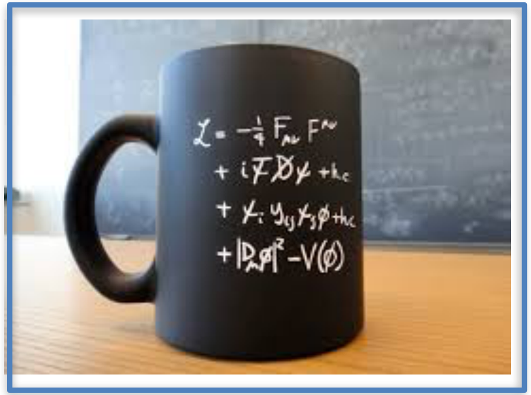
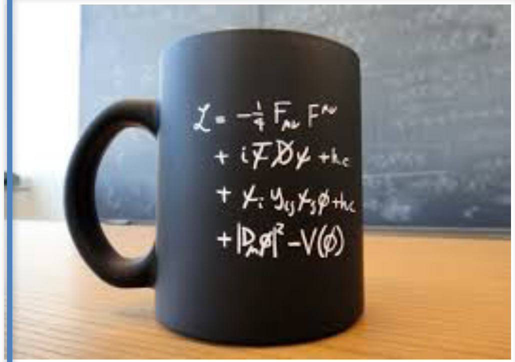
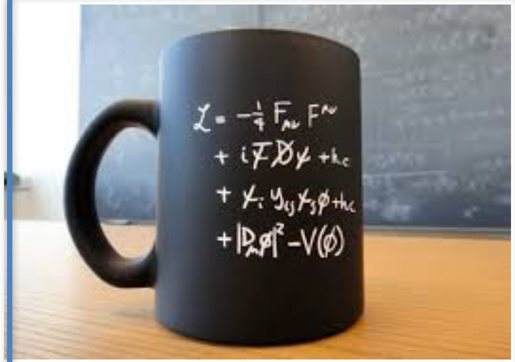

$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
$+ i\bar{\psi} \not{D} \psi + h.c.$
$+ \psi_i y_{ij} \psi_j \phi + h.c.$
$+ |D_\mu \phi|^2 - V(\phi)$

The Standard Model



$$\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\tfrac{1}{8}g^2\alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2\right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\tfrac{1}{2}g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\tfrac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\tfrac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_w MA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^-\right) - \tfrac{1}{8}g^2\tfrac{1}{c_w^2}Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-\right) - \\
\tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \tfrac{1}{2}ig_s\lambda^a_{ij}(\bar{q}^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda(\gamma\partial + m^\lambda_\nu)\nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_w A_\mu\left(-(\bar{e}^\lambda\gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j\gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\tfrac{ig}{4c_w}Z^0_\mu\{(\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{d}^\lambda_j\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)d^\lambda_j) + \\
(\bar{u}^\lambda_j\gamma^\mu(1 - \tfrac{8}{3}s_w^2 + \gamma^5)u^\lambda_j)\} + \tfrac{ig}{2\sqrt{2}}W^+_\mu\left((\bar{\nu}^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar{u}^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\tfrac{ig}{2\sqrt{2}}W^-_\mu\left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_e(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_e(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa\right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M}H(\bar{\nu}^\lambda\nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M}H(\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M}\phi^0(\bar{\nu}^\lambda\gamma^5\nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M}\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda) - \tfrac{1}{4}\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa - \\
\tfrac{1}{4}\overline{\bar{\nu}_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}}\phi^+\left(-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\tfrac{ig}{2M\sqrt{2}}\phi^-\left(m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j\right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j\gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j\gamma^5 d^\lambda_j) + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu\bar{G}^a G^b g^c_\mu + \\
\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y + igc_w W^+_\mu(\partial_\mu\bar{X}^0 X^- - \\
\partial_\mu\bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) + igc_w W^-_\mu(\partial_\mu\bar{X}^- X^0 - \\
\partial_\mu\bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) + igc_w Z^0_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \\
\partial_\mu\bar{X}^- X^-) - \tfrac{1}{2}gM\left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H\right) + \tfrac{1-2c_w^2}{2c_w}igM\left(\bar{X}^+ X^0\phi^+ - \bar{X}^- X^0\phi^-\right) + \\
\tfrac{1}{2c_w}igM\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + igMs_w\left(\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-\right) + \\
\tfrac{1}{2}igM\left(\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0\right) .
\end{gathered}$$

The Standard Model



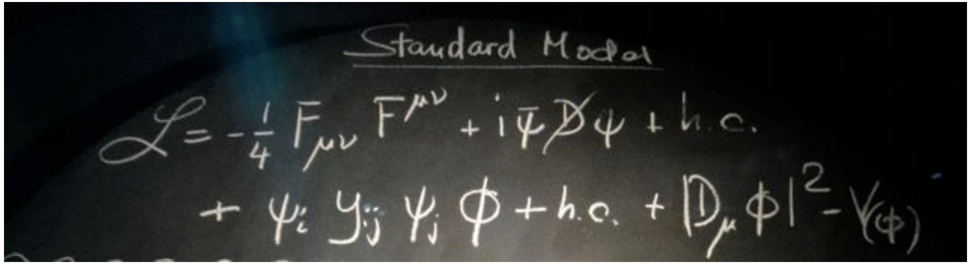
$$
\begin{gathered}
\mathcal{L}_{SM} = -\tfrac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \tfrac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \tfrac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \tfrac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - \\
W^-_\nu \partial_\nu W^+_\mu)) - \tfrac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \tfrac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w (A_\mu Z^0_\nu (W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \tfrac{1}{2}\partial_\mu H \partial_\mu H - 2M^2 \alpha_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \\
\beta_h \left(\tfrac{2M^2}{g^2} + \tfrac{2M}{g} H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-) \right) + \tfrac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M \left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^- \right) - \\
\tfrac{1}{8}g^2 \alpha_h \left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2 \right) - \\
gMW^+_\mu W^-_\mu H - \tfrac{1}{2}g\tfrac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \\
\tfrac{1}{2}ig \left(W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) - W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0) \right) + \\
\tfrac{1}{2}g \left(W^+_\mu (H\partial_\mu \phi^- - \phi^- \partial_\mu H) + W^-_\mu (H\partial_\mu \phi^+ - \phi^+ \partial_\mu H) \right) + \tfrac{1}{2}g\tfrac{1}{c_w}(Z^0_\mu (H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) + \\
M \left(\tfrac{1}{c_w} Z^0_\mu \partial_\mu \phi^0 + W^+_\mu \partial_\mu \phi^- + W^-_\mu \partial_\mu \phi^+ \right) - ig\tfrac{s_w^2}{c_w} MZ^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + igs_w MA_\mu (W^+_\mu \phi^- - \\
W^-_\mu \phi^+) - ig\tfrac{1-2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + igs_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \\
\tfrac{1}{4}g^2 W^+_\mu W^-_\mu \left(H^2 + (\phi^0)^2 + 2\phi^+\phi^- \right) - \tfrac{1}{8}g^2 \tfrac{1}{c_w^2} Z^0_\mu Z^0_\mu \left(H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^- \right) - \\
\tfrac{1}{2}g^2 \tfrac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \tfrac{1}{2}ig^2 \tfrac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \tfrac{1}{2}g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- + \\
W^-_\mu \phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \tfrac{s_w}{c_w}(2c_w^2 - 1) Z^0_\mu A_\mu \phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu \phi^+\phi^- + \tfrac{1}{2}ig_s \lambda^a_{ij} (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu - \bar{e}^\lambda (\gamma\partial + m^\lambda_e) e^\lambda - \bar{\nu}^\lambda (\gamma\partial + m^\lambda_\nu) \nu^\lambda - \bar{u}^\lambda_j (\gamma\partial + \\
m^\lambda_u) u^\lambda_j - \bar{d}^\lambda_j (\gamma\partial + m^\lambda_d) d^\lambda_j + igs_w A_\mu \left(-(\bar{e}^\lambda \gamma^\mu e^\lambda) + \tfrac{2}{3}(\bar{u}^\lambda_j \gamma^\mu u^\lambda_j) - \tfrac{1}{3}(\bar{d}^\lambda_j \gamma^\mu d^\lambda_j) \right) + \\
\tfrac{ig}{4c_w} Z^0_\mu \{ (\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) + (\bar{d}^\lambda_j \gamma^\mu (\tfrac{4}{3}s_w^2 - 1 - \gamma^5) d^\lambda_j) + \\
(\bar{u}^\lambda_j \gamma^\mu (1 - \tfrac{8}{3}s_w^2 + \gamma^5) u^\lambda_j) \} + \tfrac{ig}{2\sqrt{2}} W^+_\mu \left((\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) U^{lep}{}_{\lambda\kappa} e^\kappa) + (\bar{u}^\lambda_j \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d^\kappa_j) \right) + \\
\tfrac{ig}{2\sqrt{2}} W^-_\mu \left((\bar{e}^\kappa U^{lep\dagger}{}_{\kappa\lambda} \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\kappa\lambda} \gamma^\mu (1+\gamma^5) u^\lambda_j) \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_e (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1-\gamma^5) e^\kappa) + m^\lambda_\nu (\bar{\nu}^\lambda U^{lep}{}_{\lambda\kappa} (1+\gamma^5) e^\kappa \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_e (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1+\gamma^5) \nu^\kappa) - m^\kappa_\nu (\bar{e}^\lambda U^{lep\dagger}{}_{\lambda\kappa} (1-\gamma^5) \nu^\kappa \right) - \tfrac{g}{2}\tfrac{m^\lambda_\nu}{M} H (\bar{\nu}^\lambda \nu^\lambda) - \\
\tfrac{g}{2}\tfrac{m^\lambda_e}{M} H (\bar{e}^\lambda e^\lambda) + \tfrac{ig}{2}\tfrac{m^\lambda_\nu}{M} \phi^0 (\bar{\nu}^\lambda \gamma^5 \nu^\lambda) - \tfrac{ig}{2}\tfrac{m^\lambda_e}{M} \phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda) - \tfrac{1}{4} \bar{\nu}_\lambda M^R_{\lambda\kappa} (1-\gamma_5) \hat{\nu}_\kappa - \\
\overline{\tfrac{1}{4} \bar{\nu}_\lambda M^R_{\lambda\kappa} (1-\gamma_5) \hat{\nu}_\kappa} + \tfrac{ig}{2M\sqrt{2}} \phi^+ \left(-m^\kappa_d (\bar{u}^\lambda_j C_{\lambda\kappa} (1-\gamma^5) d^\kappa_j) + m^\lambda_u (\bar{u}^\lambda_j C_{\lambda\kappa} (1+\gamma^5) d^\kappa_j \right) + \\
\tfrac{ig}{2M\sqrt{2}} \phi^- \left(m^\lambda_d (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1+\gamma^5) u^\kappa_j) - m^\kappa_u (\bar{d}^\lambda_j C^\dagger_{\lambda\kappa} (1-\gamma^5) u^\kappa_j \right) - \tfrac{g}{2}\tfrac{m^\lambda_u}{M} H (\bar{u}^\lambda_j u^\lambda_j) - \\
\tfrac{g}{2}\tfrac{m^\lambda_d}{M} H (\bar{d}^\lambda_j d^\lambda_j) + \tfrac{ig}{2}\tfrac{m^\lambda_u}{M} \phi^0 (\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \tfrac{ig}{2}\tfrac{m^\lambda_d}{M} \phi^0 (\bar{d}^\lambda_j \gamma^5 d^\lambda_j) + \bar{G}^a \partial^2 G^a + g_s f^{abc} \partial_\mu \bar{G}^a G^b g^c_\mu + \\
\bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \tfrac{M^2}{c_w^2}) X^0 + \bar{Y} \partial^2 Y + igc_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \\
\partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + igc_w W^-_\mu (\partial_\mu \bar{X}^- X^0 - \\
\partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + igc_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) + igs_w A_\mu (\partial_\mu \bar{X}^+ X^+ - \\
\partial_\mu \bar{X}^- X^-) - \tfrac{1}{2}gM \left(\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2} \bar{X}^0 X^0 H \right) + \tfrac{1-2c_w^2}{2c_w} igM \left(\bar{X}^+ X^0 \phi^+ - \bar{X}^- X^0 \phi^- \right) + \\
\tfrac{1}{2c_w} igM \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + igMs_w \left(\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^- \right) + \\
\tfrac{1}{2} igM \left(\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0 \right) .
\end{gathered}
$$

Now verified up to the ~TeV range and working very well, but…

Open Questions

Theoretical Issues:

- Gravity
- Neutrino Masses
- Hierarchy Problem
- Flavour Problem (3 families)
- …



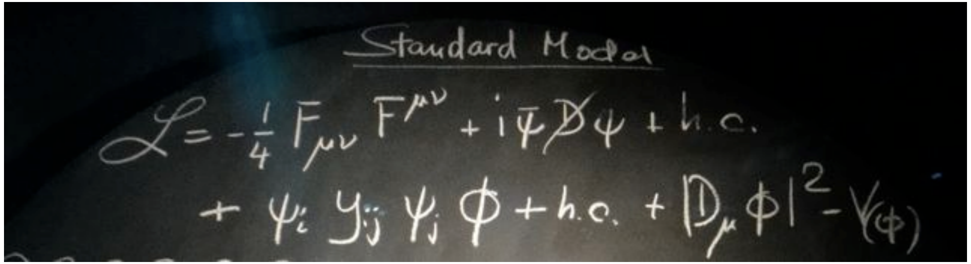
Open Questions

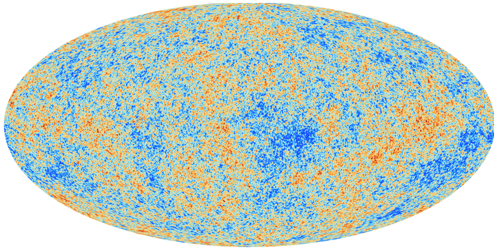
Theoretical Issues:

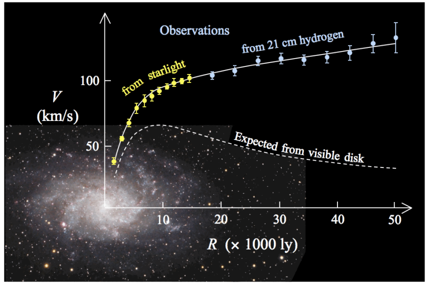
- Gravity
- Neutrino Masses
- Hierarchy Problem
- Flavour Problem (3 families)
- …

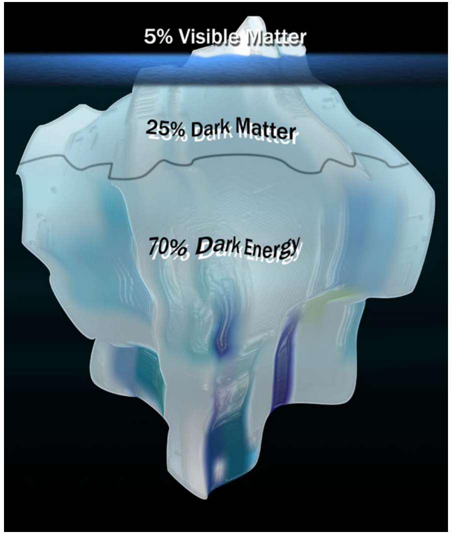
Cosmological Issues

- Dark Energy
- Dark Matter
- Inflation
- Matter/Antimatter Asymmetry
- CP violation
- …
-

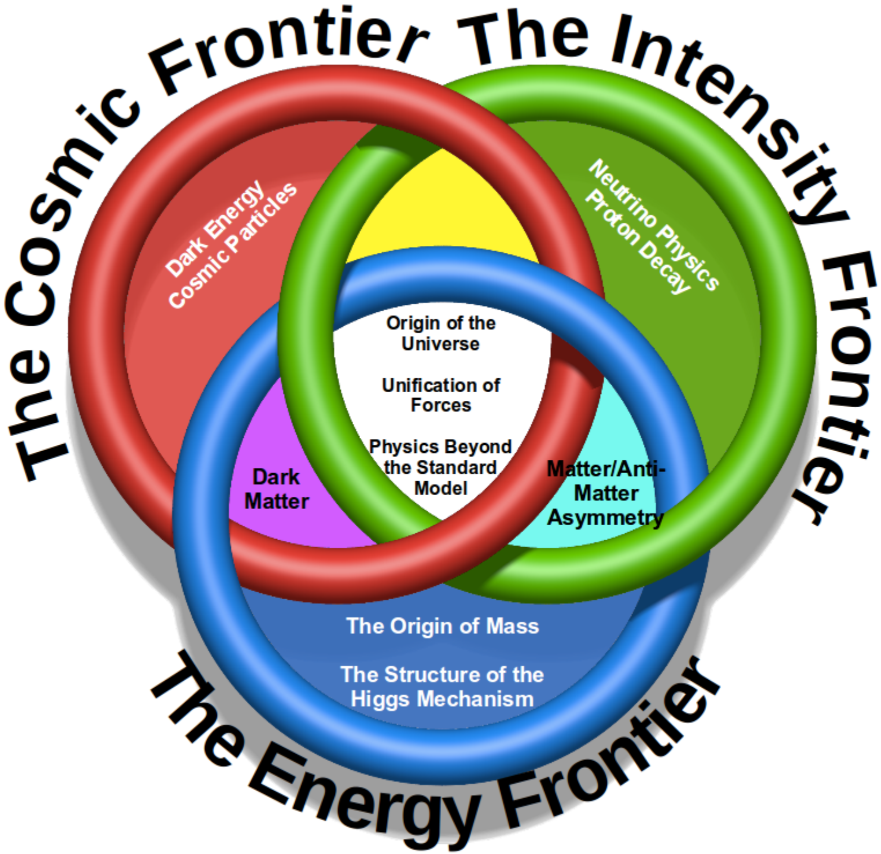




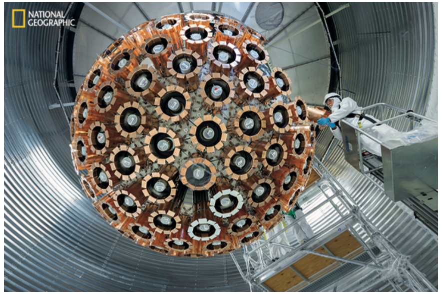


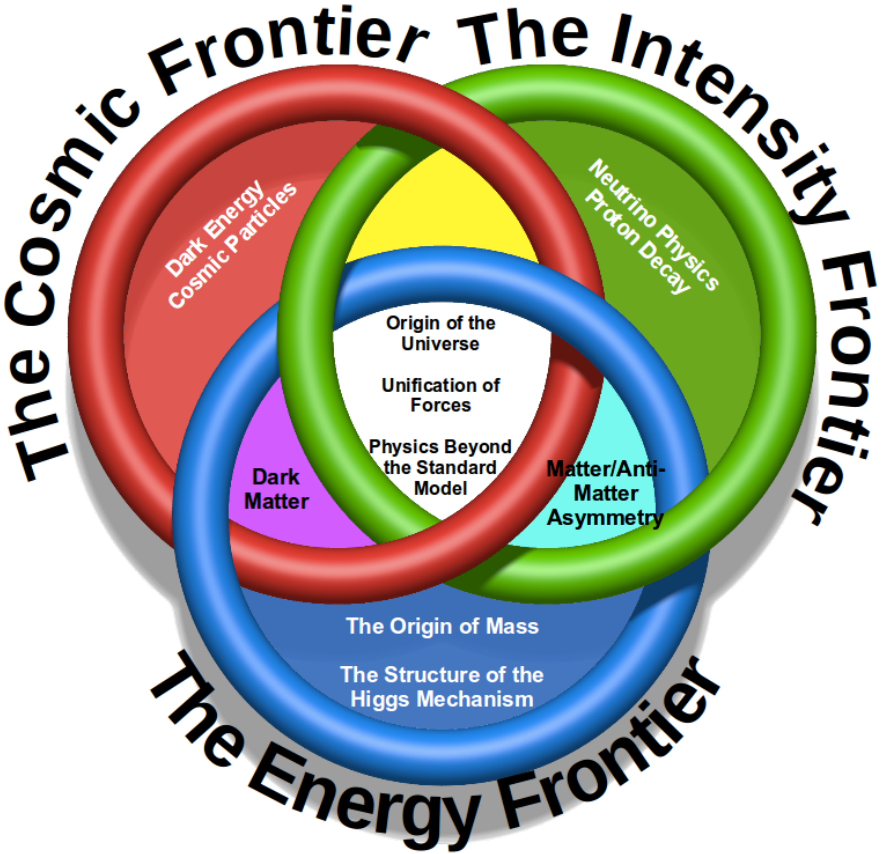


The Frontiers of Particle Physics

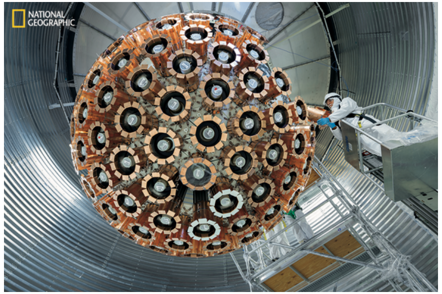


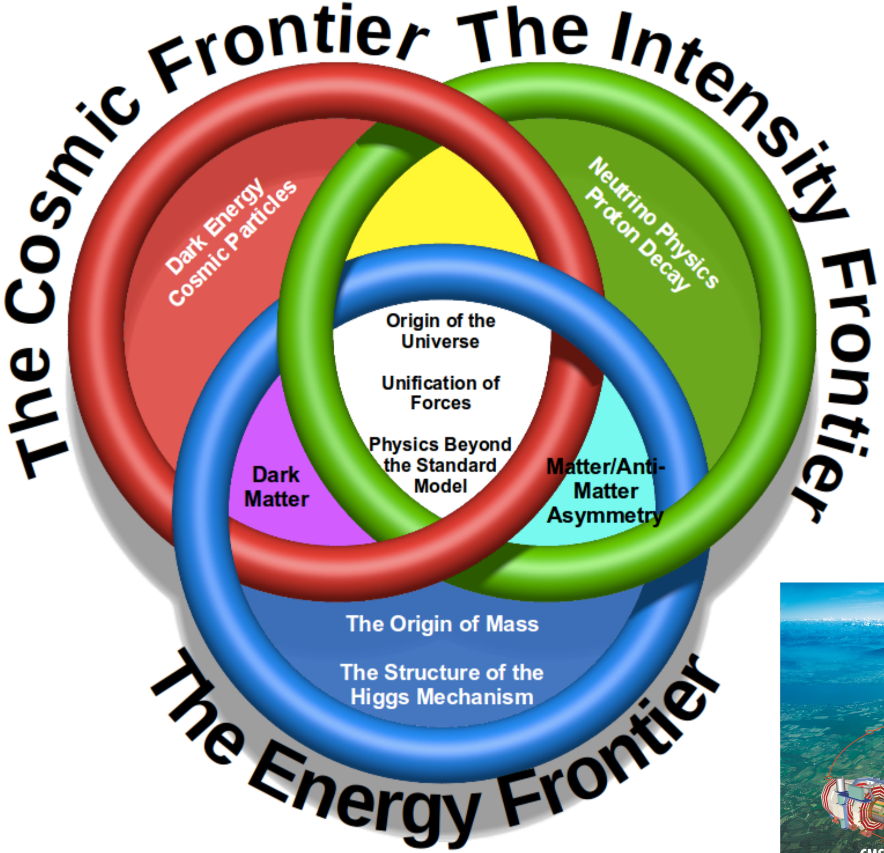
The Frontiers of Particle Physics

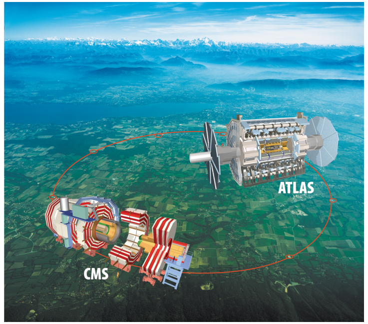


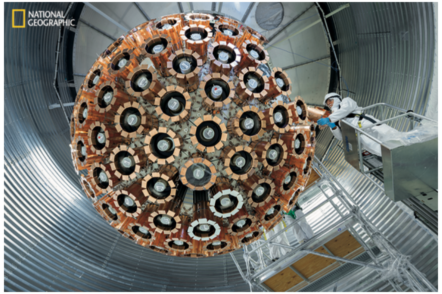


The Frontiers of Particle Physics

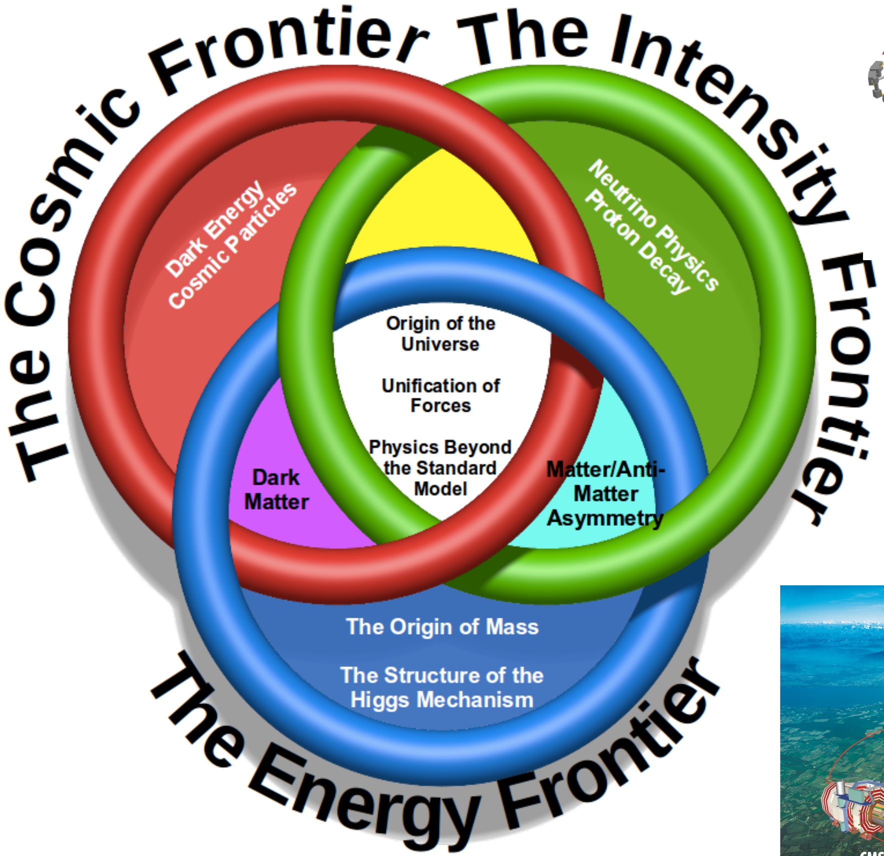


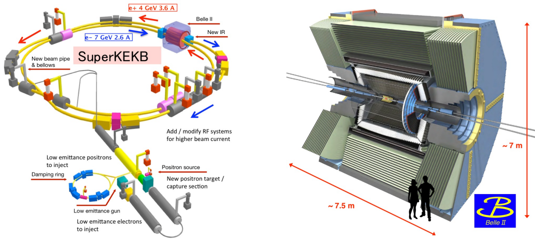


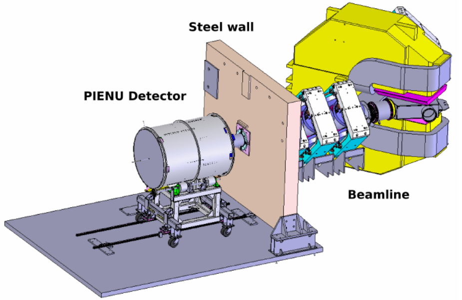


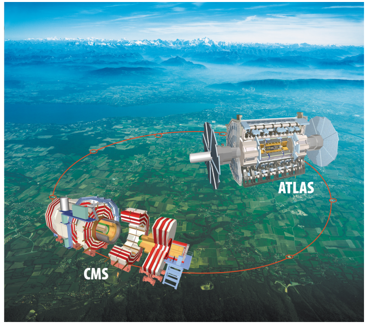



AMS


The Cosmic Frontier
The Intensity Frontier
The Energy Frontier
Dark Energy
Cosmic Particles
Neutrino Physics
Proton Decay
Origin of the Universe
Unification of Forces
Physics Beyond the Standard Model
Dark Matter
Matter/Anti-Matter Asymmetry
The Origin of Mass
The Structure of the Higgs Mechanism


SuperKEKB
Belle II


Steel wall
PIENU Detector
Beamline

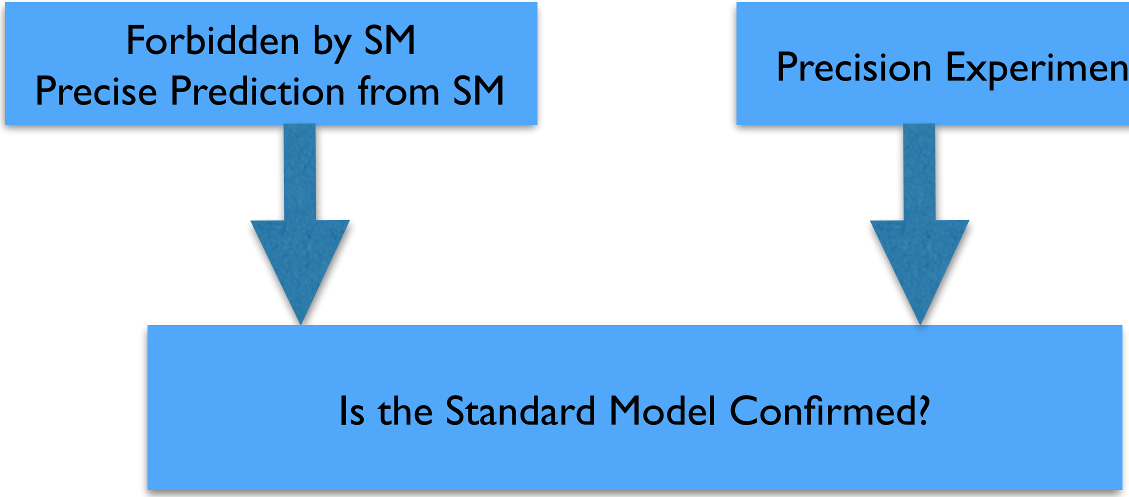

ATLAS
CMS

The Intensity/Precision Frontier

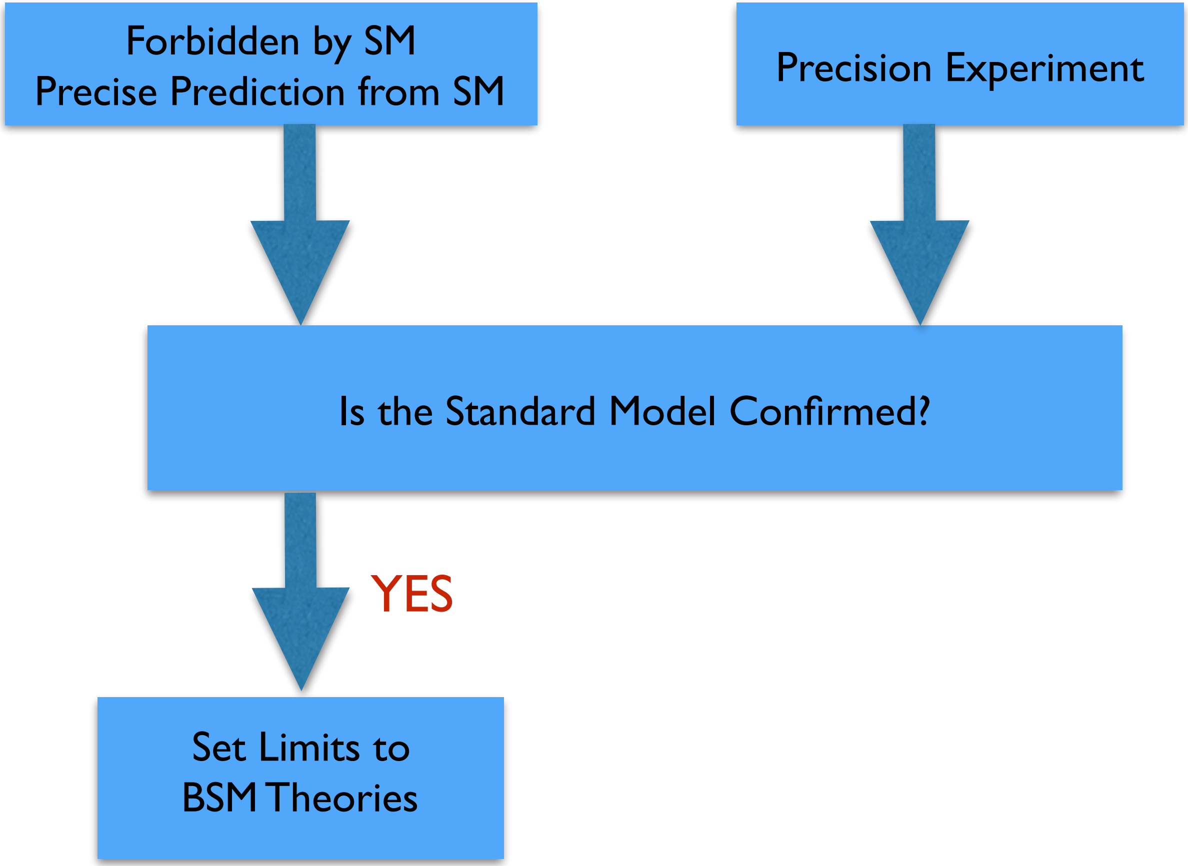
Forbidden by SM
Precise Prediction from SM

Precision Experiment

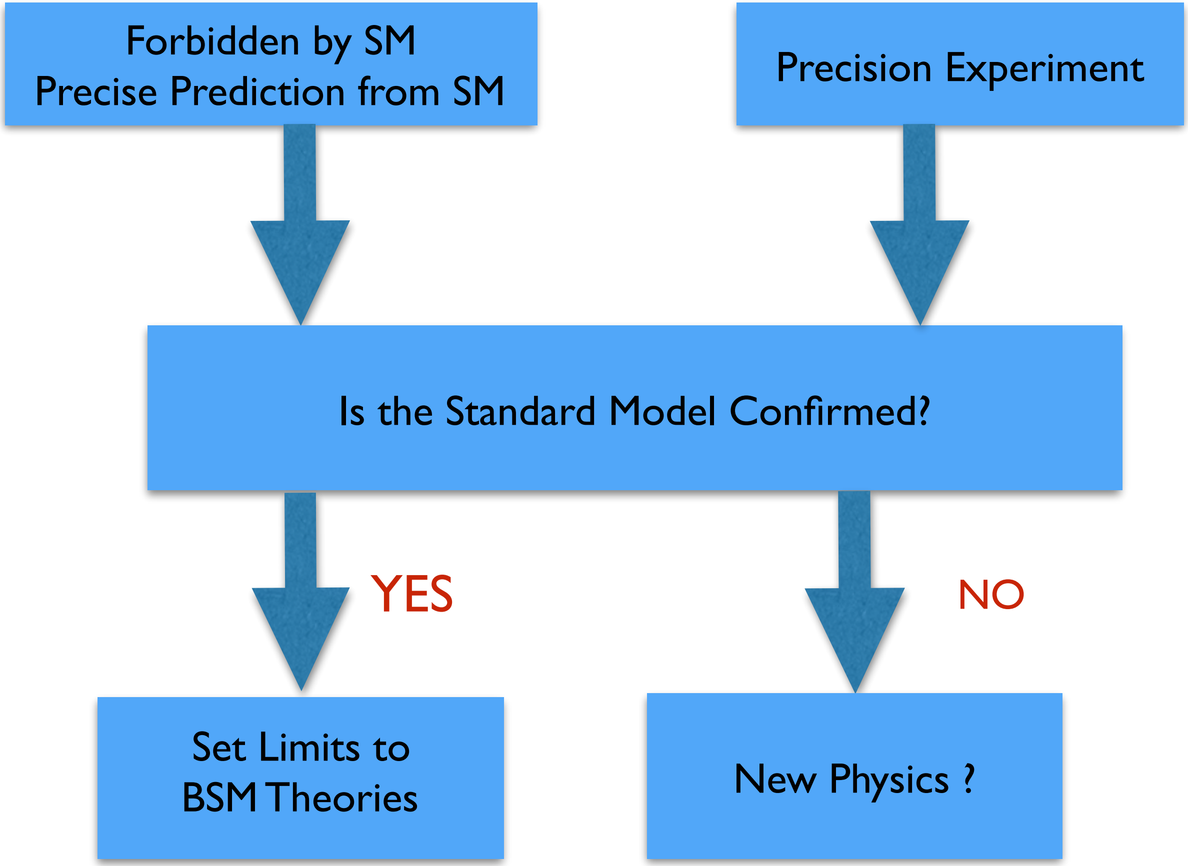
The Intensity/Precision Frontier



The Intensity/Precision Frontier



The Intensity/Precision Frontier



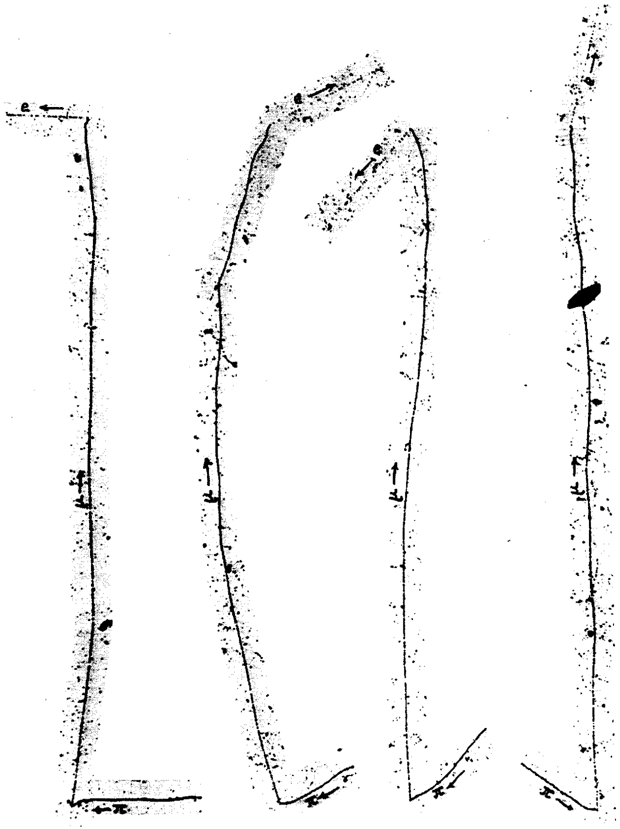
The Early History of Pions

Early History

1935: H. Yukawa predicts a new particle

1936: Discovery of the Muon

1947: C. Powell and collaborators discover the Pion
M.Lattes, H.Muirhead, G.Occhialini, C.Powell:
Nature, 159:694-697 (1947)



1949: H.Yukawa awarded the Nobel Prize.

1950: C. Powell awarded the Nobel Prize

- Pion discovered with $\pi^+ \to \mu^+ \nu$, followed by $\mu^+ \to e^+ \nu \bar{\nu}$

- But: $m_e = 0.511\ \mathrm{MeV}$

  $m_\mu = 105\ \mathrm{MeV}$

- Why don't we see $\pi^+ \to e^+ \nu$?

- 1950s: Many experimental indications that the weak interactions were violating parity. "V-A" structure:

$$H_w \sim \left(\frac{g^2 V_{ud}}{8 m_W^2}\right) \bar{l} \gamma_\lambda (1 - \gamma_5) \bar{\nu}_l \bar{u} \gamma^\lambda \gamma_5 d$$

The Pion and the Standard Model

PHYSICAL REVIEW VOLUME 76, NUMBER 10 NOVEMBER 15, 1949

Note on the Decay of the π-Meson

M. Ruderman and R. Finkelstein
California Institute of Technology, Pasadena, California

(Received July 25, 1949)

Assuming the symmetric coupling scheme proposed by Wheeler and Tiomno, and others, we have calculated the ratio of the decay rate π-meson→electron+neutrino to the decay rate of π-meson→μ-meson +neutrino. The electron-neutrino decay proceeds faster, in disagreement with experiment, unless the π-meson is pseudoscalar and the β-decay coupling is pseudovector. Hence if the symmetric coupling scheme is corect and no other direct couplings are introduced, the π-meson must be pseudoscalar and β-decay must be at least partially pseudovector. If symmetric coupling is not assumed, no conclusion of this kind can be drawn.

Meson	Scalar	f	f	f	f	f
	P-scalar	f	5.1	f	1.0×10^{-4}	f
	Vector	f	f	4.0	f	2.4
	P-vector	f	f	f	f	2.4

The Pion and the Standard Model

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Meson	Scalar	*f*	*f*	*f*	*f*	*f*
	P-scalar	*f*	5.1	*f*	1.0×10^{-4}	*f*
	Vector	*f*	*f*	4.0	*f*	2.4
	P-vector	*f*	*f*	*f*	*f*	2.4

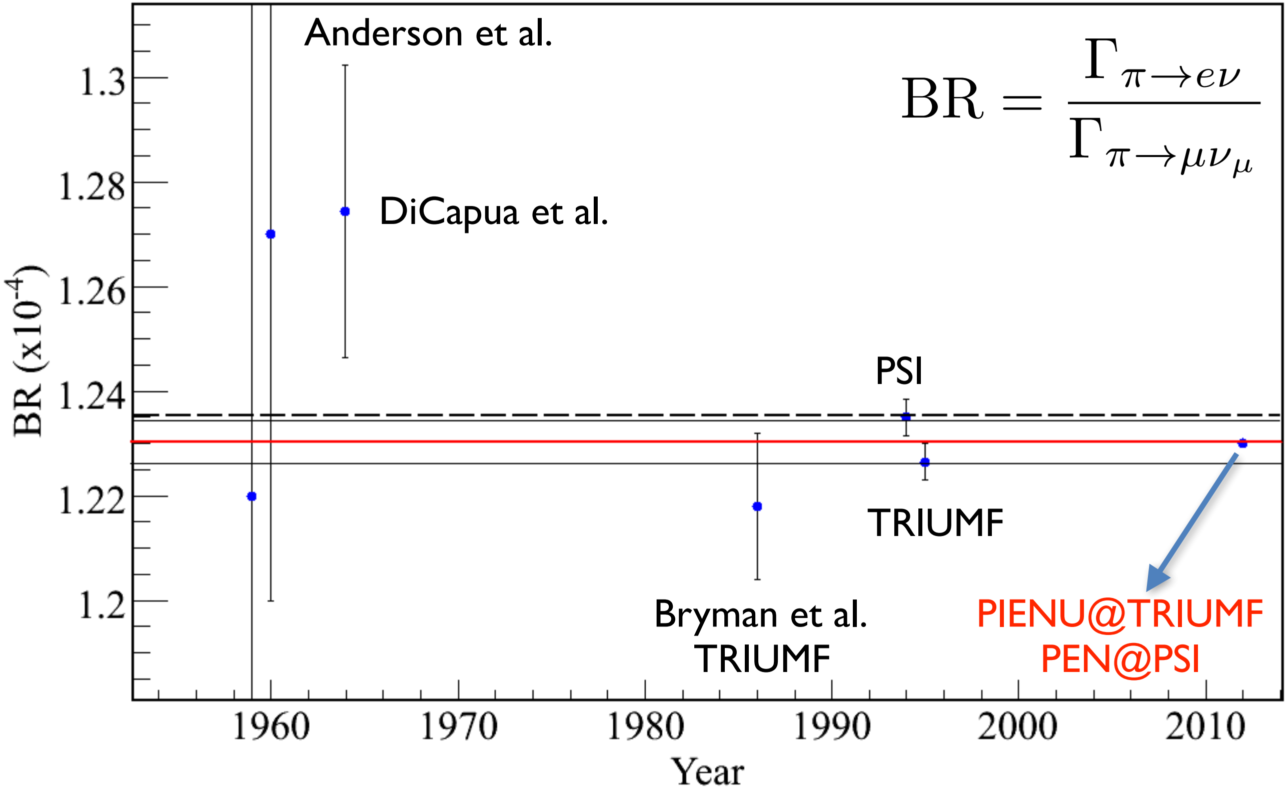
PHYSICAL REVIEW VOLUME 109, NUMBER 1 JANUARY 1, 1958

Theory of the Fermi Interaction

R. P. FEYNMAN AND M. GELL-MANN
California Institute of Technology, Pasadena, California
(Received September 16, 1957)

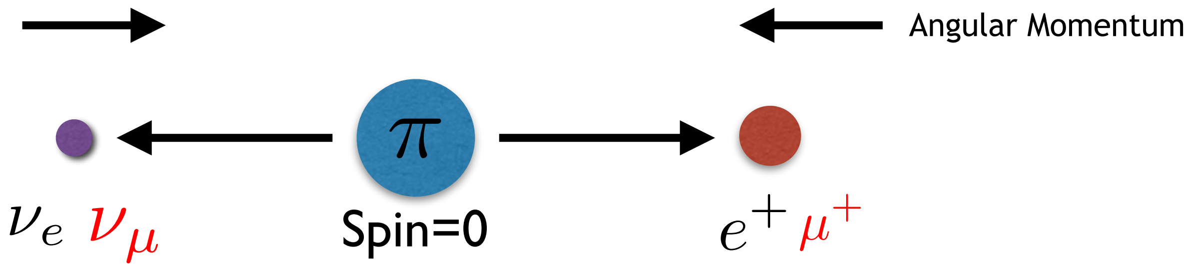
Experimentally[16] no $\pi\rightarrow e+\nu$ have been found, indicating that the ratio is less than 10^{-5}. This is a very serious discrepancy. The authors have no idea on how it can be resolved.

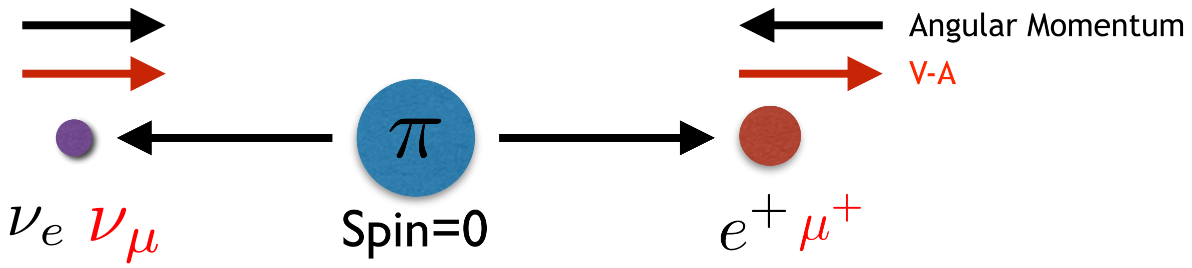
Experimental History



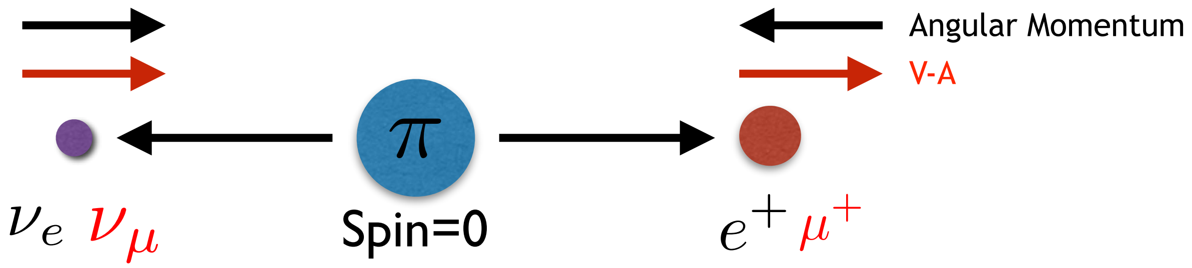
$$BR = \frac{\Gamma_{\pi \to e\nu}}{\Gamma_{\pi \to \mu\nu_\mu}}$$

Helicity Suppression




Angular Momentum
V-A
ν_e ν_μ
π
Spin=0
e^+ μ^+

Helicity Suppression

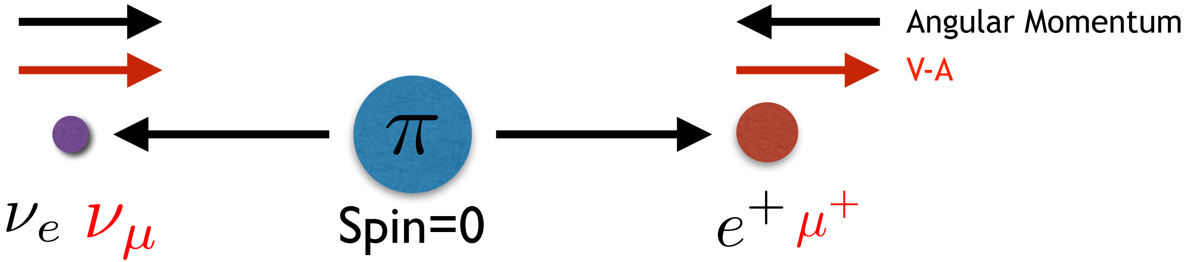


Neutrinos produced only by weak interactions:

Neutrinos: left-handed helicity

Antineutrinos: right-handed helicity

Helicity Suppression



Neutrinos produced only by weak interactions:

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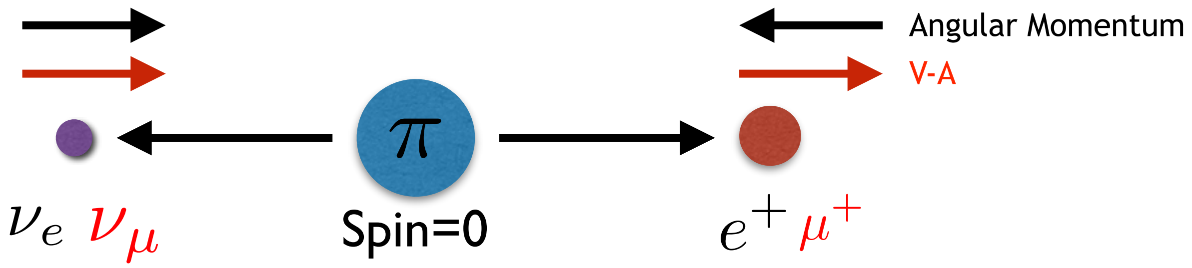
Weak interaction forces the electron into the "wrong" helicity state



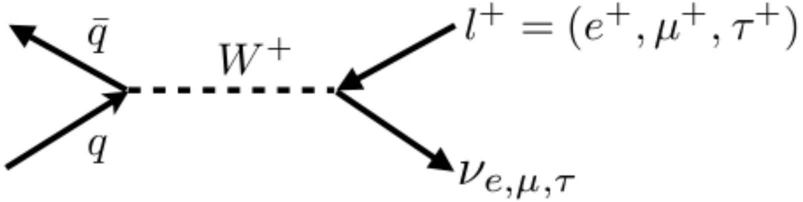
Neutrinos produced only by weak interactions:

Neutrinos: left-handed helicity

Antineutrinos: right-handed helicity

Weak interaction forces the electron into the "wrong" helicity state

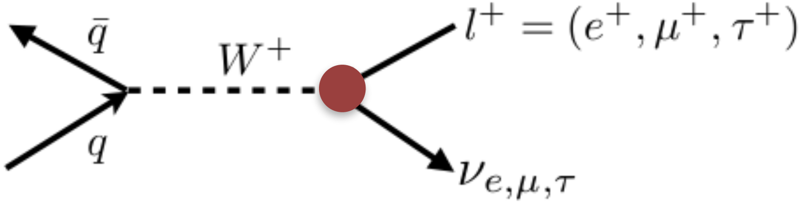
The V-A structure of the weak interactions explains why the muon decay mode is favoured!



$$\Gamma_{\pi \to l \nu_l} = G^2_{e,\mu,\tau} \frac{m_\pi f_\pi^2 m_l^2}{8\pi} \left(1 - \frac{m_l^2}{m_\pi^2}\right)^2$$

$$R_0 = \frac{\Gamma_{\pi \to e \nu_e}}{\Gamma_{\pi \to \mu \nu_\mu}} = \frac{m_e^2}{m_\mu^2} \left(\frac{m_\pi^2 - m_e^2}{m_\pi^2 - m_\mu^2}\right)^2 = 1.28336(2) \times 10^{-4}$$

Lepton Universality



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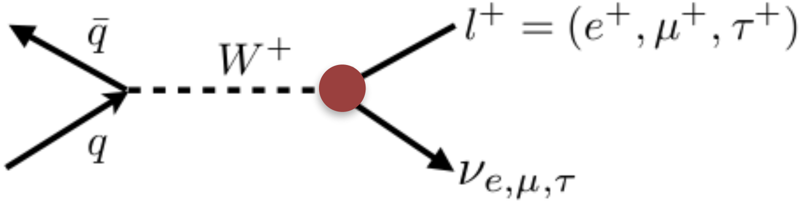

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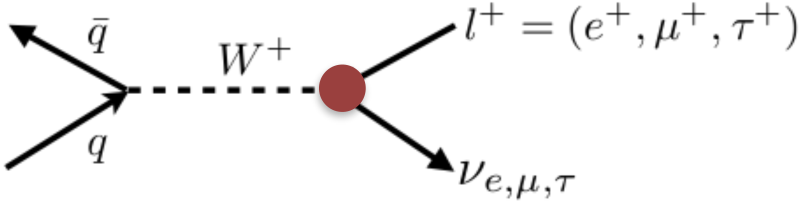
Helicity Suppression

Lepton Universality



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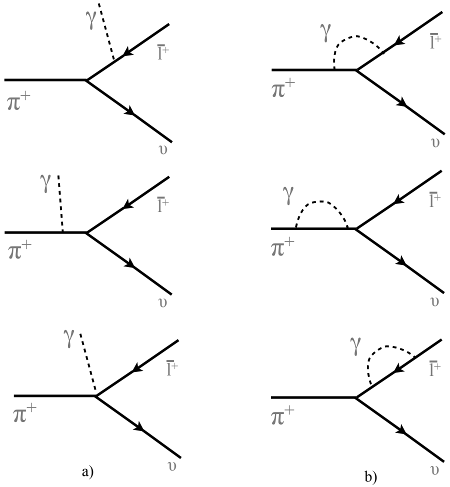
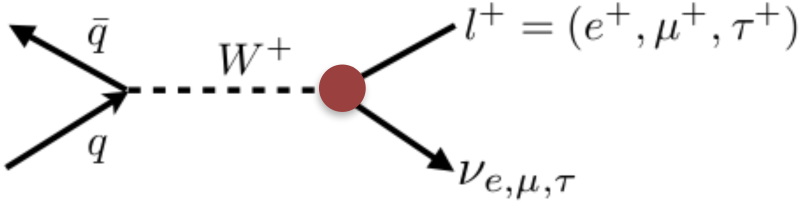
Helicity Suppression

Radiative Corrections



Lepton Universality



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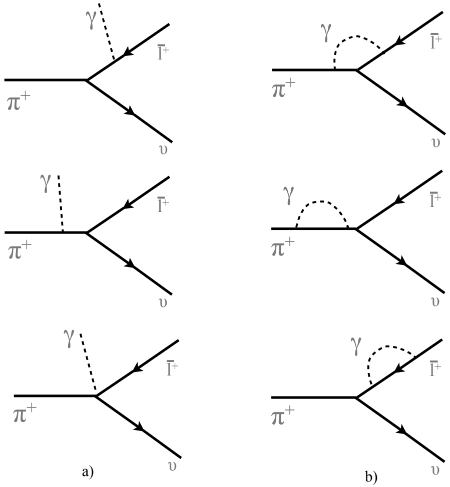
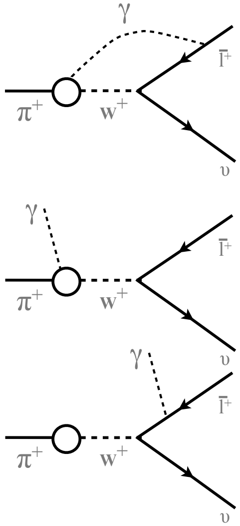
Helicity Suppression

Radiative Corrections



Structure Dependent RC

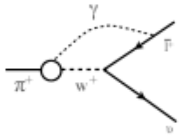


$$R = \boxed{R_0} \times \left[1 + \frac{\alpha}{\pi}\left\{F(\frac{m_e}{m_\pi}) - F(\frac{m_\mu}{m_\pi}) + \frac{m_\mu^2}{m_\rho^2}\left(c_2 \ln\frac{m_\rho^2}{m_\mu^2} + c_3\right) + c_4\frac{m_\pi^6}{m_e^2 m_\rho^4}\right\} + c_5\left(\frac{\alpha}{\pi}\ln\frac{m_\mu}{m_e}\right)^2 + ..\right]$$

$$(+SD_\pi)$$

V.Cirigliano, I.Rosell: Phys.Rev.Lett. 99(23), 231801 (2007)

M. Terent'ev: Yad. Fiz. 18(870) (1973)



$$R = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}$$

S. Berman: Phys.Rev.Lett. 1(12), 468 (1958)
T. Kinoshita: Phys.Rev.Lett. 2(11), 477 (1959)
T. Goldman, W.Wilson: Phys.Rev.D 14(9), 2428 (1976)
W. Marciano, A. Sirlin: Phys.Rev.Lett. 36(24), 1425 (1976)

Precision Calculation and Experimental Situation

$$R = \boxed{R_0} \times \left[1 + \frac{\alpha}{\pi} \left\{ F(\frac{m_e}{m_\pi}) - F(\frac{m_\mu}{m_\pi}) + \frac{m_\mu^2}{m_\rho^2} \left(c_2 \ln \frac{m_\rho^2}{m_\mu^2} + c_3 \right) + c_4 \frac{m_\pi^6}{m_e^2 m_\rho^4} \right\} + c_5 \left(\frac{\alpha}{\pi} \ln \frac{m_\mu}{m_e} \right)^2 + .. \right]$$

$(+SD_\pi)$

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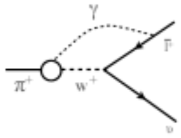

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$$R = \frac{\Gamma(\pi^+ \to e^+\nu(\gamma))}{\Gamma(\pi^+ \to \mu^+\nu(\gamma))}$$

Standard Model: $R^{SM} = 1.2353(1) \times 10^{-4}$

Experiments: $R^{exp} = 1.230 \pm 0.004 \times 10^{-4}$

TRIUMF: D.Britton et al. Phys.Rev.Lett. 68:3000-3003 (1992)
PSI: G. Czapek et al. Phys.Rev.Lett. 70:17-20 (1993)

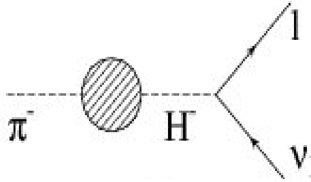
New pseudo-scalar interactions (no helicity suppression)

B.Campbell, D. Maybury: Nucl.Phys. B709, 419 (2005)

$$1 - \frac{R^{exp}}{R^{SM}} \sim \mp \frac{\sqrt{2}\pi}{G_\mu} \frac{1}{\Lambda^2} \frac{m_\pi^2}{m_e(m_d + m_u)} \sim (\frac{1\mathrm{TeV}}{\Lambda})^2 \times 10^3 \quad \Rightarrow 1000\mathrm{TeV}$$

Charged Higgs (with non-SM couplings)

O. Shanker: Nucl.Phys. B204(3), 375 (1982)

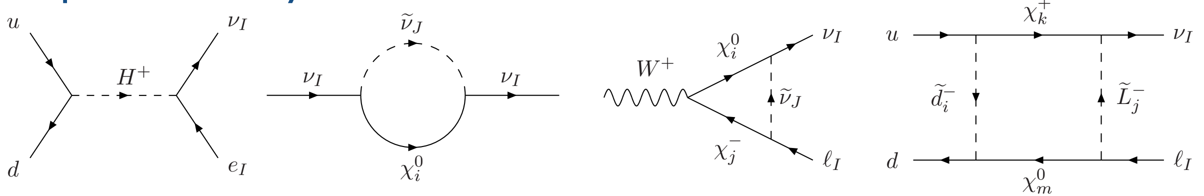


Relevant for SUSY models, Changes the BR through loop contributions

$$1 - \frac{R^{exp.}}{R^{SM}} \sim \mp \frac{2m_\pi^2}{m_e(m_d + m_u)} \frac{m_W^2}{m_{H^\pm}} \lambda_{ud}(\lambda_{e\nu} - \frac{m_e}{m_\mu} \lambda_{\mu\nu}) \qquad M_H^\pm \sim 400\mathrm{GeV}$$

SUperSYmmetry

M. Ramsey-Musolf, S.Su, S.Tulin: Phys.Rev. D76, 095017 (2007)



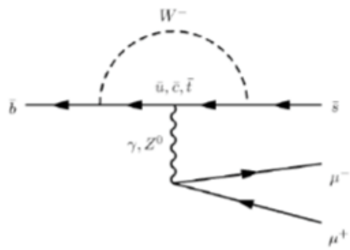
R-parity violating SUSY affects the BR already at tree-level!

And More: Leptoquarks, new scalar interactions, massive neutrinos,…

Lepton Universality Violation ???

LHCb Collaboration,
R. Aaij et al., “Test of lepton universality using B+ → K⁺l⁺l⁻ decays,” arXiv:1406.6482.

- Previously measured by Belle and BaBar at 20-50% precision level
- R_K = 1 expected from SM
- Theoretically clean observable with small corrections
- Analysis : $1<q^2<6$ GeV^2/c^4



$$R_K = \frac{B^+ \to K^+\mu^+\mu^-}{B^+ \to K^+e^+e^-} = 0.745^{+0.090}_{-0.074}(\text{stat}) \pm 0.036(\text{cyst})$$

2.6σ deviation from the SM value

Feruglio, Paradisi, Pattori, Phys. Rev. Lett. 118, 011801 (2017)

$$R^{\tau/\ell}_{D^{(*)}} = \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})_{\text{exp}}/\mathcal{B}(\bar{B} \to D^{(*)}\tau\bar{\nu})_{\text{SM}}}{\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu})_{\text{exp}}/\mathcal{B}(\bar{B} \to D^{(*)}\ell\bar{\nu})_{\text{SM}}},$$

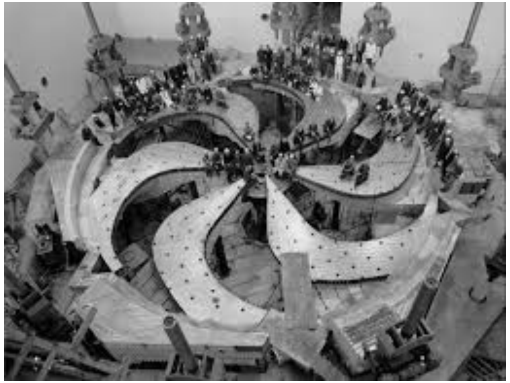
$$R^{\tau/\ell}_{D} = 1.37 \pm 0.17, \qquad R^{\tau/\ell}_{D^*} = 1.28 \pm 0.08\,.$$

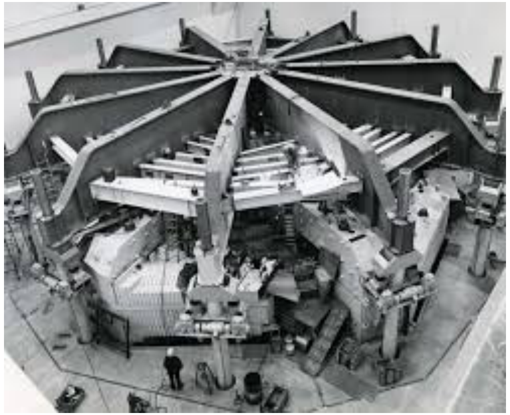
J. P. Lees *et al.* [BaBar Collaboration], Phys. Rev. D **88** (2013) 7, 072012 [arXiv:1303.0571].
M. Huschle *et al.* [Belle Collaboration], Phys. Rev. D **92** (2015) 7, 072014 [arXiv:1507.03233].
R. Aaij *et al.* [LHCb Collaboration], Phys. Rev. Lett. **115** (2015) 15, 159901 [arXiv:1506.08614].

3.9σ deviation from the SM value

The PIENU Experiment at TRIUMF

The TRIUMF Cyclotron





First Beam: 1974
Total magnet weight: 4000 Tons
Magnet diameter: 18m
Magnetic field: Up to 5600 gauss
Electric Field Frequency: 23MHz

Proton Beam:
Energy: 500 MeV
Max Extr. Current: 140 uA.

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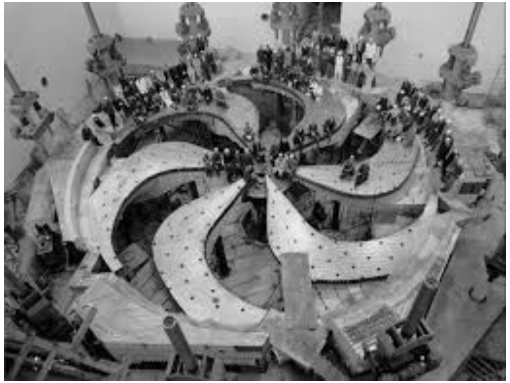

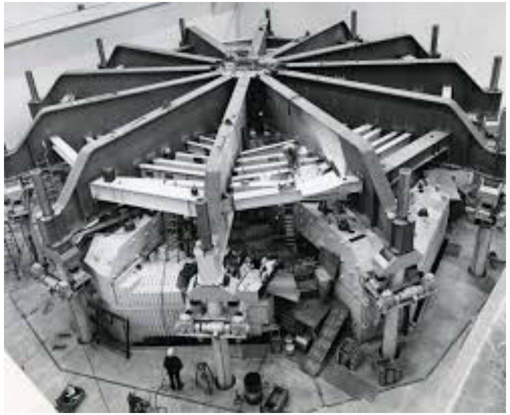

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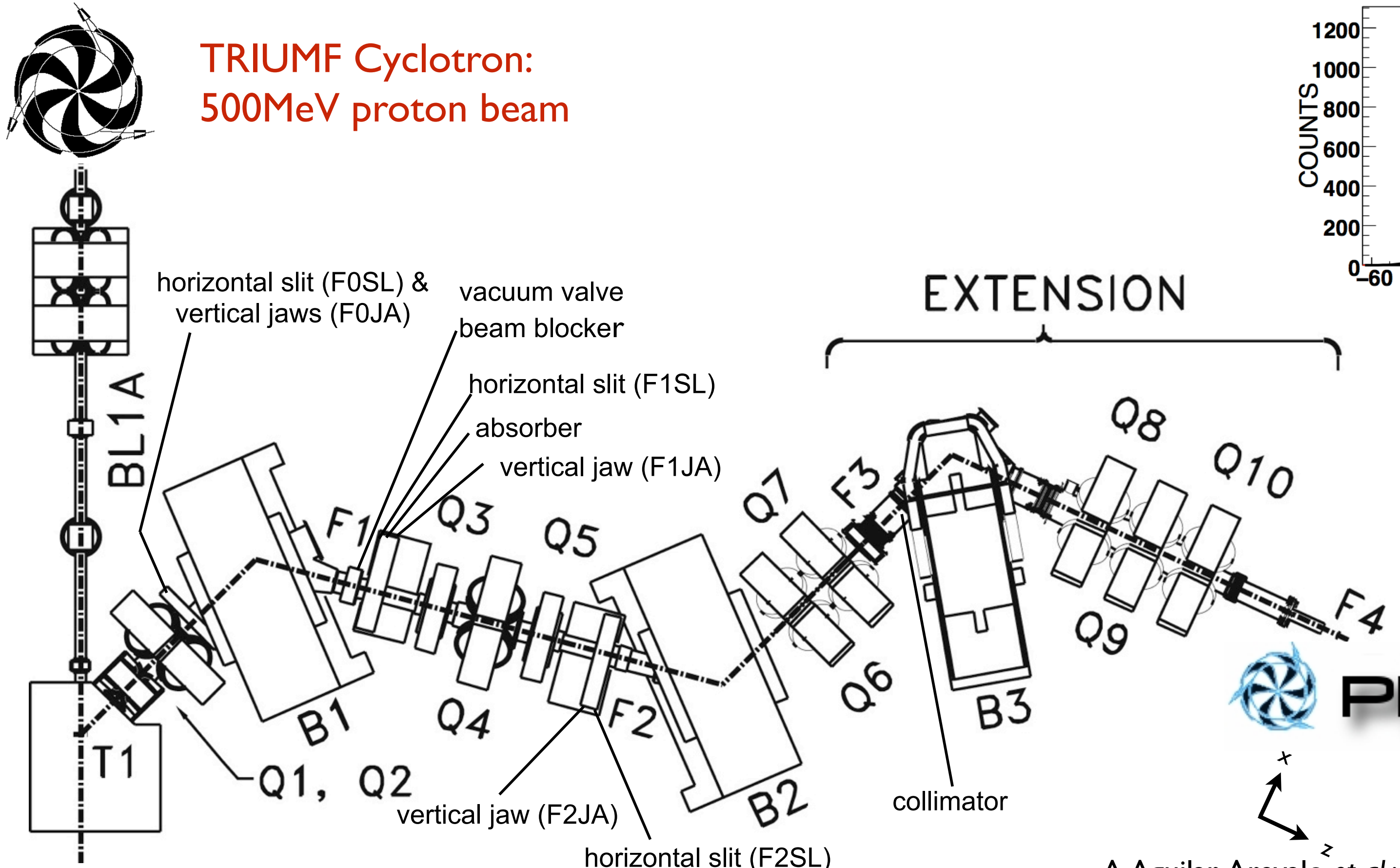
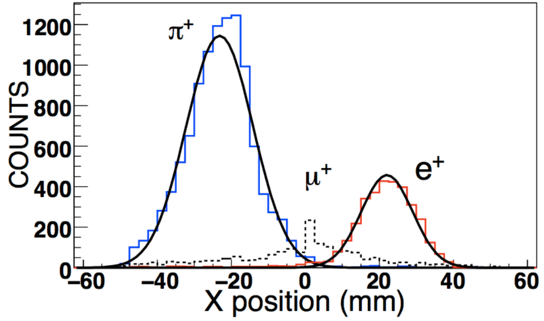
The Pion Beam

TRIUMF Cyclotron:
500MeV proton beam

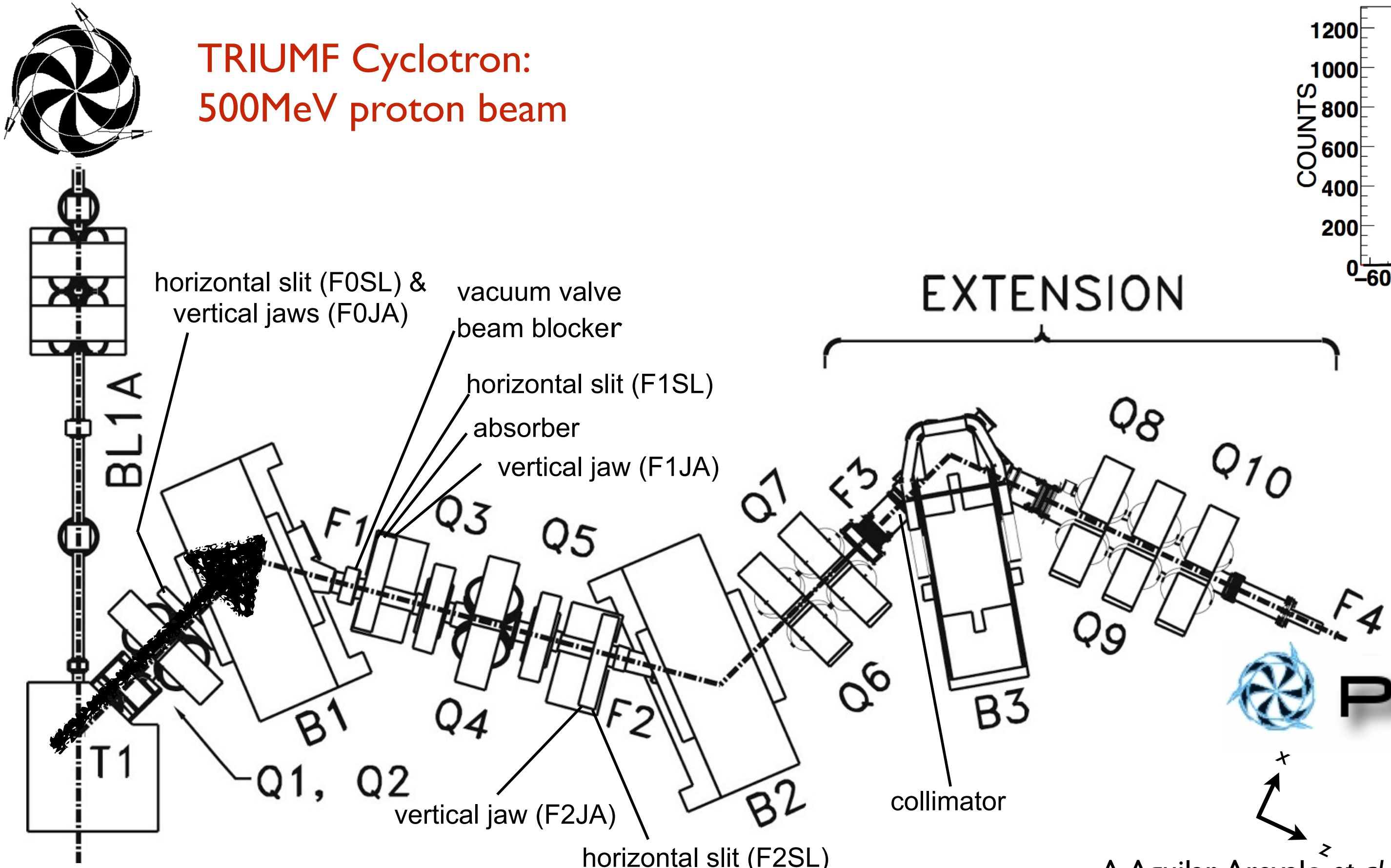


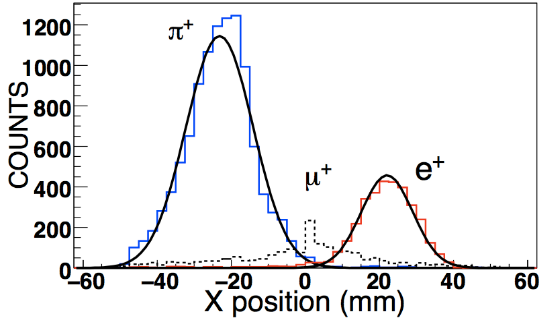


- 3-Dipoles Beamline
- 10 Quadrupoles
- Separation:
  - Energy-loss
  - Collimator
- Positron Contamination <1%
- dp/p ~ 1.5% FWHM

A.Aguilar-Arevalo *et al.*: Nucl. Instr. Meth. A621, 188 (2010)

TRIUMF Cyclotron:
500MeV proton beam





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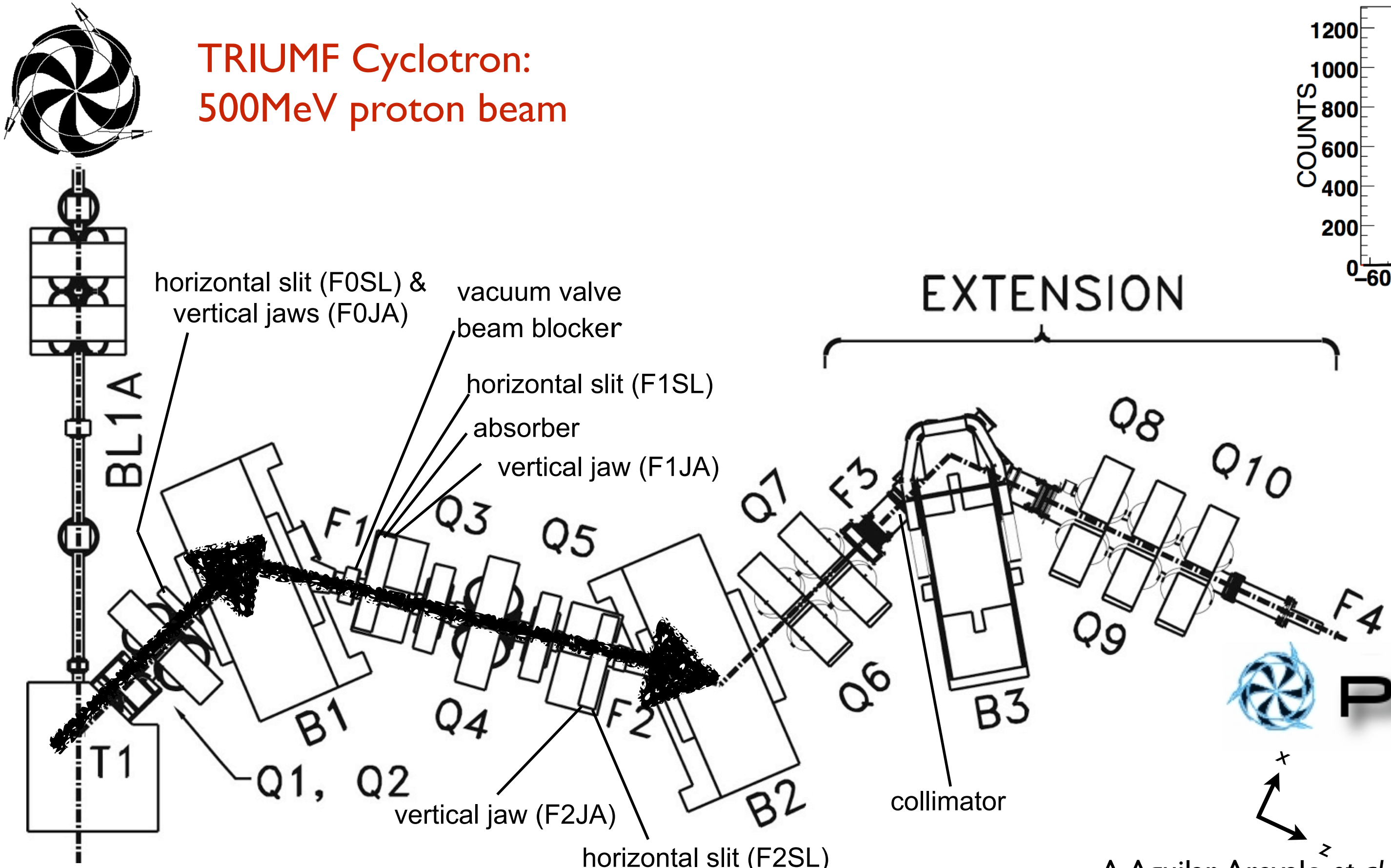

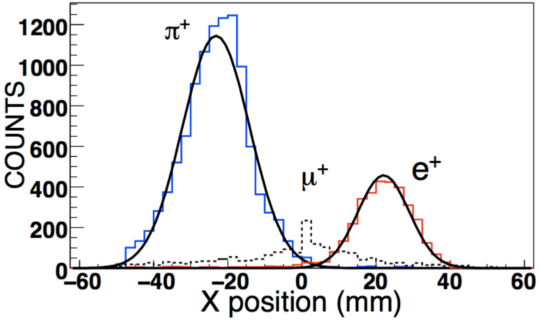

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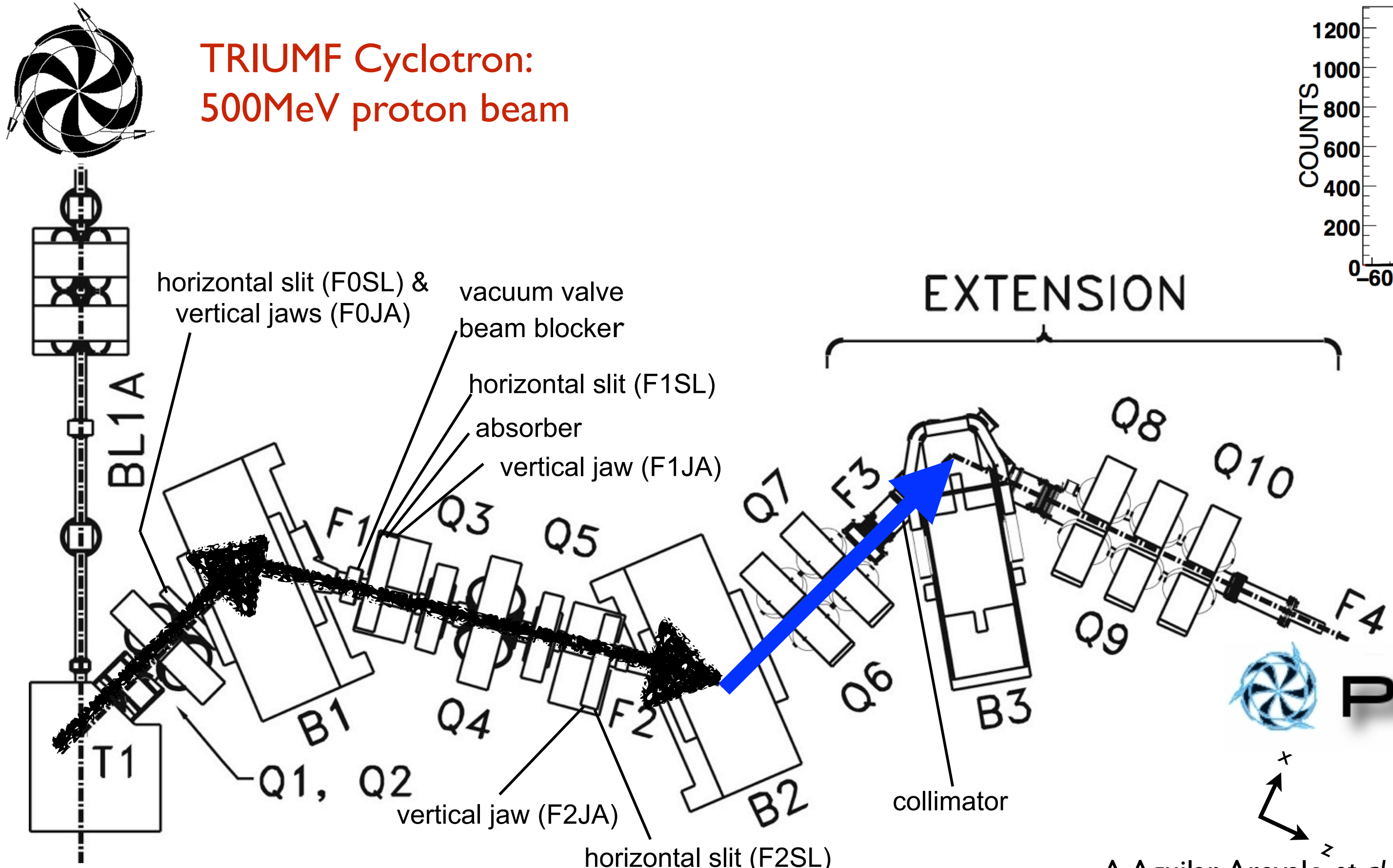

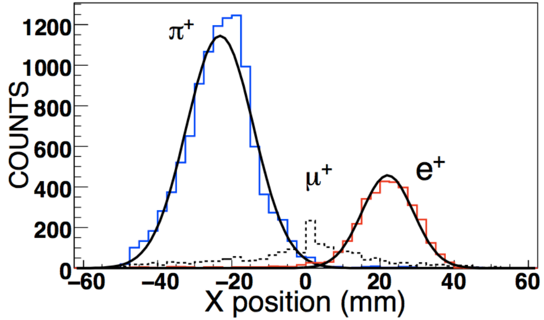

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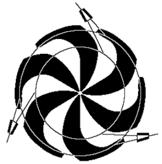
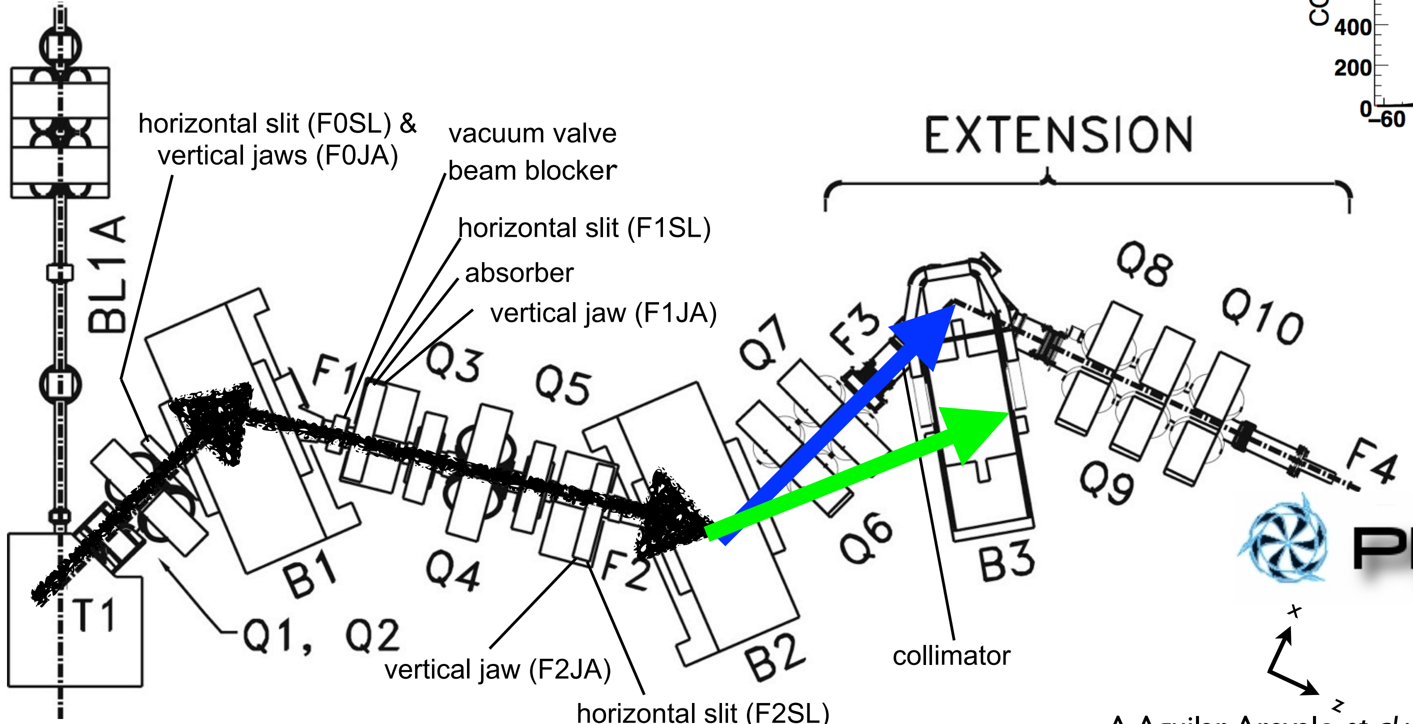
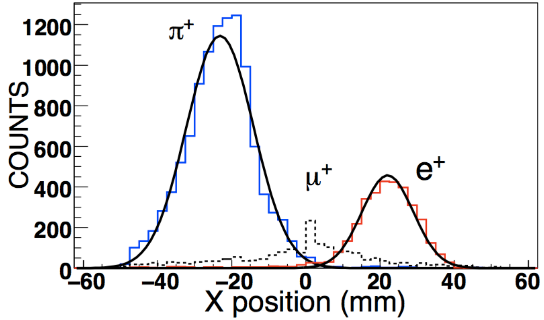


TRIUMF Cyclotron: 500MeV proton beam





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PIENU

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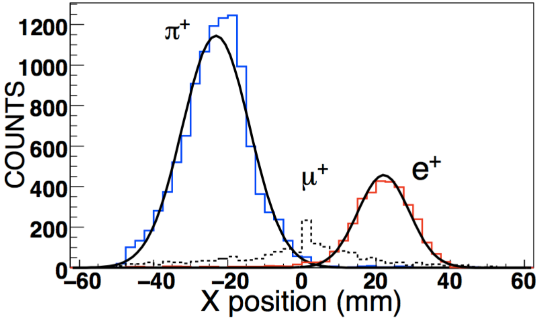

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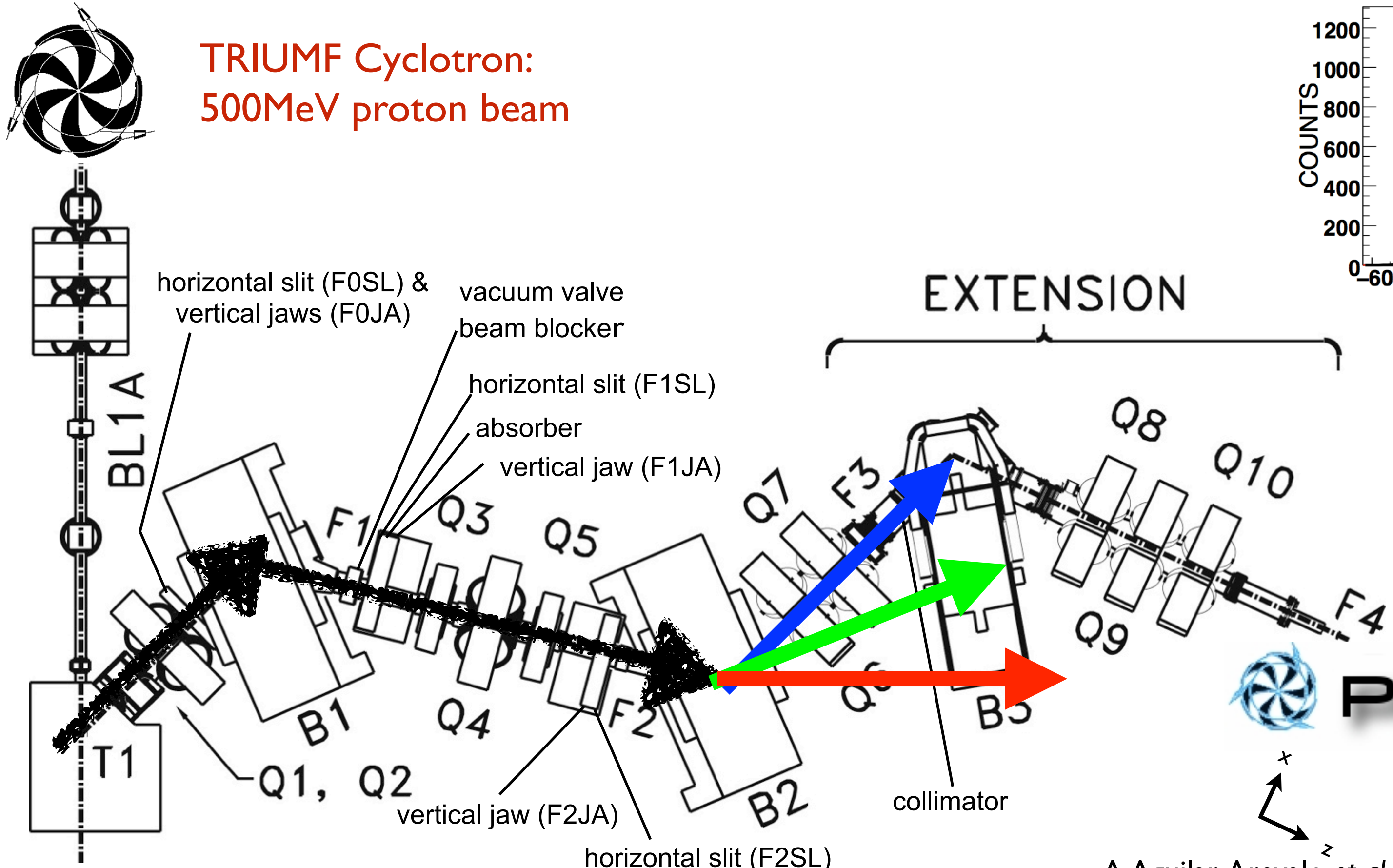

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The Pion Beam

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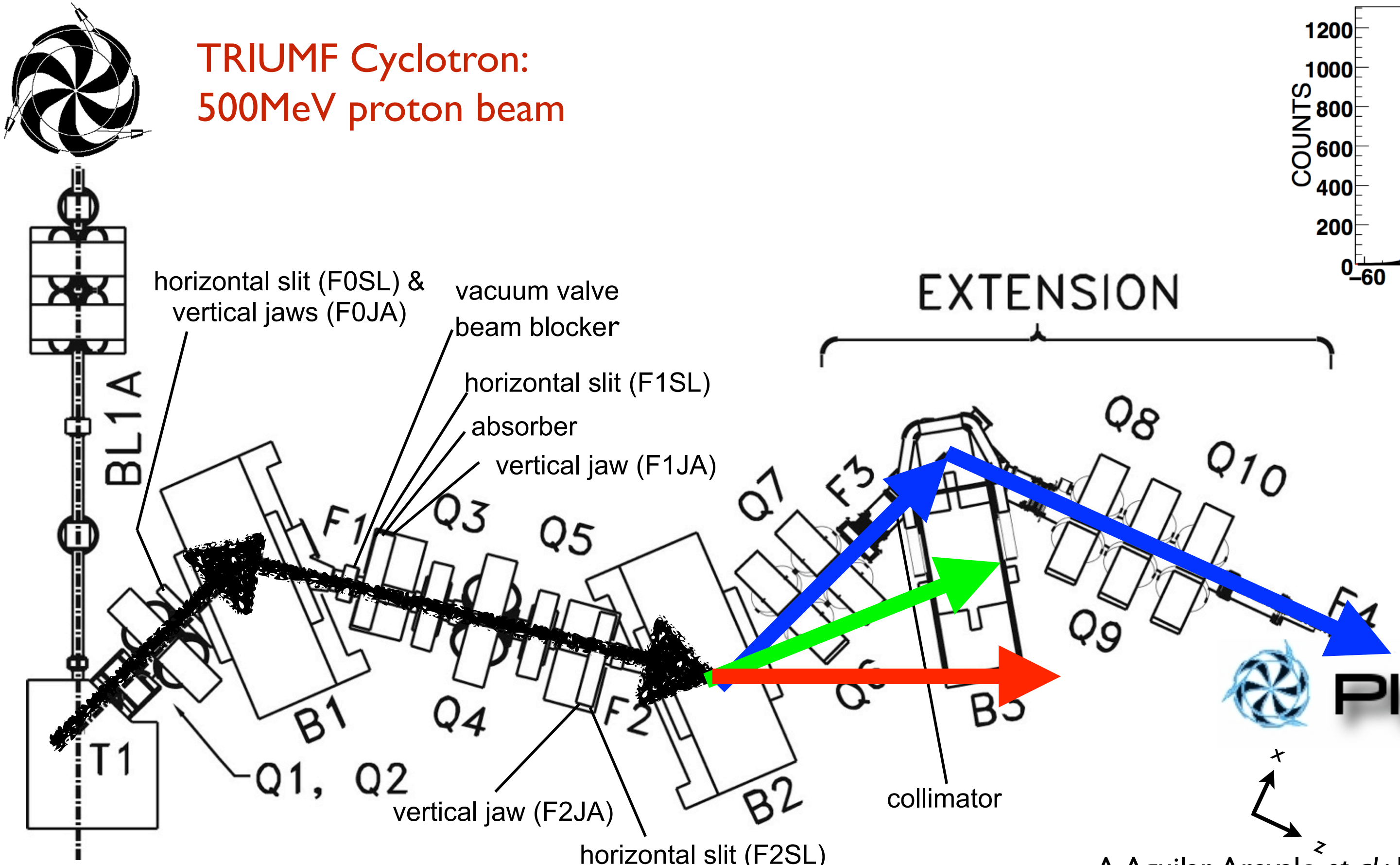

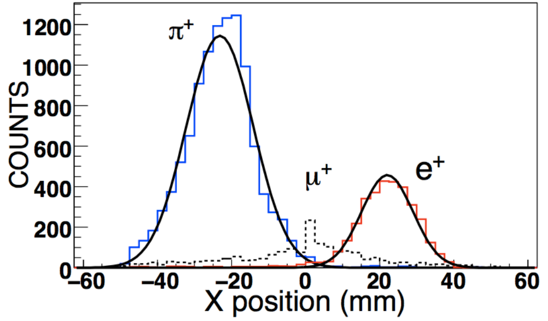

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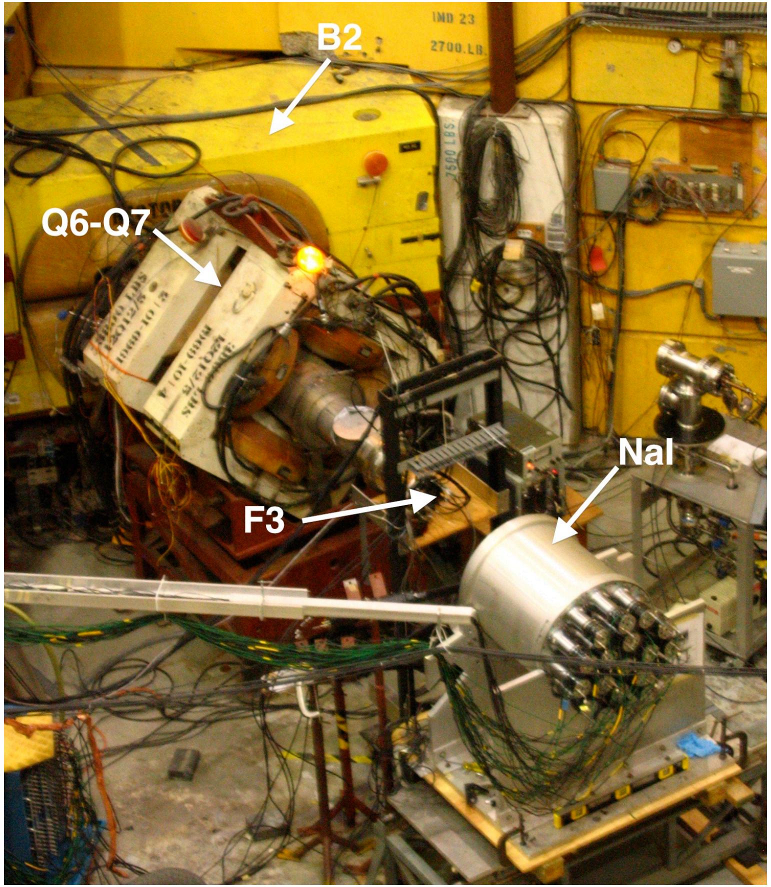
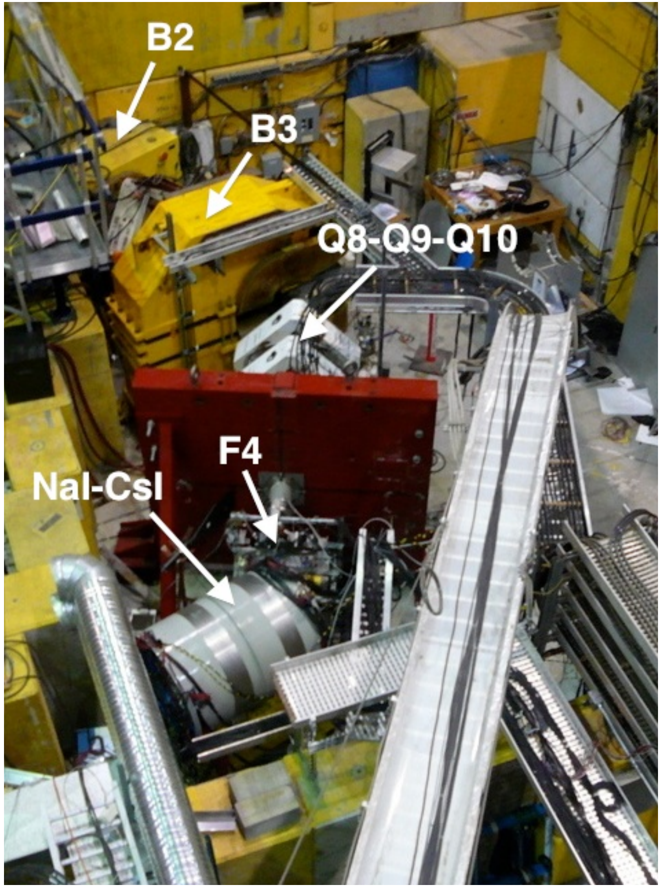




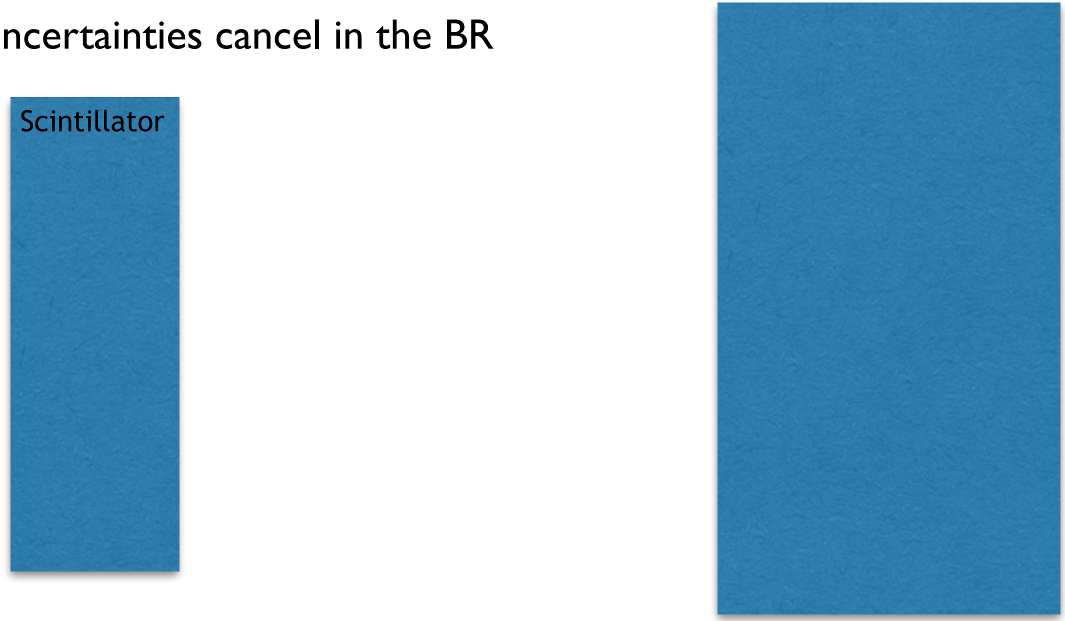
Stopped Pion Technique

Idea: Stop the pions in an active target

Measure the decay positrons from the two decays

Advantages:

- Simultaneous measurement (**energy and time**)
- Same acceptance and conditions
- Systematic uncertainties cancel in the BR



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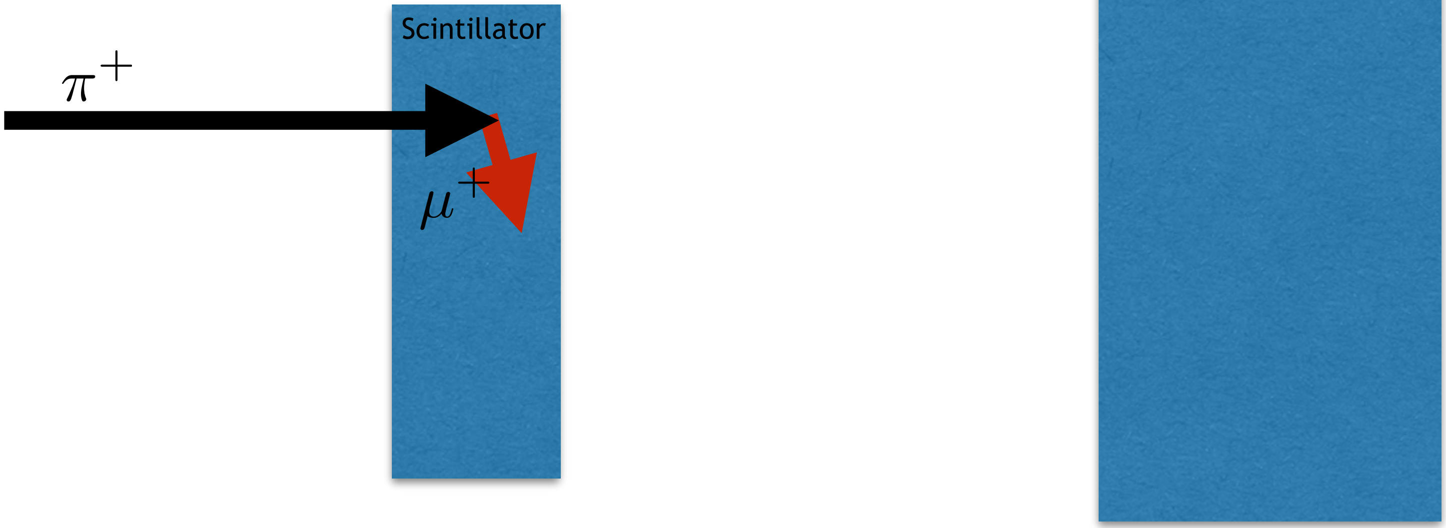

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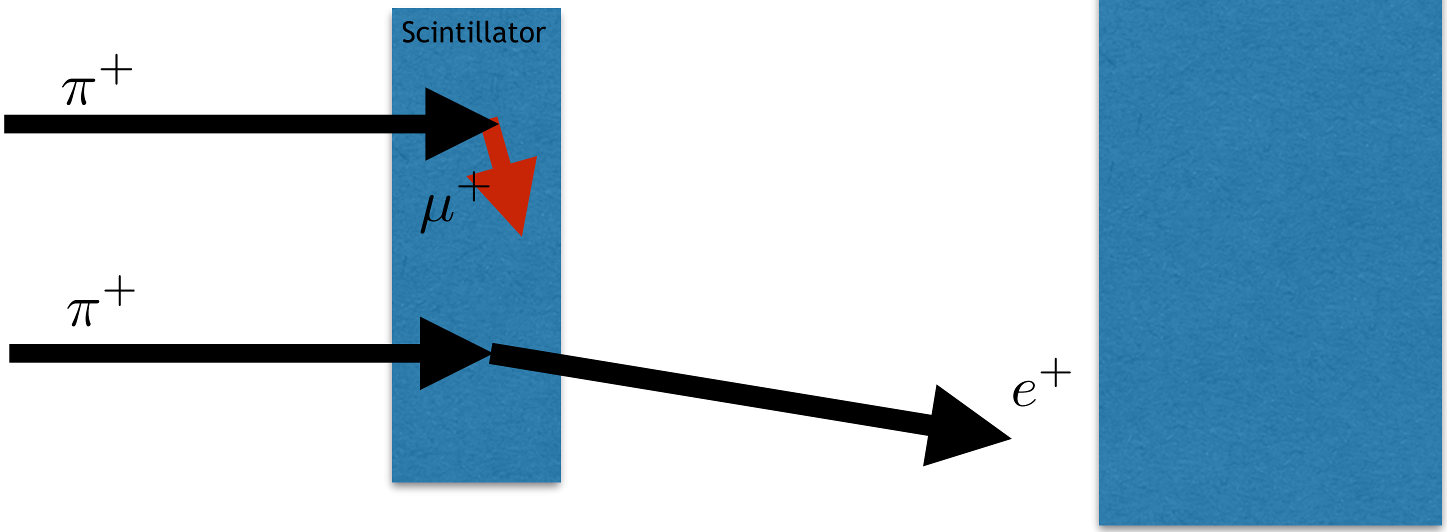

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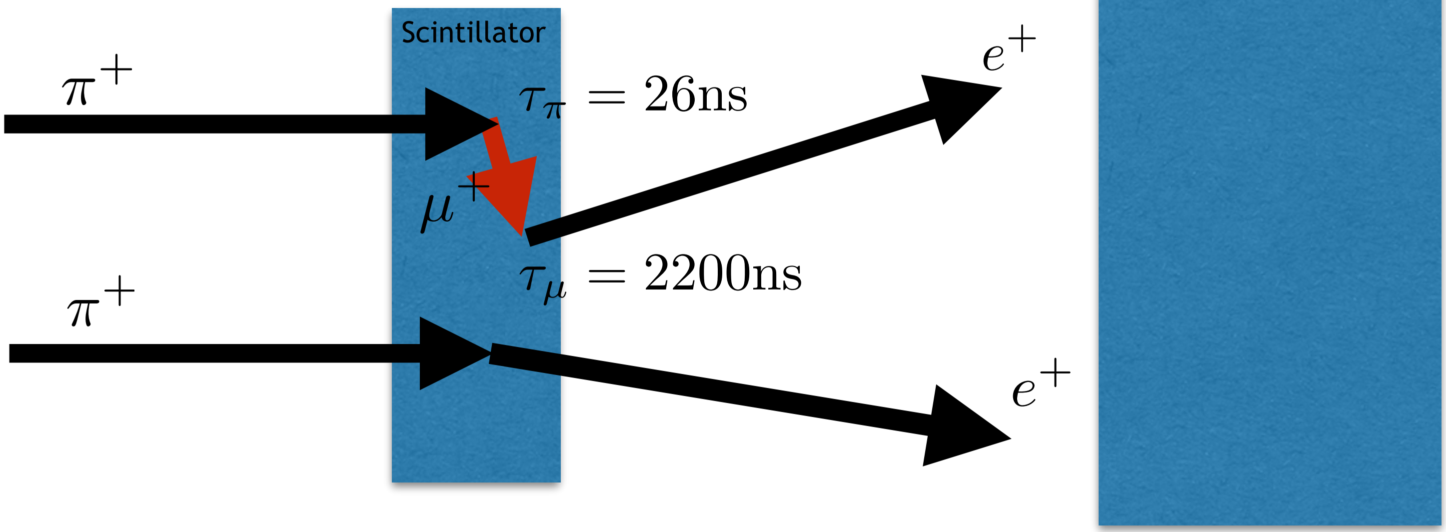

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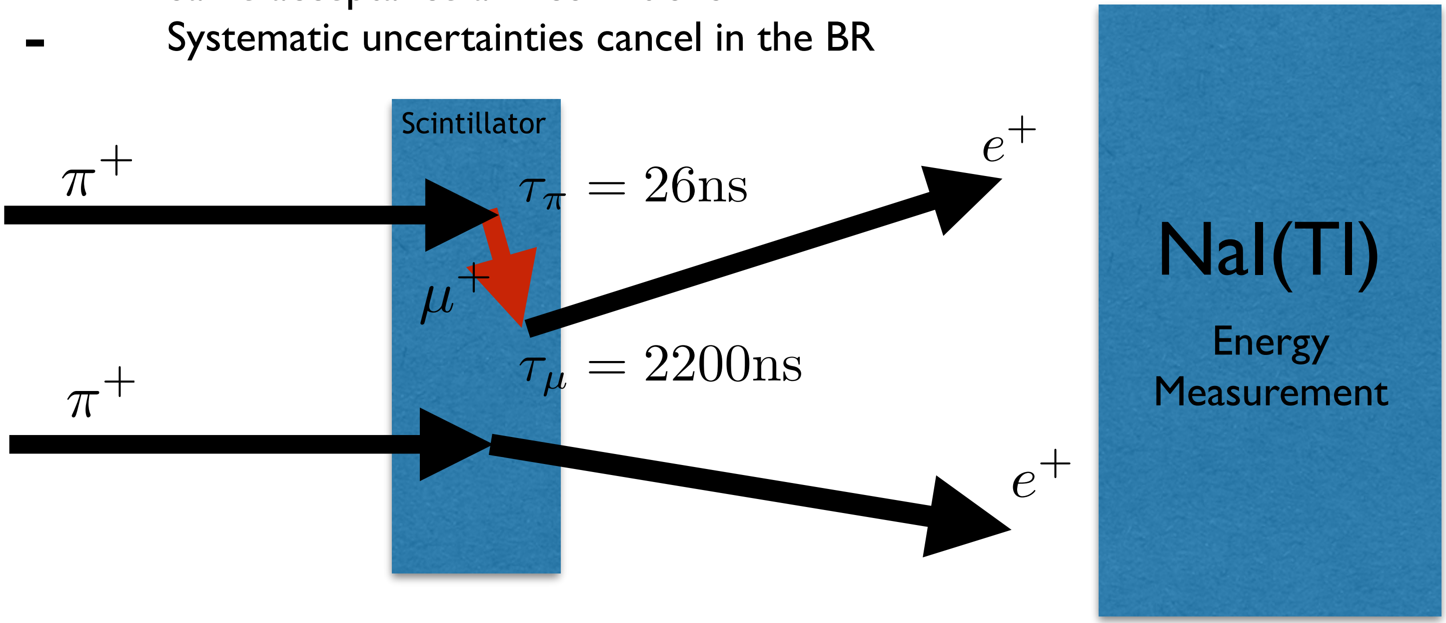

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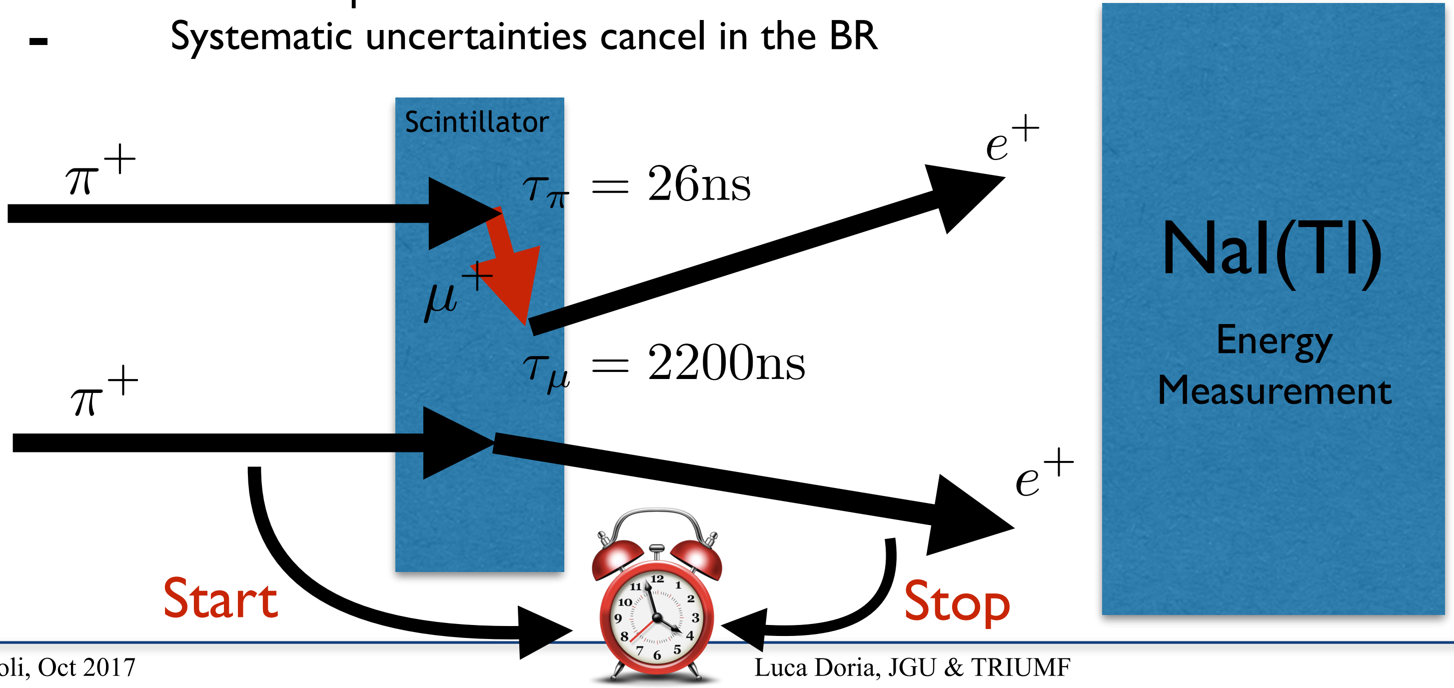


Experimental Setup

Beam:

60kHz pions @ 75 MeV/c

$$\pi : \mu : e = 85 : 14 : 1$$

Detector:

Acceptance: 20%
Plastic Scintillators
NaI(Tl) + CsI Calorimeter
Wire Chambers
Silicon Strips

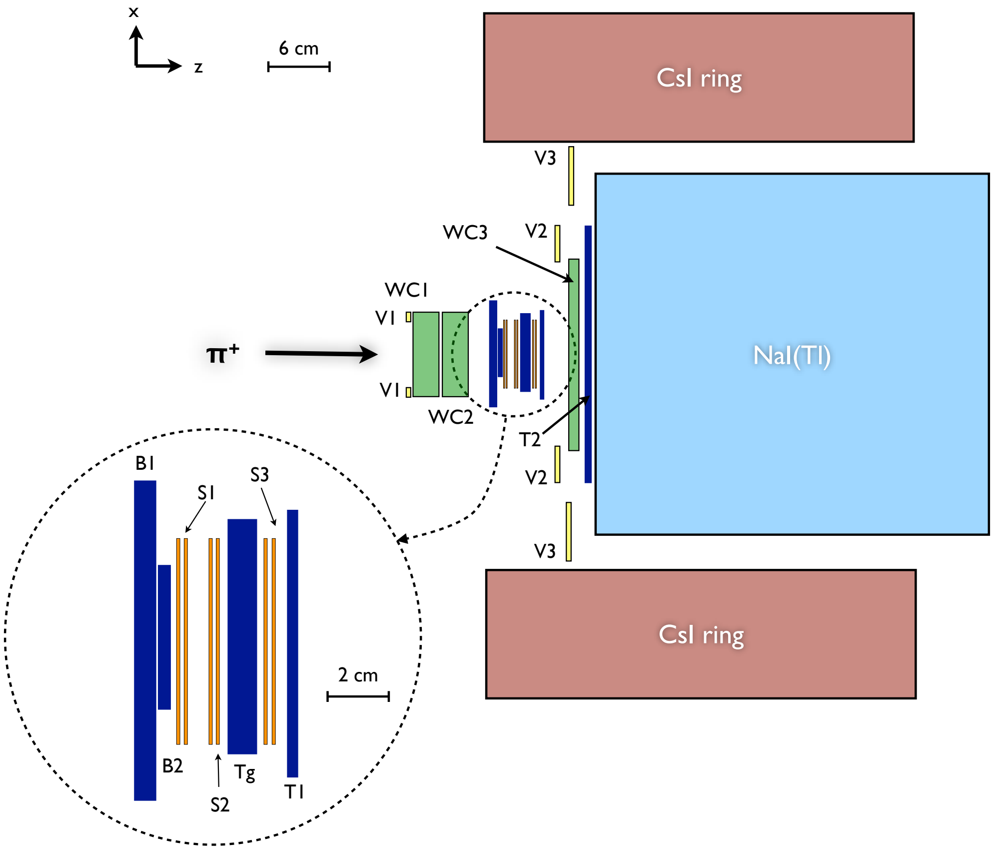
Energy resolution:

2.2% FWHM @ 70MeV

Temperature Stabilization

Data taking:

2009-2012



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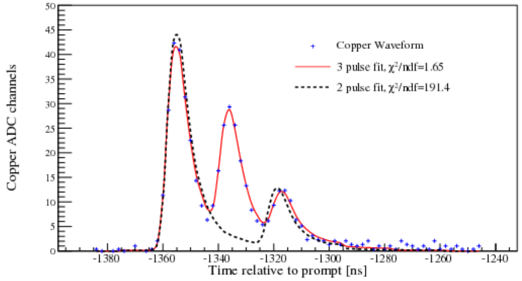
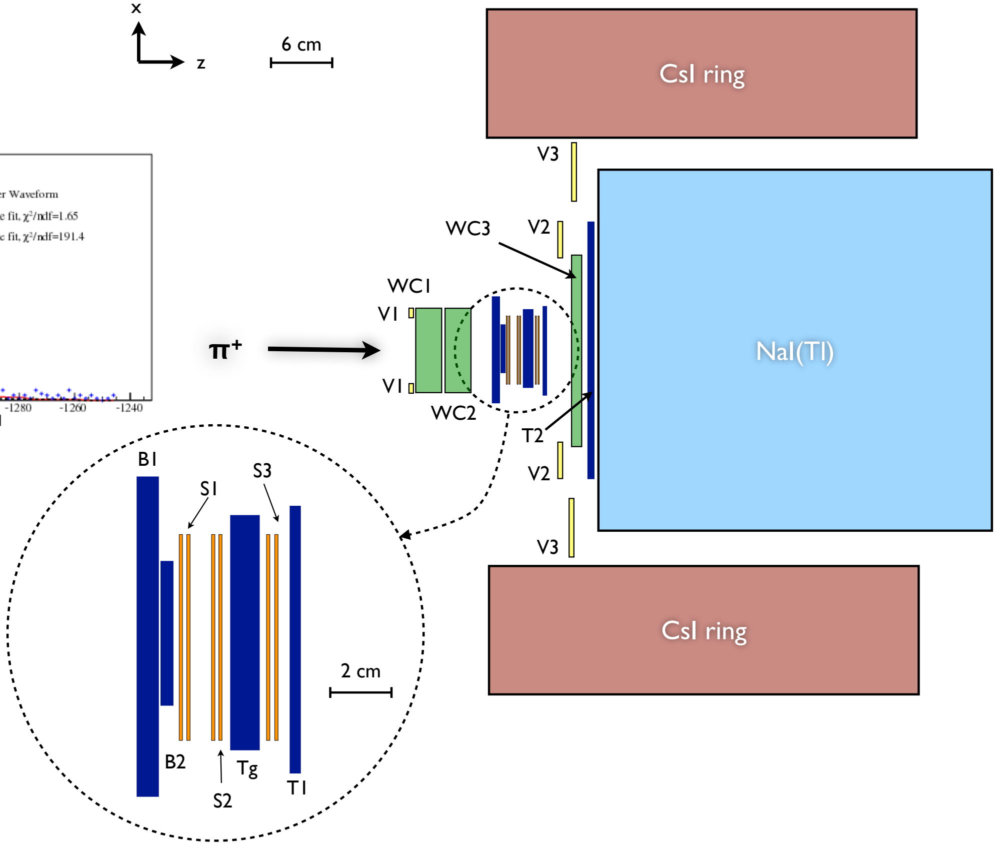




Experimental Setup: Target Region

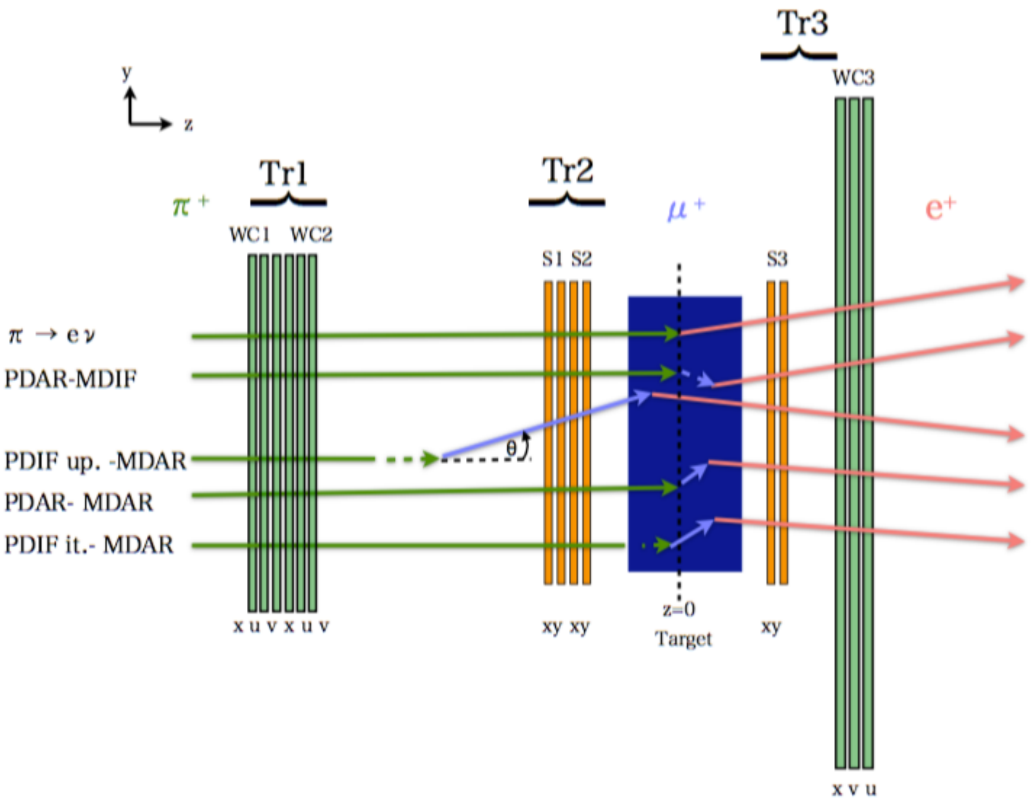
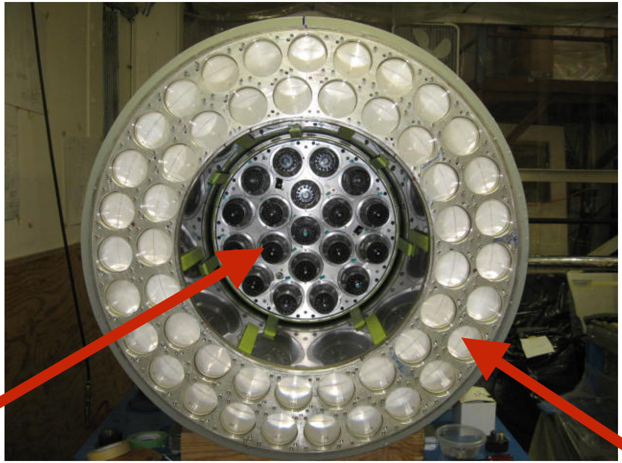
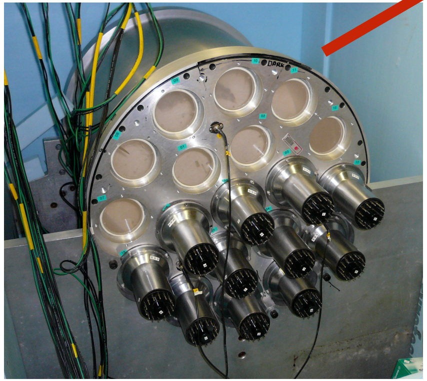


Figure from C.Malbrunot, PhD thesis (2012)

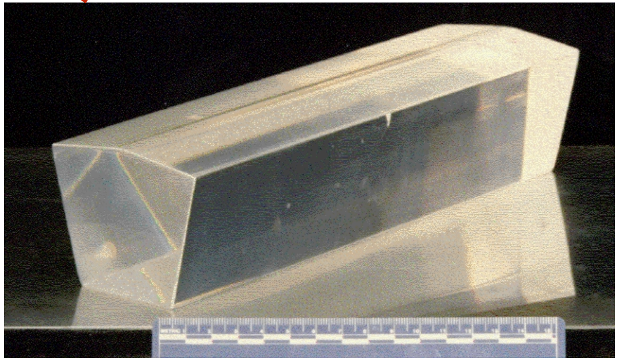
Calorimeter



“BiNa”:
Monolithic 48x48cm
NaI(Tl) crystal
19-PMTs readout

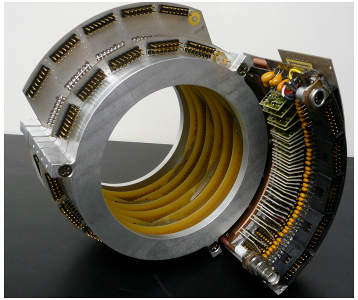
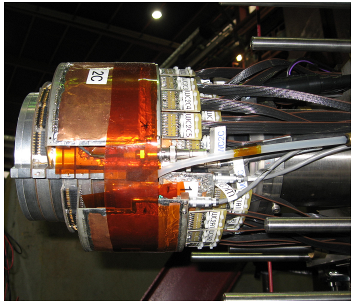


97 pure CsI crystals
single PMT readout

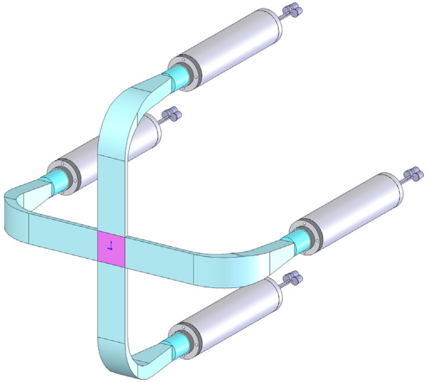
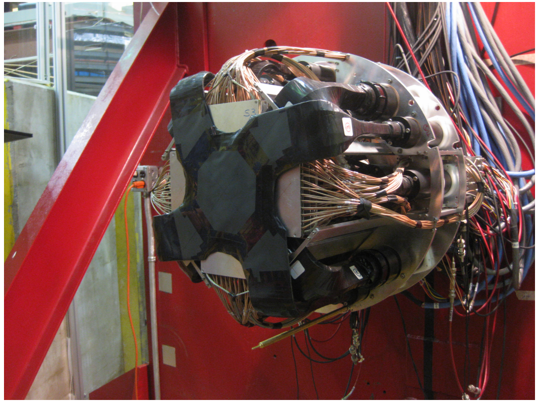


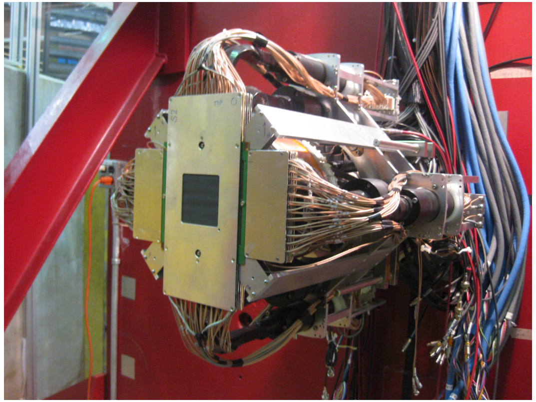
Tracking and Time/Energy Detectors

Wire Chambers

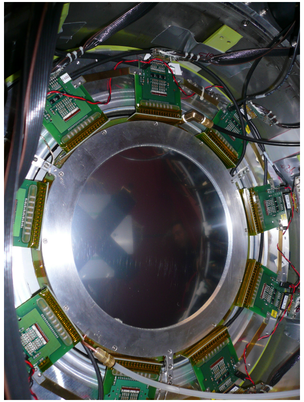



Scintillators



Silicon Detectors



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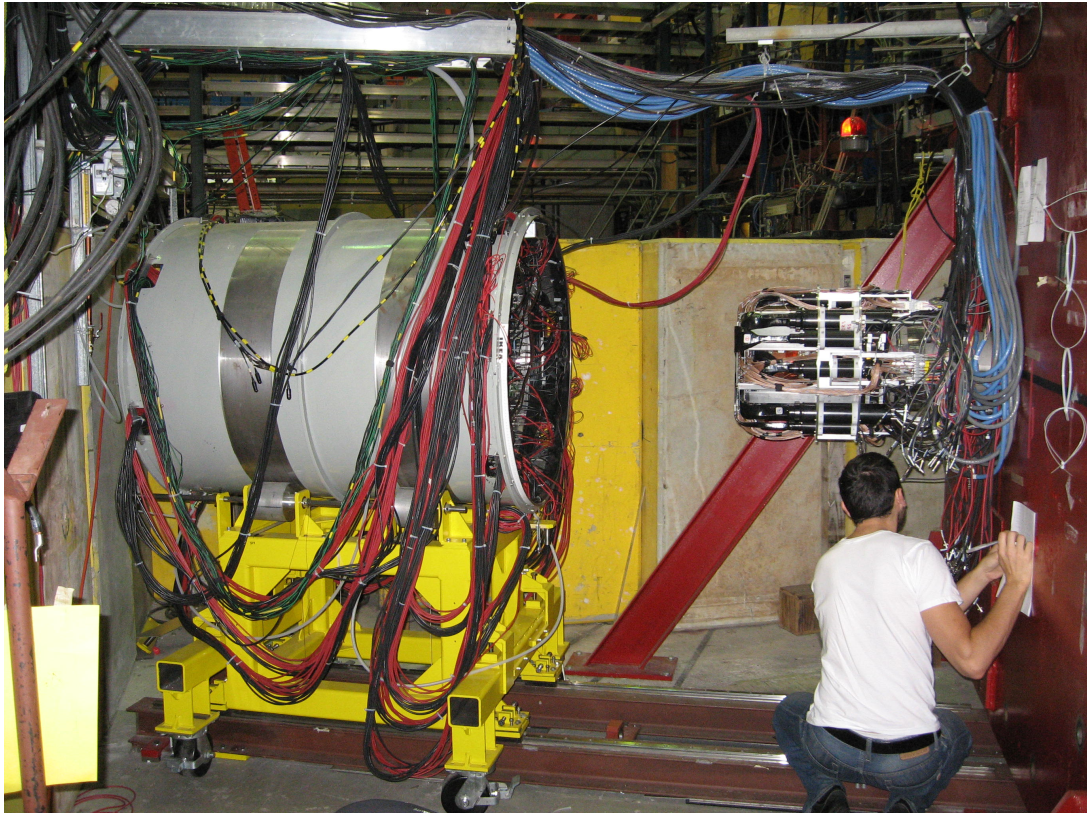
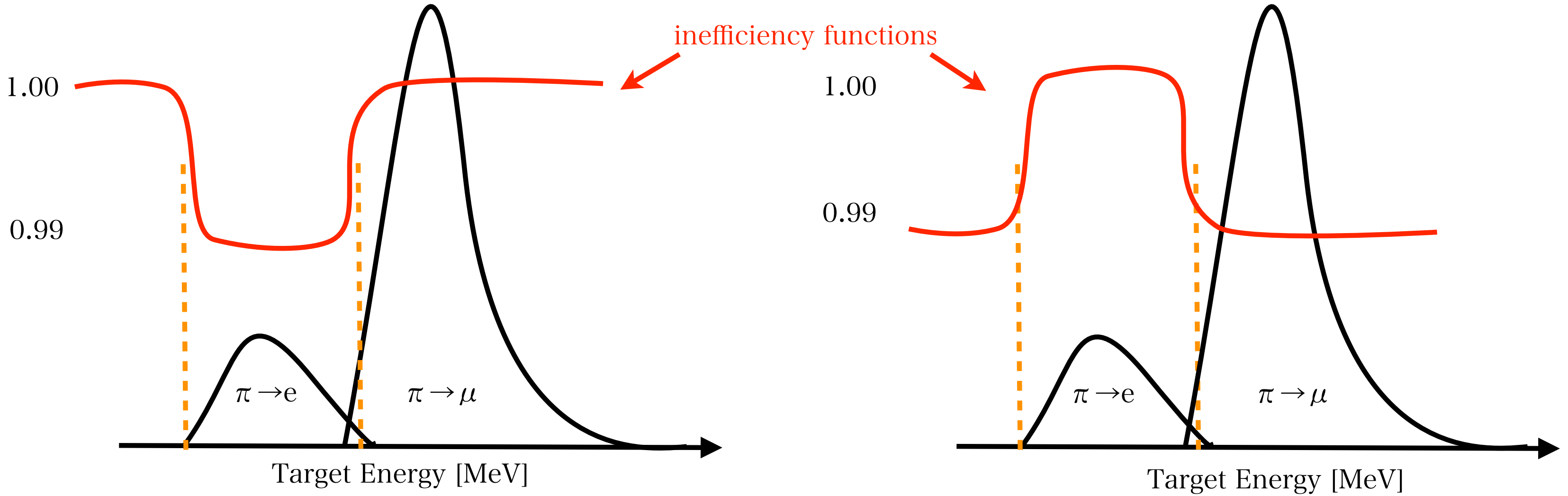


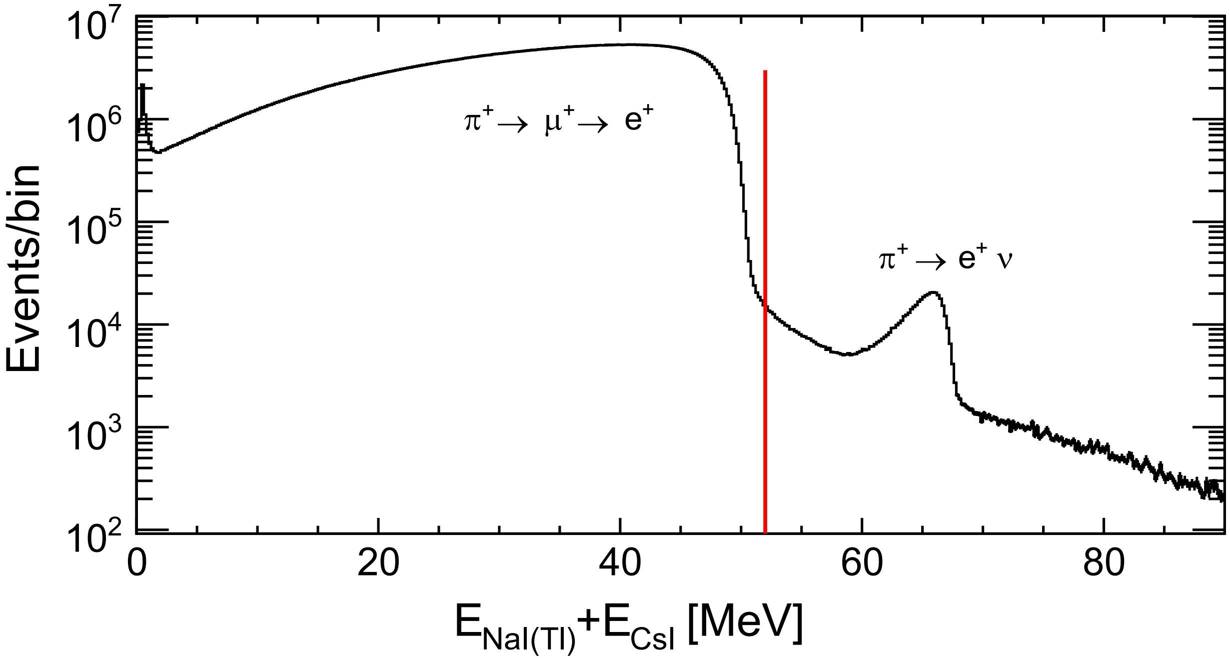
π^+ Beam

A.Aguilar-Arevalo *et al*: Nucl. Instr. Meth. A79, 38-46 (2015)

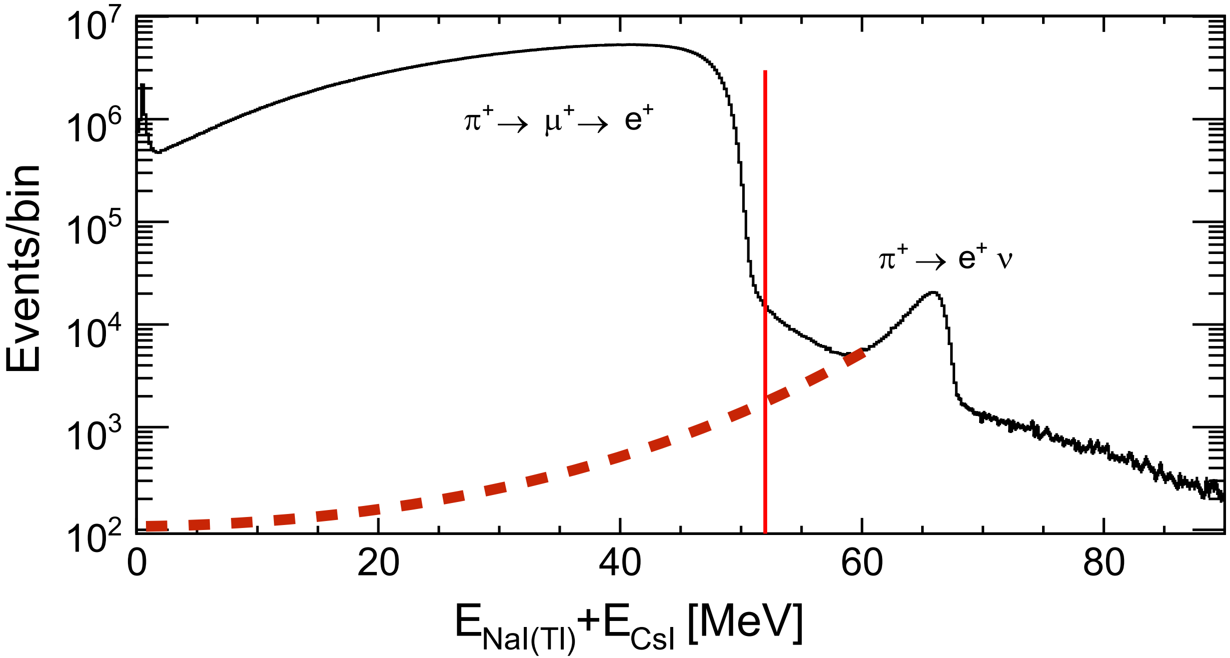
Data Analysis

- **Avoid biases in precision experiments!**
- Blinding procedure done before starting the analysis.
- One of the two decays is slightly suppressed: BR changes.
- Random and unknown inefficiency factor
- "Unblinding" only when the Collaboration agrees on the analysis procedure and systematic error estimates.





- Low Energy Tail
- Pileup



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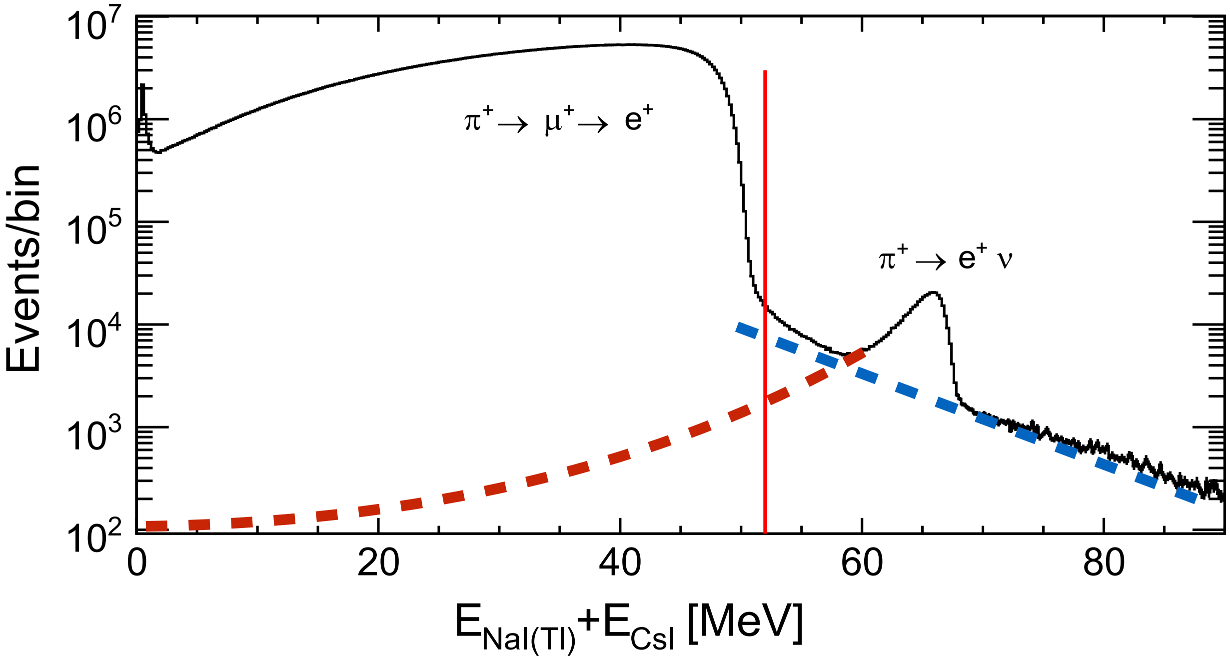

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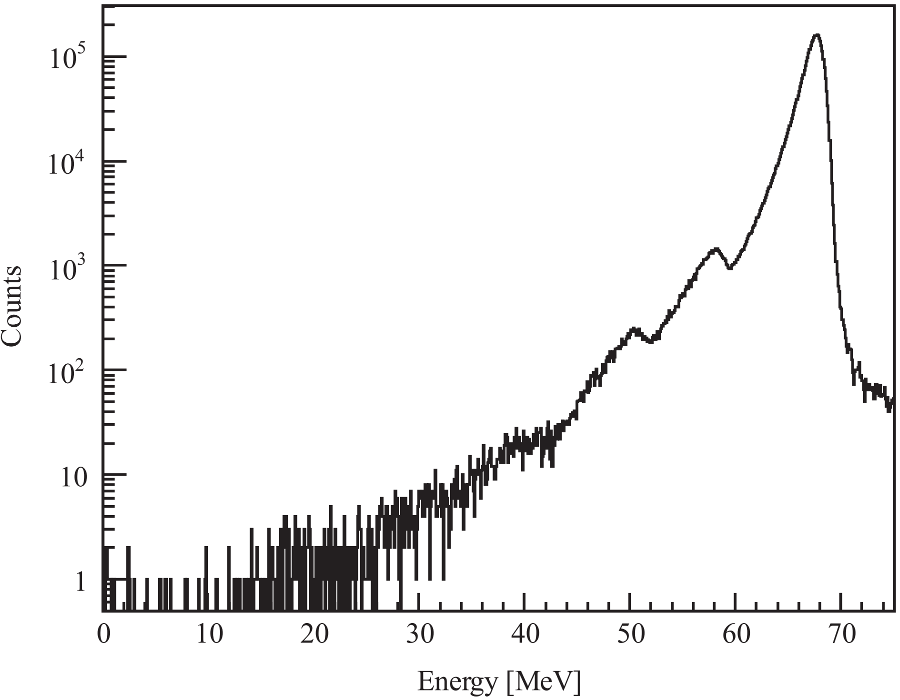
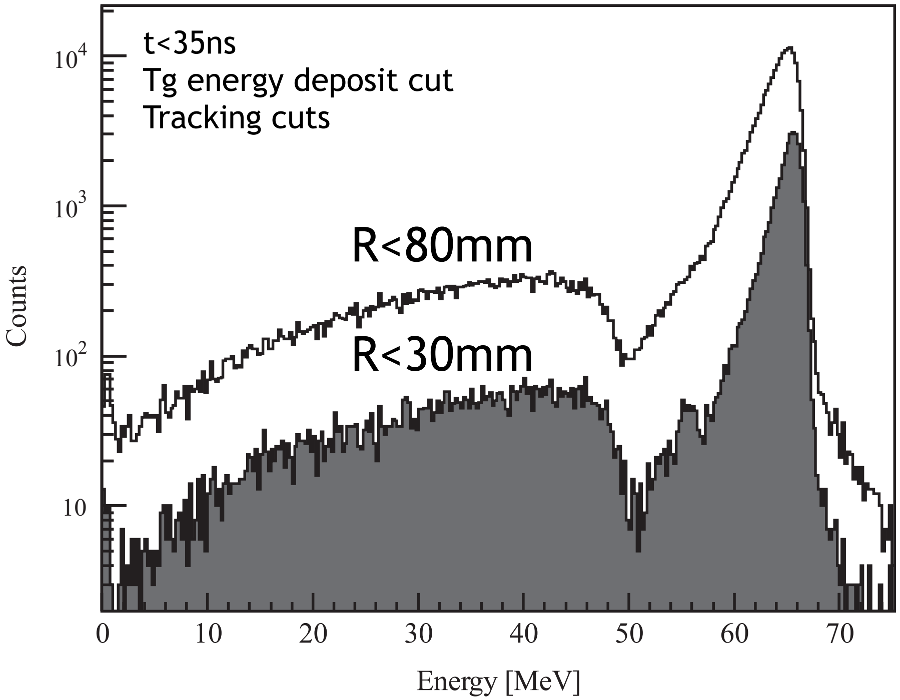
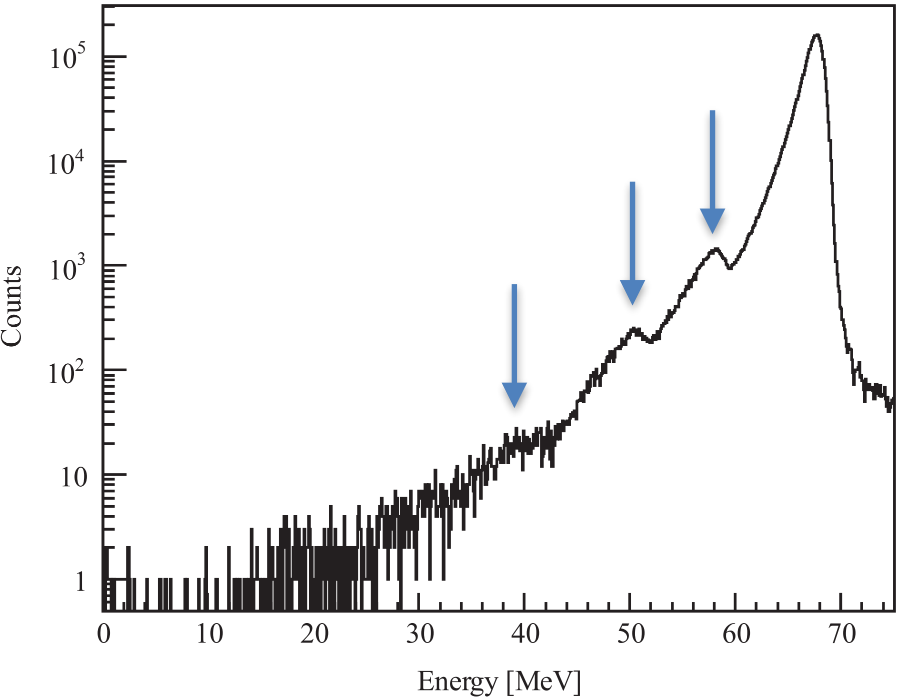
Low Energy Tail



Positron Beam: Upper limit



Suppressed Spectrum: Lower Limit



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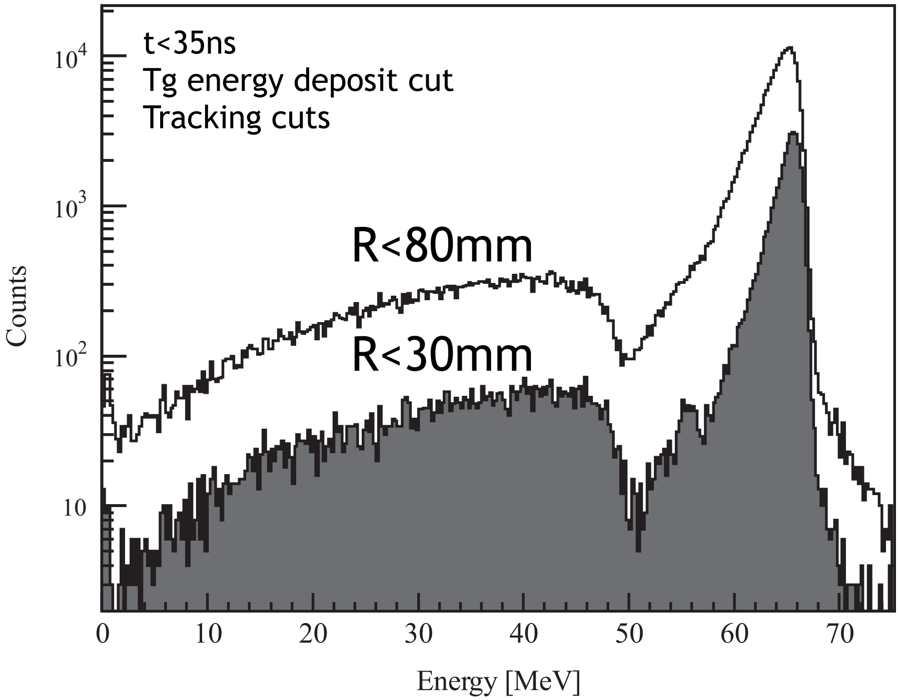

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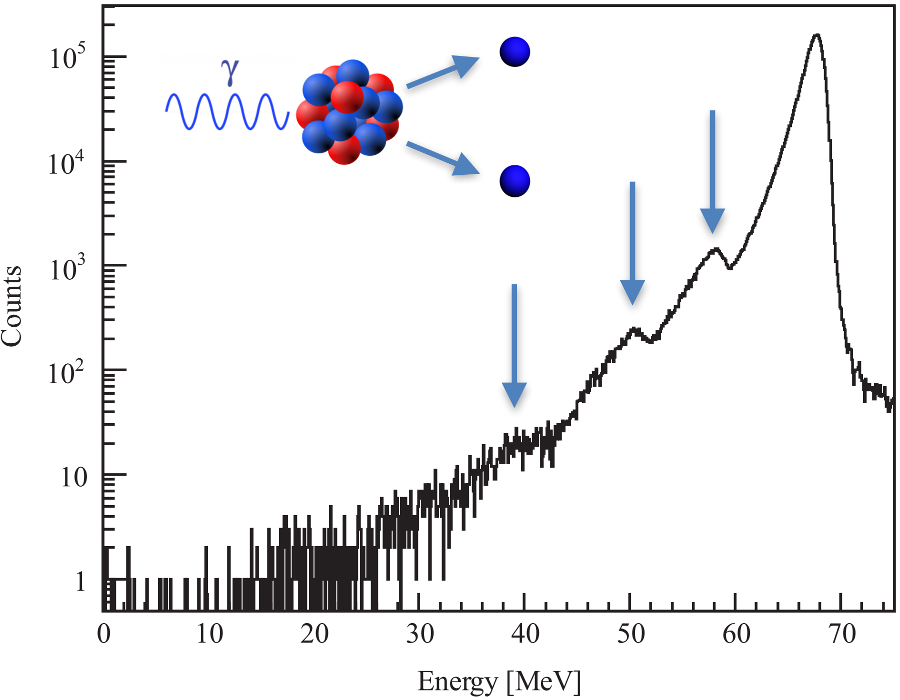

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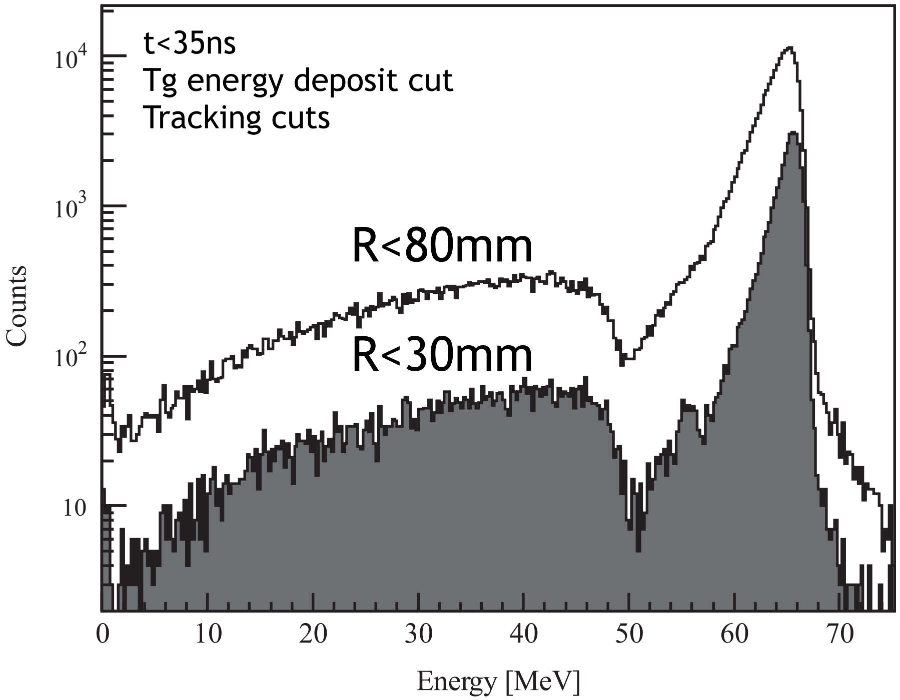
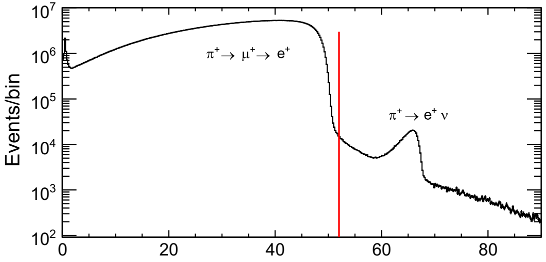


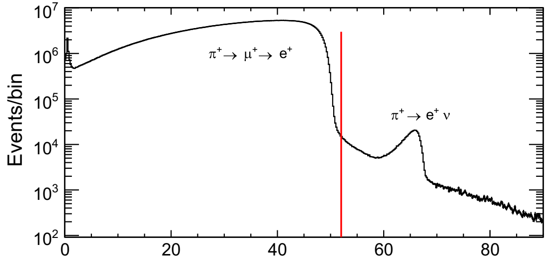
Suppressed Spectrum: Lower Limit

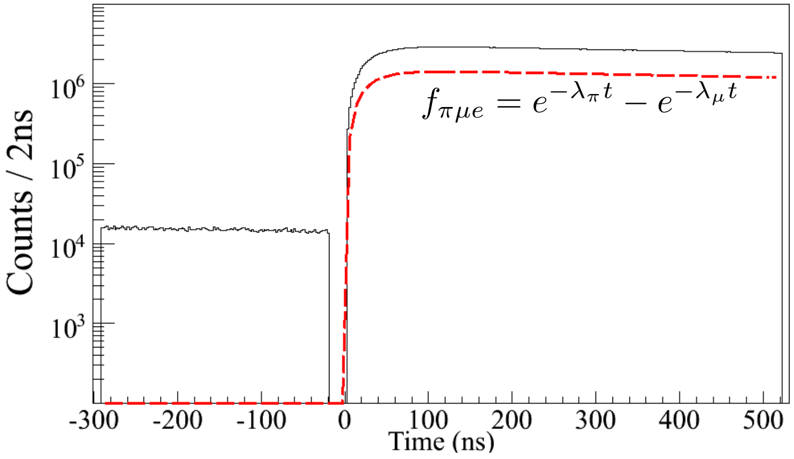
Time Spectrum Fit



E<52MeV

E>52MeV





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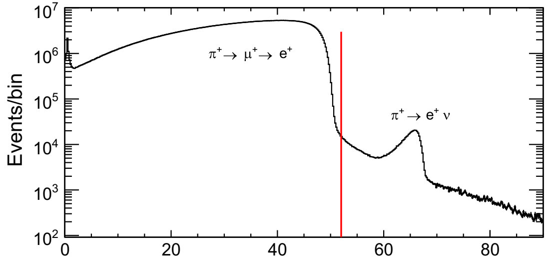

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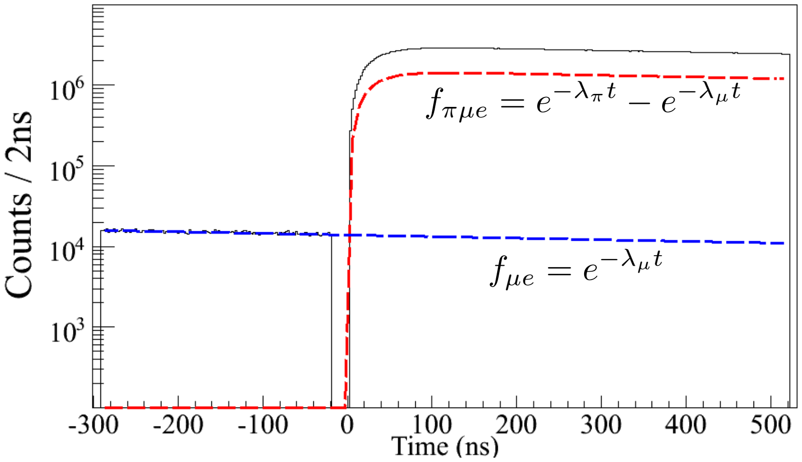

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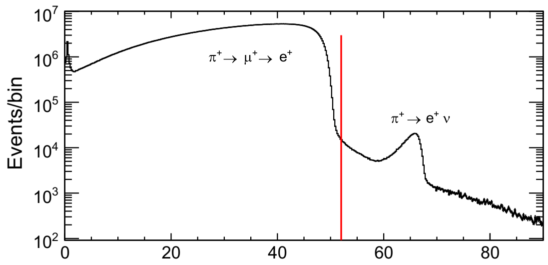

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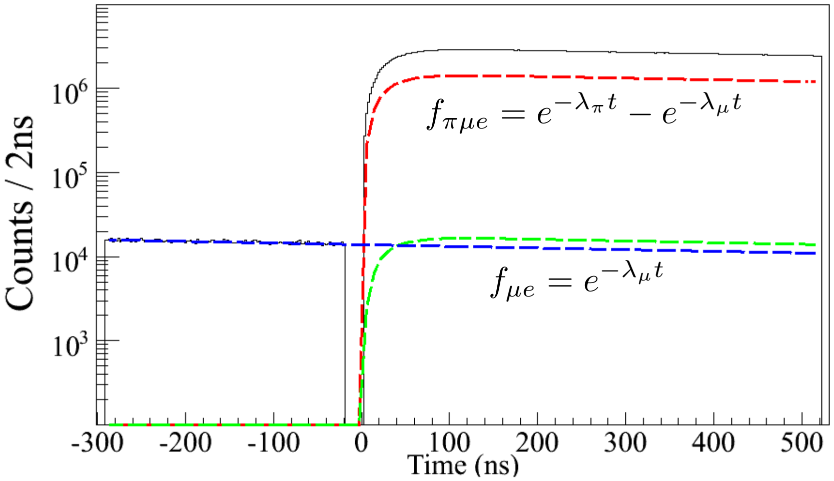

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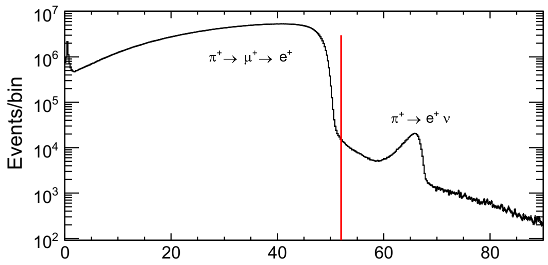
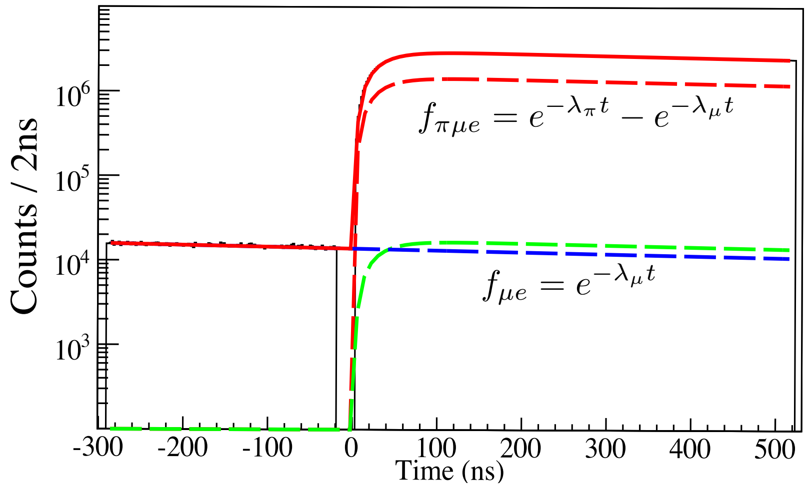
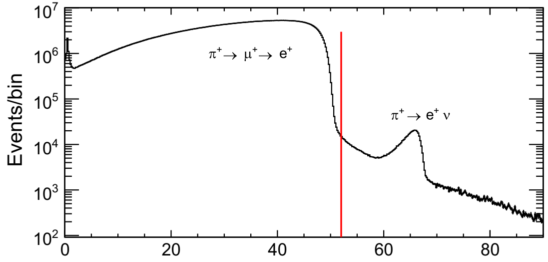


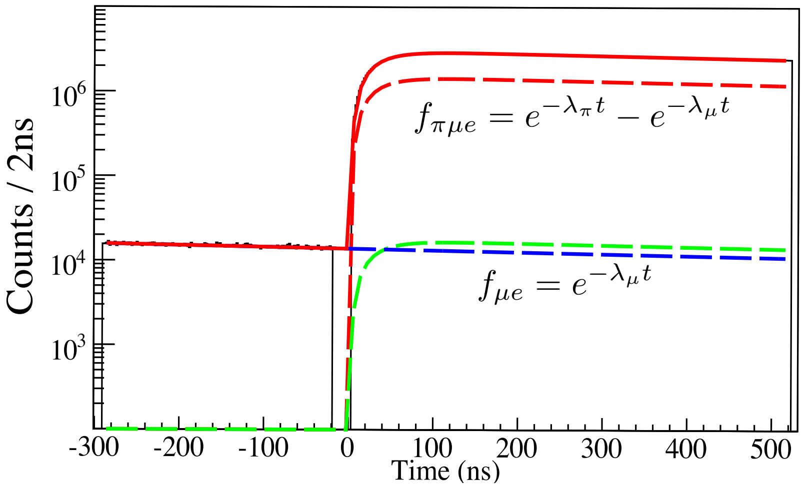


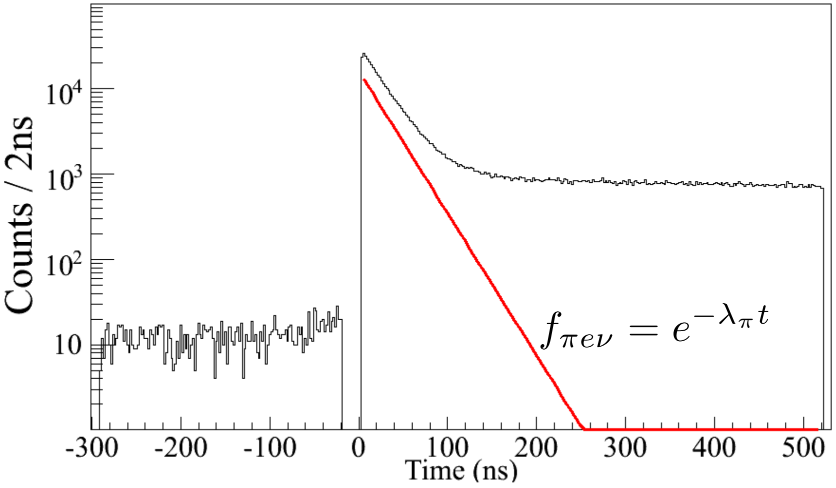
Time Spectrum Fit

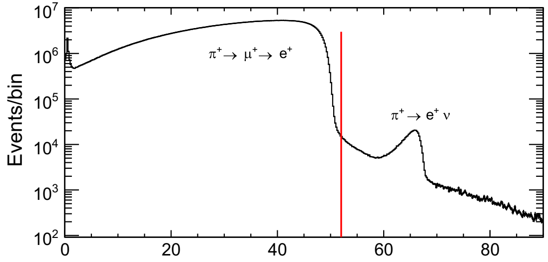


E<52MeV

E>52MeV







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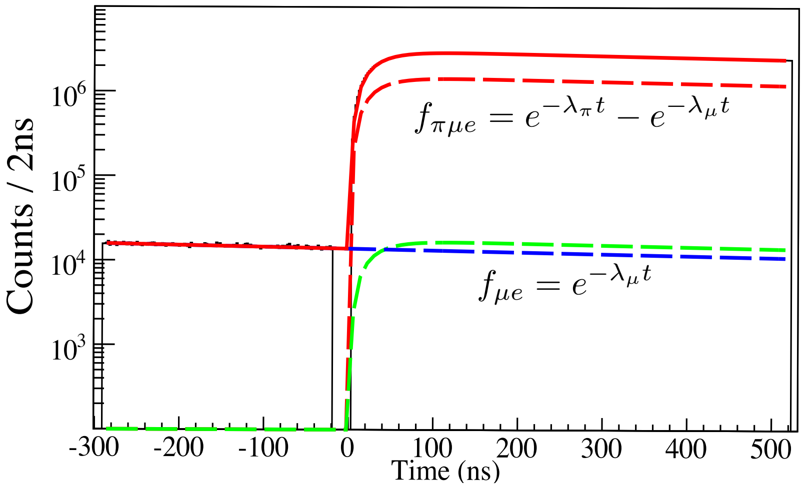

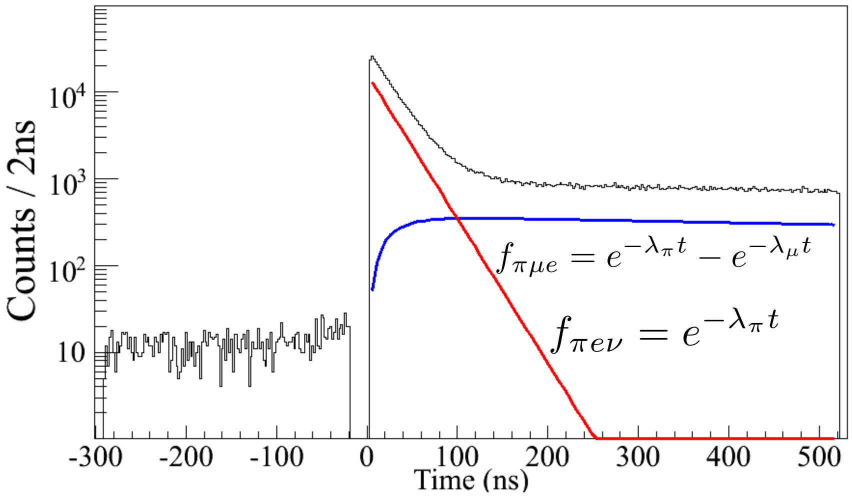

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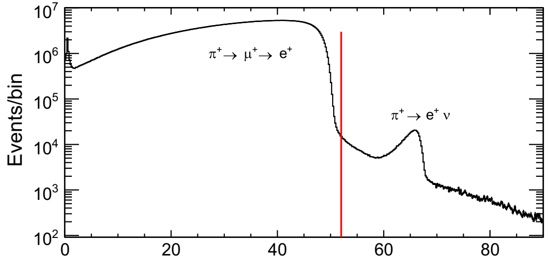

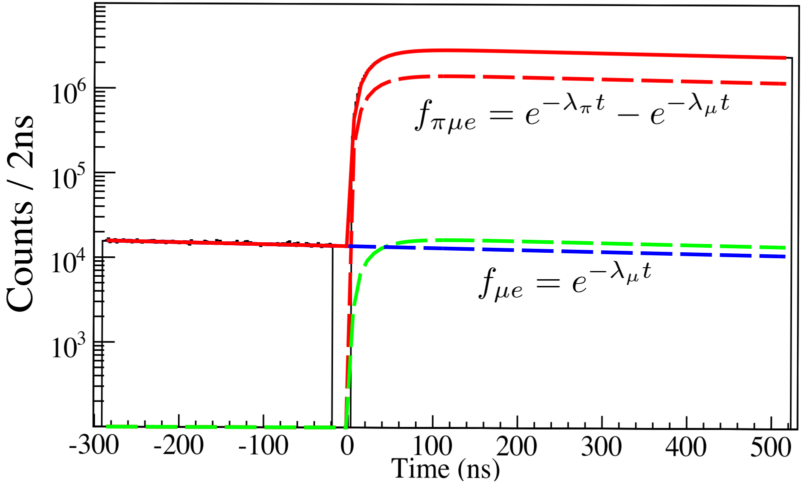

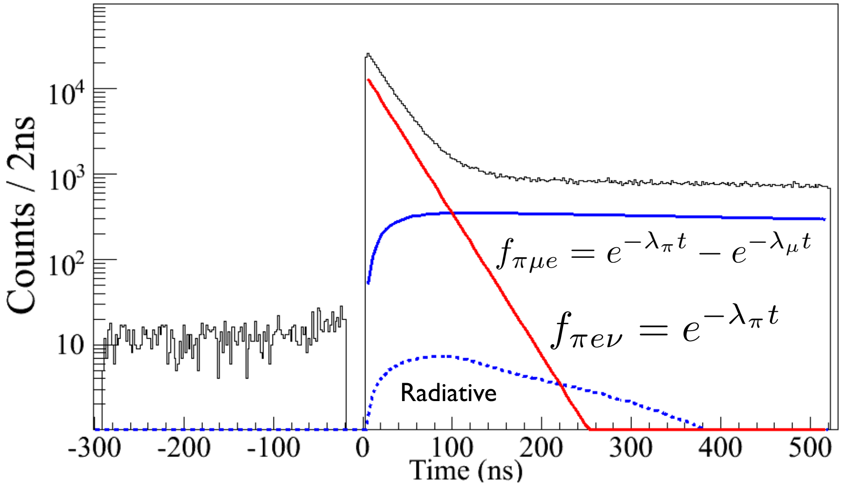

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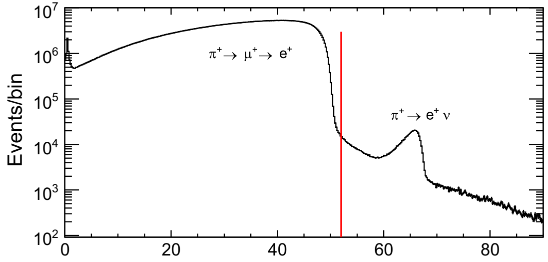

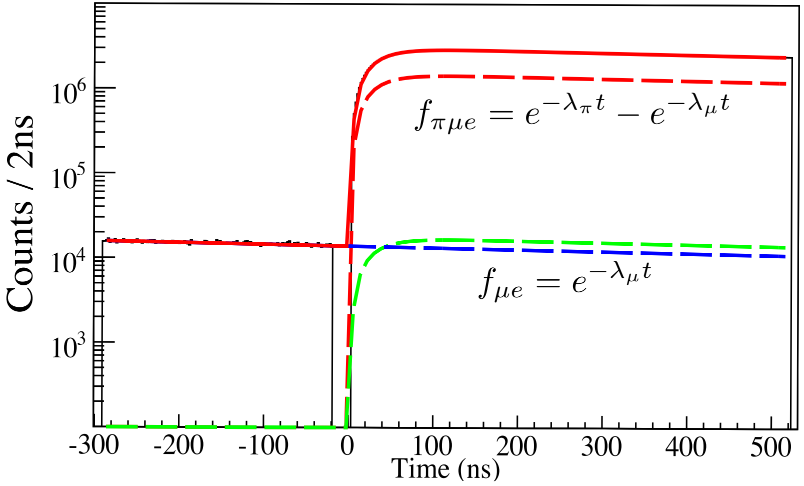

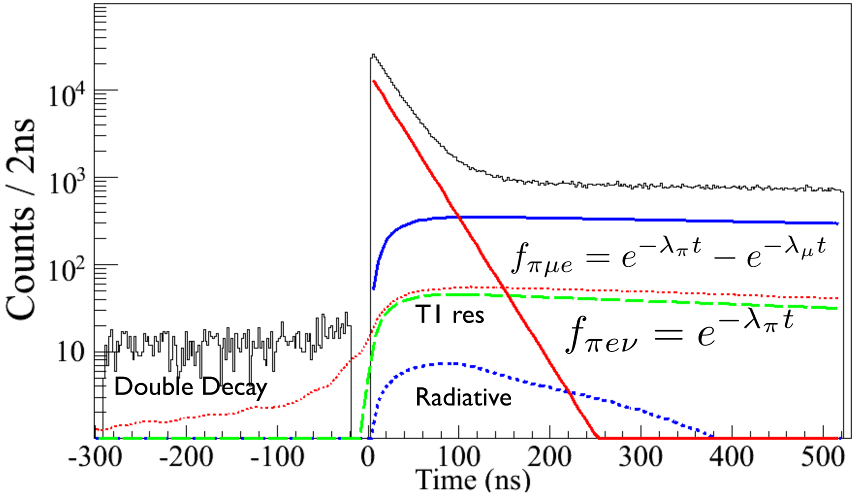

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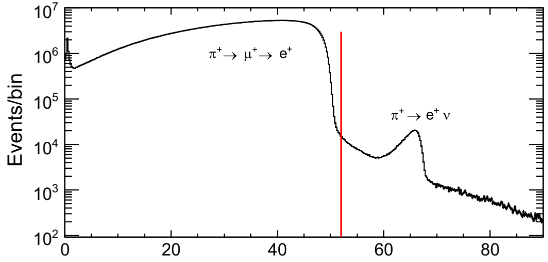
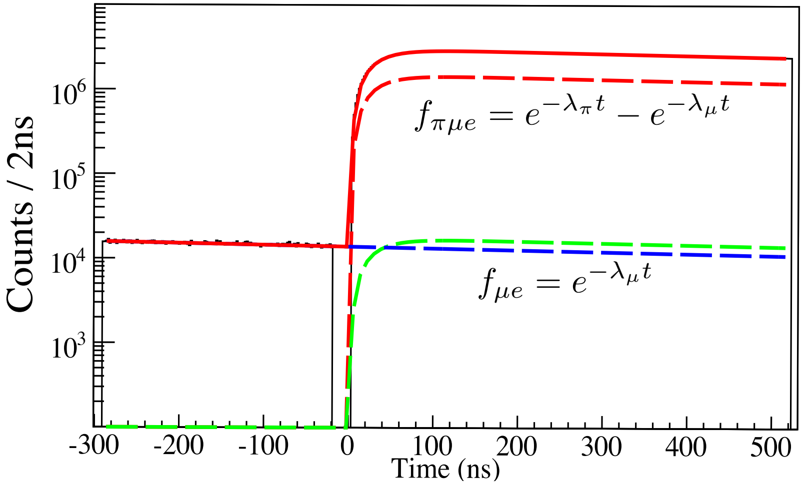
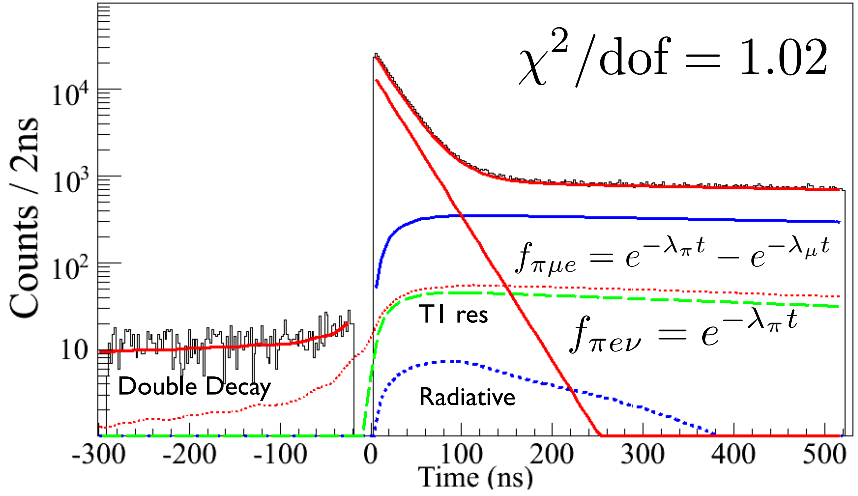






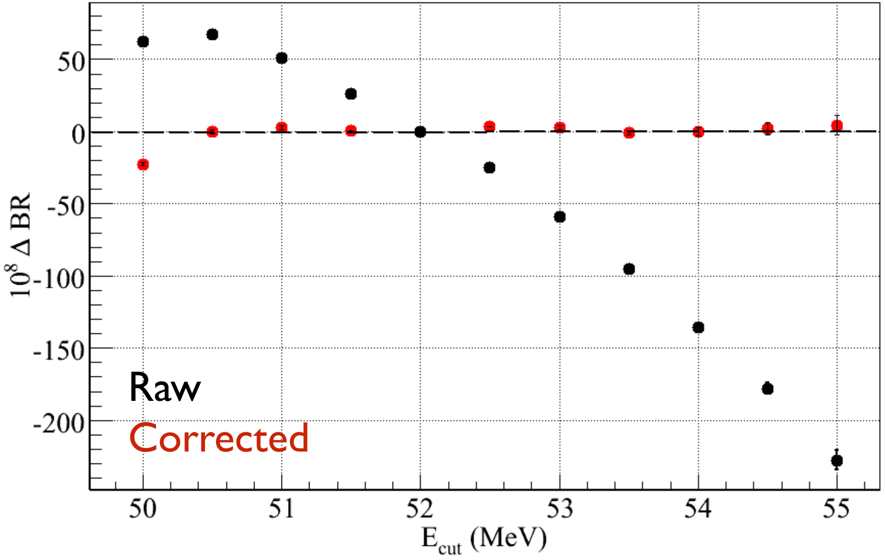
Systematic Checks

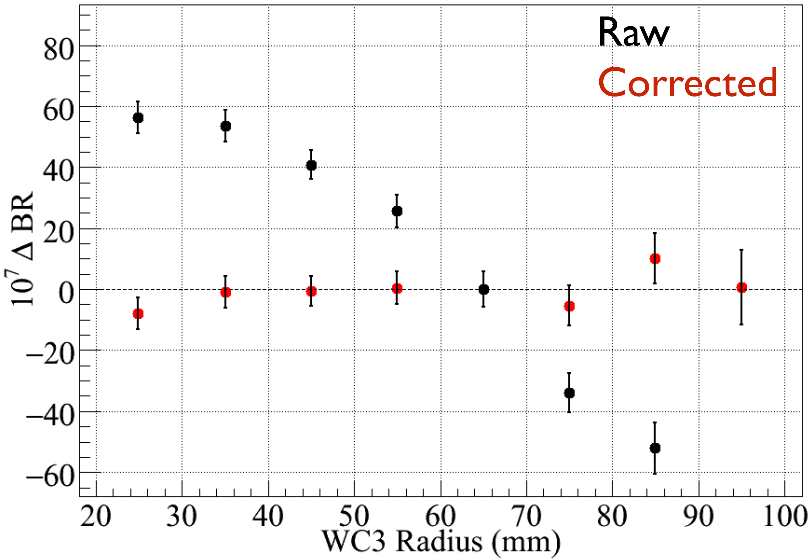
Acceptance Radius Dependence

- R= 60 mm
- Errors adjusted to statistics change
- Maximum R investigated with e^+ beam

Energy cut dependence

- Tail/muDIF corrections applied





Results

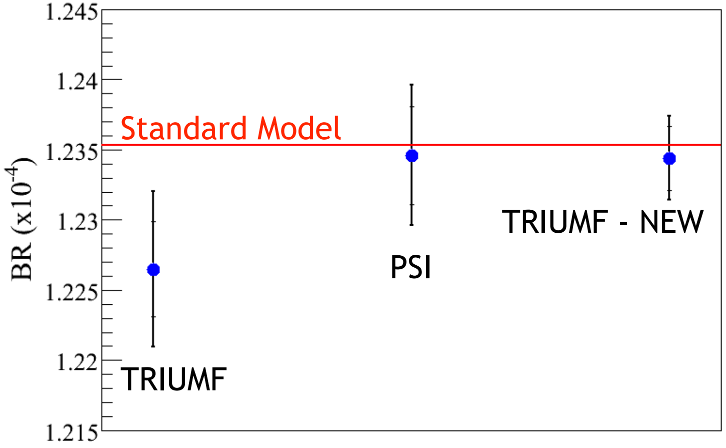
2010 Dataset Results

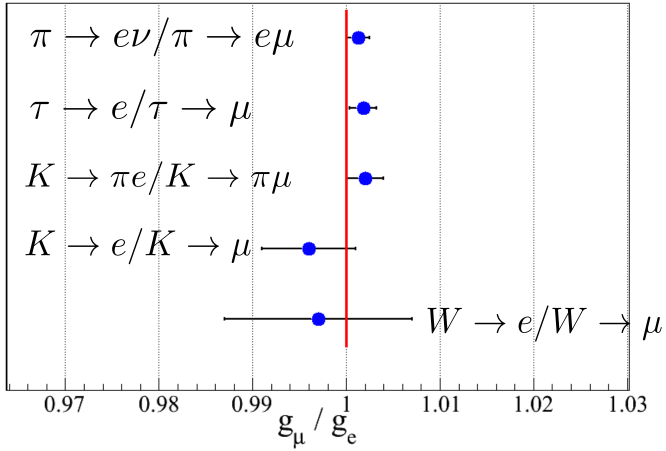
Phys. Rev. Lett. 115, 071801 (2015)

	Values	Uncertainties Stat	Uncertainties Syst
$R^{Raw}_{e/\mu}$ (10^{-4})	1.1972	0.0022	0.0005
π,μ lifetimes			0.0001
other parameters			0.0003
excluded components			0.0005
Corrections			
Acceptance	0.9991		0.0003
Low energy tail	1.0316		0.0012
Other	1.0004		0.0008
$R^{Exp}_{e/\mu}$ (10^{-4})	1.2344	0.0023	0.0019

$R^{Th}_{e/\mu}$ $(10^{-4}) = 1.2352(2)$

$e - \mu$ Universality: $g_e/g_\mu = 0.9996 \pm 0.0012$





Full Analysis

Dataset	BR	Status
2010	$1.2344 \pm 0.0023 \pm 0.0012$	Published
2011	$1.2XX \pm 0.0018 \pm 0.0013$	Completed, blind
2012	$1.2XX \pm 0.0009 \pm 0.00X$	In progress

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Final Goal: 0.1% precision

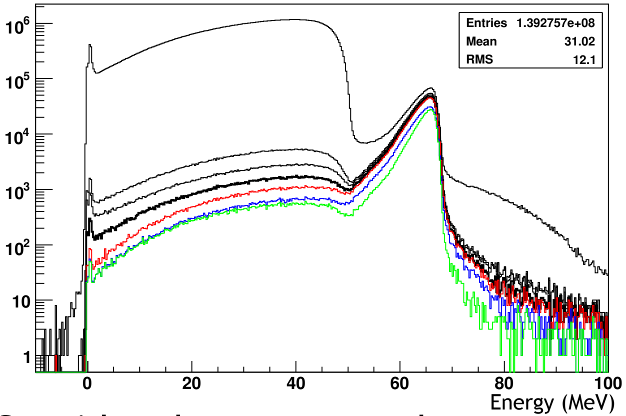
$\pi \to e\nu$ is a two-body decay

The pion decays at rest

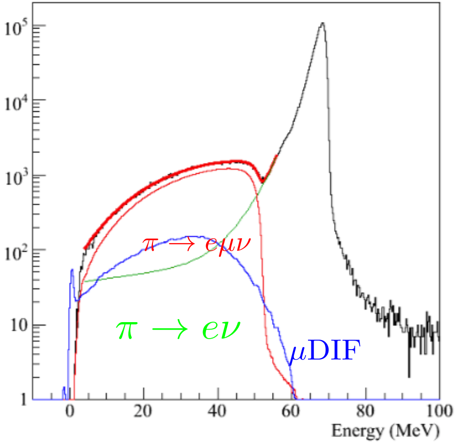
—> Kinematics fully known if e^+ is measured:

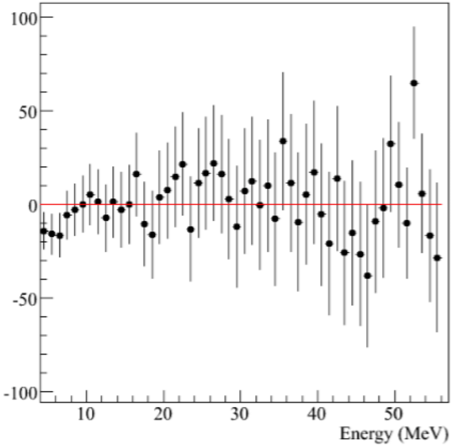
$$m_\nu = \sqrt{m_\pi^2 + m_e^2 - 2m_\pi E_e}$$

If a massive neutrino can be produced, it will show up as a peak in the energy spectrum.



1) Consider the suppressed spectrum
2) Fit the spectrum with signal+bkg shapes:
   - $\pi \to \mu\nu \to e\nu\nu$ (data, t>150ns)
   - Muon decays in flight (MC)
   - $\pi \to e\nu$ shape (MC)
3) Set upper limits to the BR for the pion decay to massive neutrinos.

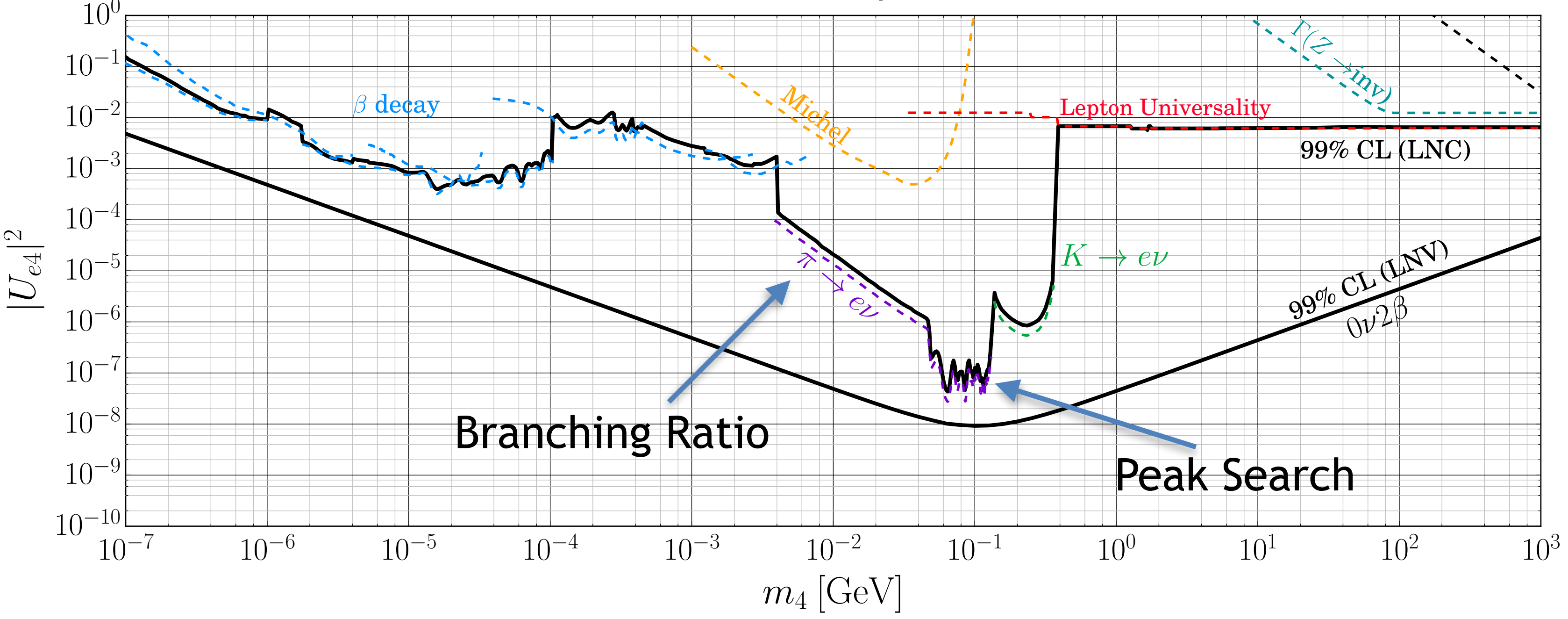




$$\frac{N(\pi \to e\nu_i)_{UL}}{N(\pi \to e\nu_l)} = |U_{ei}|^2_{UL}\rho_e$$

Present Constraints

A. de Gouvêa, A. Kobach, Phys. Rev. D 93, 033005 (2016)



(a)

D.I. Britton et al., Phys. Rev. D46, R885 (1992).
M. Aoki et al., Phys. Rev. D84, 052002 (2011).

PRELIMINARY

Plot showed only at the talk and then removed for distributing the slides. Waiting for publication, sorry!

Obtained upper limits at about 10^{-8} level

Conclusions and Outlook

- Best limit on lepton universality violation established
- Work ongoing towards full dataset analysis
- Massive neutrino searches in the MeV range in pion and muon decays
- More BSM decay searches possible: Majorons, Z', …

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Final results coming soon: stay tuned!

Thank You!
Merci!

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

TRIUMF

TRIUMF: Alberta I British Columbia I Calgary I Carleton I Guelph I Manitoba I McGill I McMaster I Montréal I Northern British Columbia I Queen's I Regina I Saint Mary's I Simon Fraser I Toronto I Victoria I Western I Winnipeg I York

Thank You!
Merci!
Danke!

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Thank You!
Merci!
Danke!
Grazie!

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