Proton Decay

质子衰变

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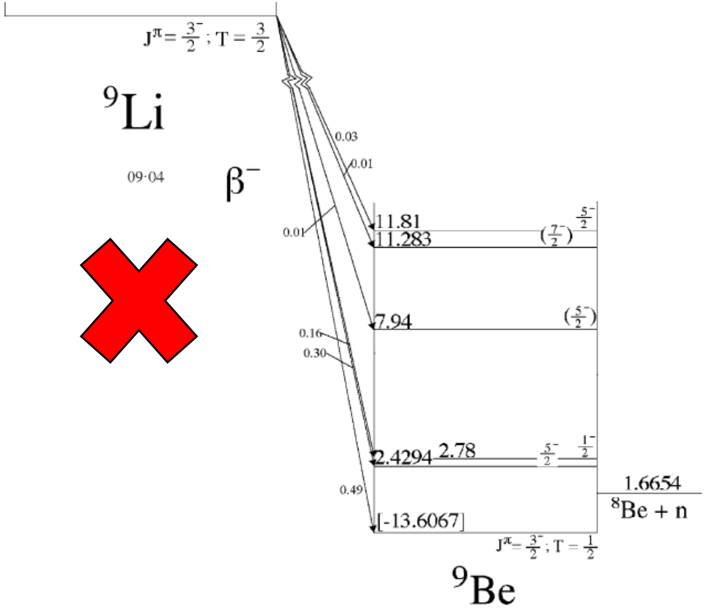
(1)大统一理论与质子衰变

什么是质子衰变?

原子核中的质子或中子发生重子数(B)破坏的衰变，也称核子衰变!

原子核的beta衰变不是核子衰变:



相当于: $n \rightarrow p + e^- + \overline{\nu}_e$

B: 1 1 0 0

核子衰变:

$$p \rightarrow e^+ + \pi^0$$

B: 1 0 0

重子数B破坏

为什么寻找核子衰变?

- ✓ 宇宙物质-反物质不对称
- ✓ 检验大统一理论
- ✓ 探究大统一能标的物理
- ✓ …

Sakharov 3 conditions:

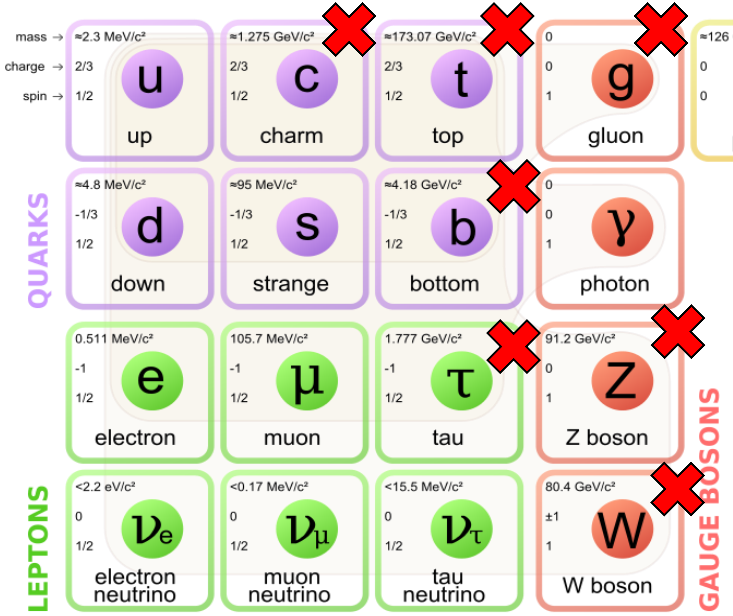
B violation; C&CP violation;
departure from thermal equilibrium

核子衰变的末态性质

核子的基本性质：

- 质子(uud)和中子(udd)都是由3夸克构成的重子
- 质量：$m_p = 938.27$ MeV, $m_n = 939.56$ MeV

可能的末态粒子：



末态质量和一定小于核子质量

$$E_N = E_1 + E_2 + E_3 + \cdots$$

$$\rightarrow m_N = \sqrt{m_1^2 + p_1^2 + \cdots} > m_1 + m_2 + \cdots$$

末态是以下3类的组合：

- 正反夸克对构成的介子：

  $\pi^{\pm}(139.6), \pi^0(135.0), K^{\pm}(493.7),$

  $K^0(497.6), \eta(548), \rho(775), \omega(782), K^*(892)$
- 轻子: 电子、缪子、中微子
- 光子

新物理粒子

满足电荷守恒；末态通常有轻子

不衰变<--重子数守恒（偶然对称性，经典层面）：

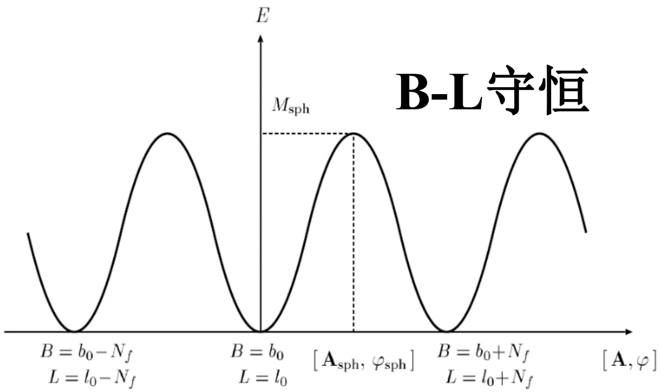
- 重子数B：正夸克1/3，反夸克-1/3
- 质子和中子的重子数为1，反质子为-1
- 介子、轻子和光子的重子数都为0
- 质子是最轻的重子 → 不衰变

核子衰变要求重子数破坏！
→超出标准模型！

标准模型中的重子数破坏过程(Sphaleron，量子效应)：

随温度下降指数压低，零温不可观测：$\tau(d \to e^+ \nu_\mu) \sim 10^{120}$ years；高温=>Leptogenesis

Sphaleron表明标准模型破坏重子数



轻子数守恒（偶然对称性）：

	e^-	μ^-	τ^-	ν_e	ν_μ	ν_τ
L_e	1	0	0	1	0	0
L_μ	0	1	0	0	1	0
L_τ	0	0	1	0	0	1

$$\bar{\nu}_e + p \to e^+ + n$$

$L_e = -1$ B = 1 $L_e = -1$ B = 1

反轻子的轻子数为−1

中微子振荡破坏 L_i，但L守恒！

标准模型的不足

- 标准模型基于$SU(3)_C \times SU(2)_L \times U(1)_Y$

  → 3个独立的耦合常数，没有将强、弱和电磁统一

- 标准模型拥有太多的自由参数：19+9
- 为什么夸克、轻子只有3代，且重复填写同样的表示?

	$SU(2)_L$ doublets	$SU(2)_L$ singlets
Quarks	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} c_L \\ s_L \end{pmatrix}, \begin{pmatrix} t_L \\ b_L \end{pmatrix}$	$u_R, d_R, c_R, s_R, t_R, b_R$
Leptons	$\begin{pmatrix} \nu_{eL} \\ e_L \end{pmatrix}, \begin{pmatrix} \nu_{\mu L} \\ \mu_L \end{pmatrix}, \begin{pmatrix} \nu_{\tau L} \\ \tau_L \end{pmatrix}$	e_R, μ_R, τ_R

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

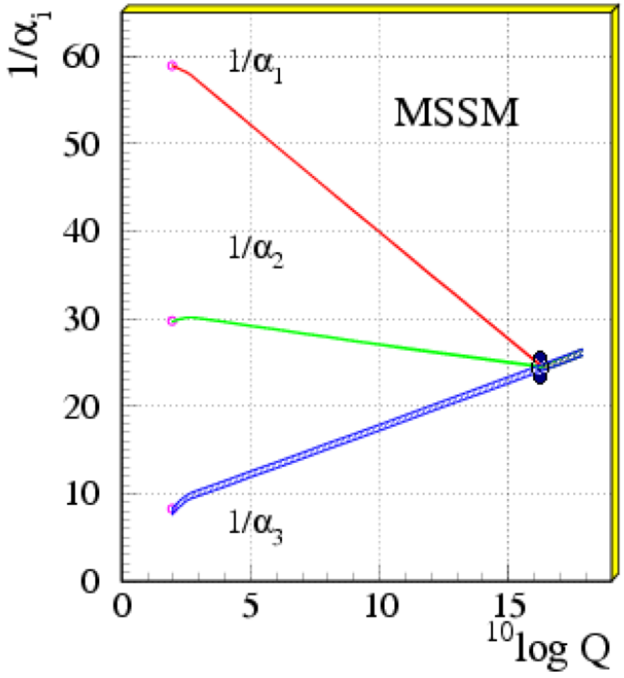
- 中微子的质量为零
- 无法解释宇宙中的物质-反物质不对称，夸克CP破坏仅产生当前观测值的10^{-18}
- 无法解释暗物质的存在

标准模型没有错误，只是复杂、任意和有一些无法解释的问题！

扩充标准模型 → 大统一理论

3个基本的要求：

① 基于更大的规范对称群[SU(5),SO(10),E6和超对称等]
② 可以自发破缺到$SU(3)_C \times SU(2)_L \times U(1)_Y$
③ 将强、弱和电磁相互作用统一



3个要求的结果：

- 一个表示中的所有粒子的电荷之和为0，即轻子和夸克必须放在一个表示中
- 新的规范玻色子会连接轻子和夸克，导致**重子数破坏**
- 重子数破坏-> 核子衰变

$$\tau_p \sim \frac{M^4}{m_p^5} \quad \rightarrow M > 10^{15}\ \text{GeV}$$

- 重子数破坏->宇宙中物质-反物质不对称
- 预测存在磁单极子 （Magnetic Monopole)

寻找质子衰变是检验大统一理论最有效的方法！

最小SU(5)大统一模型

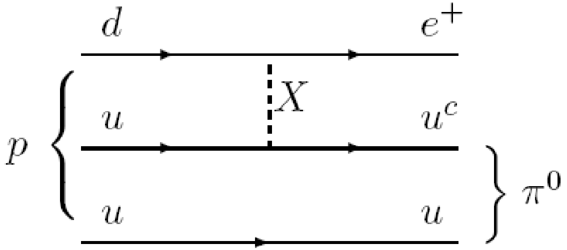
表示：

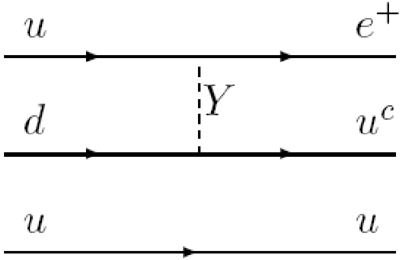
H. Georgi, S.L. Glashow, PRL 32,8 (1974)

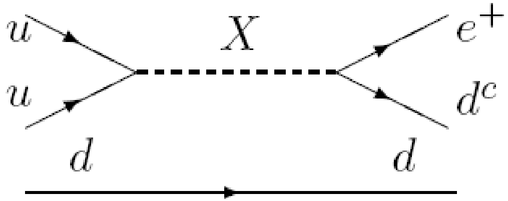
$$\bar{5} = \begin{pmatrix} d^c{}_1 \\ d^c{}_2 \\ d^c{}_3 \\ e^- \\ -\nu_e \end{pmatrix}_L = \psi_{L_a} \qquad 10 = \begin{pmatrix} 0 & u^c{}_3 & -u^c{}_2 & -u_1 & -d_1 \\ & 0 & u^c{}_1 & -u_2 & -d_2 \\ & & 0 & -u_3 & -d_3 \\ & & & 0 & -e^c \\ & & & & 0 \end{pmatrix}_L = \psi^{ab}{}_L$$

$$\begin{pmatrix} G^1_1 - 2B' & G^1_2 & G^1_3 & \bar{X}^1 & \bar{Y}^1 \\ G^2_1 & G^2_2 - 2B' & G^2_3 & \bar{X}^2 & \bar{Y}^2 \\ G^3_1 & G^3_2 & G^3_3 - 2B' & \bar{X}^3 & \bar{Y}^3 \\ X^1 & X^2 & X^3 & W'^3 + 3B' & W^+ \\ Y^1 & Y^2 & Y^3 & W^- & -W'^3 + 3B' \end{pmatrix}$$

质子衰变 $p \to e^+ + \pi^0$ 过程, 分支比最大~30% - 40%：







X和Y为新引入的超重规范玻色子，电荷分别是4/3 和1/3

理论预测和实验结果：

理论：$\tau_{p\to e^+ + \pi^0} = 4.5 \times 10^{29\pm1.7}$年

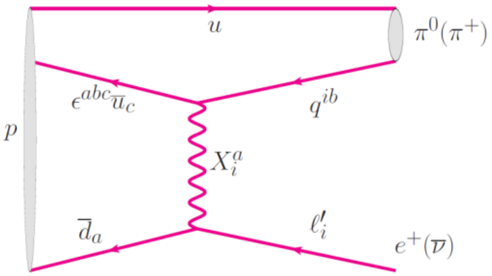
实验：$\tau_{p\to e^+ + \pi^0} > 2.4 \times 10^{34}$年

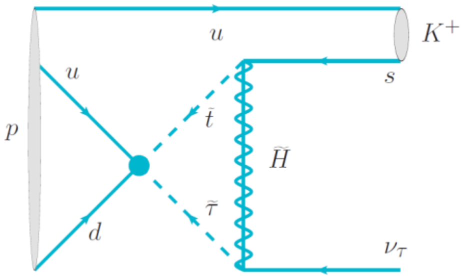
质子衰变排除最小SU(5)大统一模型！

2个显著的核子衰变道:

$p \to e^+\pi^0$

Non-SUSY GUTs

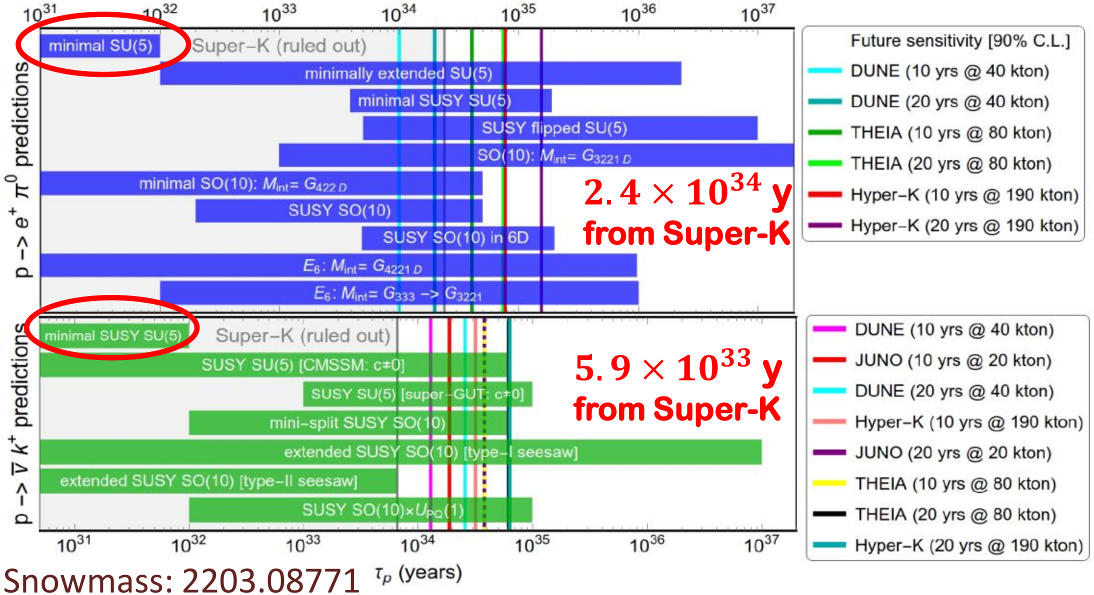




$p \to \overline{\nu}\, K^+$

SUSY GUTs

主要GUT模型的预测:



Snowmass: 2203.08771

不同核子衰变道之间的联系:

	Br.(%)				
	SU(5)				SO(10)
References	[72]	[73]	[74]	[75]	[75]
$p \to e^+\pi^0$	33	37	9	35	30
$p \to e^+\eta^0$	12	7	3	15	13
$p \to e^+\rho^0$	17	2	21	2	2
$p \to e^+\omega^0$	22	18	56	17	14
Others	17	35	11	31	31
τ_p/τ_n	0.8	1.0	1.3		

Hyper-K:1109.3262

试试寻找其他的核子衰变道？

Mode		Partial mean life (10^{30} years)	Scale Factor/ Conf. Level	P(MeV/c)
Antilepton + meson				
τ_1 $N \to e^+\pi$	B	> 5300 (n), > 16000 (p)	CL=90%	459
τ_2 $N \to \mu^+\pi$	B	> 3500 (n), > 7700 (p)	CL=90%	453
τ_3 $N \to \nu\pi$		> 1100 (n), > 390 (p)	CL=90%	459
τ_4 $p \to e^+\eta$		> 10000	CL=90%	309
τ_5 $p \to \mu^+\eta$		> 4700	CL=90%	297
τ_6 $n \to \nu\eta$		> 158	CL=90%	310
τ_7 $N \to e^+\rho$		> 217 (n), > 720 (p)	CL=90%	149
τ_8 $N \to \mu^+\rho$		> 228 (n), > 570 (p)	CL=90%	113
τ_9 $N \to \nu\rho$		> 19 (n), > 162 (p)	CL=90%	149
τ_{10} $p \to e^+\omega$		> 1600	CL=90%	143
τ_{11} $p \to \mu^+\omega$		> 2800	CL=90%	105
τ_{12} $n \to \nu\omega$		> 108	CL=90%	144
τ_{13} $N \to e^+K$	B	> 17 (n), > 1000 (p)	CL=90%	339
τ_{14} $p \to e^+K^0_S$				337
τ_{15} $p \to e^+K^0_L$				337
τ_{16} $N \to \mu^+K$	B	> 26 (n), > 1600 (p)	CL=90%	329
τ_{17} $p \to \mu^+K^0_S$				326
τ_{18} $p \to \mu^+K^0_L$				326
τ_{19} $N \to \nu K$		> 86 (n), > 5900 (p)	CL=90%	339
τ_{20} $n \to \nu K^0_S$		> 260	CL=90%	338
τ_{21} $p \to e^+K^*(892)^0$		> 84	CL=90%	45

τ_{22} $N \to \nu K^*(892)$	> 78 (n), > 51 (p)	CL=90%	45
Antilepton + mesons			
τ_{23} $p \to e^+\pi^+\pi^-$	> 82	CL=90%	448
τ_{24} $p \to e^+\pi^0\pi^0$	> 147	CL=90%	449
τ_{25} $n \to e^+\pi^-\pi^0$	> 52	CL=90%	449
τ_{26} $p \to \mu^+\pi^+\pi^-$	> 133	CL=90%	425
τ_{27} $p \to \mu^+\pi^0\pi^0$	> 101	CL=90%	427
τ_{28} $n \to \mu^+\pi^-\pi^0$	> 74	CL=90%	427
τ_{29} $n \to e^+K^0\pi^-$	> 18	CL=90%	319
Lepton + meson			
τ_{30} $n \to e^-\pi^+$	> 65	CL=90%	459
τ_{31} $n \to \mu^-\pi^+$	> 49	CL=90%	453
τ_{32} $n \to e^-\rho^+$	> 62	CL=90%	150
τ_{33} $n \to \mu^-\rho^+$	> 7	CL=90%	115
τ_{34} $n \to e^-K^+$	> 32	CL=90%	340
τ_{35} $n \to \mu^-K^+$	> 57	CL=90%	330
Lepton + mesons			
τ_{36} $p \to e^-\pi^+\pi^+$	> 30	CL=90%	448
τ_{37} $n \to e^-\pi^+\pi^0$	> 29	CL=90%	449
τ_{38} $p \to \mu^-\pi^+\pi^+$	> 17	CL=90%	425
τ_{39} $n \to \mu^-\pi^+\pi^0$	> 34	CL=90%	427
τ_{40} $p \to e^-\pi^+K^+$	> 75	CL=90%	320
τ_{41} $p \to \mu^-\pi^+K^+$	> 245	CL=90%	279
Antilepton + photon(s)			
τ_{42} $p \to e^+\gamma$	> 670	CL=90%	469
τ_{43} $p \to \mu^+\gamma$	> 478	CL=90%	463
τ_{44} $n \to \nu\gamma$	> 550	CL=90%	470
τ_{45} $p \to e^+\gamma\gamma$	> 100	CL=90%	469
τ_{46} $n \to \nu\gamma\gamma$	> 219	CL=90%	470

Antilepton + single massless			
τ_{47} $p \to e^+X$	> 790	CL=90%	
τ_{48} $p \to \mu^+X$	> 410	CL=90%	
Three (or more) leptons			
τ_{49} $p \to e^+e^+e^-$	> 793	CL=90%	469
τ_{50} $p \to e^+\mu^+\mu^-$	> 359	CL=90%	457
τ_{51} $p \to e^+\nu\nu$	> 170	CL=90%	469
τ_{52} $n \to e^+e^-\nu$	> 257	CL=90%	470
τ_{53} $n \to \mu^+e^-\nu$	> 83	CL=90%	464
τ_{54} $n \to \mu^+\mu^-\nu$	> 79	CL=90%	458
τ_{55} $p \to \mu^+e^+e^-$	> 529	CL=90%	463
τ_{56} $p \to \mu^-e^+e^+$	> 1.90×10^{14}	CL=90%	463
τ_{57} $p \to \mu^+\mu^+\mu^-$	> 675	CL=90%	439
τ_{58} $p \to \mu^+\nu\nu$	> 220	CL=90%	463
τ_{59} $p \to e^-\mu^+\mu^+$	> 6	CL=90%	457
τ_{60} $n \to 3\,\nu$	> 5×10^{-4}	CL=90%	470
τ_{61} $n \to 5\,\nu$			470
Inclusive modes			
τ_{62} $N \to e^+$ anything	> 0.6 (n, p)	CL=90%	
τ_{63} $N \to \mu^+$ anything	> 12 (n, p)	CL=90%	
τ_{64} $N \to \nu$ anything			
τ_{65} $N \to e^+\pi^0$ anything	> 0.6 (n, p)	CL=90%	
τ_{66} $N \to$ 2 bodies, ν-free			

$\Delta B = 2$ dinucleon modes		
τ_{67} $p\,p \to \pi^+\pi^+$	> 72.2	CL=90%
τ_{68} $p\,n \to \pi^+\pi^0$	> 170	CL=90%
τ_{69} $n\,n \to \pi^+\pi^-$	> 0.7	CL=90%
τ_{70} $n\,n \to \pi^0\pi^0$	> 404	CL=90%
τ_{71} $p\,p \to K^+K^+$	> 170	CL=90%
τ_{72} $p\,p \to e^+e^+$	> 5.8	CL=90%
τ_{73} $p\,p \to e^+\mu^+$	> 3.6	CL=90%
τ_{74} $p\,p \to \mu^+\mu^+$	> 1.7	CL=90%
τ_{75} $p\,n \to e^+\bar{\nu}$	> 260	CL=90%
τ_{76} $p\,n \to \mu^+\bar{\nu}$	> 200	CL=90%
τ_{77} $p\,n \to \tau^+\bar{\nu}_\tau$	> 29	CL=90%
τ_{78} $n\,n \to$ invisible	> 1.4	CL=90%
τ_{79} $n\,n \to \nu_e\bar{\nu}_e$	> 1.4	CL=90%
τ_{80} $n\,n \to \nu_\mu\bar{\nu}_\mu$	> 1.4	CL=90%
τ_{81} $p\,n \to$ invisible	> 0.06	CL=90%
τ_{82} $p\,p \to$ invisible	> 0.11	CL=90%

From PDG 2023

Total Channels: 82

Mesons: $\pi^{\pm}, \pi^0, K^{\pm}, K^0, \eta, \rho, \omega, K^*(892)$;

Leptons: $e^{\pm}, \mu^{\pm}, \nu$; **Photon:** γ

实验上至今没有发现核子衰变！

GUTs还预言了哪些未被寻找的核子衰变道？

Proton 3-body：

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \text{yr}}$
$p \to e^- + e^+ + e^+$	0	793 [46]
$p \to e^- + e^+ + \mu^+$	0	529 [46]
$p \to e^+ + e^+ + \mu^-$	0	529* [46]
$p \to e^- + \mu^+ + \mu^+$	0	6 [73] (359* [46])
$p \to e^+ + \mu^- + \mu^+$	0	359 [46]
$p \to \mu^- + \mu^+ + \mu^+$	0	675 [46]
$p \to e^+ + 2\nu$	0,2	170 [81]
$p \to \mu^+ + 2\nu$	0,2	220 [81]
$p \to e^- + 2\pi^+$	2	30 [52] (82* [46])
$p \to e^- + \pi^+ + \rho^+$	2	
$p \to e^- + K^+ + \pi^+$	2	75 [46]
$p \to e^+ + 2\gamma$	0	100 [82] (793* [46])
$p \to e^+ + \pi^- + \pi^+$	0	82 [46]
$p \to e^+ + \rho^- + \pi^+$	0	
$p \to e^+ + K^- + \pi^+$	0	75* [46]
$p \to e^+ + \pi^- + \rho^+$	0	
$p \to e^+ + \pi^- + K^+$	0	75* [46]
$p \to e^+ + 2\pi^0$	0	147 [46]
$p \to e^+ + \pi^0 + \eta$	0	
$p \to e^+ + \pi^0 + \rho^0$	0	
$p \to e^+ + \pi^0 + \omega$	0	
$p \to e^+ + \pi^0 + K^0$	0	
$p \to \mu^- + 2\pi^+$	2	17 [52] (133* [46])
$p \to \mu^- + K^+ + \pi^+$	2	245 [46]
$p \to \mu^+ + 2\gamma$	0	529* [46]
$p \to \mu^+ + \pi^- + \pi^+$	0	133 [46]
$p \to \mu^+ + K^- + \pi^+$	0	245* [46]
$p \to \mu^+ + \pi^- + K^+$	0	245* [46]
$p \to \mu^+ + 2\pi^0$	0	101 [46]
$p \to \mu^+ + \pi^0 + \eta$	0	
$p \to \mu^+ + \pi^0 + K^0$	0	
$p \to \nu + \pi^+ + \pi^0$	0,2	
$p \to \nu + \pi^+ + \eta$	0,2	
$p \to \nu + \pi^+ + \rho^0$	0,2	
$p \to \nu + \pi^+ + \omega$	0,2	
$p \to \nu + \pi^+ + K^0$	0,2	
$p \to \nu + \rho^+ + \pi^0$	0,2	
$p \to \nu + K^+ + \pi^0$	0,2	

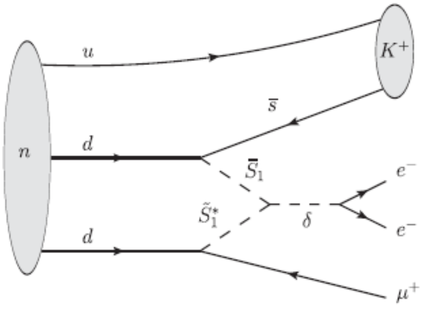
Neutron 3-body：

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \text{yr}}$
$n \to \nu + e^- + e^+$	0,2	257 [46]
$n \to \nu + e^- + \mu^+$	0,2	83 [46]
$n \to \nu + e^+ + \mu^-$	0,2	83* [46]
$n \to \nu + \mu^- + \mu^+$	0,2	79 [46]
$n \to 3\nu$	0,2,4	0.58 [83]
$n \to e^- + \pi^+ + \pi^0$	2	29 [52] (52* [46])
$n \to e^- + \pi^+ + \eta$	2	
$n \to e^- + \pi^+ + \rho^0$	2	
$n \to e^- + \pi^+ + \omega$	2	
$n \to e^- + \pi^+ + K^0$	2	
$n \to e^- + \rho^+ + \pi^0$	2	
$n \to e^- + K^+ + \pi^0$	2	
$n \to e^+ + \pi^- + \pi^0$	0	52 [46]
$n \to e^+ + \pi^- + \eta$	0	
$n \to e^+ + \pi^- + \rho^0$	0	
$n \to e^+ + \pi^- + \omega$	0	
$n \to e^+ + \pi^- + K^0$	0	18 [82]
$n \to e^+ + \rho^- + \pi^0$	0	
$n \to e^+ + K^- + \pi^0$	0	
$n \to \mu^- + \pi^+ + \pi^0$	2	34 [52] (74* [46])
$n \to \mu^- + \pi^+ + \eta$	2	
$n \to \mu^- + \pi^+ + K^0$	2	
$n \to \mu^- + K^+ + \pi^0$	2	
$n \to \mu^+ + \pi^- + \pi^0$	0	74 [46]
$n \to \mu^+ + \pi^- + \eta$	0	
$n \to \mu^+ + \pi^- + K^0$	0	
$n \to \mu^+ + K^- + \pi^0$	0	
$n \to \nu + 2\gamma$	0,2	219 [46]
$n \to \nu + \pi^- + \pi^+$	0,2	
$n \to \nu + \rho^- + \pi^+$	0,2	
$n \to \nu + K^- + \pi^+$	0,2	
$n \to \nu + \pi^- + \rho^+$	0,2	
$n \to \nu + \pi^- + K^+$	0,2	
$n \to \nu + 2\pi^0$	0,2	
$n \to \nu + \pi^0 + \eta$	0,2	
$n \to \nu + \pi^0 + \rho^0$	0,2	
$n \to \nu + \pi^0 + \omega$	0,2	
$n \to \nu + \pi^0 + K^0$	0,2	

Dinucleon decay：

Channel	$\lvert\Delta(B-L)\rvert$	$\frac{\Gamma^{-1}}{10^{30}\ \text{yr}}$
$nn \to \pi^0 + \phi$	2	
$nn \to 2\eta$	2	
$nn \to \eta + \rho^0$	2	
$nn \to \eta + \omega$	2	
$nn \to \eta + \eta'$	2	
$nn \to \eta + K^0$	2	
$nn \to \eta + K^{*,0}$	2	
$nn \to \eta + \phi$	2	
$nn \to 2\rho^0$	2	
$nn \to \rho^0 + \omega$	2	
$nn \to \eta' + \rho^0$	2	
$nn \to K^0 + \rho^0$	2	
$nn \to K^{*,0} + \rho^0$	2	
$nn \to \rho^0 + \phi$	2	
$nn \to \rho^- + \rho^+$	2	
$nn \to K^+ + \rho^-$	2	
$nn \to K^{*,+} + \rho^-$	2	
$nn \to K^- + \rho^+$	2	
$nn \to K^{*,-} + \rho^+$	2	
$nn \to 2\omega$	2	
$nn \to \eta' + \omega$	2	
$nn \to K^0 + \omega$	2	
$nn \to K^{*,0} + \omega$	2	
$nn \to \omega + \phi$	2	
$nn \to \eta' + K^0$	2	
$nn \to \eta' + K^{*,0}$	2	
$nn \to K^- + K^+$	2	170* [116]
$nn \to K^+ + K^{*,-}$	2	
$nn \to K^- + K^{*,+}$	2	
$nn \to 2K^0$	2	
$nn \to K^{*,0} + K^0$	2	
$nn \to K^0 + \phi$	2	
$nn \to 2K^{*,0}$	2	
$nn \to K^{*,-} + K^{*,+}$	2	

4-body decay:



From PRD 101, 015005 (2020)

Others?

(2) 质子衰变实验

质子衰变实验的探测能力

事例数变化：

$$\frac{dN}{dt} = -\lambda N \rightarrow N_t = N_0 e^{-\lambda t} = N_0 e^{-\frac{t}{\tau}} \qquad [t \ll \tau]$$

$$N_t = N_0\left(1 - \frac{t}{\tau}\right) \rightarrow N_0 - N_t = N_{decay} = N_0 \frac{t}{\tau}$$

N_0：靶核子数
ϵ_i：探测效率
t：实验时间
N_{S_i}：实验限制

考虑某个衰变道的分支比B_i和实验探测效率ϵ_i：

$$N_{S_i} = N_{decay} \cdot B_i \cdot \epsilon_i = B_i \cdot \epsilon_i \cdot N_0 \frac{t}{\tau} \rightarrow \frac{\tau}{B_i} = \frac{N_0 \cdot \epsilon_i}{N_{S_i}} t$$

核子衰变实验关键量：（1）曝光量$N_0 \cdot t$（2）效率ϵ_i（3）背景

简单的估算公式：$\tau/B_i > 1.5 \times M(\mathrm{kton}) \times \epsilon_i \times t \times 10^{32}\ \mathrm{yr}$

实验对事例数N_{S_i}的限制：

$$L(N_{obs}, N_S) = \frac{(N_S + N_B)^{N_{obs}}}{N_{obs}\,!} e^{-(N_S+N_B)} \rightarrow 90\% = \frac{\int_0^{N_{90}} L(N_{obs}, N_S) dN_S}{\int_0^{\infty} L(N_{obs}, N_S) dN_S}$$

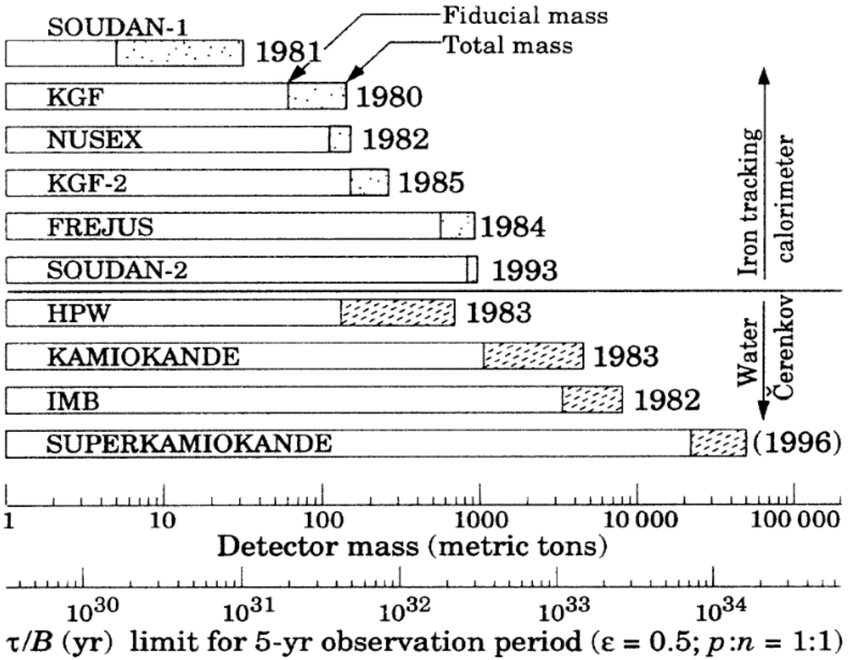
$N_{obs} = N_B$	0.0	1.0	2.0	5.0	10	20	50	100	200	1000
N_{90}	2.3	3.3	3.9	5.2	6.6	8.8	13.0	17.8	24.6	53.3

质子衰变实验的发展历史

早期实验对质子衰变的限制：

大统一理论提出之前（1950s-60s）→ 检验质子是否稳定

第一代(80s)和第二代(90s)质子衰变实验：



2000年之后，KamLAND、SNO、BOREXINO、DAMA等实验也对不可见质子衰变道给出限制。

第三代(2020s)质子衰变实验：

- Hyper-K (Water Cerenkov)
- DUNE (LAr TPC)
- JUNO (Liquid Scintillator)

Experimental tests of proton decays before GUTs

- In 1954, Reines, Cowan and Goldhaber give the first limit: $\tau(p) > 10^{22}$ yrs
- Before the discovery of $\bar{\nu}_e$ in 1956.

Phys. Rev.96, 1157 (1954)

Authors	Experiment	Decay mode	Depth (mwe)	τ_{min} (yrs)
Reines, Cowan, and Goldhaber 1954 [4]	300 ℓ liquid scint.	All (E_{ch} > 100 MeV)	200	10^{22}
Reines, Cowan and Kruse 1958 [49]	As above, with delayed neutron pulse	All	200	$4 \cdot 10^{23}$
Backenstoss et al. 1960 [8]	50 ℓ liquid Cerenkov, upward rel. sec.	At least one secondary of > 250 MeV	2400	$3 \cdot 10^{26}$
Giamati and Reines 1962 [50] Kropp and Reines 1965 [51]	200 ℓ liquid scint.	All	1760	$6 \cdot 10^{27}$ $\sim 10^{28}$
Gurr et al. 1967 [52]	Scint. hodoscope	All	8000	$2 \cdot 10^{28}$

D.H Perkins, 1984

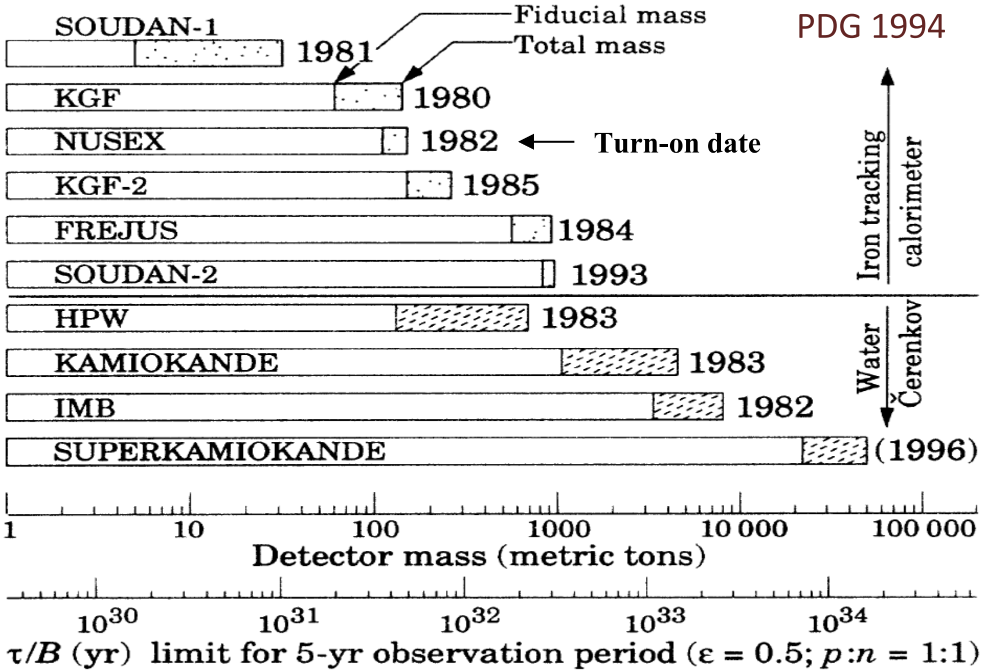
第一代质子衰变实验（80年代）

In 1974, Georgi and Glashow give SU(5) GUT, ➔ *p* lifetime $\sim 4.5\times 10^{29\pm1.7}$yrs

➔ Detector with about 1000 ton mass can test the SU(5) GUT

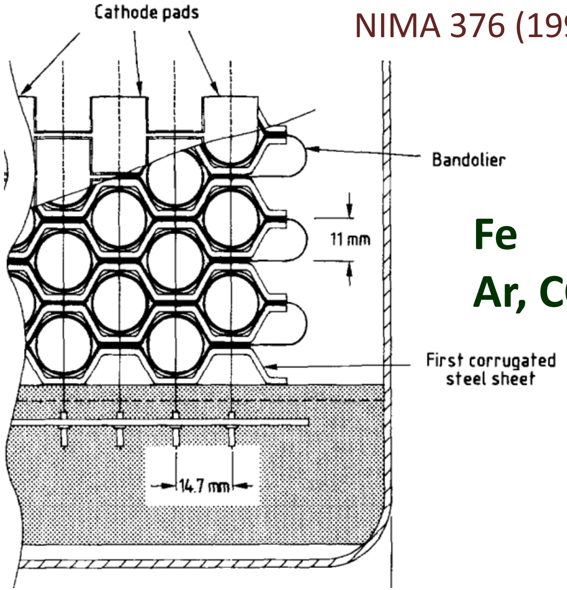
➔ The first generation of experiments are proposed and constructed

PDG 1994



SOUDAN-2 Iron tracking claorimeter

NIMA 376 (1996) 36



Fe

Ar, CO_2

They do not find the evidence for proton decay, excluding minimal SU(5)!

第二代质子衰变实验（仅有 Super-K）

Super-Kamiokande:

Super-Kamiokande => Super-Kamioka Neutrino Detection Experiment

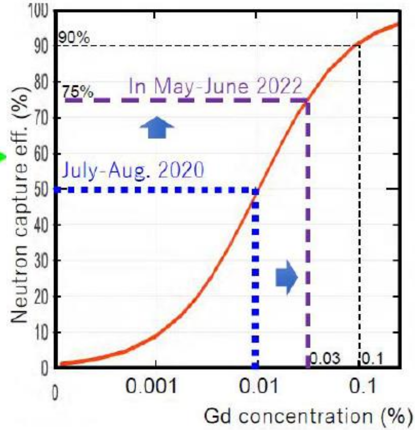
KamiokaNDE => Kamioka Nucleon Decay Experiment

Water Cerenkov, 50 kton → 22.5 kton

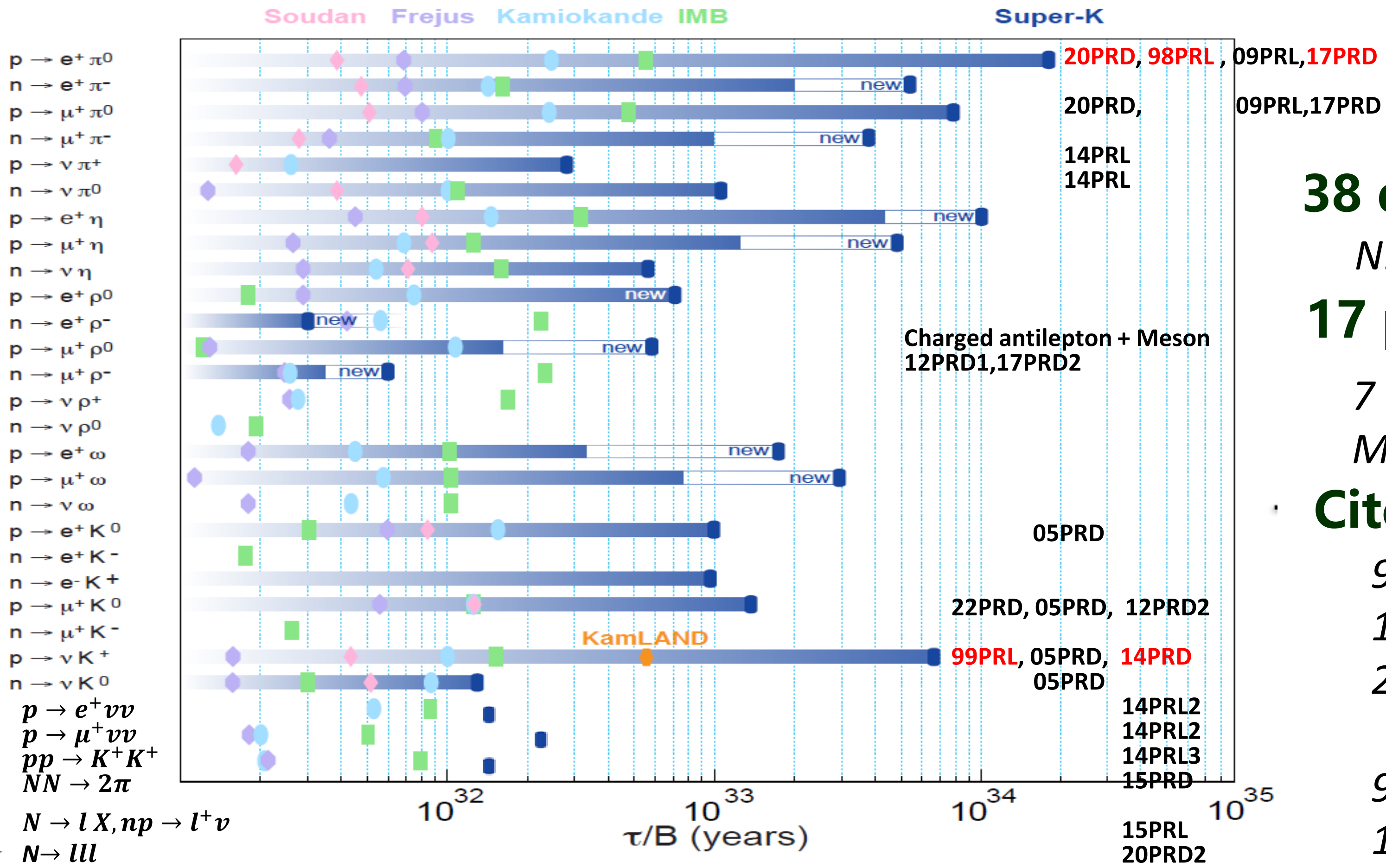
通过探测切伦科夫光来鉴别有能量粒子的类型，并重建其能量和方向等信息

Gd concentration at SK-VI:
0.011% in weight.

L.Y. Wan, Neutrino22



Super-K的质子衰变结果



38 decay modes:

N: 31; NN: 7

17 paper:

7 PRL, 10 PRD

Most after 2012

Cites:

98PRL：208

17PRD: 304

20PRD: 80

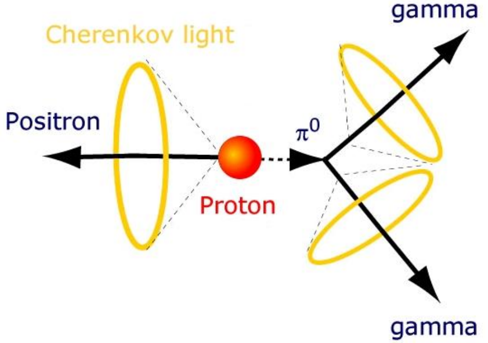
99PRL：201

14PRD: 212

Super-K searching for $p \to e^{+}\pi^{0}$

Signal features:

- Momentum of $e^{+}$and π^{0} is 460 MeV
- Kinetic energy :459 MeV and 344 MeV



Event selection:

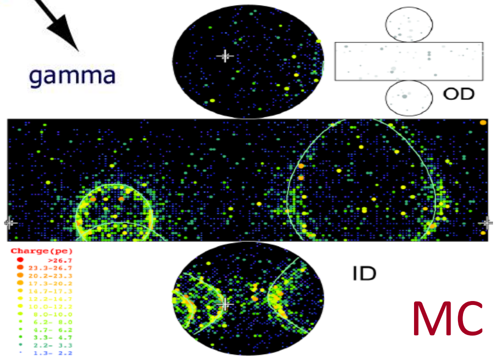
A. Two or three rings

B. e-like rings

C. Invariant mass of π^{0} (135MeV) : 85-185MeV

D. No Michel electron

E. $\vec{P}_{tot}$ (<250MeV) and M_{invar}(800-1050 MeV)



MC

Results:

450 kton years

Efficiency: ~20%

Background: ~0.6

$\tau/B(p \to e^{+}\pi^{0}) > 2.4 \times 10^{34}$ yrs

$\nu N \longrightarrow \ell N'\pi^{0}$

$\nu N \longrightarrow \nu N'\pi($

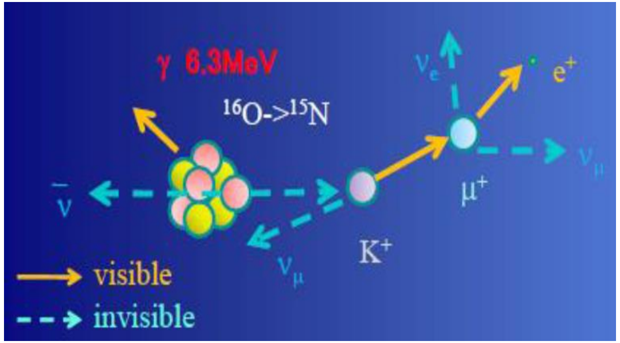
PRD 102, 112011 (2020)

Super-K searching for $p \to \bar{\nu} K^+$

Signal features:

- Momentum of $\bar{\nu}$ and K^+ is 339 MeV (105 MeV)
- 89% K^+ decay at rest (12.38ns):

  $K^+ \to \mu^+ \nu_\mu (63.43\%)$, $K^+ \to \pi^+ \pi^0 (21.13\%)$,



Event selection:

1: $K^+ \to \mu^+ \nu_\mu \to \gamma(6.3\text{MeV}, 41\%)$ from $^{16}\text{O} + \mu^+ +$ Michel e^+

2: $K^+ \to \mu^+ \nu_\mu \to$ Monoenergetic μ^+ (p = 236MeV)

3: $K^+ \to \pi^+ \pi^0 \to$ two rings from π^0 (M_{inv}, p)+ π^+(direction , e^+)

$\nu\, p \to \nu\, K^+ \Lambda$ (48%),
ν_μ CCQE (25%),

CC $1\pi^0$ with μ (38%),
kaon production (37%),
NC multi-π(11%)

Results:

260 kton years
Efficiency: ~8.4%, 9%
Background:~ 0.24, 0.45

$\tau / B(p \to \bar{\nu}\, K^+) > 5.9 \times 10^{33}$ yrs

PRD 90, 072005 (2014)

质子衰变实验的探测潜力：

$$\frac{\tau}{B_i} = \frac{N_0 \cdot \epsilon_i}{N_{S_i}} t$$

N_0：靶核子数
ϵ_i：探测效率
t：实验时间
N_{S_i}：实验限制

$N_{obs} = N_B$	0.0	1.0	2.0	5.0	10	20	50	100	200	1000
N_{90}	2.3	3.3	3.9	5.2	6.6	8.8	13.0	17.8	24.6	53.3

未来质子衰变实验的方向?

未来质子衰变实验的方向

质子衰变实验的探测潜力:

$$\frac{\tau}{B_i} = \frac{N_0 \cdot \epsilon_i}{N_{S_i}} t$$

N_0: 靶核子数
ϵ_i : 探测效率
t : 实验时间
N_{S_i}: 实验限制

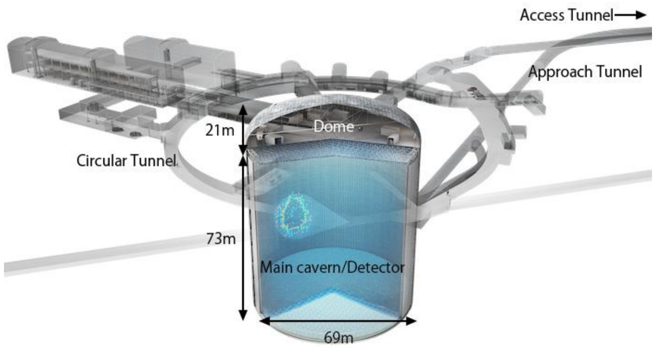
$N_{obs} = N_B$	0.0	1.0	2.0	5.0	10	20	50	100	200	1000
N_{90}	2.3	3.3	3.9	5.2	6.6	8.8	13.0	17.8	24.6	53.3

未来质子衰变实验的方向?

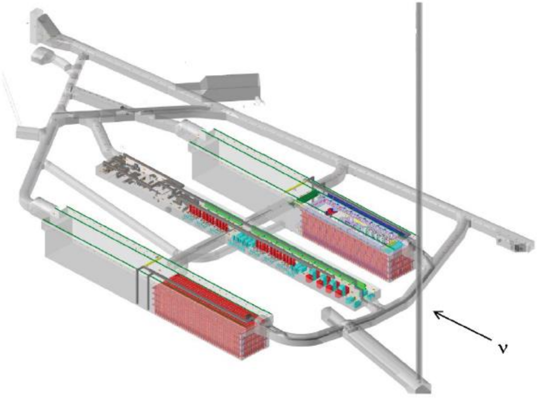
1. 增加探测器靶质量N_0 → 相对容易
2. 增加取数时间t → 提升有限
3. 保持高ϵ_i同时压低背景 → 分析方法
4. 寻找新的方法，如古矿物中的径迹：1kton*10y = 10g*10^9y
5. …

第三代核子衰变实验

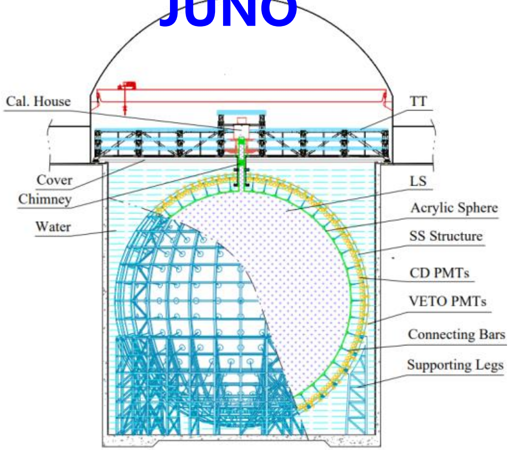
Hyper-K



DUNE



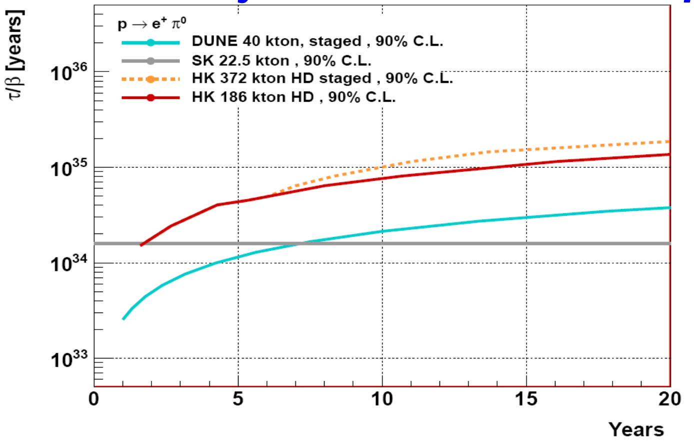
JUNO

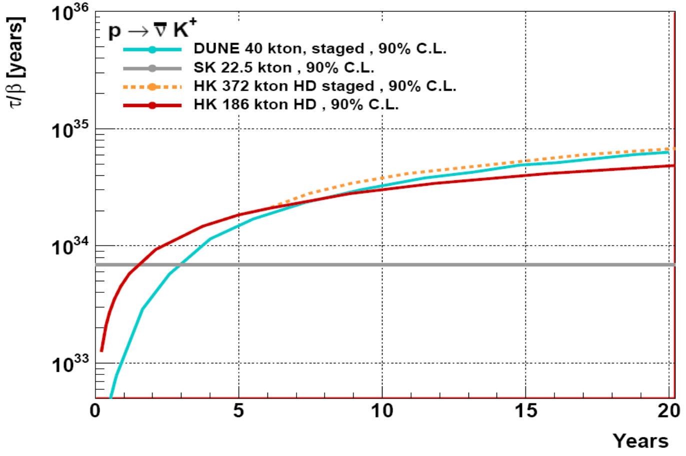


	Hyper-K	DUNE	JUNO
Mass (kton)	**258 (186)**	**4*17 (4*10)**	**20**
Target Nucleus	H_2O	Ar40	12% H， 88% C12
Technology	Water Cerenkov	LAr TPC	Liquid Scintillator
Start Time	2027	2028/29	2025

Proton decay searches in Hyper-K

Similar analysis methods with Super-K:





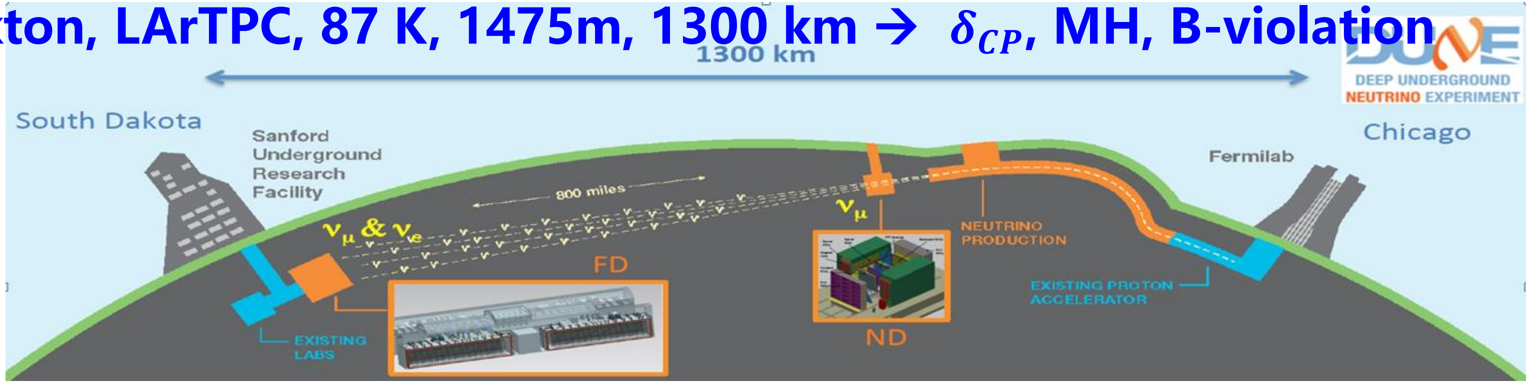
10 years sensitivity with 1 TANK:

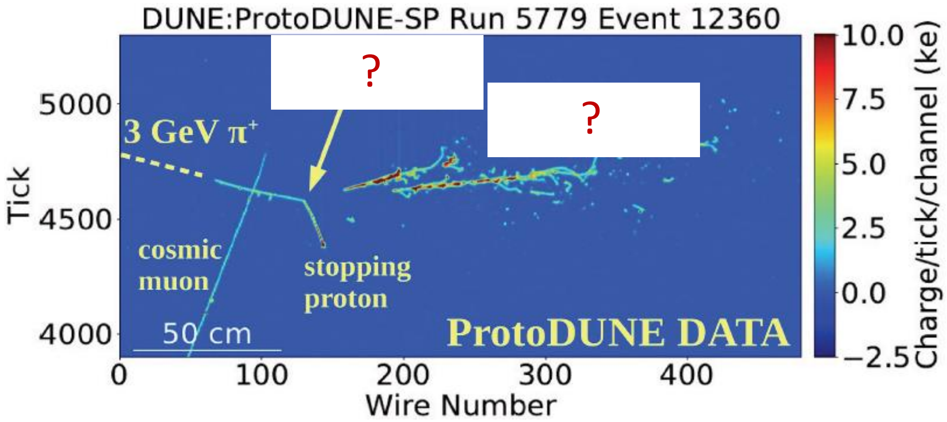
Mode	Sensitivity (90% CL) [years]	Current limit [years]
$p \to e^+\pi^0$	7.8×10^{34}	2.4×10^{34}
$p \to \overline{\nu}K^+$	3.2×10^{34}	0.59×10^{34}
$p \to \mu^+\pi^0$	7.7×10^{34}	0.77×10^{34}
$p \to e^+\eta^0$	4.3×10^{34}	1.0×10^{34}
$p \to \mu^+\eta^0$	4.9×10^{34}	0.47×10^{34}
$p \to e^+\rho^0$	0.63×10^{34}	0.07×10^{34}
$p \to \mu^+\rho^0$	0.22×10^{34}	0.06×10^{34}
$p \to e^+\omega^0$	0.86×10^{34}	0.16×10^{34}
$p \to \mu^+\omega^0$	1.3×10^{34}	0.28×10^{34}
$n \to e^+\pi^-$	2.0×10^{34}	0.53×10^{34}
$n \to \mu^+\pi^-$	1.8×10^{34}	0.35×10^{34}

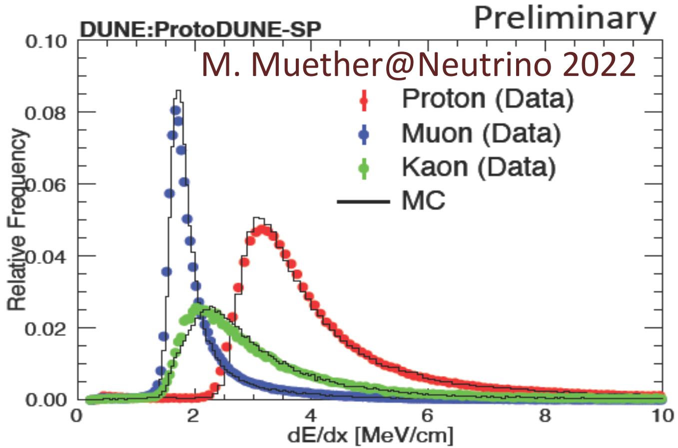
Hyper-Kamiokande Design Report: 1805.04163

Liquid Argon TPC: DUNE

4x10 kton, LArTPC, 87 K, 1475m, 1300 km → δ_{CP}, MH, B-violation





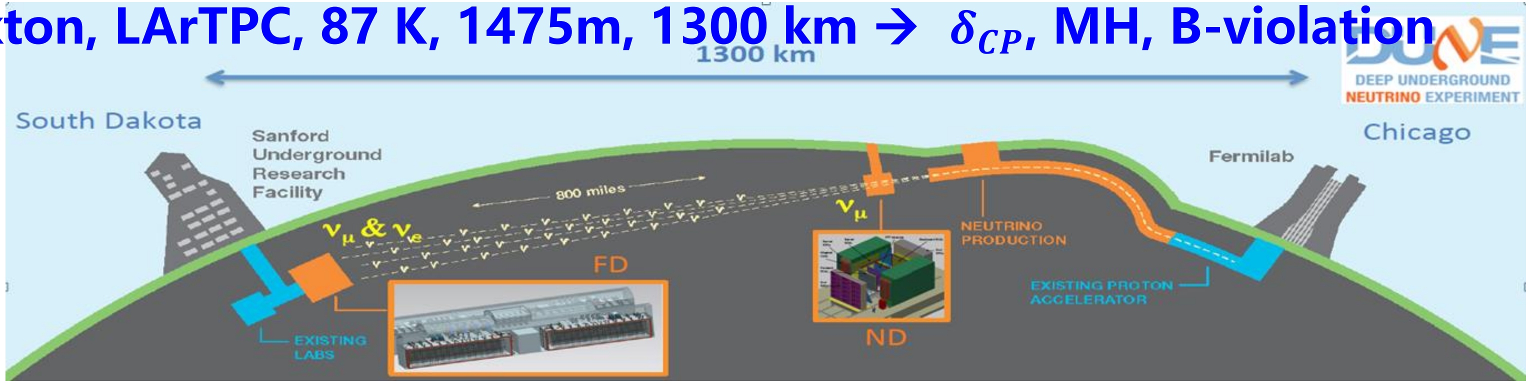


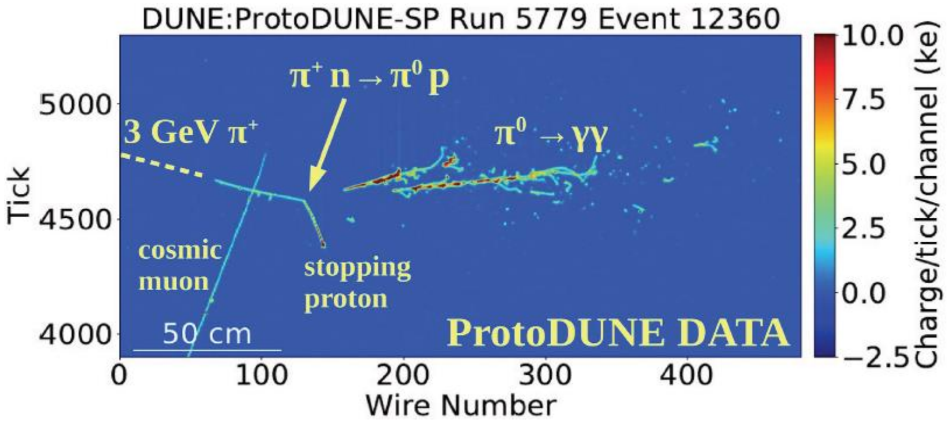
400 kton yrs ➡ $\tau/B(p \to e^+\pi^0) > 0.87 - 1.1 \times 10^{34}$ yrs (*E* smearing)

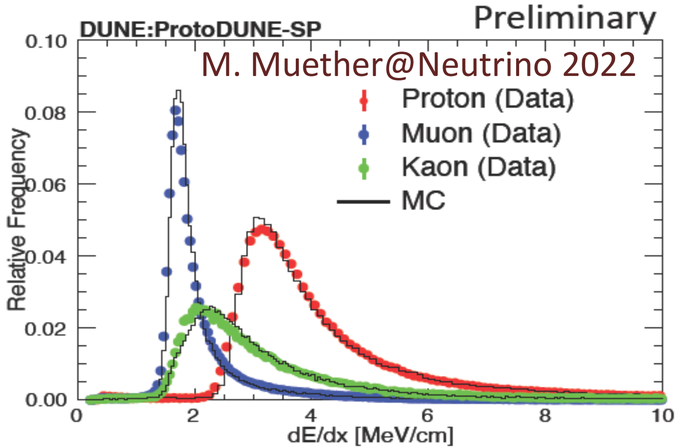
$\tau/B(p \to \bar{\nu} K^+) > 1.3 \times 10^{34}$ yrs, (30%, 0.4 bkg) DUNE Physics 2002.03005

Liquid Argon TPC: DUNE

4x10 kton, LArTPC, 87 K, 1475m, 1300 km → δ_{CP}, MH, B-violation







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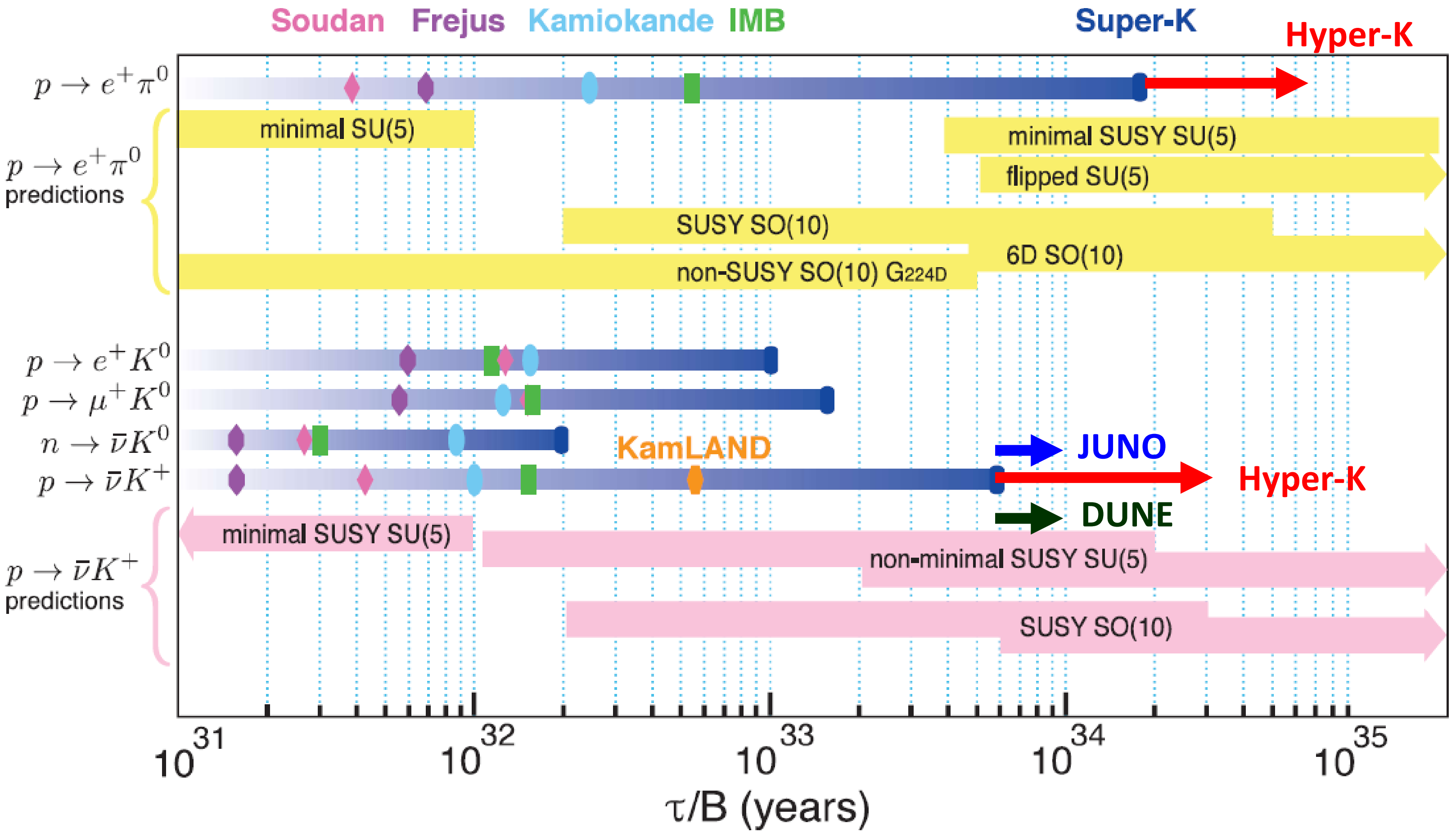
$\tau/B(p \to \bar{\nu} K^+) > 1.3 \times 10^{34}$ yrs, (30%, 0.4 bkg) DUNE Physics 2002.03005

Future sensitives of 10yrs on two favor channels



Comparison of Hyper-K, DUNE and JUNO

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Mass (kton)	258 (186)	4*17 (4*10)	20
Target Nucleus	H_2O	Ar40	12% H， 88% C12
Technology	Water Cerenkov	LAr TPC	Liquid Scintillator
Start Time	2027	2028/29	2025
Advantages	Large mass and cheap Good particle Identification Good direction resolution	Excellent track reconstruction Excellent particle Identification Good energy resolution	Excellent energy resolution 3% Excellent *E* threshold 0.7MeV
Shortcomings	Cerenkov threshold	Complex FSI for Ar40	Direction information lost

未来3大质子衰变实验！

(3) JUNO 寻找质子衰变的潜力

JUNO Detector

Top Tracker

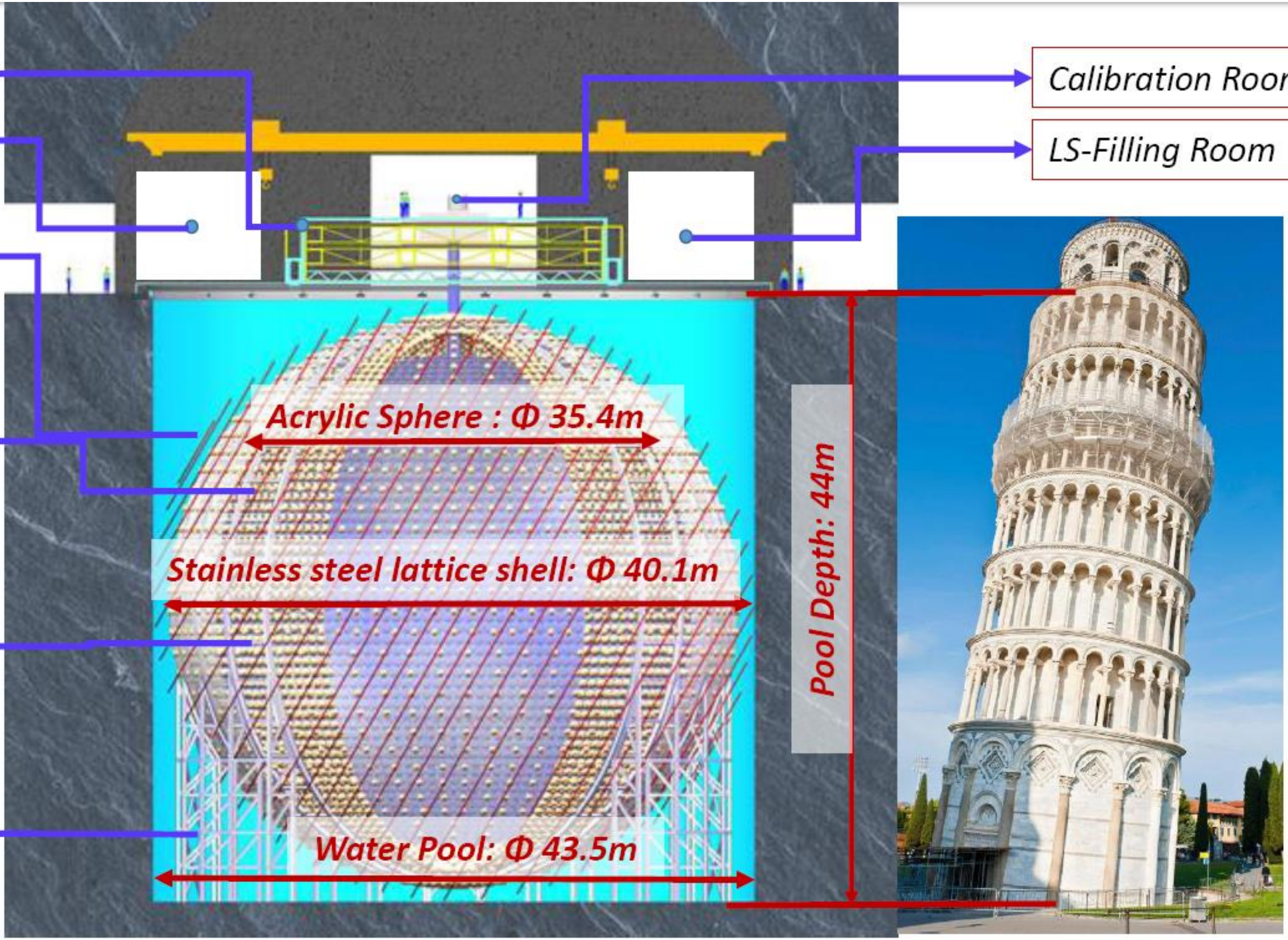
Pure water Room

Earth Magnetic Field shielding coils

Central detector:
- 20kton LS
- Acrylic Sphere
- Steel structure

PMT:
- 17612 20'' PMTs
- 25600 3'' PMTs
- 78% Coverage

WCD:
- 35 kton Pure water
- 2400 20'' PMTs



Calibration Room

LS-Filling Room

JUNO探测质子衰变的优缺点

优点:

1. Large mass (20 kton) → Free *p*: 1.43×10^{33}; Bounded *p/n*: 5.30×10^{33}
2. Excellent $\sigma_E = 3\%/\sqrt{E}$ → Mono-energy products from free *p* decay
3. Low threshold (0.2 MeV) → Residual nucleus
4. Neutron tag (2.2 MeV) → Separate signals from BG
5. 1GHz sampling rate → Waveform

缺点:

1. Difficult to reconstruct direction → can't use momentum conservation
2. Difficult to identify particles → can't effectively separate S/B

JUNO可用的物理量:

能量、位置、时间、波形、米歇尔电子数、中子数、残余核

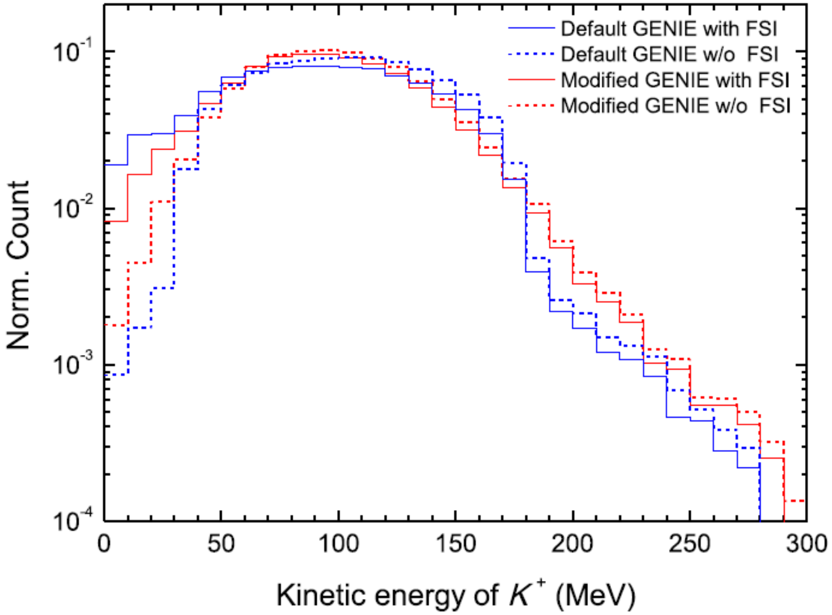
粒子方向重建的突破将会极大改善JUNO对很多核子衰变道的敏感度!

Search for $p \rightarrow \overline{\nu} K^+$ in JUNO

20 kton LS: Free proton: 1.45×10^{33}
Bound proton: 5.30×10^{33}

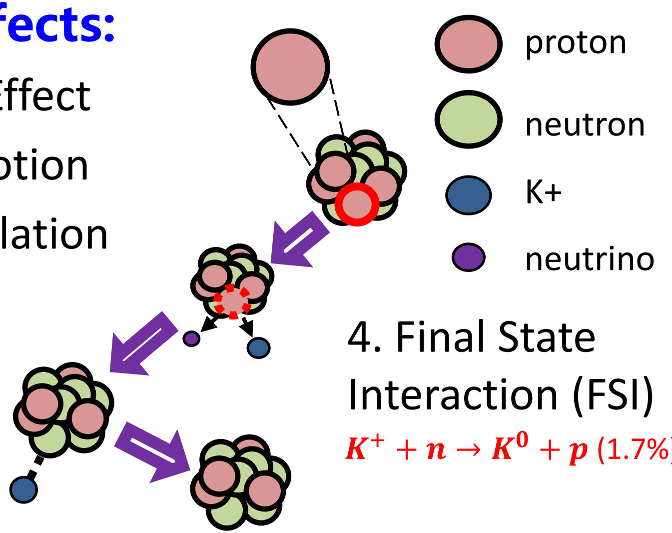
Kinetic energy of K^+

Free proton → 105 MeV
Bound proton: ↓



Nuclear Effects:

1. Binding Effect
2. Fermi Motion
3. *NN* correlation



4. Final State Interaction (FSI)
$K^+ + n \rightarrow K^0 + p$ (1.7%)

5. De-excitation of remaining nuclear: could emit **γ/p/n.**

- **Modify GENIE generator**
- **Implement de-excitation with TALYS**

H. Hu, W.L. Guo et al, PLB 831, 137183(2022)

Signal characters of $p \to \bar{\nu}\, K^{+}$ in JUNO

Triple coincident signals :

Decay mode	Branching ratio (%)	Kinetic energy sum (MeV)
$K^+ \to \mu^+\nu_\mu$	63.55 ± 0.11	152
$K^+ \to \pi^+\pi^0$	20.66 ± 0.08	354
$K^+ \to \pi^+\pi^+\pi^-$	5.59 ± 0.04	75
$K^+ \to \pi^0 e^+\nu_e$	5.07 ± 0.04	265–493
$K^+ \to \pi^0\mu^+\nu_\mu$	3.353 ± 0.034	200–388
$K^+ \to \pi^+\pi^0\pi^0$	1.761 ± 0.022	354

First pulse: K^+ kinetic energy of ~105 MeV, decay at rest 15 cm, 1.2ns

$K^+ \to \upsilon_\mu + \mu^+$

Second pulse: $\mu^+ \to e^+ + \upsilon_e + \bar{\upsilon}_\mu$

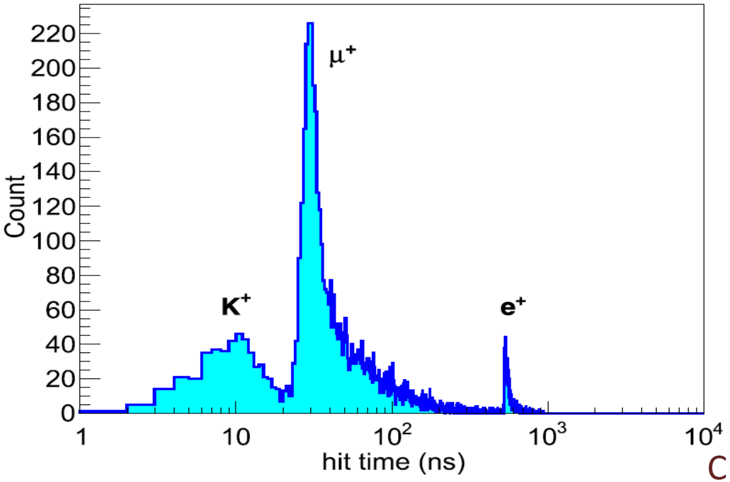
152 MeV (μ^+) or 354 MeV(π^+, π^0)

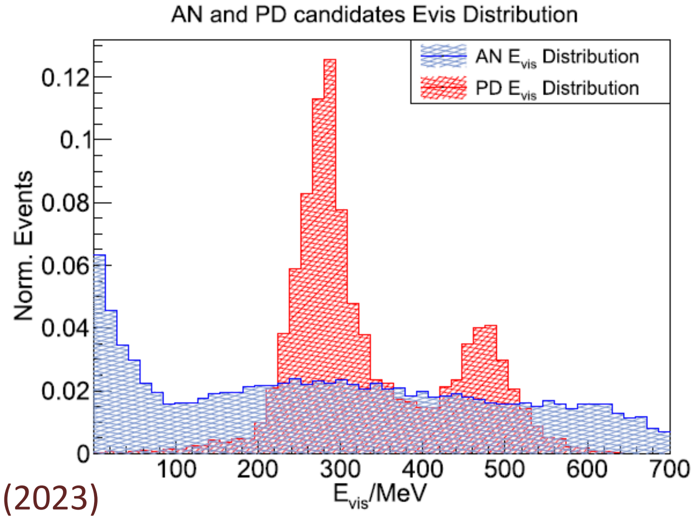
$K^+ \to \pi^+ + \pi^0$

Second pulse: $\pi^0 \xrightarrow{8.4\times10^{-8}\,\text{ns}} 2\gamma$; $\pi^+ \to \upsilon_\mu + \mu^+$

Third pulse: Michel e^+

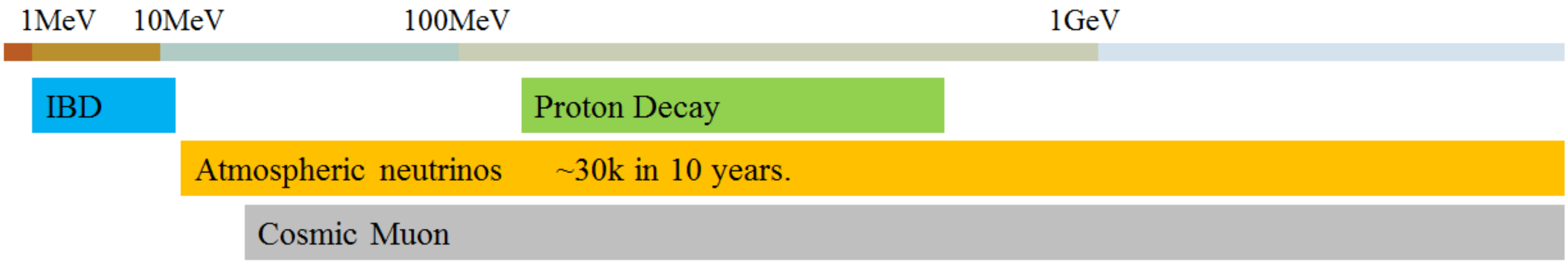
$\mu^+ \to e^+ + \upsilon_e + \bar{\upsilon}_\mu$





CPC 47, 113002 (2023)

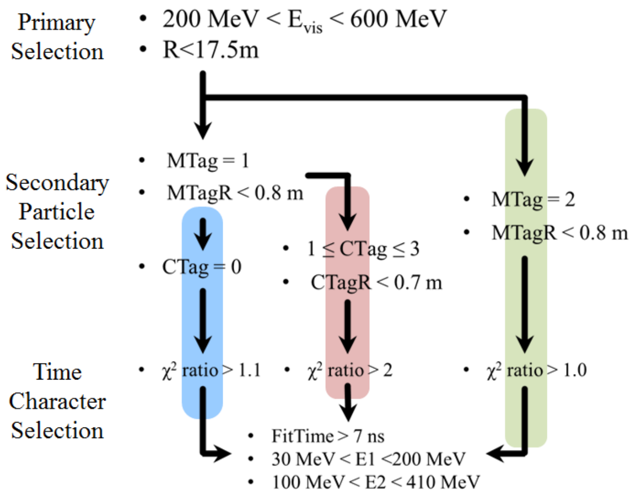
Backgrounds

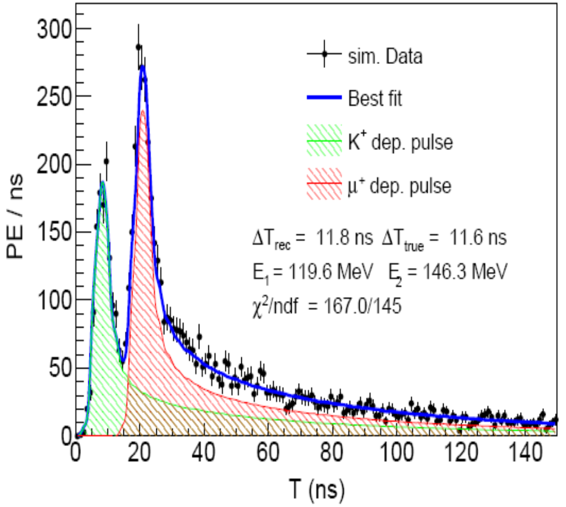


Type	Ratio (%)	Ratio with E_{vis} in [100 MeV, 600 MeV](%)	Interaction	Signal characteristics
NCES	20.2	15.8	$\nu + n \rightarrow \nu + n$ $\nu + p \rightarrow \nu + p$	Single Pulse
CCQE	45.2	64.2	$\bar{\nu}_l + p \rightarrow n + l^+$ $\nu_l + n \rightarrow p + l^-$	Single Pulse
Pion Production	33.5	19.8	$\nu_l + p \rightarrow l^- + p + \pi^+$ $\nu + p \rightarrow \nu + n + \pi^+$	Approximate Single Pulse (Second pulse too low)
Kaon Production	1.1	0.2	$\nu_l + n \rightarrow l^- + \Lambda + K^+$ $\nu_l + p \rightarrow l^- + p + K^+$	Double Pulse

- **If energetic neutrons do not lost most of the energy within ~10ns**
- **Kaon Production has a negligible contribution!**

Event Selection





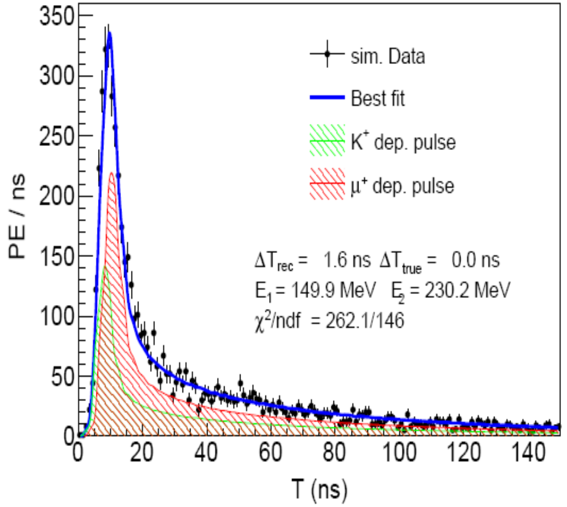


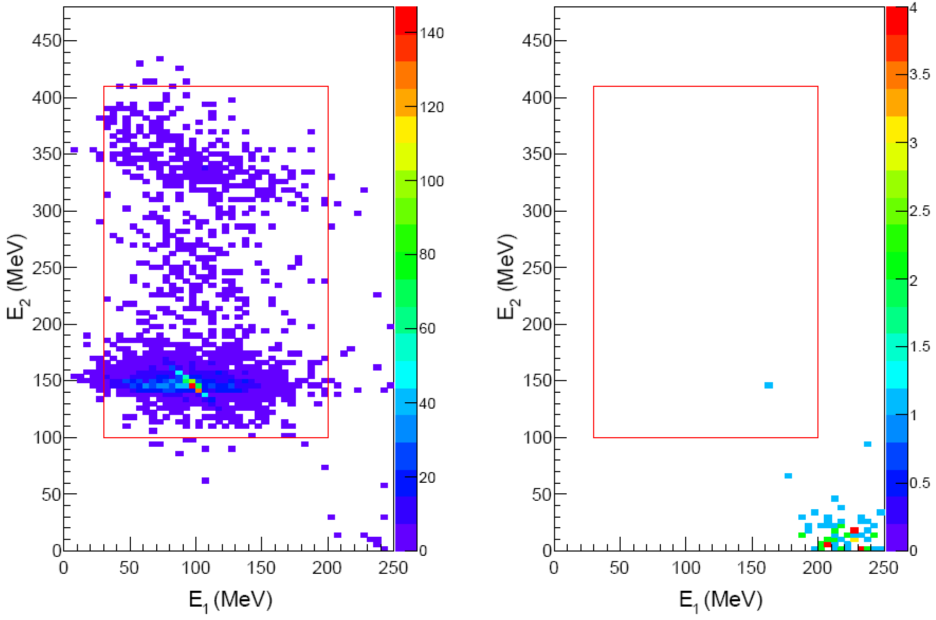
TABLE II. Detection efficiencies of $p \to \bar{\nu}K^+$ and the number of atmospheric ν background after each selection criterion. The total amount of atmospheric ν background simulated is 160 k, which corresponds to an exposure of 890 kton-years.

Criteria		Survival rate of $p \to \bar{\nu}K^+$ (%)			Survival count (fraction) of atmospheric ν		
		Sample 1	Sample 2	Sample 3	Sample 1	Sample 2	Sample 3
basic selection	E_{vis}	94.6			51299 (32.1%)		
	R_V	93.7			47849 (29.9%)		
Delayed signal selection	N_M	74.4		4.4	20739 (13.0%)		1143 (0.7%)
	ΔL_M	67.0		4.4	13796 (8.6%)		994 (0.6%)
	N_n	48.4	17.9	–	5403 (3.4%)	6857 (4.3%)	–
	ΔL_n	–	16.6	–	–	4472 (2.8%)	–
Time character selection	R_χ	45.9	9.0	3.8	4326 (2.7%)	581 (0.4%)	716 (0.4%)
	ΔT	28.3	7.7	2.4	121 (0.07%)	18 (0.01%)	30 (0.02%)
	E_1, E_2	27.4	7.3	2.2	1 (0.0006%)	0	0
Total		36.9			1		

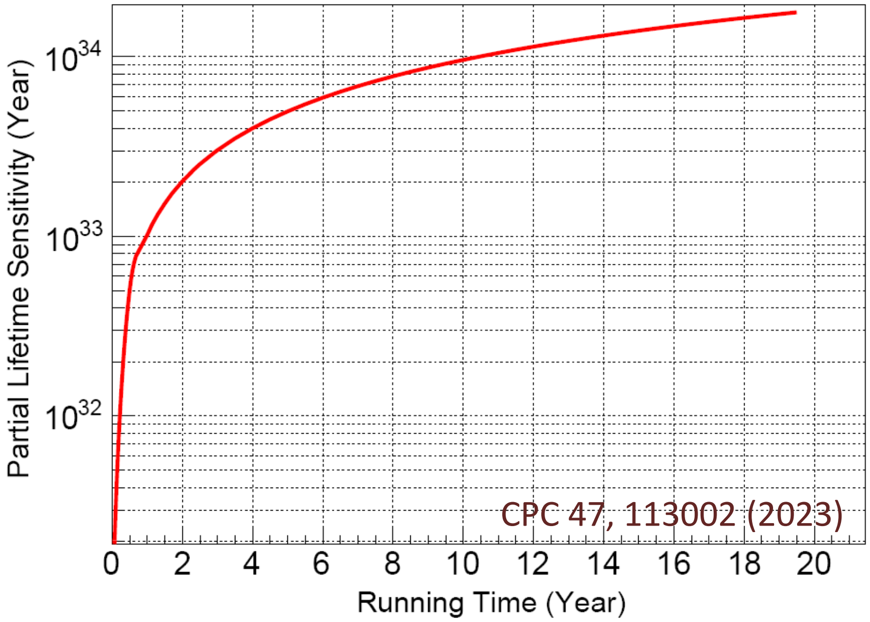
Efficiency uncertainties:

Source	Uncertainty
Statistic	1.6%
Position reconstruction	1.7%
Nuclear model	6.8%
Energy deposition model	11.1%
Total	13.2%

Sensitivity to $p \to \overline{\nu}\, K^+$



(a) $p \to \bar{\nu} K^+$ (b) atmospheric ν



Background： 0.2/10years

Efficiency： 36.9%

$$\tau/B(p \to \overline{\nu}\, K^+) > 0.96 \times 10^{34}\ \mathrm{yrs}$$

$$n \to \mu^- K^+,\quad p \to e^+ K^*(892)^0,\quad n \to \nu K^*(892)^0,\quad \text{and}\quad p \to \nu K^*(892)^+$$

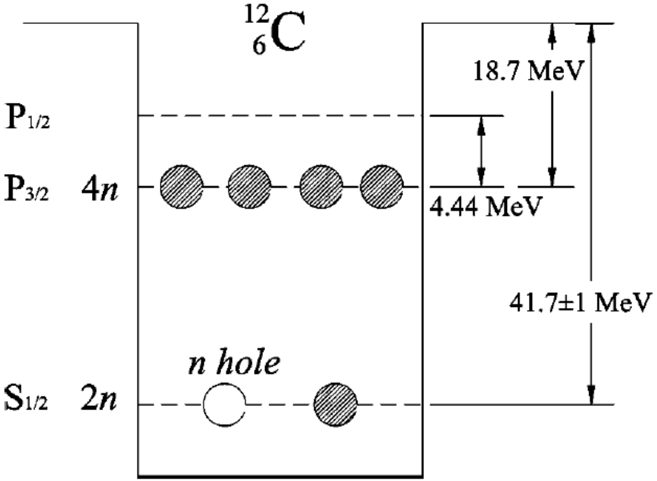
Neutron invisible decays in JUNO

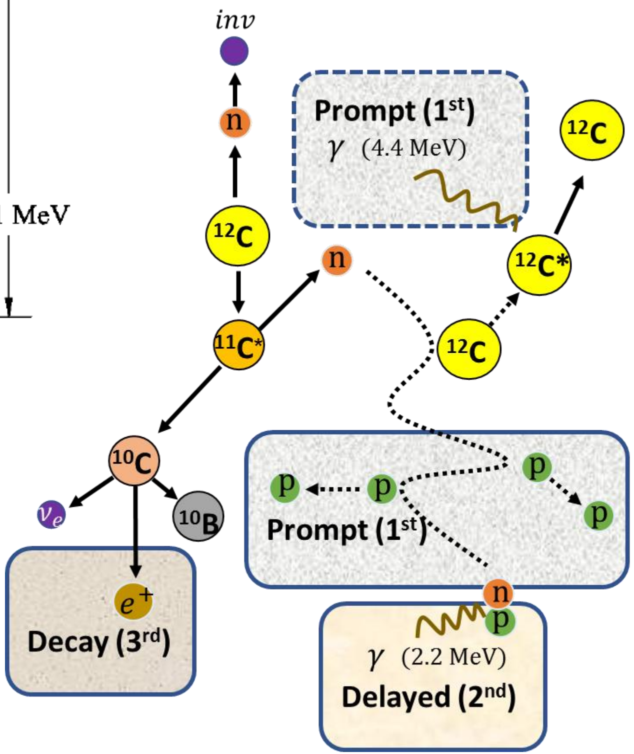
Bounded neutrons in ^{12}C :

- $n \rightarrow inv$ ($^{12}C \rightarrow {}^{11}C^*$)
- $nn \rightarrow inv$ ($^{12}C \rightarrow {}^{10}C^*$)

Invisible particle:
neutrinos, NP particles

Detect de-excitation products of $^{11}C^*$ and $^{10}C^*$





Triple coincident signals :

		Half-life Q value
$^{11}C^* \rightarrow n + {}^{10}C$	$(Br_{n1} = 3.0\%)$	[19.3 s, 3.65 MeV]
$^{11}C^* \rightarrow n + \gamma + {}^{10}C$	$(Br_{n2} = 2.8\%)$	[19.3 s, 3.65 MeV]
$^{10}C^* \rightarrow n + {}^{9}C$	$(Br_{nn1} = 6.2\%)$	[0.13 s, 16.5 MeV]
$^{10}C^* \rightarrow n + p + {}^{8}B$	$(Br_{nn2} = 6.0\%)$	[0.77 s, 18.0 MeV]

Y. Kamyshkov and E. Kolbe, PRD 67, 076007 (2003)

Background sources

Five background sources:

1. Reactor neutrinos; 2. Natural radioactivity; 3. Long-lived isotopes;
4. Fast neutrons; 5. Atmospheric neutrinos

Background combinations:

- **Single signal**
  - *Natural radioactivity*
  - *Long-lived isotopes*

  → *Single+Single+Single*

- **Double signal**
  - *IBD from reactor neutrinos*
  - *He8/Li9 from long-lived isotopes*
  - *Fast neutrons*
  - *Alpha-N from radioactivity*
  - *Atmospheric neutrino NC*

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + n + p + {}^{10}\mathrm{B}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + n + p + \alpha + {}^{6}\mathrm{Li}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + n + 2p + {}^{9}\mathrm{Be}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + n + p + d + {}^{8}\mathrm{Be}\,.$$

Double+Single

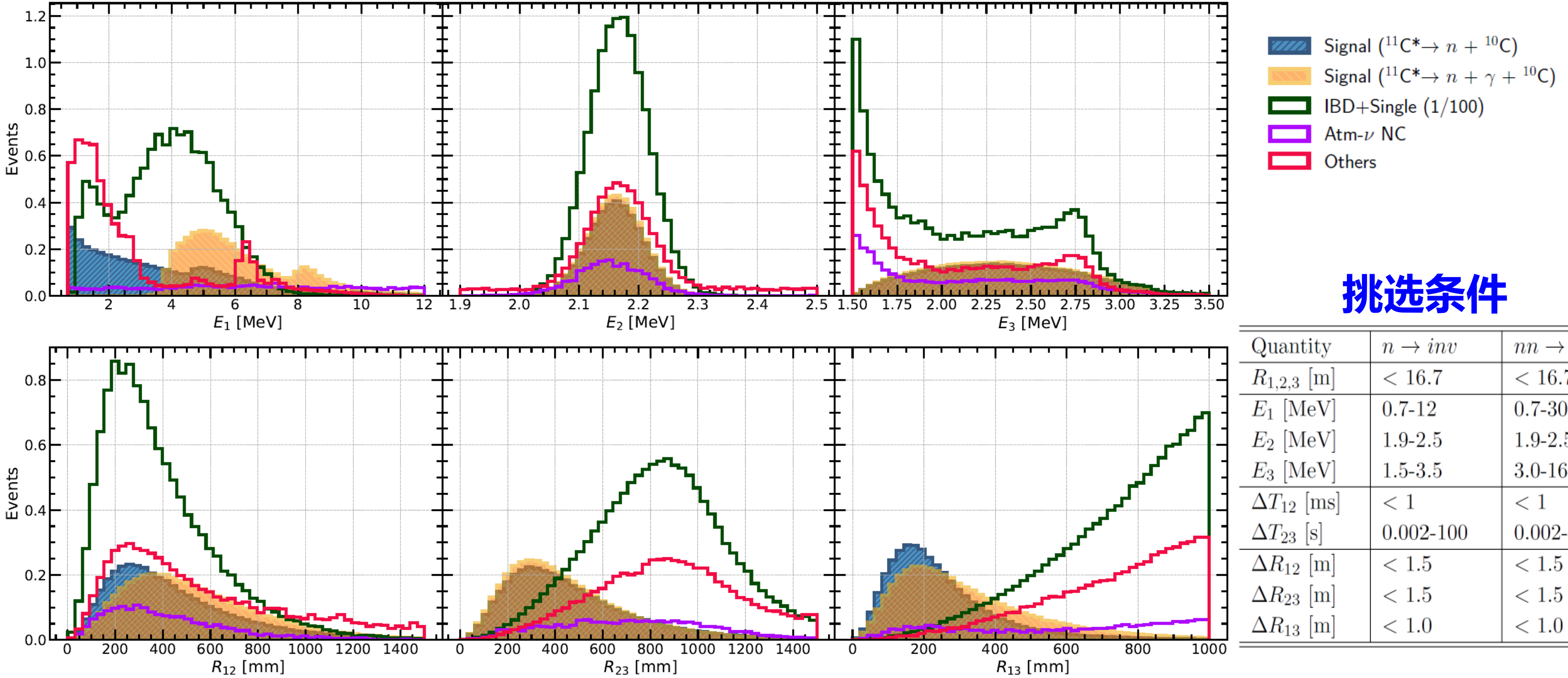
- **Triple signal**
  - *Atmospheric neutrino NC*

$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + n + {}^{11}\mathrm{C}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + 2n + {}^{10}\mathrm{C}\,,$$
$$\nu/\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \nu/\bar{\nu} + 3p + n + {}^{8}\mathrm{Li}\,,$$

→ *Triple*

Signal vs backgrounds

Dominant BKGs of $n \to inv$: *IBD + Singles (1235), Atm-ν NC (3.0) per 10 years*

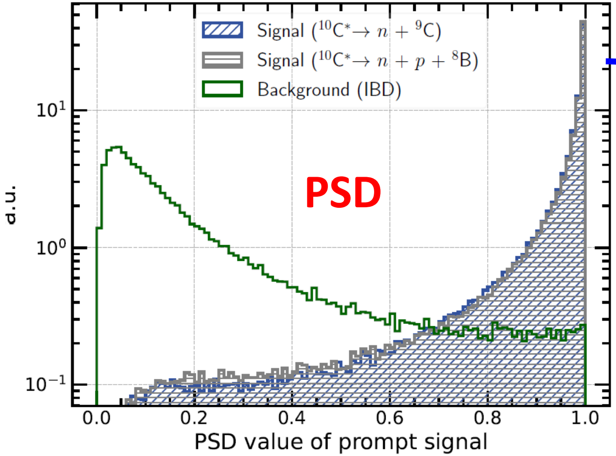


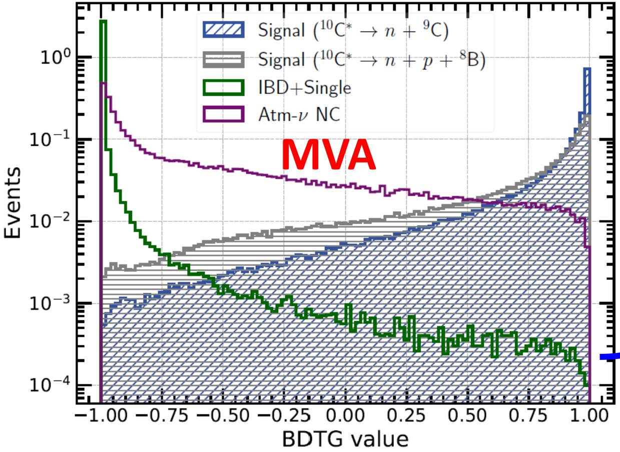
挑选条件

Quantity	$n \to inv$	$nn \to inv$
$R_{1,2,3}$ [m]	< 16.7	< 16.7
E_1 [MeV]	0.7-12	0.7-30
E_2 [MeV]	1.9-2.5	1.9-2.5
E_3 [MeV]	1.5-3.5	3.0-16.0
ΔT_{12} [ms]	< 1	< 1
ΔT_{23} [s]	0.002-100	0.002-3.0
ΔR_{12} [m]	< 1.5	< 1.5
ΔR_{23} [m]	< 1.5	< 1.5
ΔR_{13} [m]	< 1.0	< 1.0

Dominant BKGs of $nn \to inv$: *IBD + Singles (3.0), Atm-ν NC (4.3) per 10 years*

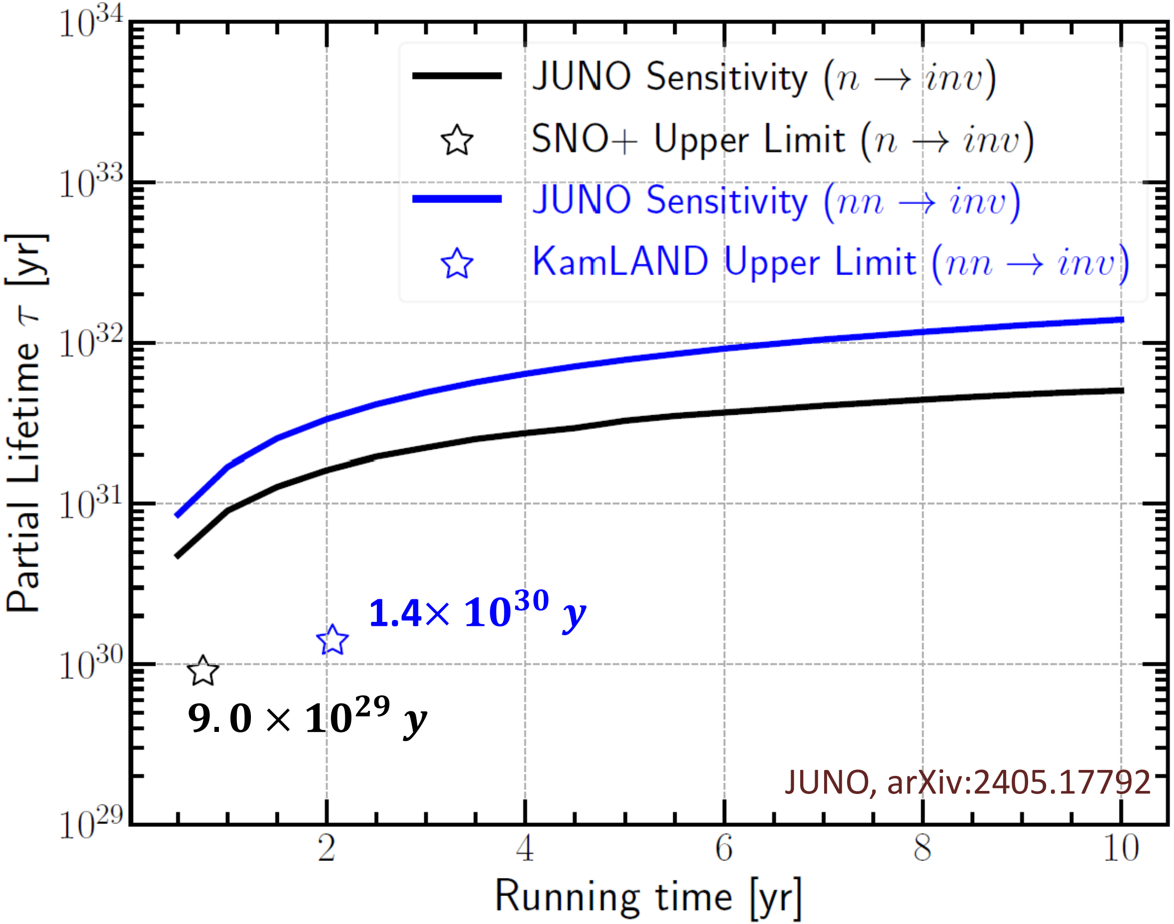
Summary of Backgrounds and Signal efficiency





Backgrounds (10 years)	$n \to inv$		$nn \to inv$	
	Basic selection	PSD + MVA	Basic selection	PSD + MVA
IBD + Single	1235 ± 50	2.72 ± 0.10	3.01 ± 0.09	0.0110 ± 0.0003
Atm-ν NC	3.0 ± 1.1	0.93 ± 0.67	4.3 ± 3.5	0.55 ± 0.63
$^{13}C(\alpha,n)^{16}O$ + Single	3.4 ± 1.4	0.036 ± 0.013	–	–
$^9Li/^8He$ + Single	1.55 ± 0.39	0.29 ± 0.17	0.13 ± 0.13	0.13 ± 0.13
Accidental	1.46 ± 0.05	0.095 ± 0.004	–	–
Total	1244 ± 50	4.07 ± 0.68	7.4 ± 3.5	0.69 ± 0.64
Signal efficiency (%)	$n \to inv$		$nn \to inv$	
	Basic selection	PSD + MVA	Basic selection	PSD + MVA
$\epsilon_{n(nn)1}$	35.6 ± 0.2	23.5 ± 0.2	54.0 ± 0.3	48.2 ± 0.3
$\epsilon_{n(nn)2}$	43.6 ± 0.3	30.3 ± 0.3	49.2 ± 0.3	36.3 ± 0.3

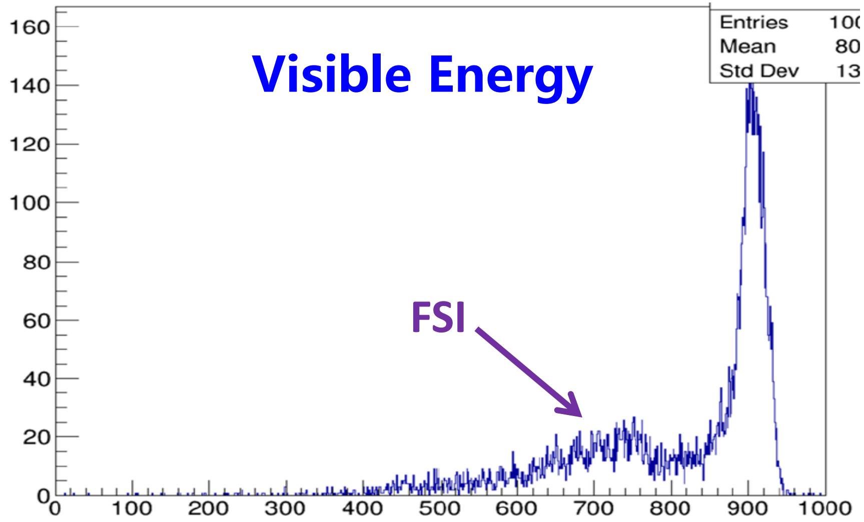
JUNO sensitivity

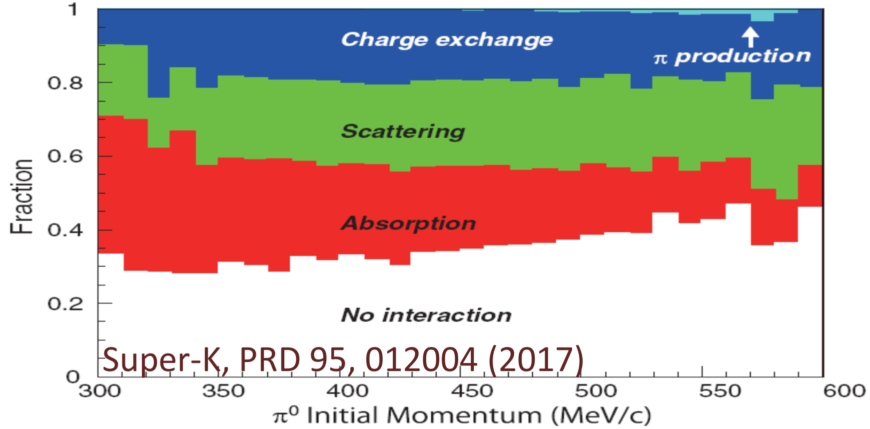


1.4×10^{32} y

5.0×10^{31} y

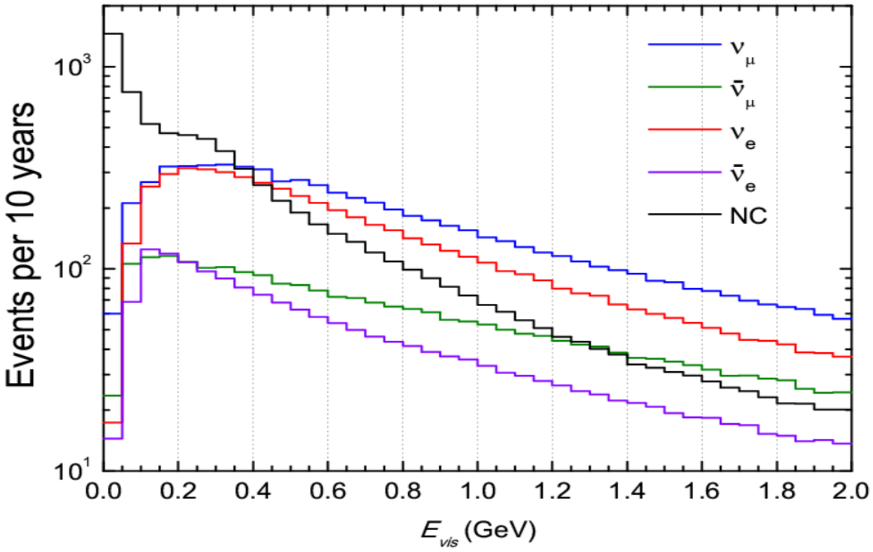
Search for $p \rightarrow e^{+} + \pi^{0}$ in JUNO





Super-K, PRD 95, 012004 (2017)

Atmospheric ν backgrounds:



10 years:

0.05-1GeV→ **18114**

(CC:11714; NC:6400)

Sensitivity estimation for $p \rightarrow e^{+} + \pi^{0}$

Event Selection: 860 MeV < Evis < 940 MeV; no Michel; no neutron capture

➡ **Signal Efficiency :** 50.9%; **Background:** **97.8**/10years

$\tau/B(p \rightarrow e^{+}\pi^{0}) > 0.19 \times 10^{34}$ yrs ($\ll 2.4 \times 10^{34}$ yrs from Super-K)

How to estimate sensitivity?

$$N_{S_i} = N_{decay} \cdot B_i \cdot \epsilon_i = B_i \cdot \epsilon_i \cdot N_0 \frac{t}{\tau} \rightarrow \frac{\tau}{B_i} = \frac{N_0 \cdot \epsilon_i}{N_{90}} t$$

- N_{S_i}: Signal number
- N_0: Nucleon number $= 6.75 \times 10^{33}$
- ϵ_i : Signal Efficiency $= 50.9\%$
- t : Running Time $= 10$ years
- N_{90}: 90% CL upper limit $= 17.7$
- N_B: Expected BG number $=97.8$

90% CL upper limit N_{90}:

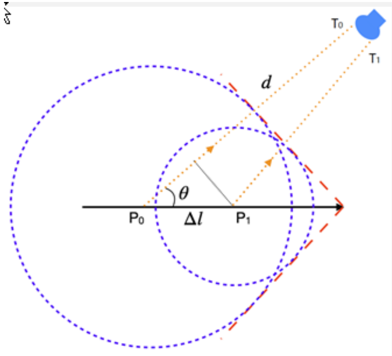
$$L(N_{obs}, N_S) = \frac{(N_S + N_B)^{N_{obs}}}{N_{obs}\,!} e^{-(N_S+N_B)} \rightarrow 90\% = \frac{\int_0^{N_{90}} L(N_{obs}, N_S) dN_S}{\int_0^{\infty} L(N_{obs}, N_S) dN_S}$$

$N_{obs} = N_B$	0.0	1.0	2.0	5.0	10	20	50	100	200	1000
N_{90}	2.3	3.3	3.9	5.2	6.6	8.8	13.0	17.8	24.6	53.3

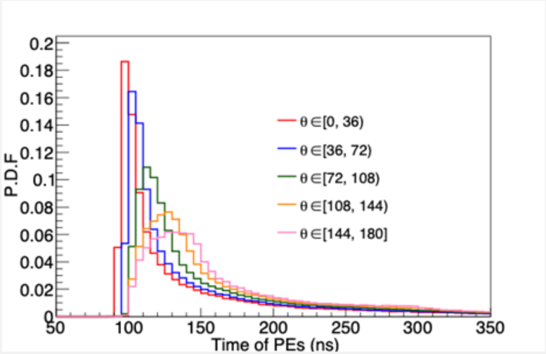
BKG number is the key quantity!!! → How to suppress BKG?

How to suppress BKG ? → Momentum information

ν directional information reflects in each PMT waveform



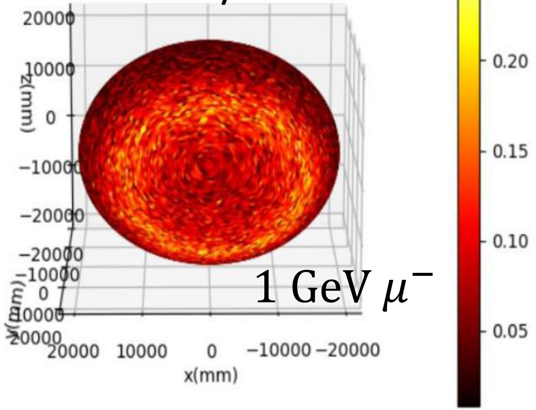
$$\frac{\Delta l}{\Delta t} \propto \frac{1}{|1-n\beta\cos\theta|}$$

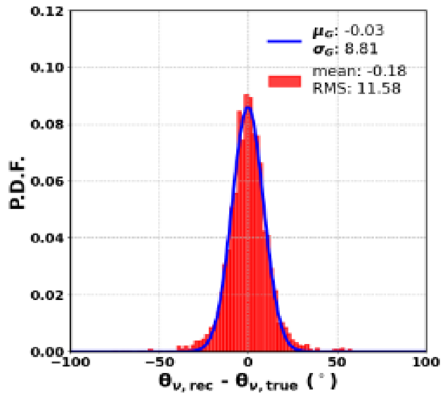


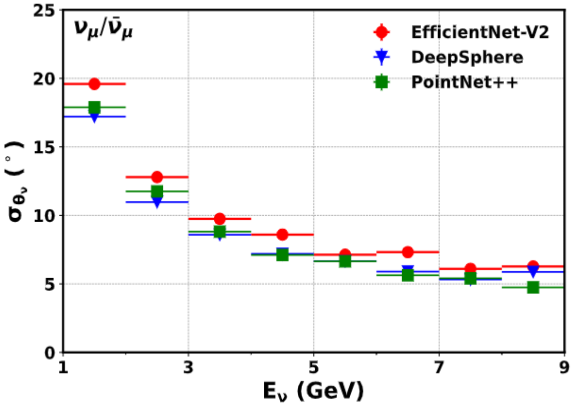
Distribution of the number of photoelectrons (PEs) over time for PMTs with different angles θ to the particle track

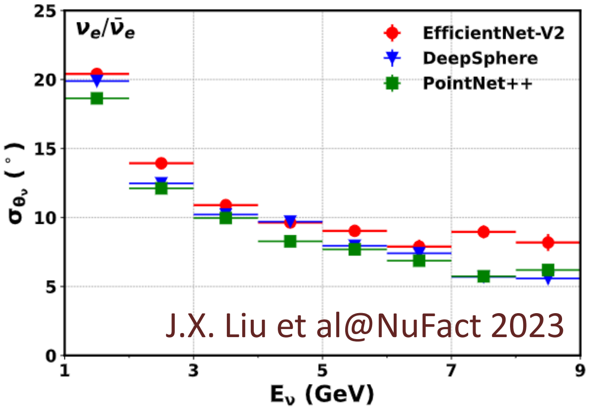
Cerenkov-like Ring:

First 4ns PEs/total PEs









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Simply estimate JUNO sensitivities to other channels (1)

Y.J. Niu et al

Antilepton+ Meson									
ID	Channels	n_b	n_{90}	$\epsilon(\%)$	$\tau_{10}(10^{33}yrs)$	$\tau_3(10^{33}yrs)$	$\tau_{exp}(10^{33}yrs)$	TECN	Rank
1	$p\to e^+\pi^0$	97.8	17.7	50.9	1.9	1	24	SKAM(20)	E
*1	$n\to e^+\pi^-$	1943.0	73.9	83.44	0.578	0.312	5.3	SKAM(17D)	E
2	$p\to \mu^+\pi^0$	152.6	21.7	54.68	1.6	0.9	16	SKAM(20)	E
*2	$n\to \mu^+\pi^-$	2101.3	76.8	85.14	0.568	0.306	3.5	SKAM(17D)	E
3	$p\to \overline{\nu}\pi^+$	7172.09,3405.55	162.8	91.24	0.366	0.199	0.39	SKAM(14E)	D
*3	$n\to \overline{\nu}\pi^0$	2668.9	86.3	59.06	0.351	0.189	1.1	SKAM(14E)	E
4	$p\to e^+\eta$	97.8	17.7	30.62	1.1	0.56	10	SKAM(17D)	E
5	$p\to \mu^+\eta$	134.1	20.4	30.62	1	0.5	4.7	SKAM(17D)	E
6	$n\to \overline{\nu}\eta$	336.1	37.8	31.42	0.528	0.2657	0.158	IMB3(99)	B
7	$p\to e^+\rho^0$	4398.9	110.4	91.11	0.5384	0.2918	0.72	SKAM(17D)	D
*7	$n\to e^+\rho^-$	2067.5	76.1	83.75	0.564	0.304	0.217	IMB3(99)	B
8	$p\to \mu^+\rho^0$	3067.4	92.4	93.48	0.6600	0.3566	0.57	SKAM(17D)	C
*8	$n\to \mu^+\rho^-$	2323.6	80.6	87.71	0.557	0.301	0.228	IMB3(99)	B
9	$p\to \overline{\nu}\rho^+$	1657.6,1394.7,102.8	81.8	70.17	0.559	0.300	0.162	IMB3(99)	B
*9	$n\to \overline{\nu}\rho^0$	214.1	25.5	41	0.8237	0.432	0.019	IMB(88)	A
10	$p\to e^+\omega$	1:1024.2,97.8 2:4398.9	106.1	30.61	0.1947	0.1052	1.6	SKAM(17D)	E
11	$p\to \mu^+\omega$	1:116.2, 118.7 2:3067.4	45.5	30.44	0.4425	0.2303	2.8	SKAM(17D)	E
12	$n\to \overline{\nu}\omega$	1: 640 2:4398.9	92.2	28.23	0.1623	0.087	0.108	IMB3(99)	C

Three and more leptons									
ID	Channels	n_{bkg}	n_{90}	$\epsilon(\%)$	$\tau_{10}(10^{33}yrs)$	$\tau_3(10^{33}yrs)$	$\tau_{exp}(10^{33}yrs)$	TECN	Rank
49	$p\to e^+e^+e^-$	97.8	17.7	77.78	2.9	1.5	34	SKAM(20)	E
50	$p\to e^+\mu^+\mu^-$	24.5	9.6	79.24	5.38	2.58	9.2	SKAM(20)	D
51	$p\to e^+\overline{\nu}\nu$	2460.1	83	90.83	0.714	0.386	0.17	SKAM(14)	B
52	$n\to e^+e^-\overline{\nu}$	1255.7	59.7	88.39	0.758	0.408	0.257	IMB3(99)	B
53	$n\to \mu^+e^-\overline{\nu}$	1256.7	59.7	90.75	0.779	0.419	0.083	IMB3(99)	A
54	$n\to \mu^+\mu^-\overline{\nu}$	115.4	19.1	89.37	2.397	1.237	0.079	IMB3(99)	A
55	$n\to \mu^+e^+e^-$	133.9	20.4	83.3	2.1	1.1	23	SKAM(20)	E
56	$n\to \mu^+\mu^+\mu^-$	0.0	2.4	83.15	17.7	5.3	10	SKAM(20)	A
57	$p\to \mu^+\overline{\nu}\nu$	983.1	52.9	82.33	1.015	0.544	0.22	SKAM(20)	B
58	$p\to e^-\mu^+\mu^+$	23.1	9.29	68.43	4.8	2.3	11	SKAM(20)	D

Only use:

1. Energy
2. Michel $e^{\pm}$
3. n capture
4. Assumption

VS Super-K?

Simply estimate JUNO sensitivities to other channels (2)

Antilepton+Mesons									
ID	Channels	n_{bkg}	n_90	$\epsilon(\%)$	$\tau_{10}(10^{33}yrs)$	$\tau_3(10^{33}yrs)$	$\tau_{exp}(10^{33}yrs)$	TECN	Rank
23	$p \to e^+\pi^+\pi^-$	4398.9	110.4	91.11	0.5384	0.2918	0.082	IMB3(99)	A
24	$p \to e^+\pi^0\pi^0$	214.1	25.5	41	1.049	0.550	0.147	IMB3(99)	A
25	$n \to e^+\pi^-\pi^0$	2067.5	76.1	83.75	0.564	0.304	0.052	IMB3(99)	A
26	$p \to \mu^+\pi^+\pi^-$	3067.4	92.4	93.48	0.6600	0.3566	0.133	IMB3(99)	B
27	$p \to \mu^+\pi^0\pi^0$	3591.5	99.9	93.84	0.613	0.332	0.101	IMB3(99)	A
28	$n \to \mu^+\pi^-\pi^0$	2323.6	80.6	87.71	0.557	0.301	0.074	IMB3(99)	A
29	$n \to e^+\pi^-K^0$	2932.3,460.2	96	96.71	0.516	0.279	0.018	IMB3(91)	A
Lepton+Meson									
ID	Channels	n_{bkg}	n_{90}	$\epsilon(\%)$	$\tau_{10}(10^{33}yrs)$	$\tau_3(10^{33}yrs)$	$\tau_{exp}(10^{33}yrs)$	TECN	Rank
30	$n \to e^-\pi^+$	1070.4,818.8,163.2	66	80.13	0.622	0.333	0.065	FREJ(88)	A
31	$n \to \mu^-\pi^+$	1308.9,118,219	40	79.98	1.024	0.534	0.049	IMB(88)	A
32	$n \to e^-\rho^+$	1657.6,1394.7,102.8	81.8	70.17	0.439	0.236	0.062	IMB(88)	A
33	$n \to \mu^-\rho^+$	1899.5,192.398,197.6	42.6	74.56	0.897	0.472	0.007	IMB(88)	A
34	$n \to \mu^-K^+$	257.7,132.0	33	59.54	0.924	0.583	0.032	FREJ(91B)	A
35	$n \to \mu^-K^+$	42.6,27.7	14.5	58.95	2.083	1.053	0.057	FREJ(91B)	A
Lepton+Mesons									
ID	Channels	n_{bkg}	n_{90}	$\epsilon(\%)$	$\tau_{10}(10^{33}yrs)$	$\tau_3(10^{33}yrs)$	$\tau_{exp}(10^{33}yrs)$	TECN	Rank
36	$p \to e^-\pi^+\pi^+$	534.7,46.6,76.6	27.2	41.06	0.985	0.502	0.03	FREJ(91B)	A
37	$n \to e^-\pi^+\pi^0$	1657.6,1394.7,102.8	81.8	70.17	0.439	0.236	0.029	FREJ(91B)	A
38	$p \to \mu^-\pi^+\pi^+$	79.4,0.6,53.6	7.5	54.06	4.702	1.763	0.017	FREJ(91B)	A
39	$n \to \mu^-\pi^+\pi^0$	1899.5,192.398,197.6	42.6	74.56	0.897	0.472	0.034	FREJ(91B)	A
40	$p \to e^-\pi^+K^+$	32.9,314.8,581.3	19.2	57.54	1.955	0.963	0.075	IMB3(99)	A
41	$p \to \mu^-\pi^+K^+$	0.1,89.3,0.5	3.2	63.48	12.942	4.284	0.245	IMB3(99)	A
Antilepton+Photon(s)									
ID	Channels	n_{bkg}	n_{90}	$\epsilon(\%)$	$\tau_{10}(10^{33}yrs)$	$\tau_3(10^{33}yrs)$	$\tau_{exp}(10^{33}yrs)$	TECN	Rank
42	$p \to e^+\gamma$	97.8	17.7	75.88	2.8	1.442	0.67	IMB3(99)	A
43	$p \to \mu^+\gamma$	100.1	17.9	77.83	2.8366	1.4647	0.478	IMB3(99)	A
44	$n \to \overline{\nu}\gamma$	1011.0	53.7	86.69	0.827	0.444	0.55	SKAM(15)	C
45	$p \to e^+\gamma\gamma$	97.8	17.7	76.04	2.8	1.44	0.1	FREJ(91)	A
46	$n \to \overline{\nu}\gamma\gamma$	1552.3	66.2	88.83	0.987	0.370	0.219	IMB3(99)	B

A: Its result is much better than the best limit so far, if we get 3 years' events, we can come out on top.In this rank, τ_3 is at least 3 times bigger than τ_{exp}.
B: In this rank, τ_3 is bigger than τ_{exp}.And this channel is worthwhile studying more.
C: We have a better result than before for 10 years' data, but $\tau_3 < \tau_{exp}$.
D: $\tau_{10} < \tau_{exp}$, The disparity between our outcome and theirs is a litte big. We can do more but may do in vain.
E:There is a big tap comparing to current limit τ_{exp}, we would better give up it.
OPEN:There is a better method to take event selection or the result is not very reliable.

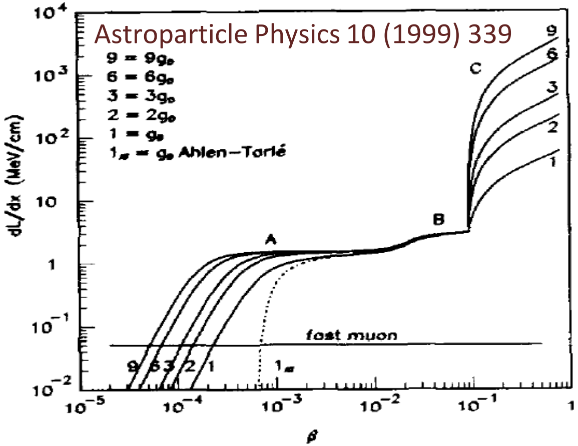
(4) 寻找其他相关的新物理

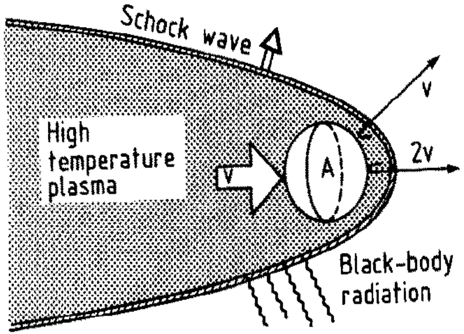
4.1 GUT magnetic monopole

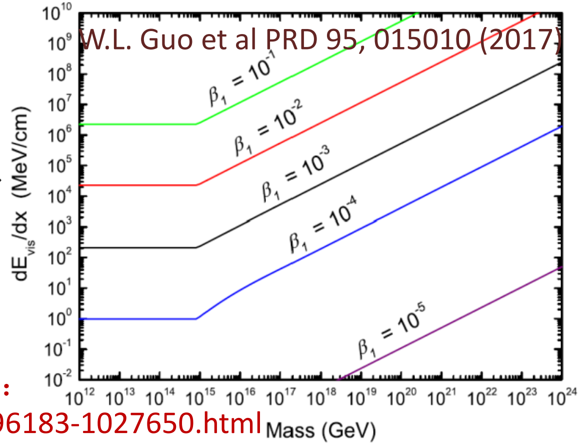
大统一理论预言磁单极子的存在：

- GUT monopoles can be produced in the very early Universe
- Mass: $M_M \sim 10^{16} - 10^{18}$ GeV; Velocity: $\boldsymbol{\beta \sim 10^{-3}}$; Charge : $g = n\, g_D$

磁单极子穿过JUNO会产生闪烁光： **奇异夸克物质（SQM）能产生类似的信号：**







寻找《三体》中的“水滴”杀手：
https://blog.sciencenet.cn/blog-296183-1027650.html

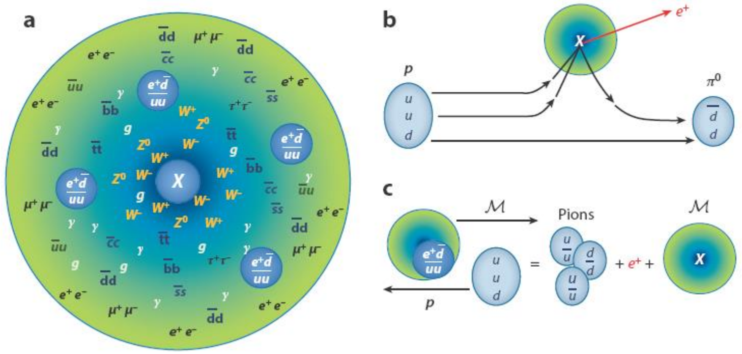
Continuous trigger events in a line with the same energy for long time in JUNO LS!!!

- SQM is a hypothetical strongly interacting matter composed of roughly equal numbers of u, d, s quarks and a small amount of electrons; **Absolutely stable;** $\boldsymbol{\rho_N = 3.6 \times 10^{14} g/cm^3}$
- A > $\mathbf{10^7}$ **Nuclearites (奇异核素),** typical $\boldsymbol{\beta \sim 10^{-3}}$ (galaxy velocity)

4.2 Proton decays catalyzed by GUT monopoles

大统一理论中预言磁单极子的存在:

- **Rubakov-Callen effect,** GUT model dependent
- Catalysis σ_R is the order of **strong interaction**



直接探测磁单极子:

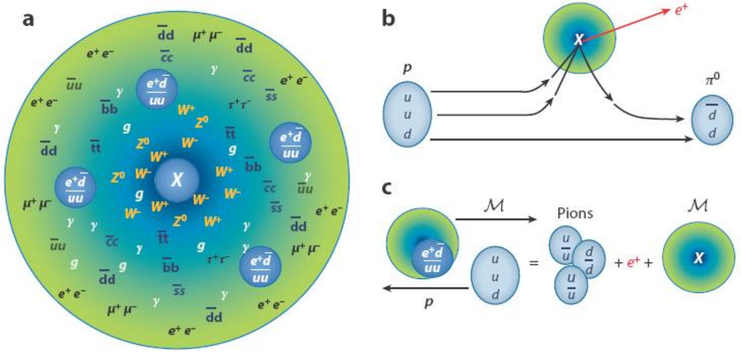
速度~10^{-3}

想象一下磁单极子穿过JUNO会产生什么样的信号?

4.2 Proton decays catalyzed by GUT monopoles

大统一理论中预言磁单极子的存在:

- **Rubakov-Callen effect,** GUT model dependent
- Catalysis σ_R is the order of **strong interaction**



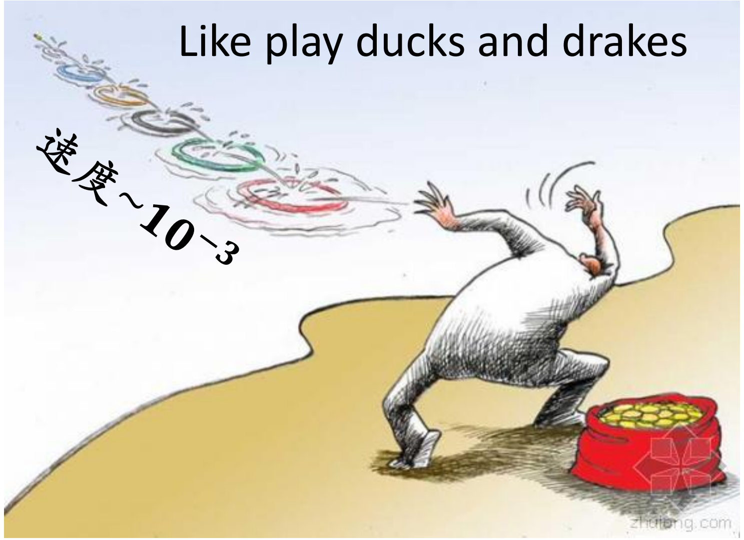
间接探测磁单极子:

宇宙中的磁单极在穿越太阳时会损失能量，进而被捕获并集中在其中心，催化质子衰变
→ 可以有多种末态，只有ν可以到达地球!

$$M + p \to M + \mu^+ + K^0,\ K^0 + p \to K^+ + n,$$
$$K^+ \to \mu^+ + \nu_\mu (236\ \mathrm{MeV})$$

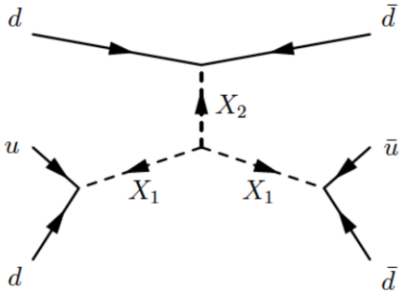
H.Hu, W.L. Guo et al, JCAP 06 (2022) 003

直接探测磁单极子:

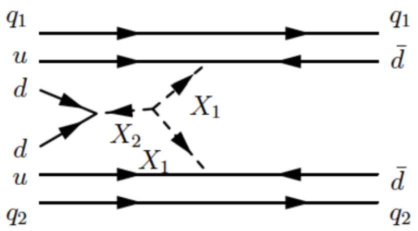


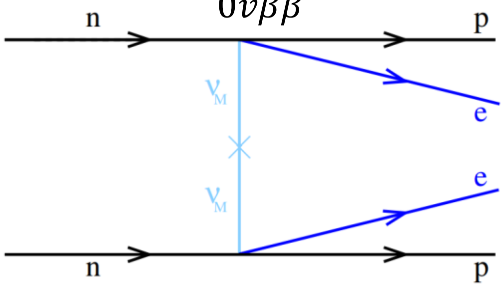
Discrete trigger events in a line with the same energy for long time in JUNO LS!!!

nnbar oscillation
(free neutron or inside nucleus)



dinucleon decay





$\Delta B = 0, \Delta L = 2$

$n-\bar{n}$ oscillation searches:

- free neutrons
  - neutron sources
- bound neutrons
  - v experiments

$\bar{n} + N$ annihilation → ~ 2 GeV

ID	Channel	ID	Channel
1	$p+\bar{n}\to\pi^++\pi^0$	9	$n+\bar{n}\to 2\pi^0$
2	$p+\bar{n}\to\pi^++2\pi^0$	10	$n+\bar{n}\to\pi^++\pi^-+\pi^0$
3	$p+\bar{n}\to\pi^++3\pi^0$	11	$n+\bar{n}\to\pi^++\pi^-+2\pi^0$
4	$p+\bar{n}\to 2\pi^++\pi^-+\pi^0$	12	$n+\bar{n}\to\pi^++\pi^-+3\pi^0$
5	$p+\bar{n}\to 2\pi^++\pi^-+2\pi^0$	13	$n+\bar{n}\to 2\pi^++2\pi^-$
6	$p+\bar{n}\to 2\pi^++\pi^-+2\omega$	14	$n+\bar{n}\to 2\pi^++2\pi^-+\pi^0$
7	$p+\bar{n}\to 3\pi^++2\pi^-+\pi^0$	15	$n+\bar{n}\to\pi^++\pi^-+\omega$
8	$n+\bar{n}\to\pi^++\pi^-$	16	$n+\bar{n}\to 2\pi^++2\pi^-+2\pi^0$

Signal is similar with two nucleon decay case

总结

- ✓ 寻找核子衰变意义重大：宇宙物质-反物质不对称、检验GUTs
- ✓ 第三代核子衰变实验(JUNO, Hyepr-K,DUNE)在几年内将相继运行
- ✓ 未来15年核子衰变的实验限制将得到极大的提升
- ✓ JUNO在一些衰变道是有优势的，值得全面深入研究
- ✓ 3个实验既竞争又互补：不同探测技术、不同靶核(C12,O16,Ar40)


Keep digging new physics !
Thanks for your attention!