Fourth Workshop on

Hadron Physics in China and Opportunities in US

The radiative decays of ϕ mesons in pp collisions

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Introduction

In quark model, ϕ is the lightest quarkonium:

ϕ ($s\bar{s}$) (1020 MeV)

Estimate the strong and EM fields energy:

$$H = \frac{p^2}{2\mu} + V_{strong} + V_{EM}$$

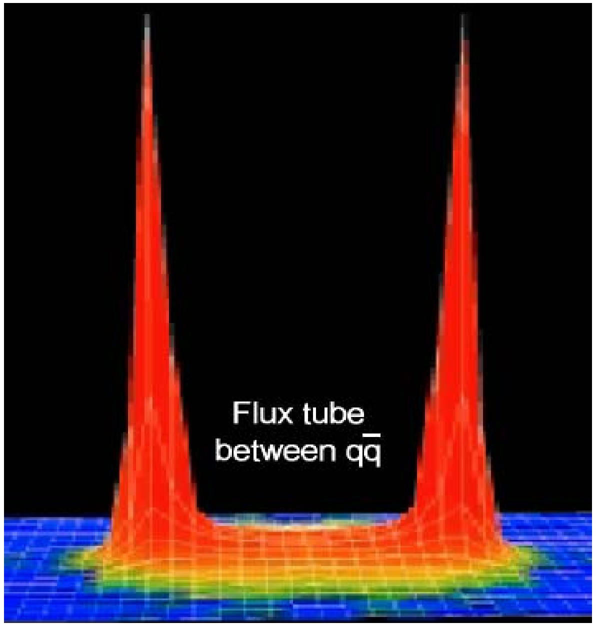
$$V_{strong} = \sigma r - \frac{4}{3}\frac{\alpha_s}{r} + C \qquad V_{EM} = -\frac{\alpha}{r} Q_q^{\,2}$$

$$p \bullet r \approx \hbar \;,\;\; r = 1\text{ fm } (=5\text{ GeV}^{-1}) \;,\;\; p = 0.2\text{ GeV/c}$$

$$\sigma = 0.18\text{ GeV}^2,\;\; \alpha_s \approx 0.5\;,\;\; V_{stong} \approx 770\text{ MeV}$$

$$\mu = m_q m_{\bar{q}} / (m_q + m_{\bar{q}})\;,\; m_s = m_{\bar{s}} = 0.45\text{ GeV/c}^2$$

$$p^2 / 2\mu = 90\text{ MeV} \qquad V_{EM} = -0.16\text{ MeV} \ll V_{strong}$$



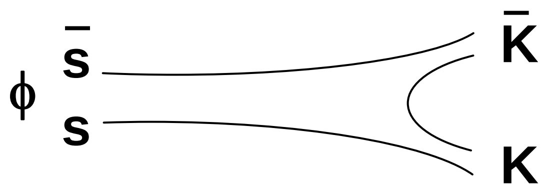
$\phi \rightarrow \eta\,\gamma$ (363 MeV)

$\phi \rightarrow \pi^0\,\gamma$ (501 MeV)

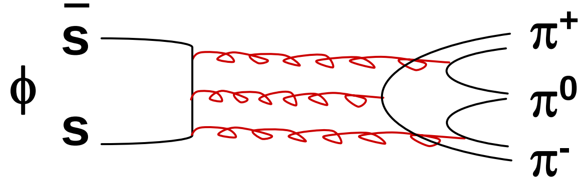
Radiative energy ~ hundreds MeV, which could only come from the strong field.

ϕ meson decay modes

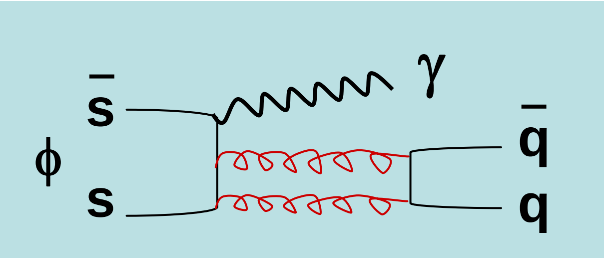
OZI rule plays the role:



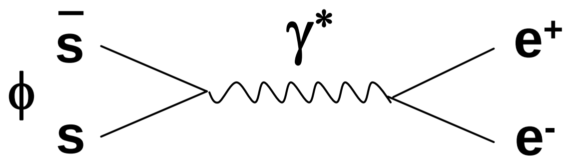
$\phi \rightarrow K\bar{K}$ **(83.1%)**



$\phi \rightarrow ggg \rightarrow \pi^+\pi^-\pi^0 / \rho\pi$ **(15.32%)**



$\phi \rightarrow \gamma gg \rightarrow \gamma M / \gamma M_1 M_2$



$\phi \rightarrow \gamma^* \rightarrow e^+e^- / \mu^+\mu^-$ **(10^{-4})**

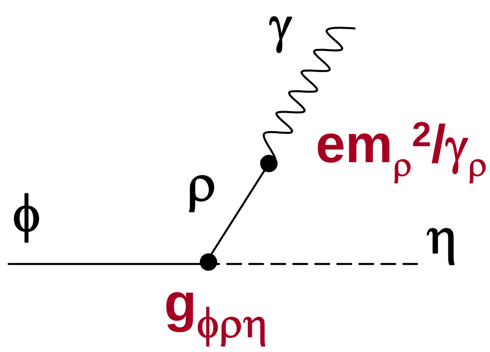
M (10^{-2}-10^{-5}) = η, π^0, **a_0/f_0(980)**, η'**(958)**

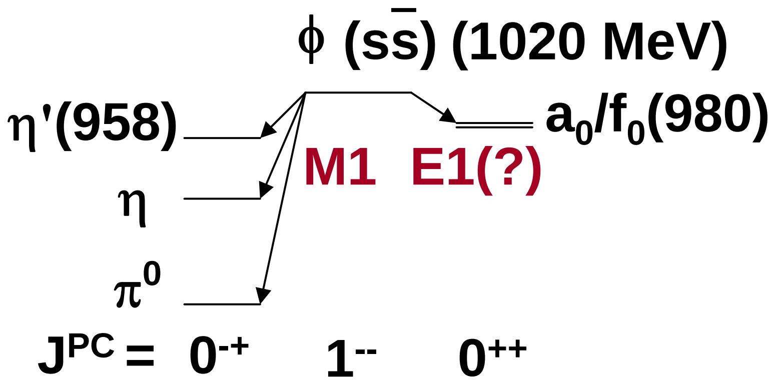
M_1M_2 (10^{-4}-10^{-5}) = $\pi^+\pi^-$, $\pi^0\pi^0$, $\pi^0\eta$

Radiative modes have small branch ratios, but they can decay to most of lightest ones.

Theoretical models

Two theoretical models can calculate the radiative decay widths:





Vector meson dominance

O'Donnell Rev. Mod. Phys. **53**(1981)673

$$\Gamma(V \to e^+e^-) = \frac{4\pi}{3}\frac{\alpha^2}{\gamma_V^2} m_V$$

It is not based on gluons and quarks to understand hadron production and decays.

Quark model

Close et.al. PRD **65**(2002)092003

E1 $$M \sim (E_A - E_B)\int d^3r \psi_B^*(\vec{r})\hat{r}\psi_A(\vec{r})$$

M1 $$M \sim \frac{1}{m_q} E_\gamma \int d^3r \psi_B^*(\vec{r})\psi_A(\vec{r})$$

What about the case when constituents change after decay?

Energy conversion between two fields

Hypothesis: gluon field could be coupled with photon field

$$H = H_0 + H_I$$

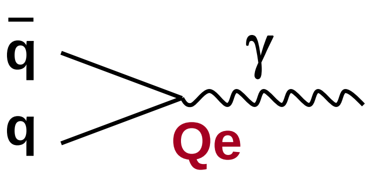
$$H_0 = \frac{\vec{p}^{\,2}}{2\mu} + V_{strong} + V_{EM}$$

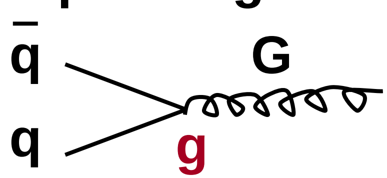
$$H_I = \frac{1}{2\mu}\left\{\left(\vec{p} - \frac{Qe}{c}\vec{A} - \frac{g}{c}\frac{\lambda^a}{2}\vec{B}^a\right)^2 - \vec{p}^{\,2}\right\}$$

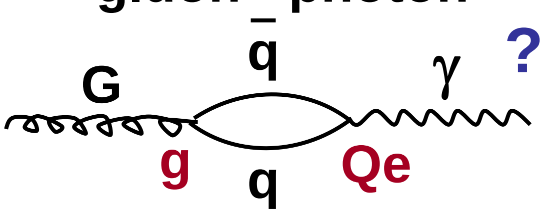
photon gluon

The square items of A, B are not considered here, so only cross-items left.

$$= \frac{1}{2\mu}\left\{ \underbrace{-\frac{Qe}{c}(\vec{p}\bullet\vec{A} + \vec{A}\bullet\vec{p})}_{\text{quark - photon}} \underbrace{- \frac{g}{c}\frac{\lambda^a}{2}(\vec{p}\bullet\vec{B}^a + \vec{B}^a\bullet\vec{p})}_{\text{quark - gluon}} + \underbrace{\frac{gQe}{c^2}\frac{\lambda^a}{2}(\vec{A}\bullet\vec{B}^a + \vec{B}^a\bullet\vec{A})}_{\text{gluon - photon}} \right\}$$



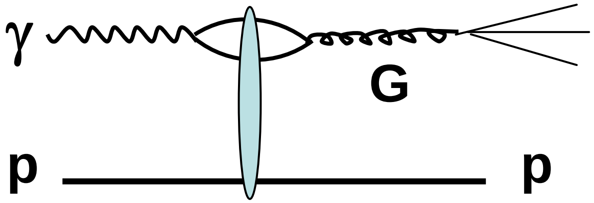


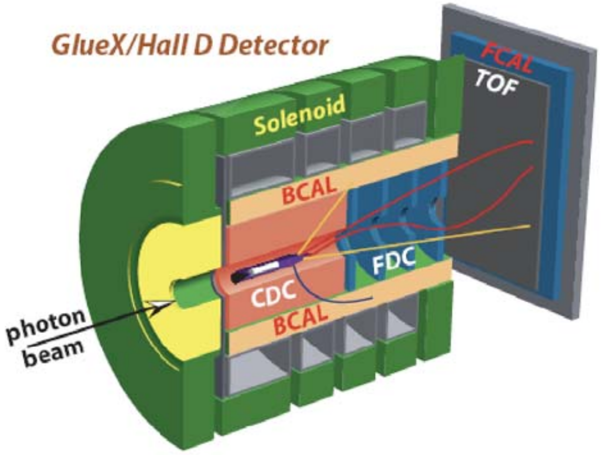


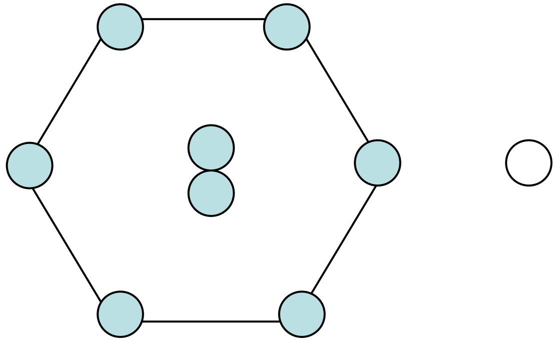
Could we test this hypothesis in the experiment?

Gluon production in γp collisions

JLab 12 GeV upgrade







$3 \otimes \overline{3} = \quad 8 \quad + \quad 1$

SU(3) flavor singlet: $\eta_1 \quad \omega_1$

$$(u\bar{u} + d\bar{d} + s\bar{s})/\sqrt{3}$$

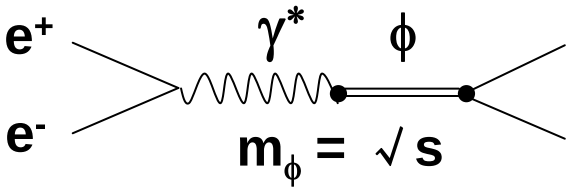
SU(3) color singlet: glueball?

$$(r\bar{r} + g\bar{g} + b\bar{b})/\sqrt{3}$$

Search color singlet states or glueballs

ϕ meson production

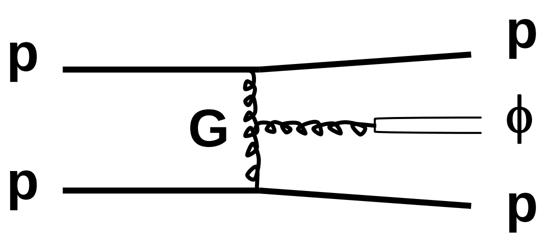
preparation → **transformation** → **measurement**   **Lucien Hardy**



ϕ-factory DAϕNE at Frascati, Italy

Kluge W. NPB(Proc. Suppl.) **135**(2004)357

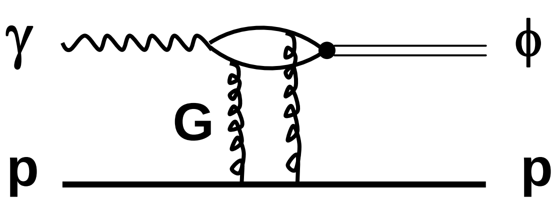
$P_{e+} = - P_{e-} = 0.510$ GeV/c



COSY at FZ-Jülich, Germany

ANKE(COSY) Colla. PRL **96**(2006)242301

$P_{p1} = 3.7$ GeV/c, $P_{p2} = 0$



CEBAF 6 GeV at JLab, US

CLAS(JLab) Colla. PRL **85**(2000)4682

$P_\gamma = 3.3\text{-}3.9$ GeV/c, $P_p = 0$

ϕ meson study in pp collisions

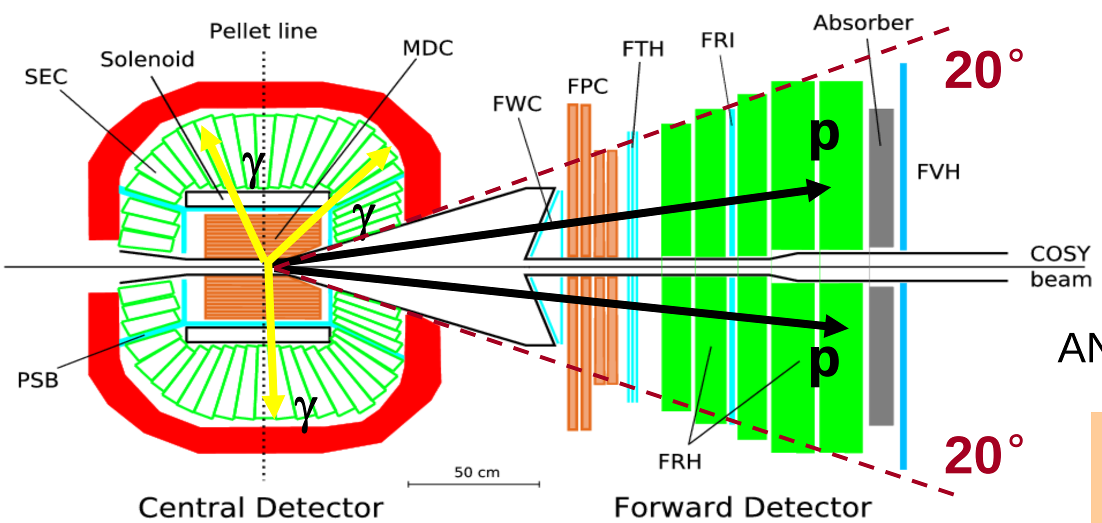
It is possible to study ϕ meson radiative decays with WASA@COSY.

$pp \to pp\ \phi(1.3\%) \to pp\ \gamma\eta(39.3\%) \to pp\ 3\gamma$

$$N_1 = L_{int} \cdot \sigma \cdot 1.3\% \cdot 39.3\% = 6.6 \cdot 10^4$$

$pp \to pp\ \phi(0.13\%) \to pp\ \gamma\pi^0(98.8\%) \to pp\ 3\gamma$

$$N_2 = L_{int} \cdot \sigma \cdot 0.13\% \cdot 98.8\% = 1.7 \cdot 10^4$$

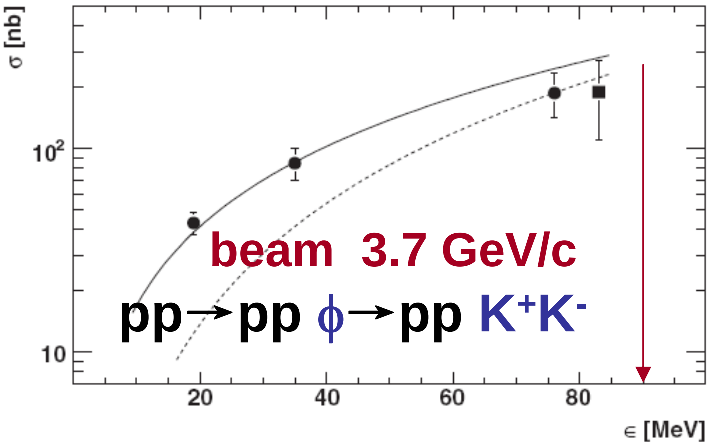


WASA@COSY Detector

Lumin. L = $2.5 \cdot 10^{31}\ cm^{-2}s^{-1}$

1 month $L_{int} = 6.5 \cdot 10^4\ nb^{-1}$

Total $\sigma(pp \to pp\ \phi) \approx 200$ nb



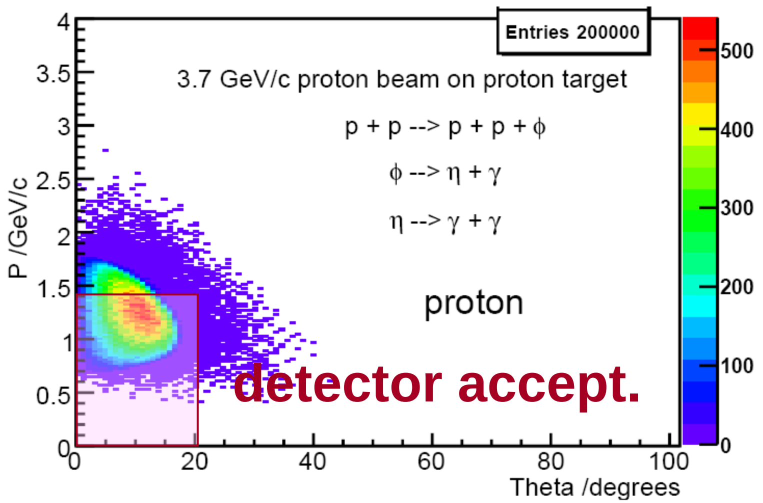
ANKE(COSY) Colla. PRL **96**(2006)242301

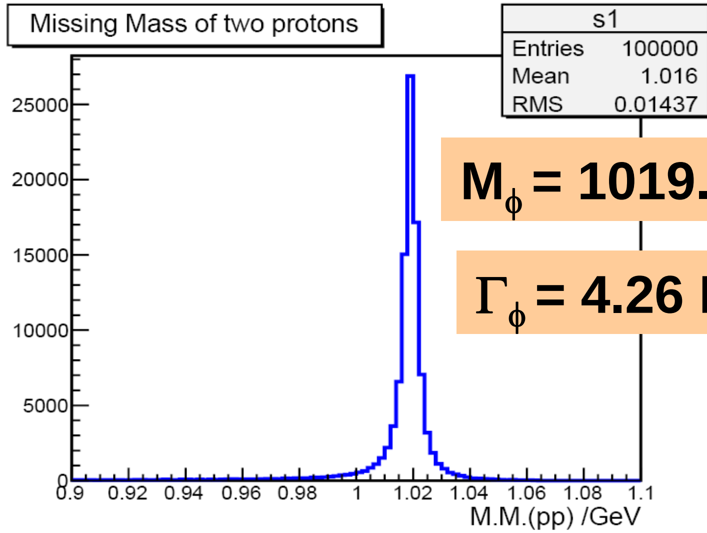
The statistics is reduced by acceptance, reconstructed and cut efficiency.

Monte Carlo (1): event generator

p(3.7 GeV/c) + p(fixed)→pp ϕ→pp $\gamma\eta$→pp 3γ

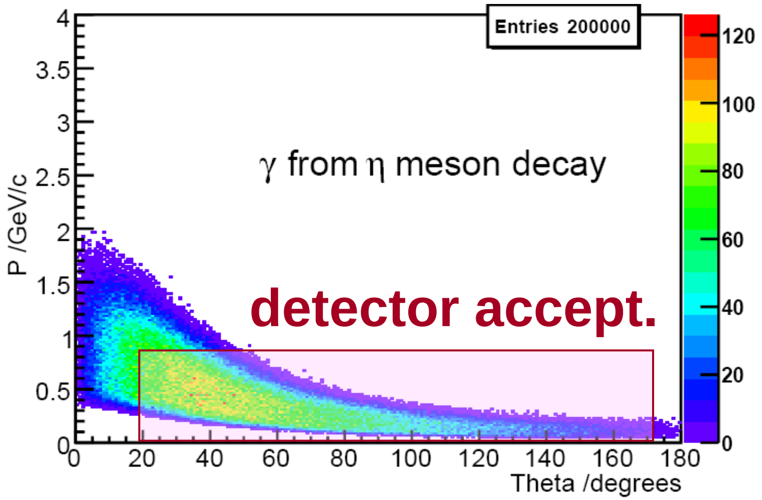
simulate $10\cdot10^5$ events

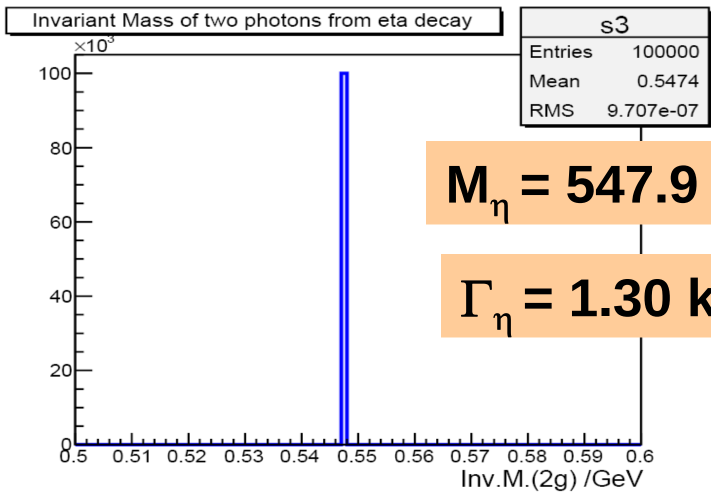




M_ϕ = 1019.5 MeV

Γ_ϕ = 4.26 MeV



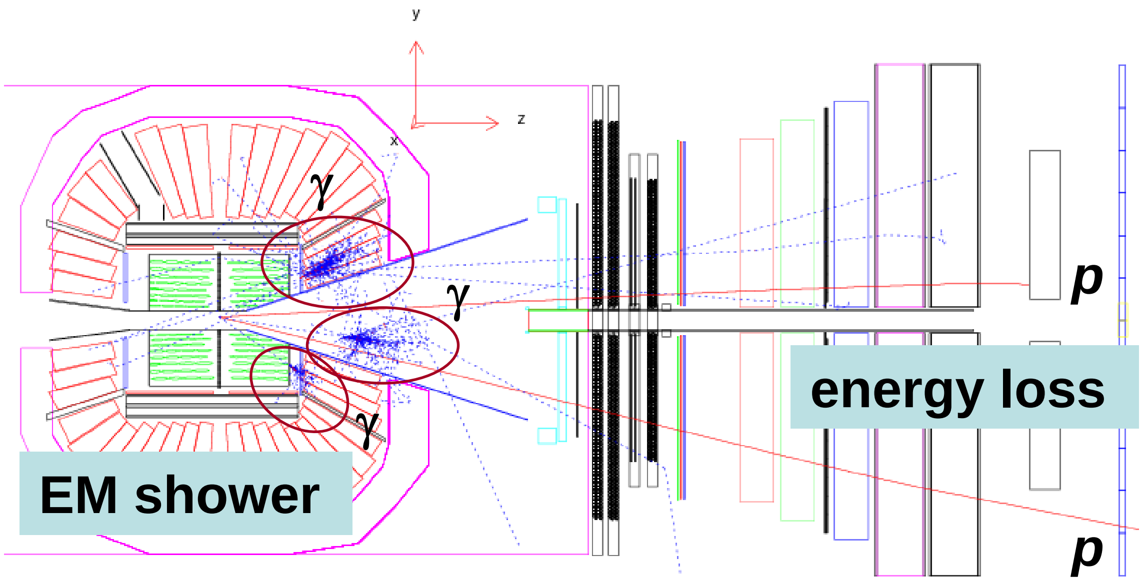


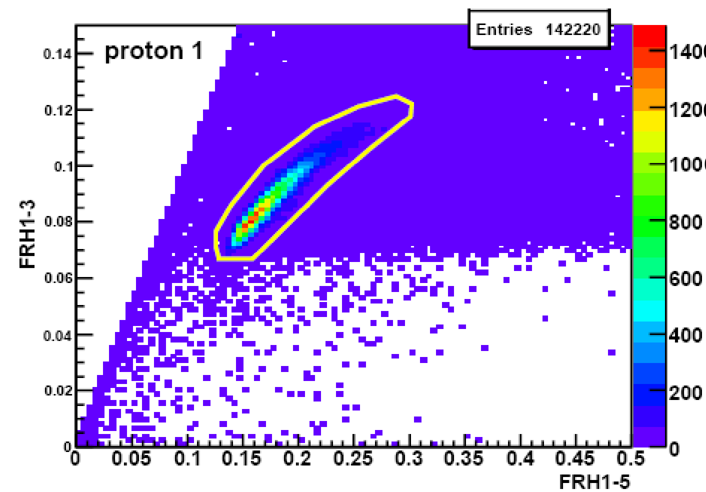
M_η = 547.9 MeV

Γ_η = 1.30 keV

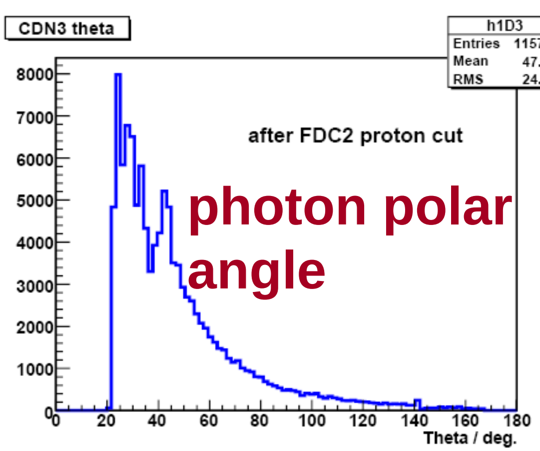
Monte Carlo (2): detector reconstruction

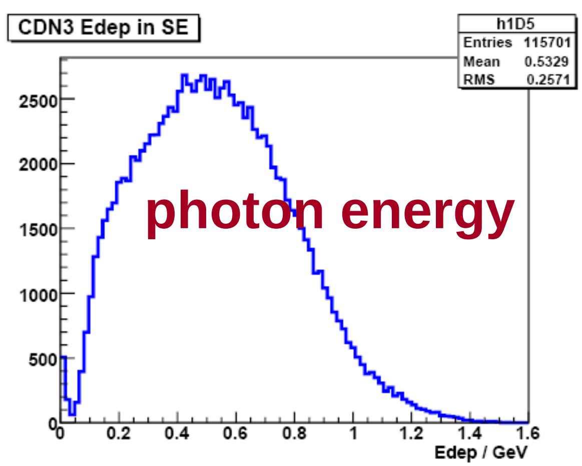
It is for the final particles of 2 protons and 3 photons.

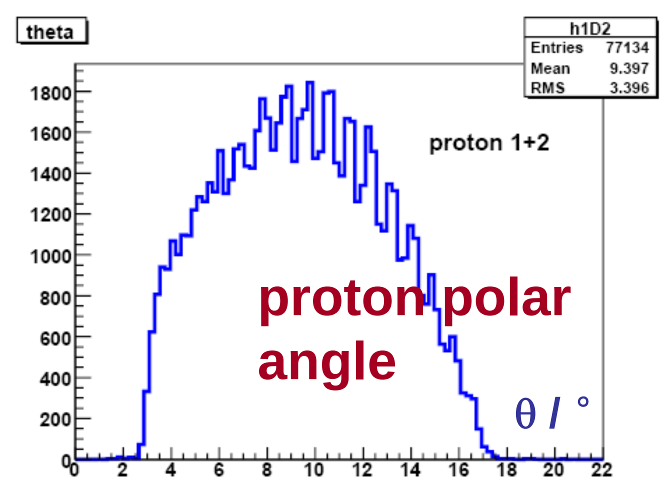




ΔE-E selection of protons



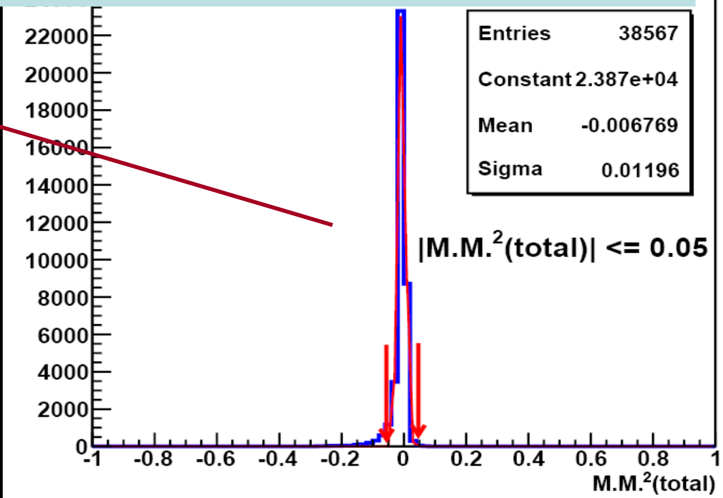




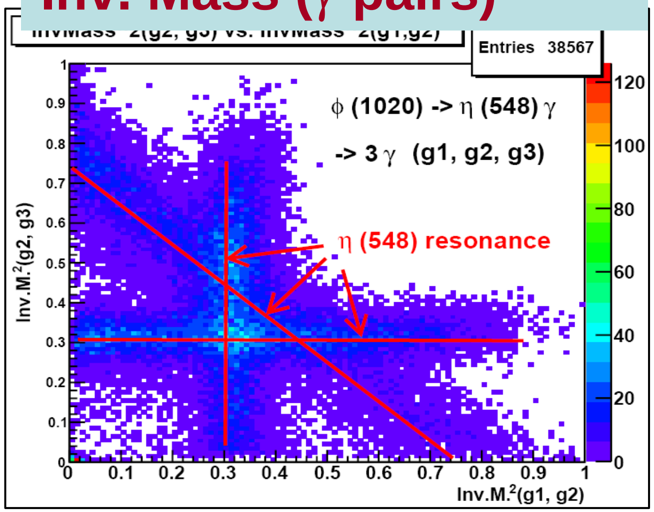
Monte Carlo (3): physical analysis

Accept.	Recon. Eff.	Cut Eff.
36.6%	10.5%	95.0%
2 protons in forward, 3 photons in central detectors	particle identification & 4-momenta reconstruction	4-momenta conservation & Inv. Mass & Miss. Mass etc.

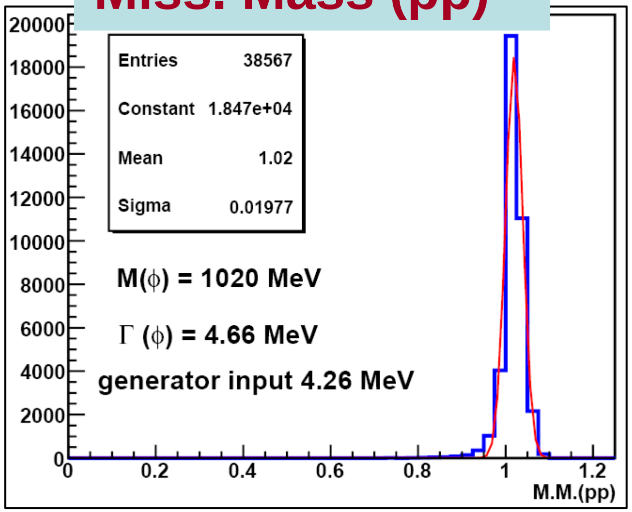
Miss. Mass² (total final)



Inv. Mass (γ-pairs)



Miss. Mass (pp)



The total efficiency is 3.65%, which reduces the final statistics to $2.4 \cdot 10^3$ in one month.

Background decays to be study

$pp \to pp\ \omega(782)(0.05\%) \to pp\ \gamma\eta(39.3\%) \to pp\ 3\gamma$ — $N_3 = 9.6 \cdot 10^4$

total $\sigma(pp \to pp\ \omega) \approx$ 7 500 nb — 1 month L_{int}

DISTO Colla. PRL **83**(1999)492

$pp \to pp\ \omega(782)(8.3\%) \to pp\ \gamma\pi^0(98.8\%) \to pp\ 3\gamma$ — $N_4 = 4.0 \cdot 10^7$

$pp \to pp\ \rho^0(770)(0.03\%) \to pp\ \gamma\eta(39.3\%) \to pp\ 3\gamma$ — $N_5 = 1.8 \cdot 10^5$

total $\sigma(pp \to pp\ \rho^0) \approx$ 23 400 nb — 1 month L_{int}

DISTO Colla. PRL **89**(2002)092001

$pp \to pp\ \rho^0(770)(0.06\%) \to pp\ \gamma\pi^0(98.8\%) \to pp\ 3\gamma$ — $N_6 = 9.0 \cdot 10^5$

4γ in final state, but one is lost in forward detector

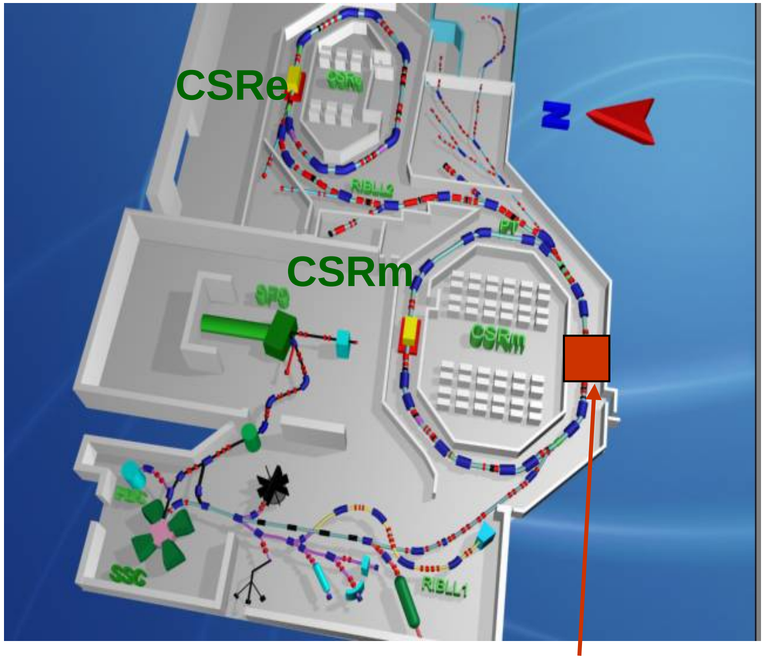
$pp \to pp\ \pi^0\pi^0 \to pp\ 4\gamma \to pp\ 3\gamma\ (\gamma)$ — **main background**

WASA(CELSIUS) Colla. PLB **679**(2009)30

Thank you!

兰州重离子加速器上的强子物理研究

兰州重离子加速器-冷却储存环



兰州强子物理谱仪

CSRm:

1.1 AGeV($^{12}C^{6+}$)

2.8 GeV ($^{1}H^{1+}$) 质子束流

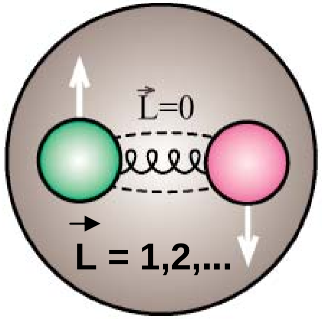
CSRe:

0.76 AGeV ($^{12}C^{6+}$)

轻介子

q = u , d , s 夸克

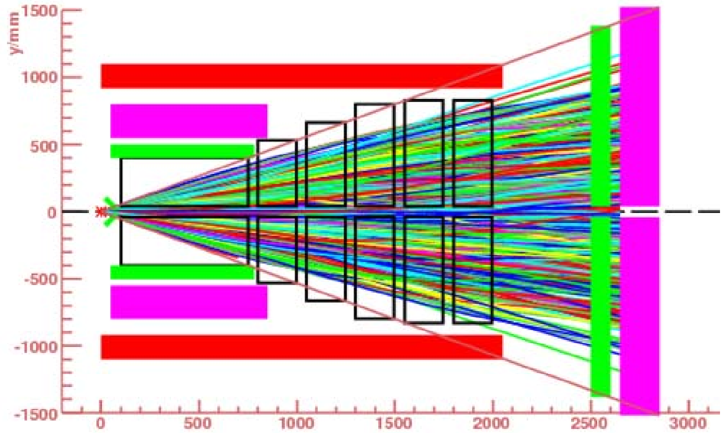
$\bar{q}$ = $\bar{u}$, $\bar{d}$, $\bar{s}$ 反夸克



Meson ($q\bar{q}$)

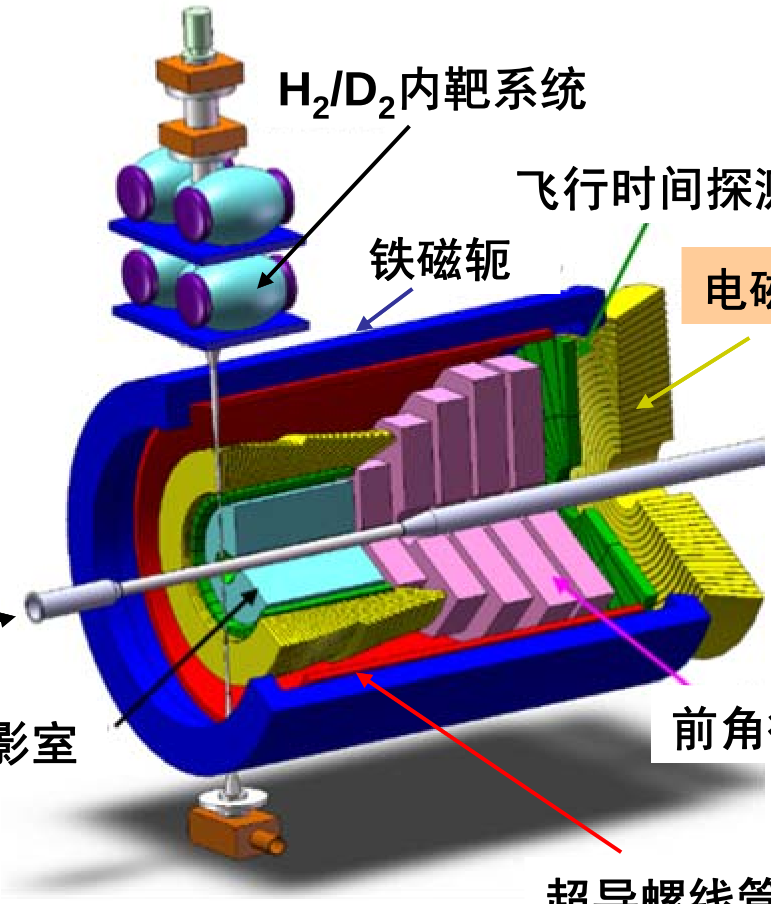
在质子-质子反应中的产生和衰变

计算机模拟研究



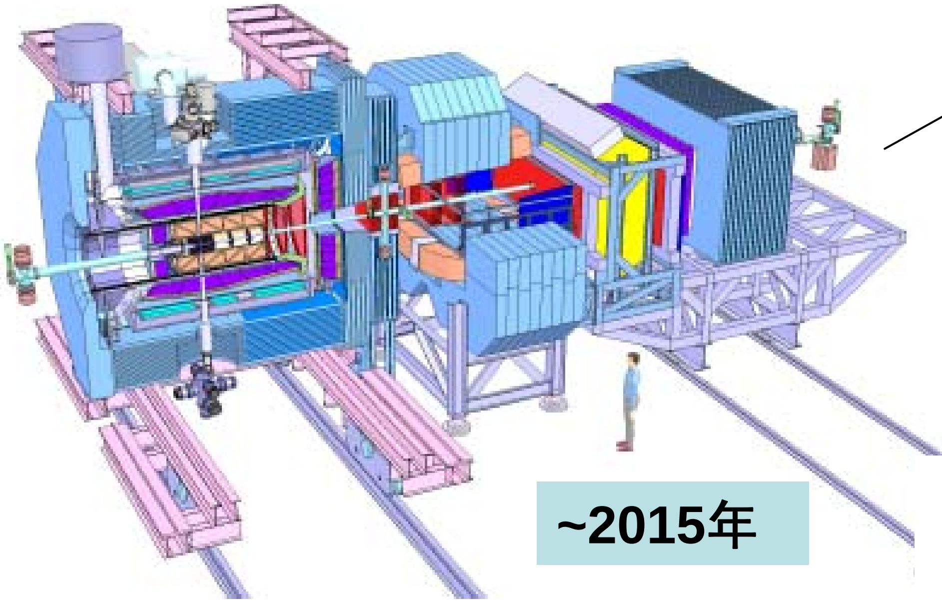
Hadron Physics LanzhoU Spectrometer

- 兰州重离子加速器冷却储存环可以提供质子束流。
- 通过对轻介子的电磁辐射衰变研究来优化强子谱仪的设计。



由于经费来源问题，什么时候建造这个谱仪还没有明确。

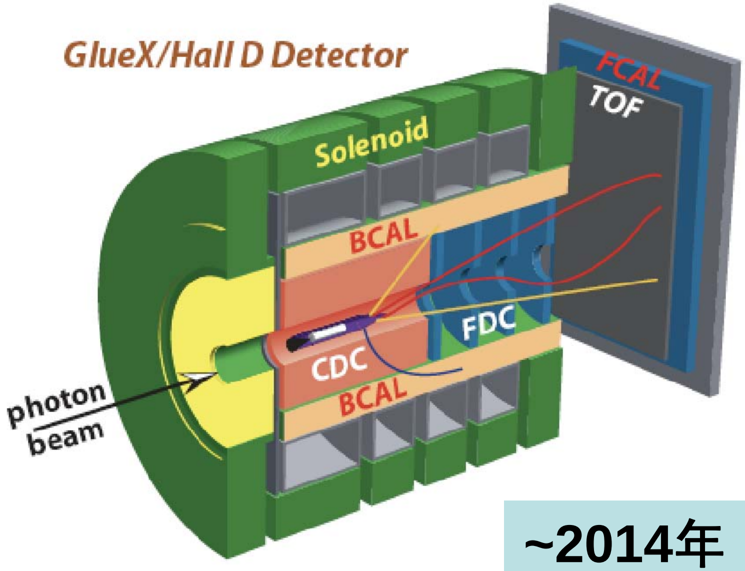
国外的研究情况



~2015年

德国GSI的正在建造的反质子研究项目中的PANDA探测器

- 粲偶素的介子谱
- 胶子激发态的寻找（如胶球）
- 核介质效应等

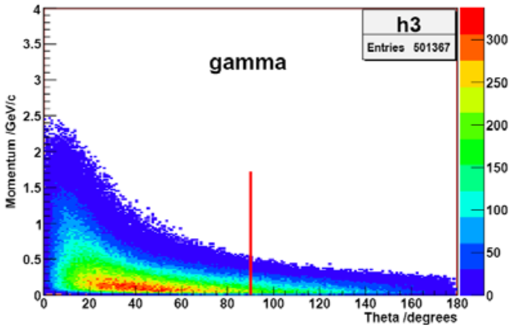


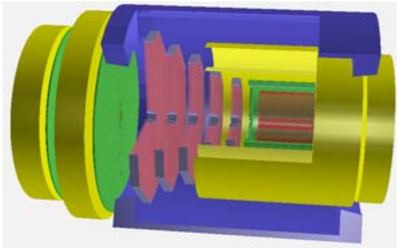
~2014年

美国JLAB在升级到12 GeV的改造项目中要建造的GlueX探测器

- 9 GeV线性极化的光子束流
- 核子中的胶子激发及胶子激发态
- QCD和轻介子谱等

模拟研究的内容和意义





- 物理目标的可行性分析
- 优化探测器的设计
- 为谱仪提供一个完整的模拟和数据分析平台