Proposed High Energy Spectrometer at HIAF & potential η meson physics studies

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HIAF

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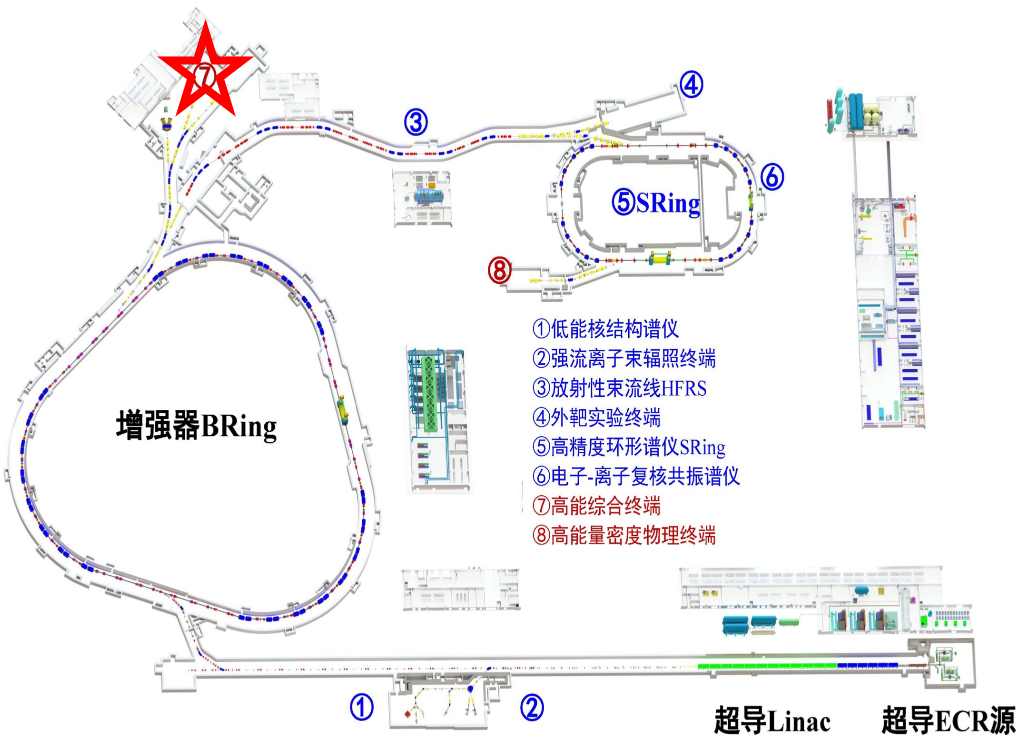
To be finished with construction in 2025

HIAF & HIAF-U



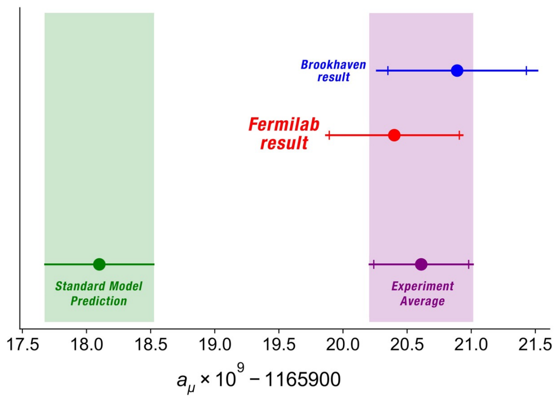
	E_k (GeV/u)	$\sqrt{s_{NN}}$ (GeV)
HIAF U beam	<2.45	<2.85
HIAF-U U beam	<9.1	<4.54
HIAF p beam	<9.3	<4.58

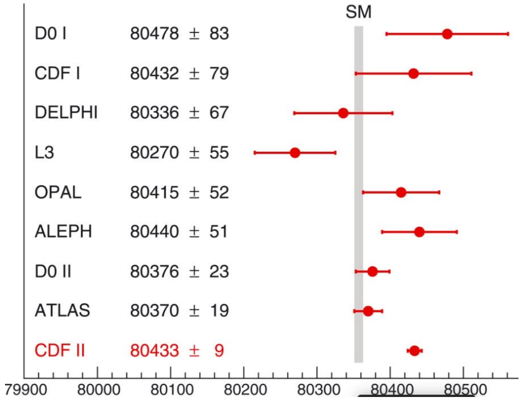
He Zhao

Monday Aug. 5

- HIAF can provide high-intensity proton beam up to 9.3GeV
  - η meson physics, light hadron physics…
- HIAF / HIAF-U can provide high-intensity U beam with energy up to 2.45 / 9.1 GeV/u
  - nuclear matter phase structure, equation of state & hypernucleus researches…

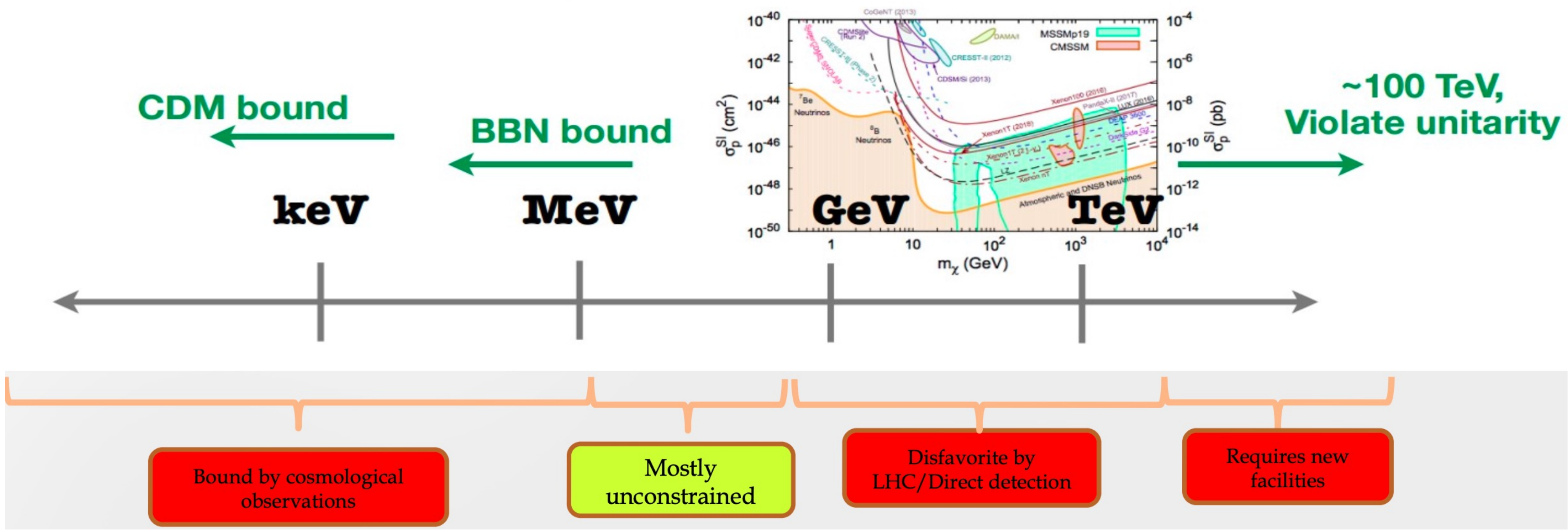
η meson physics





- The standard model of particle physics confronts several problems, calling for new physics beyond the current standard model
- High-luminosity / high-precision is an important frontier for the discovery of new physics
  - e.g. abnormal magnet moment of μ (g-2), W mass

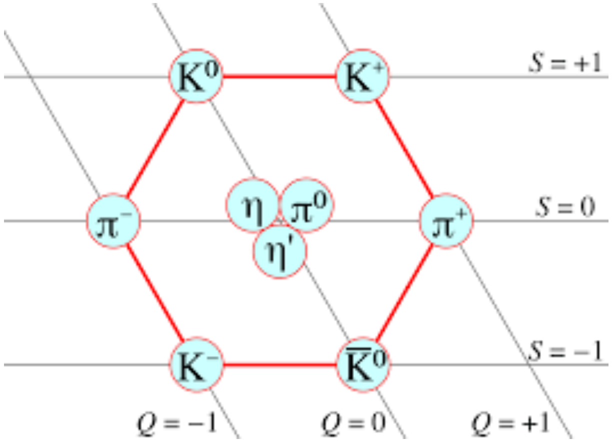
η meson physics



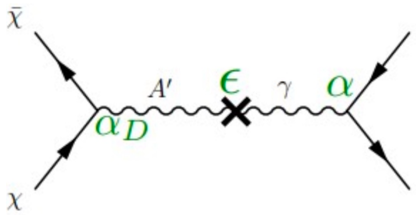
- In the search for dark matter particles, the parameter space for traditional WIMP (GeV~100TeV) is gradually being excluded by experiments
- Light dark matter particles (MeV~GeV) are currented less constrained by experiments
- High-intensity accelerators are powerful tools for light dark matter particle search

η meson physics

- η / η’ & Higgs are the only known particles with all-zero quantum numbers
  - Q = I = J = S = B = L = 0
- ⇒ Standard-model decays are suppressed
- ⇒ BR with new physics are relatively enhanced



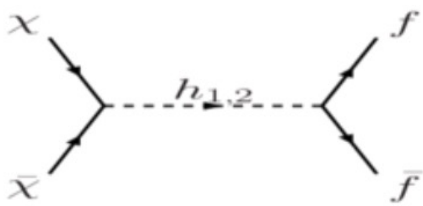
- η / η’ decays can be used to explore various portals to the dark sector and fundamental symmetries



dark photon

$\eta \to \gamma A'$

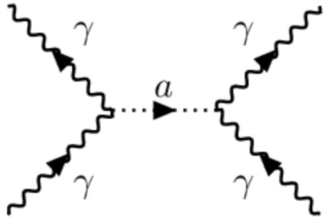
$A' \to \mu^+\mu^-$ / e^+e^-



dark Higgs

$\eta \to \pi^0 H$

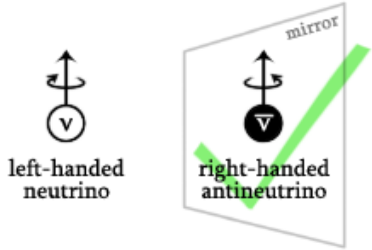
$H \to \mu^+\mu^-$ / e^+e^-



axion(-like particle)

$\eta \to \pi\pi a$

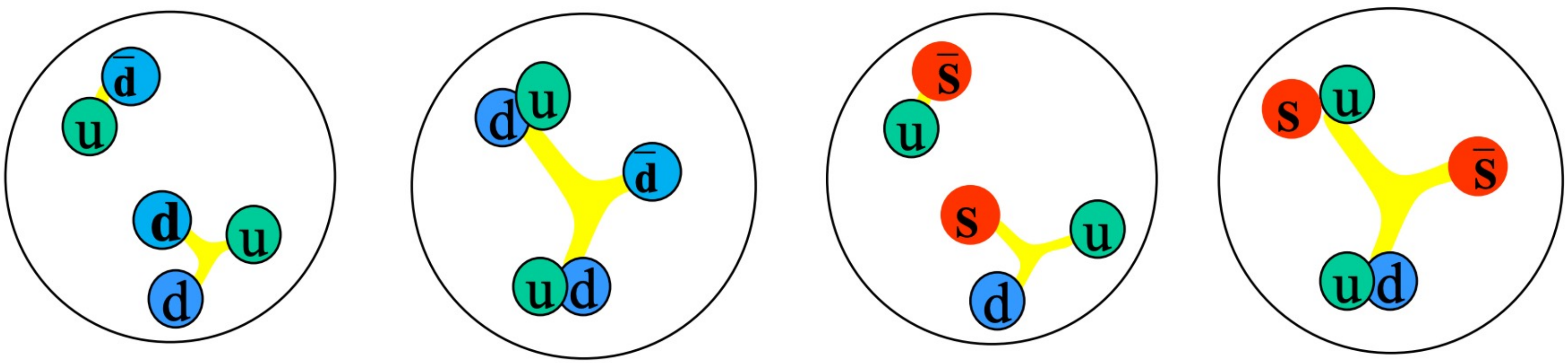
$a \to \gamma\gamma$ / $\mu^+\mu^-$ / e^+e^-



CP invariance

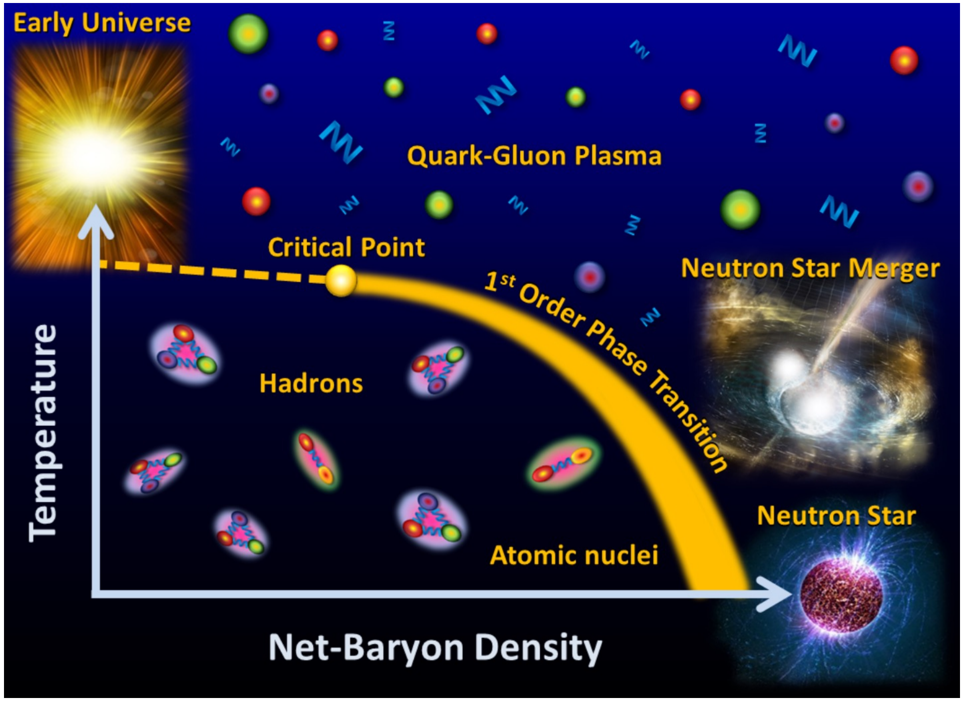
$\eta \to \pi^0\pi^+\pi^-$

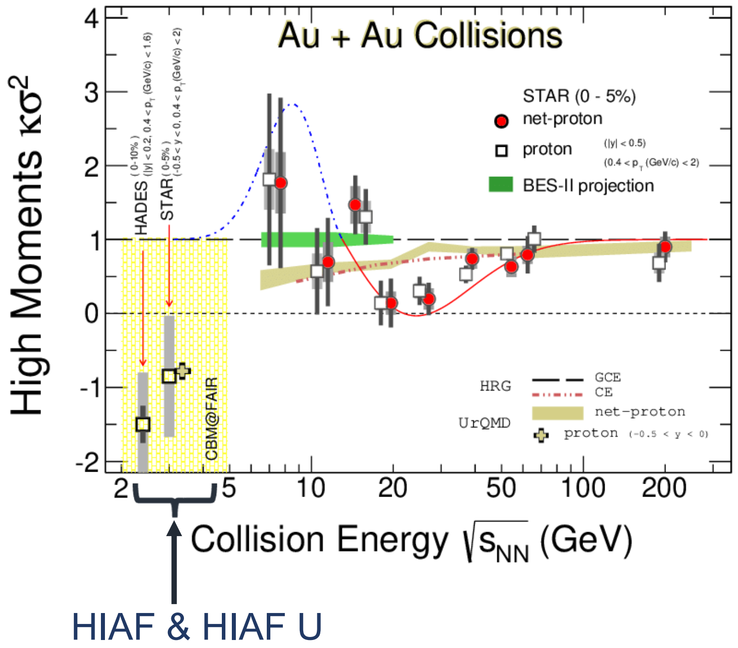
Light hadron physics



- HIAF provides beam with good energy range and luminosity for light hadron physics studies

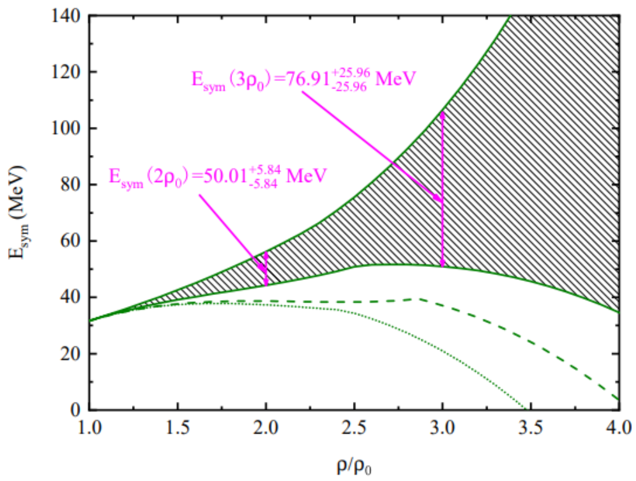
Nuclear matter phase structure

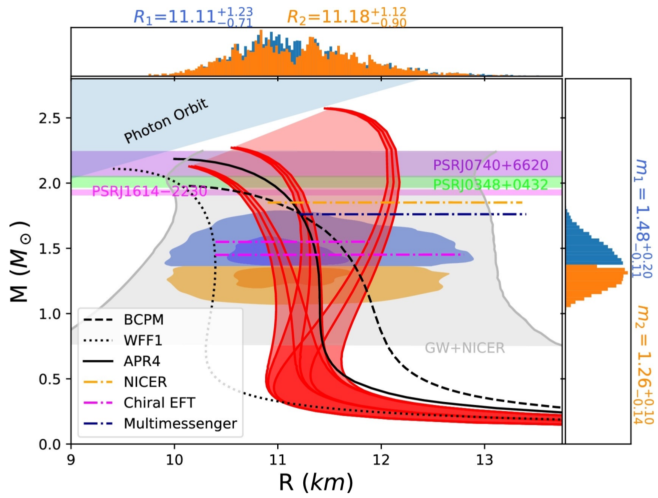


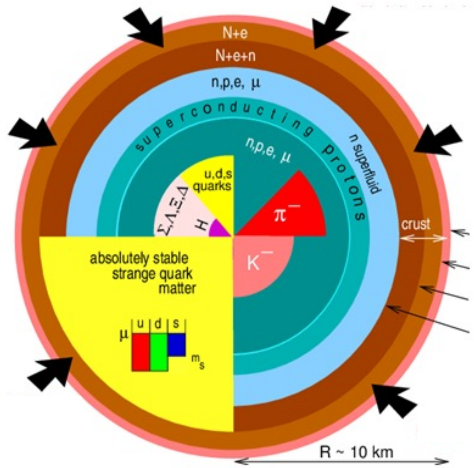


- The nuclear matter phase diagram can be scanned by heavy ion collisions at different energies.
- The 1st order phase transition and the critical point can be searched.

Nuclear matter equation of state

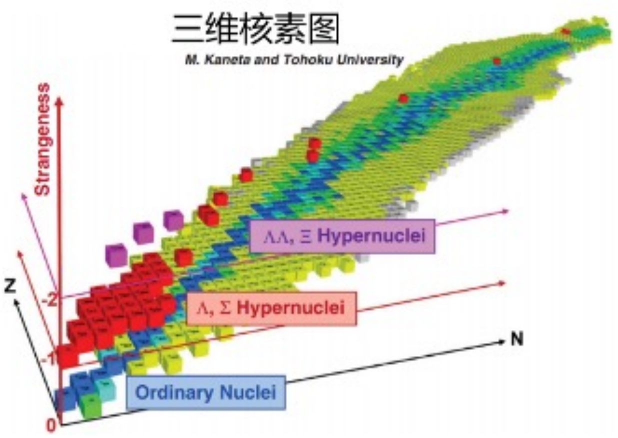


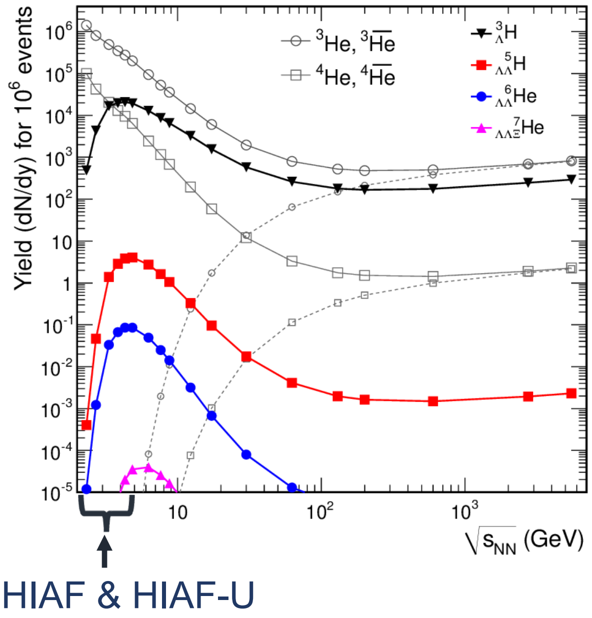


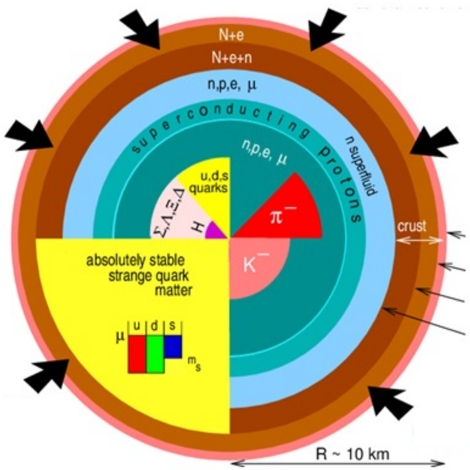


- nuclear matter equation of state
- ⇒ structure and properties of neutron stars

Hypernuclei







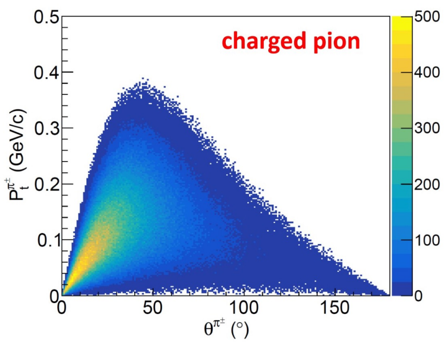
Aiqiang Guo

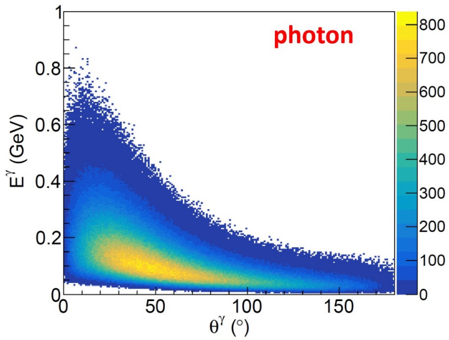
Thursday Aug. 8

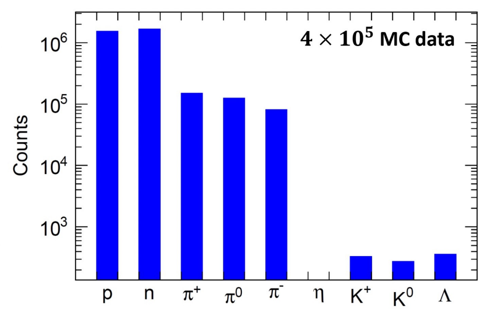
- hypernucleus properties & discovery of new (multi-strange) hypernuclei
- ⇒ hyperon-nucleon & hyperon-hyperon interactions
- ⇒ structure and properties of neutron stars

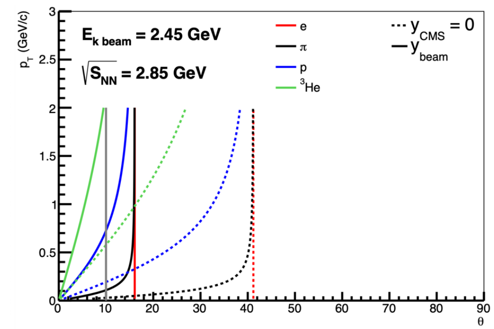
Spectrometer requirements

$\eta \rightarrow \pi^+\pi^-\pi^0(\gamma\gamma)$



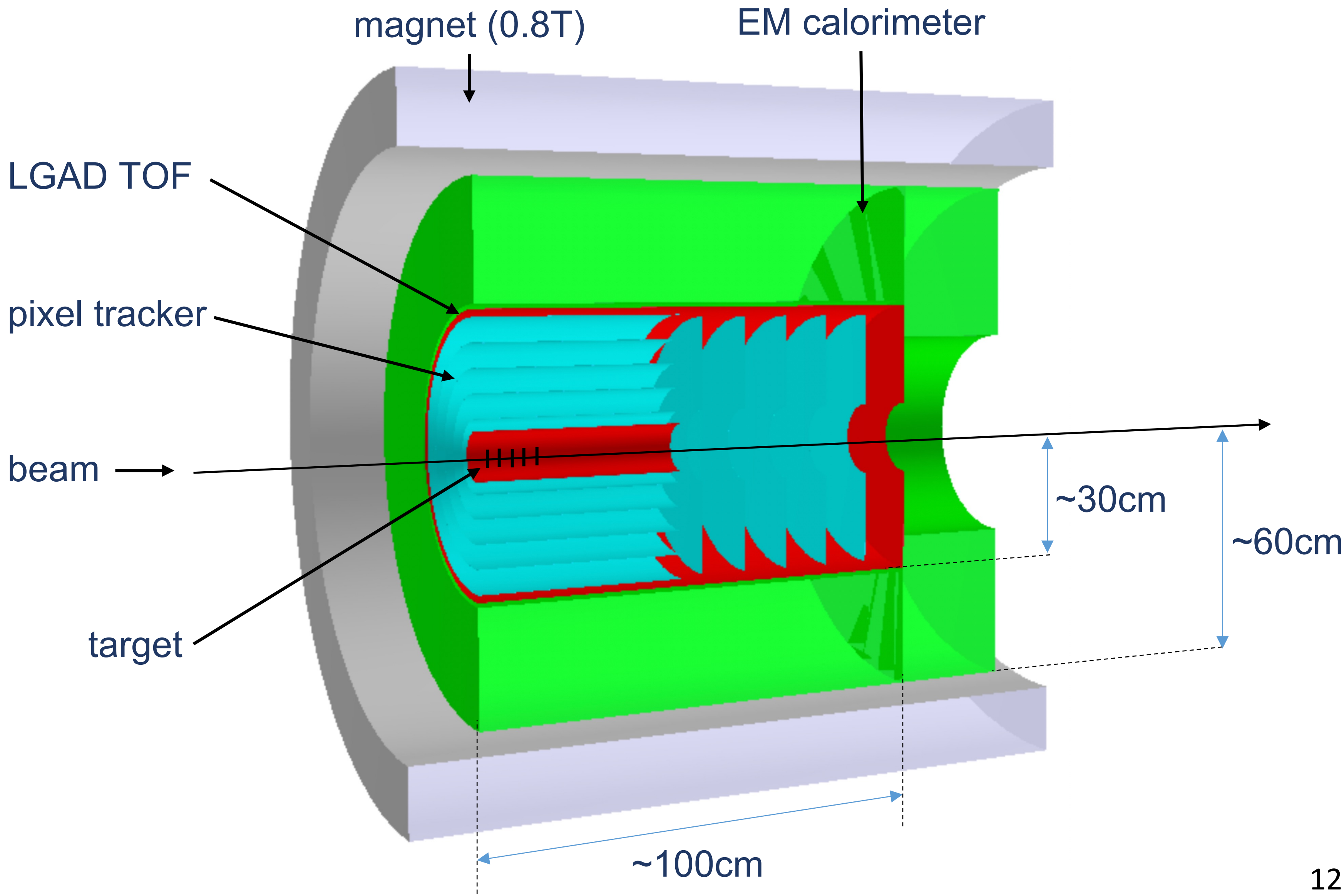




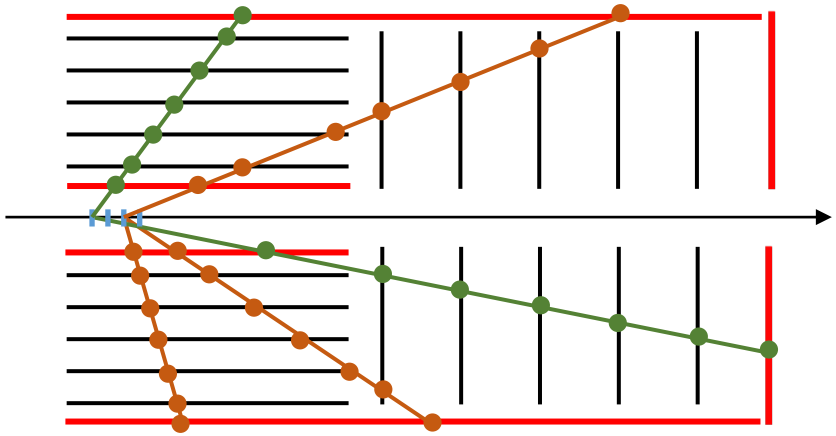


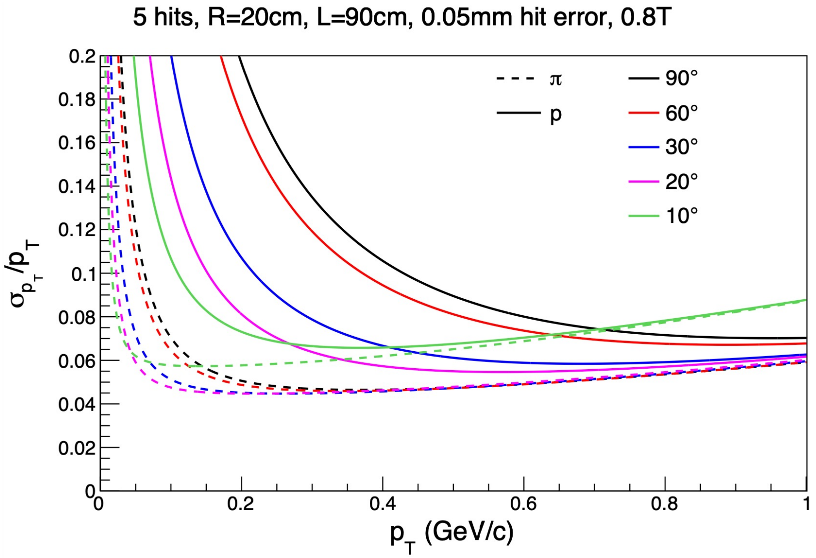
- Identification of e^{+-}, γ, π^{+-}, K^{+-}, p, d, t, He^3, He^4
  - π^{+-}/e^{+-}~100, n/γ~8 ⇒ important to identify e^{+-} over π^{+-} & γ over n backgrounds
- Charged particles transverse momentum: 50MeV-500MeV
- γ energy: 50MeV-1GeV
- Large acceptance (θ:10º~100º, φ:0~2π)
  - cover center-of-mass rapidity for heavy-ion collisions
- Precise vertex reconstruction ⇒ reducing hypernucleus background
- High event rate, far beyond existing experiments at similar energy ranges

Conceptual design



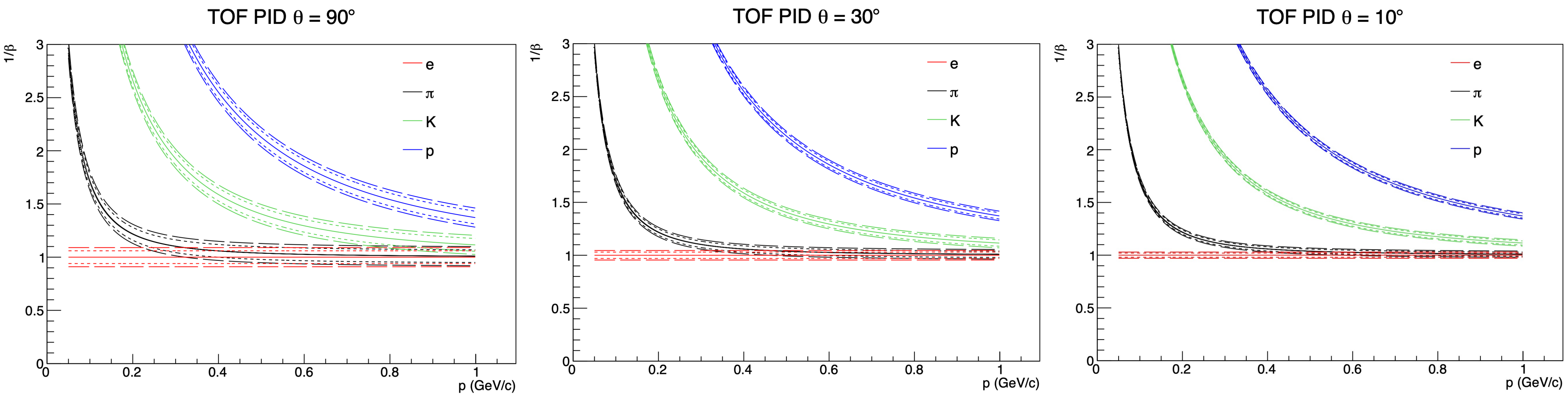
Pixel tracker





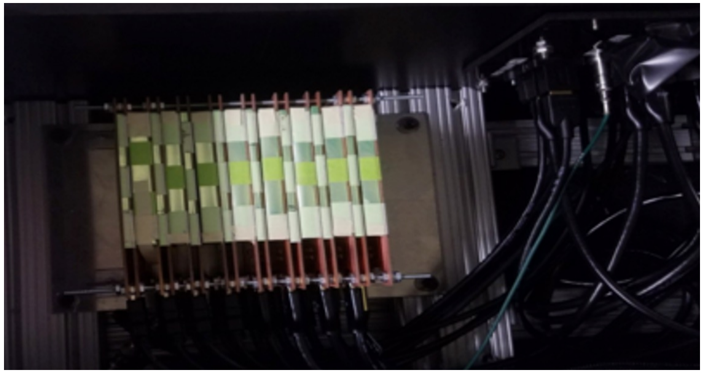
- ~100μm pixel size
  - acceptable momentum resolution even with short track length
  - good vertex resolution for decay particle reconstruction
- Energy & time dual readout
  - Distinguish hits from different events by time: Δt <10ns (1/100MHz)
  - dE/dx to identify light nuclei with different Z
- Single pixel dead time ~1μs (1/1MHz)
  - occupancy~10^{-4} even with 100MHz event rate × 4 tracks/event

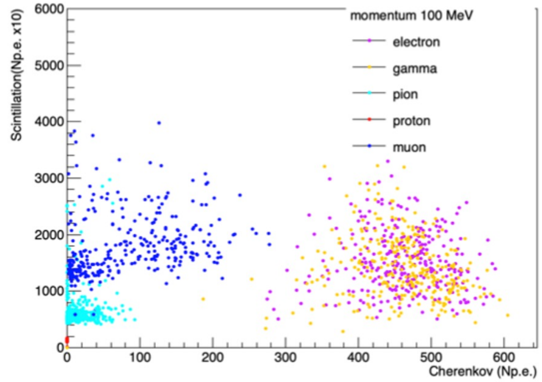
LGAD TOF

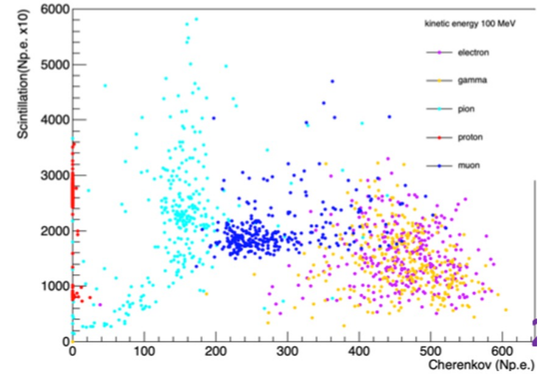


- Inner barrel (start time) + outer barrel & end cap (end time)
- Δt~30ps
- Good particle identification
  - e / π separation at high momentum to be complemented by EMC

Dual-readout calorimeter



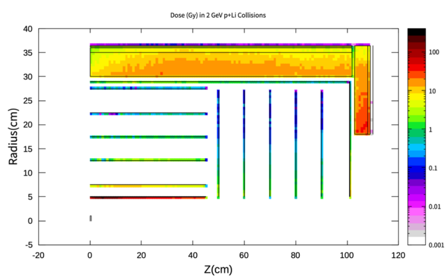


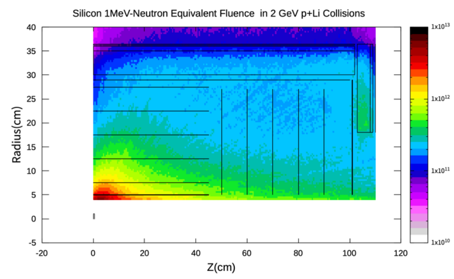


- “ADRIANO2” type of calorimeter developed by the REDTOP collaboration
- Pb glass + scintillator dual-readout ⇒ very good e^{+-} vs. π^{+-} & γ vs. n PID
  - Pb glass: Cherenkov light, signal only for EM showers
  - scintillator: signal for both EM and hadronic showers
- ΔE/E~3% @1GeV
- Δt~200ps to distinguish signals from different events
- shaping time (module dead time) < μs
  - ⇒ occupancy < 10% even with 100MHz event rate × 4 tracks/event

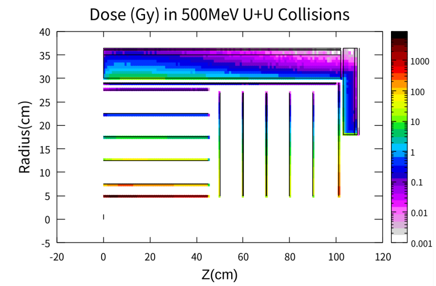
Radiation hardness

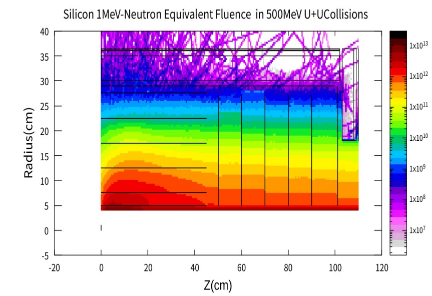
2 GeV p+Li





500 MeV U+U





	simulation with FLUKA		reference radiation hardness		
	Dose (Gy)	Si1MeV fluence (neq/cm2)	detector/material	Dose (Gy)	Si1MeV fluence (neq/cm2)
innermost Si	3000	3×10^{12}	pixel	2×10^{4}	1.7×10^{13}
			LGAD		1×10^{15}
innermost EMC	50	3×10^{11}	lead glass	20	
			SiPM		1×10^{14}

- Most detector components can sustain the radiation
- Lead glass will receive a dose that is close to its limit (TF101: 1% transmittance loss after a radiation dose of 20 Gy)

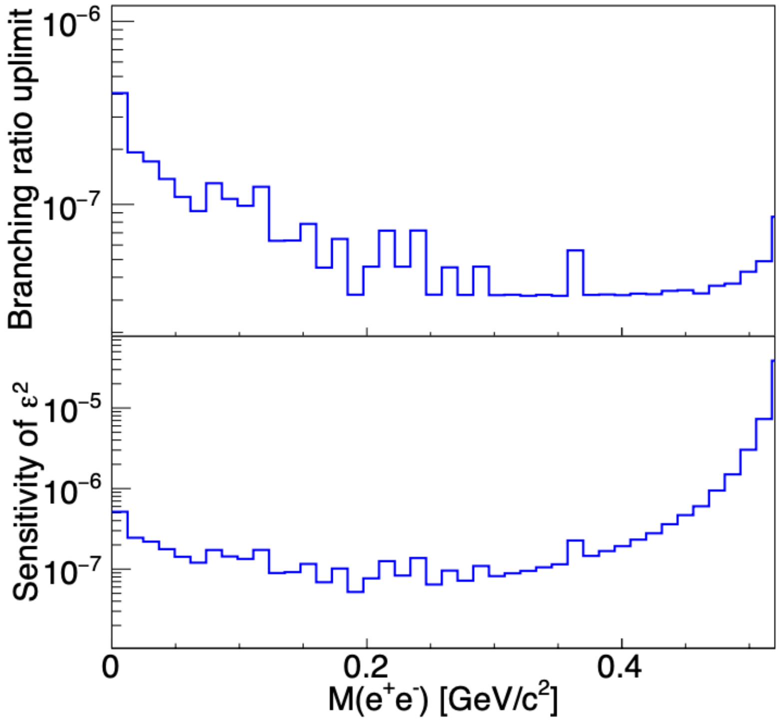
Data rate

- Heavy ion physics:
  - 1MHz
  - ~100 track
  - 7 hits / track
  - 1M*100*6 = 700M hits / s
- η meson physics:
  - ~>100MHz
  - ~4 track
  - 6 hits / track
  - 100M*4*6 = 2400M hits / s
- CEE for reference:
  - 10kHz
  - ~100 track
  - ~30 hits / track
  - ~20 digi / hit
  - 10k*100*30*20 = 600M digi / s

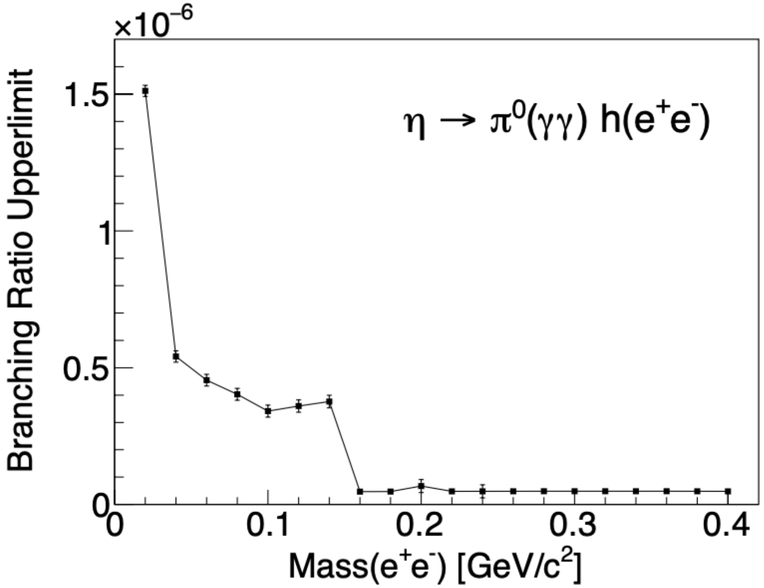
- Data rate on the same order of magnitude as CEE

Dark photon & dark higgs search

$\eta \to e^+e^-\gamma$



dark photon search



dark higgs search

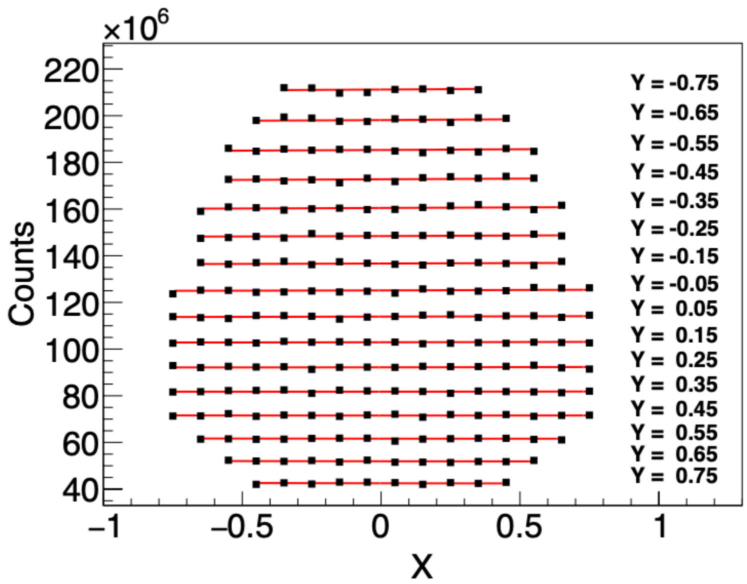
- 1.8 GeV p + ^{7}Li
- 1 month running at 100MHz, average / peak beam intensity = 30%
- 6×10^{11} η produced

C & CP violation

$$u \equiv (p_{\pi^+} + p_{\pi^0})^2$$
$$t \equiv (p_{\pi^-} + p_{\pi^0})^2$$
$$s \equiv (p_{\pi^+} + p_{\pi^-})^2$$

$$X \equiv \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{Q_\eta} = \frac{\sqrt{3}}{2m_\eta Q_\eta}(u - t),$$
$$Y \equiv \frac{3T_{\pi^0}}{Q_\eta} - 1 = \frac{3}{2m_\eta Q_\eta}[(m_\eta - m_{\pi^0})^2 - s] - 1,$$

$$N(X,Y) = N_0(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3 + ...),$$



- 1.8 GeV p + ^{7}Li
- 1 month running at 100MHz, average / peak beam intensity = 30%
- $\Delta c \sim 5 \times 10^{-5}$
  - ~2 orders of magnitude smaller than COSY and KLOE-II results

Name of the spectrometer

- China HyperNuclei Spectrometer (CHNS)
- Solenoidal Silicon Spectrometer (SSS)
- GeV-Energy Silicon Tracker (GEST)

Noun [edit]

gest (*countable* and *uncountable*, *plural* **gests**)

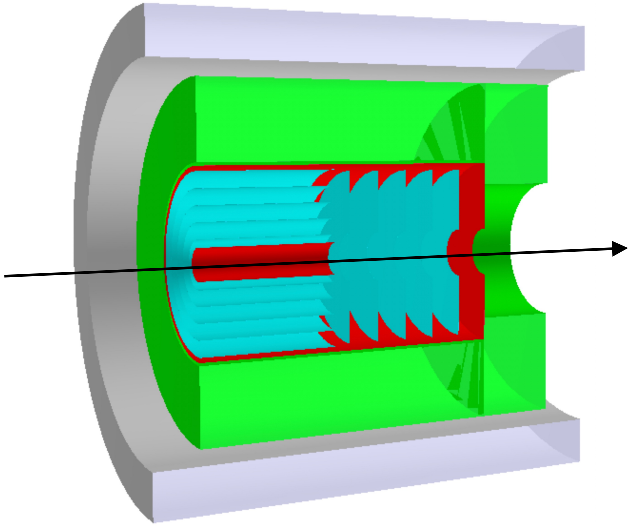
1. (*archaic*) A story or adventure; a verse or prose romance. [quotations ▼]
2. (*archaic*) An action represented in sports, plays, or on the stage; show; ceremony. [quotations ▼]
3. (*archaic*) bearing; deportment [quotations ▼]
4. (*obsolete*) A gesture or action. [quotations ▼]

- Silicon Tracker At Huizhou (STAH)

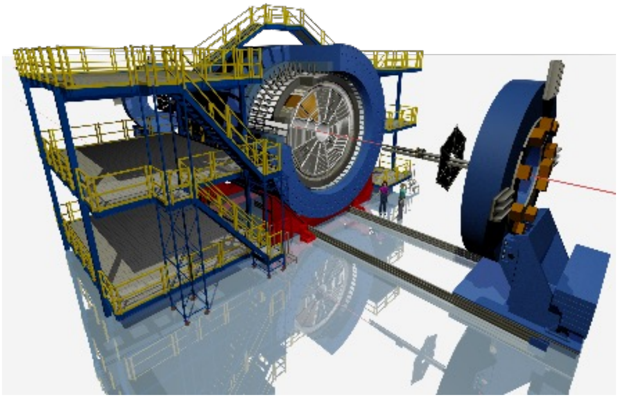
- … more ideas welcome

Summary

- We propose to build a solenoidal spectrometer at HIAF, with
  - energy-time dual-readout all-pixel tracking
    - ~100μm pixel size
    - compact spectrometer ⇒ low cost
    - ~0 background for hypernuclei
  - Cherenkov-scintillation dual-readout calorimeter
    - good e^{+-} vs. π^{+-} & γ vs. n PID
  - ultra-high event rate
    - >100MHz for proton beam
    - >MHz for heavy-ion collisions
- Potential physics:
  - η meson ⇒ beyond standard model, light hadron
  - nuclear matter phase structure, equation of state, hypernuclei



P.S. I: versatile, too good to be true?



- STAR – glowing for 25 years

+ vertex detector

good tracking with large acceptance + EM calorimeter + TOF + muon detector + inner TPC + forward tracking & calorimeter

discovery & properties of QGP + proton spin + antimatter + phase transition & critical point + ultra-peripheral collisions

- A specific experiment for one goal may work; a versatile experiment may also work
- Serious considerations, simulations, discussions & hardware R+D are needed
  - ideas & contributions always welcome
- When considering HIAF's 1st high-energy experiment, it does not hurt to be open-minded at first – if some goals do conflict, we can discuss and give up some aspects

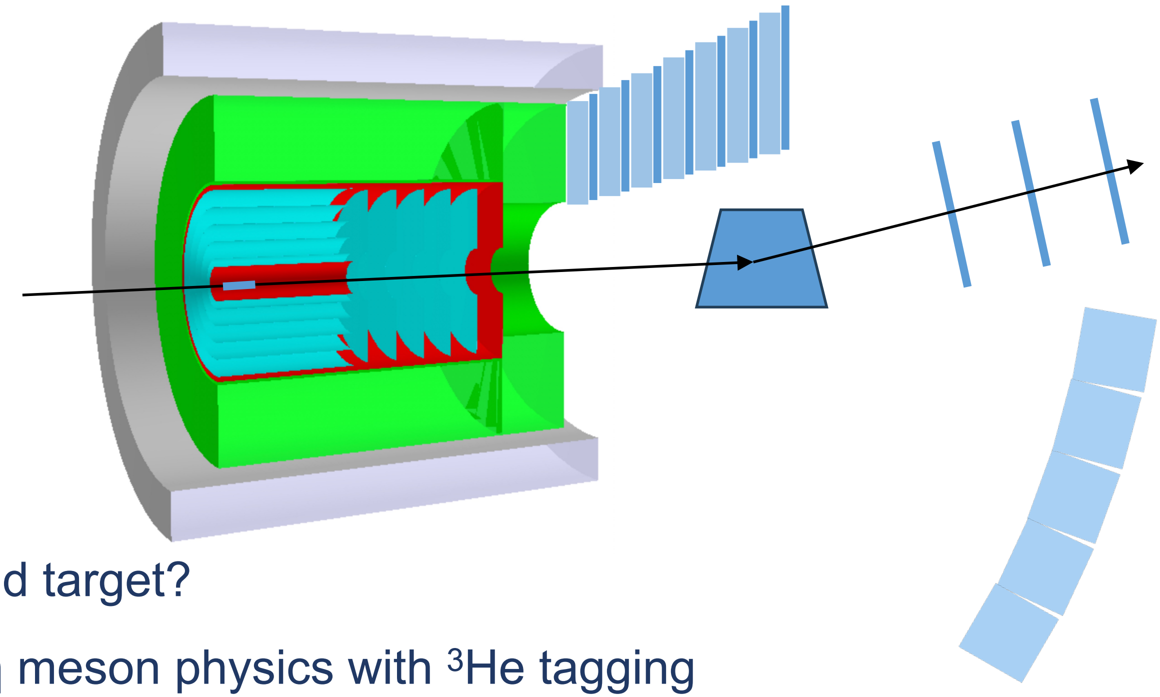
P.S. II: future's future

polarized beam & target?

- spin physics

muon detector: plastic dead layer + MRPC?

- +2 times of decay channels for η meson physics



projectile endoscope?

- projectile-like hypernuclei
- short-range correlation

liquid target?

- η meson physics with ^{3}He tagging
- short-range correlation

neutron wall: liquid scintillator?

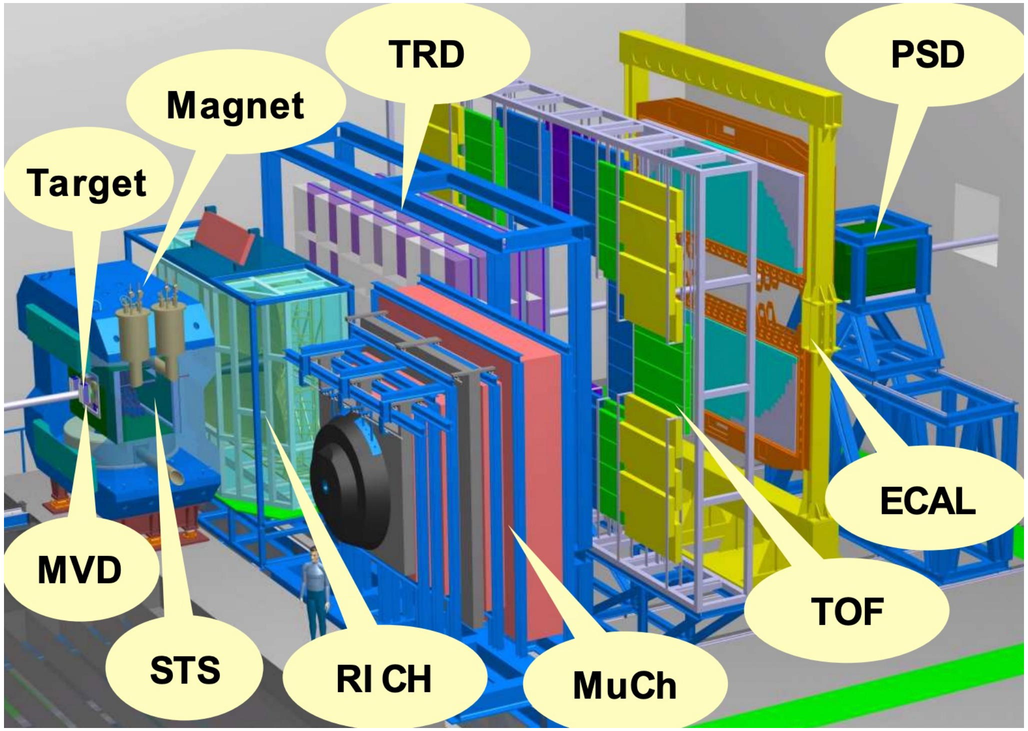
- light hadron physics
- 3-body short-range correlation

- ideas & contributions always welcome

Thanks ☺

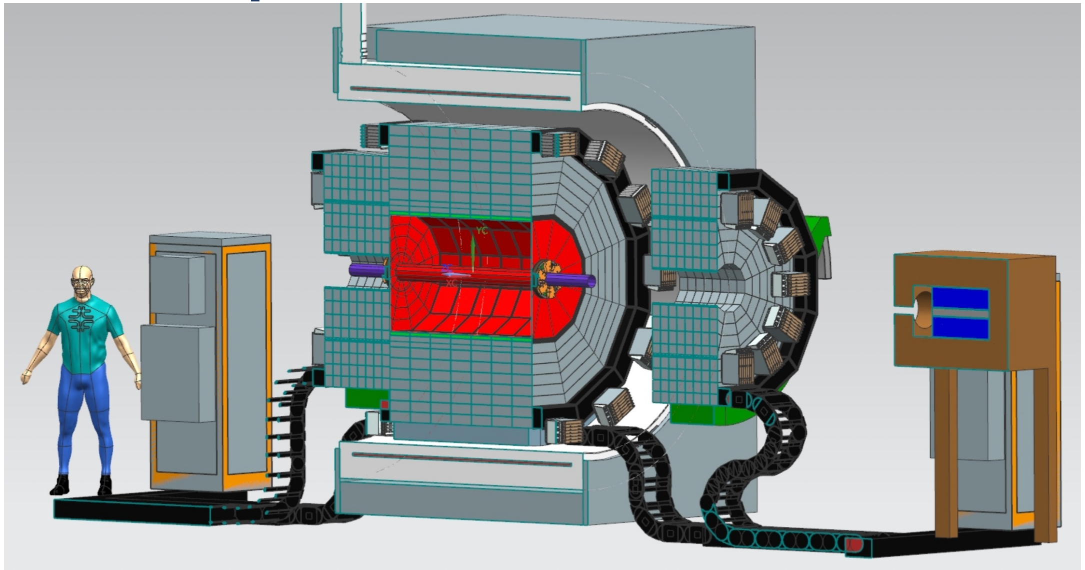
Back-up

Comparison - CBM



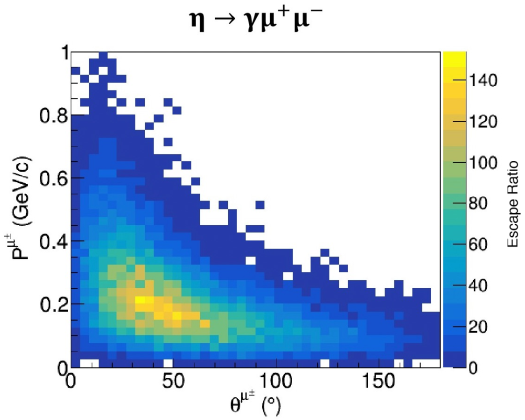
- ~55M euro, ~400M yuan
- Planed to finish with construction in 2028
- μ mode operating alone
- E_k: 2.5-11 AGeV, close to HIAF + HIAF-U (0.8-9.1 AGeV)
- event rate <10MHz, our proposed spectrometer at HIAF >1MHz

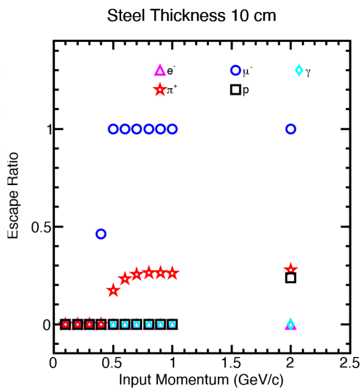
Comparison - REDTOP

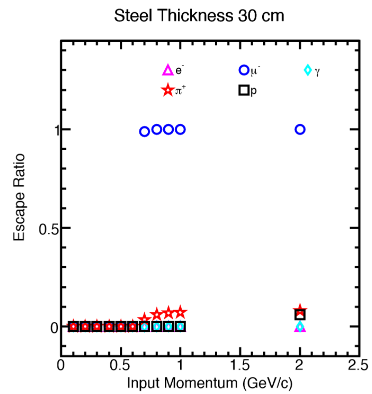


- 82-152M USD, 560–1000M yuan
- In the stage of proposal
- Event rate 500MHz, our proposed spectrometer at HIAF >100MHz
- No dE/dx measurement, can not meet the requirements of nuclear matter phase structure and hypernuclei studies
- Calorimeter with Cherenkov light & scintillation light dual read out (EM + hadron)
  - good e & γ PID (suppression of π & neutron background)
  - can measure neutrons

μ detector







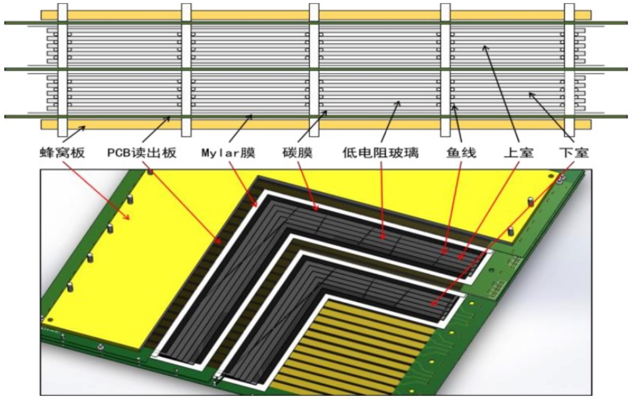
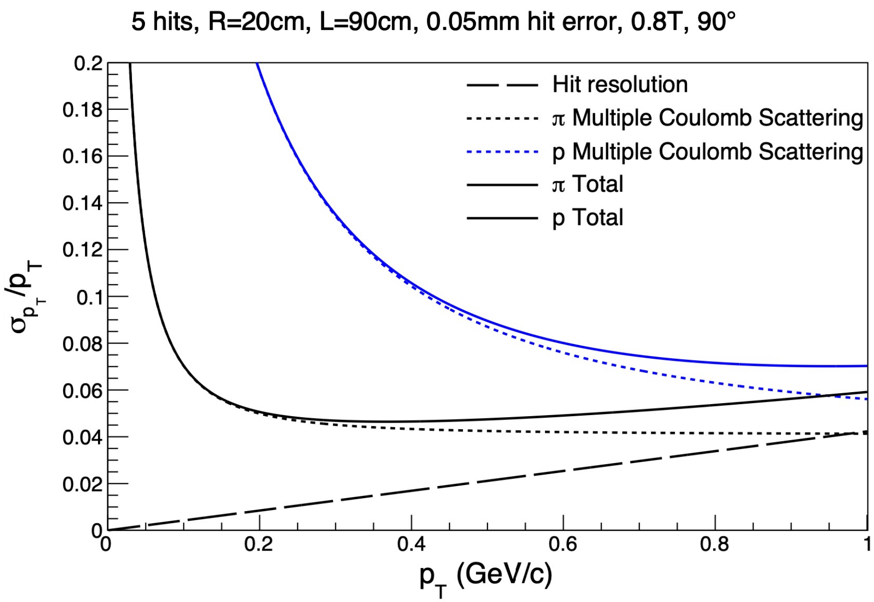
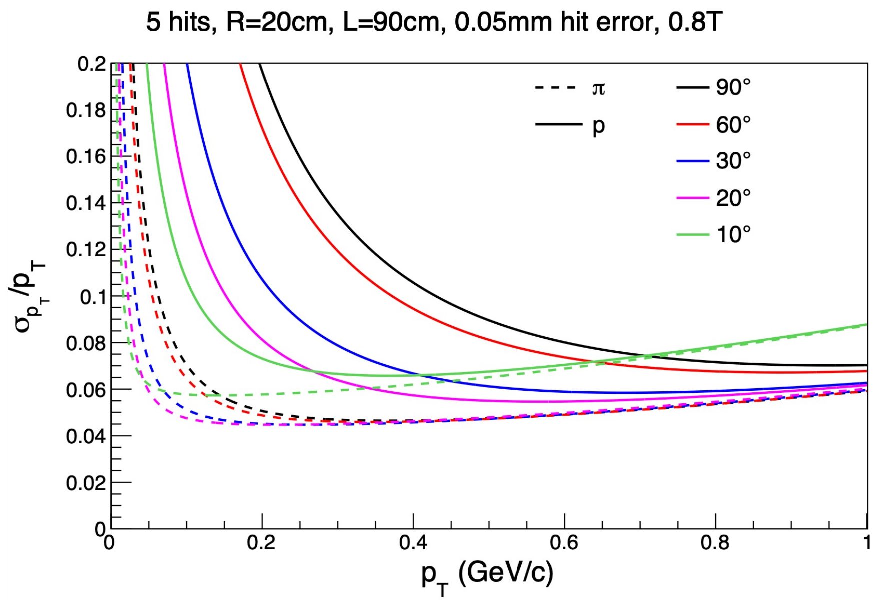


图 10　eTOF MRPC 结构示意图。

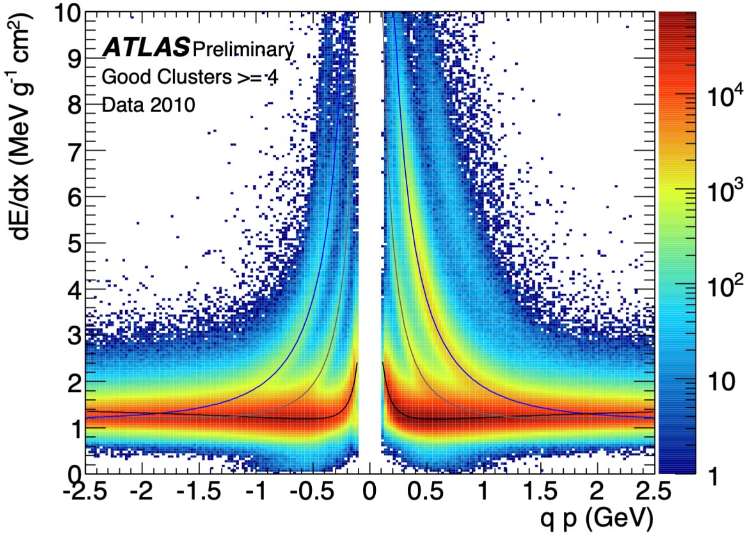
- MRPC, like CEE/STAR TOF
- With 25cm CsI + 30cm Fe stopping material, μ^{+-} with p>0.7GeV/c can be chosen, π^{+-} suppressed by 1 order of magnitude, other hadrons fully stopped
- Less stopping material, μ^{+-} with lower p can be detected, but lower π^{+-} suppression
- Read out strip pitch 25mm; 2-side readout provides position information along the strip: 100ps*c=30mm ⇒ 2D cm-level position resolution
- Time resolution ~70ps, 4D match to track
- Inside & outside the magnet yoke in the current design, can add more layers for different stopping material thicknesses
- Area ~11 m^2　　cost: 5M yuan

Pixel tracker

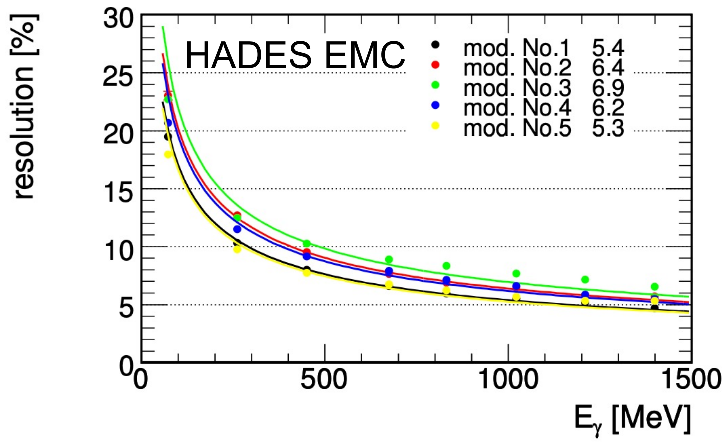


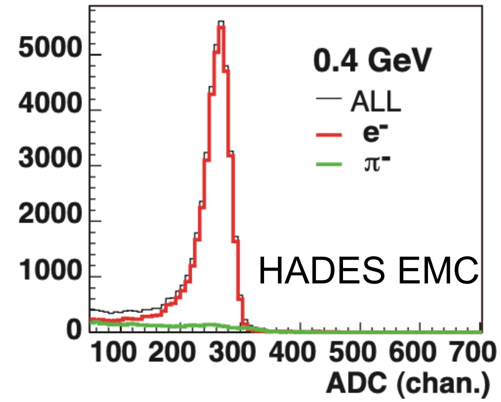


- With a magnetic field of 0.8 T, momentum resolution of 4-7% for most particles
- Particles with p_T as low as 50MeV can reach the outermost LGAD TOF layer, to ensure good efficiency at low p_T
- dE/dx measurement precise enough to identify light nuclei with different Z



Calorimeter

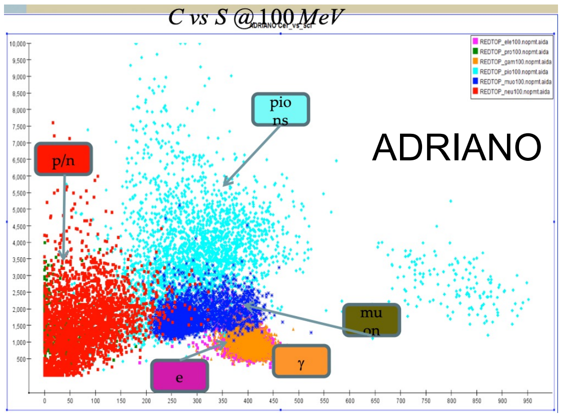


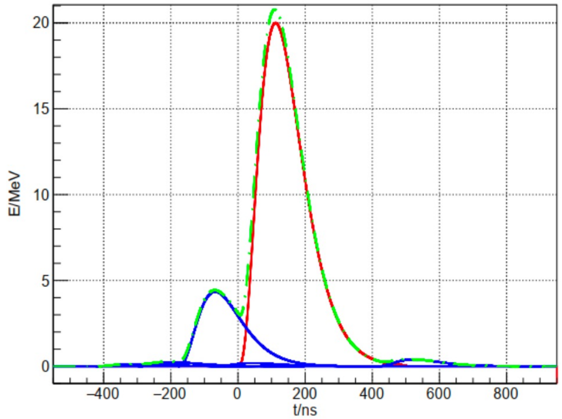


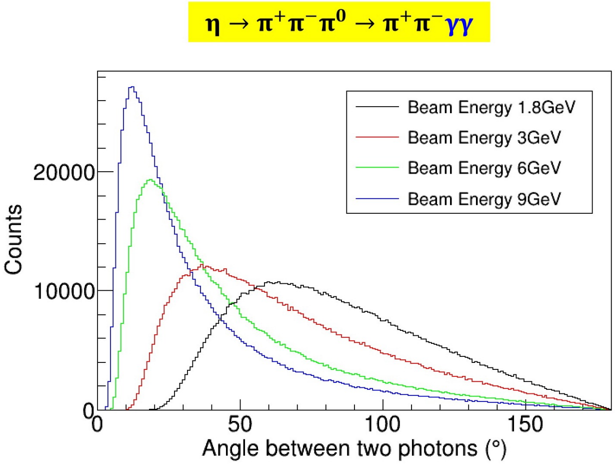
	ΔE/E @ 50MeV	ΔE/E @ 1GeV	Δt (ps)	Shaping time (ns)	reference	cost (M yuan)
Pb glass	~25%⇒	~6%⇒	215ps @ 0.8GeV	~500	HADES	~<10
Undoped CsI	~7%	~2%	600ps @ 1GeV⇒	~1000	STCF	~58
Pb + plastic scint.	~20%	~6%	~100ps @ 1GeV	?	NICA-MPD	~<10
ADRIANO2	~22%	~5%⇒3%	⇒80ps	?	REDTOP	167⇒

- Various techniques under consideration, detailed simulation going on to choose the best technique
- Pb glass: low energy hadrons in hadronic showers do not generate Cherenkov light. So n & π backgrounds will be suppressed comparing with γ & e.

Calorimeter

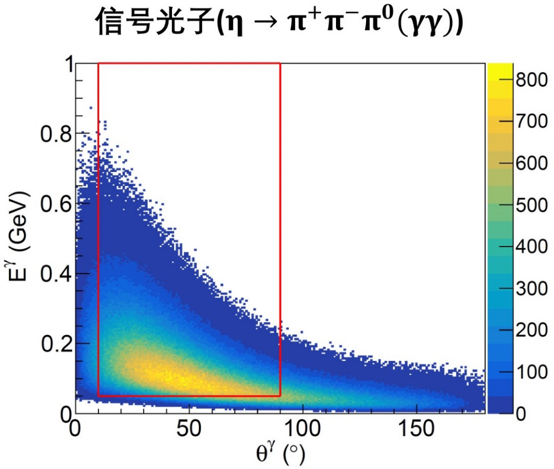


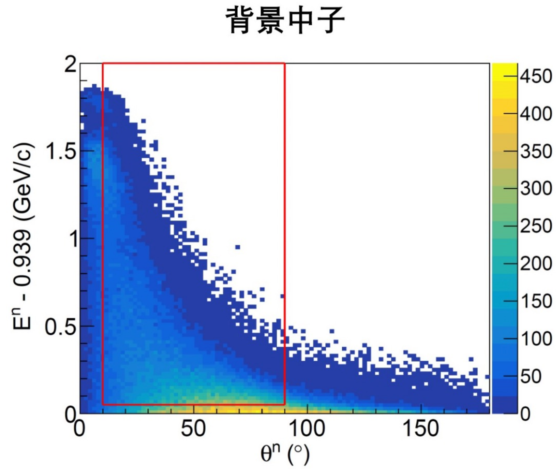


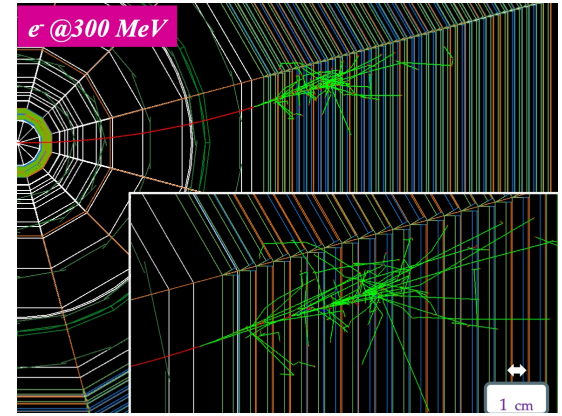


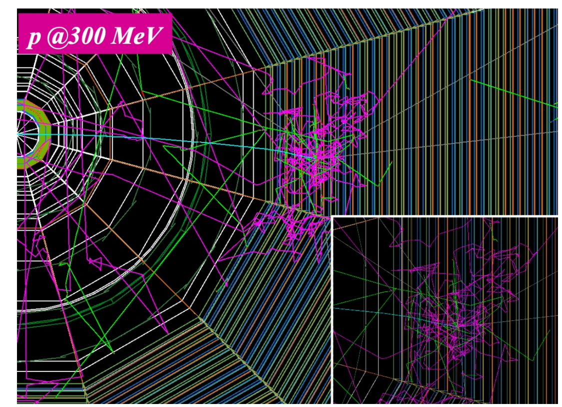
- ADRIANO2: Cherenkov light & scintillation light dual read out for PID
    - The 167M yuan cost include 40cm-thick EMC (high granularity) + 40cm-thick hadronic calorimeter (with stopping layers), EMC alone will be cheaper
- Sub-μs level module dead time (electronics shaping time) required, all the currently considered techniques should be OK
    - Event rate >100MHz, ~10 modules hit / event (4p+4n), ~1000 modules
    - Contributions from pile-up events can be obtained by fitting the signal shape
- The angle between 2 γ from π^0 is usually large, no high requirement for granularity
- Radiation dose (both ionization and neutron) are being estimated with simulation

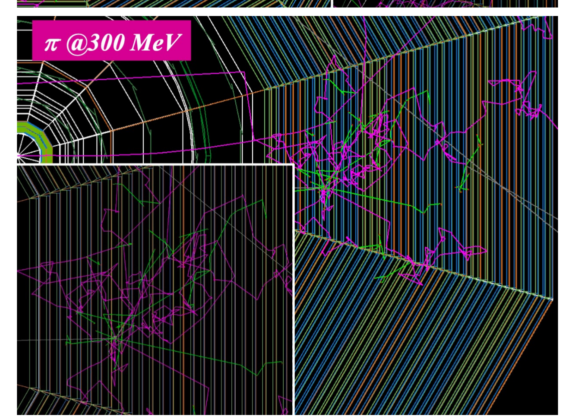
γ-n & e-π identification





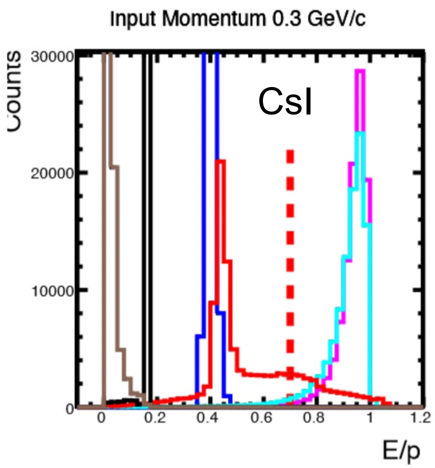


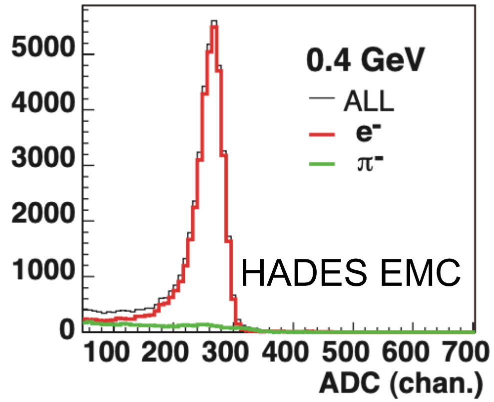


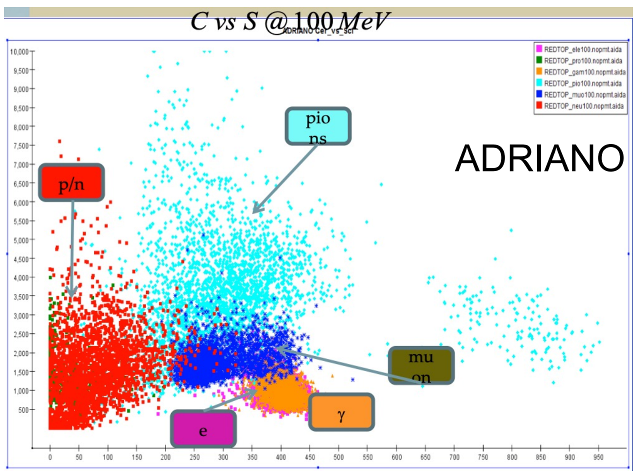


- n/γ~8   π/e~100
- Whether the shower happens
  - Pb glass radiation length 1.27cm, nuclear interaction length 24.5cm
  - For 12 radiation lengths, the chance that a neutron does not interact ~54%
- Dimension and shape of the shower
  - signal concentrated in 1 module vs. spread over many modules

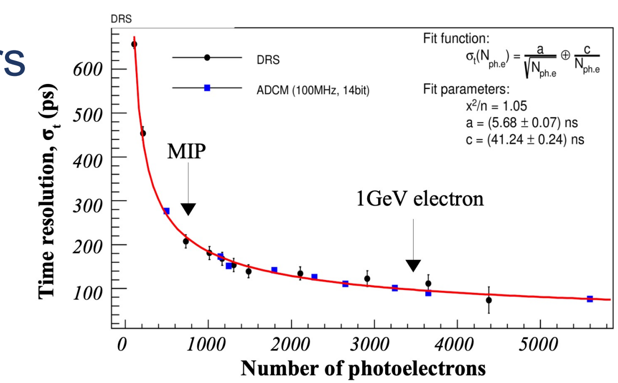
γ-n & e-π identification



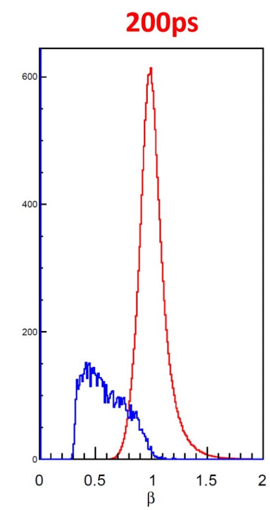




- Electron E/p~1 (only appliable to e-π)
- Low energy hadrons in hadronic showers do not generate Cherenkov light:
  - Pb glass: lower signal for hadrons
  - ADRIANO2: dual read out



NICA-MPD EMC



reconstructed γ/n velocity

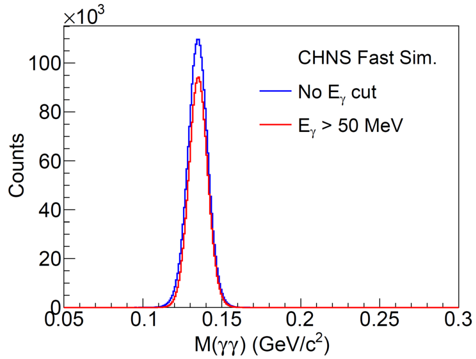
- Time of flight
  - ~200ps time resolution will provide some γ-n separation
  - However, time resolution usually get worse for lower signals
- GEANT simulation on-going to study γ-n & e-π separation for different techniques

Cost

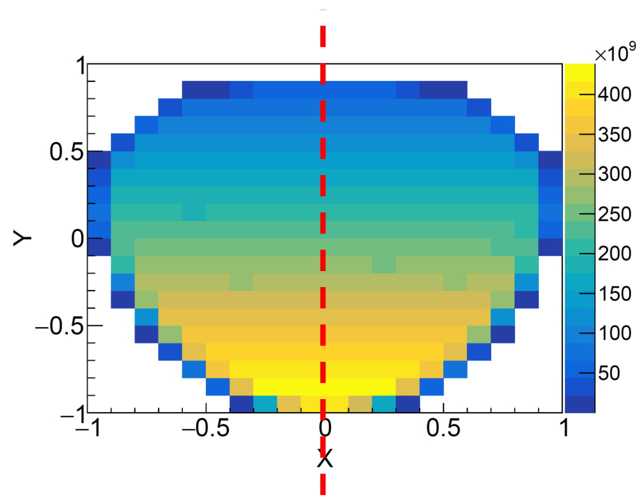
Sub-system	cost (M Chinese yuan)
Target	0.5
pixel tracker	14 + 12 (R&D)
LGAD TOF	33
EMC (Pb glass)	10
MRPC MTD	5
Solenoid	6
Supporting structure	1
DAQ	16
Total	85.5 + 12 (R&D)

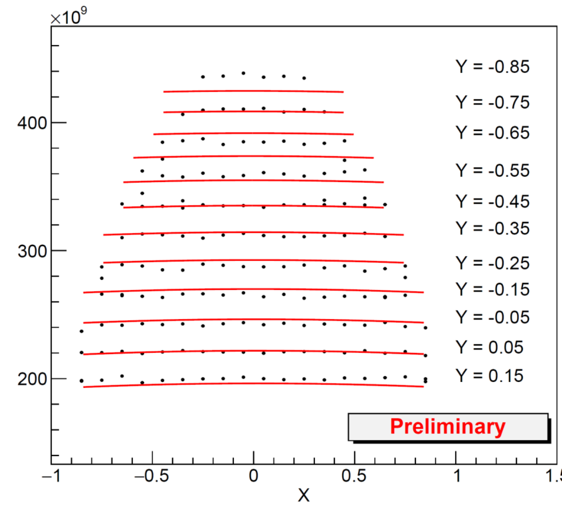
- In China, 100M yuan is an important threshold for scientific project budgets.
  - Below 100M, there is chance for application every year.
  - Above 100M, there is one chance every 5 years, and it’s much more difficult.

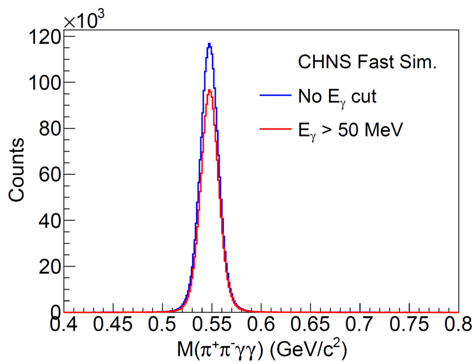
(Very preliminary) $\eta \to \pi^+ \pi^- \pi^0 (\gamma\gamma)$ fast simulation



$$|A(X,Y)|^2 \simeq N(1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + hXY^2 + lX^3 + \ldots)$$







NO.	NAME	VALUE	ERROR
1	N	2.34197e+11	7.64137e+04
2	a	-1.04898e+00	1.49290e-06
3	b	-2.02919e-01	1.97655e-06
4	c	5.23094e-04	4.40604e-07
5	d	-1.63753e-02	9.30251e-07
6	e	1.49152e-03	1.69850e-06

$c = -0.007 \pm 0.009(\text{stat}),$ **WASA@COSY**

$e = -0.020 \pm 0.023(\text{stat}) \pm 0.029(\text{syst})$

- Considering p & E resolution
- Background not considered yet (future work)
- Total reconstruction efficiency ~16%
- Assuming constant beam intensity
- ~6.4×10^{13} η with 1 month running
- 4 orders of magnitude more precise than COSY result

慢引出束流时间结构

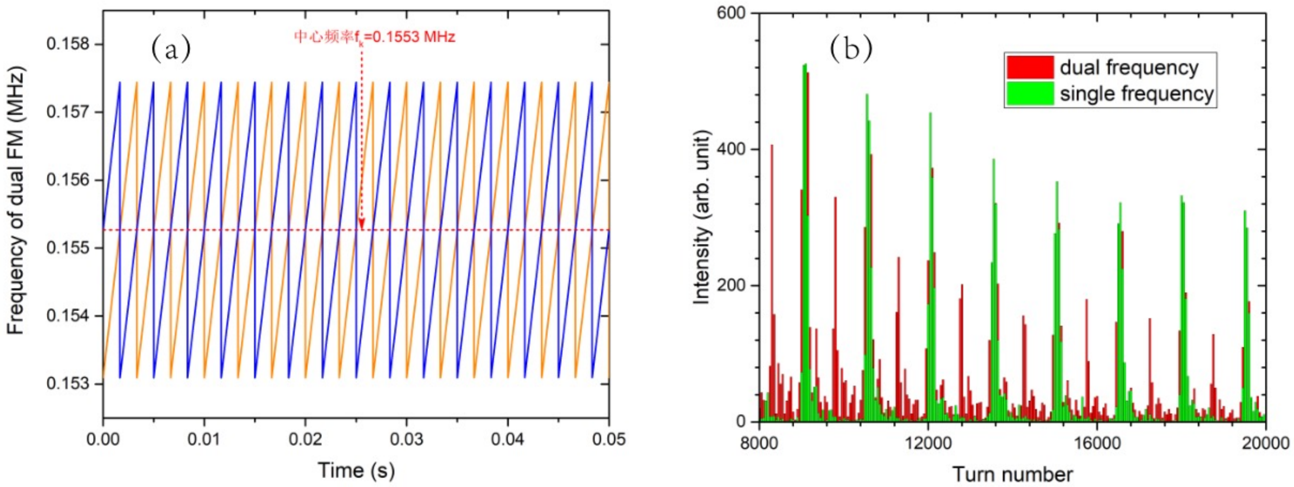


图 5.13 （a）RKO双频调制时频率随时间变化，（b）RKO双频调制对spill时间结构的影响

Figure 5.13 (a) the frequency variation with time in the dual FM process of RKO, (b) the influence of dual frequency modulation of RKO on the spill structure

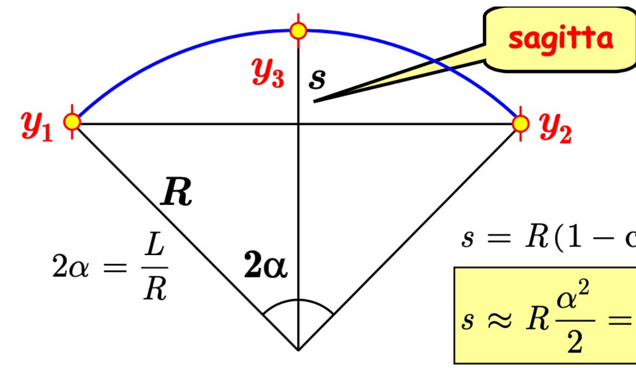
- BRing出来的spill的时间结构
- 红色是双频扫描的，1个峰和1个峰的重复频率在10~30kHz之间，峰与峰之间的束流较少
- BRing引出平台一个周期大约2us，按照3s的引出平顶，总共1.5e6圈，1e11ppp的流强，平均一圈才6.7e4个离子，估计涨落会比较大，也会有时间结构，需要模拟

径迹探测器动量分辨率

- hit误差部分贡献：

$$\frac{\delta p}{p^2} = \frac{\sigma}{0.3BL^2}\sqrt{4C_N}$$

$$C_N = \frac{180N^3}{(N-1)(N+1)(N+2)(N+3)}$$



$$s = R(1-\cos\alpha)$$

$$s \approx R\frac{\alpha^2}{2} = \frac{L^2}{8R}$$

$$R = \frac{p}{0.3B}$$

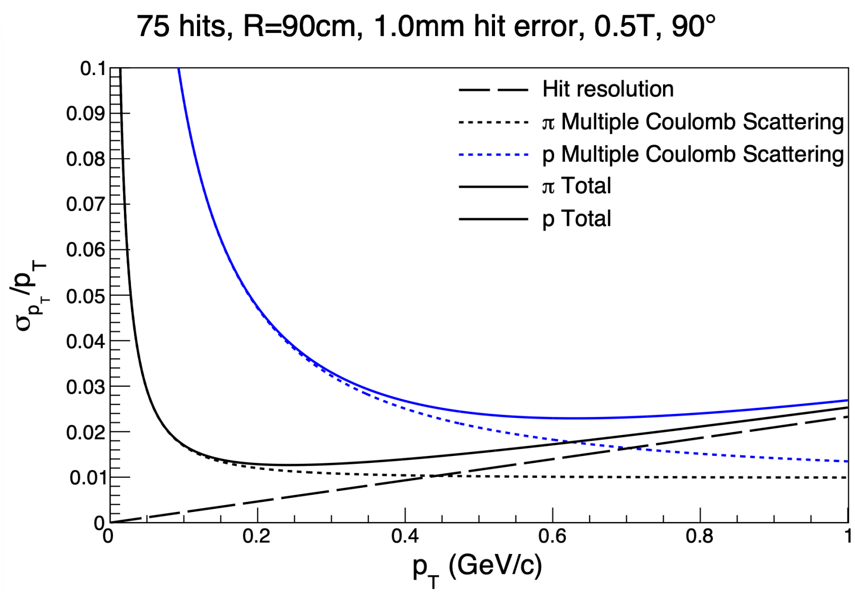
An Introduction to Charged Particles Tracking
– Francesco Ragusa

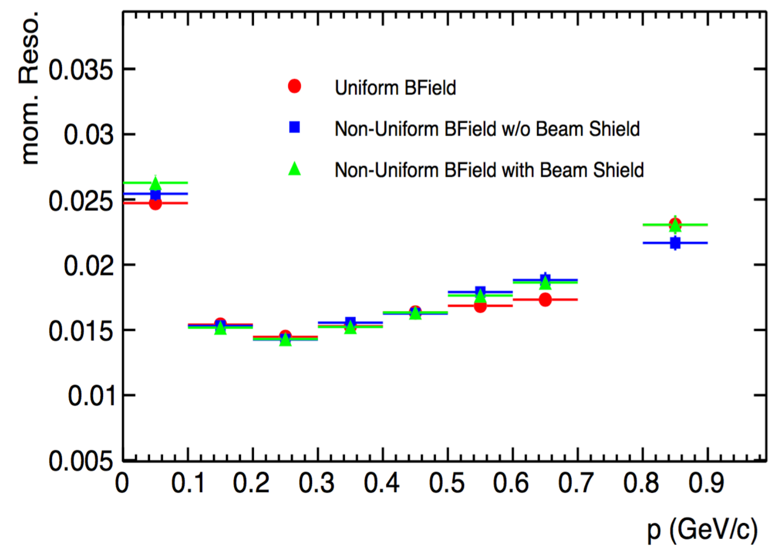
- 多次库伦散射MCS部分贡献：

$$\theta_0 = \frac{13.6}{\beta cp} z\sqrt{x/X_0}\,[1+0.038\ln(x/X_0)]$$

  - 先计算长度l/2的径迹的散射角度θ_0
  - 再计算长度l/2的径迹两端θ_0的角度对应的曲率$1/R = \theta_0/(l/2)$
  - 最后导出MCS动量分辨率贡献 $R = \frac{p}{0.3B}$
  - 这一部分贡献只是一个大概估算，实际情况取决于hit误差与MCS相对贡献大小等

径迹探测器动量分辨率

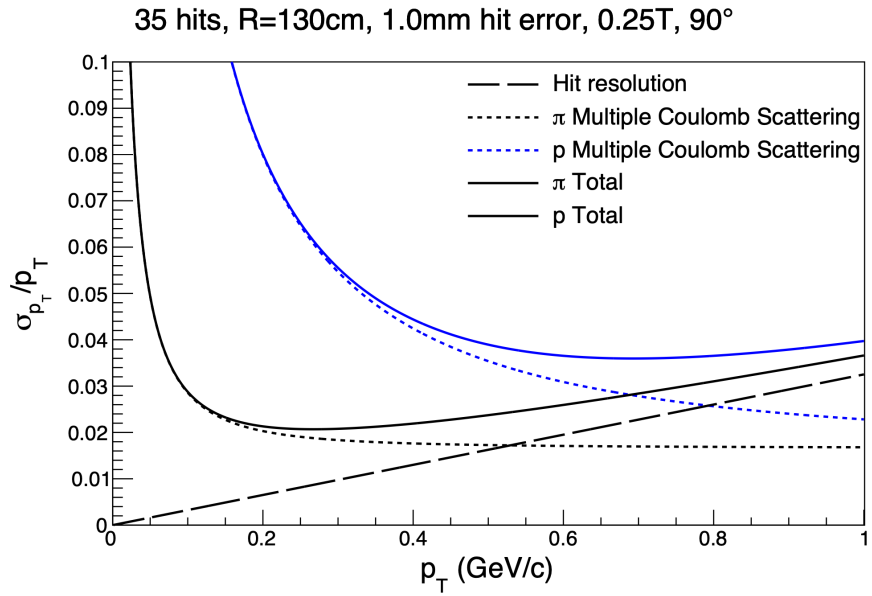


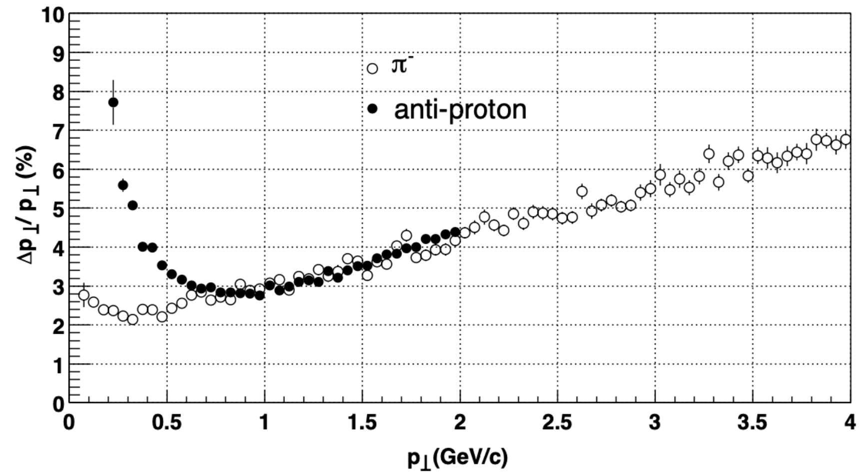


Dhananjaya

- CEE 1-box TPC与模拟结果(pion)比较

径迹探测器动量分辨率





Nuclear Instruments and Methods in Physics Research A 499 (2003) 659–678

- STAR TPC 0.5T磁场下结果，与发表文章的比较

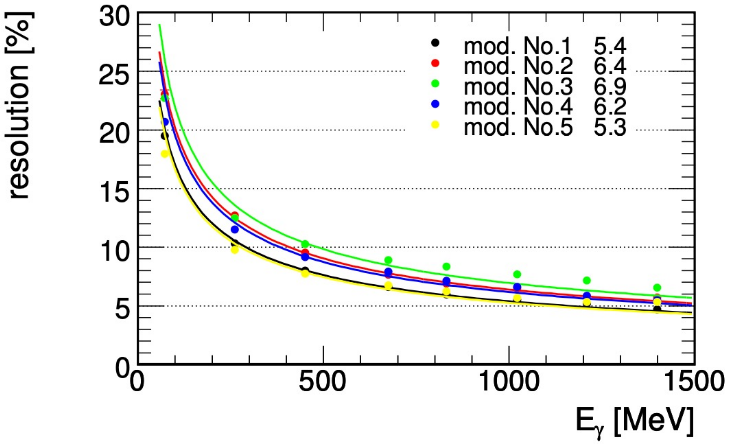
硅径迹探测器

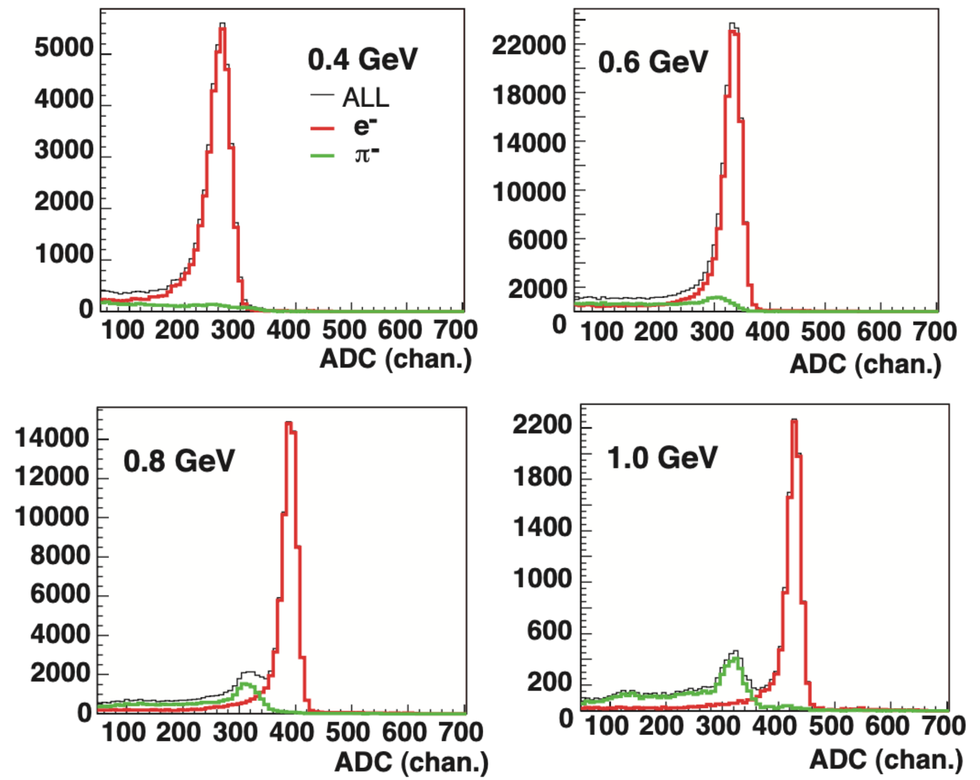
- 造价
  - 400元/cm^2 (芯片100 + FPCB电子学100 + 支撑结构等200）+ 1200万研发费用 + 300万劳务费
  - 总面积28000 cm^2 ⇒ 400 * 28000 = 1100万
    - 桶部：最外层25cm半径，30cm长，最外层面积 3.14*25*2*30 = 4700 cm^2，5层，总面积 4700*6/2 = 14000 cm^2
    - 前端：30cm半径，5层，3.14*30*30*5 = 14000 cm^2
  - 总造价1100万 + 1200万 + 300万 = 2600万

LGAD飞行时间探测器

- 造价
  - LGAD传感器（高能所-微电子所，2平方米）面积： 900万
  - ASIC （TSMC芯片，有不确定性）： 600万
  - 模块组装（倒装焊等）： 400万
  - 电子学读出板：500万
  - 高压系统（假设每个模块单独供高压）：300万
  - 低压系统：100万
  - 冷却系统：300万
  - 电缆等：200万

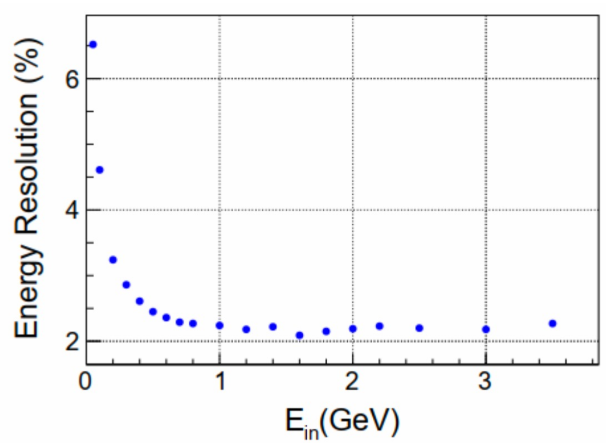
铅玻璃

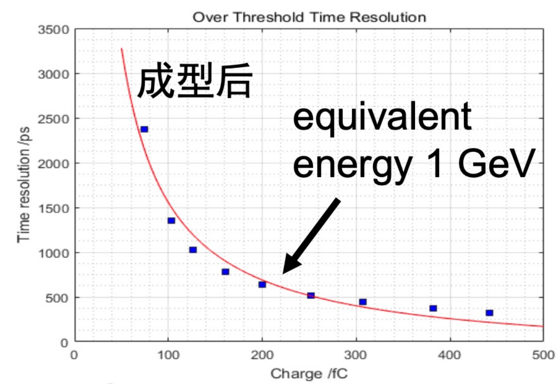




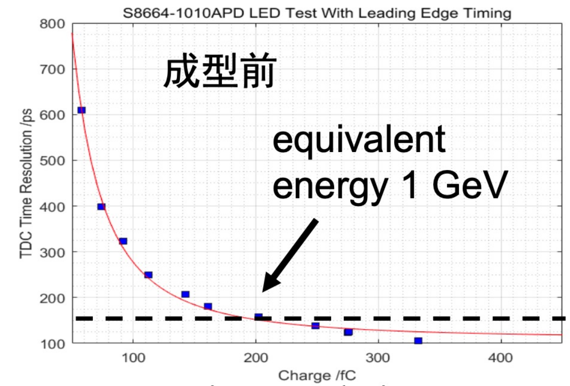
- HADES EMC
- 能量分辨率 ~6% @ 1GeV，~25% @ 50MeV
- 时间分辨~215ps （0.8 GeV电子）
- 成型时间~0.5 μs
- 强子簇射切伦科夫光产额低于电子簇射，有利于压低中子、 π本底
- 造价：~<1000万

纯CsI

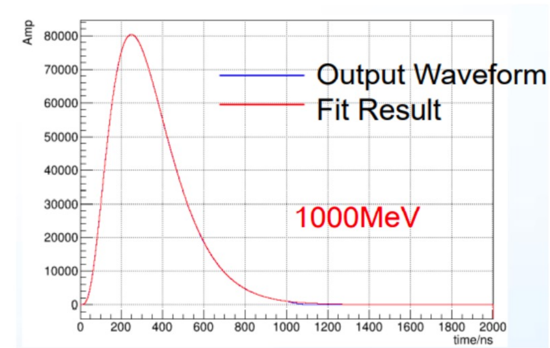


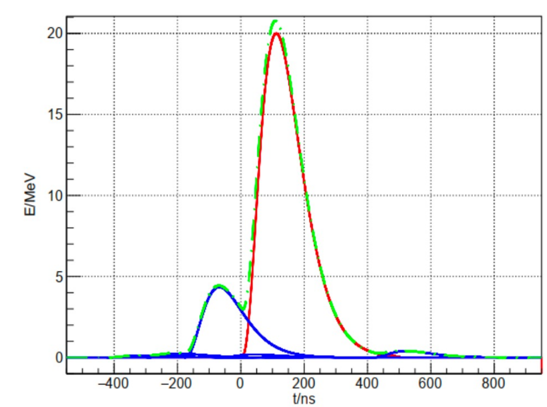


Time resolution



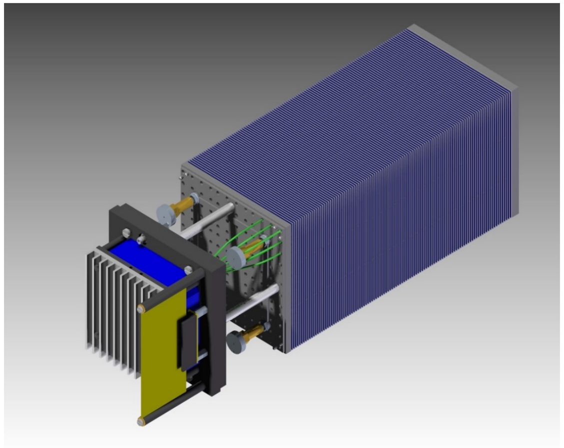
Time resolution

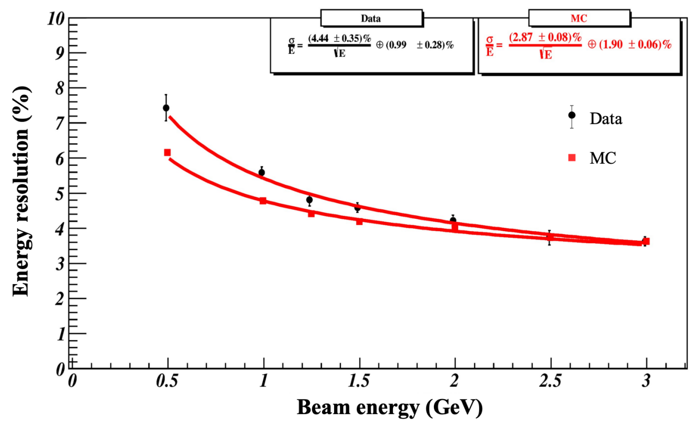


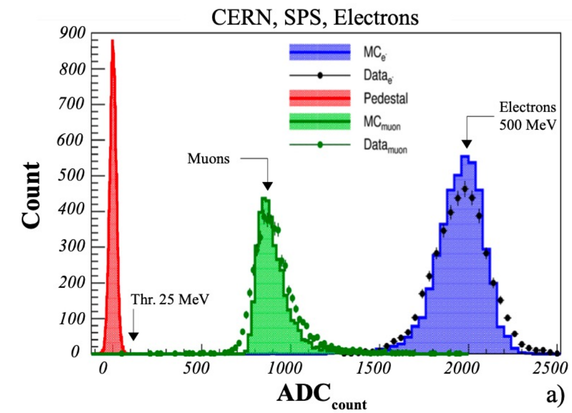


- 科大STCF预研
- 能量分辨率 ~2% @ 1GeV，~7% @ 50MeV
- 时间分辨
  - 成型前：~150ps @ 1GeV，小信号~1ns
  - 成型后：600ps @ 1GeV，<u>小信号几个ns</u>
- 成型时间~1 μs
- 造价：5800万（ θ=10-100度）/ 4000万（ θ=10-60度）

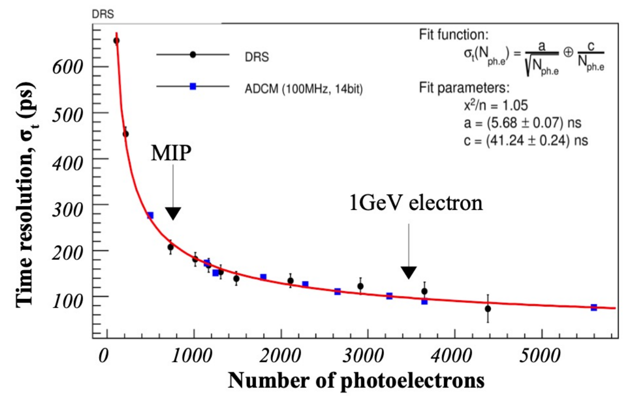
采样型

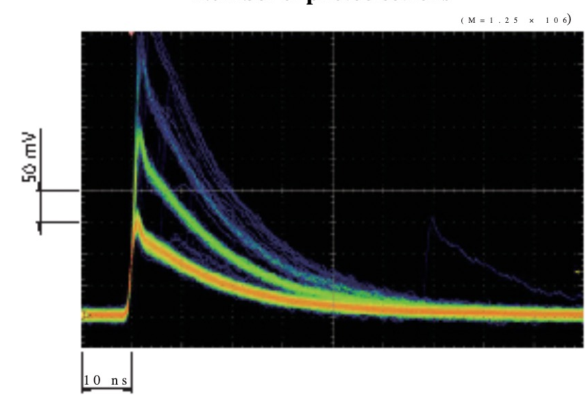






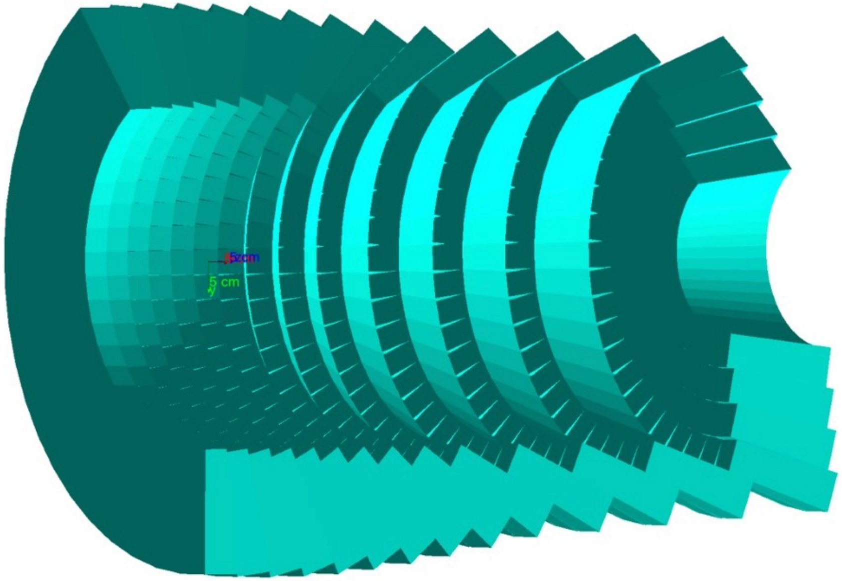
- NICA-MPD量能器，国内清华等参与研制生产
- 0.3mm铅 + 1.5mm塑闪（铅辐射长度0.56cm）
- 能量分辨率~6%@1GeV，~20%@50MeV（公式推算）
- 阈值可设在25MeV
- 时间分辨~100ps @ 1GeV，~500ps @ 50MeV
- Micro-Pixel Avalanche Diodes (MAPD)死时间~50ns
    - 还有没有另外的电子学成型时间？
- 造价~<1千万
    - MPD ECAL 4.5m直径，6m长，第一期造价~3千万





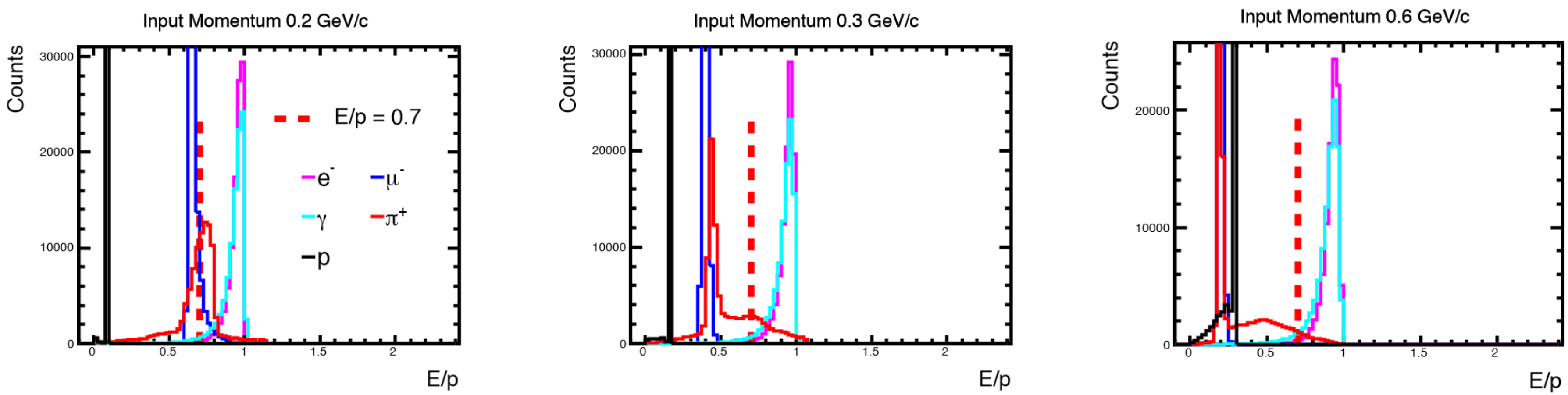
纯CsI电磁量能器

Module	角度	数量	短边(cm)	长边(cm)
Shape 1	6.5	10	4.23	6.5
Shape 2	3	4	5.45	6.5
Shape 3	3	3	5.45	6.5

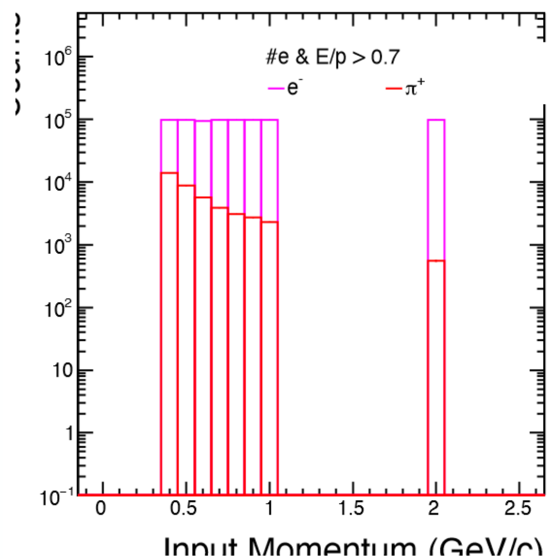


- 纯CsI晶体
  - 光衰减时间：6ns / 35ns快慢成分
  - 光产额：2.3 / 5.6% NaI
- 共~800块晶体，每块长20cm，尾端面6.5cm×6.5cm
- 每块晶体4片APD读出
- 能量分辨率 ~3% @ 1GeV
- 时间分辨好于1ns， 可在100MHz事例率下区分不同事例
- 耐辐射性：100krad未见性能变化，10^{12}中子/cm^{2}辐射后光产额降低0-20%
- 中科大、近物所等 （STCF EMC预研）
- 造价：5800万（ θ=10-100度）/ 4000万（ θ=10-60度）

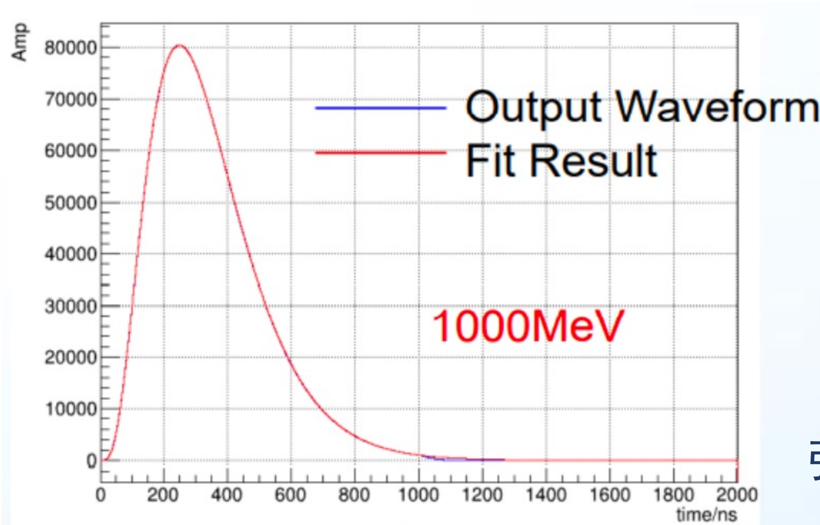
纯CsI电磁量能器



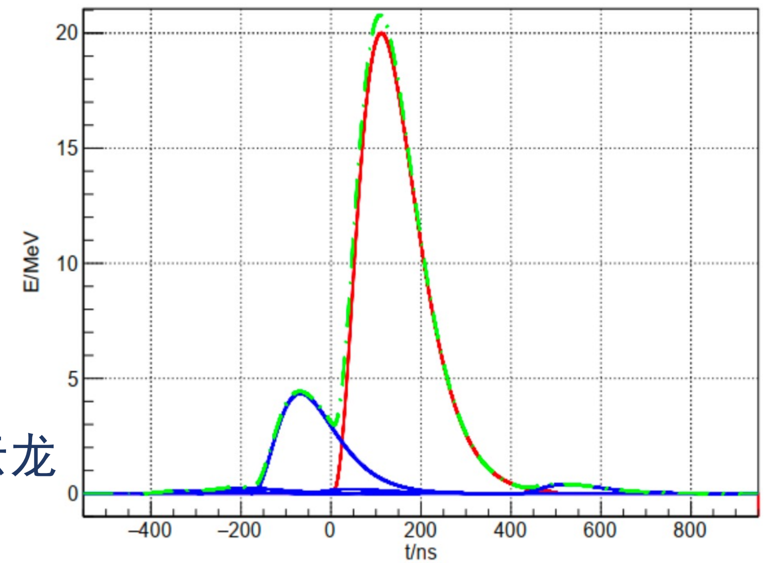
- 从0.2GeV/c动量开始，具有较好的e / π鉴别能力
- π压低一个量级以上



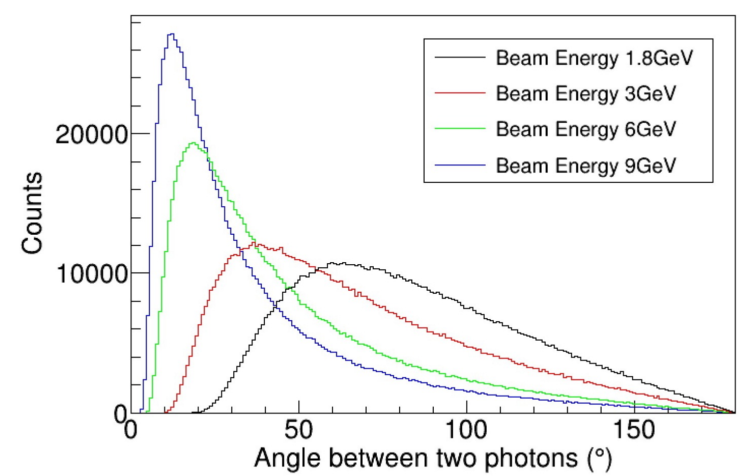
纯CsI电磁量能器



张云龙



$\eta \rightarrow \pi^+\pi^-\pi^0 \rightarrow \pi^+\pi^-\gamma\gamma$



- 电子学输出信号波形可长达1000ns
- 考虑100MHz事例率
- 每事例4个带电粒子+4中子可能簇射
- 每个晶体堆积事例概率~1
- 可用波形采样、拟合处理事例堆积
- 衰变双光子夹角较大，晶体尺寸满足分辨要求

EMC抗辐照性能要求估计

- 电离辐射剂量
  - 100MHz事例率，每个事例1.8GeV能量，一半能量均匀沉积在前角40cm半径，25cm厚的晶体里，则一个月的辐射剂量为
  - 100e6*1.8*3600*24*30*1.60218e-10*0.5 / (3.14*40*40*25*4.51/1000) = 66 Gy
- 中子辐射剂量：
  - 100MHz事例率，每个事例4个中子，一半均匀射向前角40cm半径晶体，则一个月的总中子通量量为
  - 100e6*4*3600*24*30*0.5 / (3.14*40*40) = 1e11 n / cm^2
- 与mu2e实验测试使用剂量(900 Gy、 9e11 n / cm^2)在一个量级 *J. Phys.: Conf. Ser.* **928** 012041
- 可以通过150° C高温退火去除辐射影响Nuclear Instruments and Methods in Physics Research A 432 (1999) 138

缪子探测器

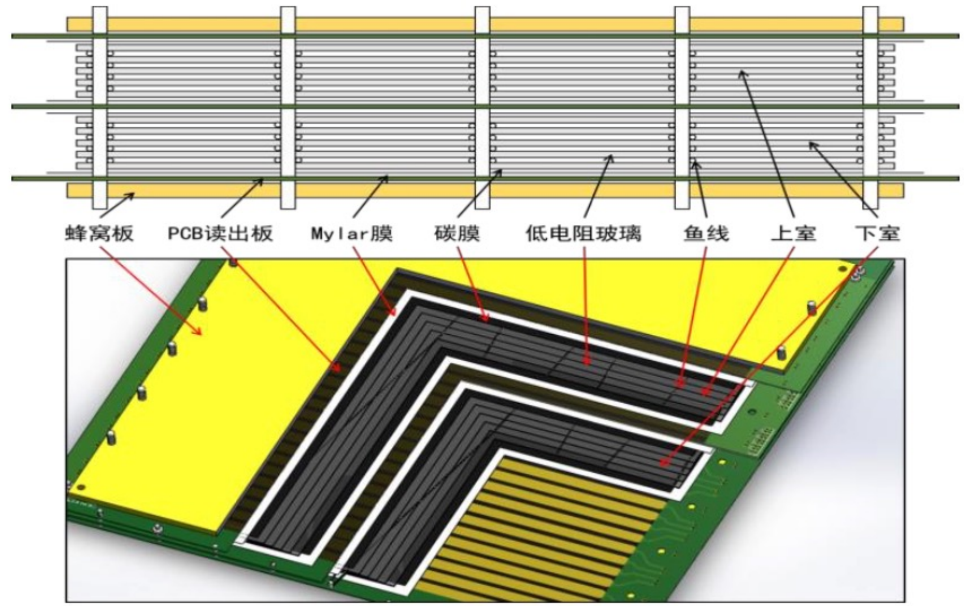


图 10　eTOF MRPC 结构示意图。

- MRPC，类似CEE ETOF
- 读出条pitch 25mm；双端读出时间差得到沿读出条方向位置信息：100ps*c=30mm
- 两个维度均可得到cm量级的位置分辨率，与几十ps的时间分辨配合，可以与径迹进行4维配对，压低强子簇射本底
- 面积：3.14*0.55*0.55 + 3.14*0.8*0.8 + 2*3.14*0.55*1 + 2*3.14*0.8*1 = 11 m^2
- 造价：CEE ETOF 8m^2， 350万 ⇒ 11 m^2, 500万

Beam dump

Back-up

e & muon

C, T, CP-violation

- CP Violation via Dalitz plot mirror asymmetry: $\eta \to \pi^o \pi^+ \pi^-$
- CP Violation (Type I – P and T odd , C even): $\eta \to 4\pi^o \to 8\gamma$
- CP Violation (Type II - C and T odd , P even): $\eta \to \pi^o e^+e^-$ **and** $\eta \to 3\gamma$
- Test of CP invariance via μ longitudinal polarization: $\eta \to \mu^+\mu^-$
- CP inv. via γ^* polarization studies: $\eta \to \pi^+\pi^- e^+e^-$ & $\eta \to \pi^+\pi^-\mu^+\mu^-$
- CP invariance in angular correlation studies: $\eta \to \mu^+\mu^- e^+e^-$
- CP invariance in angular correlation studies: $\eta \to \mu^+\mu^-\pi^+\pi^-$
- CP invariance in μ polar. in studies: $\eta \to \pi^o \mu^+\mu^-$
- T invar. via μ transverse polarization: $\eta \to \pi^o\mu^+\mu^-$ and $\eta \to \gamma\mu^+\mu^-$
- CPT violation: μ polar. in $\eta \to \pi^+\mu^-\nu$ vs $\eta \to \pi^-\mu^+\nu$ - γ polar. in $\eta \to \gamma\gamma$

Other discrete symmetry violations

- Lepton Flavor Violation: $\eta \to \mu^+e^- + c.c.$
- Radiative Lepton Flavor Violation: $\eta \to \gamma(\mu^+e^- + c.c.$
- Double lepton Flavor Violation: $\eta \to \mu^+\mu^+e^-e^- + c.c.$

Non-η/η′ based BSM Physics

- Neutral pion decay: $\pi^o \to \gamma A' \to \gamma e^+e^-$
- ALP's searches in Primakoff processes: $p\,Z \to p\,Z\,a \to l^+l^-$ (F. Kahlhoefer)
- Charged pion and kaon decays: $\pi+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$ and $K+ \to \mu^+\nu A' \to \mu^+\nu e^+e^-$
- Dark photon and ALP searches in Drell-Yan processes: $qqbar \to A'/a \to l^+l^-$

New particles and forces searches

- Scalar meson searches (charged channel): $\eta \to \pi^o H$ with $H \to e^+e^-$ and $H \to \mu^+\mu^-$
- Dark photon searches: $\eta \to \gamma A'$ with $A' \to e^+e^-$
- Protophobic fifth force searches : $\eta \to \gamma X_{17}$ with $X_{17} \to \pi^+\pi^-$
- QCD axion searches : $\eta \to \pi\pi a_{17}$ with $a_{17} \to e^+e^-$
- New leptophobic baryonic force searches : $\eta \to \gamma B$ with $B \to e^+e^-$ or $B \to \gamma\pi^o$
- Indirect searches for dark photons new gauge bosons and leptoquark: $\eta \to \mu^+\mu^-$ and $\eta \to e^+e^-$
- Search for true muonium: $\eta \to \gamma(\mu^+\mu^-)|_{2M_\mu} \to \gamma e^+e^-$
- Lepton Universality
- $\eta \to \pi^o H$ with $H \to \nu N_2$, $N_2 \to h'N_1$, $h' \to e^+e^-$

Other Precision Physics measurements

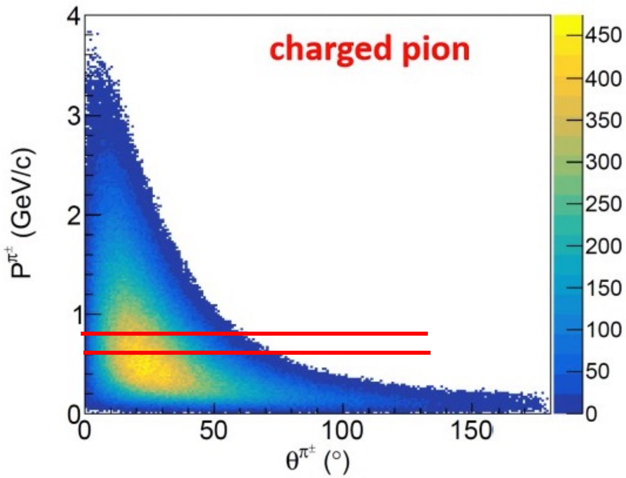
- Proton radius anomaly: $\eta \to \gamma\mu^+\mu^-$ vs $\eta \to \gamma e^+e^-$
- All unseen leptonic decay mode of η / η′ (SM predicts 10^{-6} -10^{-9})

High precision studies on medium energy physics

- Nuclear models
- Chiral perturbation theory
- Non-perturbative QCD
- Isospin breaking due to the u-d quark mass difference
- Octet-singlet mixing angle
- Electromagnetic transition form-factors (important input for g-2)

- 绝大部分eta衰变道研究需要电子 & / 缪子

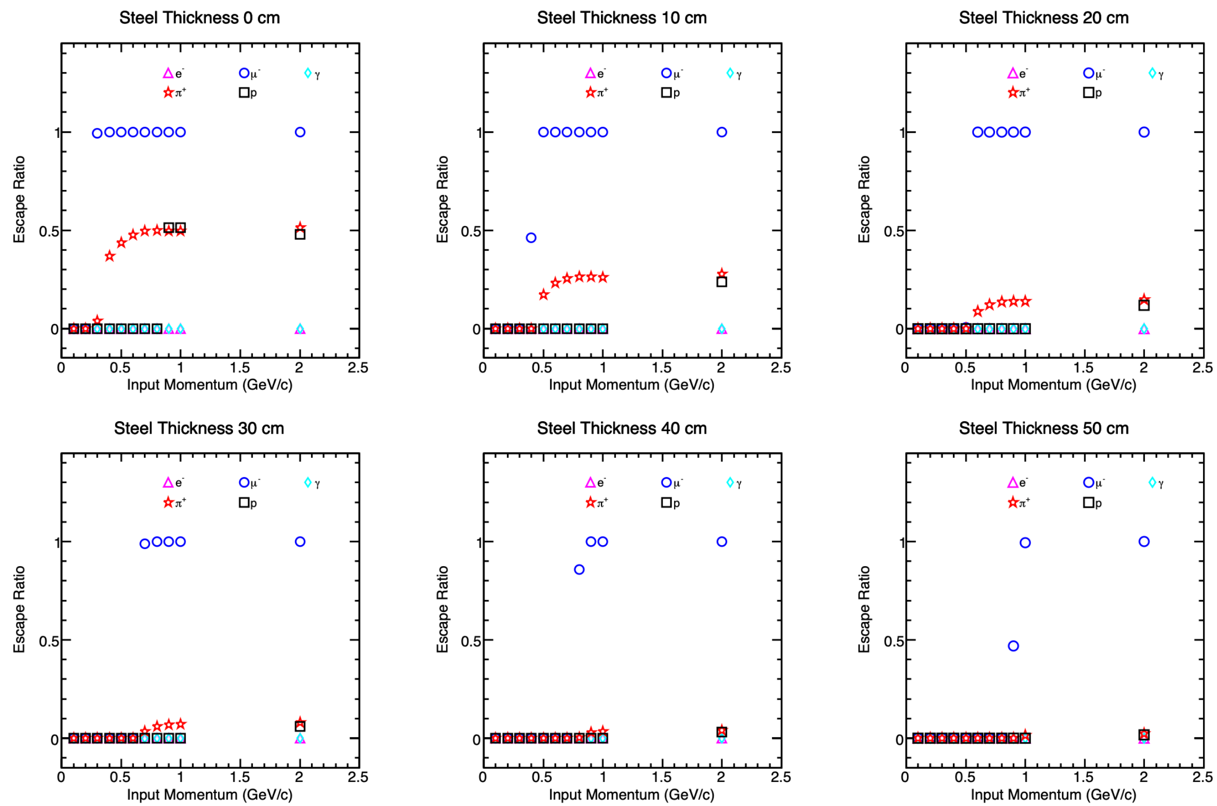
缪子鉴别



eta衰变的pi+-分布

近似为衰变缪子分布

王荣



孙旭

- 低动量下鉴别缪子、高效排除pi+-，很困难 ⇒ 可能只需要覆盖前角10-60度范围
- 可以调节EMC+铁的厚度，选取一定动量以上的缪子进行鉴别
- 例如，选取25cm CsI + 20cm铁，可以选择0.6GeV/c以上缪子，pi+-排除在7倍左右
- 选取25cm CsI + 40cm铁，可以选择0.8GeV/c以上缪子，pi+-排除在30倍左右
- 需要结合真实物理eta、本底产额、衰变运动学进行模拟，决定最佳铁厚度

量能器（晶体）

Table 6.2 Properties of scintillating crystals applied in particle physics experiments

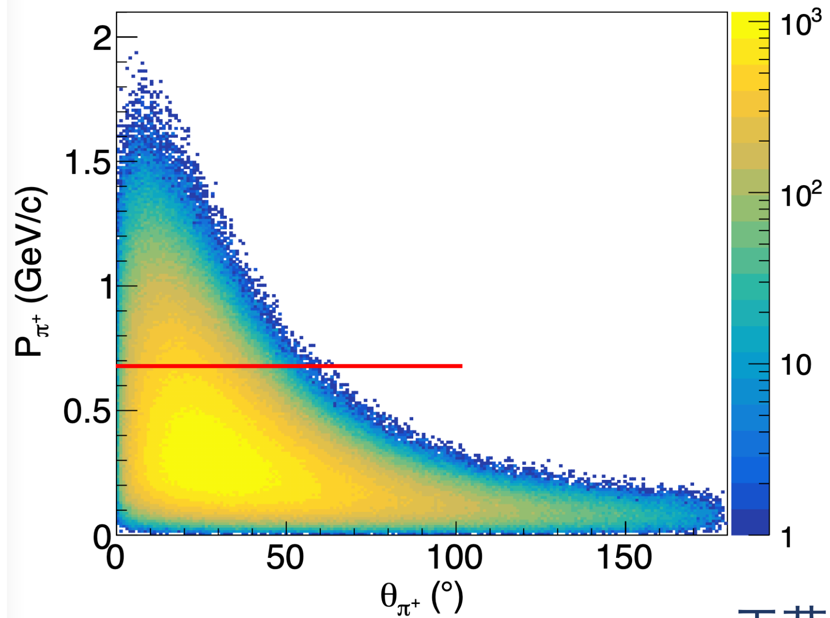
	NAI(Tl)	CsI(Tl)	CsI	BaF_2	CeF_3	BGO	$PbWO_4$	LYSO
Density [g cm^{-3}]	3.67	4.51	4.51	4.89	6.16	7.13	8.3	7.1
Radiation length [cm]	2.59	1.85	1.85	2.06	1.68	1.12	0.89	1.16
Molière radius [cm]	4.8	3.5	3.5	3.4	2.6	2.3	2.0	2.07
Interaction length [cm]	41.4	37.0	37.0	29.9	26.2	21.8	18.0	20.3
dE/dx)mip [MeV cm^{-1}]	4.79	5.61	5.61	6.37	8.0	8.92	9.4	9.2
Refractive index [at λ_{peak}]	1.85	1.79	1.95	1.50	1.62	2.15	2.2	1.8
Hygroscopicity	Yes	Slight	Slight	No	No	No	No	No
Emission spectrum, λ_{peak}								
Slow component [nm]	410	560	420	300	340	480	510	
Fast component [nm]			310	220	300		510	420
Light yield rel. to NaI								
Slow component	100	45	5.6	21	6.6	9	0.3	
Fast component			2.3	2.7	2.0		0.4	75
Decay time [ns]								
Slow component	230	1300	35	630	30	300	50	
Fast component			6	0.9	9		10	35

林德旭

- 考虑到几百MHz的事例率，需要光衰减时间~ns量级
- 初步考虑纯CsI，紫外扩展的SiPM，只对6ns快成分敏感 ~3个事件堆积，可以接受
    - 能量分辨率~2.3%@1GeV，总造价约1亿，科大STCF正在进行相关预研
- BaF2快成分光衰减时间0.9ns，但比CsI贵2-3倍 ⇒ ~2亿量能器造价，可能太贵了

切伦科夫探测器(待定)

- 是否需要，取决于TOF和EMC能否在整个动量范围衔接电子鉴别
  - TOF：e / pi 鉴别 @ p<0.3 GeV/c
  - EMC: ?



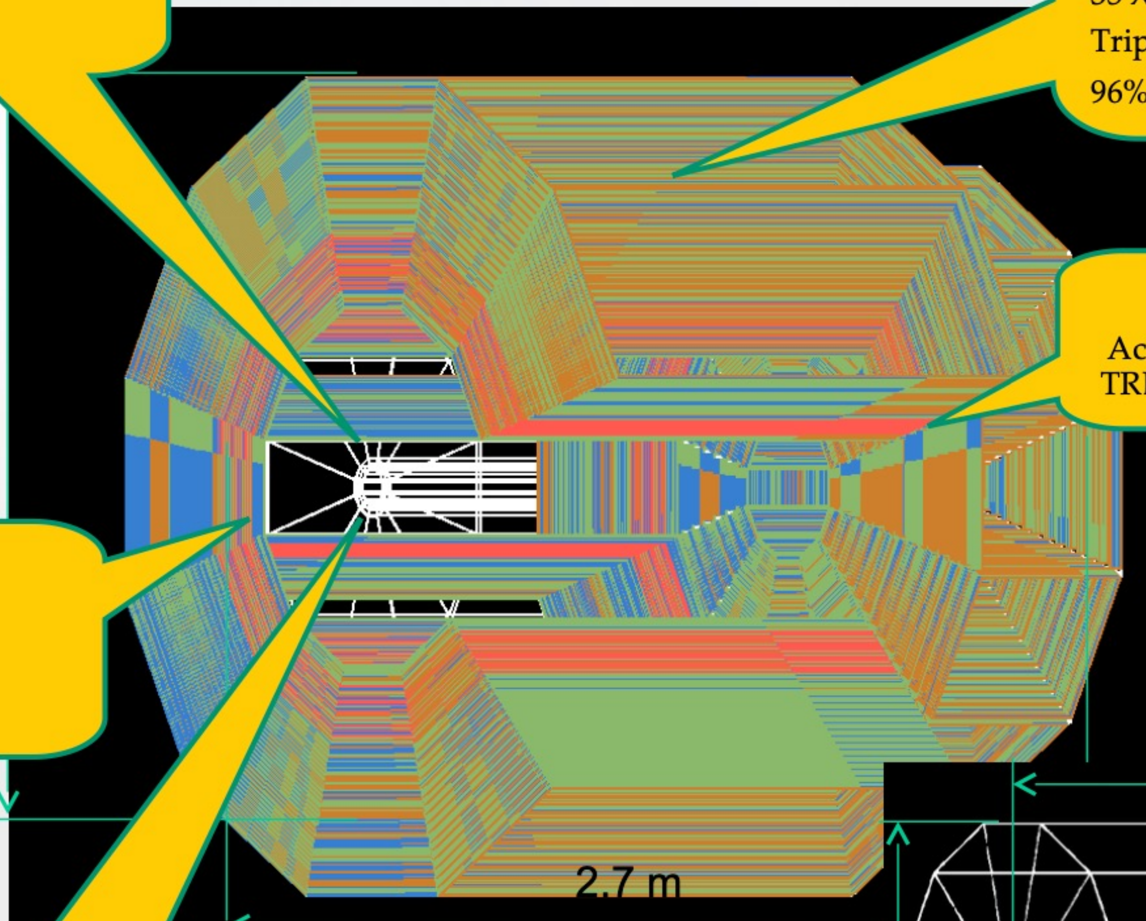
王荣

- 与REDTOP的CTOF类似
- 气凝胶介质，选择折射率1.02
- 只有粒子beta > 1/1.02 = 0.98，才会发出切伦科夫光
  - e: p > 2.5 MeV ⇒ 几乎所有电子可见
  - pi: p > 685 MeV ⇒ 排除绝大部分强子，更高动量e pi鉴别依靠电磁量能器
- 只探测有无切伦科夫光，不成像
  - 制作成简单、统一的模块：暗盒、白膜、SiPM读出
  - 无需成像系统、无需高精度的平面 ⇒ 低成本、低风险
- REDTOP CTOF造价（最便宜版本）：0.6 M USD ⇒ 400万元

REDTOP detector

Central Tracker
~ 1m x 1.5 m
Thin LGAD
98% coverage

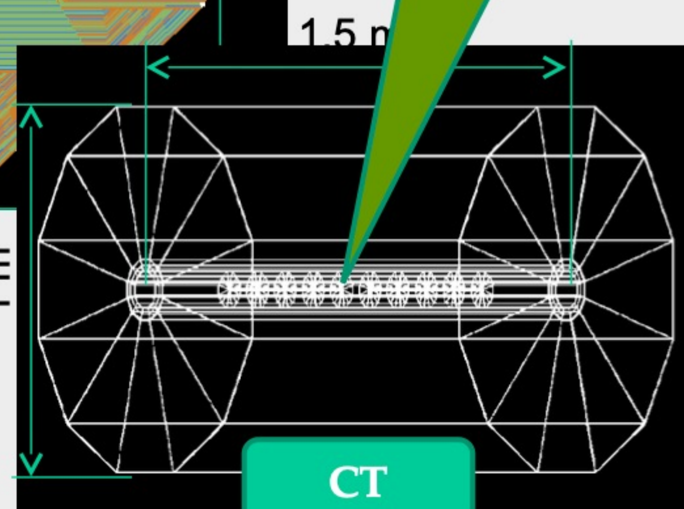
ADRIANO2 Calorimeter (tiles)
Scint. + heavy glass sandwich
35 X_0, 2.9λ_I (~ 64 cm deep)
Triple-readout +PFA
96% coverage



μ-polarizer
Active version (from TREK exp.) - optional

CTOF
~ 1m x 1.5 m
Lead-glass tiles
98% coverage

10x Be or Li targets
•0.33 mm thin
•Spaced 10 cm



Fiber tracker or ITS3
for rejection of γ-conversion and vertexing