Reimei WS at Tokai/J-PARC
August/09/2016

Hadron Physics at J-PARC K10 beam line

Hiroaki Ohnishi
RIKEN/RCNP Osaka Univ.

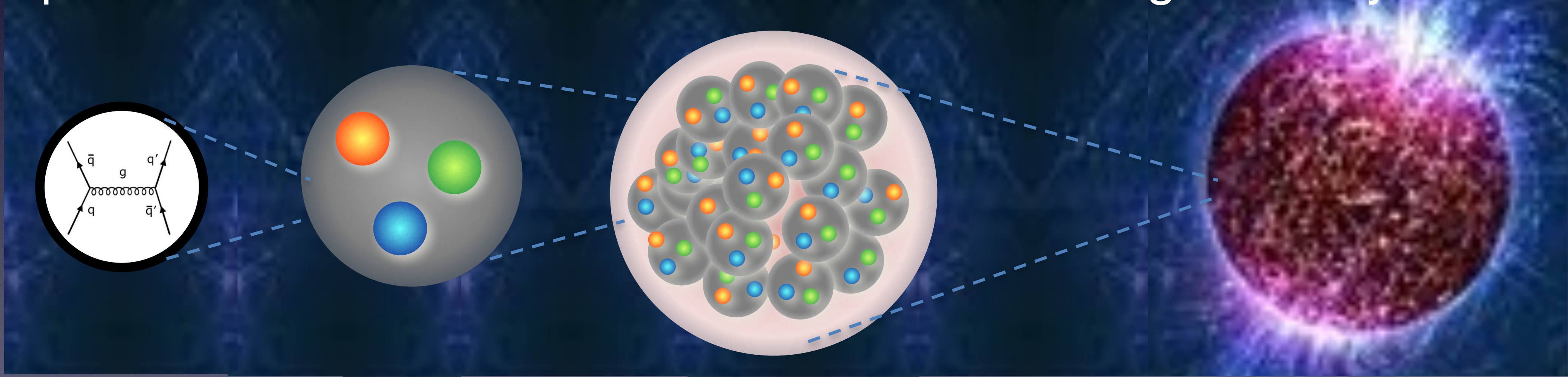
How the matter created by QCD

QCD is the “theory” to describe strong interaction

Final goal is to understand strong interacting matter

quark/hadron/nuclei to high density nuclear matter

quark hadron nuclei high-density matter



However, even the first step

how hadron created from quarks is not clear yet.

Questions need to be answered

- How hadrons are formed from quarks What is the effective DoF to describe hadron?
- How the property of the hadron are changing when the environmental condition is changed, such as high density?

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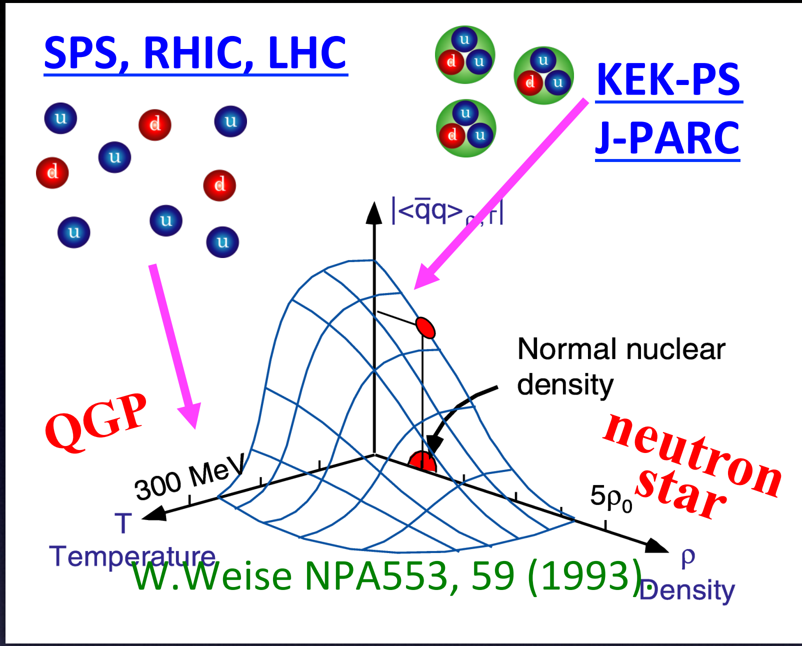
Hadron in nuclear media



- quark condensates $<\bar{q}q>$ will change as a function of T/ρ
- $<\bar{q}q>=0$ will be realize at high T and ρ (restoration of chiral symm.)
- relation exist between $<\bar{q}q>$ and Hadron mass, for example, Gell-Mann-Oakes-Renner relation

$$-4m_q<\bar{q}q>=m_\pi^2 f_\pi^2$$

$$-(m_q+m_s)<\bar{q}q+\bar{s}s>=m_K^2 f_K^2$$

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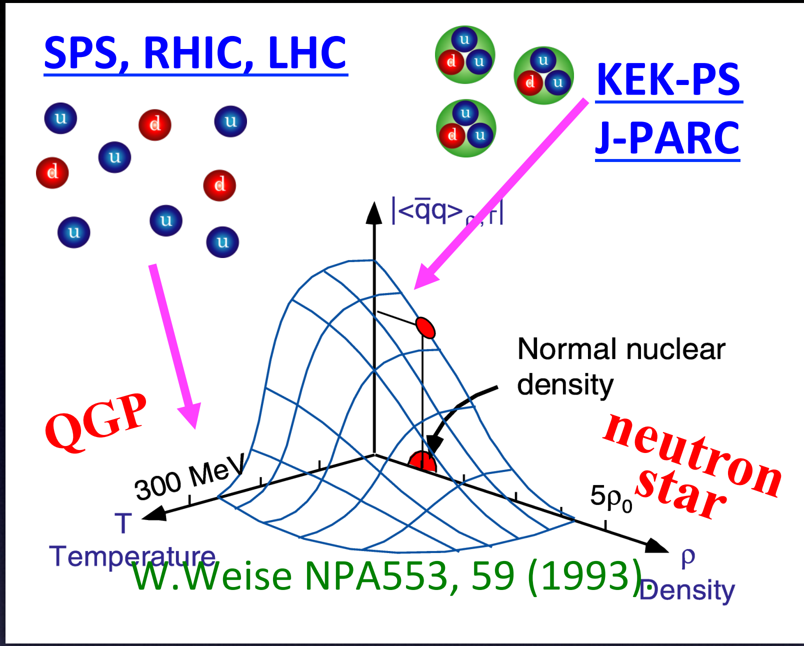

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Meson property will change under the extremely condition

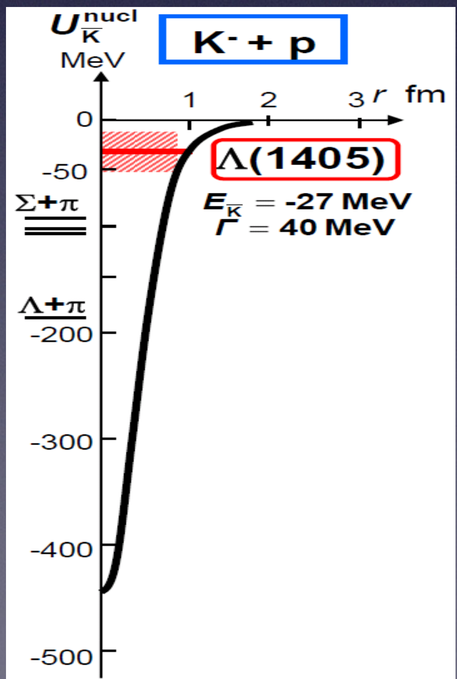
The property of the hadron in nucleus

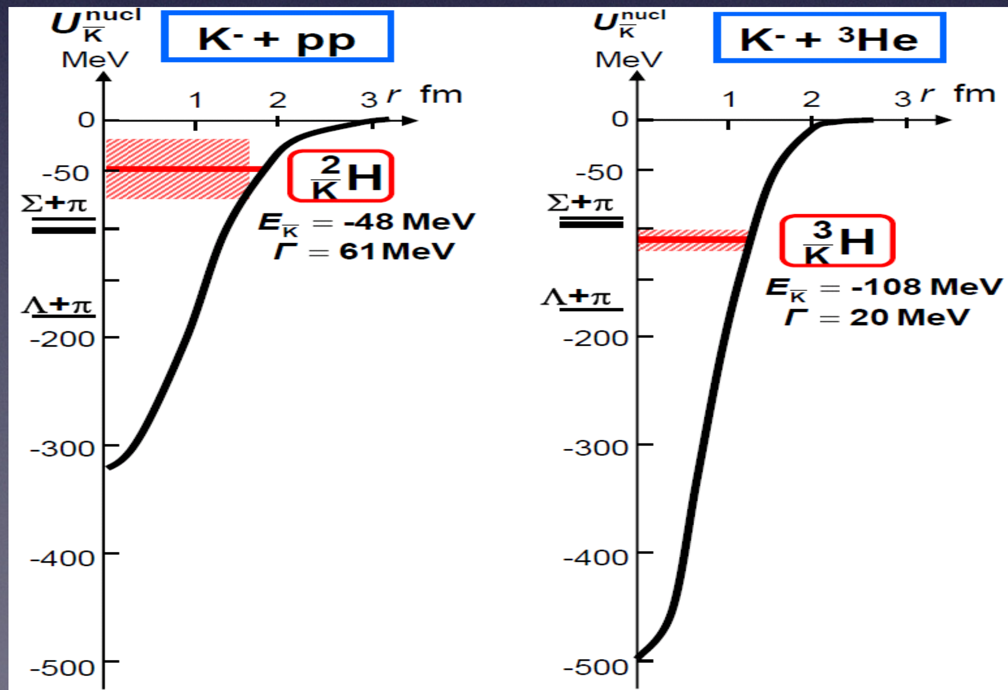
- Meson in nucleus will be a good probe to investigate QCD vacuum structure, $c.f. < q\bar{q} >_\rho @ \ \rho \neq 0$
- different meson will probe different condensation parameters

$$\begin{cases} \pi & : -4m_q < \bar{q}q >= m_\pi^2 f_\pi^2 \\ \text{K} & : -(m_q + m_s) < \bar{q}q + \bar{s}s >= m_K^2 f_K^2 \\ \rho, \omega \text{ (light } q\bar{q} \text{)} & : < \bar{q}q >_\rho^2 + < \bar{u}\gamma_\mu D_\mu u >_\rho \\ \phi \ (\bar{s}s) & : m_s < \bar{s}s >_\rho + \cdots \\ \text{D (light-heavy)} & : m_Q < \bar{q}q >_\rho + \cdots \end{cases}$$

One example: Kaon($\bar{K}$) in nucleus

- $\bar{K}$ and N interaction is strongly attractive (Λ(1405) play the leading role in $\bar{K}$N interaction)
- If attraction is strong enough, Kaonic nucleus ($\bar{K}$ nucleus bound state) will be cleated

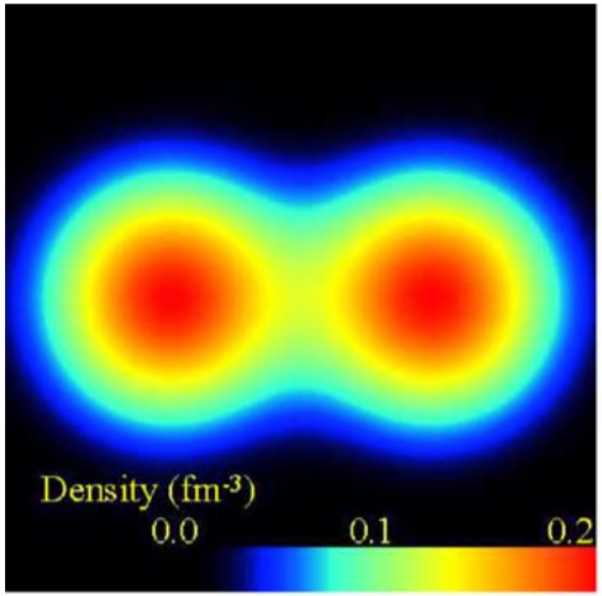




Y.Akaishi & T.Yamazaki, PLB535, 70(2002).

Why Kaonic nucleus

- why Kaonic nucleus is interesting/important?
  - High density nuclear matter could be produced due to strong attraction between $\bar{K}$ and nucleon



(a) ^{8}Be

A. Doté et al. / Physics Letters B 590 (2004) 51–56

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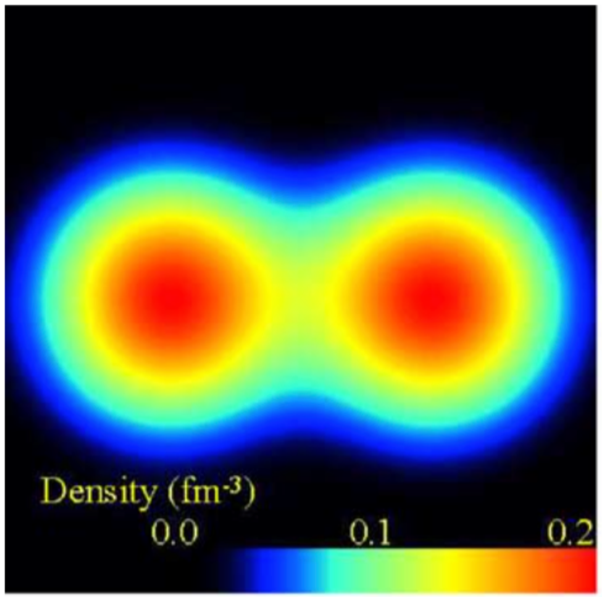
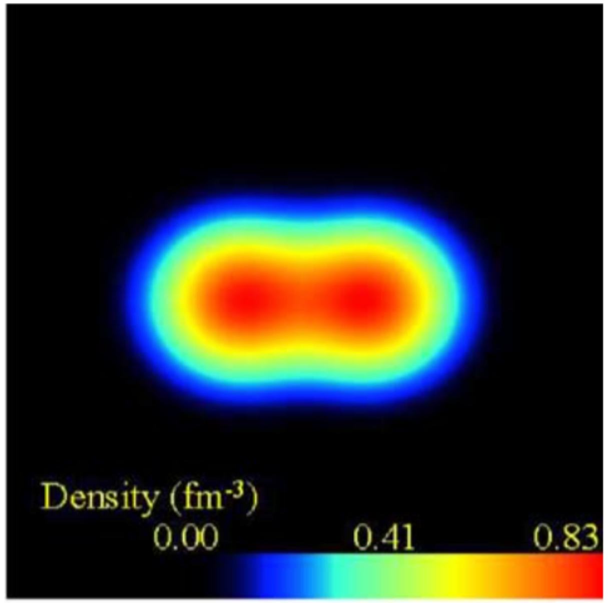


(a) ^{8}Be

adding $\bar{K}$



(b) ^{8}BeK^{-}

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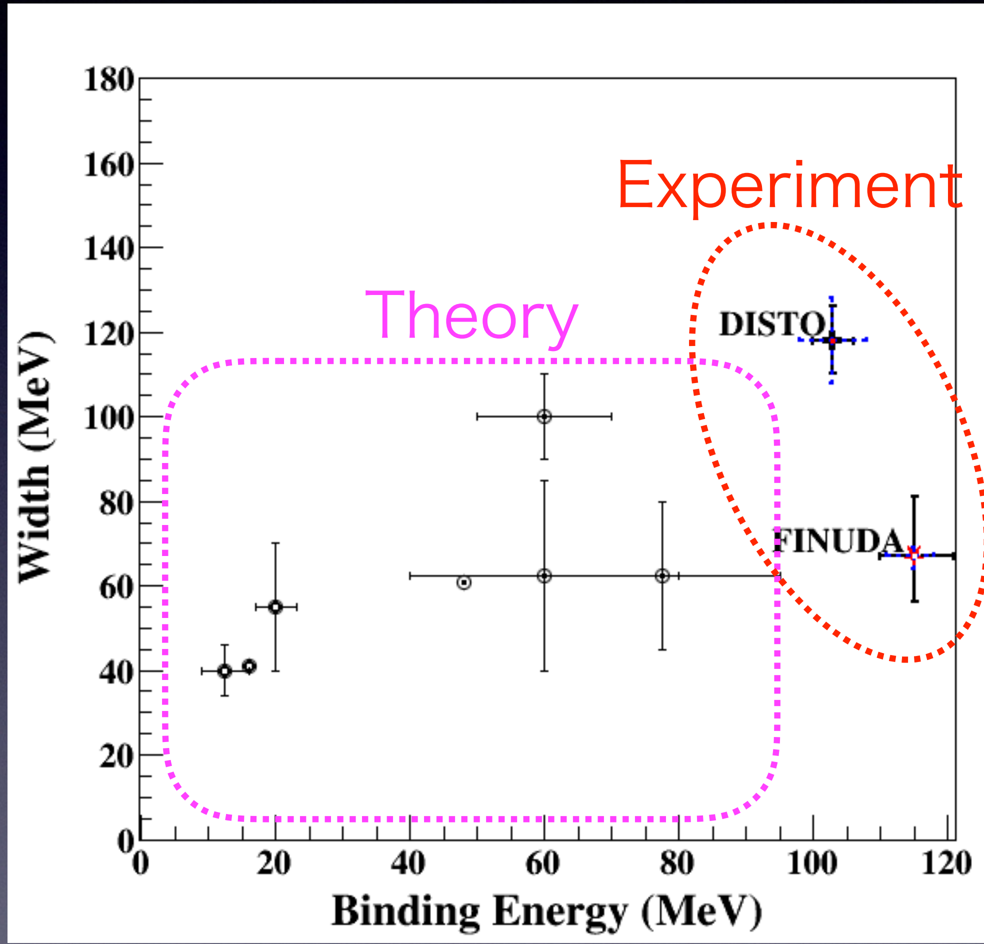

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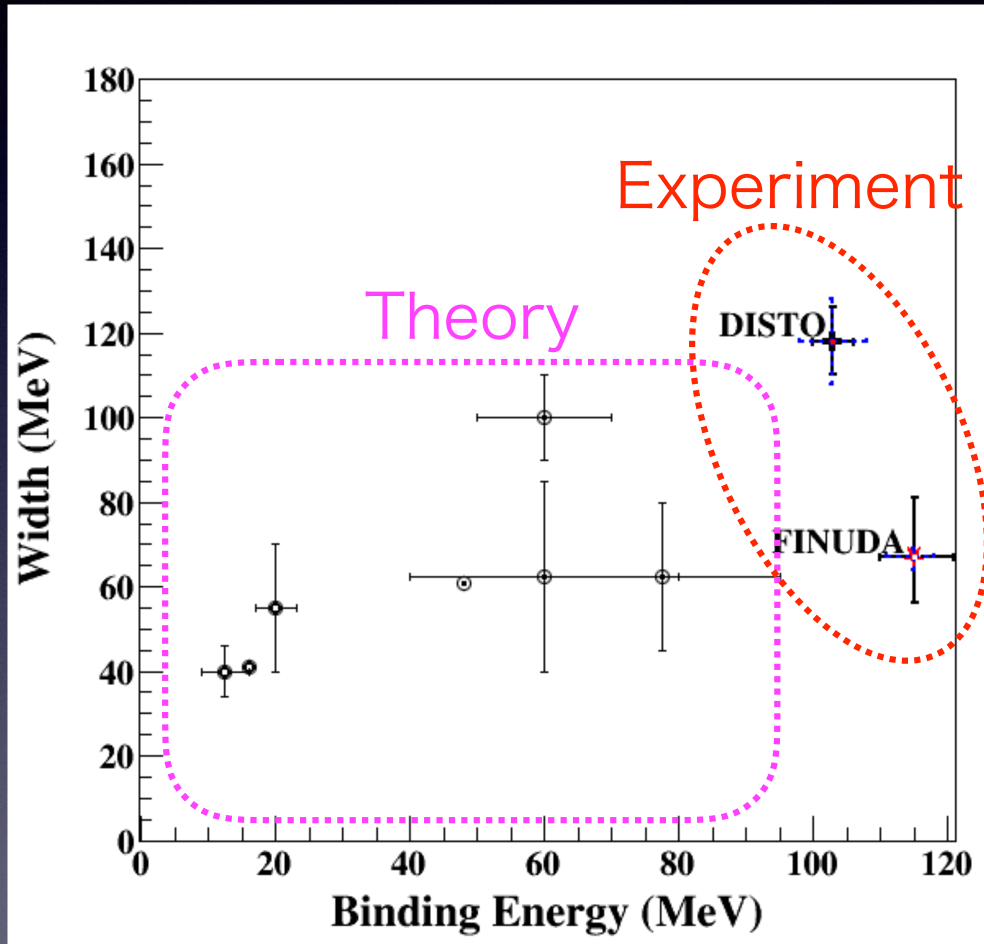

Recently , new very important results are reported from J-PARC

K-pp(or S=-1 dibaryon)?

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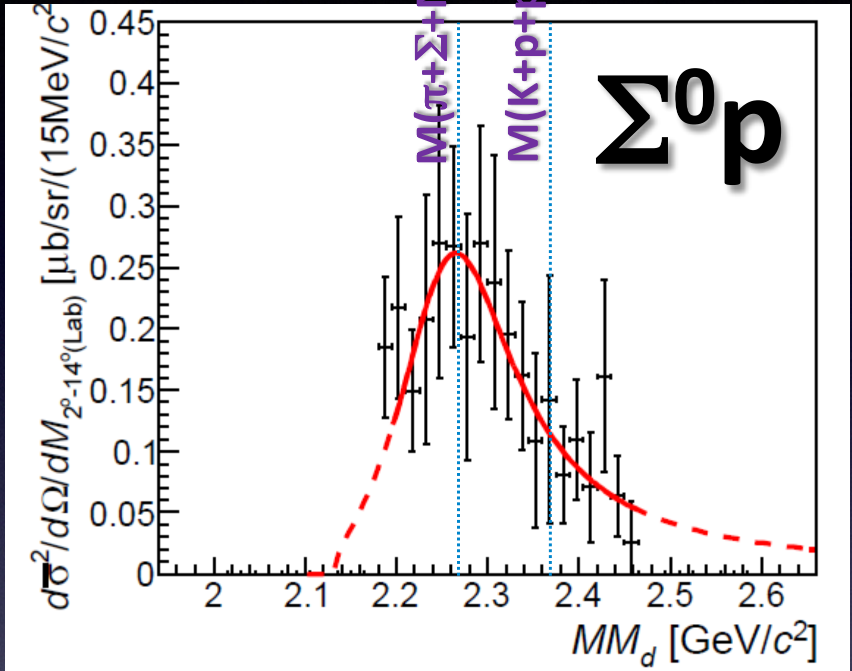
d(π^+,K$^+$) reaction/E27



Y. Ichikawa et al., **PTEP (2015) 021D01**

- "K$^-$pp"-like structure in **Σ^0p** decay mode:
  - Mass *Relativistic Breit-Wigner*

    $2275\ ^{+17}_{-18}\ (\text{stat.})\ ^{+21}_{-30}\ (\text{syst.})\ \text{MeV}/c^2$
  - Binding energy

    $95\ ^{+18}_{-17}\ (\text{stat.})\ ^{+30}_{-21}\ (\text{syst.})\ \text{MeV}$
  - Width

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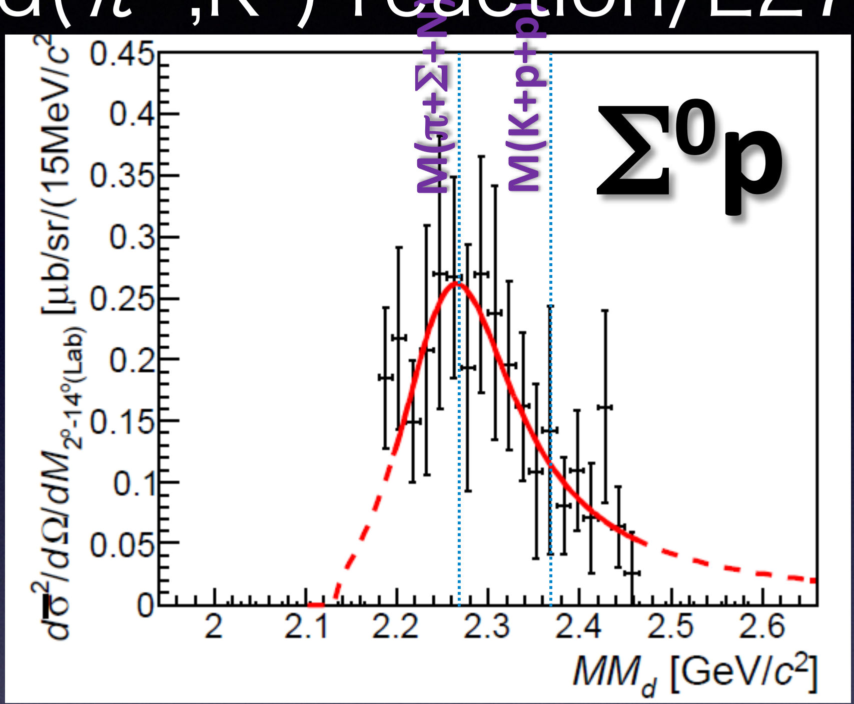

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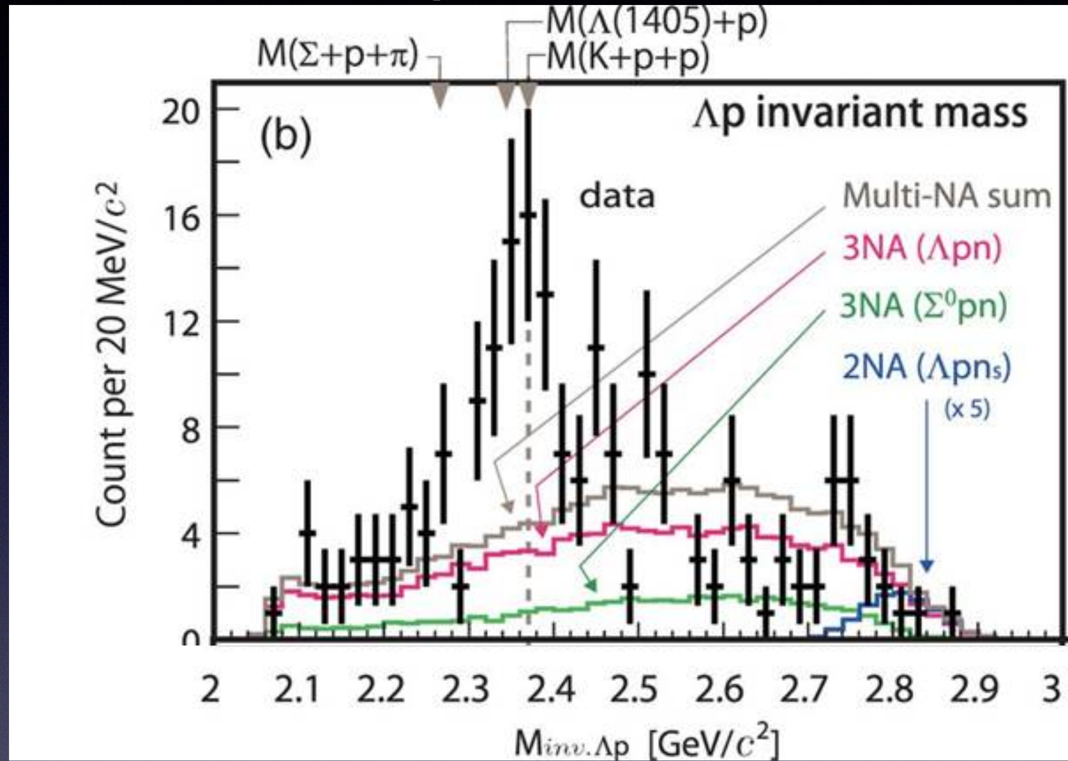
^{3}He(K-,Λp)n reaction/E15



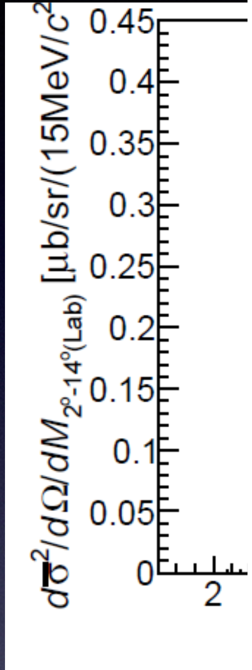
Y. Sada et al., PTEP (2016) 051D01.

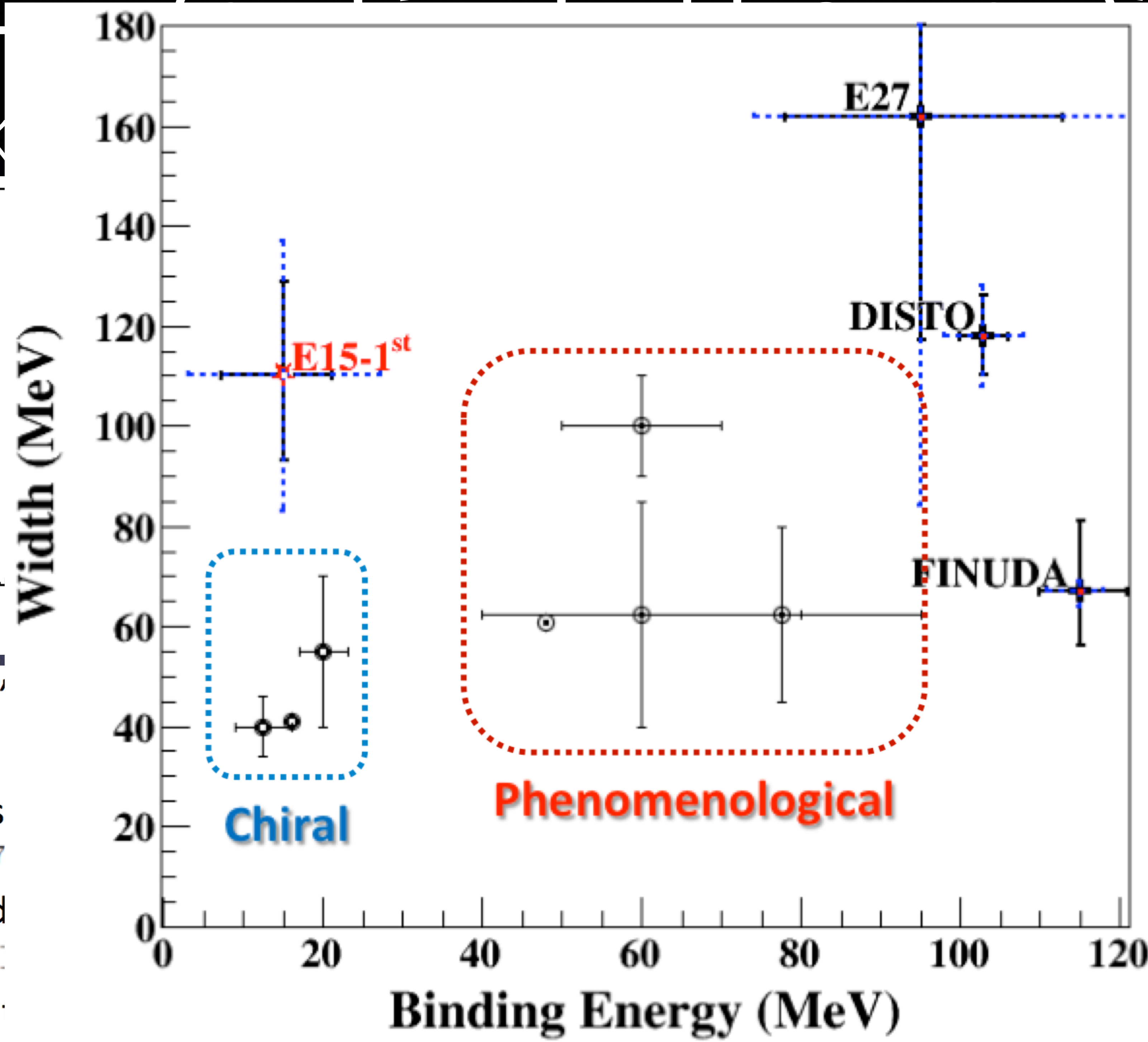
B.E = 15^{+6}_{-8} (stat.) ± 12(syst.) MeV/c²
Γ = 110^{+19}_{-17}(stat.) ± 27(syst.) MeV/c²
Q = 400^{+60}_{-40} MeV/c

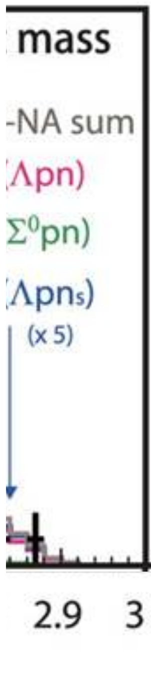
$$\frac{d^2\sigma_X}{dM_{inv.\Lambda p}dq} \propto \rho_3(\Lambda pn) \times \frac{(\Gamma_X/2)^2}{(M_{inv.\Lambda p} - M_X)^2 + (\Gamma_X/2)^2} \times |\exp(-q^2/2Q_X^2)|^2,$$

K- ... ?

d(π^+,K ... E15







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- "K-pp" ... decay
  - Mas ... MeV/c²
    227
  - Bind ... MeV/c²
    95
  - Wid
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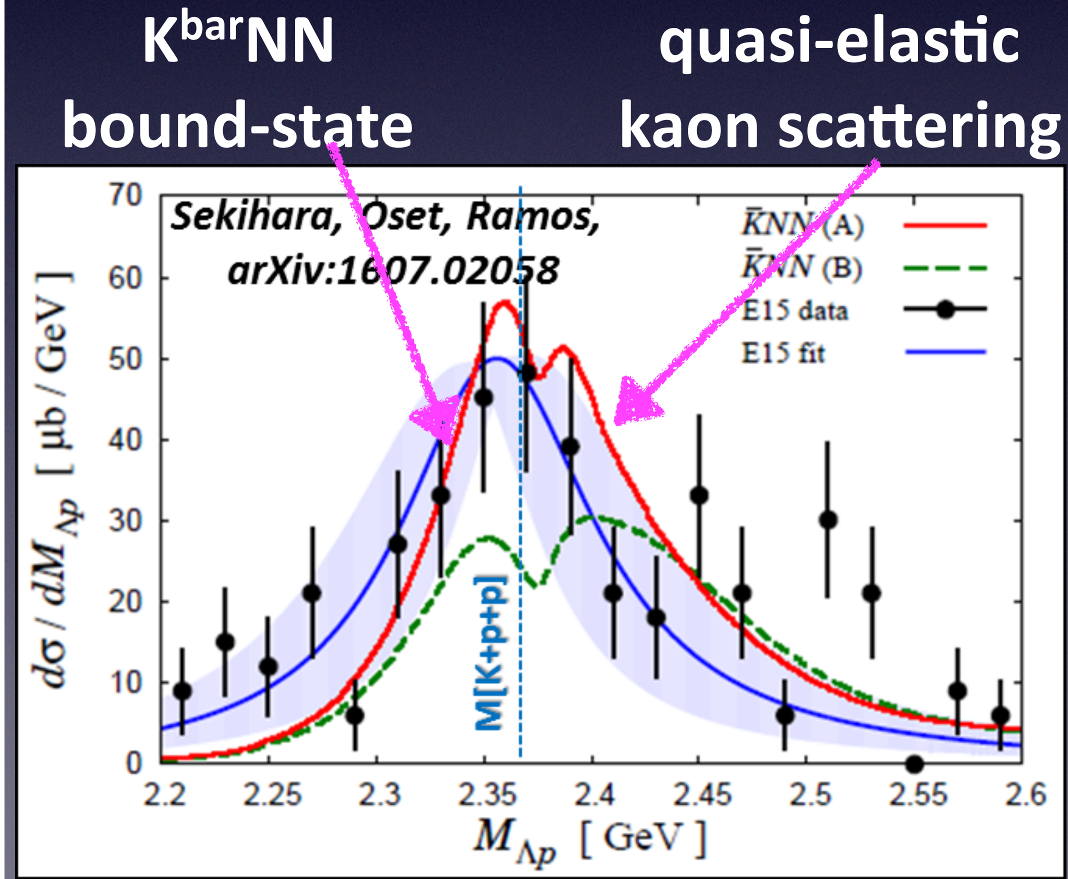
Theoretical interpretation and new data

- Sekihara, Oset, Ramos, arXiv:1607.02058
  - Two peak structures near the KNN threshold are predicted



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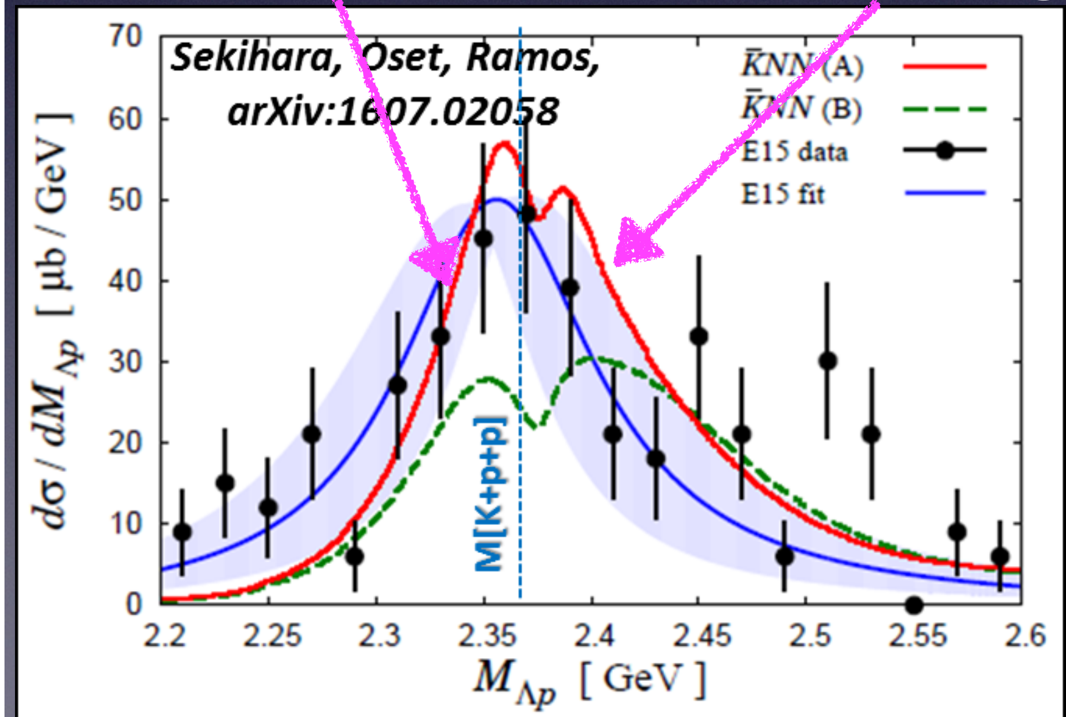
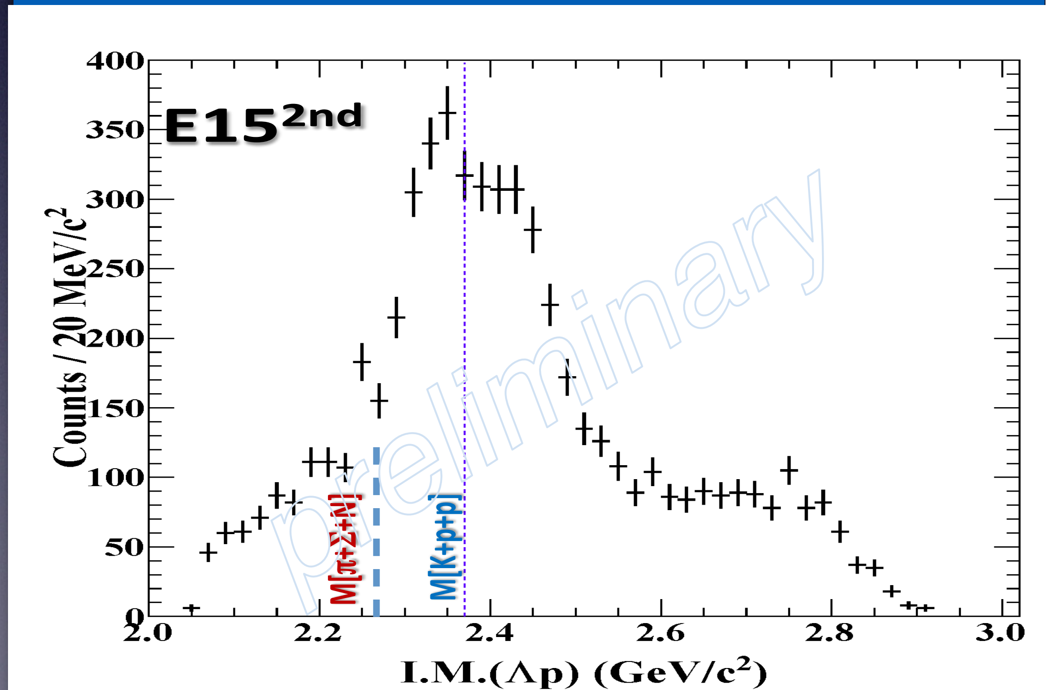
K^bar NN bound-state

quasi-elastic kaon scattering



New high statistics data from E15



data indicates two peaks!

Meson in nucleus

- $\overline{K}$ nucleus will be studied insensibly at J-PARC (for example search for the bound state other than $\overline{K}NN$)
- It will be very interesting, if we will be able to produce “double $\overline{K}$ in nucleus”.
  it may be possible, via (K-,K+) reaction or $\overline{p}_{stop}$ on ^{3}He ($\overline{p}_{stop}$ +^{3}He → K+K+ K-K-pn)
  But, it will be difficult due to huge background
- HI collision will be good place to search such exotic state, even though huge background is expected.

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What will be next?

Lesson from resent progress on hadron physics

Recent discoveries

- Many tetra/penta-quark candidates are discovered at collider experiments such as Belle/LHCb, etc.

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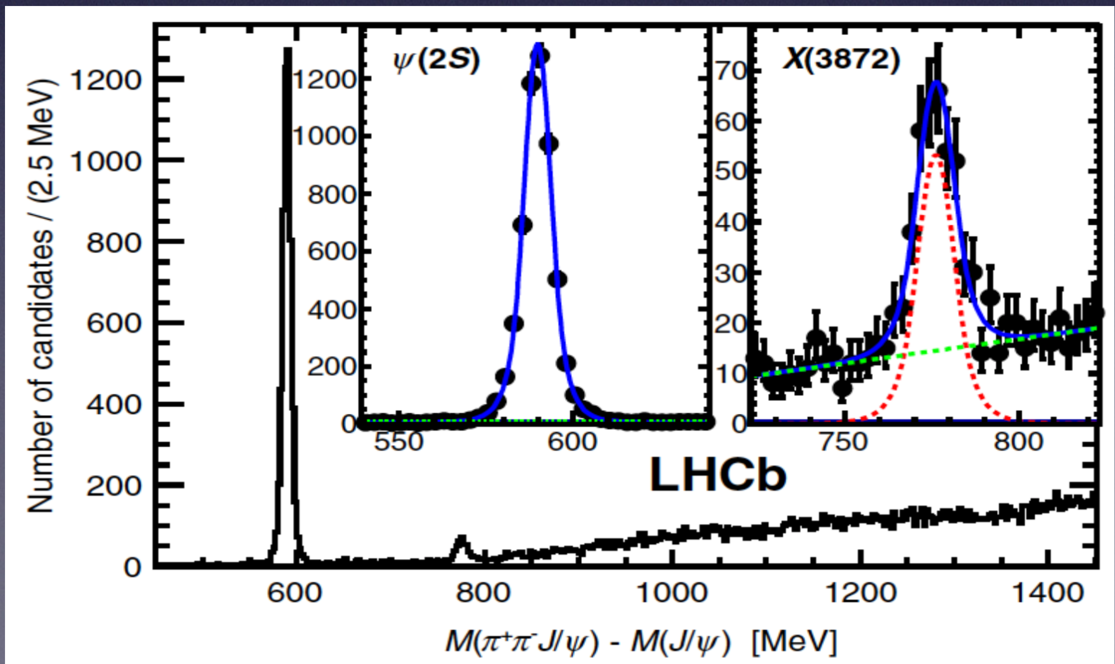
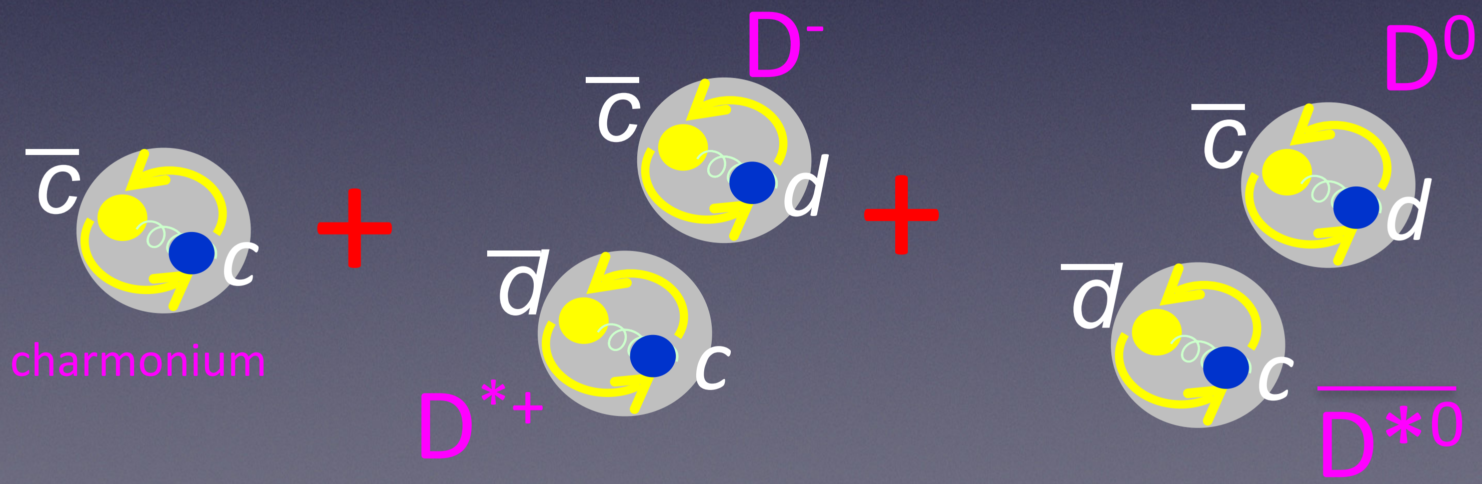


X(3872)

- discovered inB$^{\pm}$→K$^{\pm}$π^{+}π^{-}J/ψ decay
- Known decay mode: X(3872) →π^{+}π^{-}J/ψ
- J^{PC} = 1^{++} (recently determained)
- Now X(3872) is understood as mixture of
  - $\bar{c}c$
  - $D^{*0}\overline{D^0}$
  - $D^{*+}D^{-}$



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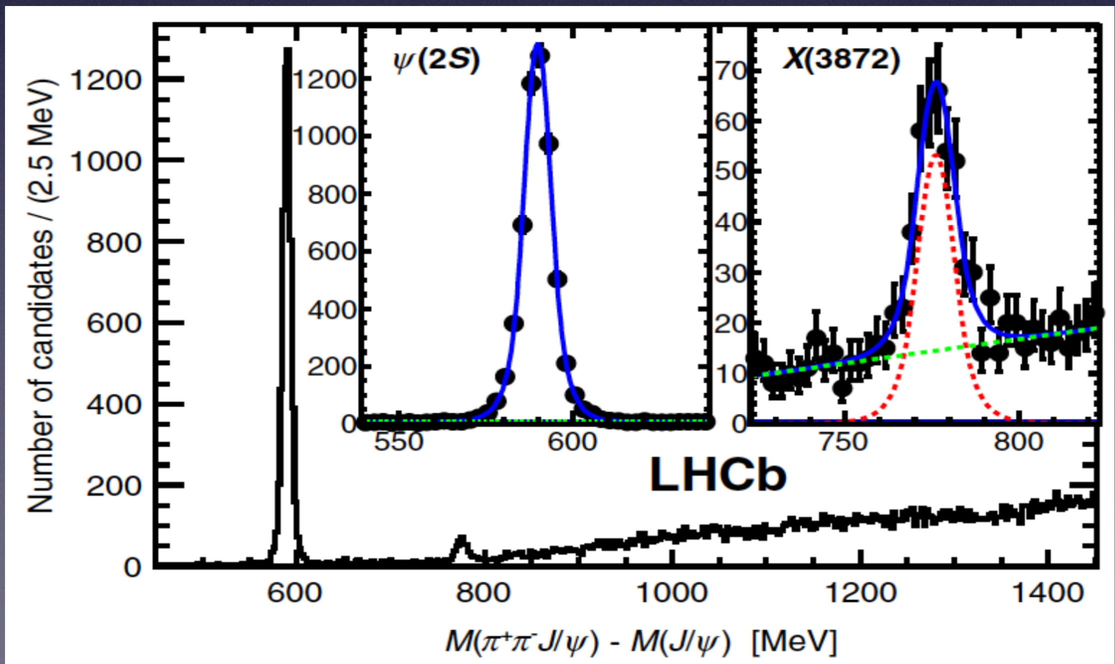

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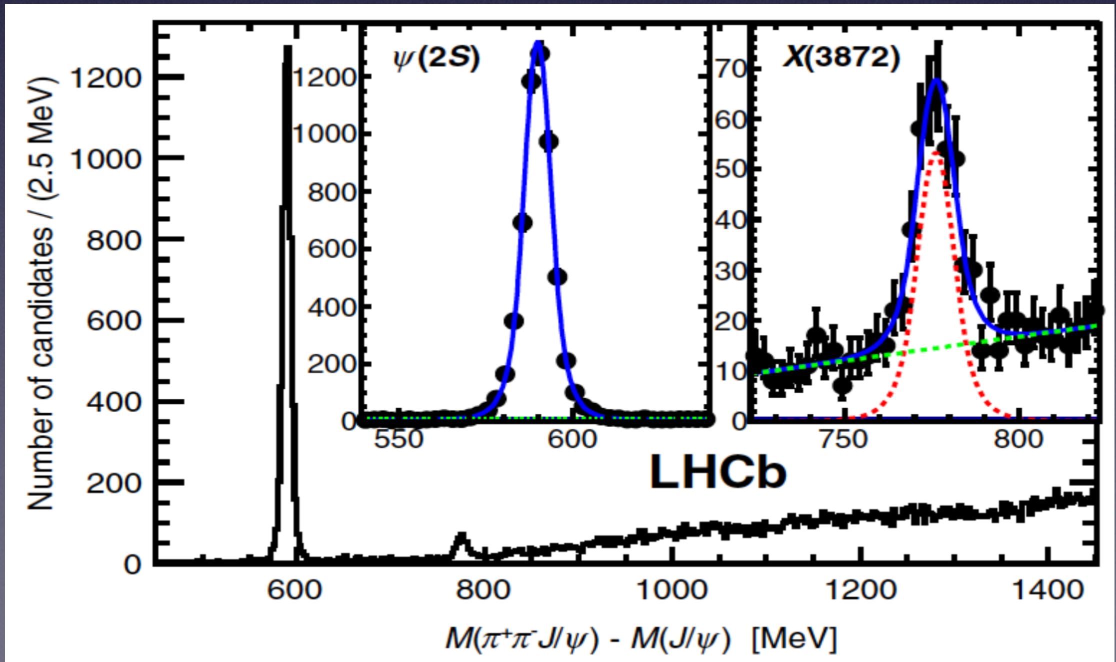
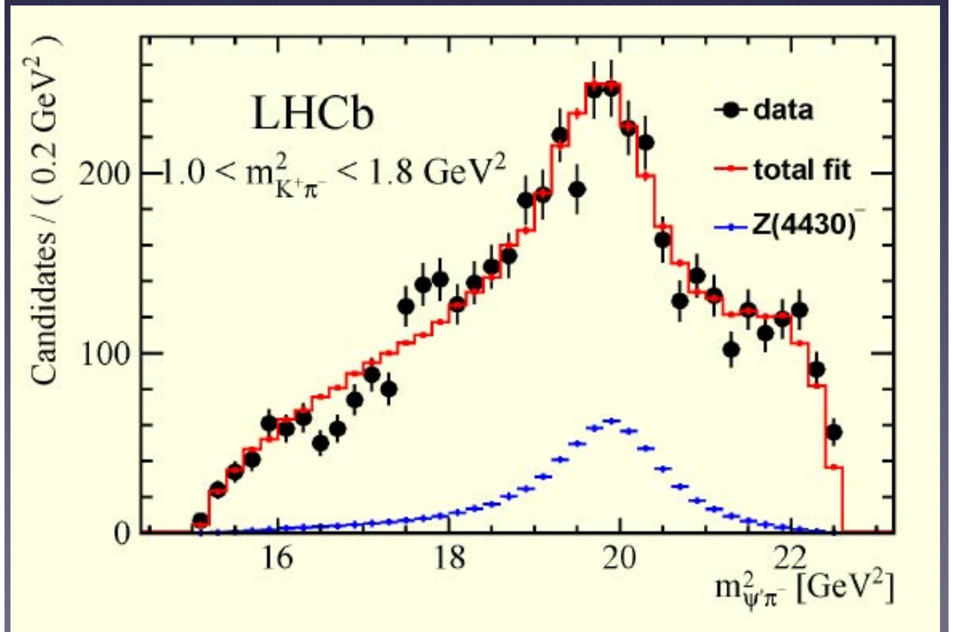
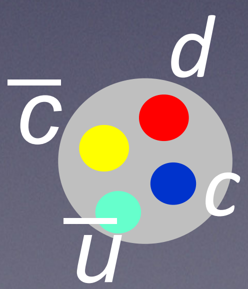


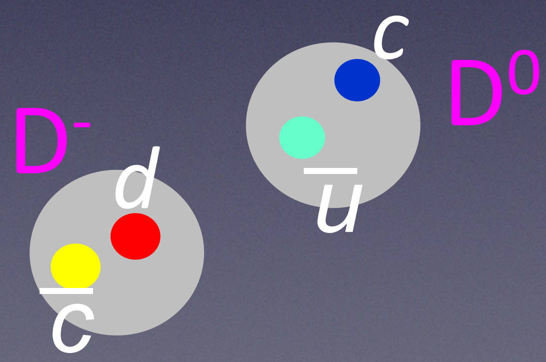


$Z^+(4430)$

- discovered in B decay.
- known Decay mode : Z+ → ψ' π+
  the state must contained $\bar{c}c$, but with charge!
  – minimum quark content might be $\bar{c}c\bar{d}u$
    - Genuine tetra quark?
    - qq + $\bar{q}\bar{q}$ (di-quark and anti di-quark)
    - $D\bar{D}$ molecule ?
    - mixture of above states



or/and



Structure of the Z resonance is not clear yet

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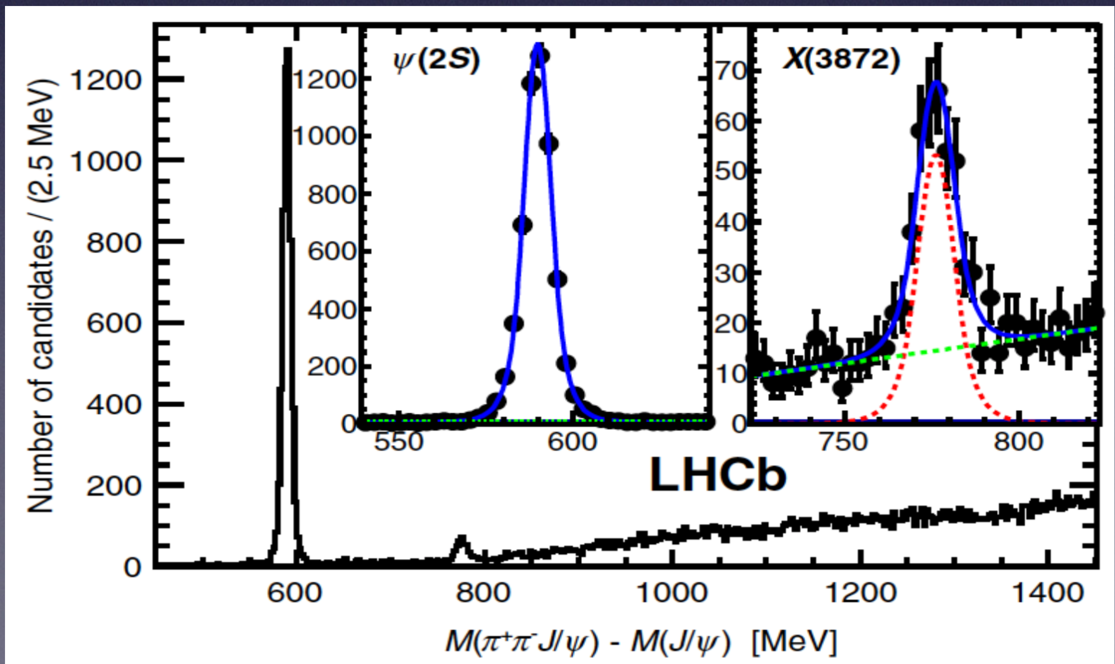

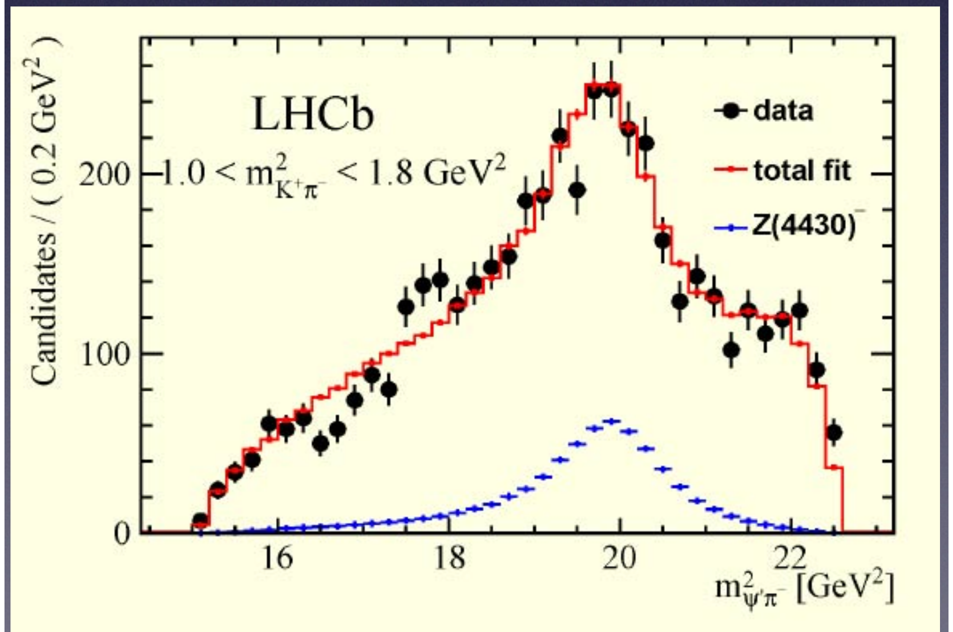

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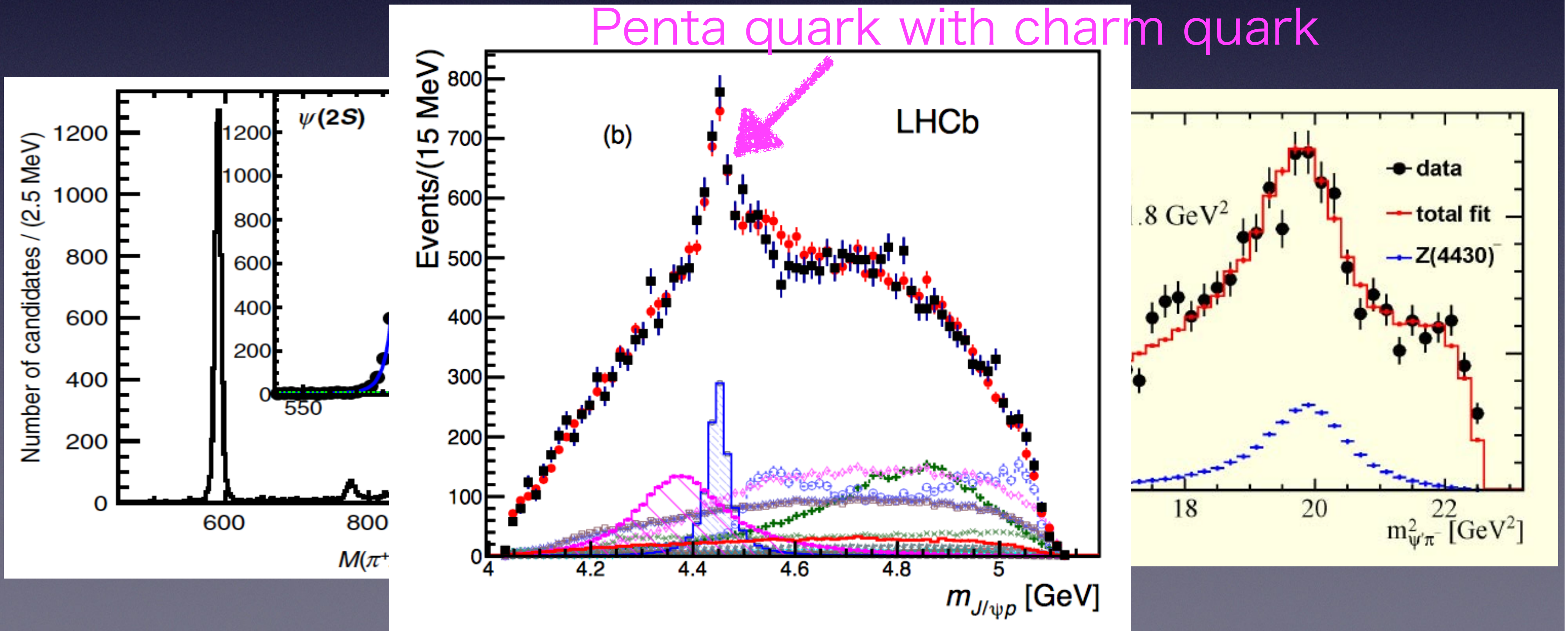

charm quark will play important roles to understand hadron

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D meson in nuclear media?

D meson in nucleus

- Uniqueness for D meson
  - Modification is magnified largely due to mass of charm quark ($m_Q < \bar{q}q >_\rho$)
  - different interaction pattern for $\bar{D}(\bar{c}q), D(c\bar{q})$: only $\bar{D}(\bar{c}q)$ may suffering the effect of “Pauli Blocking”

    $\rightarrow$ interaction for $\bar{D}(\bar{c}q), D(c\bar{q})$ could be very different

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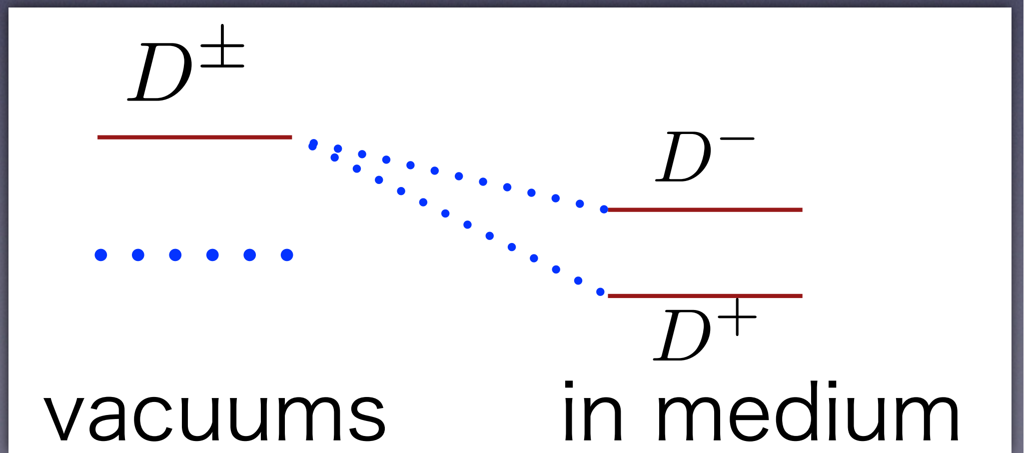
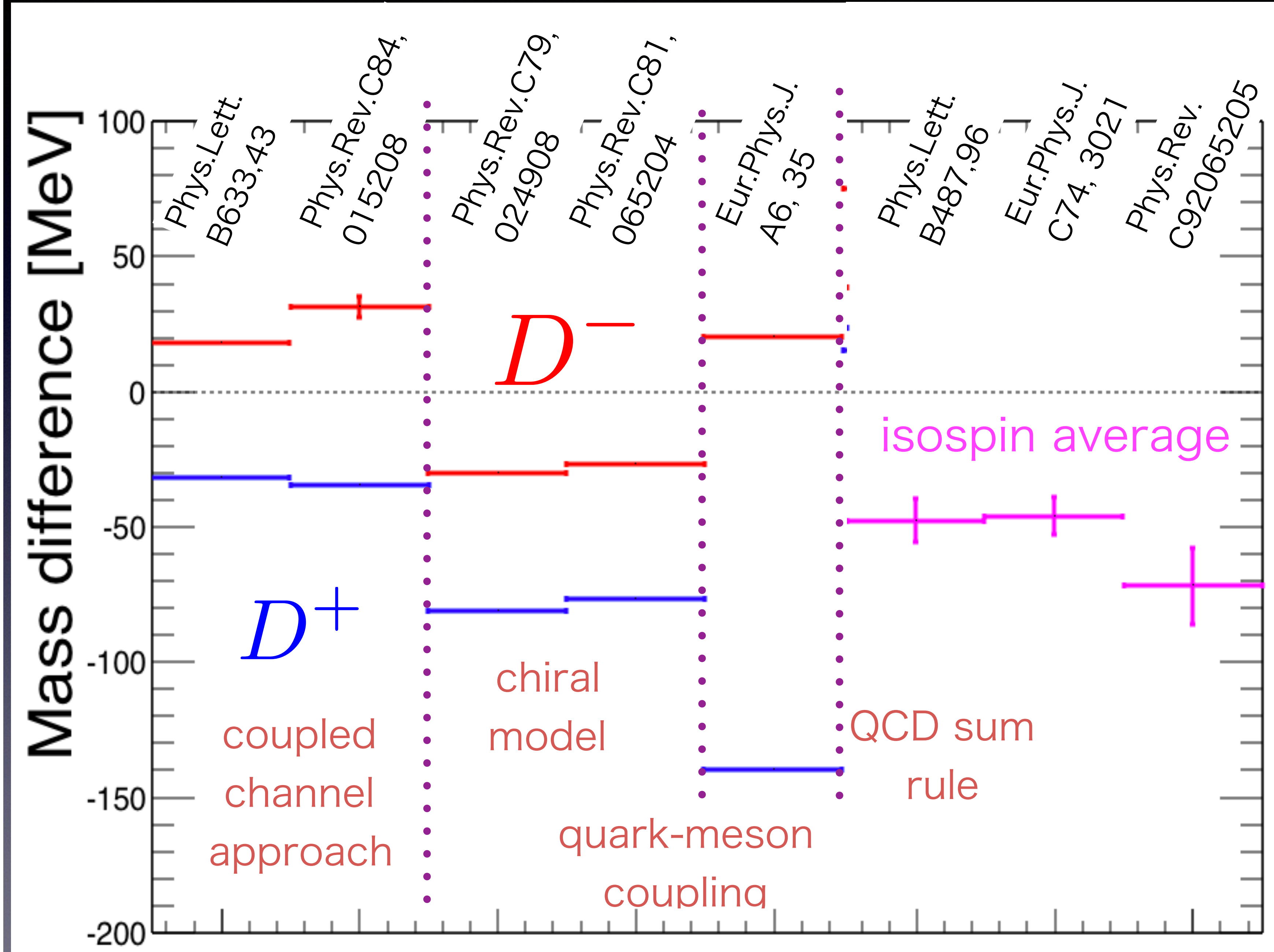
mass separation between $\bar{D}$, D in nuclear media is expected



Prediction of D⁺D⁻ mass splitting



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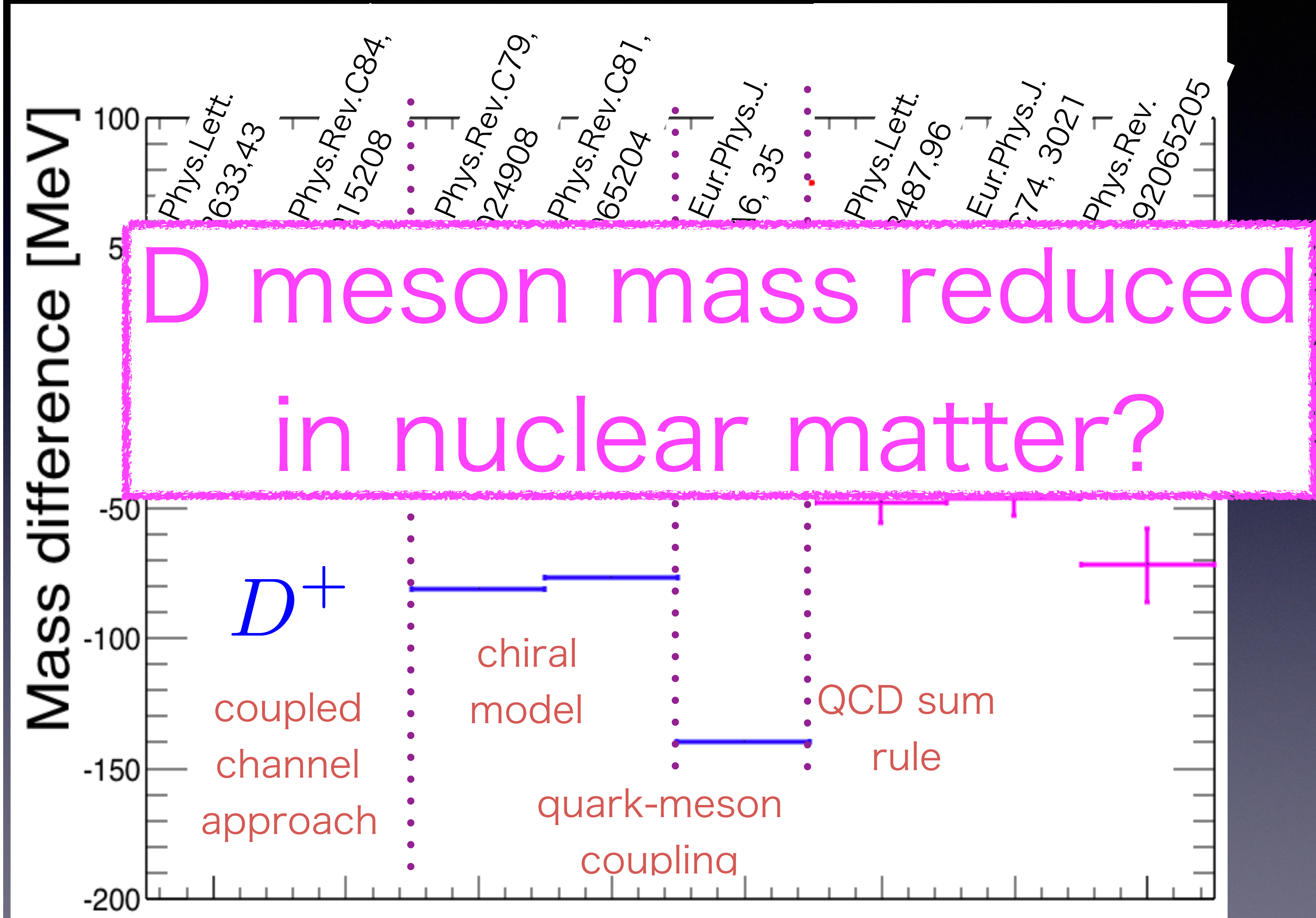

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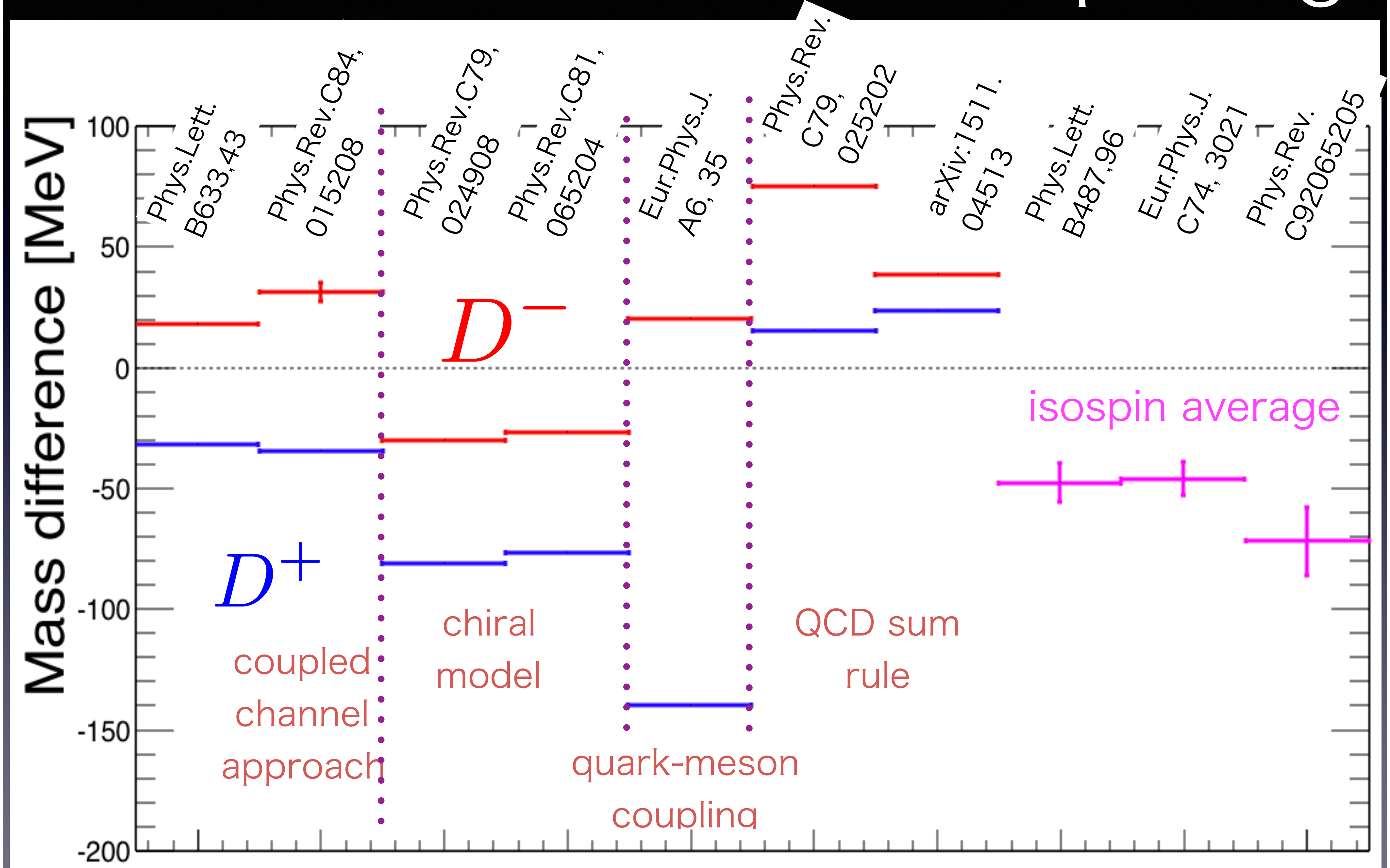

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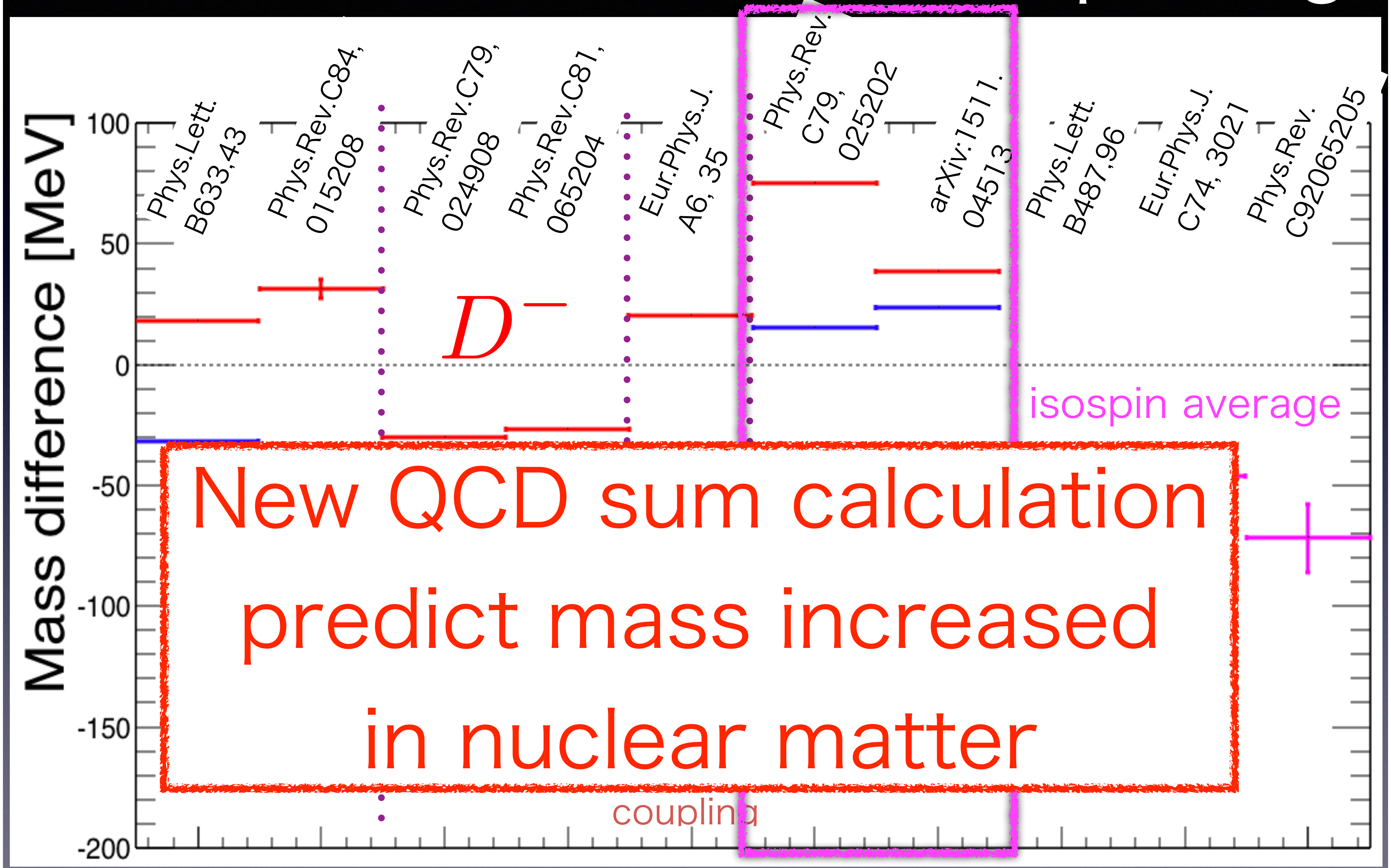


How to produce D mesons at J-PARC?

How to produce D mesons at J-PARC?

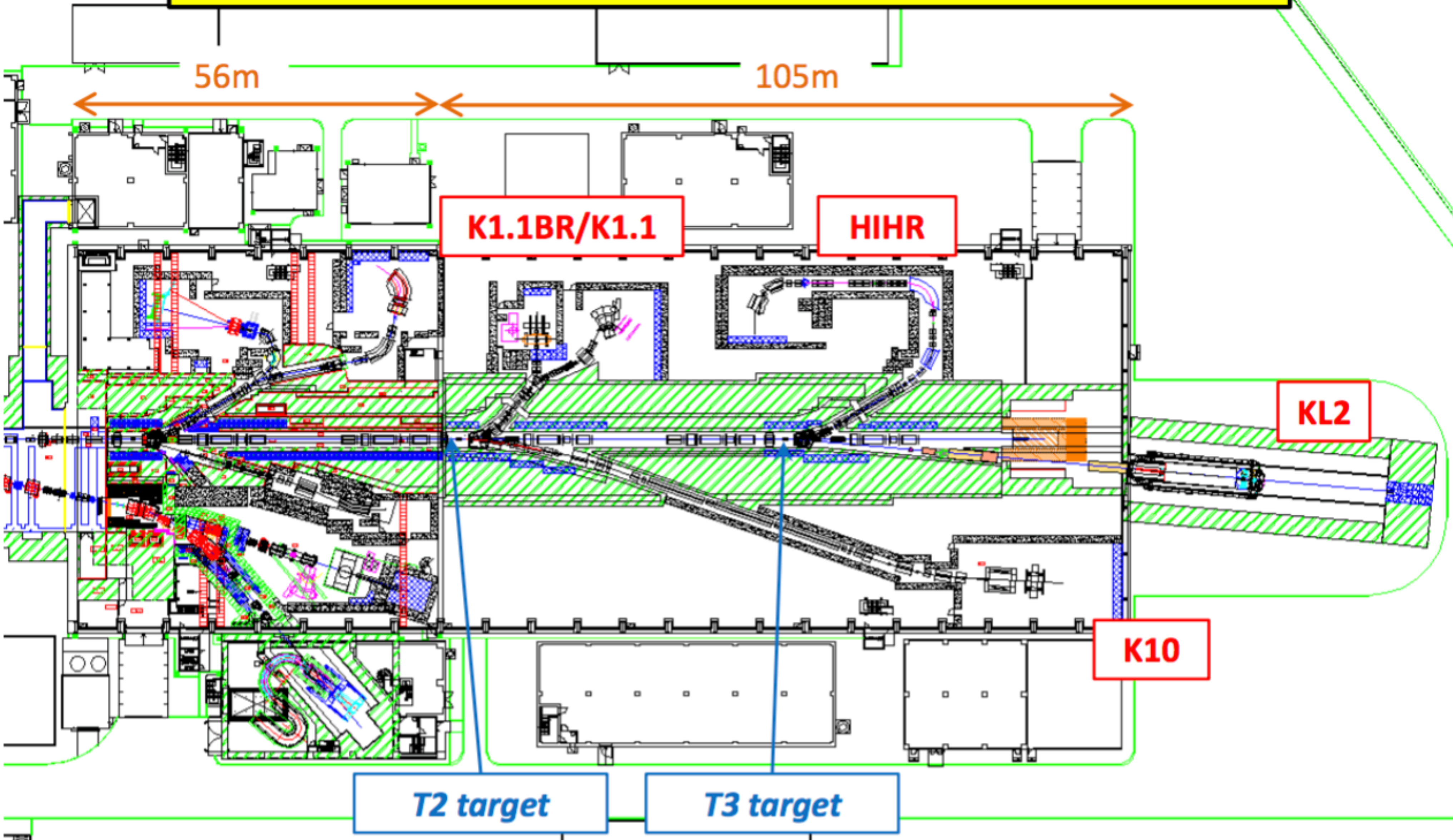
high momentum
high intensity
antiproton beam

How to produce

One of the Physics program at K10

antiproton beam

Extension of J-PARC Hadron Facility



- HD-hall is extended by 105m.
- Two more production targets

H. Takahashi (KEK)

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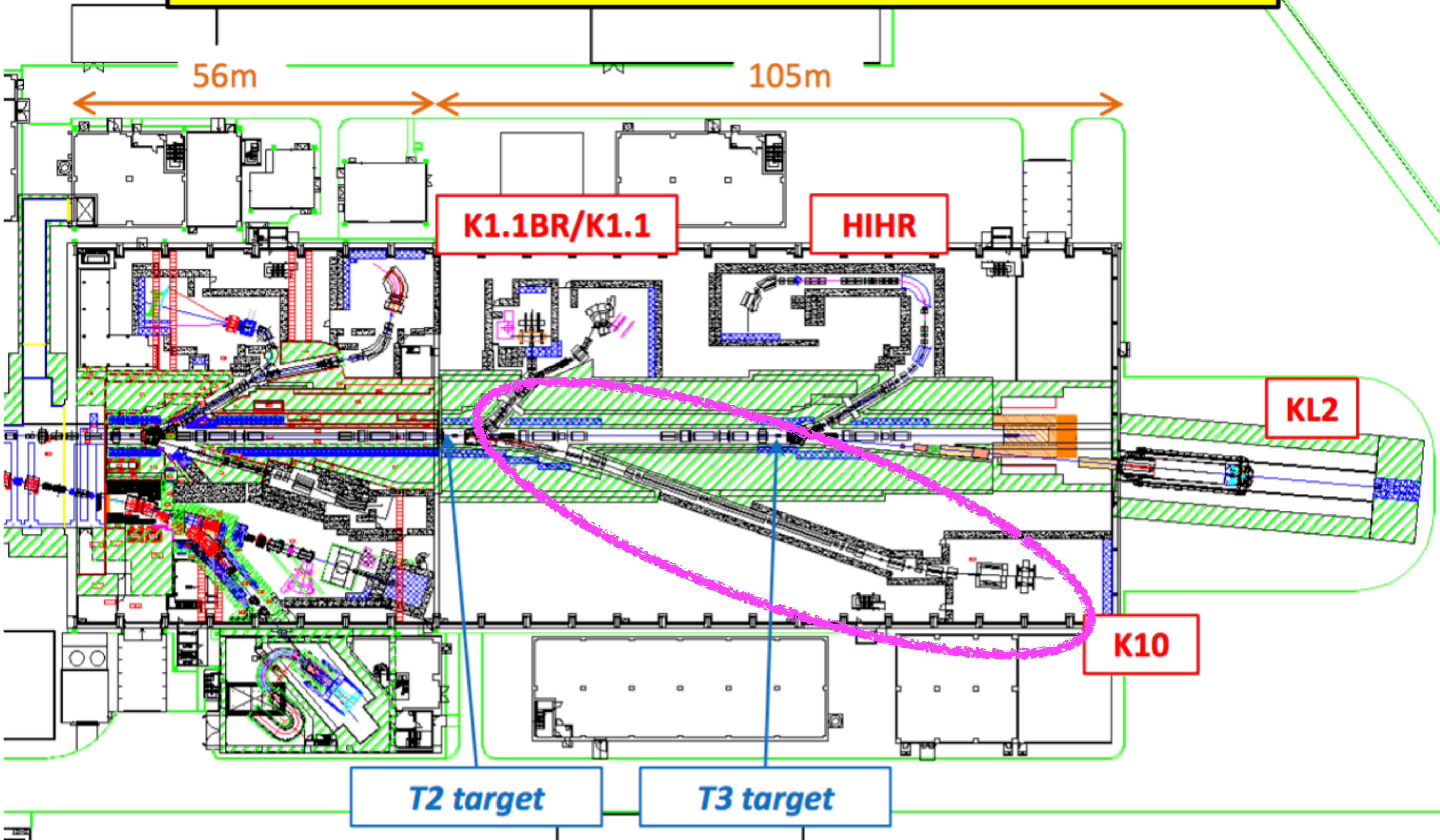

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H. Takahashi (KEK)

Intensity – ES option

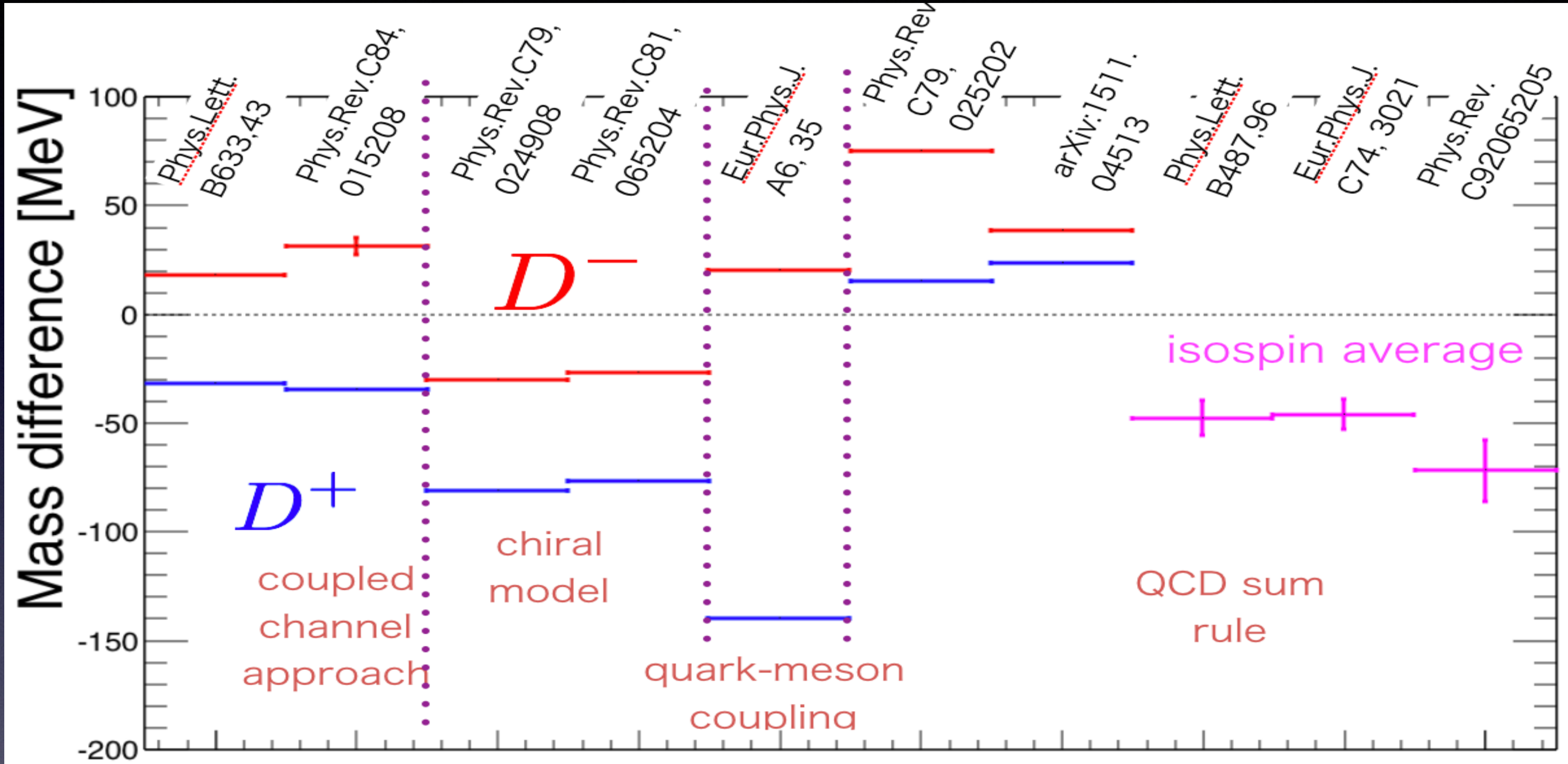
- Primary proton beam power: 50kW
- Production target: 50% loss
- Spill cycle: 5.52sec
- Slit conditions are varied to achieve moderate purity for each case.

	acceptance [msr-%]	intensity [/spill]	$K^-:\pi^-$ $pbar:\pi^-$
4GeV/c K^-	0.33	1.7E6	1.1 : 1
4GeV/c pbar	1.2	1.6E7	81 : 1
6GeV/c pbar	0.55	7.8E6	1 : 3.4

※ decay μ and cloud π are not included.

H. Takahashi(KEK)

charmed meson in nuclear matter



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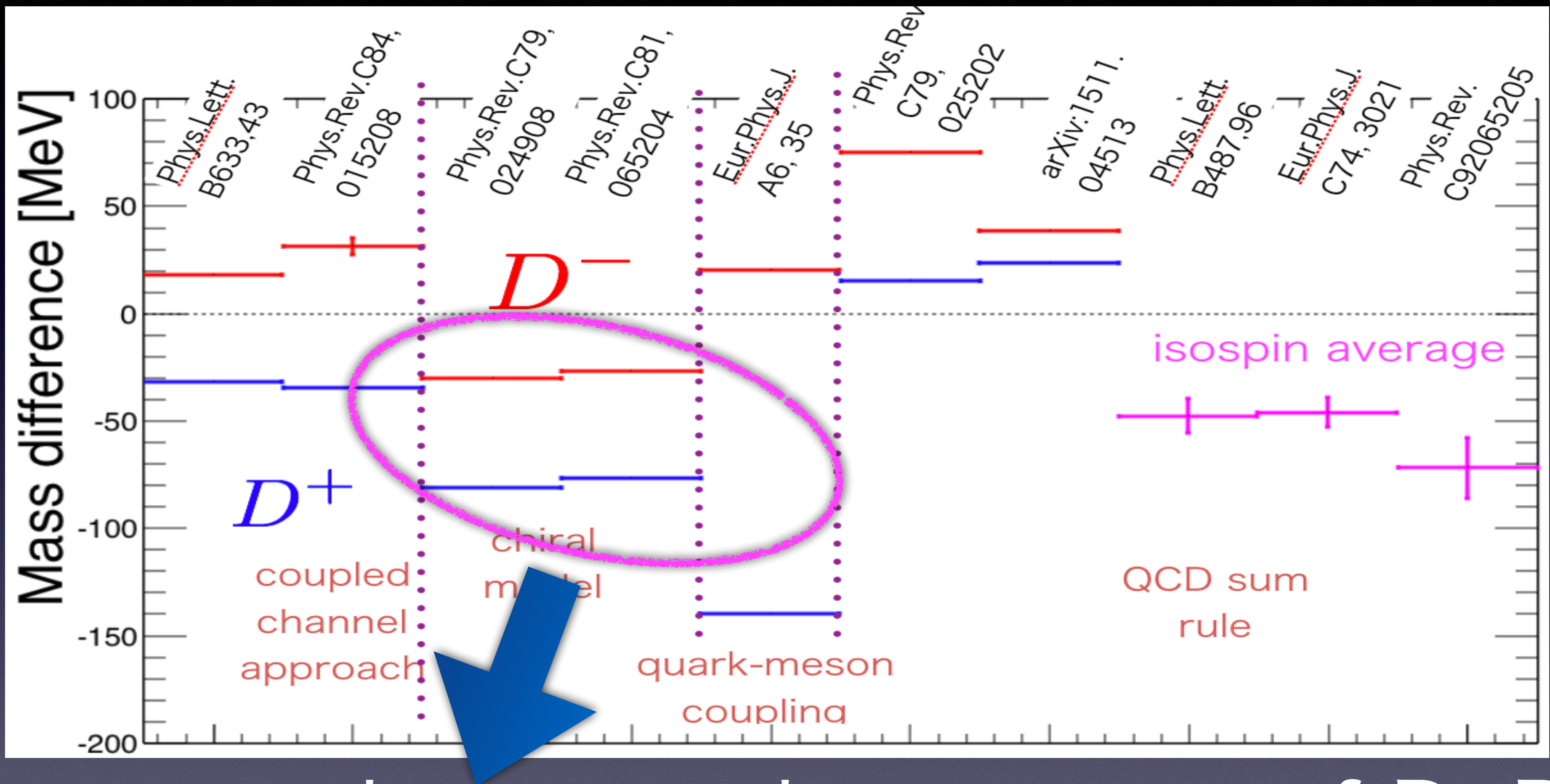
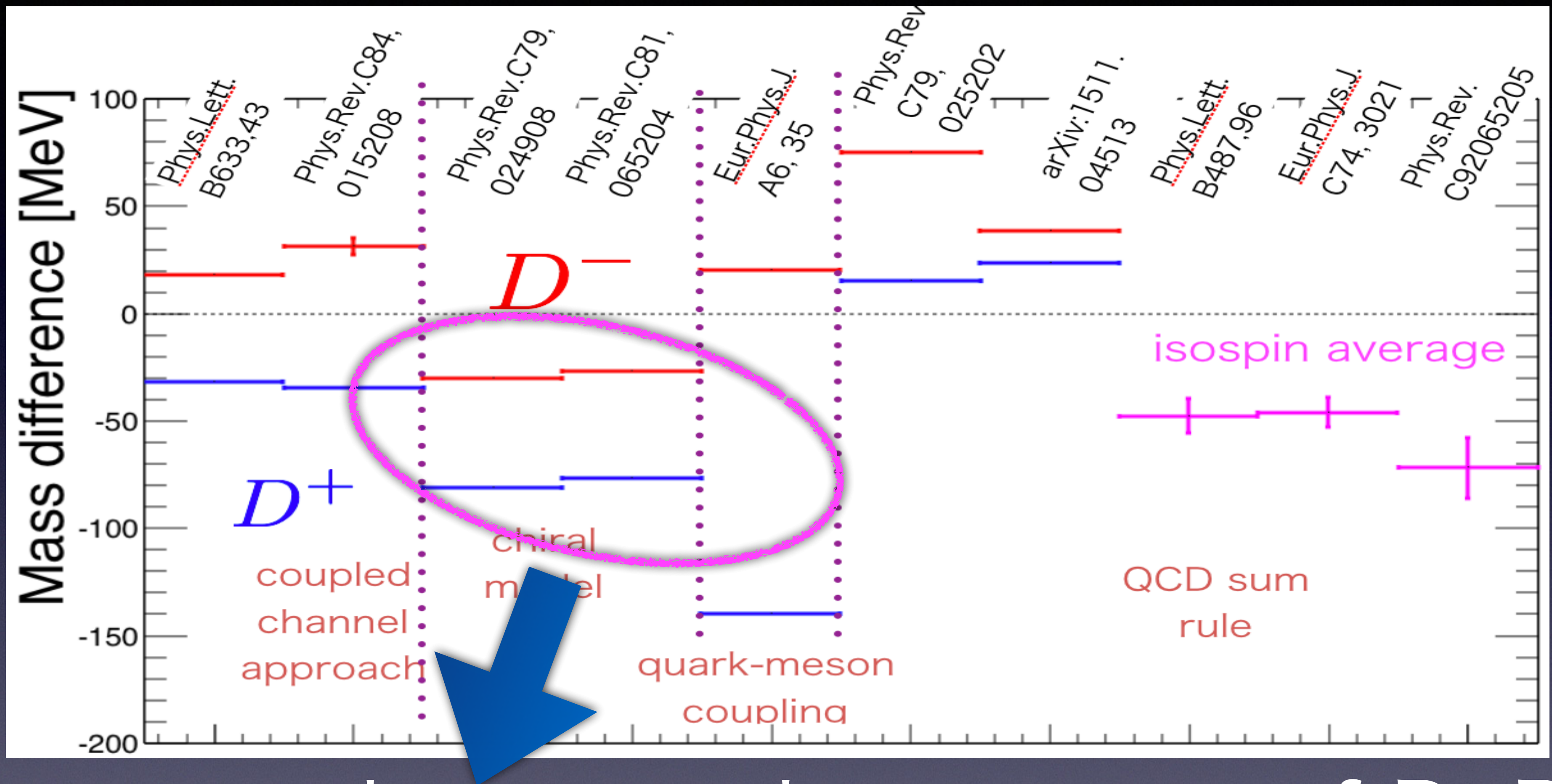


- we may observe enhancement of D+D- production at threshold

charmed meson in nuclear matter



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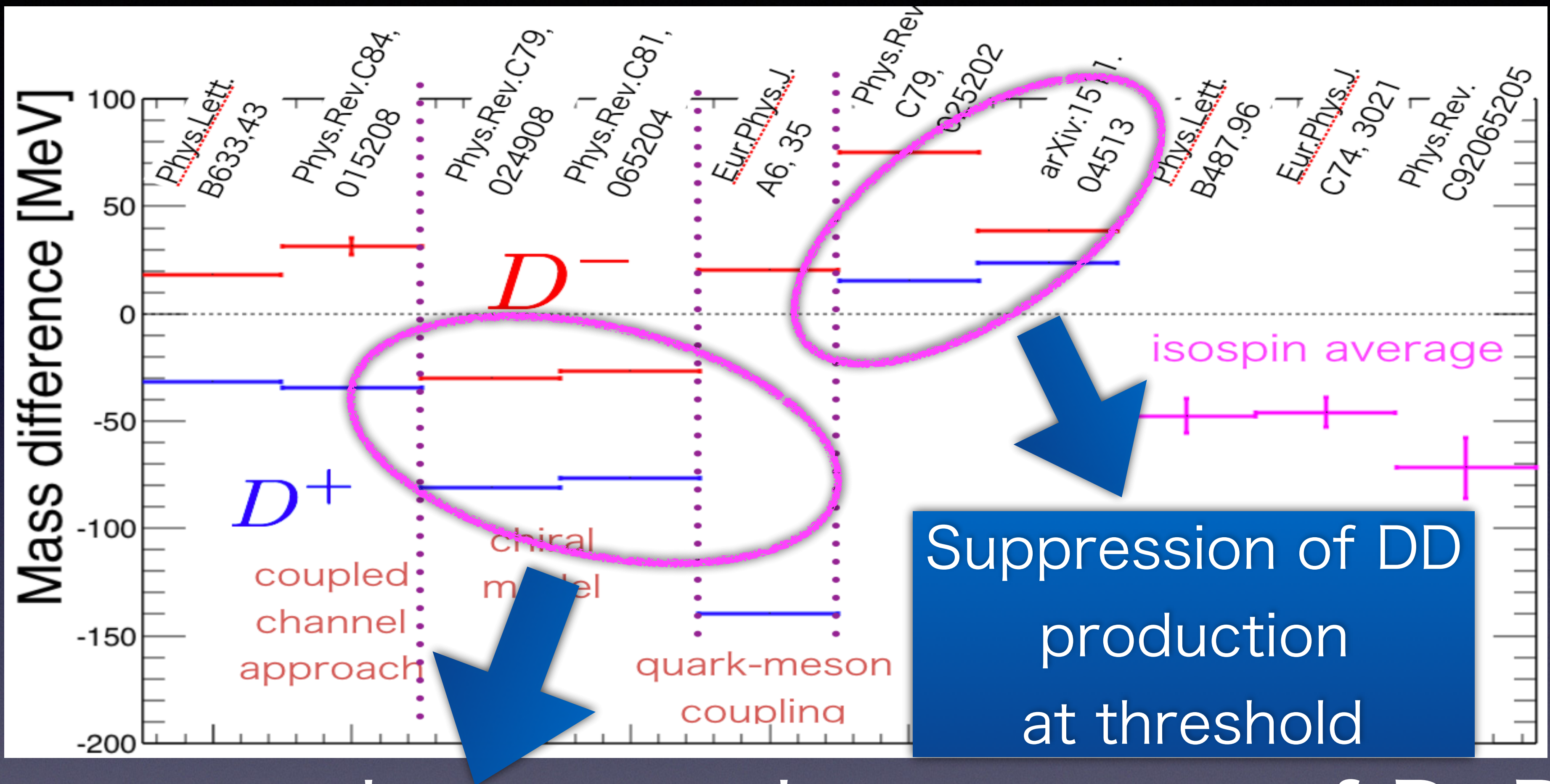
charmed meson in nuclear matter



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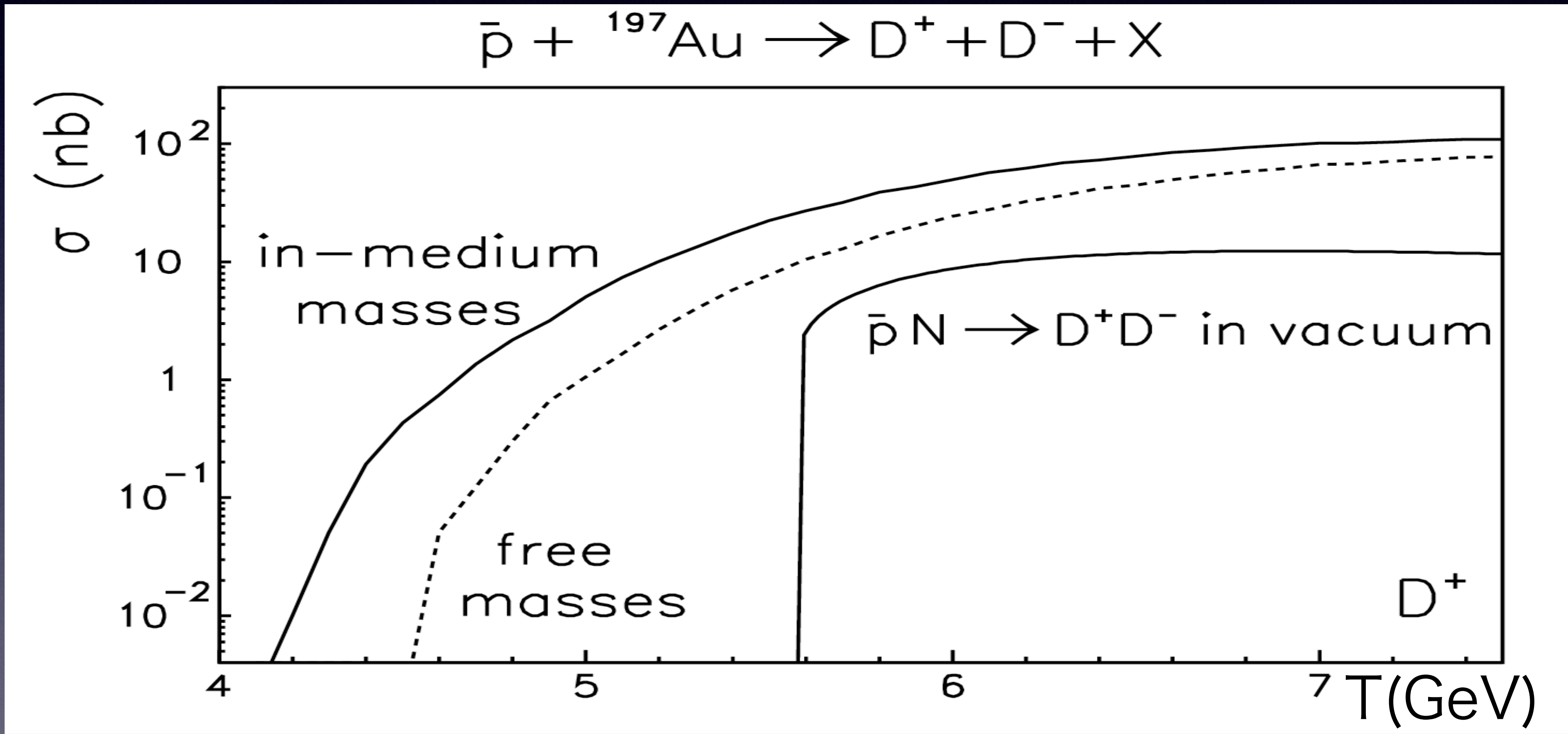
- Sub-threshold enhancement of D+D- production on pbar-A interaction (Euro.Phys.J A,351)



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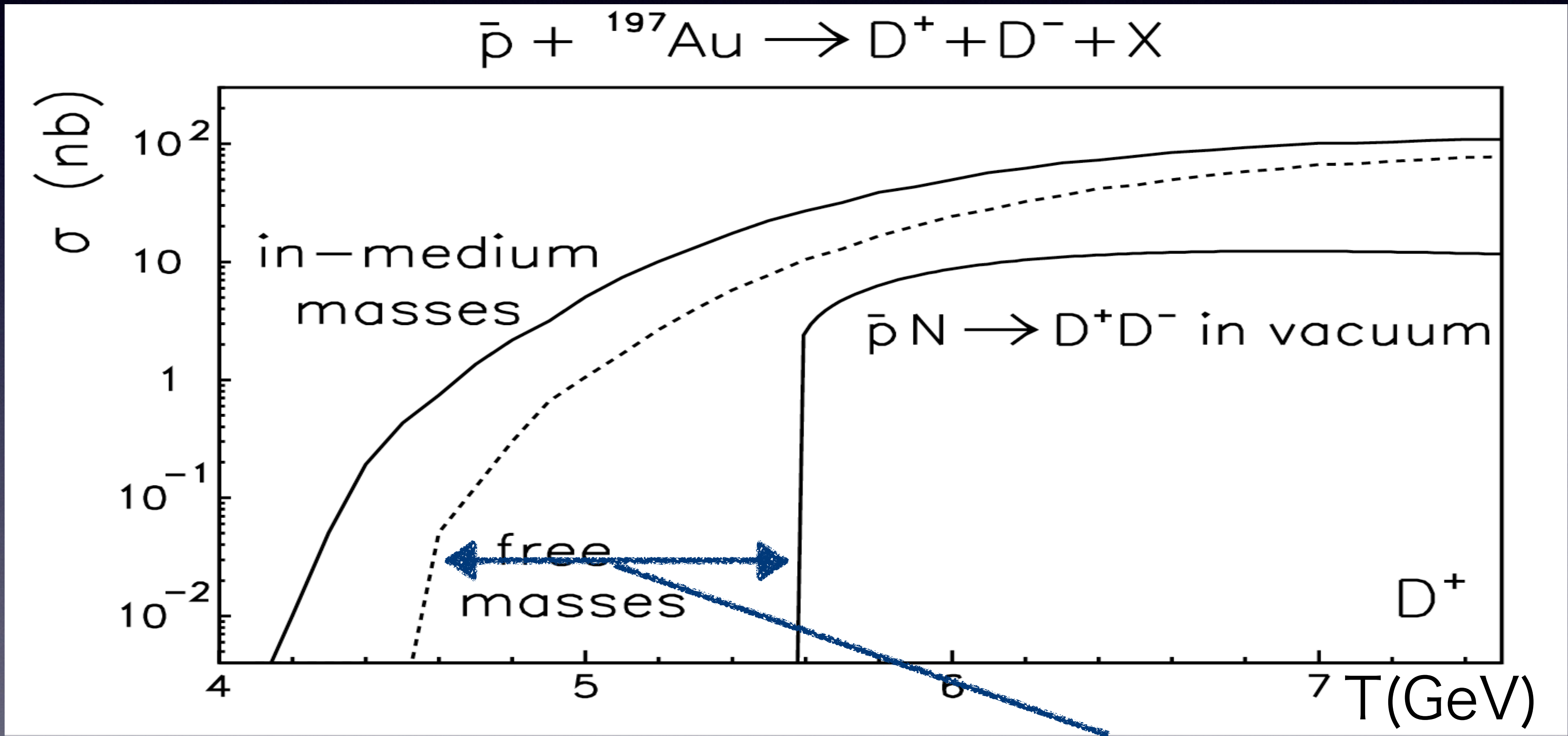
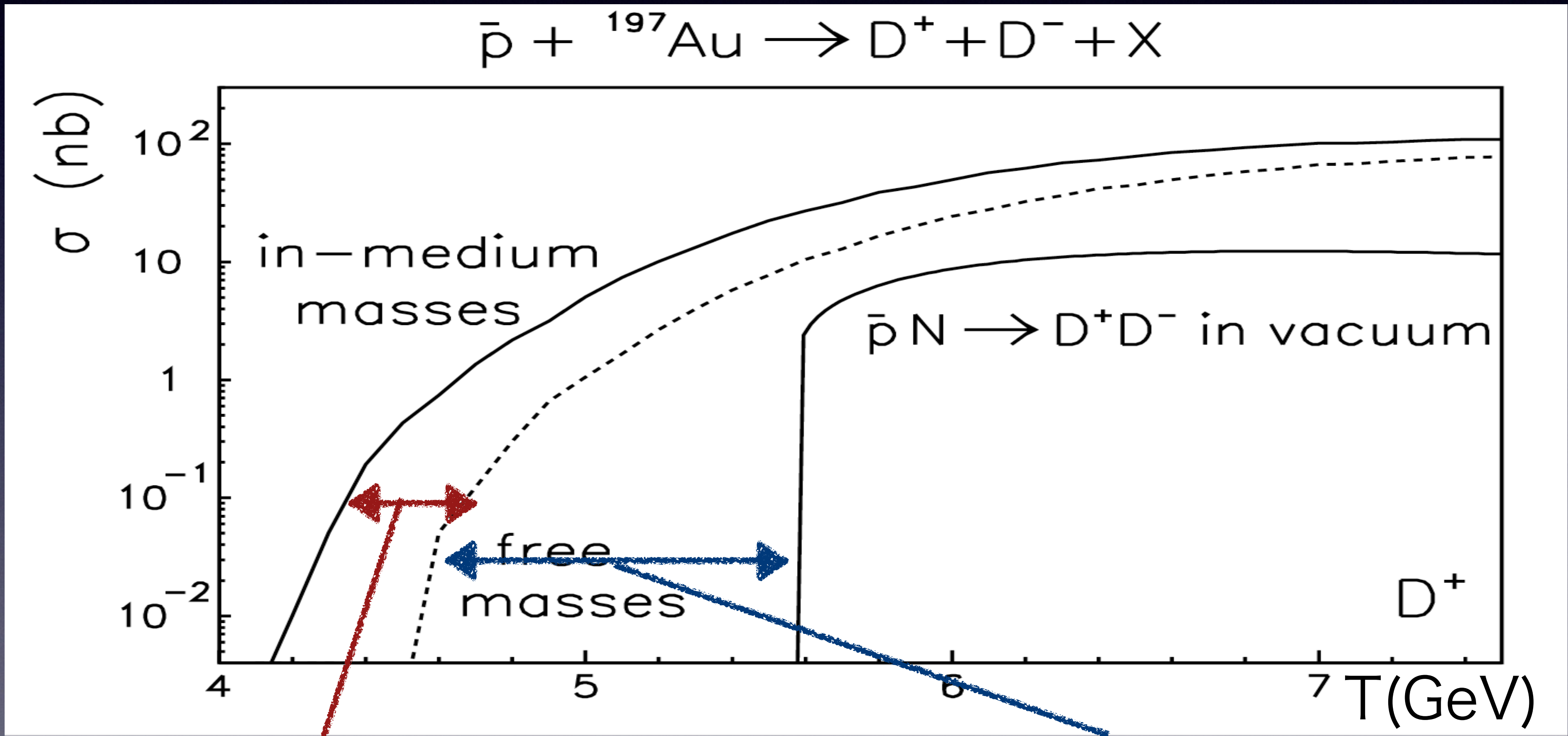


reduction because of fermi-motion of nucleonin nucleus

charmed meson in nuclear matter

- Sub-threshold enhancement of D+D- production on pbar-A interaction (Euro.Phys.J A,351)



due to mass reduction

reduction because of fermi-motion of nucleonin nucleus

charmed meson in nuclear matter

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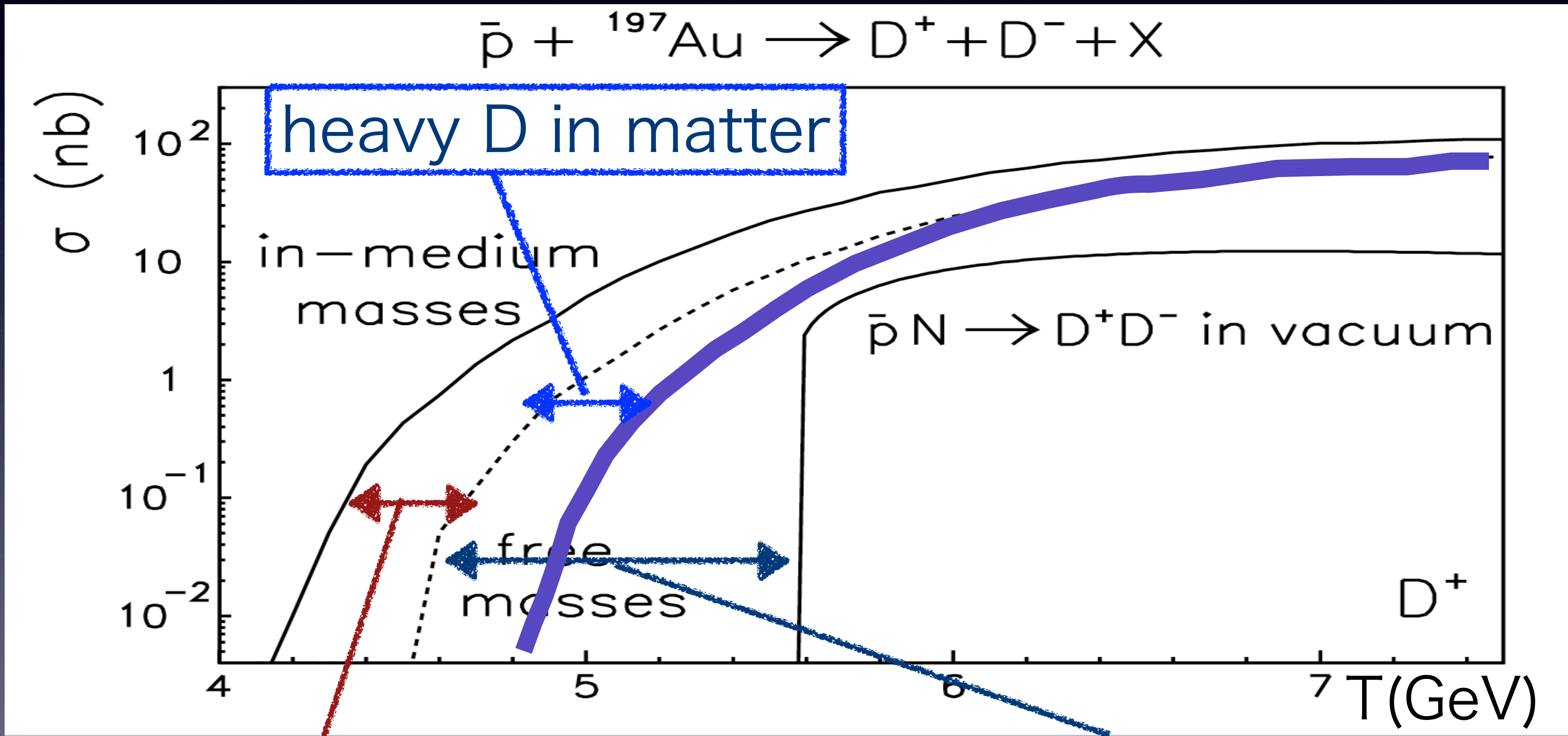

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charmed meson in nuclear matter

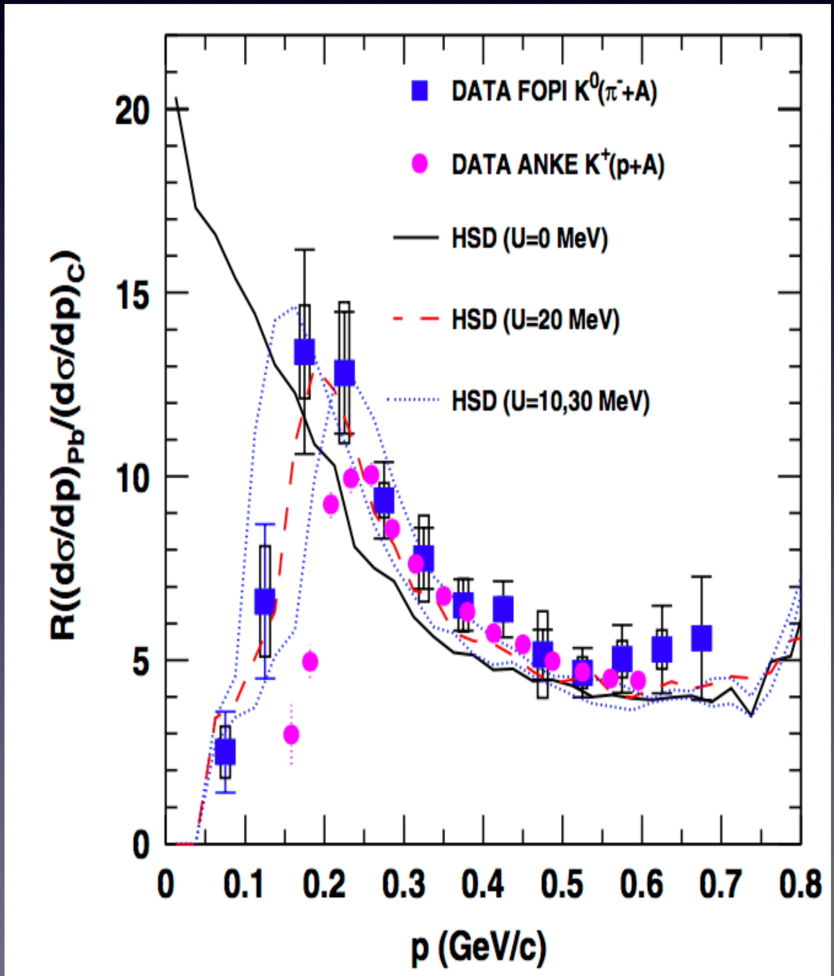
Lesson from strange meson:

How to deduce $\bar{K}N$ interaction strength?

charmed meson in nuclear matter

Lesson from strange meson:

How to deduce KN interaction strength?



Phys. Rev. Lett. 102 (2009) 182501

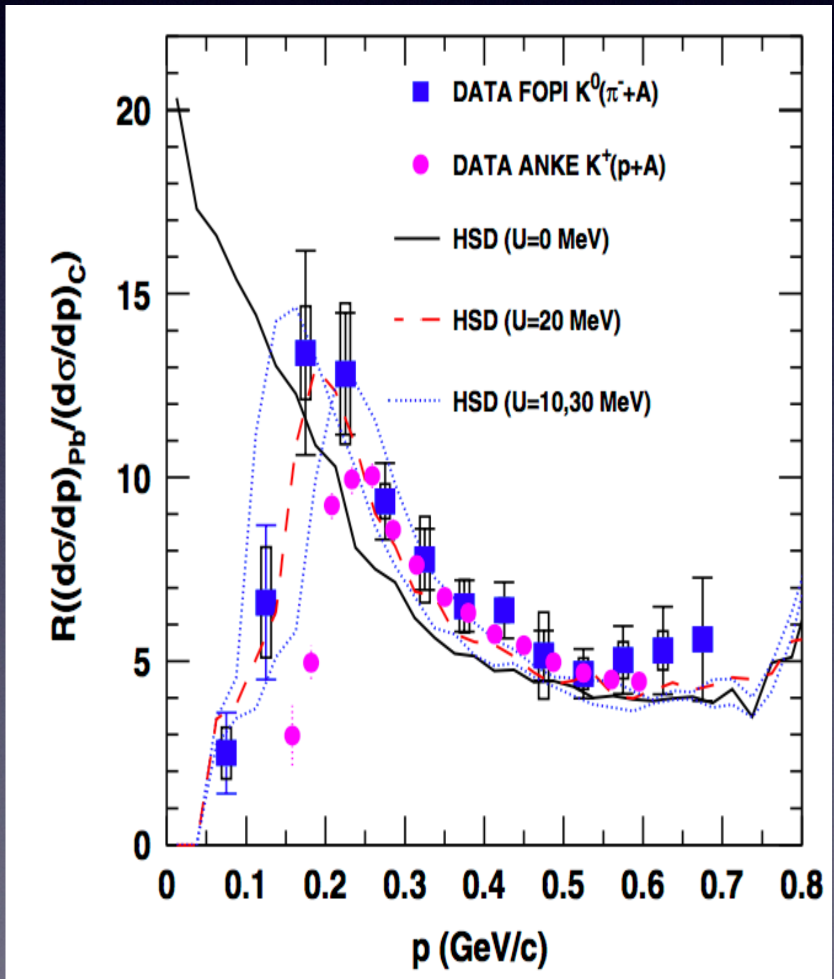
compare momentum spectra for example, C and Pb

The spectra will contained information about real part for KN potential

charmed meson in nuclear matter

Lesson from strange meson:

How to deduce KN interaction strength?



Phys. Rev. Lett. 102 (2009) 182501

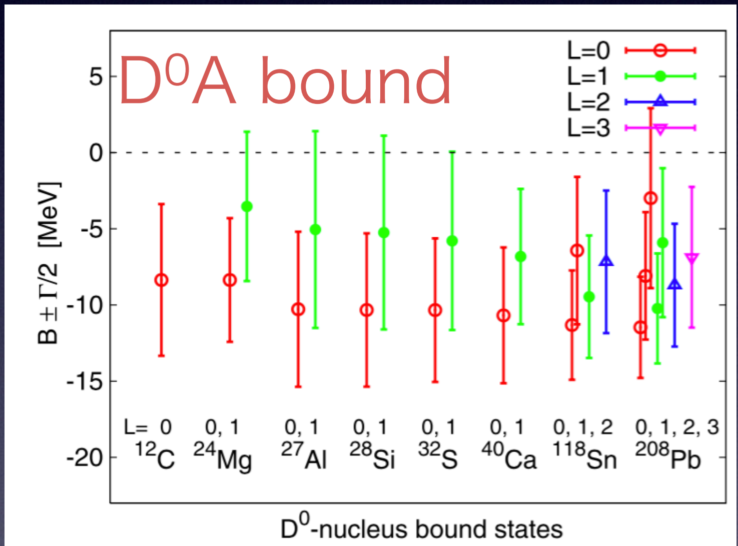
compare momentum spectra for example, C and Pb

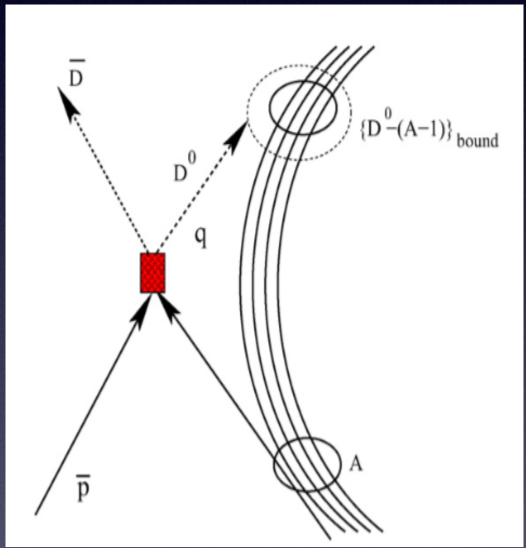
The spectra will contained information about real part for KN potential

same measurement can be possible on D mesons to investigate DN interaction

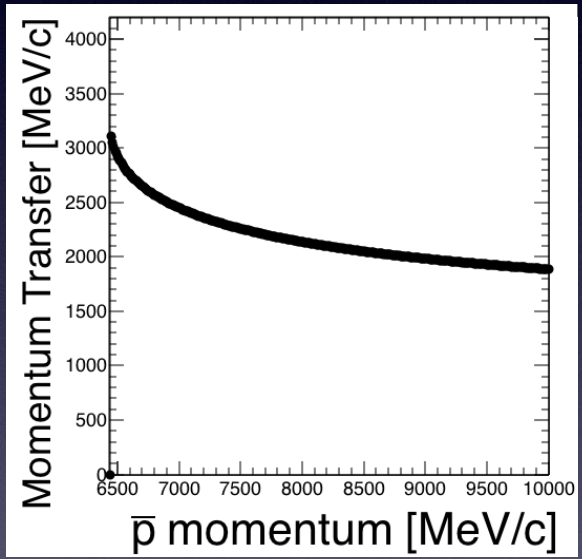
D meson nuclear bound state?

Theory tells us that $\bar{D}$ or D meson bound state might be exist





Physics Letters B 690 (2010) 369



- However, no way to produce slow D meson

D meson momentum ~ 2 GeV/c @ 10 GeV/c $\bar{p}$

Production of slow D meson

Production of slow D meson

- (Probably) Best elementary process to produce slowly moving D meson will be

Production of slow D meson

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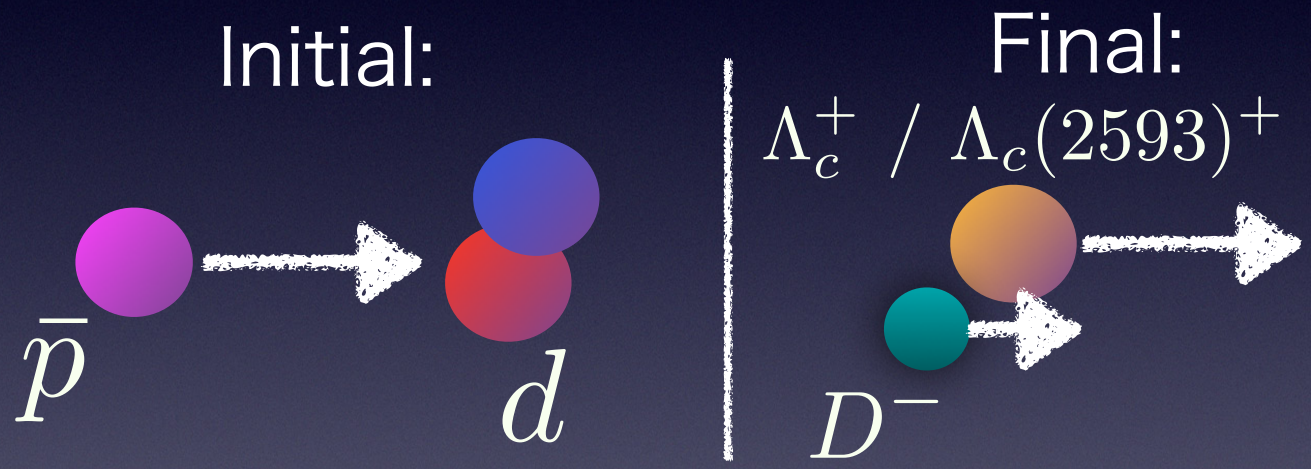
$$\bar{p} + d \to D^- \Lambda_c^+ \ \text{(forward)}$$



Production of slow D meson

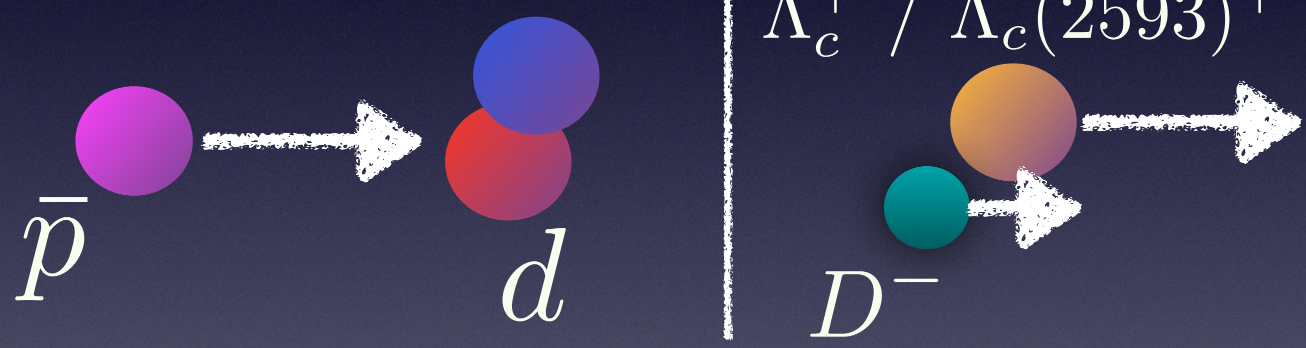
- (Probably) Best elementary process to produce slowly moving D meson will be

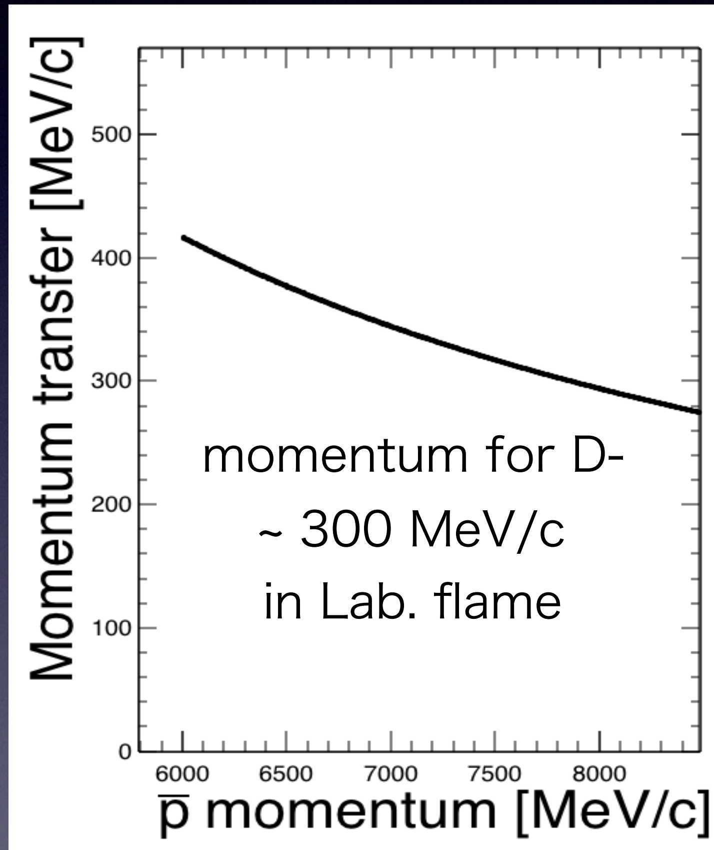
$$\bar{p} + d \to D^- \Lambda_c^+ \ \text{(forward)}$$

Initial:

Final:

$\Lambda_c^+ \ / \ \Lambda_c(2593)^+$





Momentum of D- produced this elementary process is ~ 300 MeV/c

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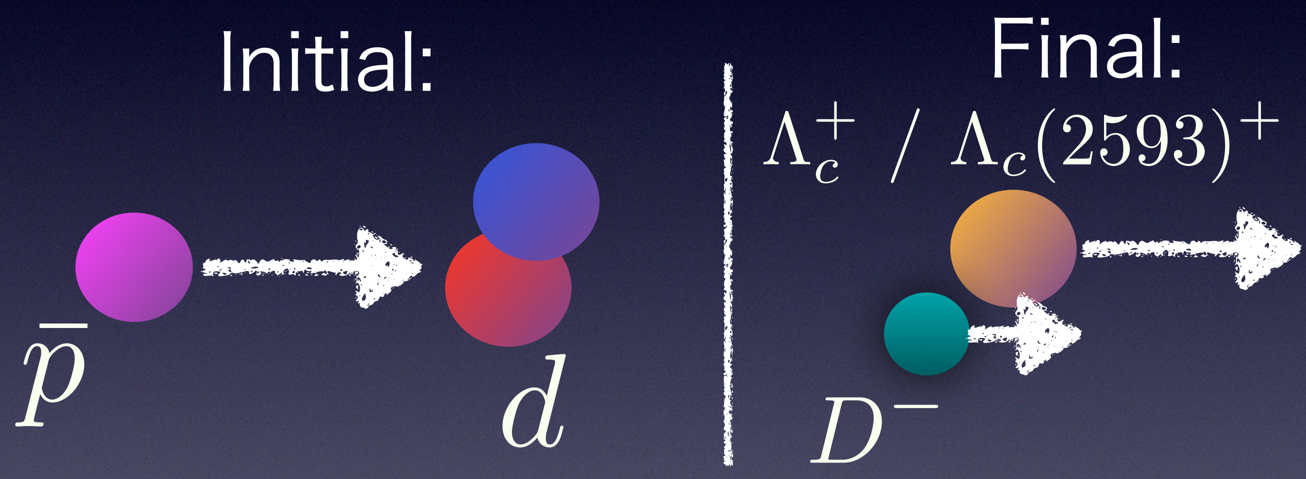
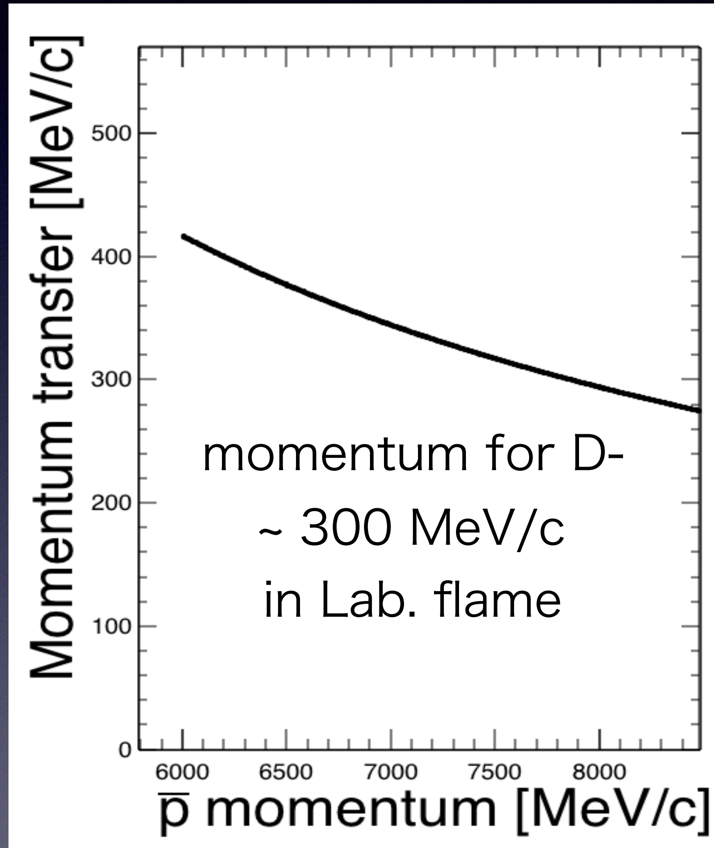




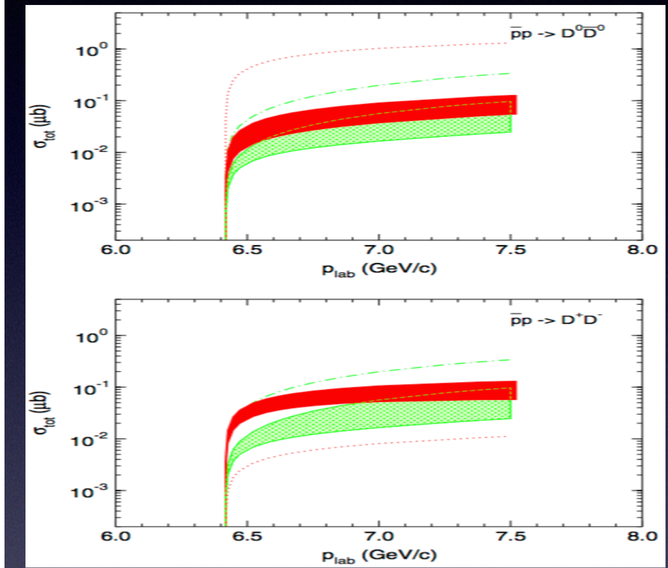
Momentum of D- produced this elementary process is ~ 300 MeV/c

Good process to produce D mesic nucleus
(if $\bar{D}N$ interaction is attractive)

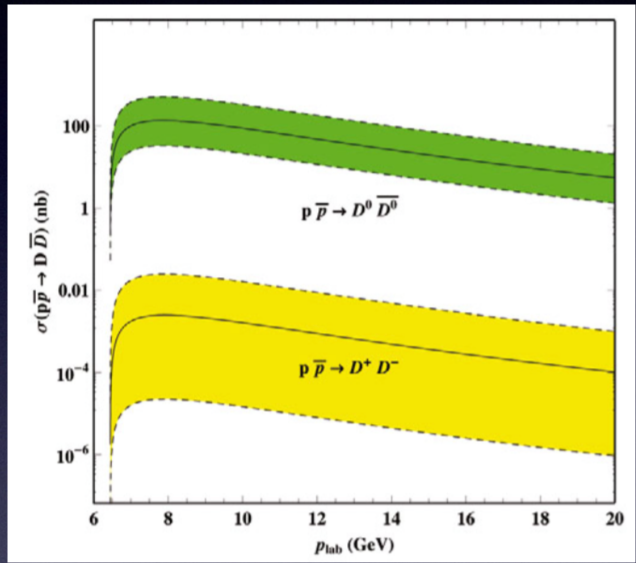
Possible DAY-1 experiment at K10

$\bar{D}D$ production cross section

- No experimental data available for $\bar{D}D$ production on $\bar{p}p$ reaction near the threshold

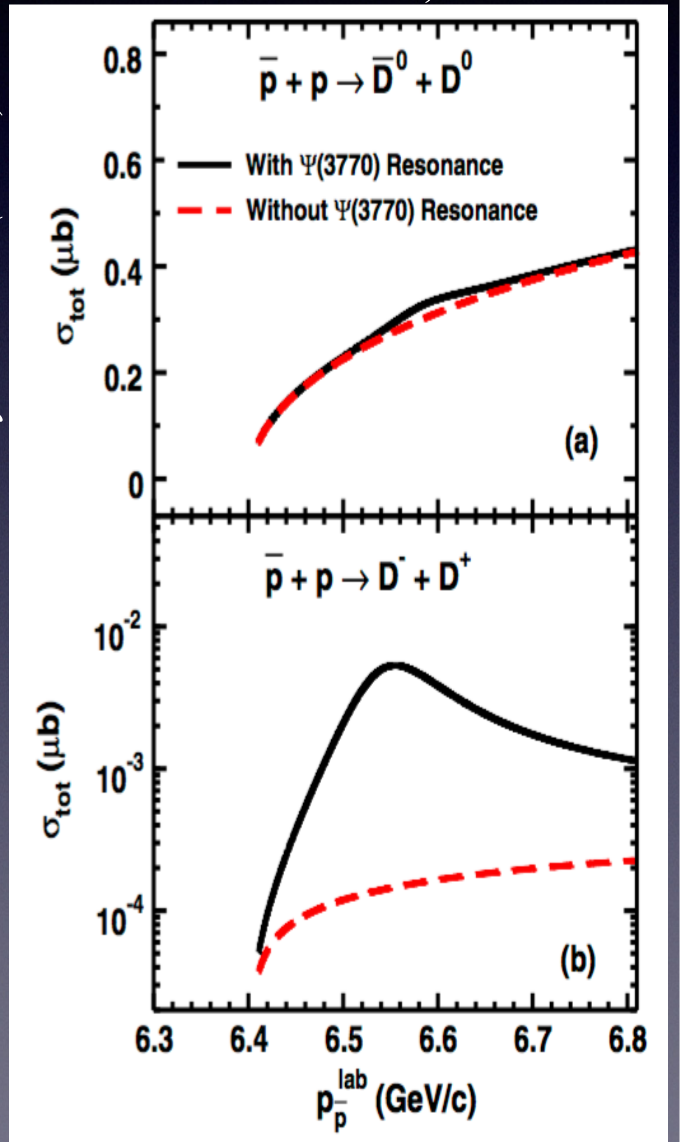


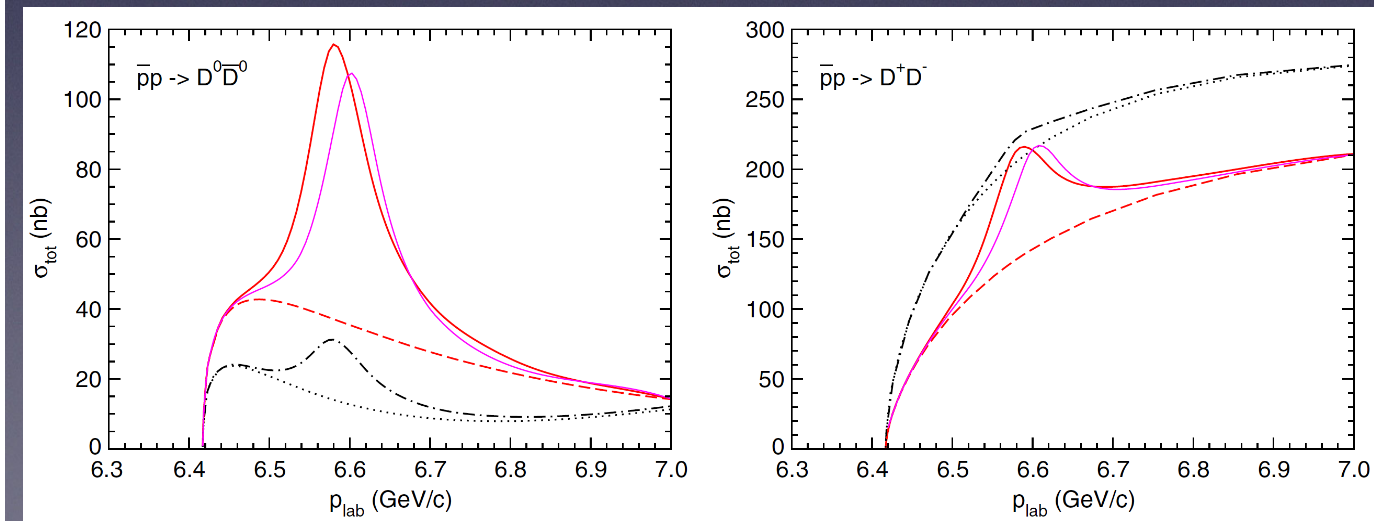
PRD89,114003



Eur.Phys.J. A48 (2012) 31

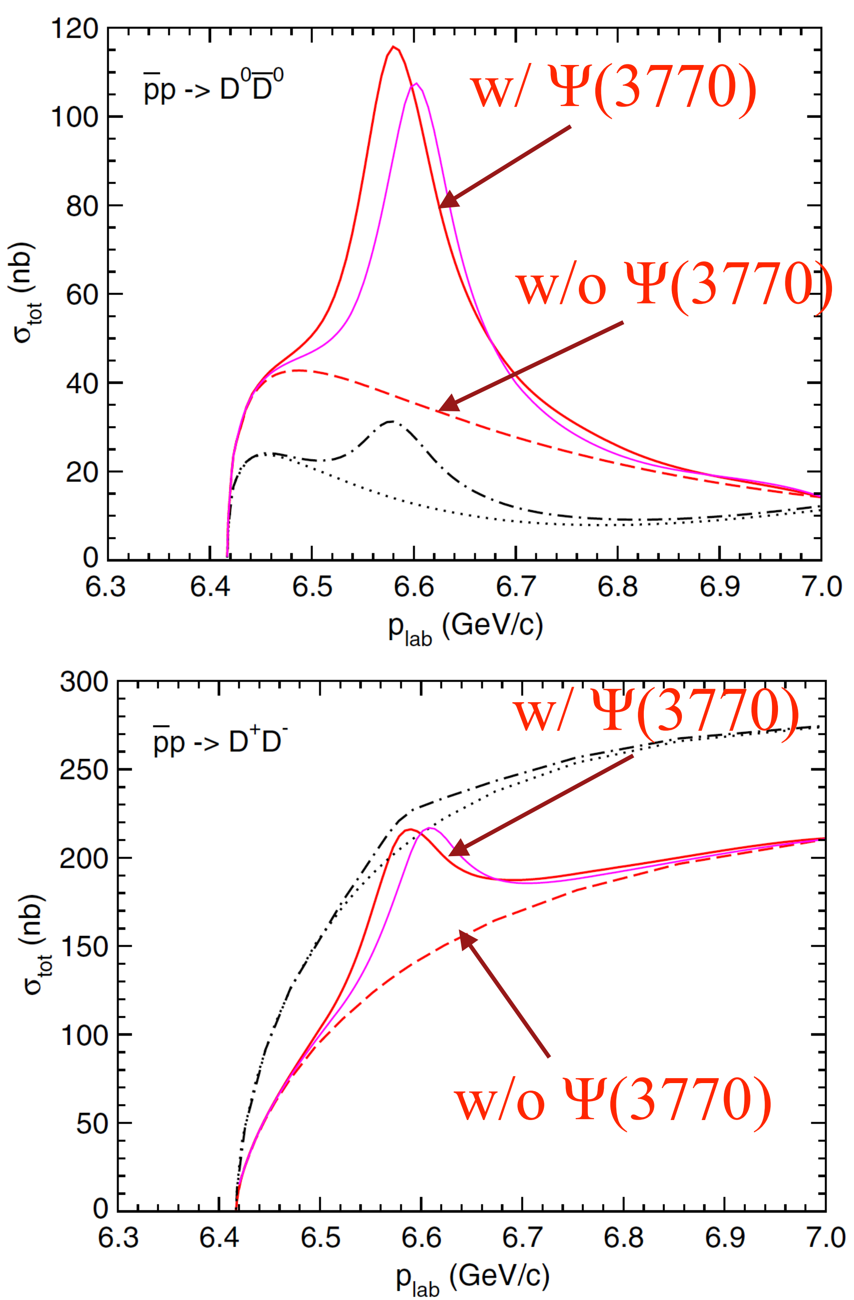
PRD93,034016





PHYSICAL REVIEW D 91, 114022 (2015)

$\bar{D}D$ production cross section



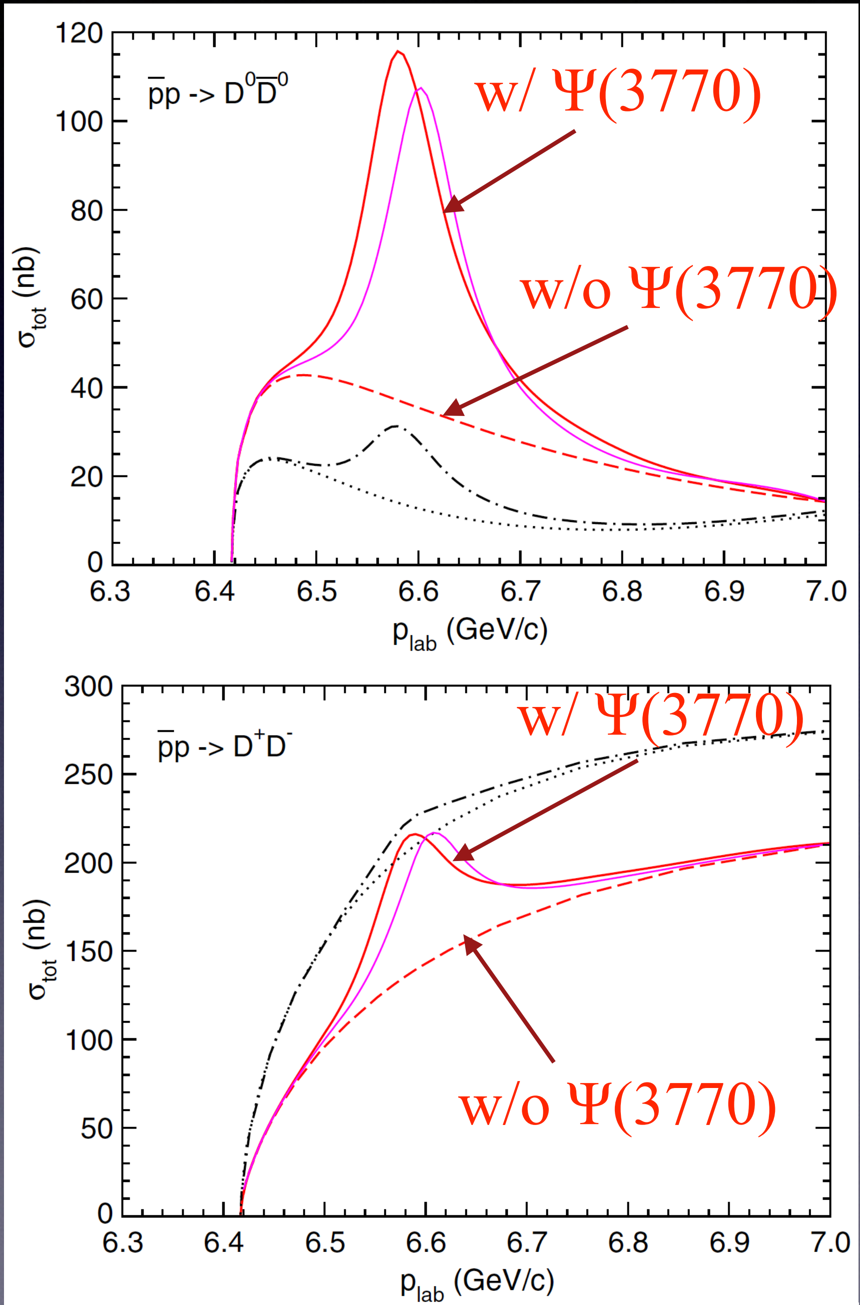
PHYSICAL REVIEW D **91,** 114022 (2015)

$\bar{D}^0 D^0$ production cross section at threshold will be sensitive with $\Psi(3770)$

if $\Psi(3770)$ is normal charmonium (like $\Psi(2S)$), it will have strong coupling to $\overline{p}p$

Enhancement of $\bar{D}D$ production cross section expected near threshold

$\bar{D}D$ production cross section at J-PARC



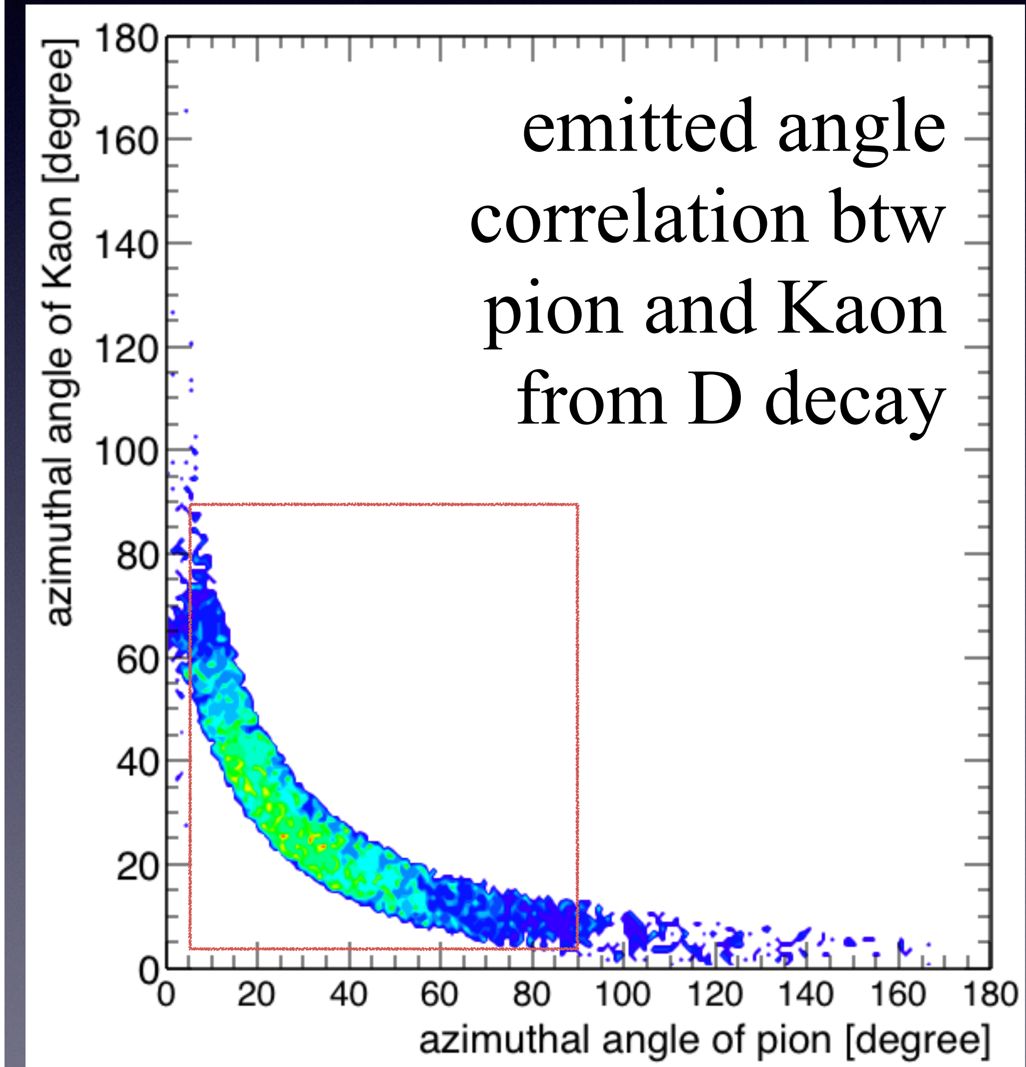
PHYSICAL REVIEW D **91,** 114022 (2015)

- Production cross section
  - ~ 100 nb ($\bar{D}^0 D^0$) @6.6GeV/c
  - ~ 200 nb ($D^- D^+$) @6.6GeV/c
- Beam intensity
  - $3\text{x}10^7$ $\bar{p}$ /6s (100 kW)
- Produced D pairs/100 days
  - $6\ \text{x}10^6$ ($\bar{D}^0 D^0$)
  - $1.2\ \text{x}10^7$ ($D^- D^+$)
    - Ψ(3770)→J/Ψππ→μμππ
      - ~ $6\ \text{x}10^2$

Consideration for the detector

- Focusing on the $\bar{p}p \to \bar{D}D$ channel
- Momentum range for produced D

: 2.4 GeV/c - 4.6 GeV/c



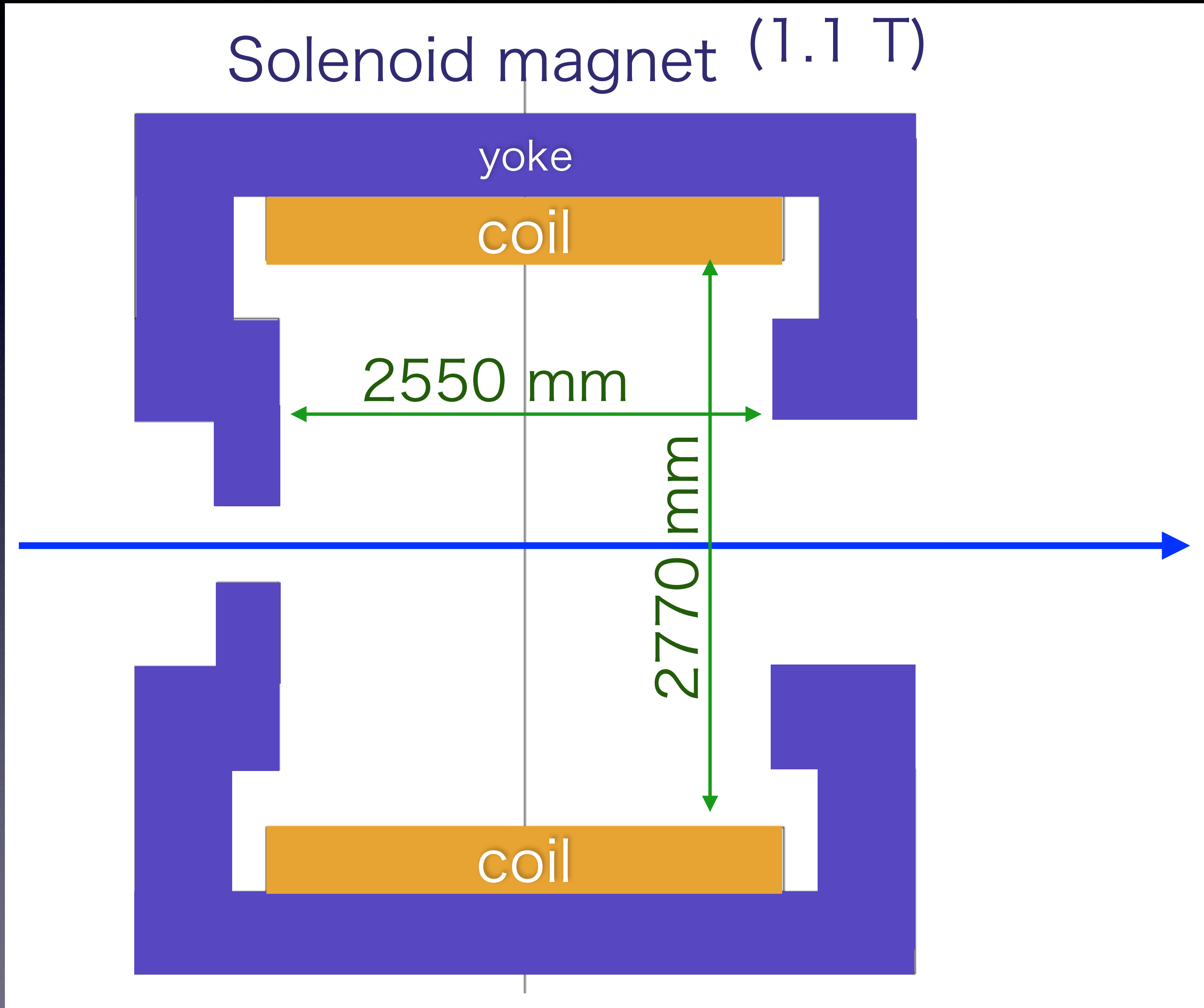
concept of the detector

-> Large acceptance coverage

angler coverage :

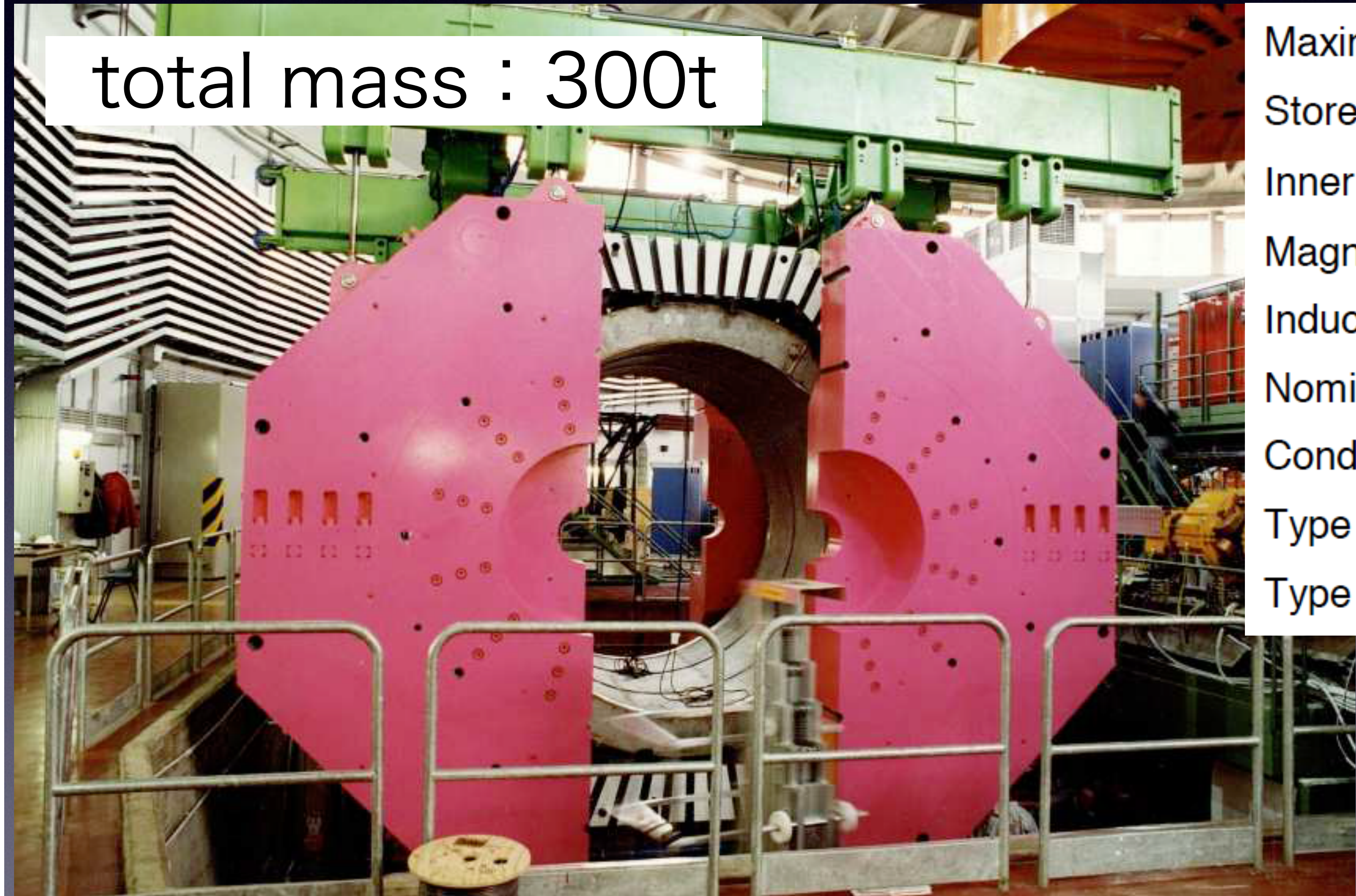
- azimuthal : 5° - 90°
- polar : 2π

Baseline design for the detector



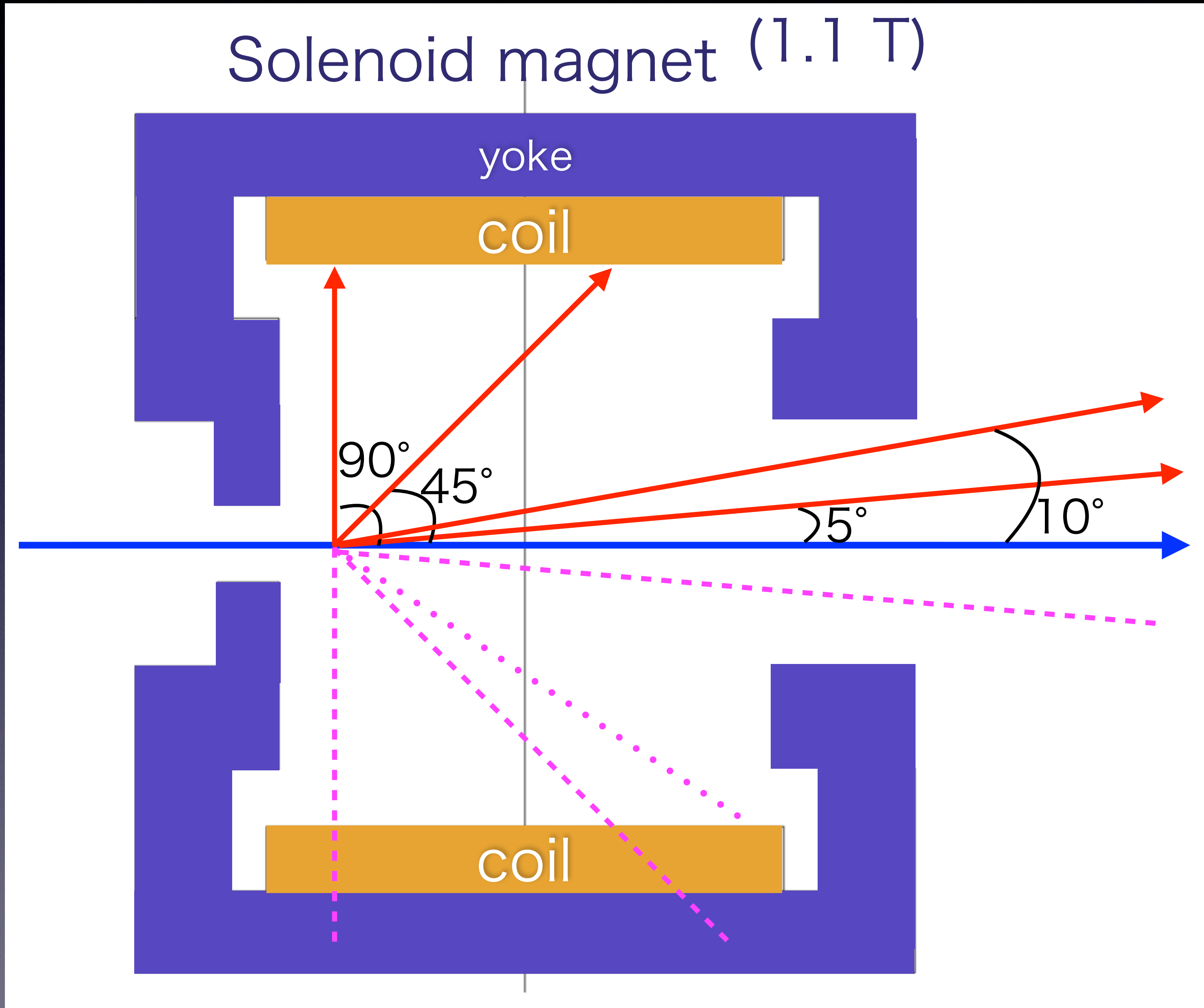
Large solenoid magnet

Large solenoid magnet (like FINUDA magnet at Frascati)



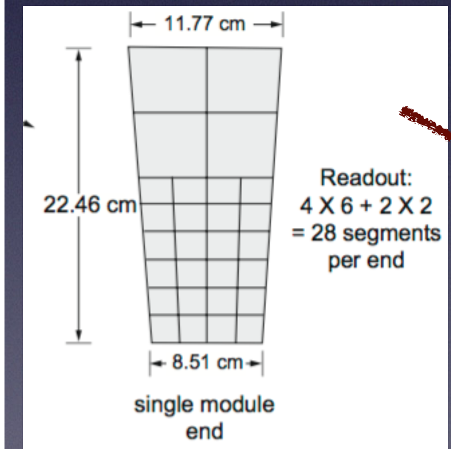
Maximum field	1.1 T
Stored energy	8.1 MJ
Inner diameter	ϕ 2929 mm
Magnet length	2200 mm
Inductance	2.2 H
Nominal current	2845 A
Conductor	NbTi–Al coextr.
Type of winding	Outer mandrel
Type of cooling	indirect

Baseline design for the detector

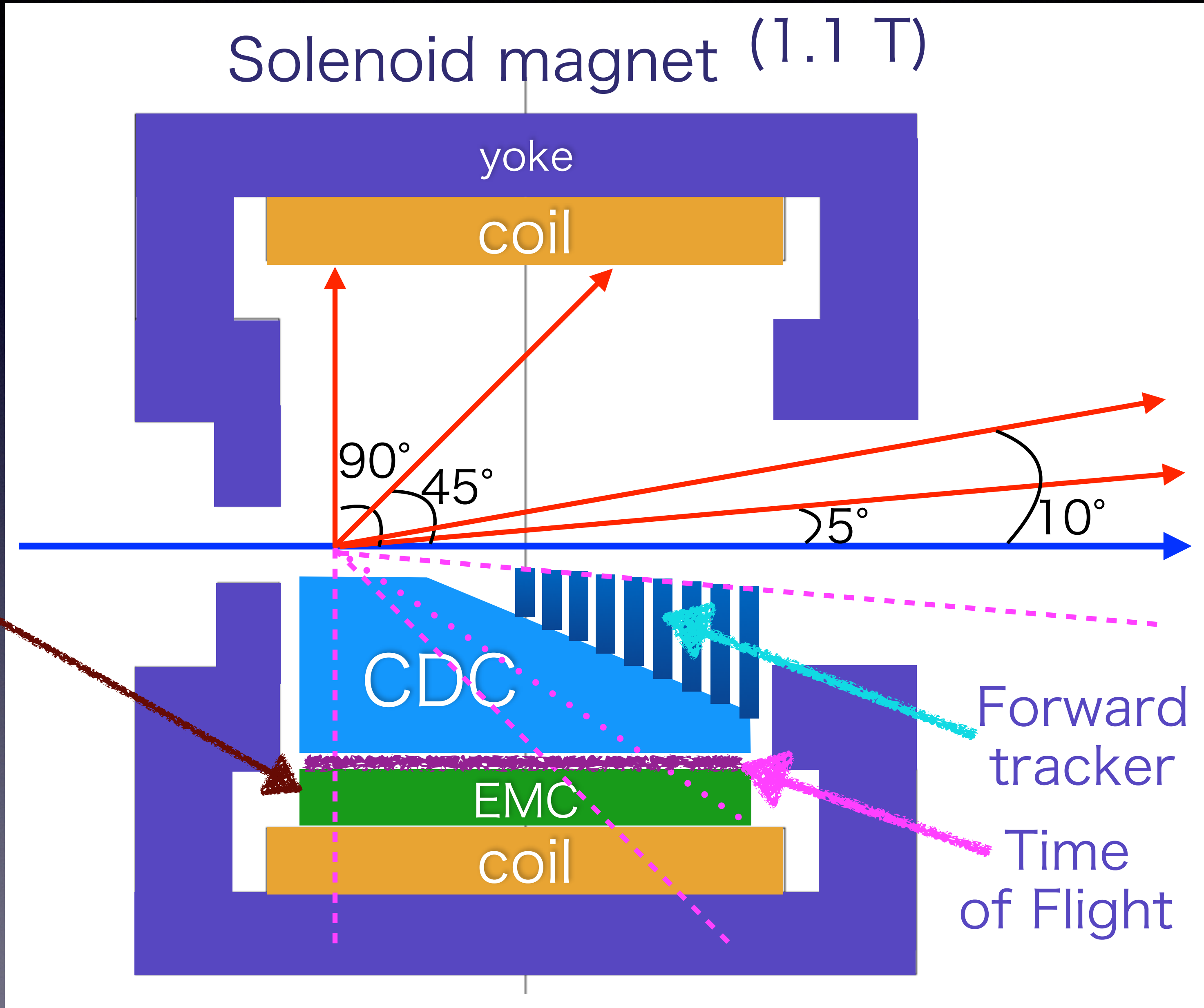


Baseline design for the detector

EM Cal

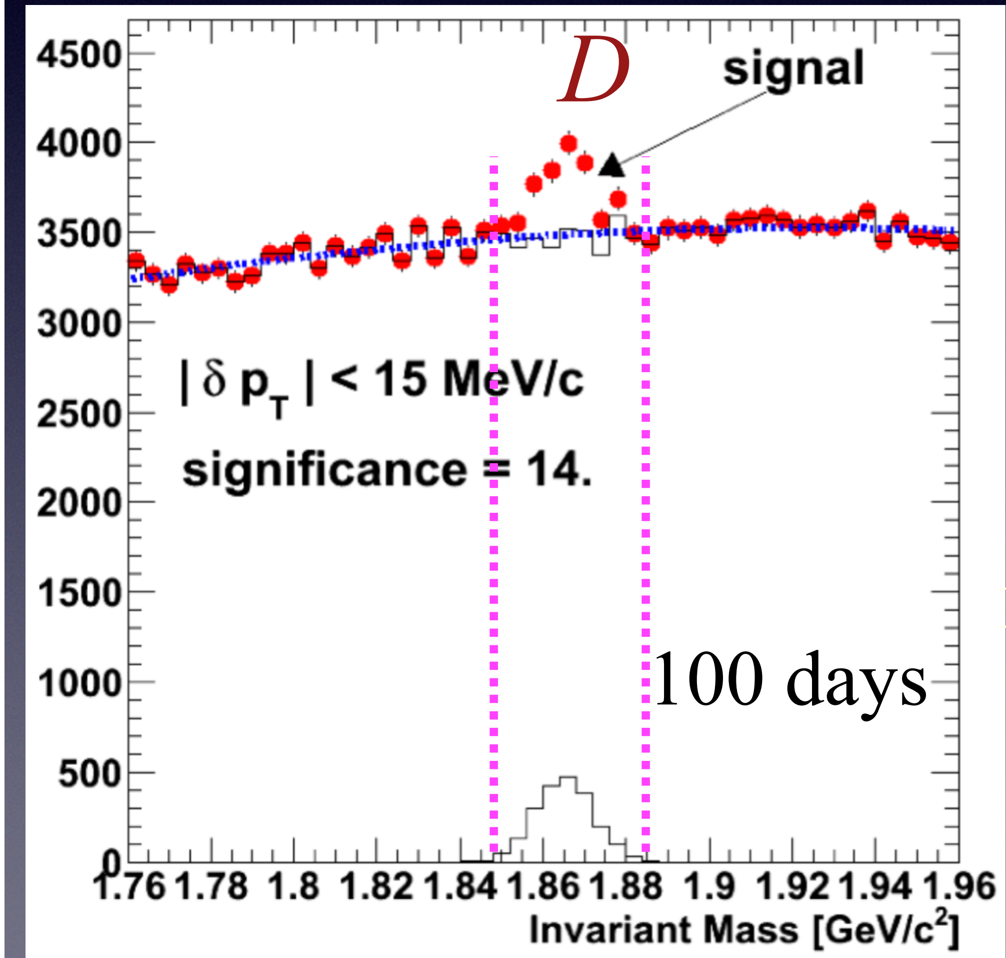


Lead-Scinti
calorimeter
(KLOE type)



Signal and Background

$$\bar{p}p \to D^0\bar{D}^0 \to K^+\pi^-K^-\pi^+ \quad \text{(signal)}$$
$$\bar{p}p \to K^+\pi^-K^-\pi^+ \quad \text{(background)}$$



$$\sigma_{\bar{D}D} : \sigma_{K^+\pi^-K^-\pi^+}$$
$$=1:1000$$

$$10^7/pulse,\ 6.6\ GeV/c\ \ \bar{p}$$

Required :

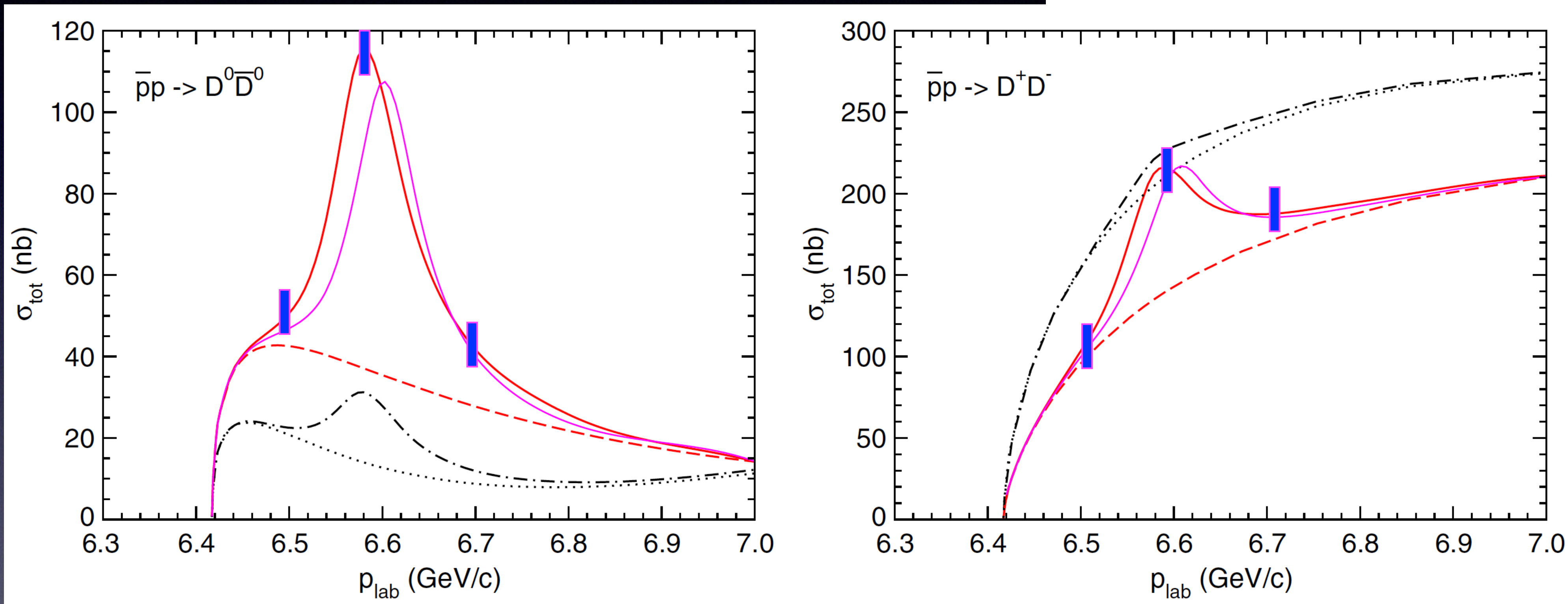
detected all 4 tracks

$$1.83\ GeV < M_{inv}(K^+\pi^-) < 1.89\ GeV$$

Precision on cross section measurement ~ 10% level

Expected precision of $\bar{D}D$ measurement

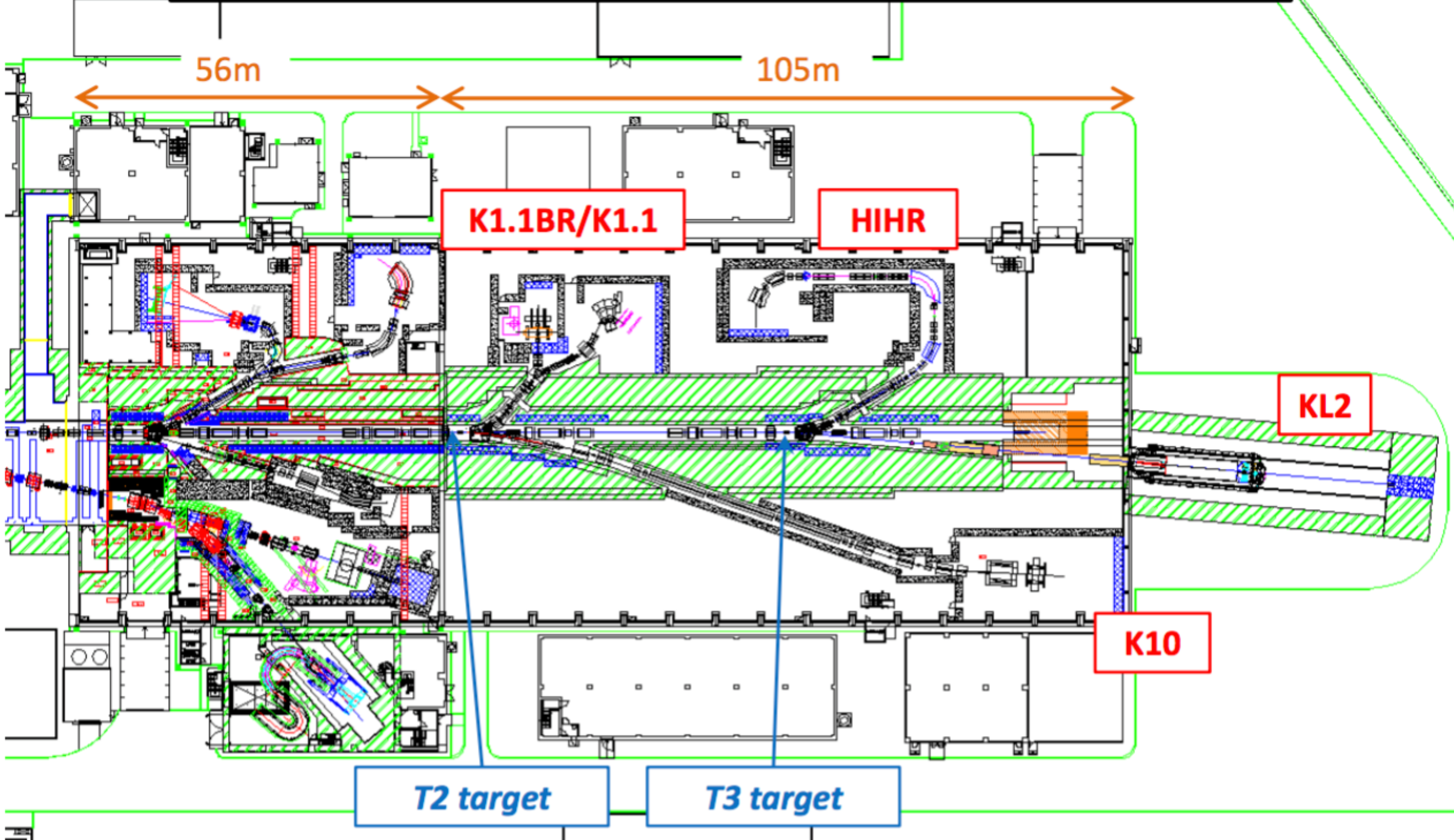
PHYSICAL REVIEW D 91, 114022 (2015)



We may conclude whether the contribution from $\Psi(3770)$ exist on the $\bar{D}D$ production at threshold or not.

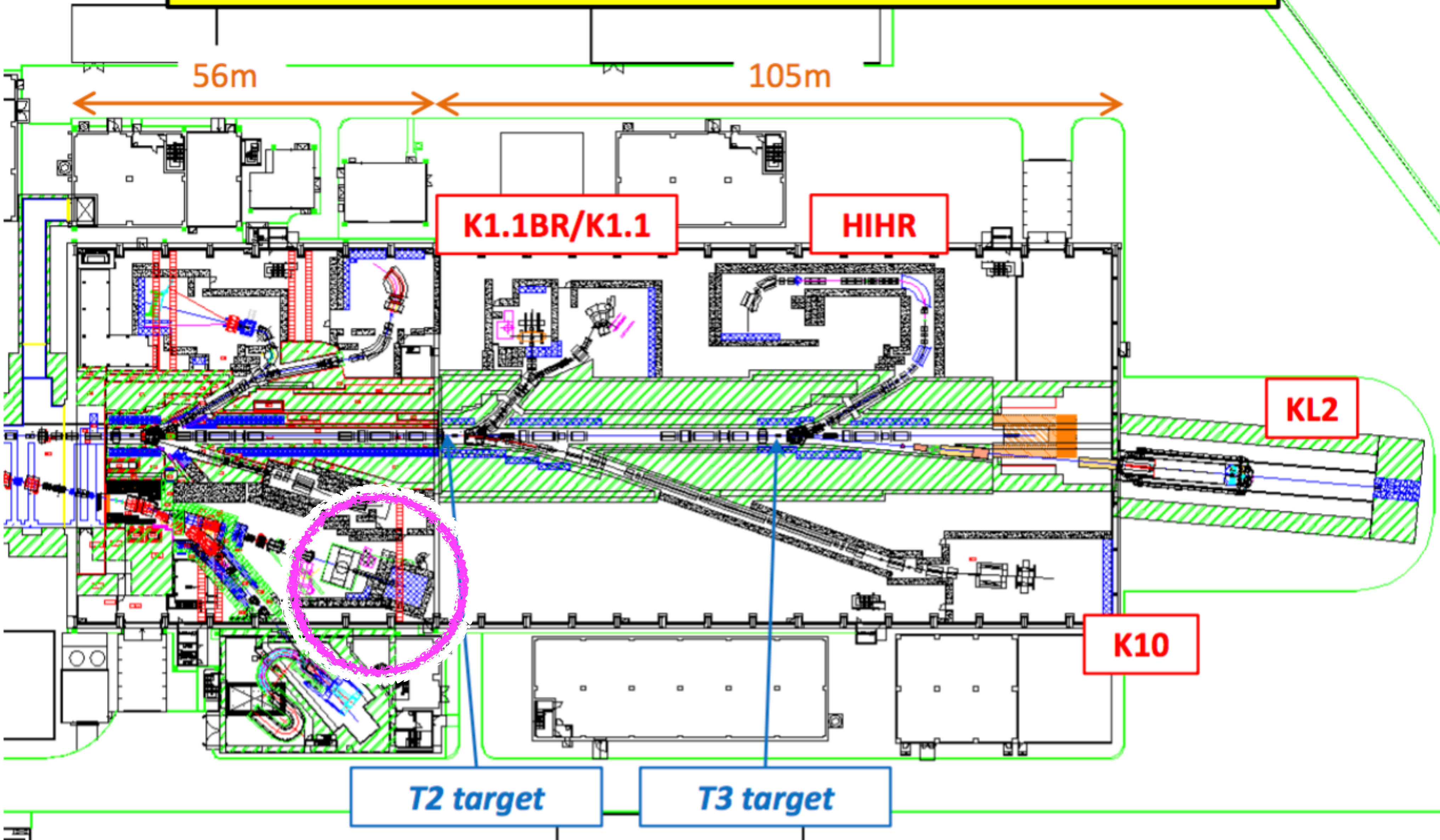
Heavy ion beam with K10 spectrometer

Extension of J-PARC Hadron Facility



- HD-hall is extended by 105m.
- Two more production targets

Extension of J-PARC Hadron Facility



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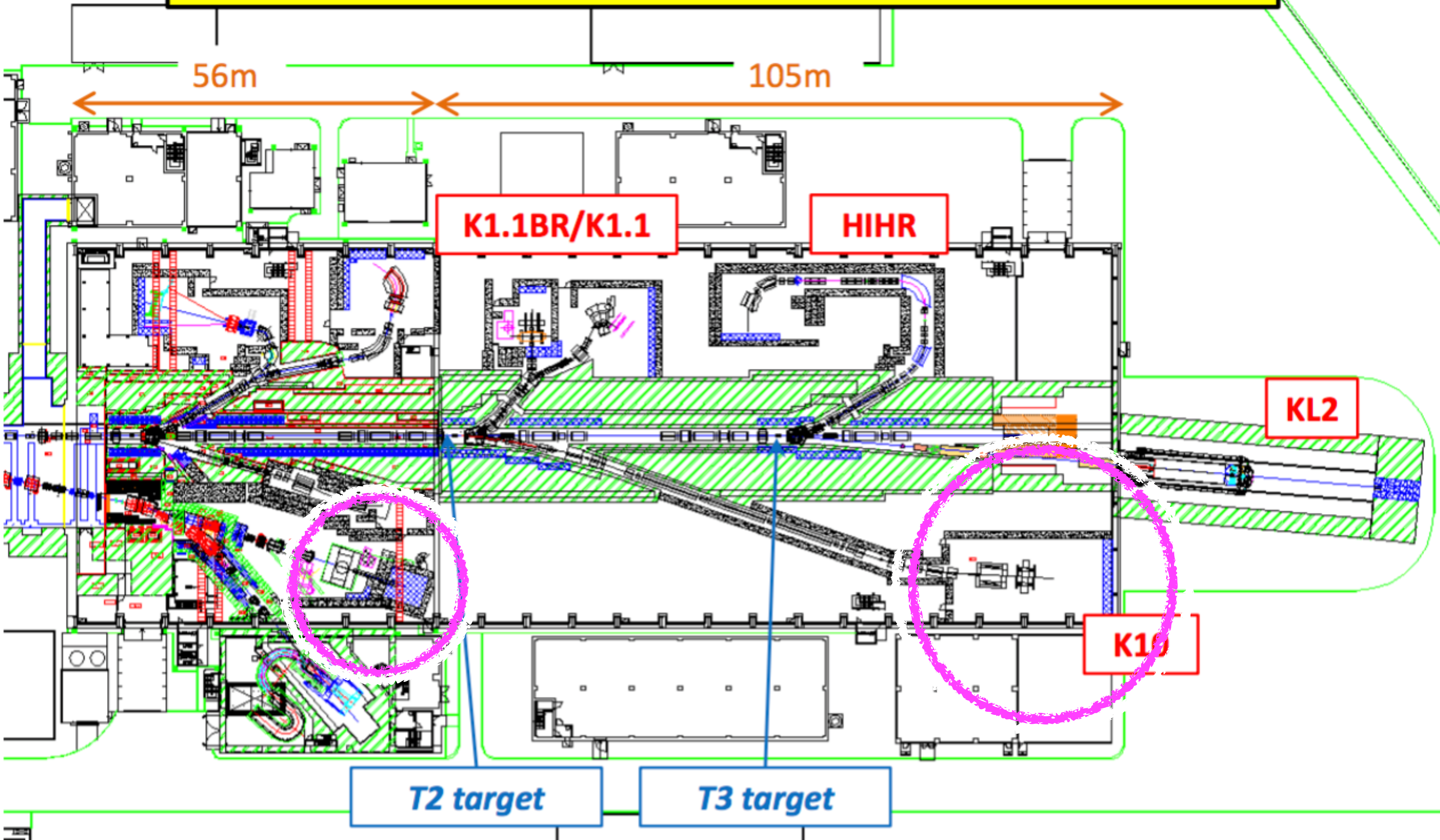

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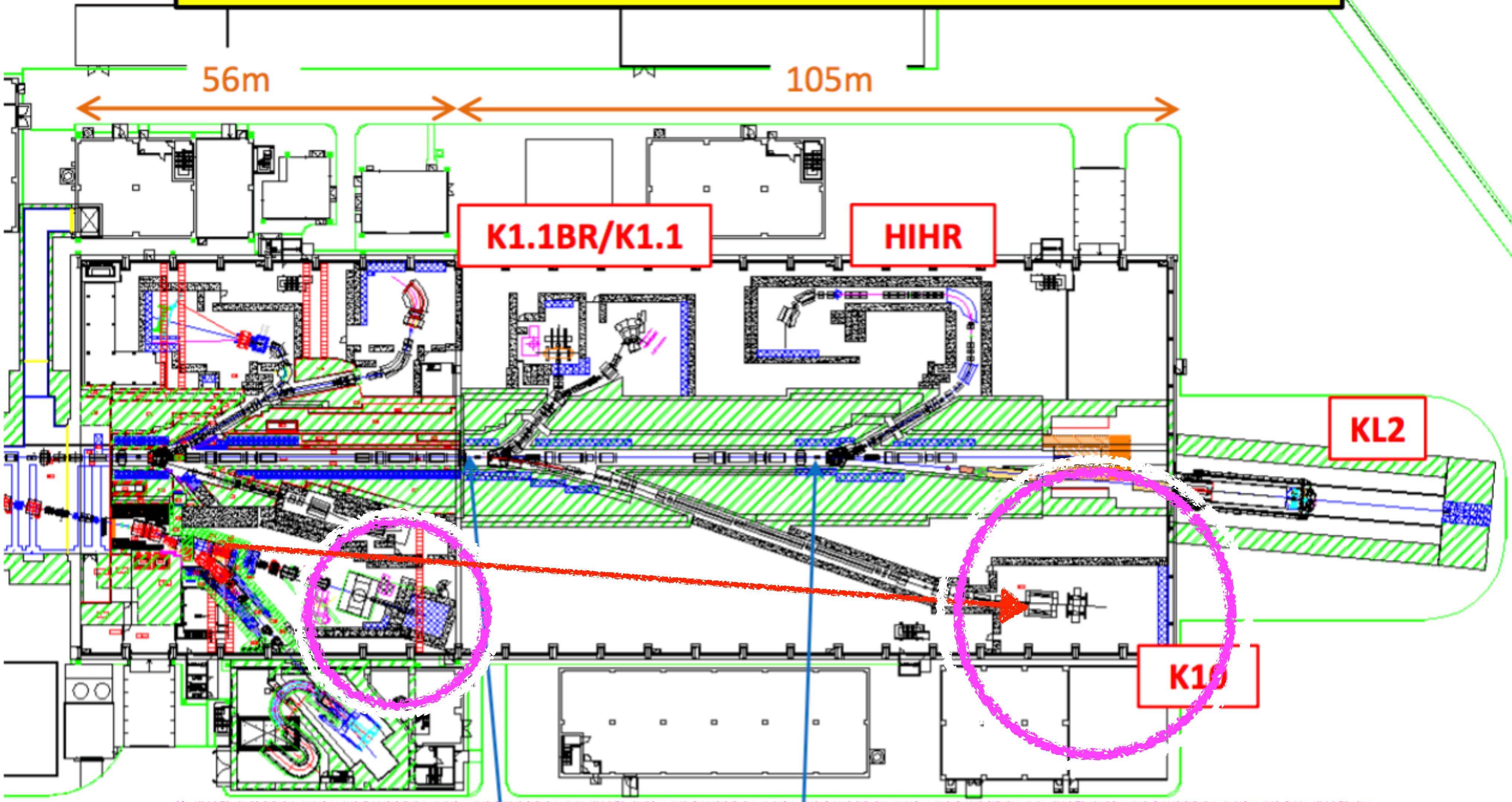

HI collision experiment can be done with beam transfer line from High-p to K10

5m.

- Two more production targets

Summary

- Meson in nucleus will give us unique information about the QCD vacuum
  ($< \bar{q}q >$ in finite density)

- charmed meson in nucleus will be one of the key topics which can be realized at J-PARC K10

- Spectrometer at K10 is going to be multi-purpose / large acceptance detector.
  once beam transport line from High-p to K10 is constructed, HI experiment with K10 spectrometer will be possible.