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Reactor Antineutrino Detection in Double-Chooz: New Techniques for Background Reduction, Rates & Spectra

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Background sources in Double-Chooz

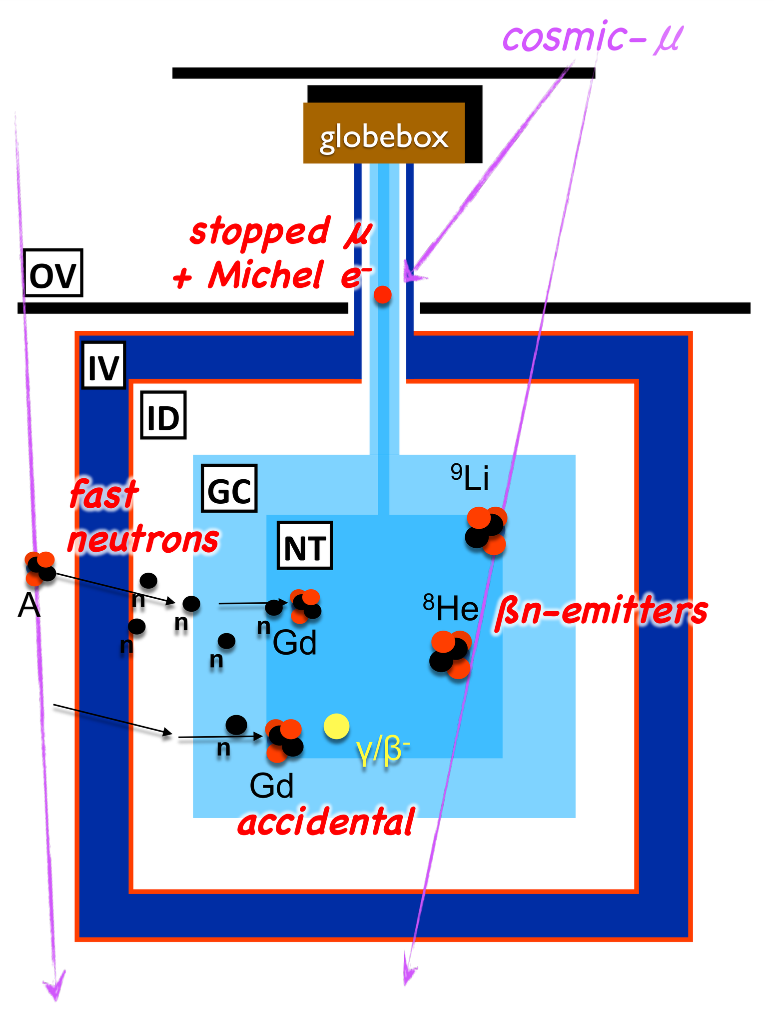
Gd-III IBD Candidate Selection Criteria

- Criteria optimized for background reduction
- Several new veto techniques introduced

→ lower background rates, compared to Gd-II reduction of uncertainties by factor 2

Muon Veto	μ-tagging	E_{ID} > 20 MeV, Q_{IV} > 30 k[a.u.]
	Δt(μ)	1 ms
Light Noise Rejection	Q_{max}/Q_{tot}	≤0.12
	RMS(t,Q)	2D cut
	ΔQ	30 k[a.u.]
IBD Selection	Δt	[0.5;150] μs
	ΔR	≤ 1 m
	E_{prompt}	[0.5; 20] MeV
	$E_{delayed}$	[4; 10] MeV
	multiplicity	[-0.2,0.6] ms
Background Rejection	Outer Veto Veto (OVV)	
	Inner Veto Veto (IVV)	
	Functional Value Veto (FVV)	
	Li/He reduction (LiR)	

Background Sources



Backgrounds that mimic the IBD signature:

- μ-induced **βn-instable isotopes**: ^{9}Li (+^{8}He)
- **Fast neutrons** (FN) from by-passing μ's (typically several at once)
- **Stopped muons** (SM) entering the detector through the chimney
- **Accidental** coincidences of single events
- **α-n-reactions** on ^{13}C (from $^{210/4}$Po decay)
- Coincident decays of ^{12}**B-**^{12}**B** pairs or ^{12}**B-n** coincidences (from same parent μ)

Overview of Residual Backgrounds

Rates and uncertainties can be determined

- *exclusively* using regular data sample
- *inclusively* in Reactor Off-Off-period

Dominating BG uncertainty in DC-III: ^{9}Li+^{8}He

Background	rate [d^{-1}]	shape	energy range	BG/S [%]	δ(BG) [%]	cf. DC-II
^{9}Li+^{8}He	$0.97^{+0.41}_{-0.16}$	Li/He tag	[0;12] MeV	**2.61**	**0.78**	1.3
FN+SM	0.60±0.05	IV tag	[0;20] MeV	1.62	0.13	1.9
ACC	0.070±0.005	off-time	<3 MeV	0.19	0.01	3.7
^{12}B-^{12}B/n	<0.003(1σ)	-	[0;13] MeV	-	-	7.0
^{13}C(α,n)^{16}O	<0.1	-	<2 MeV	-	-	same

Background sources: FN – fast neutrons, SM – stopped muons, ACC – accidentals, ^{12}B-^{12}B/n produced by same muon
Rate from exclusive measurement, shape by special selection tags, energy range corresponds spectral prediction
BG/S: background-to-signal ratio, δ(BG): uncertainty on BG relative to S, cf. DC-II: reduction compared to earlier paper

Veto Techniques for Background Reduction

Functional Value Veto (FVV)

Idea: Tag stopped muons (SM) + light noise (LN) by their inconsistency with a point-like energy deposition.

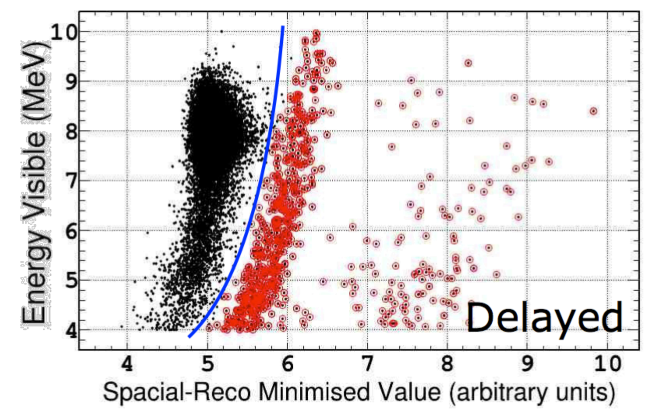
Veto Strategy:

- Spatial reconstruction based on photon time-of-flight differences of PMT hits, assuming a point-like event.
- Functional value ($\mathrm{FV} = -\ln\mathcal{L}$) is the negative log-likelihood minimized in event reconstruction:

$$\mathcal{L}(\mathbf{X}) = \prod_{q_i=0} f_q(0;\mu_i) \prod_{q_i>0} f_q(q_i;\mu_i) f_t\left(t_i; t_i^{(\mathrm{pred})}, \mu_i\right)$$

- For a given energy, SM (in chimney) and LN (front of PMT bases) are identified by their larger FV (using the delayed event of the IBD candidate)

→ **most SM are rejected by FVV**



Functional value (quality of reco) vs. delayed event energy. SM and LN identified by their large FV.

Cut condition: E>0.068e$^{FV/1.23}$

Light Noise (LN) Cuts

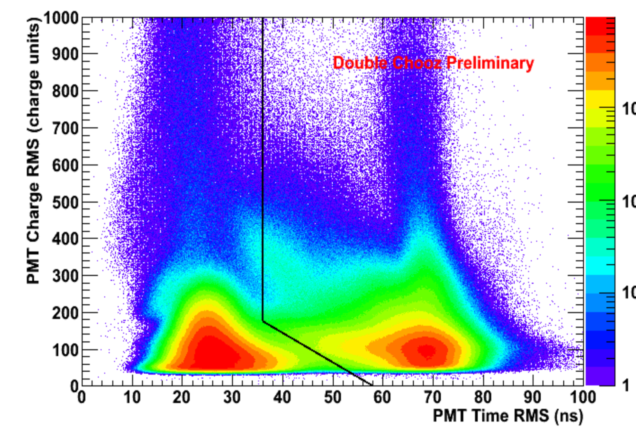
Idea: Identify LN specific light pattern.

Identification Strategy:

- Light emission at PMT base: "Light Noise"
- typical time pattern: Strong signal at LN-emitting PMT often followed by neighboring PMTs

→ Check of homogeneity of PMT timing and charge distributions:

- difference in charge of LN-emitting PMT and surrounding PMTs: ΔQ, Q_{max}/Q_{tot}
- spread of 1st photon arrival times and detected charge: 2D cut applied



RMS of PMT start times and charge: Light noise is removed by the indicated 2D cut.

Lithium reduction (LiR)

Idea: Tagging of ^{9}Li+^{8}He events by selecting likely parent muons

Selection strategy:

- He/Li produced by showering muons close to the μ track.
- Identify Li parent μ's by neutron multiplicity n_n, short distance to IBD candidate $d_{\mu\nu}$ and maximum time difference 700ms.

$$\mathcal{L}(n_n, d_{\mu\nu}) = p(n_n) \cdot p(d_{\mu\nu})$$

- Profiles *p* have been obtained by studying the μ-production of ^{12}B.

→ IBD events related to a likely parent μ are vetoed ($\mathcal{L} > 0.4$)

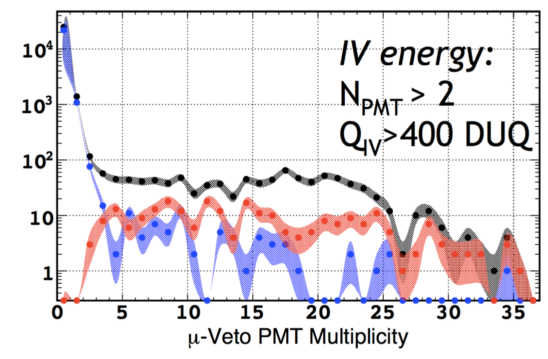
Added effect: Due to showering muon veto, short-lived (τ=29 ms) ^{12}B-^{12}B/n coincidences removed

Inner Veto Veto (IVV)

Aim: Tag background coming from outside the detector with the IV: FN and SM [similar to OV]

Tagging Strategy:

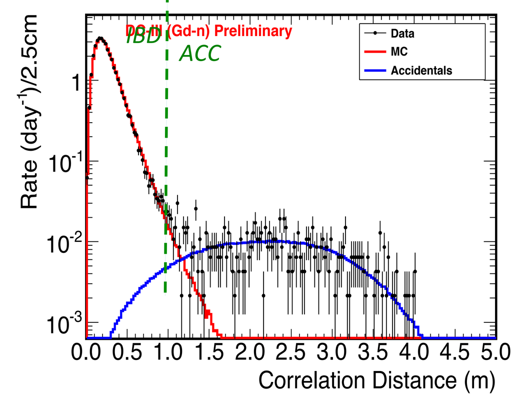
- parent μ not seen, but IV detects n's via proton recoils & n-captures
- use time/distance correlation between ID-IV to reduce over-efficiency by random coincidences



Prompt-Delayed Radial Cut

Idea: Reject spatially uncorrelated events (accidentals) while keeping IBDs (strong correlation)

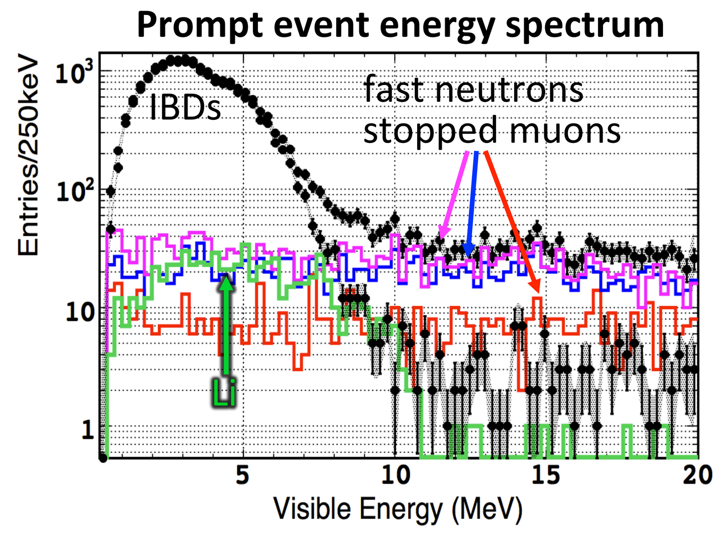
→ **Cut condition: ΔR < 1m**



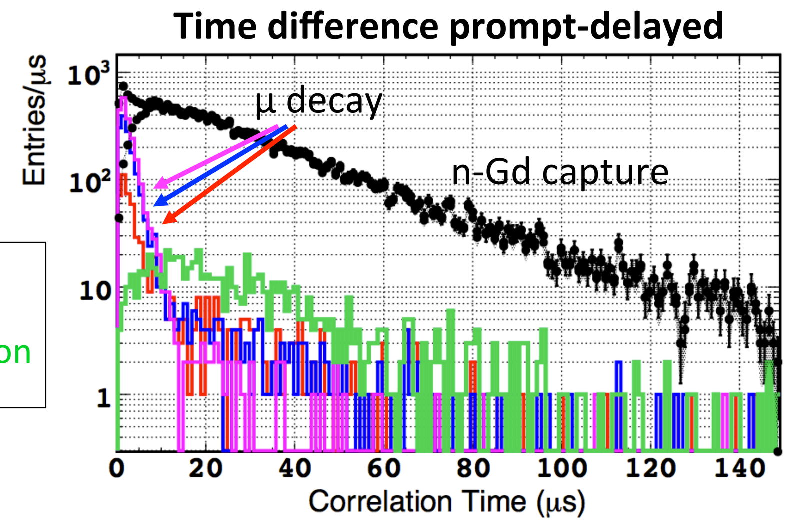
ΔR distribution of candidates: Expected IBD distribution and accidentals are overlayed.

Effect of vetoes and selection on IBD candidates

Prompt event energy spectrum



Time difference prompt-delayed



Prompt event spectra & Δt-distributions of vetoed events:

→ FV+IV+OV remove SM (τ=2.2μs) and FN (E_p>12 MeV)

→ Li-tagged sample features expected spectral shape

FN/SM veto efficiency	absolute (per veto)	uncorrelated fraction	relative to others
IVV	24%	7%	40%
OVV	62%	7%	41%
FVV	71%	19%	66%
total	90%	33%	-

FN/SM tagging is highly redundant → robust rejection

Veto	Efficiency	Inefficiency
IVV	FN/SM: 24%	<0.1%
Li Red	Li: >50%	0.54%
LN Cut	LN: >95%	<0.1%
ΔR Cut	Acc: 86%	0.4%
FVV	FN/SM: 71%	<0.1%
OVV	FN/SM: 62%	<0.1%

→ Substantial reduction of all BGs

→ Inefficiencies introduced for IBDs have been evaluated to be small

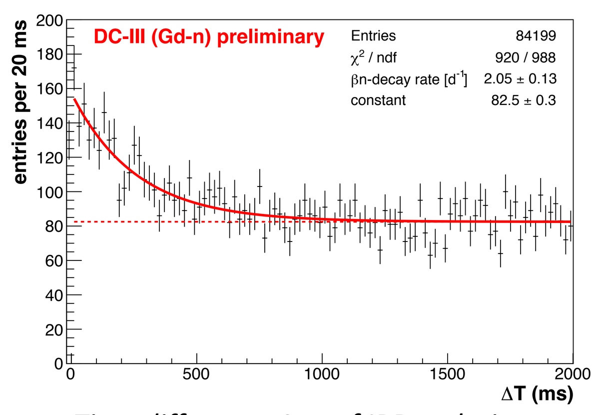
Exclusive measurements of background residuals

Cosmogenic ßn-emitters: ^{9}Li, ^{8}He

Rate estimate

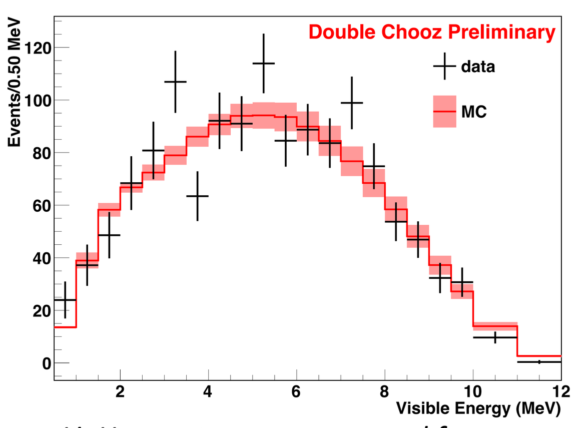
βn-rate based on fit to Δt-distribution of IBD candidates to muons.

- *Minimum rate* estimate based on data selection optimized for βn-tagging using μ visible energy E_{vis}, neutron multiplicity and lateral distance $d_{\mu\nu}$.
- *Mean rate* estimate based on Δt-fits to IBD candidates close to μ tracks ($d_{\mu\nu}$<1m)
- extrapolation for large $d_{\mu\nu}$ uses lateral distance profile obtained from high-E_{vis} muon sample.



Time difference $\Delta t_{\mu\nu}$ of IBDs relative to preceding μ's. Fit assumes correlation based on the ^{9}Li life time (τ=257ms). Constant contribution due to uncorrelated μ-IBD pairs.

^{9}Li+^{8}He	Rate [d^{-1}]
Total	$2.10^{+0.41}_{-0.16}$
LiR-tagged	1.12±0.05
Residual	$\mathbf{0.97^{+0.41}_{-0.16}}$



Prompt spectrum

- Selected with likelihood tag, both n-Gd and n-H captures
- Background subtracted with off-time muon selection.

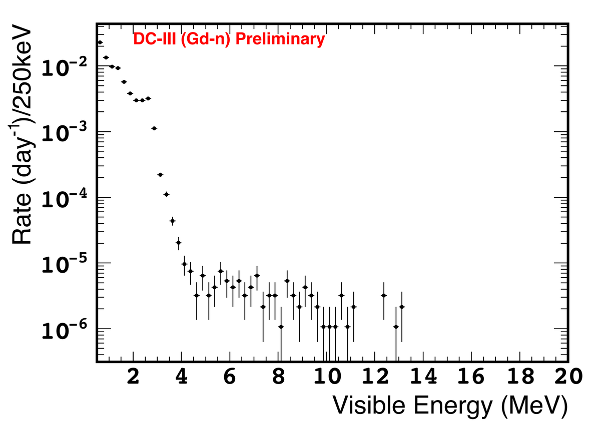
Li+He spectrum as measured from data selected on the Li reduction tag. Data shape is consistent with the prediction (red curve).

Accidentals

- Rate and spectrum derived from time-uncorrelated samples (offtime coincidence windows shifted by 1s+δt) to remove correlated event contribution.
- Increase of statistics by 2000 windows with δt = n x 800 μs

→ **Rate: 0.070±0.005 d^{-1}**

→ **Prompt event spectrum** dominated by natural radioactivity



Other backgrounds

- Rate of ^{12}**B-**^{12}**B/n coincidences** determined analogously to accidental BG, but varying delay of off-time window.
- Excess for short time offsets follows ^{12}B life time (τ=29 ms).

→ **Rate ^{12}B-^{12}B/n < 0.003 d^{-1}**

- upper limit on αn-reaction rate on ^{13}C determined from ^{214}Po peak at E_{vis}≈0.47 MeV

→ **Rate ^{13}C(α,n)^{16}O < 0.0025 d^{-1}**

BG	DC-II [d^{-1}]	DC-III [d^{-1}]
^{9}Li+^{8}He	1.25±0.54	$0.97^{+0.41}_{-0.16}$
FN+SM	1.14±0.34*	0.60±0.05
Acc	0.261±0.002	0.070±0.005

* *Rate has been scaled from DC-II prompt energy selection window (0.5 < E < 12 MeV)*

Fast neutrons (FN) and stopped muons (SM)

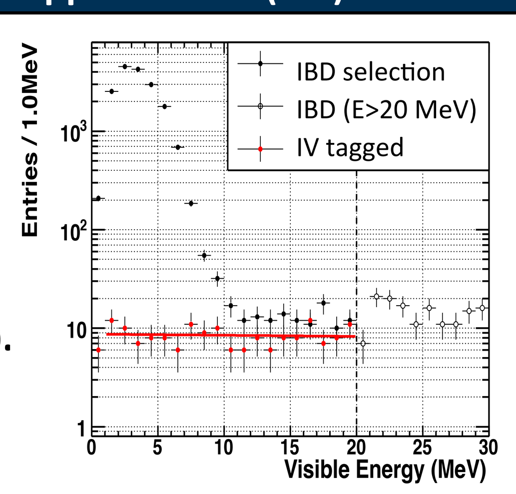
After vetoes, residual correlated events dominated by FN (most SM rejected by FVV)

Spectrum is evaluated based on IV-tagged sample (figure)

→ linear fit is consistent with a **flat distribution in NT (not GC).**

Rate is measured from [20,30] MeV window using spectral shape to extrapolate

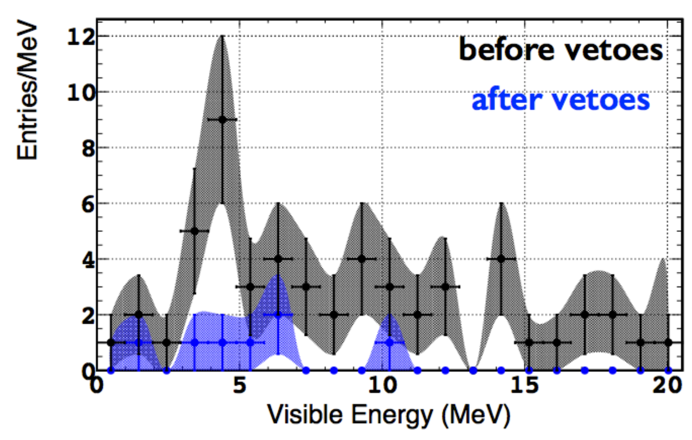
→ **Rate: 0.60 ± 0.05 d^{-1}**



FN+SM prompt energy spectrum from IV-tagged event sample.

Inclusive Background Constraints

Prompt spectrum from Reactor-Off-Off Period



based on 7.3d of data

After subtraction of residual reactor neutrinos:

- Rate before vetoes: 7.3 ± 1.0 d^{-1}
- **Rate after vetoes: 0.76 ± 0.37 d^{-1}**

→ **Background reduced to ~10%** (cf. FN+SM rejection efficiency)

Comparison to exclusive measurement

- Exclusive expectation: $1.57^{+0.42}_{-0.18}$ d^{-1}

→ rates consistent within 2σ level

→ lower inclusive rate leaves no room for unknown background sources

Background in Oscillation Fit

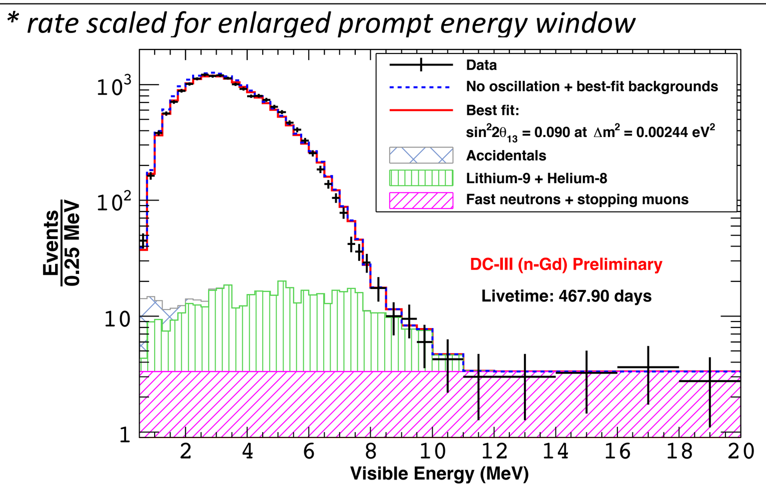
Uncertainties on dominant background rates constrained by fit via the distinct prompt spectra of signal and backgrounds.

(see DC poster: "New measurements and future capabilities of the Double Chooz reactor antineutrino experiment").

Background rates (events/day)

Source		Fit input	Fit output
^{9}Li+^{8}He	DC-II	1.25 ± 0.54	1.00 ± 0.29
	DC-III	$0.97^{+0.41}_{-0.16}$	$0.80^{+0.15}_{-0.13}$
FN+SM	DC-II*	1.14 ± 0.34	1.09 ± 0.22
	DC-III	0.60 ± 0.05	0.56 ± 0.04

* *rate scaled for enlarged prompt energy window*



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