Compact and Tightly Selective-Opening Secure Public-key Encryption Schemes

Asiacrypt 2022

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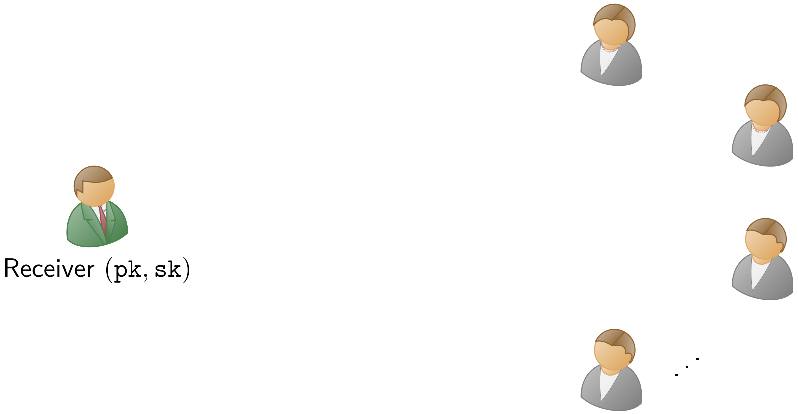
(Sender) Selective Opening Security



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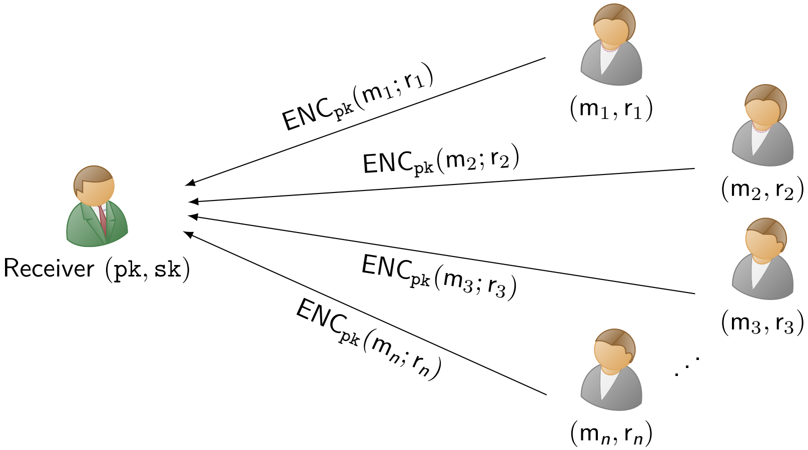

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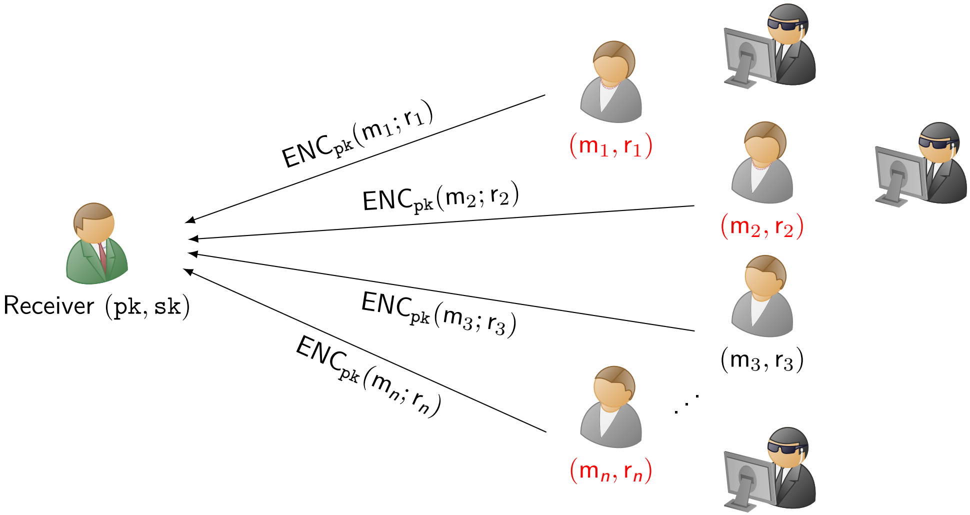

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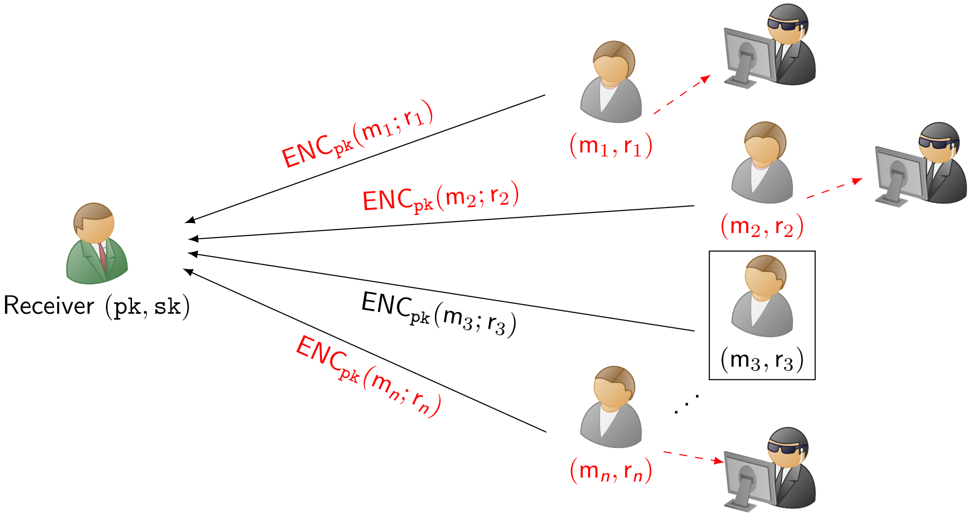

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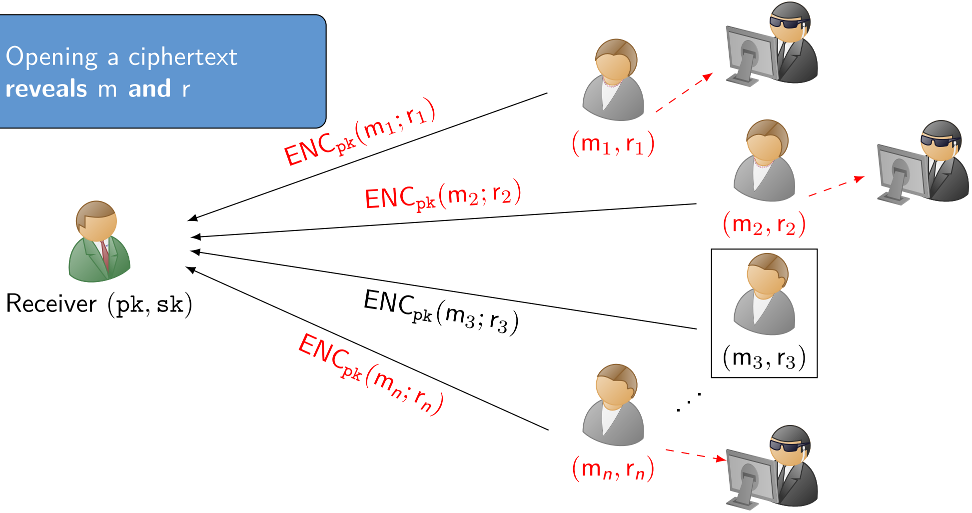
Opening a ciphertext
reveals m **and** r



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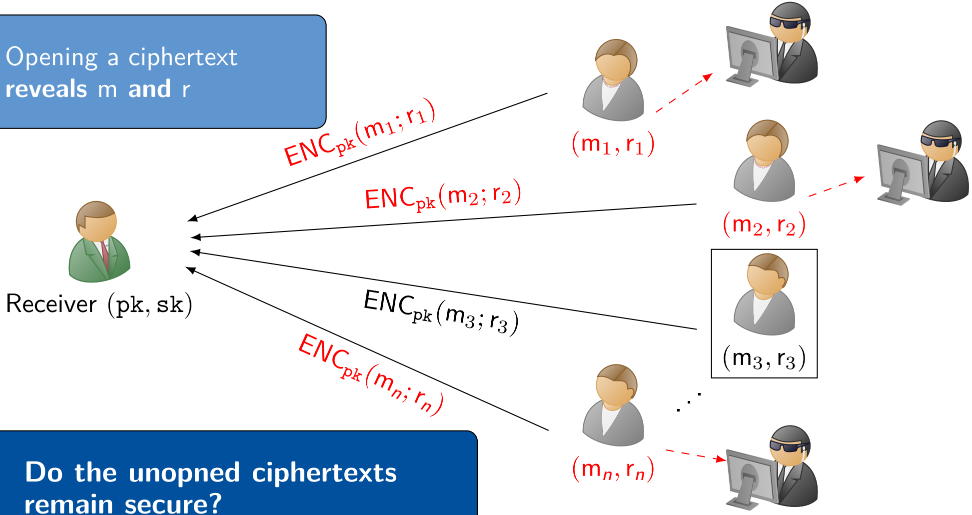

Do the unopned ciphertexts remain secure?

Selective Opening Security

- Sender Selective Opening (SO) Security:

  Even if the adversary can open some of the challenge ciphertexts, the unopened challenge ciphertexts remain secure.

- Motivations:

  Sender corruptions, randomness leakage...

Selective Opening Security

- Dates back to [DNRS99]

Selective Opening Security

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- Definitions for SO security [DNRS99, BHY09, HLOV11, BHK12...]

Selective Opening Security

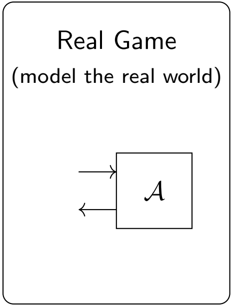
- Two flavors of SO(-CCA) security notions.
  - Indistinguishability-based SO (IND-SO) Security [BHY09, BHK12]
  - Simulation-based SO (SIM-SO) Security [DNRS99, BHY09]

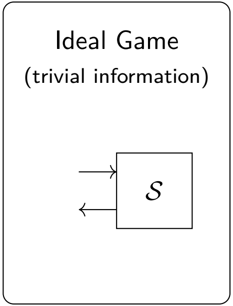
Selective Opening Security

- Two flavors of SO(-CCA) security notions.
  - Indistinguishability-based SO (IND-SO) Security [BHY09, BHK12]
  - Simulation-based SO (SIM-SO) Security [DNRS99, BHY09]
- **SIM-SO** implies (weak) IND-SO [BHK12]

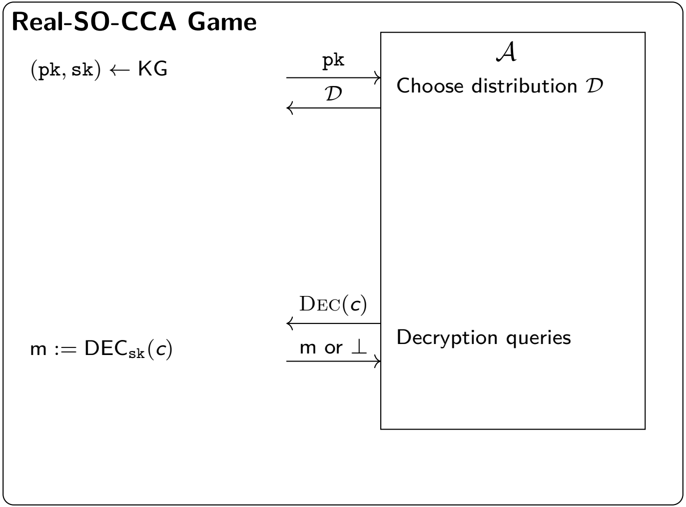
SIM-SO-CCA Security

- Real game and Ideal game
  - Real game models real world scenario
  - $\mathcal{S}$ learns trivial information in the ideal game





SIM-SO-CCA Security - Real Game



SIM-SO-CCA Security - Real Game

Real-SO-CCA Game

Challenger		$\mathcal{A}$
$(\mathrm{pk}, \mathrm{sk}) \leftarrow \mathsf{KG}$	$\xrightarrow{\mathrm{pk}}$	
	$\xleftarrow{\mathcal{D}}$	Choose distribution $\mathcal{D}$
$(\mathsf{m}_1, \dots, \mathsf{m}_n) \leftarrow \mathcal{D}$ $(\mathsf{r}_1, \dots, \mathsf{r}_n) \leftarrow \$$ $\forall i : \mathsf{c}_i := \mathsf{ENC}_{\mathrm{pk}}(\mathsf{m}_i, \mathsf{r}_i)$	$\xrightarrow{\mathsf{c}_1, \dots, \mathsf{c}_n}$	
Require $c \notin \{\mathsf{c}_1, \dots, \mathsf{c}_n\}$ $\mathsf{m} := \mathsf{DEC}_{\mathrm{sk}}(c)$	$\xleftarrow{\textsc{Dec}(c)}$ $\xrightarrow{\mathsf{m} \text{ or } \perp}$	Decryption queries

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$\mathcal{I} := \mathcal{I} \cup \{i\}$	$\xrightarrow{\mathsf{m}_i, \mathsf{r}_i}$	Opening queries
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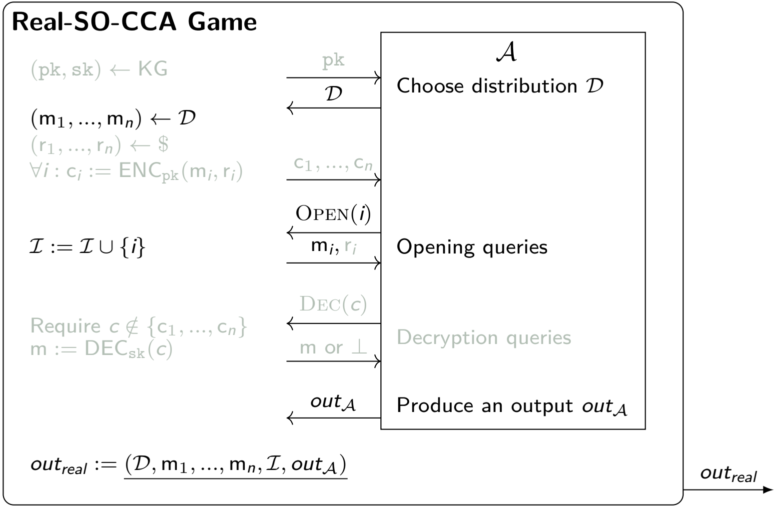
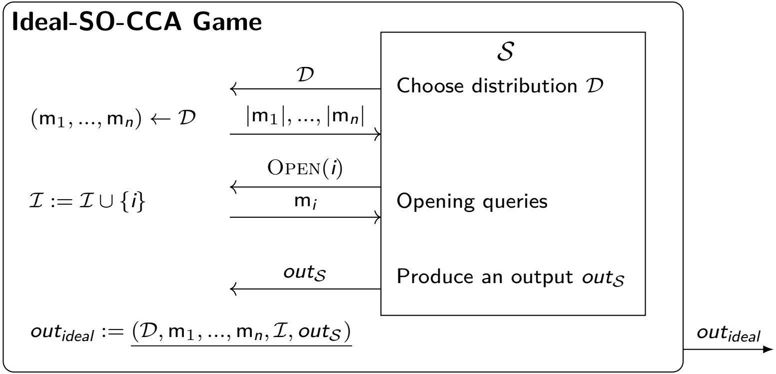
$out_{real} := \underline{(\mathcal{D}, \mathsf{m}_1, \ldots, \mathsf{m}_n, \mathcal{I}, out_{\mathcal{A}})}$

$\xrightarrow{out_{real}}$

SIM-SO-CCA Security - Real Game

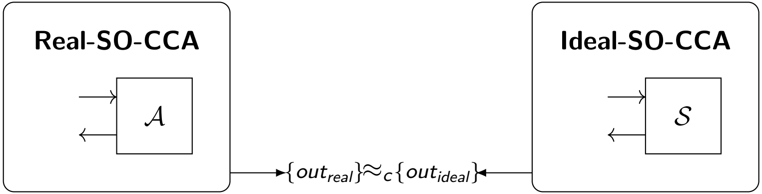


SIM-SO-CCA Security - Ideal Game



SIM-SO-CCA Security

- SIM-SO-CCA security: $\forall \mathcal{A}$, there exists a simulator $\mathcal{S}$ (both are PPT) such that...



- $\mathcal{S}$ simulates the "behavior" of $\mathcal{A}$ (e.g., they choose the same messages distribution, open the same ciphertexts, produce the same output...)

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SIM-SO-CCA

- SIM-SO-CCA is strictly stronger than IND-CCA [BDWY11]

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  - Hybrid argument + IND-CCA does not work

$$\boxed{c_1} \quad \boxed{c_2} \quad \cdots \quad \boxed{c_i} \quad \cdots \quad \boxed{c_n}$$

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Cannot open c_1...

SIM-SO-CCA

- SIM-SO-CCA is strictly stronger than IND-CCA [BDWY11]
- Non-trivial to achieve...
  - Hybrid argument + IND-CCA does not work
- "Guess" technique?
  - may work [HJKS15], but non-tight...

Tightness and Compactness

- Security reduction: $\epsilon_{\mathcal{A}} \leq L \cdot \epsilon_P$
  - $\epsilon_{\mathcal{A}}$: Advantage of breaking SO security
  - ϵ_P: Advantage of breaking some hard problem P
  - L: Security loss
- Tight security: $L = O(1)$.
- Non-tight: $L = O(n)$, $L = O(\ \#\mathrm{RO\ queries}\ )$,...

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- Tight security: $L = O(1)$.
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- Practical relevance:
  - Parameters selection...

Tightness and Compactness

Can we have SIM-SO-CCA scheme with tight security?

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Yes, but with long ciphertext or long public key...

Table: Some group-based SIM-SO PKEs with tight security

Scheme	$\lvert\text{public key}\rvert_{\mathbb{G}}$	$\lvert\text{ciphertext}\rvert_{\mathbb{G}}$
[HJR16]	$O(\ell^2)$	$O(1)$
[LLHG18]	$O(1)$	$O(\ell)$
[JL21]	$O(\ell^2)$	$O(\ell/\log\lambda)$

* λ: security parameter
* ℓ: Length of message
* $|\cdot|_{\mathbb{G}}$: The number of group element

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Tightness and Compactness

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Yes, but with long ciphertext or long public key... (Not compact)

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- Tight security
- Compact public key
- Compact ciphertext

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Tightness and Compactness

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at the same time? Even in the random oracle model (ROM)?

Our Contributions

Compact and tightly SIM-SO-CCA secure PKE in the ROM:

- Three direct constructions
  - Based on strong Diffie-Hellman (stDH)
  - Based on computational Diffie-Hellman (CDH), by using TDH technique [CKS08]
  - Based on decisional Diffie-Hellman (DDH)
- Generic construction
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  4. $d = K \oplus \mathrm{m}$
  5. $t = \mathrm{MAC}_k(R, d)$
  6. Output (R, d, t)

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The DHIES scheme in [HJKS15]

- The ciphertext has this form:

$$(R = g^r,\ d = K \oplus \mathrm{m},\ t = \mathrm{MAC}_k(R, d)) \ \text{, where } (K, k) = H(R, \mathtt{pk}^r)$$

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Proof Sketch (SIM-SO-CCA security).

- Use n-stDH: Given $\left(X, \{R_i\}_{i \in [n]}\right)$ and DDH_X oracle, find $\mathrm{CDH}(X, R_i)$.

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- Cannot open (R_i, d_i, t_i), since r_i's are unknown
- Non-tight reduction:
  - Use "Guess" technique, $O(n)$.
  - RO does not help for tightness...

Our Contributions

Our approach: "Dual" Naor-Yung technique

	Ciphertext	Randomness
DHIES:	$(R = g^r,\ d = \mathsf{m} \oplus K,\ t = \mathsf{MAC}_k(R))$	$r \leftarrow \mathbb{Z}_p$

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- (K, k) is derived from $CDH(\mathtt{pk}, R_0)$ or $CDH(\mathtt{pk}, R_1)$

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- $(K, k) = H(b, R_0, R_1, \mathtt{pk}^{r_b})$, where $b \leftarrow \{0, 1\}$

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  - $r_{1-b} \leftarrow \mathbb{Z}_p, R_{1-b} := g^{r_{1-b}}$

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  - $r_{1-b} \leftarrow \mathbb{Z}_p$, $R_{1-b} := g^{r_{1-b}}$
  - Or $R_{1-b} \leftarrow \mathbb{G}$ (if $\mathbb{G}$ is sampleable...)

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- Forget the dlog: Oblivious randomness
- Use oblivious randomness to respond OPEN queries...
  - E.g., if r_0 is unknown, return $(1, r_1, R_0)$.

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$$\big(R_0, R_1, d, t = \mathrm{MAC}_k(R_0, R_1, d)\big)\ \text{, where } b \leftarrow \{0,1\}, (K, k) = H(b, R_0, R_1, \mathtt{pk}^{r_b})$$

Proof sketch

- Use n-stDH assumption...
- Embed challenge into R_0 or R_1...

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Proof sketch

- Use n-stDH assumption...
- Embed challenge into R_0 or R_1...
- Can open any challenge ciphertext (R_0, R_1, d, t)
  - E.g., return $(b', r_{b'}, R_{1-b'})$ if $r_{1-b'}$ is unknown...

Summary

Summary of our tight reduction

- Based on DHIES in [HJKS15]
- "Dual Naor-Yung" technique
  - Two valid randomness
  - Use oblivious randomness to "forget" the dlog
- Can open any challenge ciphertext (tight reduction)
- Ignore some details: Reprogramming ROs...

Summary

Table: Comparison with some group-based SO-CCA PKE

Scheme	Ass.	Tight?	$\lvert c\rvert_{\mathbb{G}}$	$\lvert \mathtt{pk}\rvert_{\mathbb{G}}$	ROM/StdM?
DHIES [HJKS15]	stDH	✗	$O(1)$	$O(1)$	ROM
FO [HJKS15]	CDH	✗	$O(1)$	$O(1)$	ROM
KEM+XAC [LLHG18]	DDH	✓	$O(\ell)$	$O(1)$	StdM
ABO-LTF [JL21]	DH	✓	$O(\ell/\log\lambda)$	$O(\ell^2)$	StdM
stDH-based scheme	stDH	✓	$O(1)$	$O(1)$	ROM
CDH-based scheme	CDH	✓	$O(1)$	$O(1)$	ROM
DDH-based scheme	DDH	✓	$O(1)$	$O(1)$	ROM
FO (based on [BHY09])	DDH	✓	$O(1)$	$O(1)$	ROM

Summary

Can we have a SIM-SO-CCA scheme achieves

- Tight security
- Compact public key
- Compact ciphertext

at the same time?

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- YES, in the ROM.
- In the StdM? Still Unknown

Q & A

Thank you!