Foundations of Multi-Designated Verifier Signature

Comprehensive Formalization and New Constructions in Subset Simulation

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What is **multi-designated verifier signature?**

Multi-designated verifier signature (MDVS)

[LV04,ZAYS12, DHM+20]

Verifier 1

$(vpk_1, vsk_1) \leftarrow \mathrm{VKGen}(pp)$

$pp \leftarrow \mathrm{Setup}(1^\kappa)$

Signer

$(spk, ssk) \leftarrow \mathrm{SKGen}(pp)$

Verifier 2

$(vpk_2, vsk_2) \leftarrow \mathrm{VKGen}(pp)$

Verifier 3

$(vpk_3, vsk_3) \leftarrow \mathrm{VKGen}(pp)$

[LV04] F. Laguillaumie and D. Vergnaud. Multi-designated verifiers signatures. ICICS 2004.
[ZAYS12] Y. Zhang, M. H. Au, G. Yang, and W. Susilo. (strong) multi-designated verifiers signatures secure against rogue key attack. Network and System Security 2012.
[DHM+20] I. Damgård et al., Stronger security and constructions of multi-designated verifier signatures. TCC 2020.

Multi-designated verifier signature (MDVS)

[LV04,ZAYS12, DHM+20]

Verifier 1

(vpk_1, vsk_1)

Signer

(spk, ssk)

Verifier 2

(vpk_2, vsk_2)

$\boldsymbol{D} := \{\boldsymbol{vpk_1}, \boldsymbol{vpk_2}\}$

$\sigma \leftarrow \mathrm{Sign}(ssk, \boldsymbol{D}, m)$

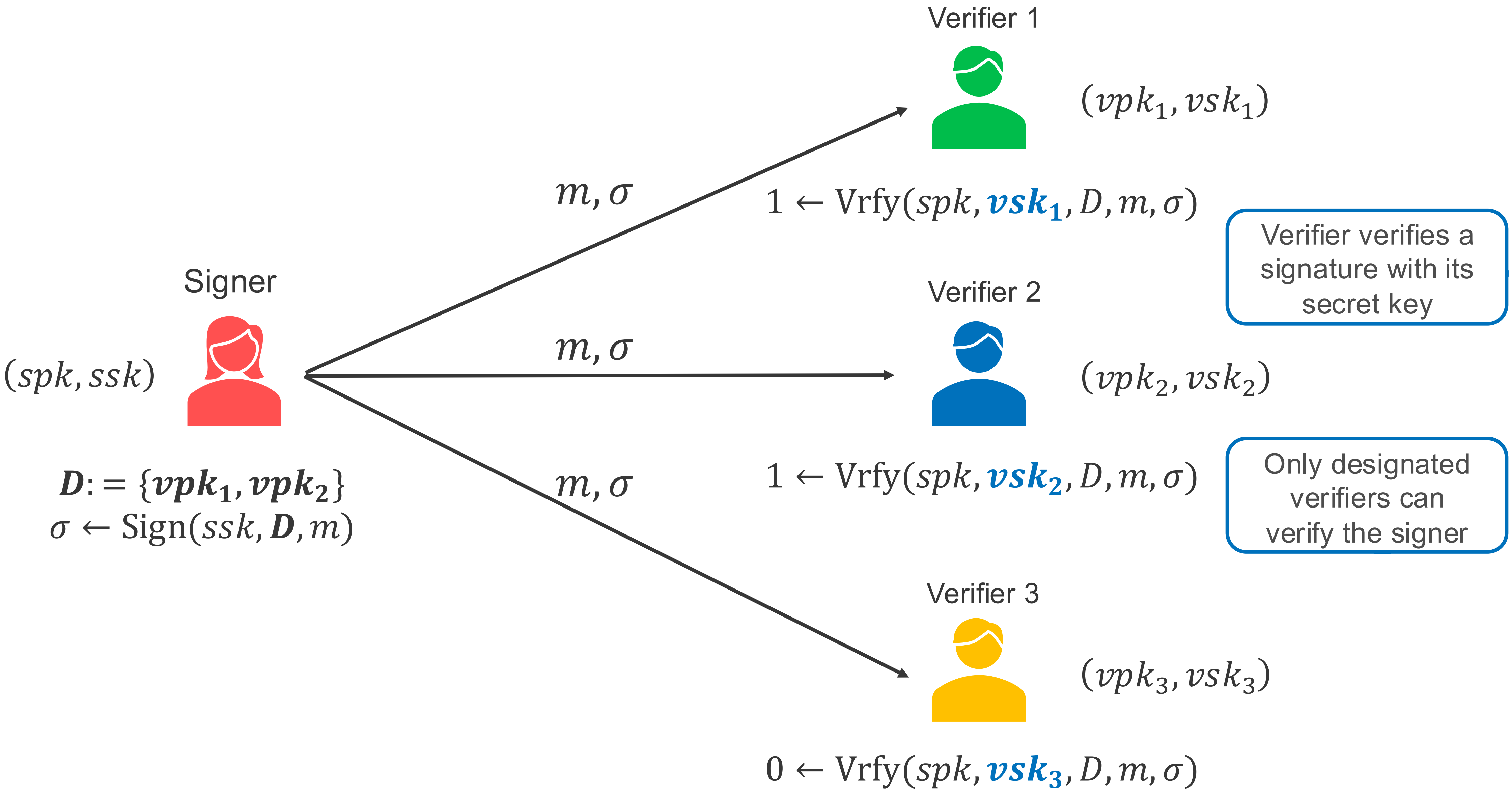
Signer specifies the verifiers

Verifier 3

(vpk_3, vsk_3)

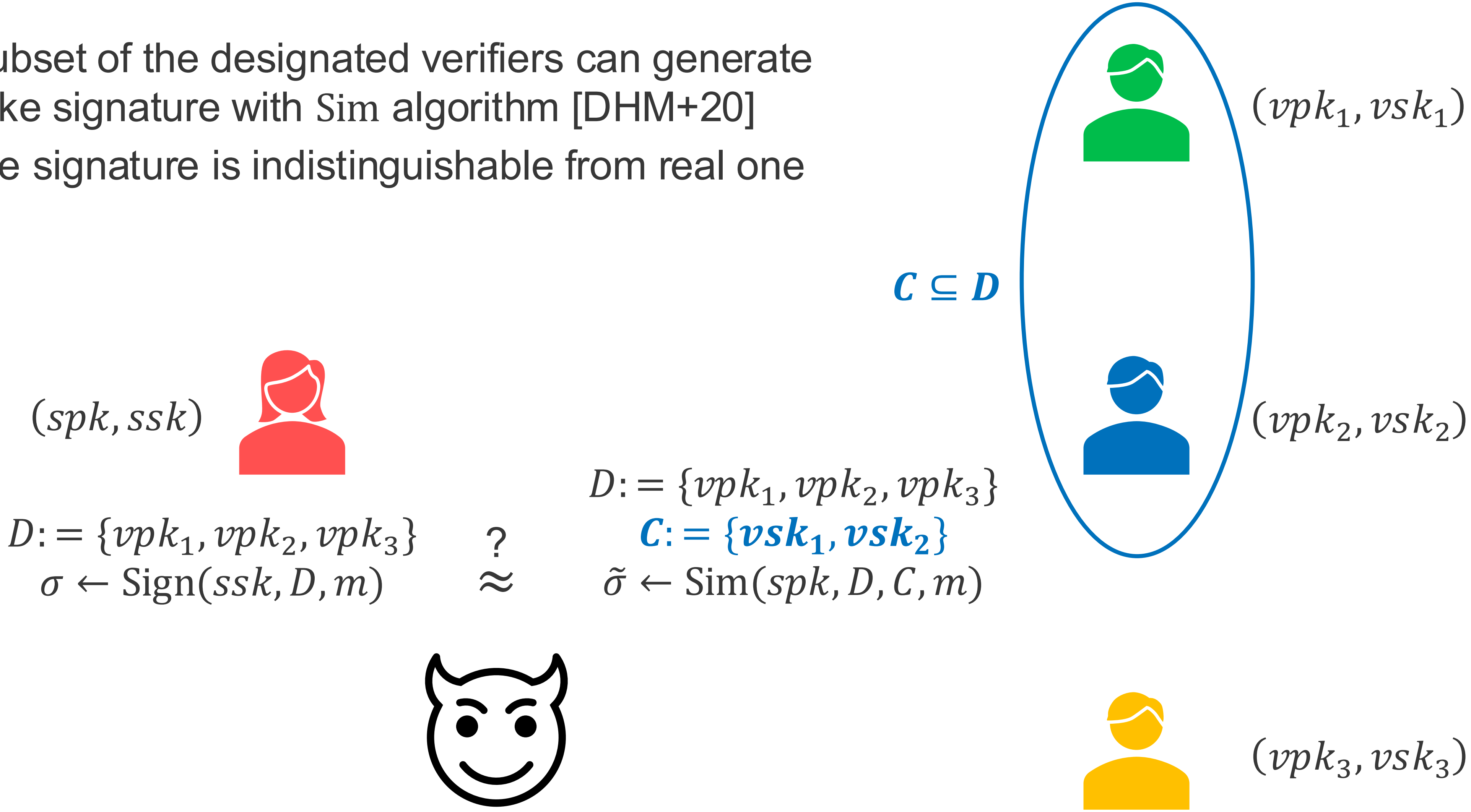
Multi-designated verifier signature (MDVS)

[LV04,ZAYS12, DHM+20]



Special property of MDVS

- A subset of the designated verifiers can generate a fake signature with Sim algorithm [DHM+20]
- Fake signature is indistinguishable from real one



Applications of MDVS

- Deniable authentication in secure group messaging [MPR22,DHM+20,CHMR23]
  - Senders can claim that the signature is a fake one since it may be simulated by designated verifiers
- Watermarking for large language models (LLMs) [HZM+24]
  - Authenticate output texts from LLMs so that only designated detectors can verify whether the texts are generated by LLMs or humans

[CHMR23] S. Chakraborty et al., Deniable authentication when signing keys leak. EUROCRYPT 2023.
[MPR22] U. Maurer et al, “Multi-designated receiver signed public key encryption,” EUROCRYPT 2022.
[HZM+24] Z. Huang et al., “Multi-designated detector watermarking for language models,” Cryptology ePrint Archive, 2024.

Motivation and our goal

While MDVS is becoming more attractive,
its security is ambiguous ☹

- Different security notions in the literature [ZAYS12, DHM+20, CHMR23]
  - Those differences and relations are not fully discussed

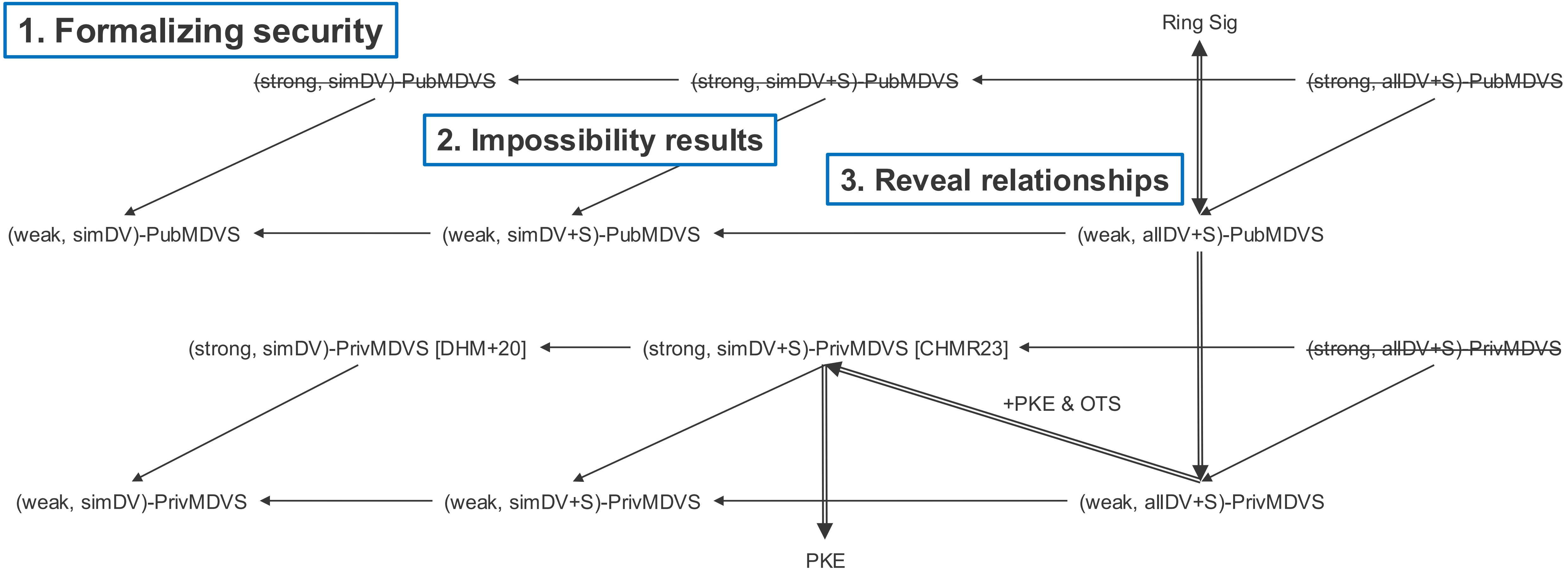
⇩

-Our goal-
Clarify the security of MDVS for the creation of applications

- Organize various security definitions of MDVS and reveal their relations
- Provide a (simple) construction of MDVS with various types of security
  - Existing constructions [DHM+20,CHMR23] are too complex

Our contributions

Comprehensive formalization and analysis of MDVS



Formalize security definitions of **MDVS**

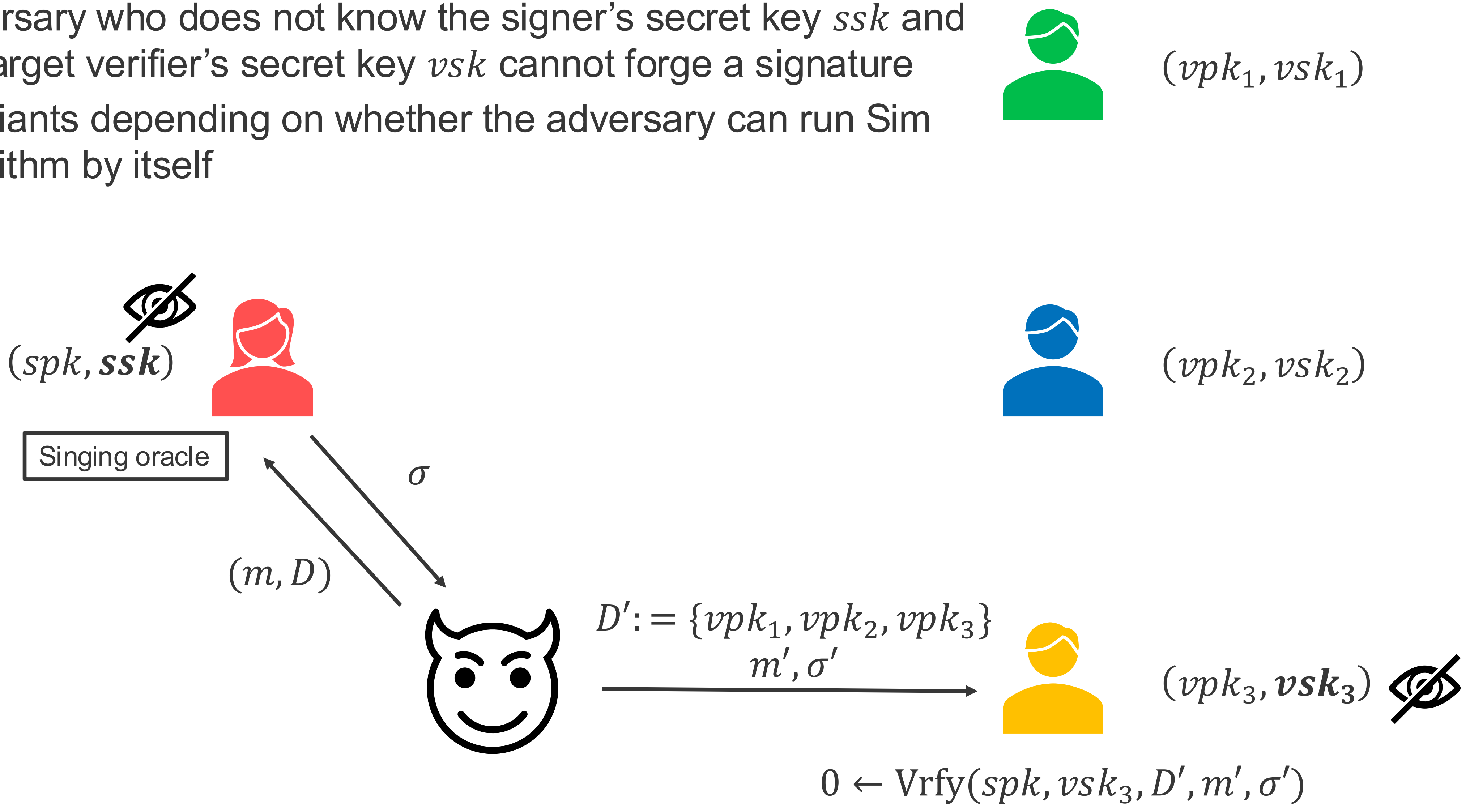
Formalize security definitions of **MDVS**

- We start with formalizing the existing security definitions in [ZAYS12, DHM+20, CHMR23]

- Fundamental notions are unforgeability and OTR
- Start with unforgeability and OTR in [ZAYS12, DHM+20, CHMR23]

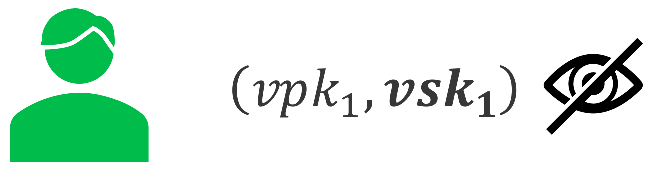
Property of MDVS: Unforgeability

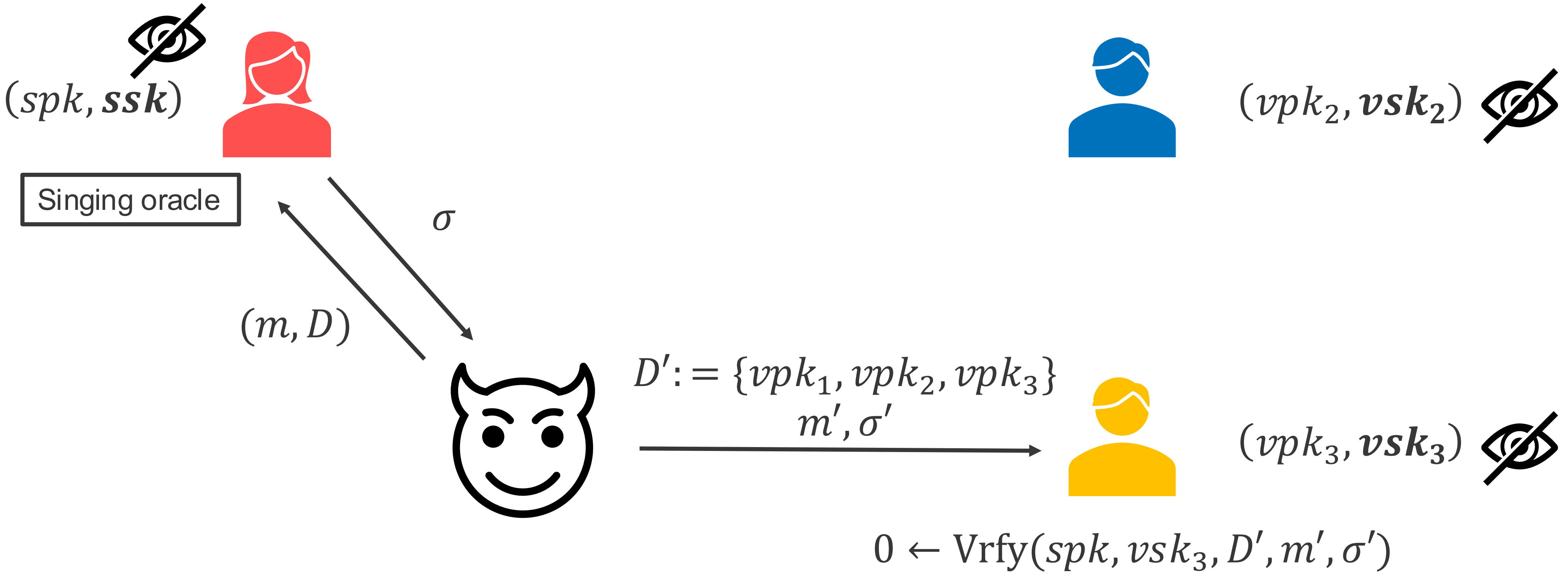
- Adversary who does not know the signer's secret key ssk and the target verifier's secret key vsk cannot forge a signature
- 2 variants depending on whether the adversary can run Sim algorithm by itself



Variations of unforgeability

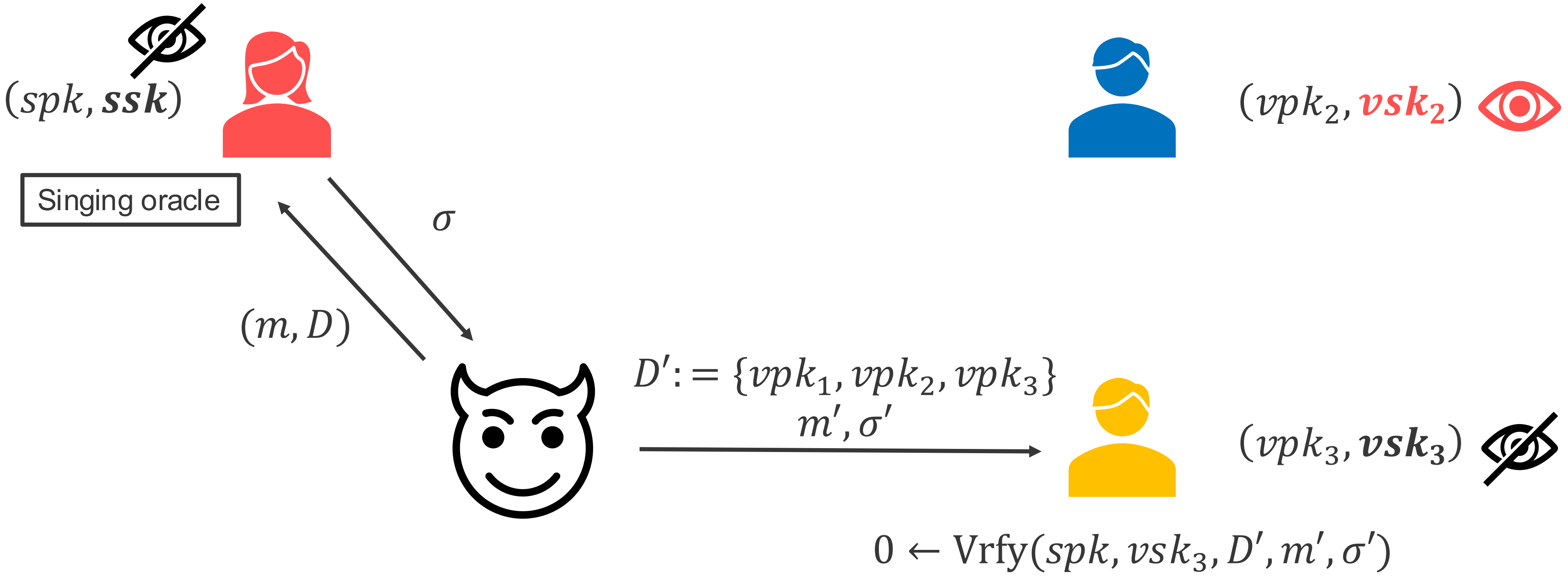
- 2 variants depending on whether the adversary can run Sim algorithm by itself
  - **Weak**: Cannot run Sim = any vsk in D are unknown [ZAYS12]
    - Fake signature is valid for any vsk in D





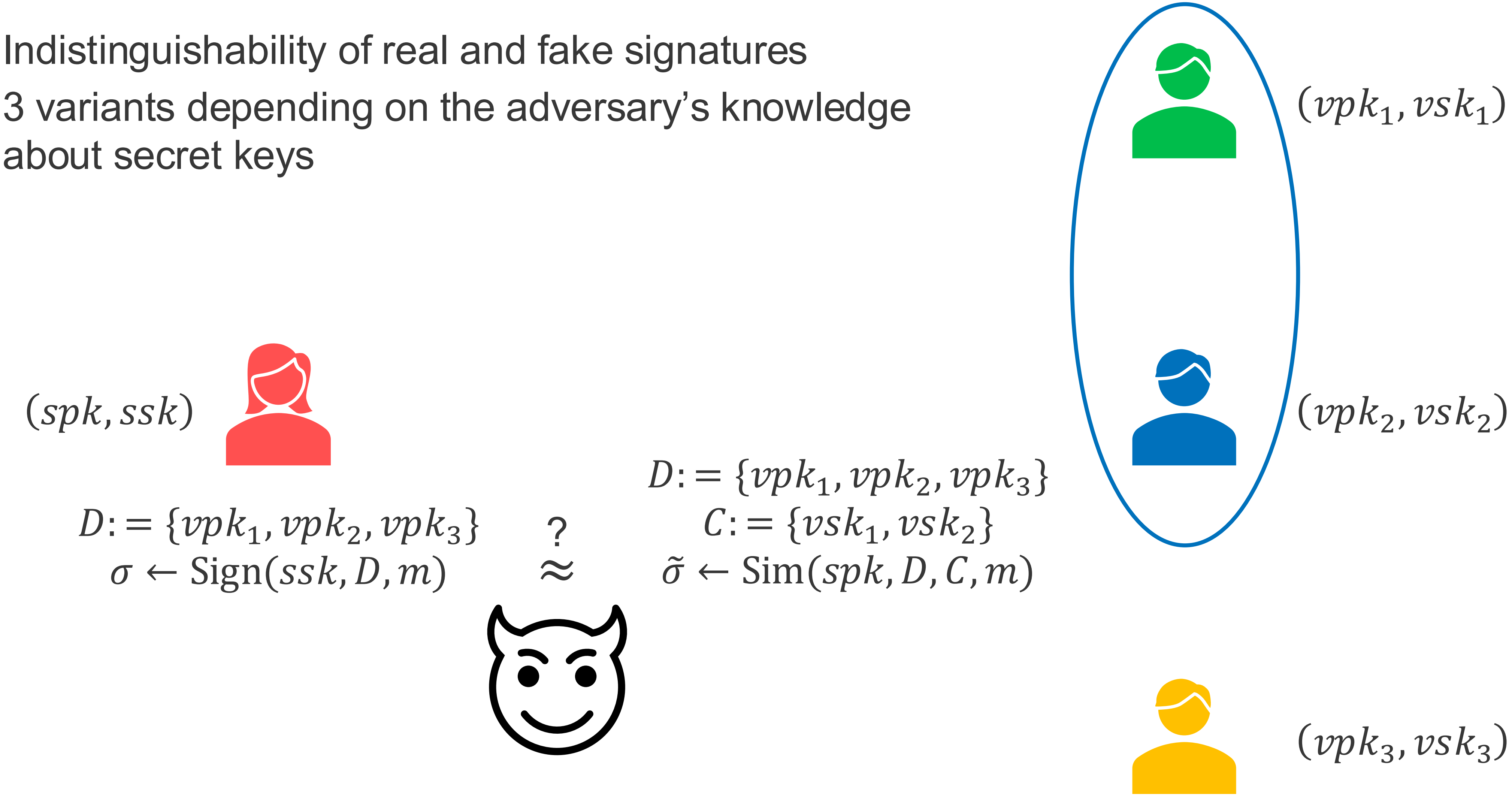
Variations of unforgeability

- 2 variants depending on whether the adversary can run Sim algorithm by itself
  - Weak: Cannot run Sim = any vsk in D are unknown [ZAYS12]
    - Fake signature is valid for any vsk in D
  - **Strong**: Can run Sim = some vsk in D is known [DHM+20]
    - Fake signature is invalid for any vsk in $D \setminus C$



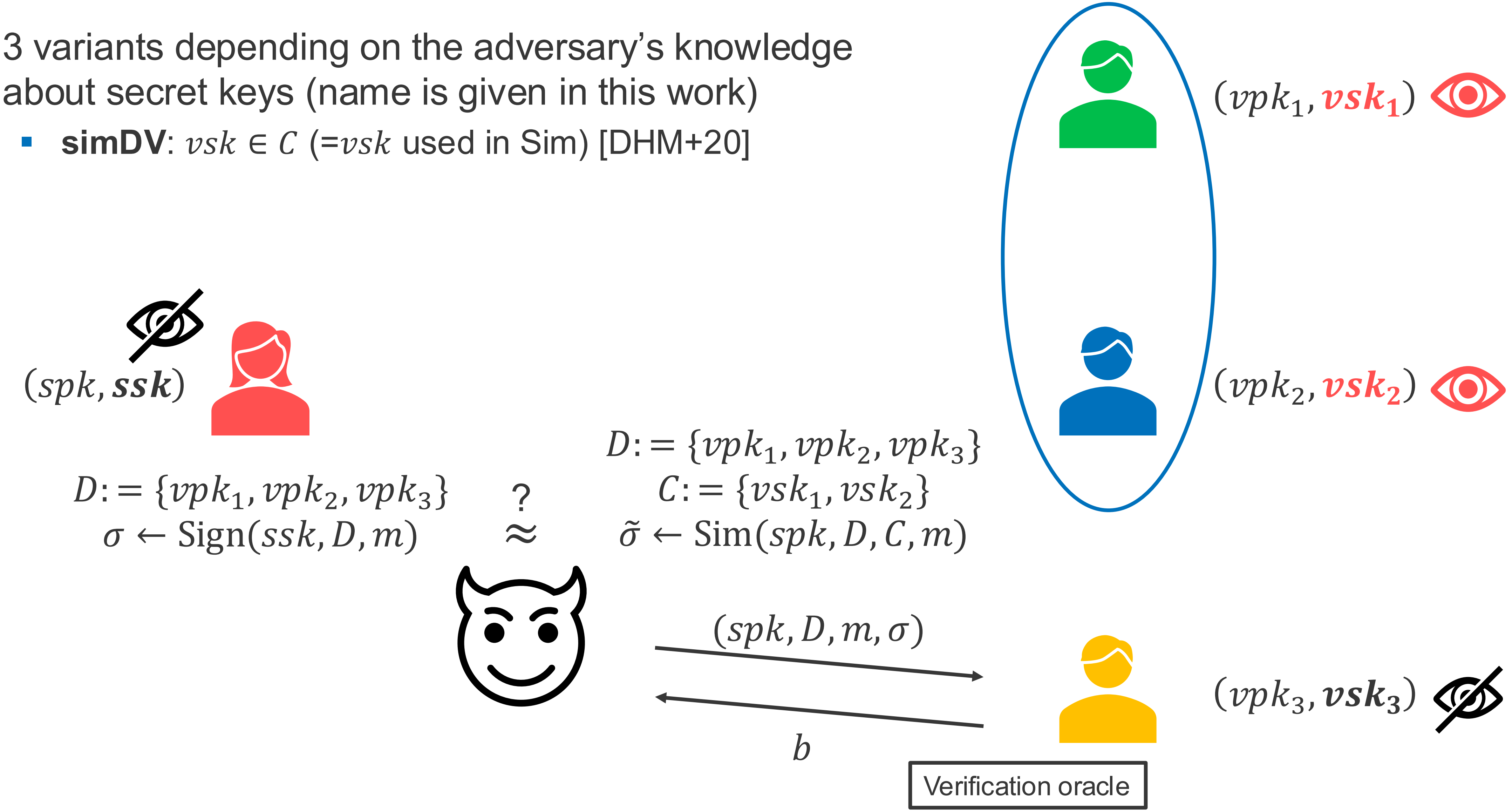
Property of MDVS: Off-the-record (OTR)

- Indistinguishability of real and fake signatures
- 3 variants depending on the adversary's knowledge about secret keys



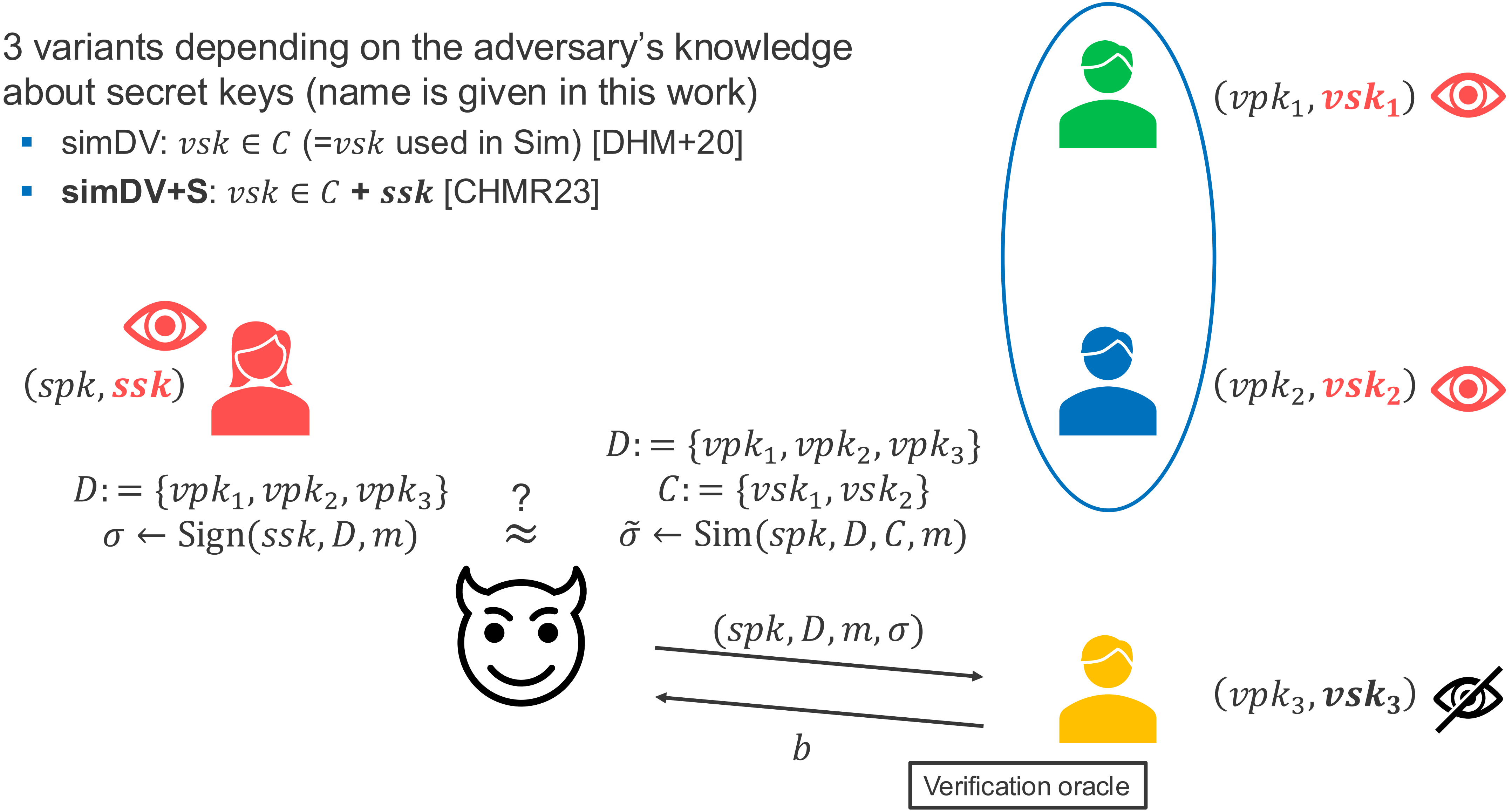
Variations of off-the-record (OTR)

- 3 variants depending on the adversary's knowledge about secret keys (name is given in this work)
  - **simDV**: $vsk \in C$ (=vsk used in Sim) [DHM+20]



Variations of off-the-record (OTR)

- 3 variants depending on the adversary's knowledge about secret keys (name is given in this work)
  - simDV: $vsk \in C$ (=vsk used in Sim) [DHM+20]
  - **simDV+S**: $vsk \in C$ **+** $\boldsymbol{ssk}$ [CHMR23]



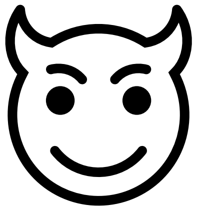
Variations of off-the-record (OTR)

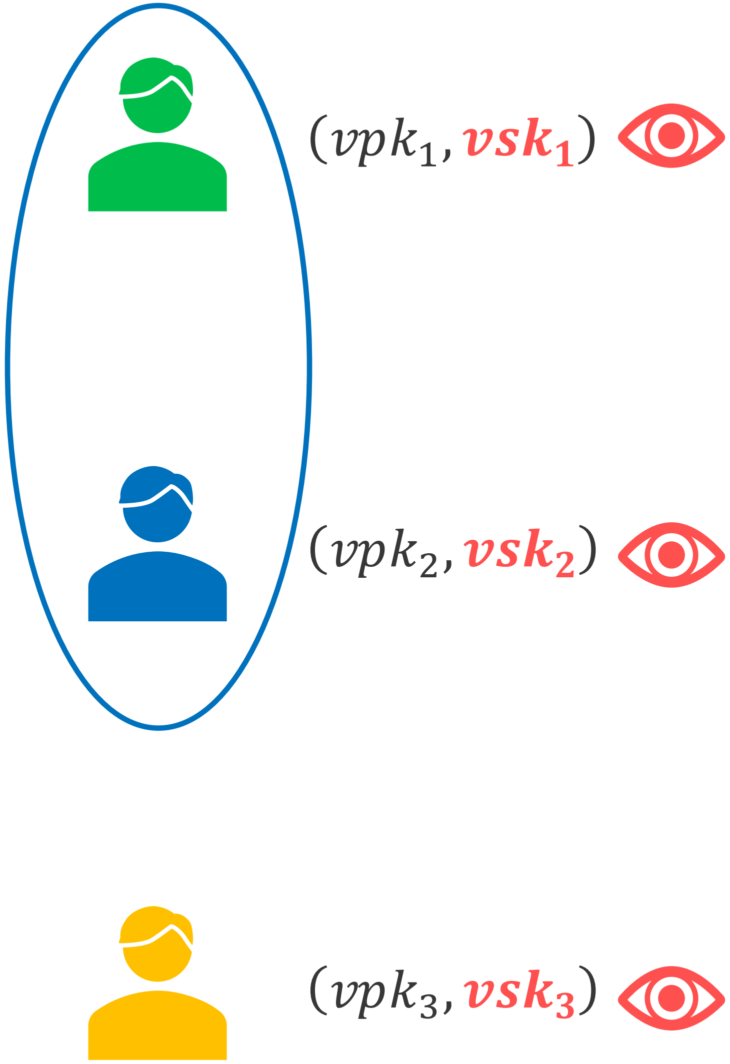
- 3 variants depending on the adversary's knowledge about secret keys (name is given in this work)
  - simDV: $vsk \in C$ (=vsk used in Sim) [DHM+20]
  - simDV+S: $vsk \in C$ + ssk [CHMR23]
  - **allDV+S**: **all** $\boldsymbol{vsk}$ + ssk [ZAYS12]

$$D := \{vpk_1, vpk_2, vpk_3\}$$
$$\sigma \leftarrow \mathrm{Sign}(ssk, D, m)$$

$$\overset{?}{\approx}$$

$$D := \{vpk_1, vpk_2, vpk_3\}$$
$$C := \{vsk_1, vsk_2\}$$
$$\tilde{\sigma} \leftarrow \mathrm{Sim}(spk, D, C, m)$$





Verifiability: public and private

- We can define publicly verifiable MDVS
  - Signature verification does not use any secret keys
  - Considered in (Single)DVS [BFG+22]
    - Public verifiable DVS and ring signature are equivalent [BFG+22,HKKP22]

(spk, ssk)  $\xrightarrow{m,\sigma}$  (vpk_2, vsk_2)

$D := \{vpk_1, vpk_2, vpk_3\}$
$\sigma \leftarrow \mathrm{Sign}(ssk, D, m)$

Private verification: $1/0 \leftarrow \mathbf{Priv}\mathrm{Vrfy}(spk, \boldsymbol{vsk_2}, D, m, \sigma)$

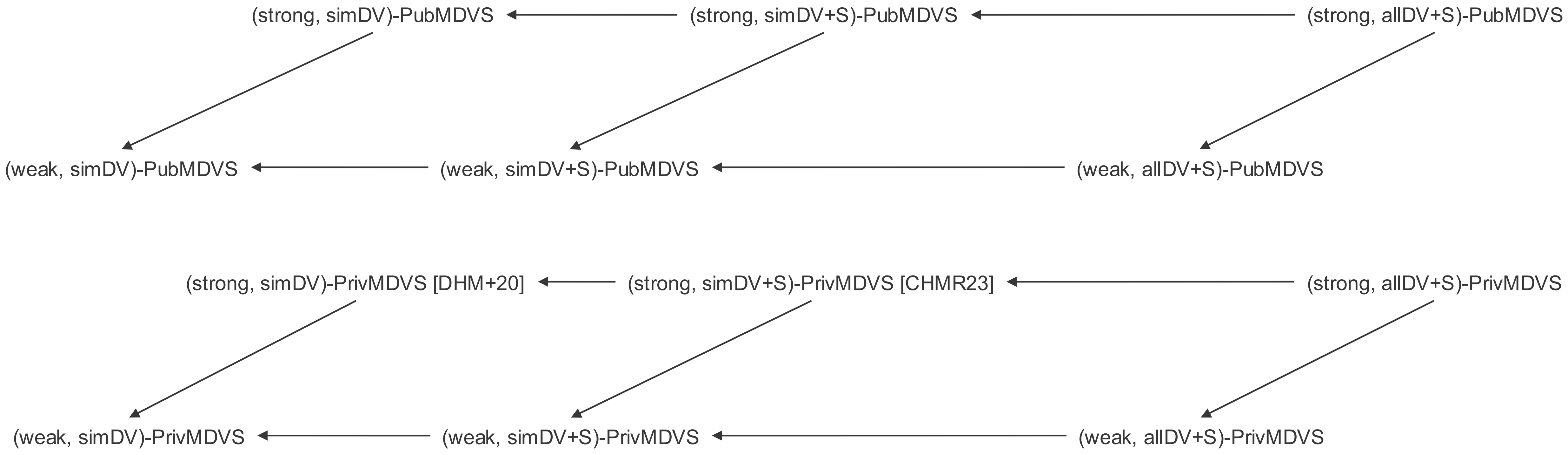
or

Public verification: $1/0 \leftarrow \mathbf{Pub}\mathrm{Vrfy}(spk, D, m, \sigma)$

[BFG+22] J. Brendel, R. Fiedler, F. Günther, C. Janson, and D. Stebila. Post-quantum asynchronous deniable key exchange and the signal handshake. PKC 2022.
[HKKP22] K. Hashimoto, S. Katsumata, K. Kwiatkowski, and T. Prest. An Efficient and Generic Construction for Signal's Handshake (X3DH): Post-Quantum, State Leakage Secure, and Deniable. Journal of Cryptology, 2022.

Identify possible MDVSs

{weak, strong}-Unf x {simDV, simDV+S, allDV+S}-OTR
x {Priv, Pub}-Verify = 12 variants of MDVS



Comprehensive analysis of MDVS

Analysis of MDVS

Q1: Can we realize all of the MDVSs?

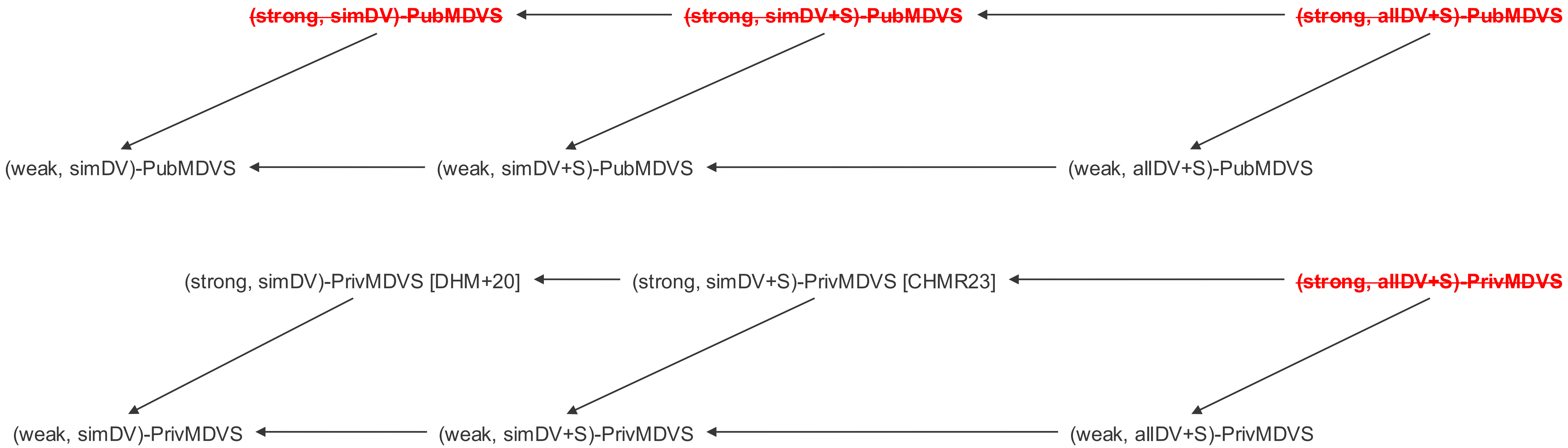
$$\begin{tikzcd}
\text{(strong, simDV)-PubMDVS} \arrow[d] & \text{(strong, simDV+S)-PubMDVS} \arrow[l] \arrow[d] & \text{(strong, allDV+S)-PubMDVS} \arrow[l] \arrow[d] \\
\text{(weak, simDV)-PubMDVS} & \text{(weak, simDV+S)-PubMDVS} \arrow[l] & \text{(weak, allDV+S)-PubMDVS} \arrow[l]
\end{tikzcd}$$

$$\begin{tikzcd}
\text{(strong, simDV)-PrivMDVS [DHM+20]} \arrow[d] & \text{(strong, simDV+S)-PrivMDVS [CHMR23]} \arrow[l] \arrow[d] & \text{(strong, allDV+S)-PrivMDVS} \arrow[l] \arrow[d] \\
\text{(weak, simDV)-PrivMDVS} & \text{(weak, simDV+S)-PrivMDVS} \arrow[l] & \text{(weak, allDV+S)-PrivMDVS} \arrow[l]
\end{tikzcd}$$

Impossibility in MDVS

A: We cannot construct the following MDVS schemes

- Strong unforgeability and allDV+S OTR are conflict in PrivMDVS
- Strong unforgeability and any OTR are conflict in PubMDVS



Analysis of MDVS

We identified that some of MDVS cannot be realized

Q2: How do we construct other MDVSs?

~~(strong, simDV)-PubMDVS~~ ~~(strong, simDV+S)-PubMDVS~~ ~~(strong, allDV+S)-PubMDVS~~

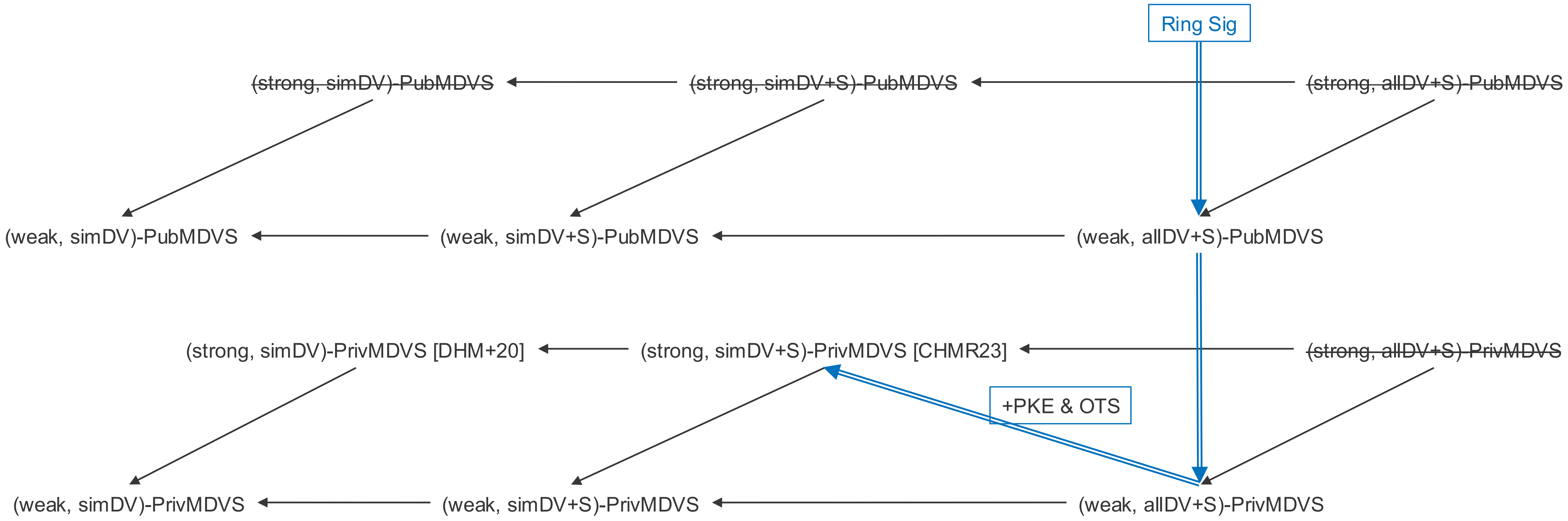
(weak, simDV)-PubMDVS **(weak, simDV+S)-PubMDVS** **(weak, allDV+S)-PubMDVS**

(strong, simDV)-PrivMDVS [DHM+20] **(strong, simDV+S)-PrivMDVS [CHMR23]** ~~(strong, allDV+S)-PrivMDVS~~

(weak, simDV)-PrivMDVS **(weak, simDV+S)-PrivMDVS** **(weak, allDV+S)-PrivMDVS**

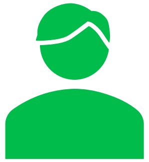
New constructions of MDVS

A2: New constructions based on ring signatures and PKE



(weak, allDV+S)-PubMDVS from RS

- Ring R consists of designated verifier set D and spk
- Weak-Unf: Unforgeability of RS
- allDV+S: Anonymity w.r.t. full key exposure of RS



$(vpk_1, vsk_1) \leftarrow \mathrm{RS.KGen}()$

$(spk, ssk) \leftarrow \mathrm{RS.KGen}()$

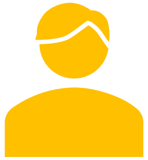
m, σ

$(vpk_2, vsk_2) \leftarrow \mathrm{RS.KGen}()$

$\underline{\mathrm{MDVS.Sign}(ssk, D, m):}$
// $D := \{vpk_1, vpk_2, vpk_3\}$
$\sigma \leftarrow \mathrm{RS.Sign}(ssk, D \cup \{spk\}, m)$

$\underline{\mathrm{MDVS.PubVrfy}(spk, D, m, \sigma):}$
$b \leftarrow \mathrm{RS.Vrfy}(D \cup \{spk\}, m, \sigma)$

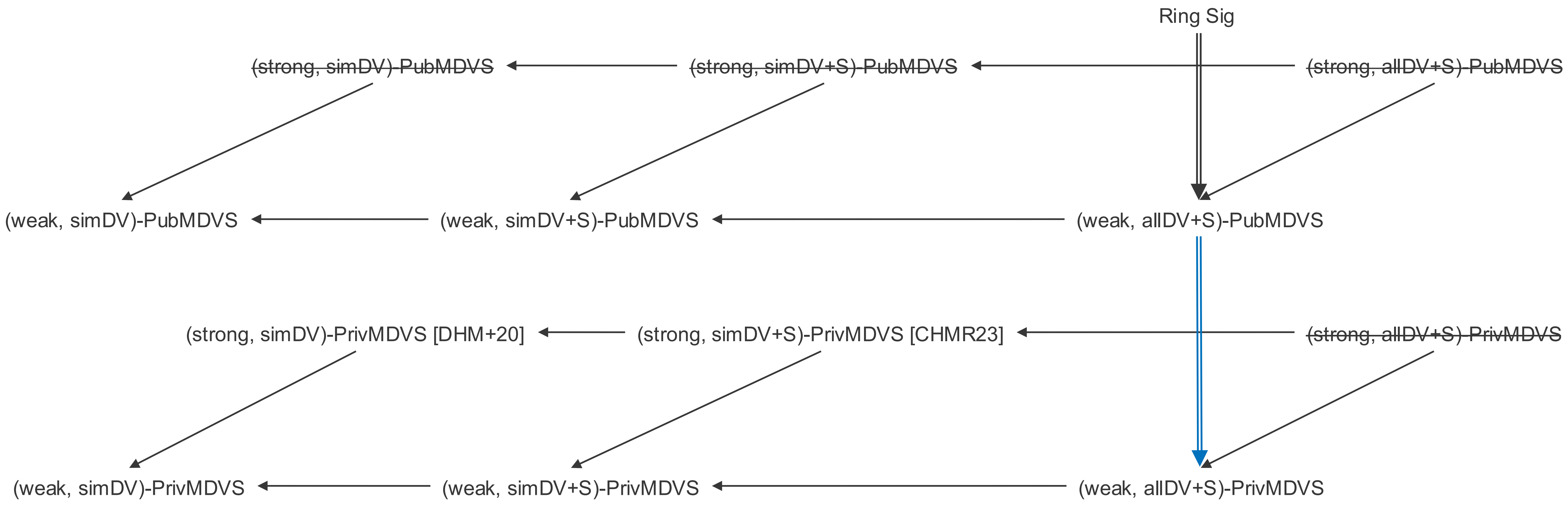
$\underline{\mathrm{MDVS.Sim}\ (spk, D, C, m):}$
$vsk \leftarrow C$ // Chose e.g., 1st one
$\sigma \leftarrow \mathrm{RS.Sign}(vsk, D \cup \{spk\}, m)$



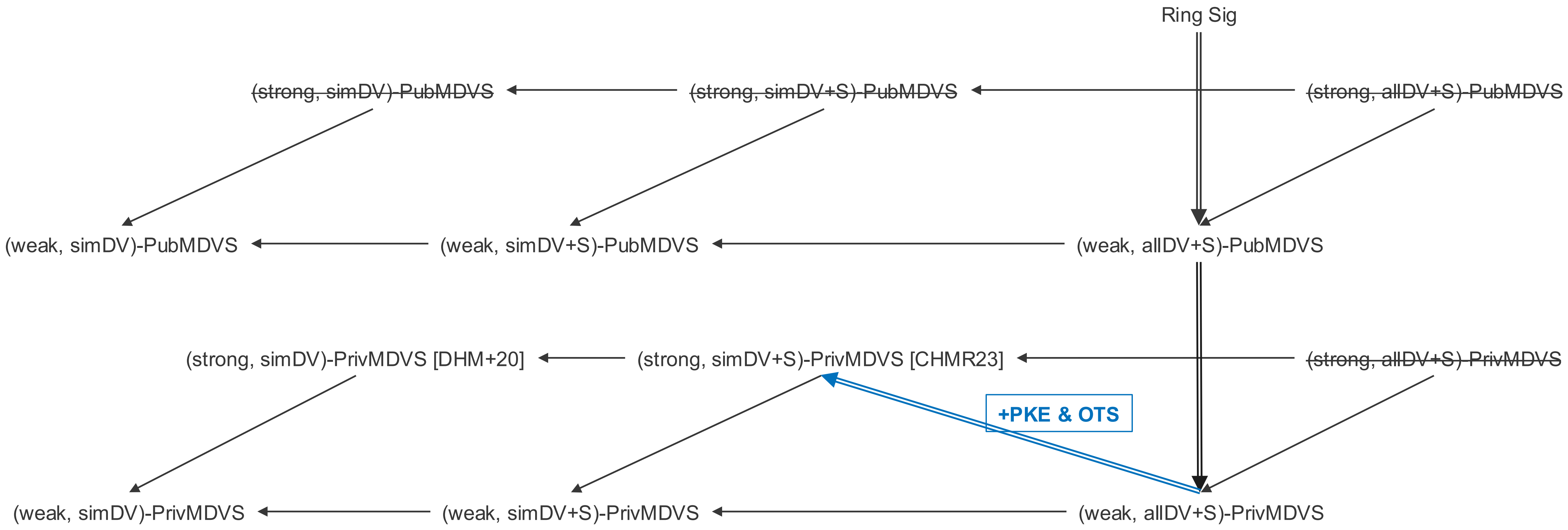
$(vpk_3, vsk_3) \leftarrow \mathrm{RS.KGen}()$

(weak, allDV+S)-PrivMDVS from PubMDVS

- Each algorithm of PrivMDVS runs the corresponding one of PubMDVS
  - $\mathrm{PrivVrfy}(spk, vsk, D, m, \sigma)$: Run $\mathrm{PubVrfy}(spk, D, m, \sigma)$ (ignore vsk)
  - allDV+S-OTR and OTR for PubVrfy have the same situation



Construct (strong, simDV+S)-PrivMDVS from (weak, allDV+S)-PrivMDVS with PKE and OTS



(weak, allDV+S)-PrivMDVS $\overset{+\text{PKE}}{\Longrightarrow}$ (strong, simDV+S)-PrivMDVS

(weak, allDV+S)-PrivMDVS

$\underline{\text{MDVS}'.\text{Sign}(ssk, D, m):}$
For each $vpk_j \in D$:
$\quad \boldsymbol{\sigma_j \leftarrow \text{MDVS}.\text{Sign}(ssk, \{vpk_j\}, m)}$
$\sigma \leftarrow \{\sigma_j\}$

- Pair-wise signature for signer and each verifier
  - Each verifier checks the signature sent to itself
- It achieves strong unforgeability
  - Adversary does not know both ssk and the target verifier's vsk
    $\Rightarrow$ It cannot generate both real sign and fake sig
  - Implied from weak unforgeability of PrivMDVS

(weak, allDV+S)-PrivMDVS $\overset{+\text{PKE}}{\Longrightarrow}$ (strong, simDV+S)-PrivMDVS

(weak, allDV+S)-PrivMDVS

$\underline{\mathrm{MDVS}'.\mathrm{Sign}(ssk, D, m):}$
For each $vpk_j \in D$:
$\sigma_j \leftarrow \mathrm{MDVS}.\mathrm{Sign}(ssk, \{vpk_j\}, m)$
$\sigma \leftarrow \{\sigma_j\}$

Can generate a fake signature for verifiers in C ☺

$\underline{\mathrm{MDVS}'.\mathrm{Sim}(spk, D, C, m):}$
For each $vpk_j \in D$:
If $vsk_j \in C$: $\boldsymbol{\sigma_j \leftarrow \mathrm{MDVS}.\mathrm{Sim}(spk, \{vpk_j\}, \{vsk_j\}, m)}$
Else: $\boldsymbol{\sigma_j \leftarrow 0}$
$\sigma \leftarrow \{\sigma_j\}$

Cannot generate a fake signature for verifiers not in C ☹

(weak, allDV+S)-PrivMDVS $\xRightarrow{+\text{PKE}}$ (strong, simDV+S)-PrivMDVS

(weak, allDV+S)-PrivMDVS + PKE

$\underline{\mathrm{MDVS}'.\mathrm{Sign}(ssk, D, m):}$
For each $(vpk_j, pk_j) \in D$:
$\sigma_j \leftarrow \mathrm{MDVS}.\mathrm{Sign}(ssk, \{vpk_j\}, m)$
$\boldsymbol{CT_j \leftarrow \mathrm{PKE}.\mathrm{Enc}(pk_j, \sigma_j)}$
$\sigma \leftarrow \{CT_j\}$

$\underline{\mathrm{MDVS}'.\mathrm{Sim}(spk, D, C, m):}$
For each $(vpk_j, pk_j) \in D$:
If $vsk_j \in C$: $\sigma_j \leftarrow \mathrm{MDVS}.\mathrm{Sim}(spk, \{vpk_j\}, \{vsk_j\}, m)$
Else: $\sigma_j \leftarrow 0$
$\boldsymbol{CT_j \leftarrow \mathrm{PKE}.\mathrm{Enc}(pk_j, \sigma_j)}$
$\sigma \leftarrow \{CT_j\}$

Encrypt each signature with verifier's PKE key $\boldsymbol{pk}$

(weak, allDV+S)-PrivMDVS $\xRightarrow{\text{+PKE}}$ (strong, simDV+S)-PrivMDVS

(weak, allDV+S)-PrivMDVS + PKE

<u>$\mathrm{MDVS}'.\mathrm{Sign}(ssk, D, m)$:</u>
For each $(vpk_j, pk_j) \in D$:
  $\sigma_j \leftarrow \mathrm{MDVS}.\mathrm{Sign}(ssk, \{vpk_j\}, m)$
  $\boldsymbol{CT_j \leftarrow \mathrm{PKE}.\mathrm{Enc}(pk_j, \sigma_j)}$
$\sigma \leftarrow \{CT_j\}$

<u>$\mathrm{MDVS}'.\mathrm{Sim}(spk, D, C, m)$:</u>
For each $(vpk_j, pk_j) \in D$:
  If $vsk_j \in C$: $\sigma_j \leftarrow \mathrm{MDVS}.\mathrm{Sim}(spk, \{vpk_j\}, \{vsk_j\}, m)$
  Else: $\sigma_j \leftarrow 0$
  $\boldsymbol{CT_j \leftarrow \mathrm{PKE}.\mathrm{Enc}(pk_j, \sigma_j)}$
$\sigma \leftarrow \{CT_j\}$

- Verifier not in C: Security of PKE ensures indistinguishability
  - simDV: Adversary does not know verifiers' PKE key outside C
- Verifier in C: allDV+S-OTR ensures indistinguishability

$\Rightarrow$ simDV+S-OTR

(weak, allDV+S)-PrivMDVS $\overset{+\text{PKE}}{\Longrightarrow}$ (strong, simDV+S)-PrivMDVS

(weak, allDV+S)-PrivMDVS + IND-CCA PKE + Strong OTS = (strong, simDV+S)-PrivMDVS

$\underline{\mathrm{MDVS}'.\mathrm{Sign}(ssk, D, m):}$
$(ovk, osk) \leftarrow \mathrm{OTS.Gen}()$
For each $(vpk_j, pk_j) \in D$:
  $\sigma_j \leftarrow \mathrm{MDVS.Sign}\big(ssk, \{vpk_j\}, m\big)$
  $CT_j \leftarrow \mathrm{PKE.Enc}(pk_j, \sigma_j || ovk)$
$osig \leftarrow \mathrm{OTS.Sign}(osk, spk||D||m||\{CT_j\})$
$\sigma \leftarrow \big(\{CT_j\}, ovk, osig\big)$

$\underline{\mathrm{MDVS}'.\mathrm{Sim}(spk, D, C, m):}$
$(ovk, osk) \leftarrow \mathrm{OTS.Gen}()$
For each $(vpk_j, pk_j) \in D$:
  If $vsk_j \in C$: $\sigma_j \leftarrow \mathrm{MDVS.Sim}\big(spk, \{vpk_j\}, \{vsk_j\}, m\big)$
  Else: $\sigma_j \leftarrow 0$
  $CT_j \leftarrow \mathrm{PKE.Enc}(pk_j, \sigma_j || ovk)$
$osig \leftarrow \mathrm{OTS.Sign}(osk, spk||D||m||\{CT_j\})$
$\sigma \leftarrow \big(\{CT_j\}, ovk, osig\big)$

- **Use OTS to prevent verifing CT_j with another $spk||D||m$**
- **Use CCA PKE to answer verification oracle**

Efficiency of MDVS

Evaluate the signature size and the running time in classical and PQ settings of
Scheme 1: (weak, allDV+S)-PrivMDVS from RS and
Scheme 2: (strong, simDV+S)-PrivMDVS from RS+PKE

Signature size

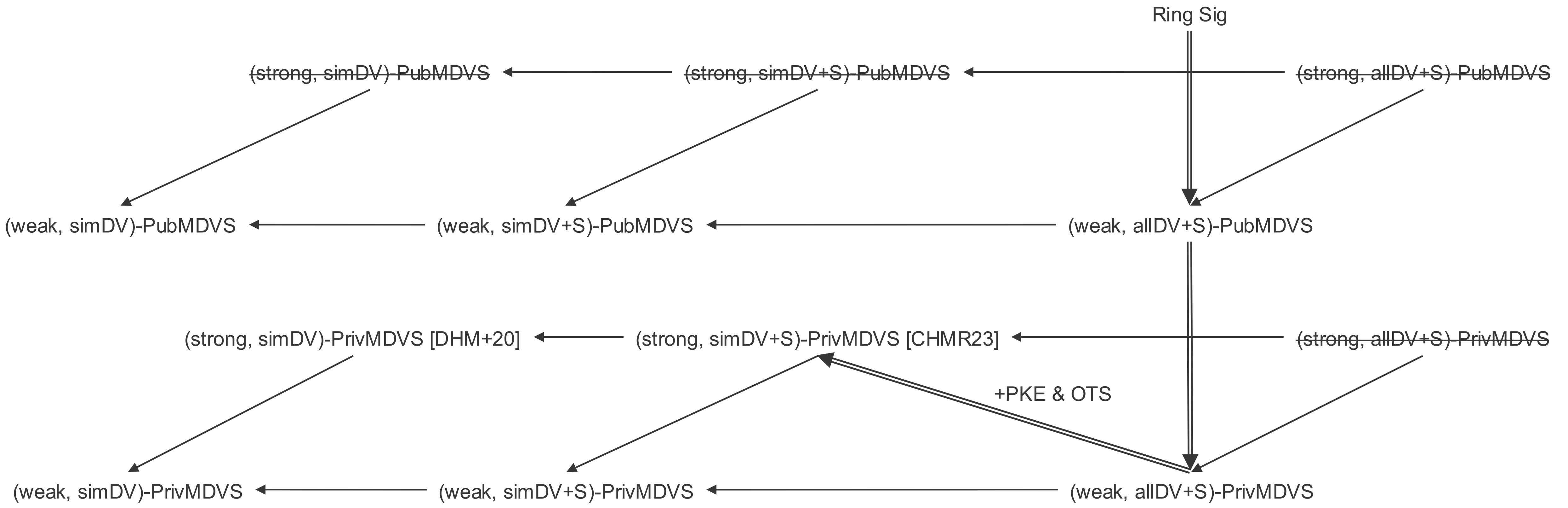
#Verifiers	2^1	2^3	2^6	2^{10}	PQ?
Scheme 1	195 B 4.5 KB	327 B 4.6 KB	525 B 6.0 KB	789 B 31.2 KB	X O
Scheme 2	614 B 17.9 KB	2168 B 59.3 KB	16672 B 445.7 KB	265312 B 7069.7 KB	X O

Signing time

#Verifiers	2^1	2^3	2^6	2^{10}	PQ?
Scheme 1	8 ms 2348 ms	36 ms 3015 ms	266 ms 7247 ms	4118 ms 72920 ms	X O
Scheme 2	17 ms 4696 ms	67 ms 18784 ms	538 ms 150273 ms	8602 ms 2404362 ms	X O

Relations from MDVS to other primitives

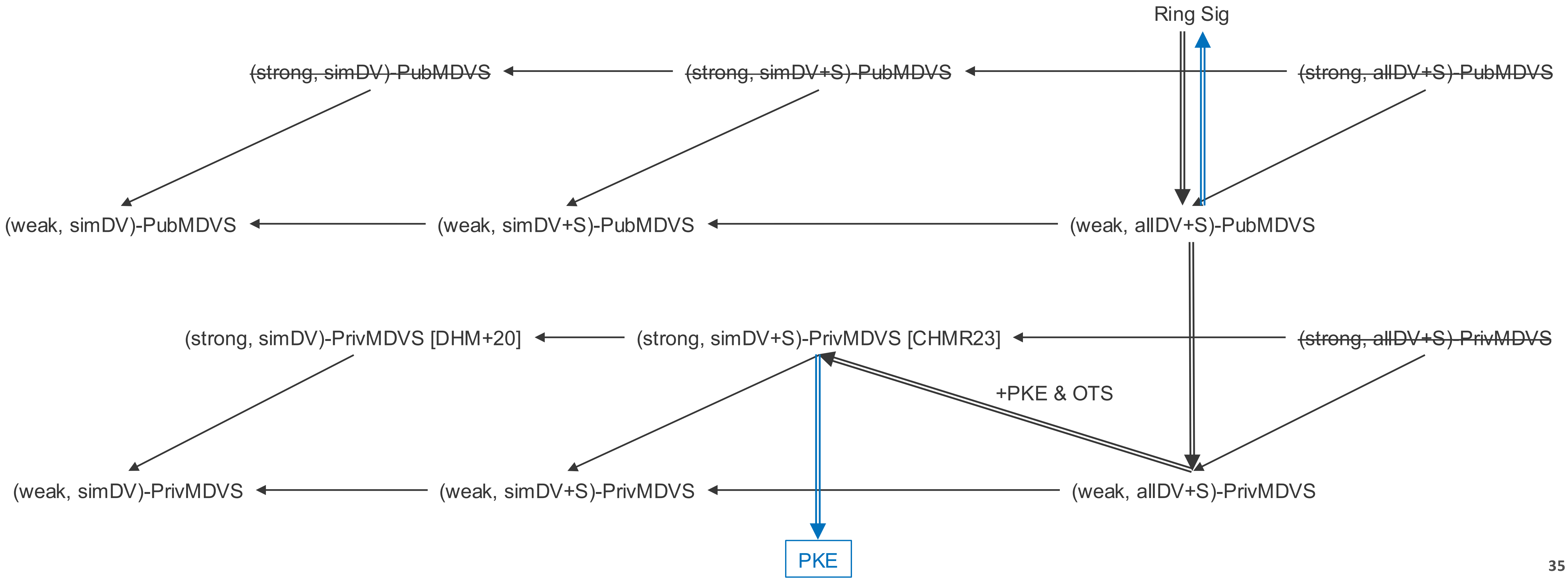
Q3: MDVS implies other cryptographic primitives?



Relations to other primitives

A3: Obtain the following implication results

- (weak, allDV+S)-PubMDVS implies ring signatures (i.e., they are equivalent)
- (strong, simDV+S)-PrivMDVS implies PKE

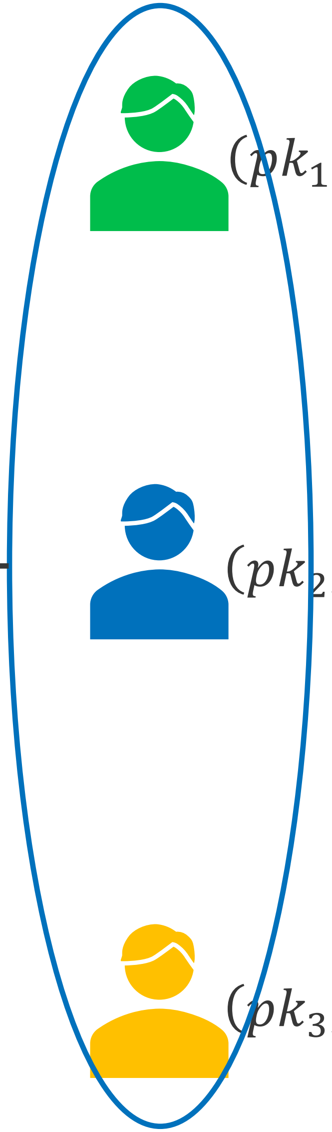


(weak, allDV+S)-PubMDVS ⇒ RS

- Prepare a virtual signer in public parameter, and designated verifier set D is considered ring R
- RS.Sign runs MDVS.Sim to generate signatures
- Require MDVS.PubVrfy for public verifiability of RS

$$pp_{RS} \coloneqq (pp_{MDVS}, \boldsymbol{spk})$$

m, σ



$(pk_1, sk_1) \leftarrow \mathrm{MDVS.VKGen}()$

$D =$ ring R

$(pk_2, sk_2) \leftarrow \mathrm{MDVS.VKGen}()$

$(pk_3, sk_3) \leftarrow \mathrm{MDVS.VKGen}()$

<u>RS. Sign(sk_2, R, m):</u>
// $R := \{pk_1, pk_2, pk_3\}$
$\sigma \leftarrow \mathrm{MDVS.Sim}\ (spk, D, \{sk_2\}, m)$

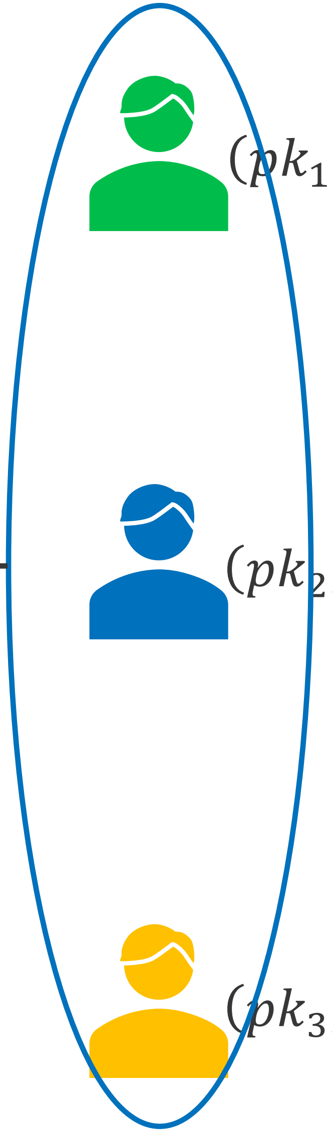
<u>RS. Vrfy(m, R, σ):</u>
$b \leftarrow \mathrm{MDVS.PubVrfy}(spk, R, m, \sigma)$

(weak, allDV+S)-PubMDVS ⇒ RS

- Unforgeability of RS: weak-Unf of MDVS
  - allDV+S-OTR ensures real sig ≈ fake sig
- Anonymity of RS: allDV+S-OTR of MDVS
  - Any fake signatures are indistinguishable from real signature

$pp_{RS} \coloneqq (pp_{MDVS}, \boldsymbol{spk})$

m, σ



$(pk_1, sk_1) \leftarrow \mathrm{MDVS.VKGen}()$

$D = \text{ring } R$

$(pk_2, sk_2) \leftarrow \mathrm{MDVS.VKGen}()$

$(pk_3, sk_3) \leftarrow \mathrm{MDVS.VKGen}()$

<u>$\mathrm{RS.Sign}(sk_2, R, m)$:</u>
// $R := \{pk_1, pk_2, pk_3\}$
$\sigma \leftarrow \mathrm{MDVS.Sim}\,(spk, D, \{sk_2\}, m)$

<u>$\mathrm{RS.Vrfy}(m, R, \sigma)$:</u>
$b \leftarrow \mathrm{MDVS.PubVrfy}(spk, R, m, \sigma)$

(strong, simDV+S)-PrivMDVS ⇒ IND-CCA PKE

$$pp_{PKE} := (pp_{MDVS}, \underbrace{spk, ssk}_{\text{signer's key}}, \underbrace{vpk, vsk}_{\text{verifier's key}}, \overbrace{m}^{\text{some message for signing}})$$

$pk := \widehat{vpk}$

$(pk, sk) := \left(\widehat{vpk}, \widehat{vsk}\right) \leftarrow \mathrm{VKGen}()$

$$CT := \sigma$$

<u>Enc($pk, M \in \{0,1\}$):</u>
If $M = 1$
$\sigma \leftarrow \mathrm{Sign}(ssk, \{vpk, \widehat{vpk}\}, m)$
If $M = 0$
$\sigma \leftarrow \mathrm{Sim}(spk, \{vpk, \widehat{vpk}\}, \{vsk\}, m)$

<u>Dec(sk, CT):</u>
$M \leftarrow \mathrm{PrivVrfy}(\mathrm{spk}, \widehat{vsk}, \{vpk, \widehat{vpk}\}, \sigma, m)$

(strong, simDV+S)-PrivMDVS ⇒ IND-CCA PKE

<u>Sender secretly sends information on "whether or not σ is simulated"</u>

$$pp_{PKE} := (pp_{MDVS}, spk, ssk, vpk, vsk, m)$$

$pk := \widehat{vpk}$

$sk := \widehat{vsk}$

$CT := \sigma$

<u>Enc($pk, M \in \{0,1\}$):</u>
If $M = 1$
$\sigma \leftarrow \mathrm{Sign}(ssk, \{vpk, \widehat{vpk}\}, m)$
If $M = 0$
$\sigma \leftarrow \mathrm{Sim}(spk, \{vpk, \widehat{vpk}\}, \{vsk\}, m)$

<u>Dec(sk, CT):</u>
$M \leftarrow \mathrm{PrivVrfy}(\mathrm{spk}, \widehat{vsk}, \{vpk, \widehat{vpk}\}, \sigma, m)$

- Receiver knows $\widehat{vsk}$
  ⇒ two signatures are distinguishable (Strong-Unf)
  - Real sig ⇒ $\mathrm{PrivVrfy}(\sigma) = 1$ (correctness)
  - Fake sig ⇒ $\mathrm{PrivVrfy}(\sigma) = 0$ ($\widehat{vsk}$ is not used in Sim)

(strong, simDV+S)-PrivMDVS ⇒ IND-CCA PKE

<u>Sender secretly sends information on "whether or not σ is simulated"</u>

$$pp_{PKE} := (pp_{MDVS}, spk, ssk, vpk, vsk, m)$$

$pk := \widehat{vpk}$

$CT := \sigma$

$sk := \widehat{vsk}$

<u>Enc($pk, M \in \{0,1\}$):</u>
If $M = 1$
$\quad \sigma \leftarrow \mathrm{Sign}(ssk, \{vpk, \widehat{vpk}\}, m)$
If $M = 0$
$\quad \sigma \leftarrow \mathrm{Sim}(spk, \{vpk, \widehat{vpk}\}, \{vsk\}, m)$

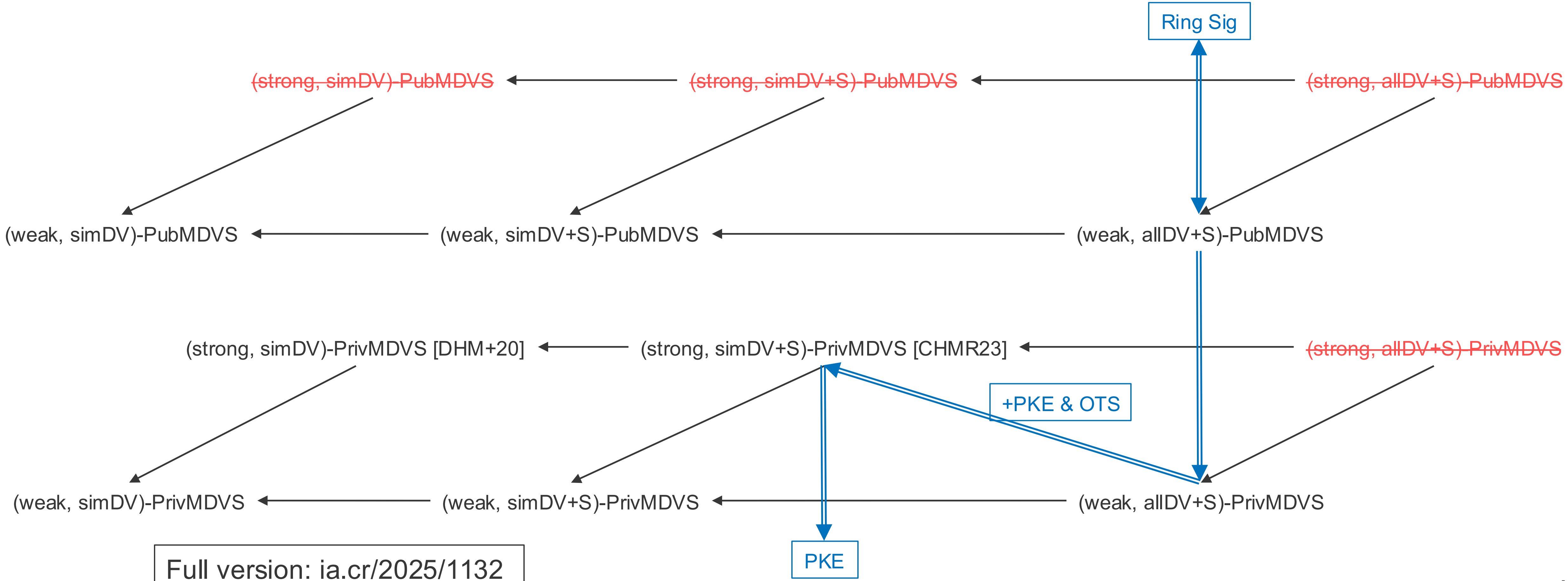
<u>Dec(sk, CT):</u>
$\quad M \leftarrow \mathrm{PrivVrfy}(\mathrm{spk}, \widehat{vsk}, \{vpk, \widehat{vpk}\}, \sigma, m)$

- Adversary does not know $\widehat{vsk}$
  ⇒ signatures are indistinguishable (simDV+S-OTR)
  - Publish ssk to encrypt publicly ⇒ <u>require +S-OTR</u>
- Verify oracle in MDVS = Dec oracle in PKE ⇒ CCA

Conclusion

Summary of our results

Comprehensive formalization and analysis of MDVS



Full version: ia.cr/2025/1132

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